Thermo-mechanical analyses and tests on laser welding process

Rafal Ortwein, Jakub Tabin, Tomasz Ślęzak

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

WPMAG 2025 Final meeting (14-16.01.2025)

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2. FEM model of welding
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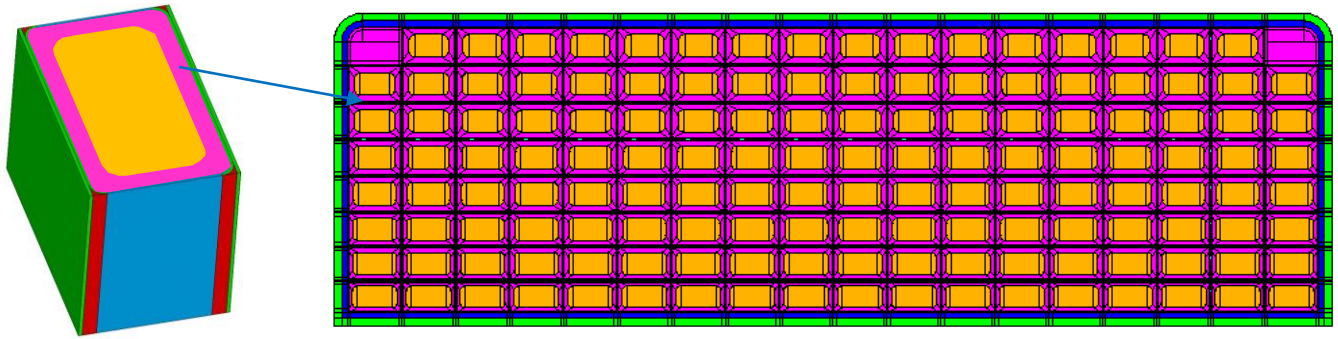
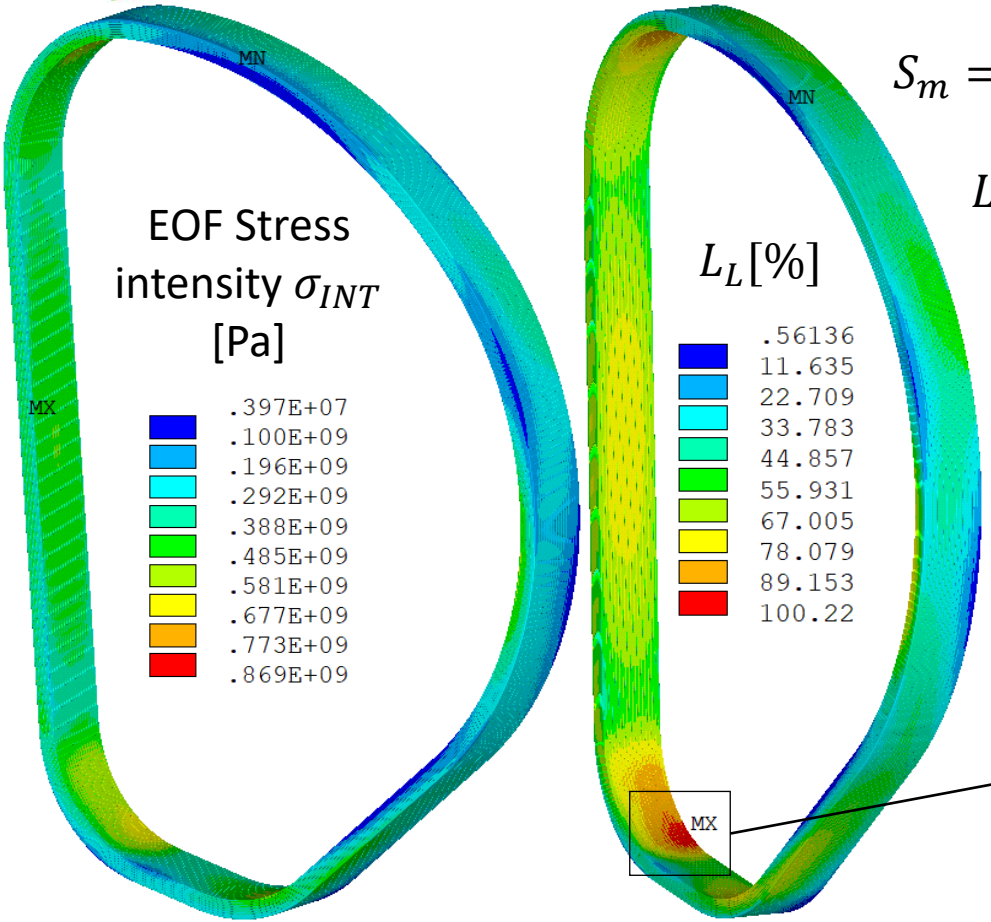
7. Residual stress measurements
8. Conclusions/next steps

1. Introduction & motivation (1/4)

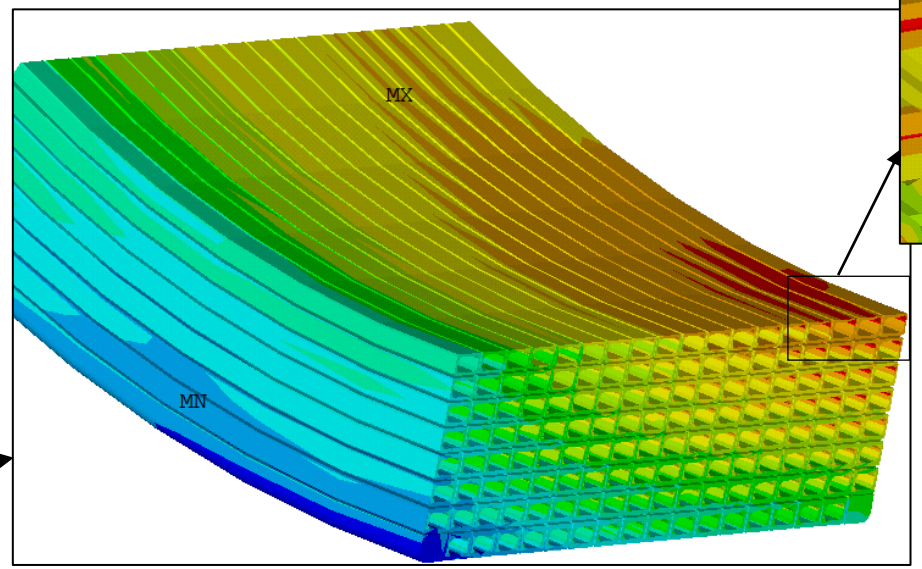
Mechanical analysis of the DEMO winding packs (2023) (2RCXLZ v1.1)

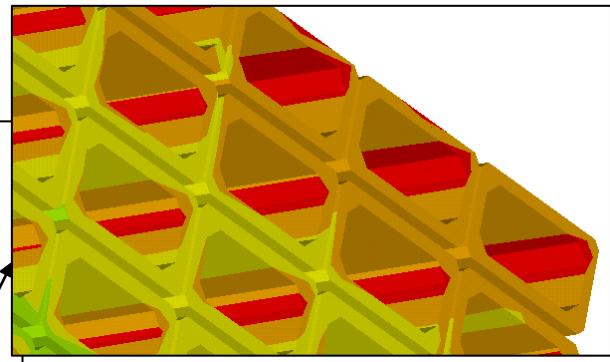




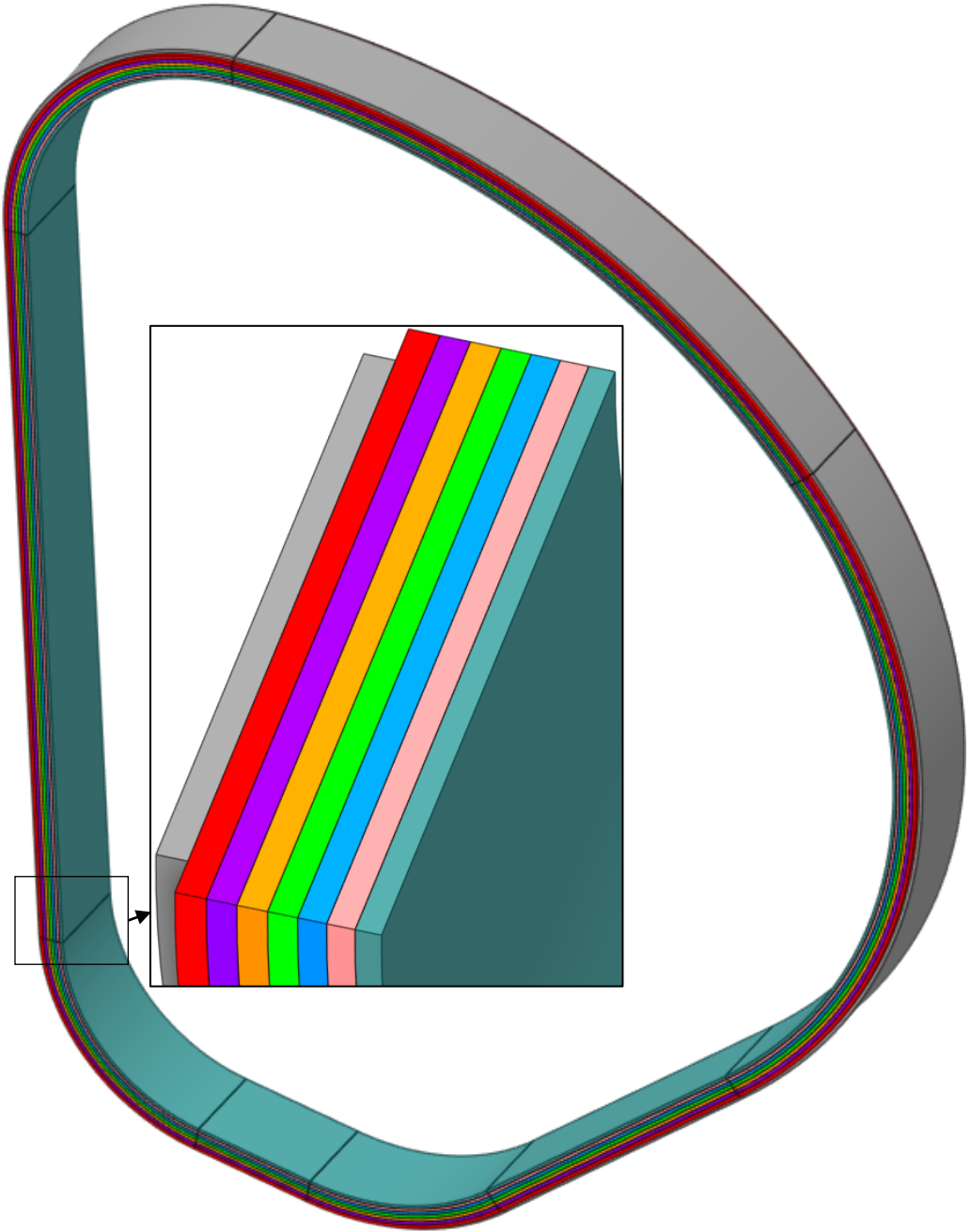
$$S_m = \frac{2}{3}\sigma_0 = \frac{2}{3}1000 = 667\ MPa$$

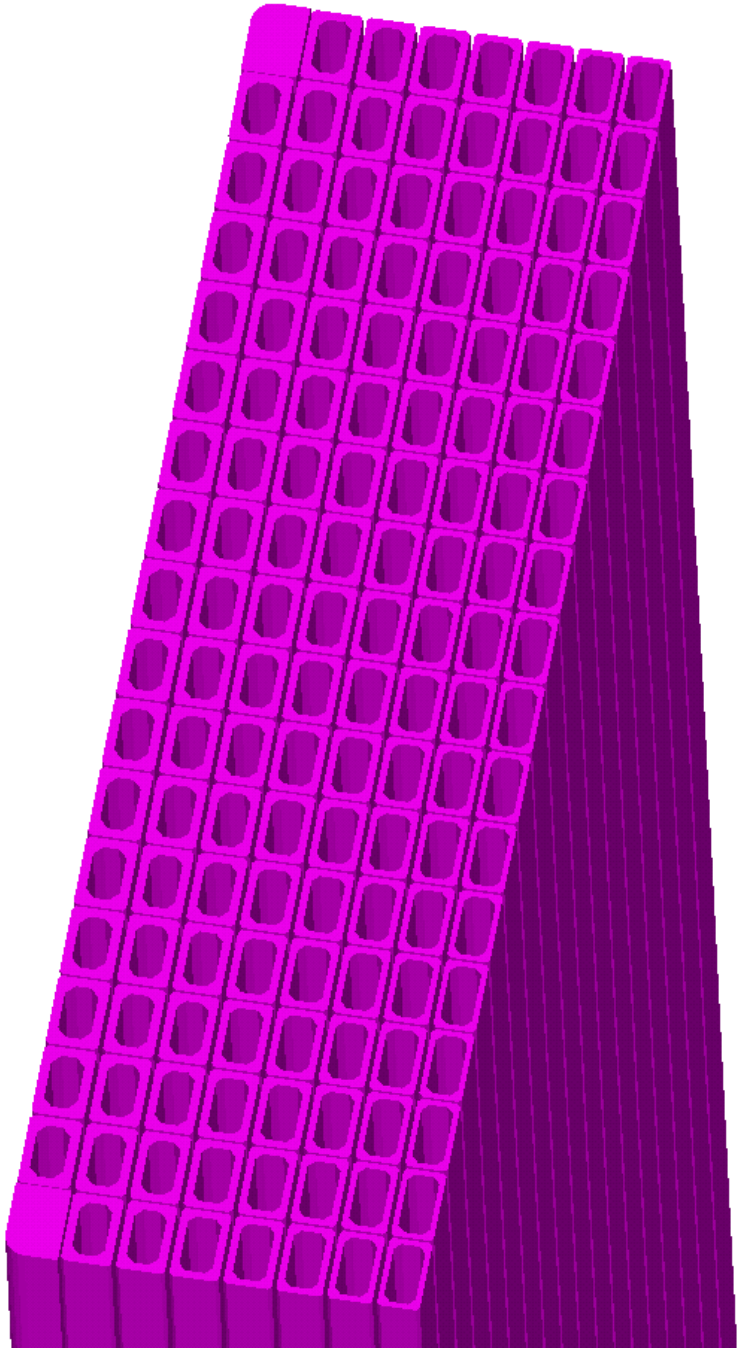
$$L_L = \frac{\sigma_{INT}}{S_m}100\ \%$$





1. Introduction & motivation (1/4)

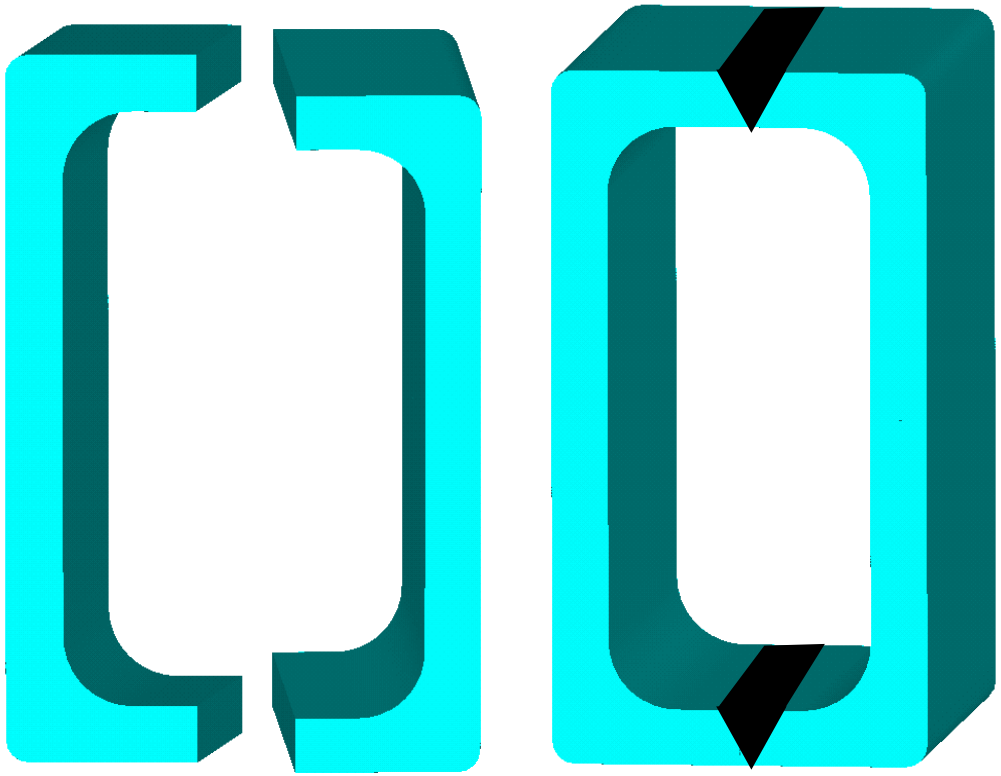


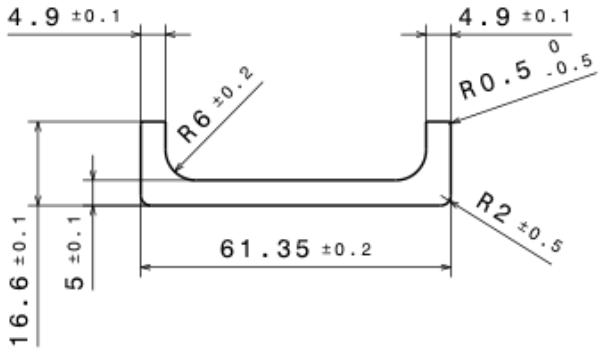


Layer [-]	~Jacket length [m]	Length of seam weld [m]
1	847	1694
2	852	1704
3	857	1714
4	863	1725
5	868	1736
6	874	1747
7	879	1759
8	787	1573
	Total	13652

1. Introduction & motivation (1/4)

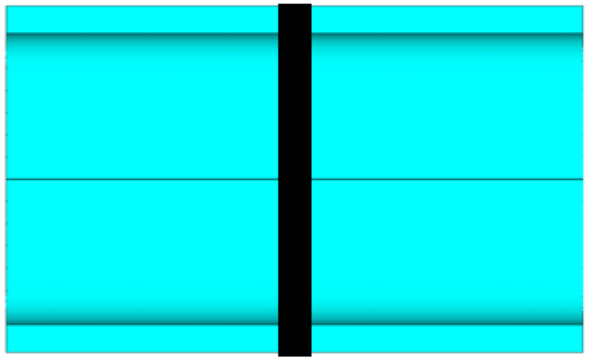
Seam (longitudinal weld) – laser welding
Automatic method

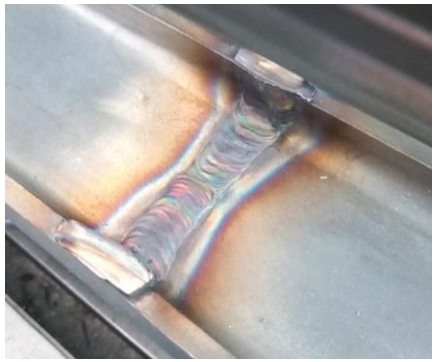




History of welding trials:

1) Cryotech (2023)





2) Montanstahl (2025)

- Continuous pieces of 100 m length, manufactured with hot rolling

2. FEM model of welding

Thermal model

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

For the laser welding

Moving heat source model

Mechanical model

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

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

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

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

2. FEM model of welding

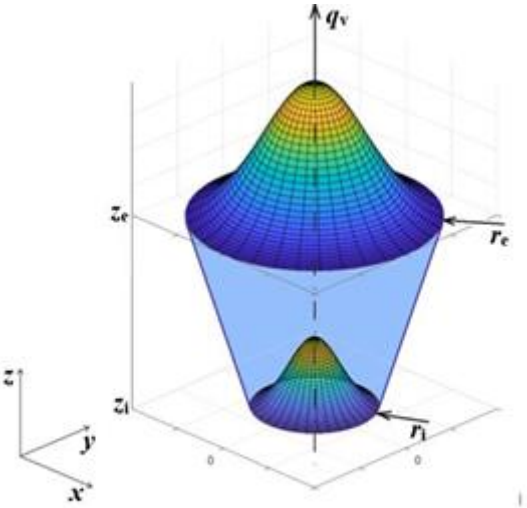


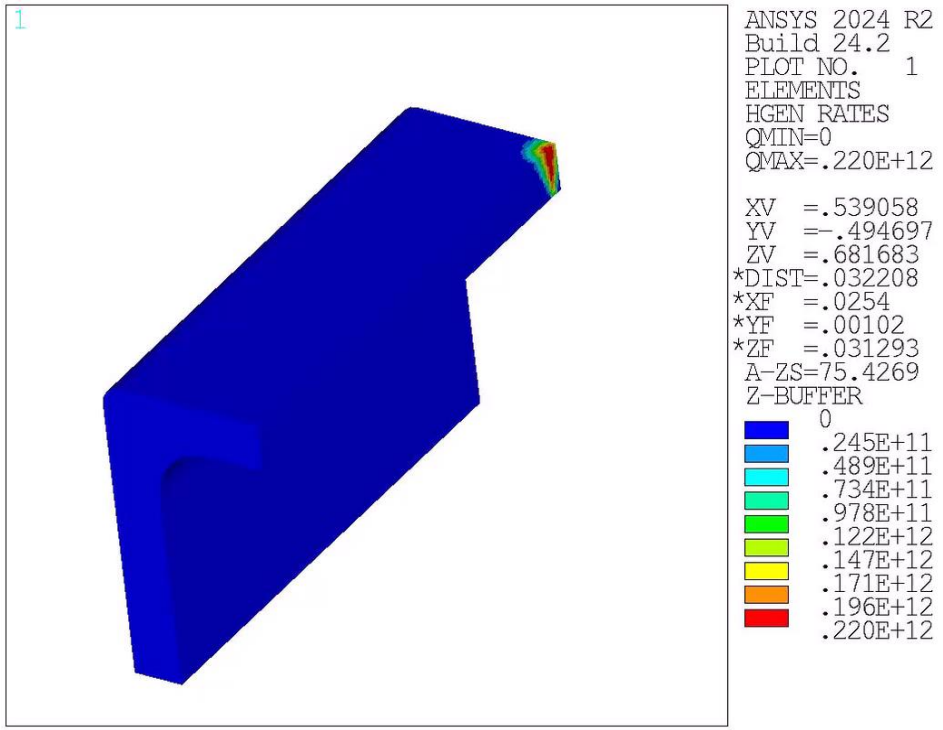
Figure 7. Conical heat source model

$$Q_v = Q_0 e^{\frac{-3r^2}{r_0^2}} \qquad r_0(z) = r_e - \frac{(r_e - r_i)}{(z_e - z_i)}(z_e - z) \qquad r^2 = x^2 + [y - (y_0 + vt)]^2$$

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

Green – parameters related to the size of the laser beam
Red – laser velocity

Parameters:
r_e – radius at the top
r_i – radius at the bottom
v - laser velocity
P – laser power [W]
η – laser efficiency (assumed 1)



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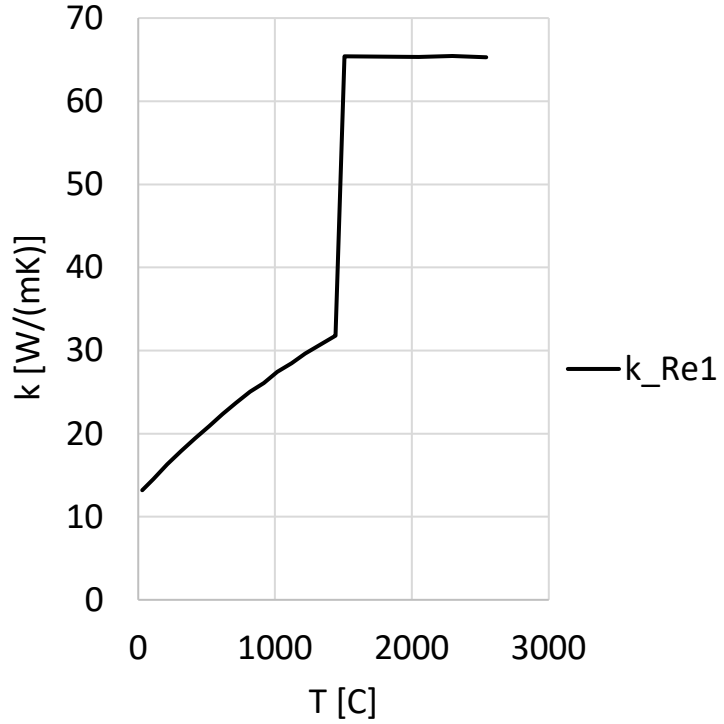
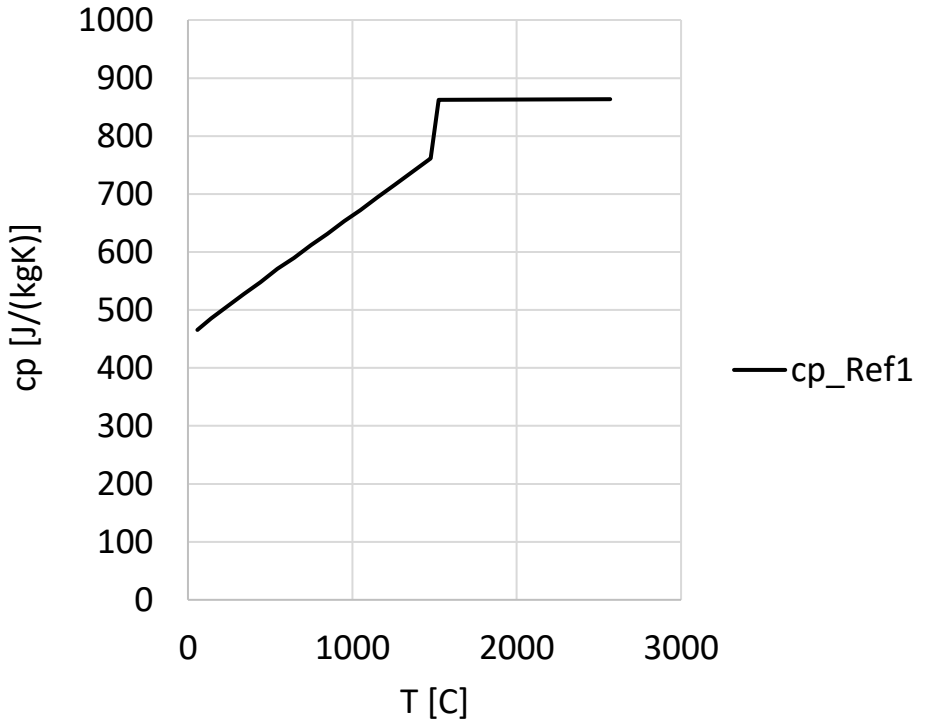
$\varrho(T)$ $c_p(T)$ $k(T)$

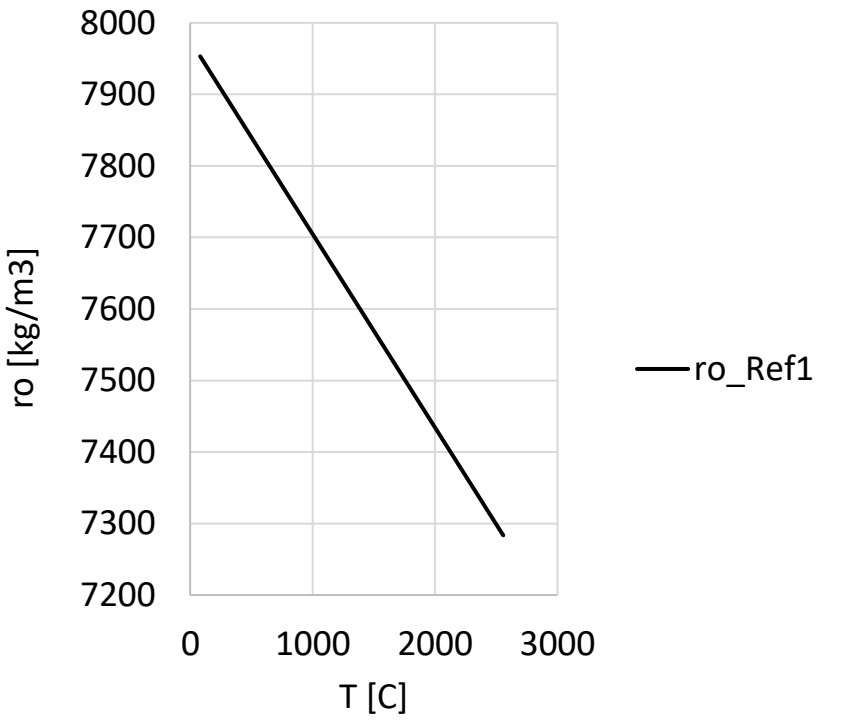
Temperatures above melting are of no importance for the residual stress analysis

	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

Thermal properties of 316L







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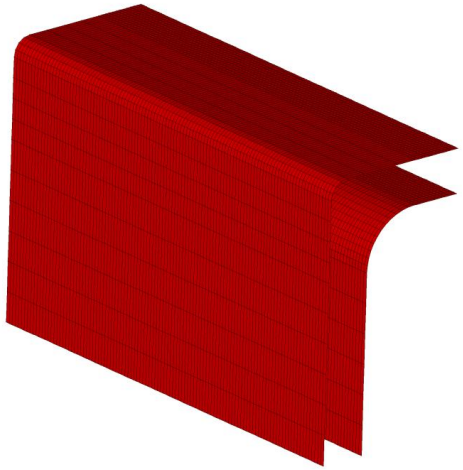
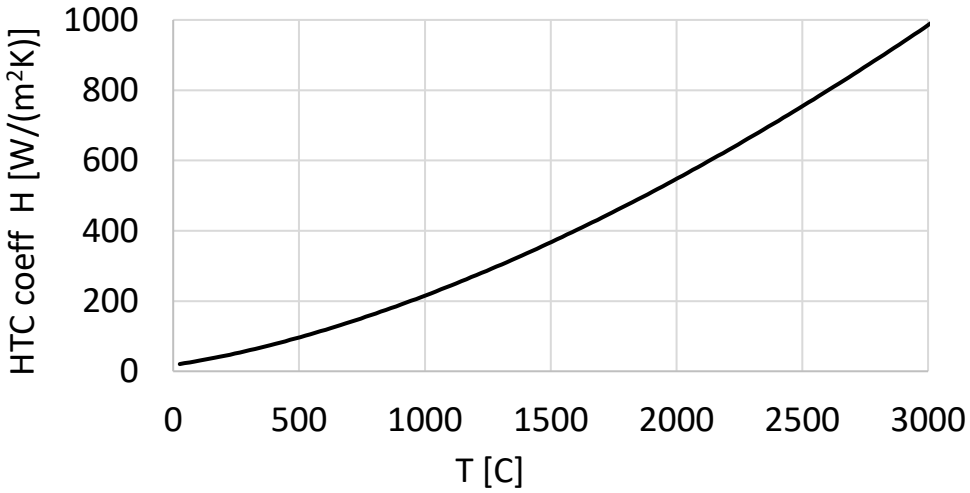
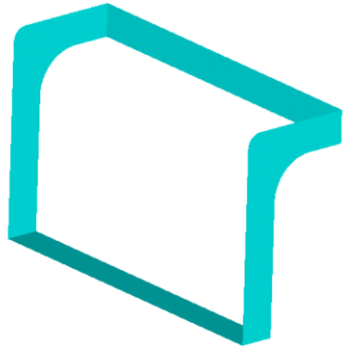


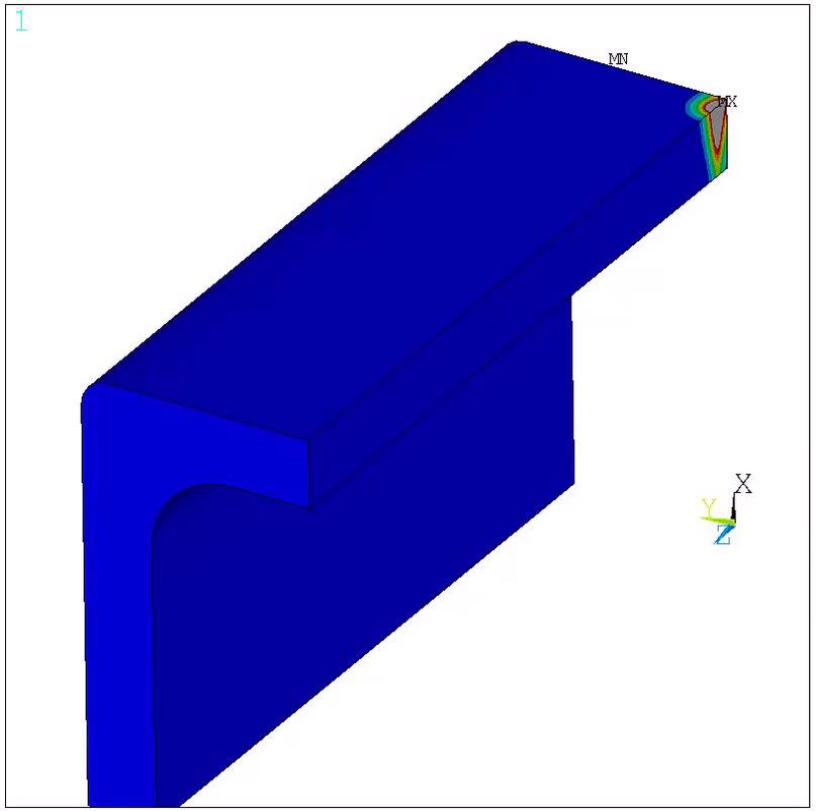
$$H = 2.4 \cdot 10^{-3} \varepsilon T^{1.61}$$

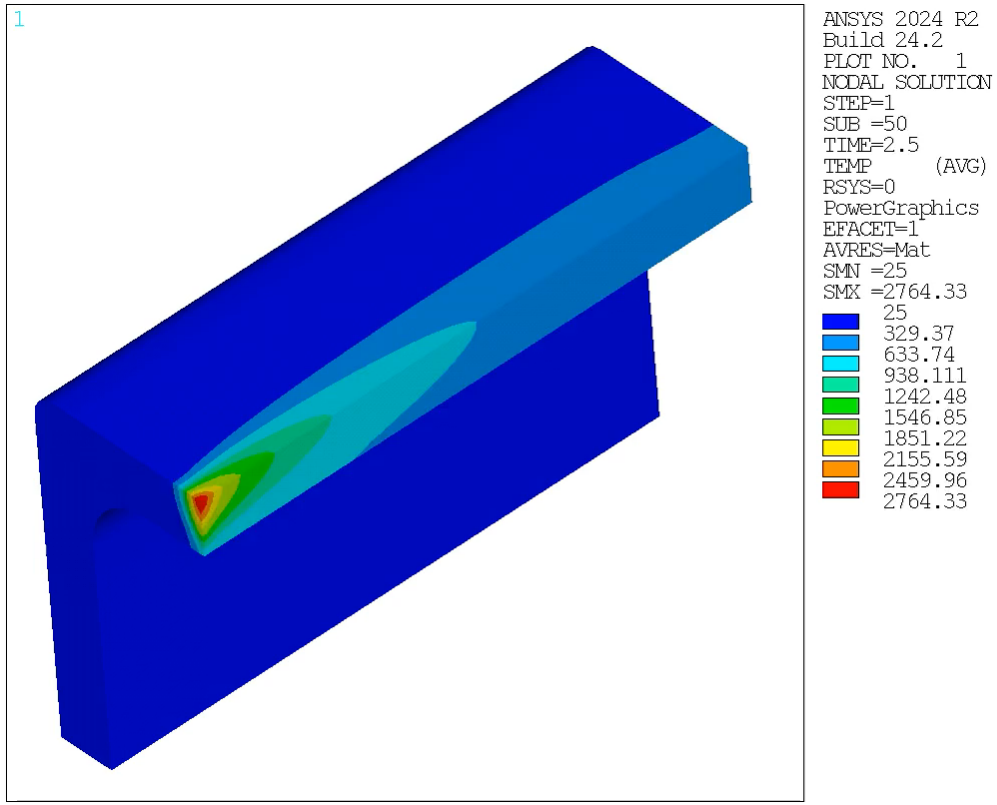
$$\varepsilon = 0.9$$





adiabatic interfaces





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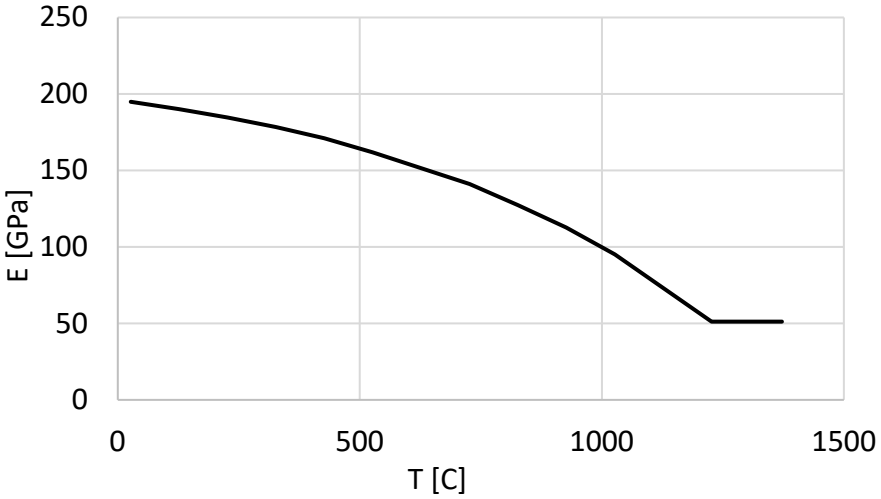
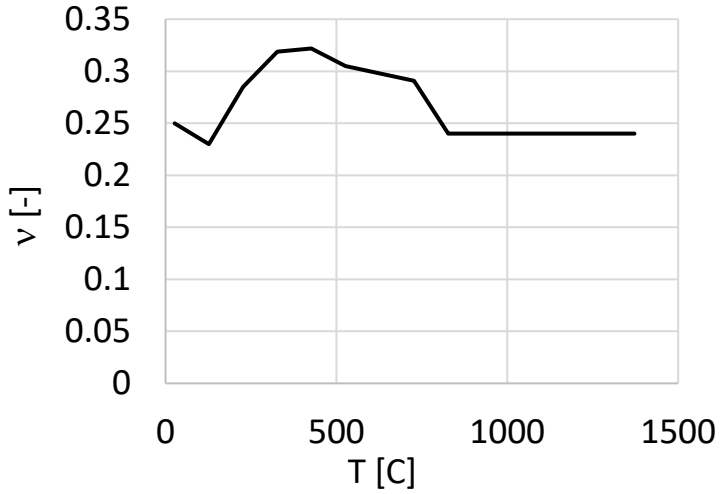
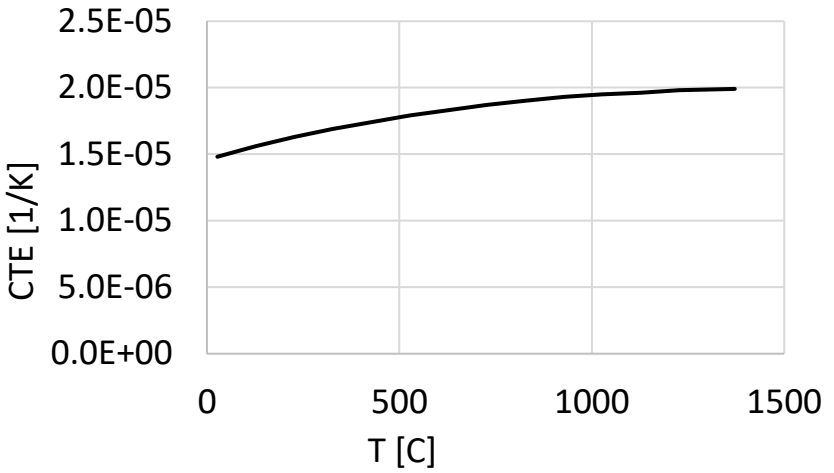
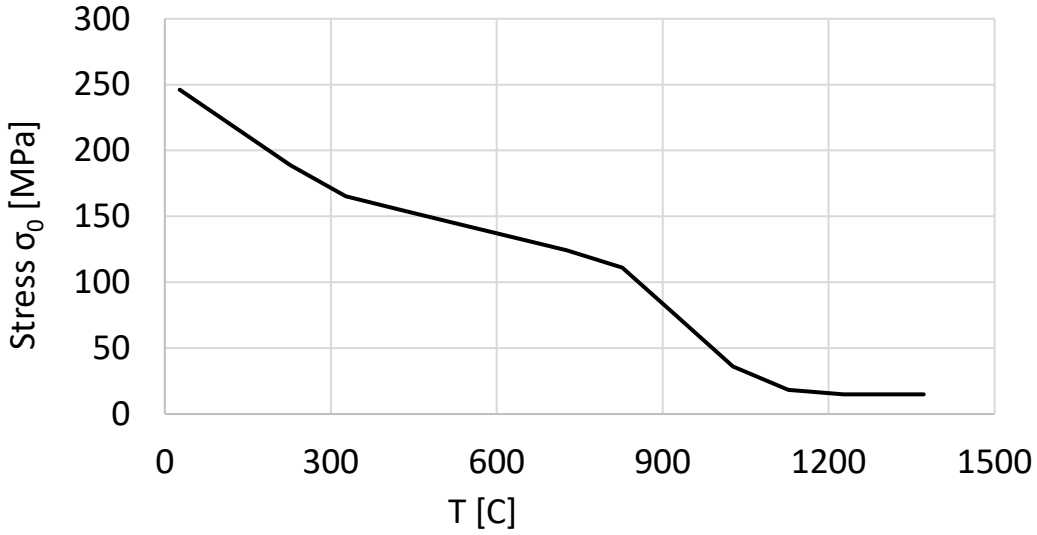
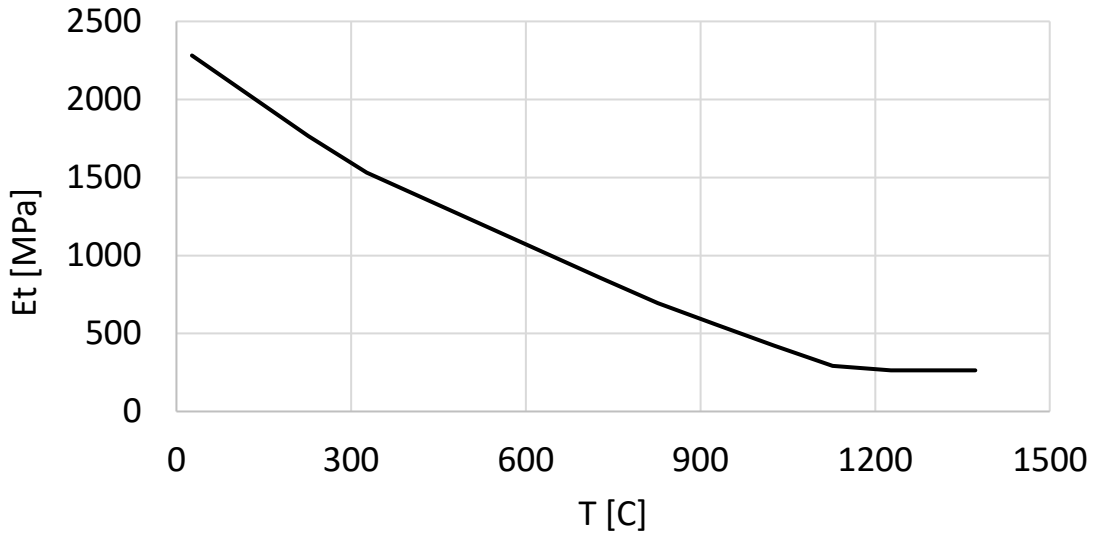






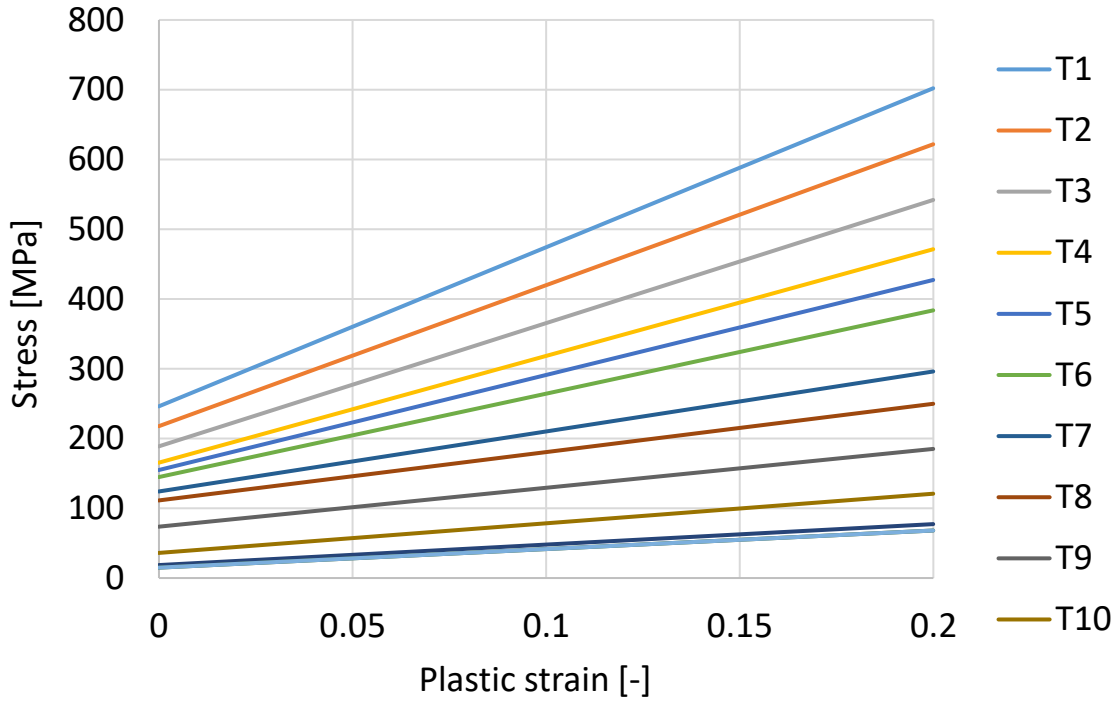




Ref4	*FEM analysis of thermal and residual stress profile in selective laser melting of 316L stainless steel*
Ref5	*Experimental and numerical study on residual stress and geometric distortion in powder bed fusion process*

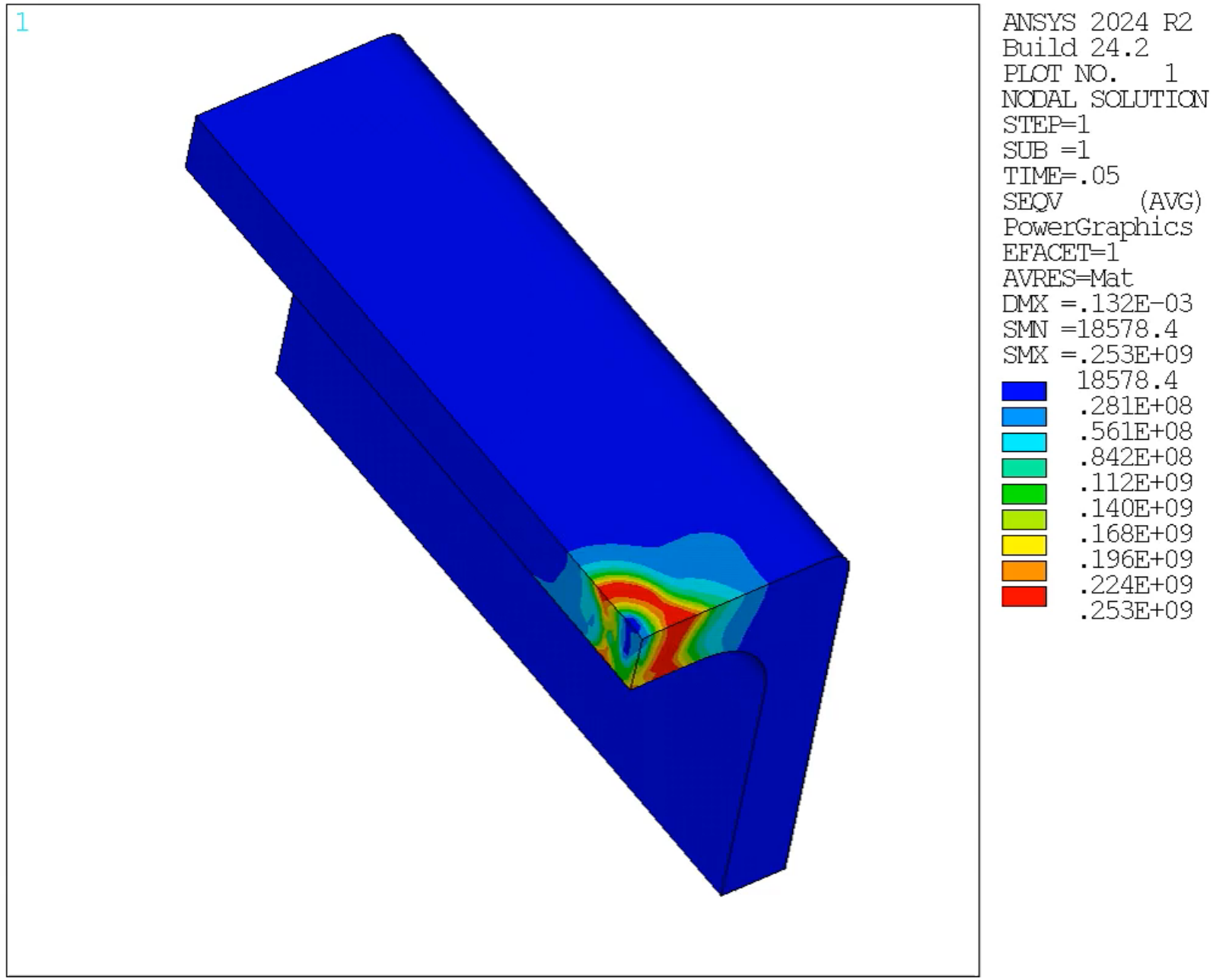
2. FEM model of welding

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



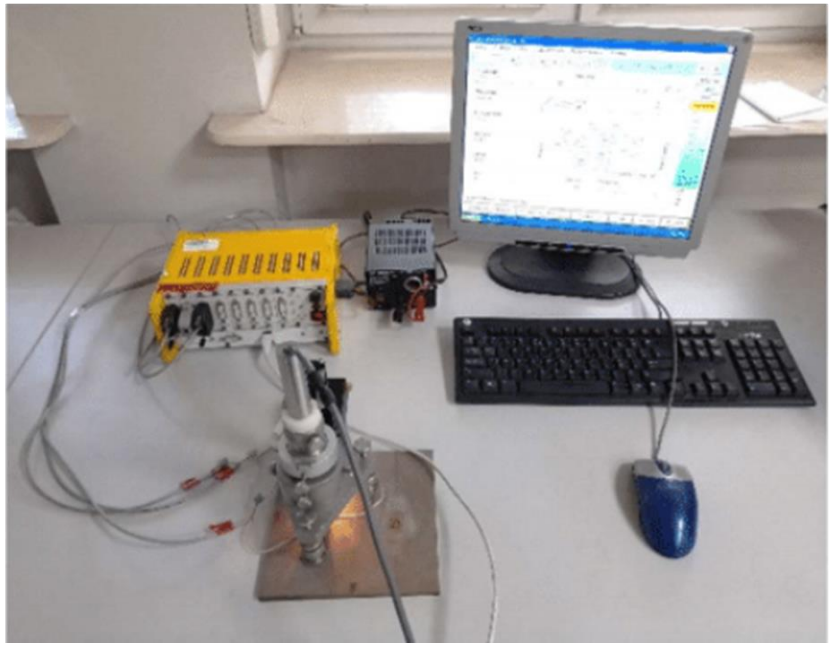
	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13
Plastic str.	26.85	126.85	226.85	326.85	426.85	526.85	726.85	826.85	926.85	1026.9	1126.9	1226.9	1372
0	246	217.4	188.8	165.2	154.9	144.7	124.2	111.1	73.6	36	18.4	15	15
0.2	702	622	541.8	471.4	427.5	383.7	295.92	249.82	185.24	120.6	77.08	68	68

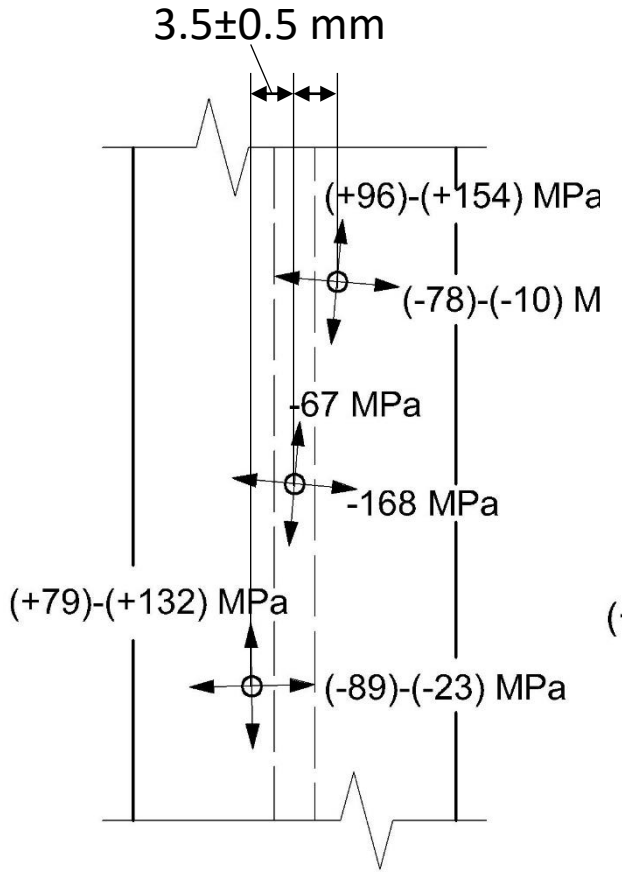
2. FEM model of welding



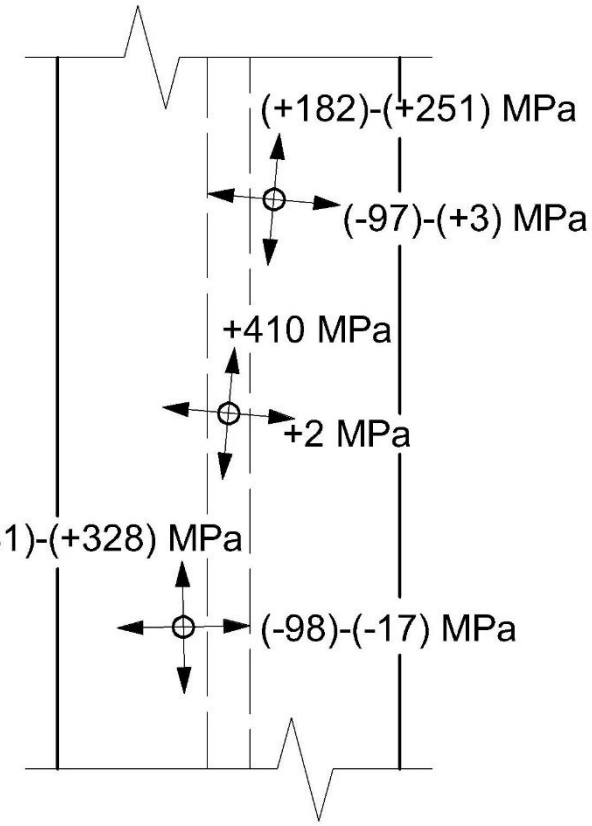
3. Residual stresses: measurements vs FEM

Hole drilling strain gauge method





Depth ~0.25 mm

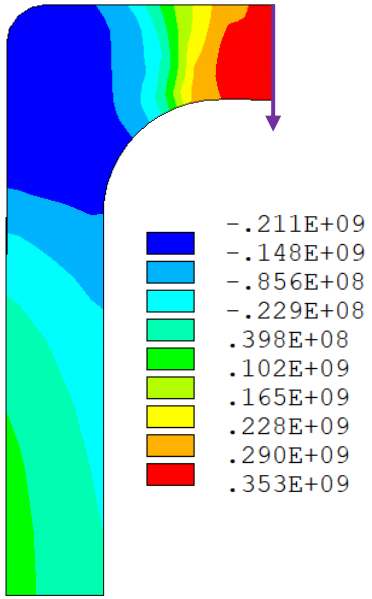


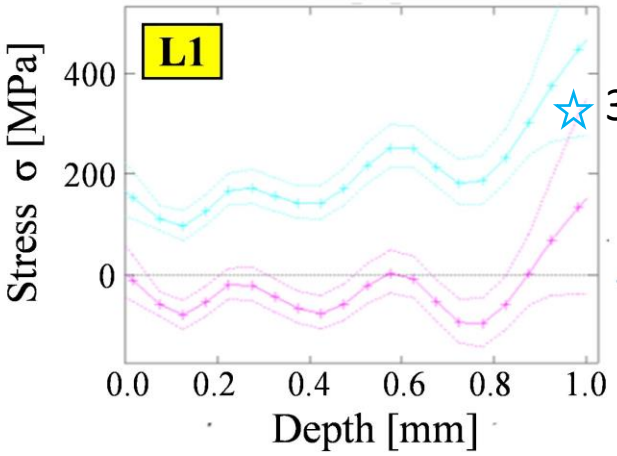
Depth 0.5-0.8 mm

J. Tabin et al. Microstructure, mechanical properties and residual stress of welded stainless-steel jackets for React & Wind conductor in EU-DEMO. Fusion Engineering and Design 222 (2026) 115503

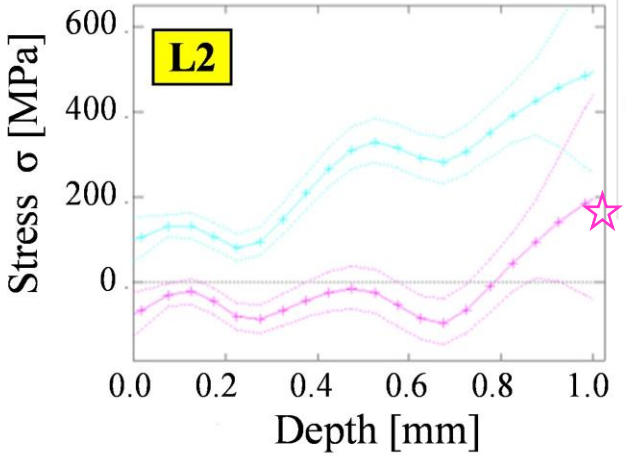
3. Residual stresses: measurements vs FEM

σ_Z (σ_1) [Pa]

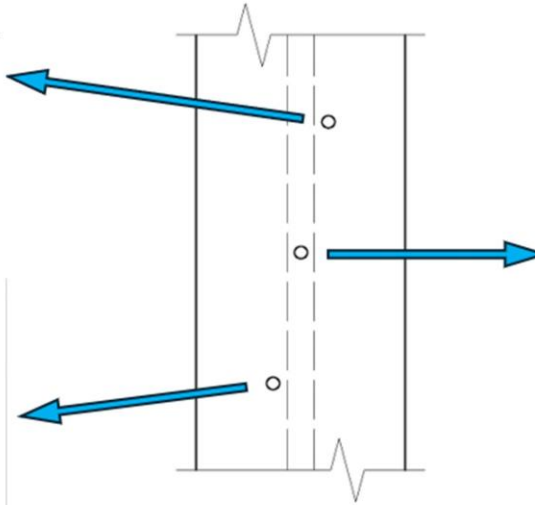


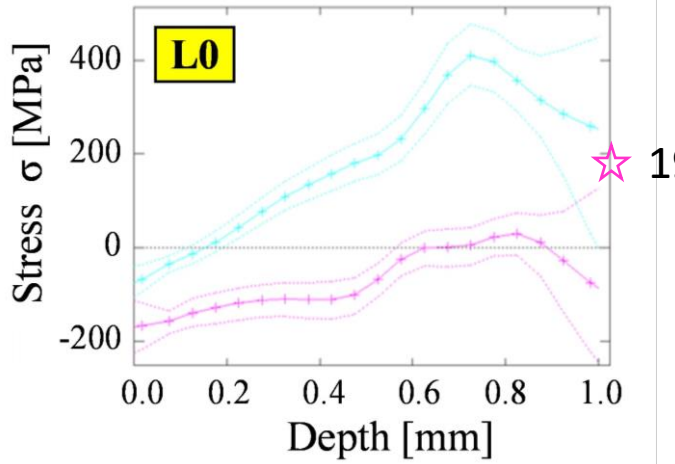


353 MPa



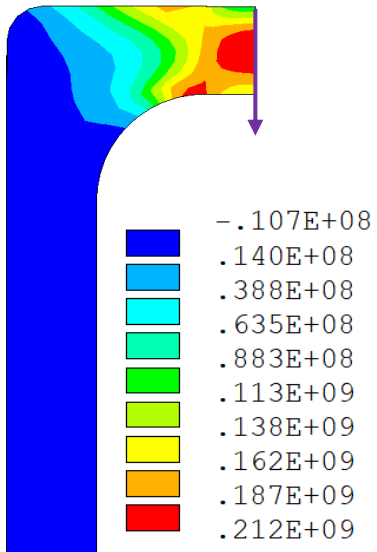
160 MPa

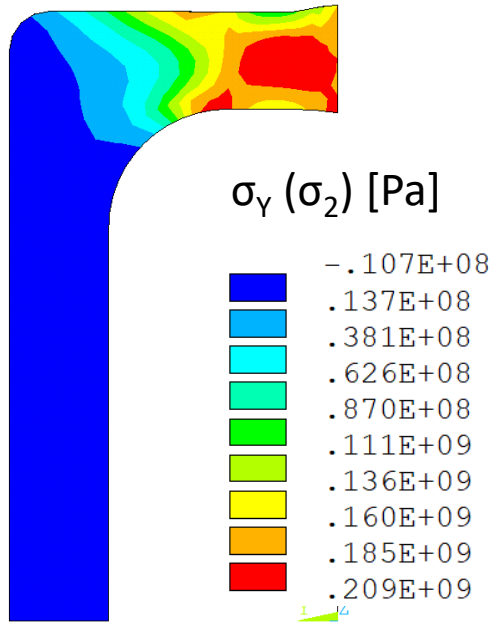




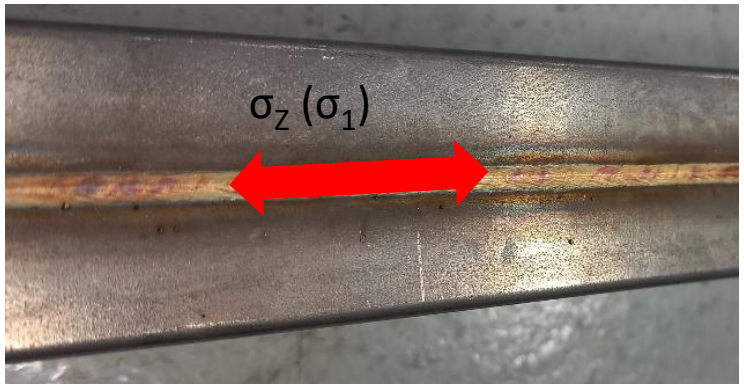
190 MPa

σ_Y (σ_2) [Pa]



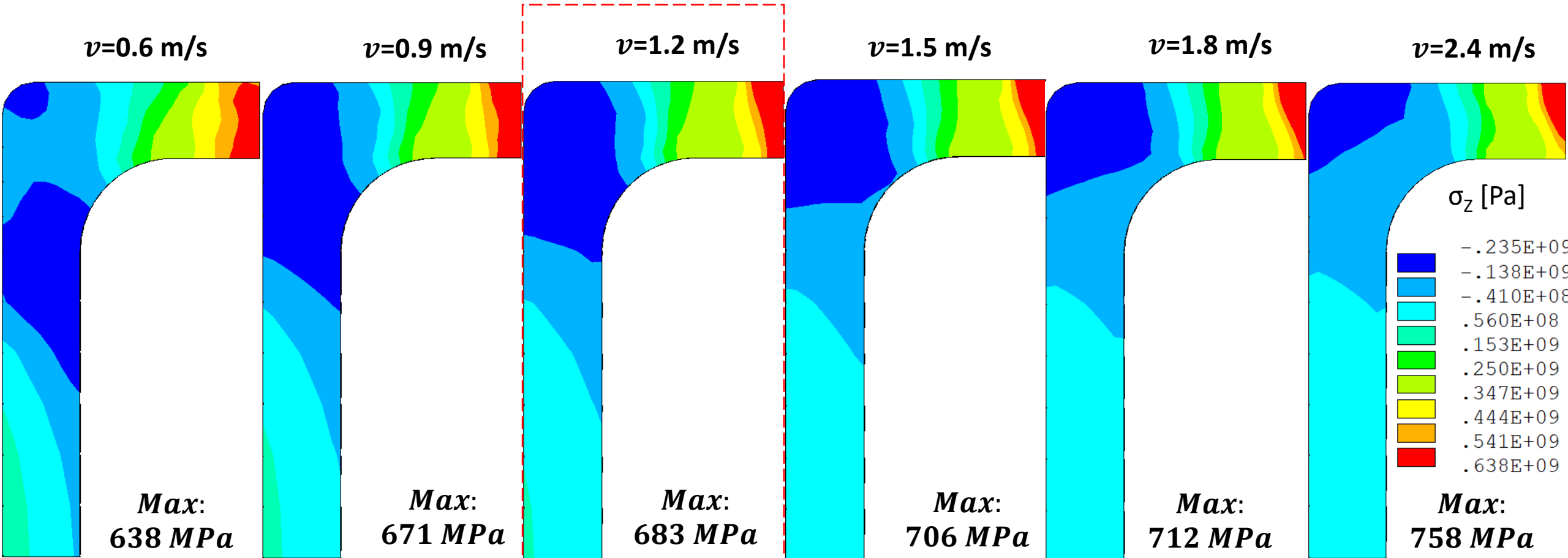


4. Sensitivity study



Welding velocity

Stress σ_z



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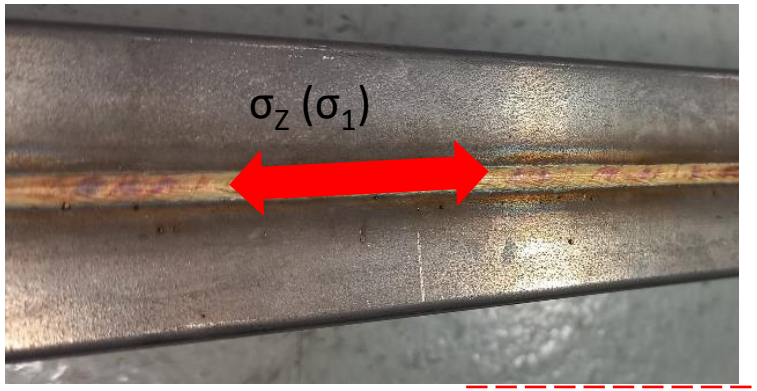
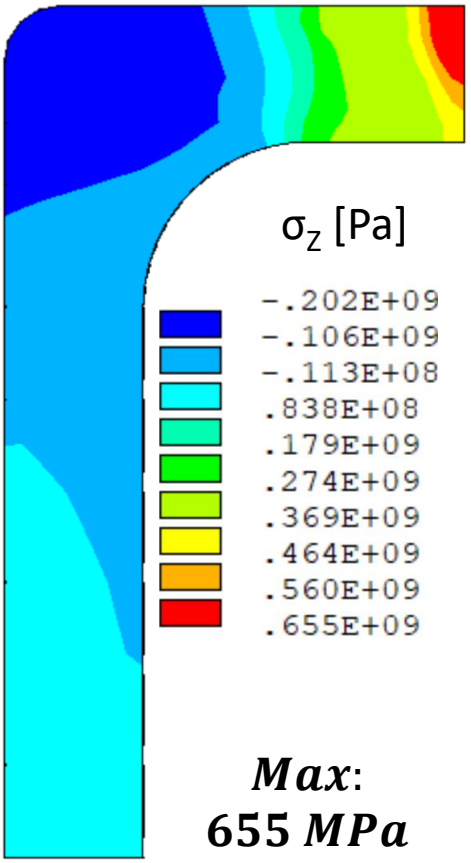


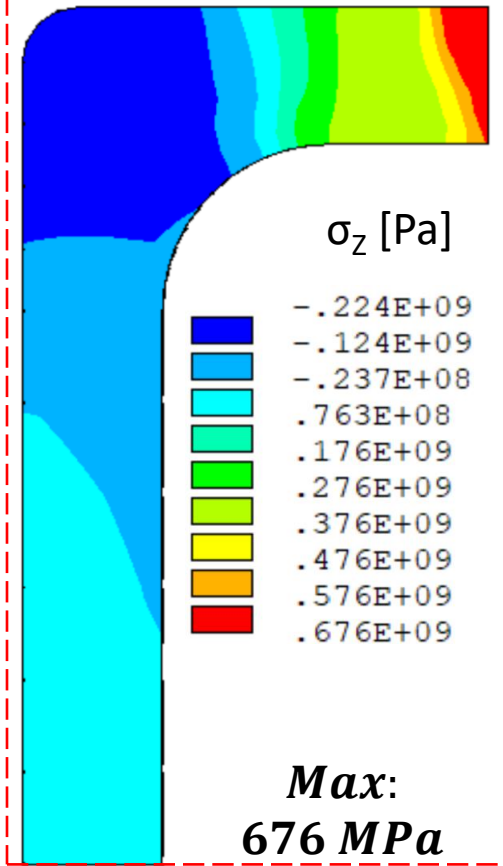
Laser power

$P = 2000\ W$



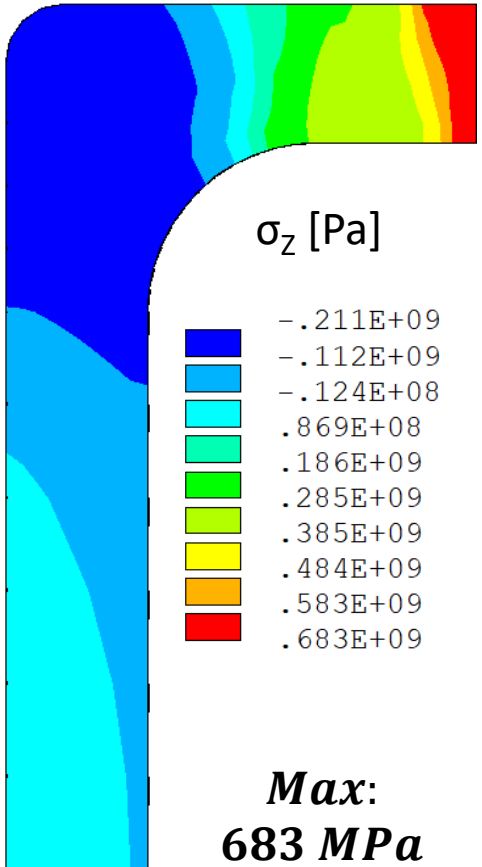
Max: 655 MPa

$P = 3000\ W$



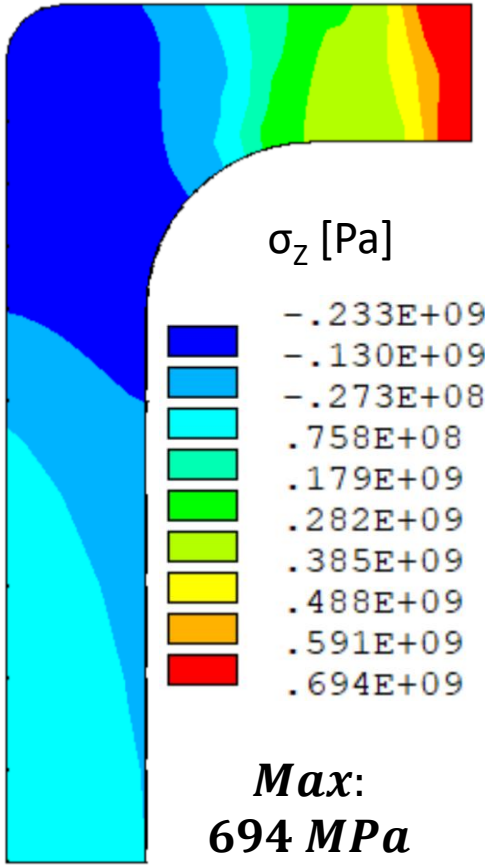
Max: 676 MPa

$P = 4000\ W$



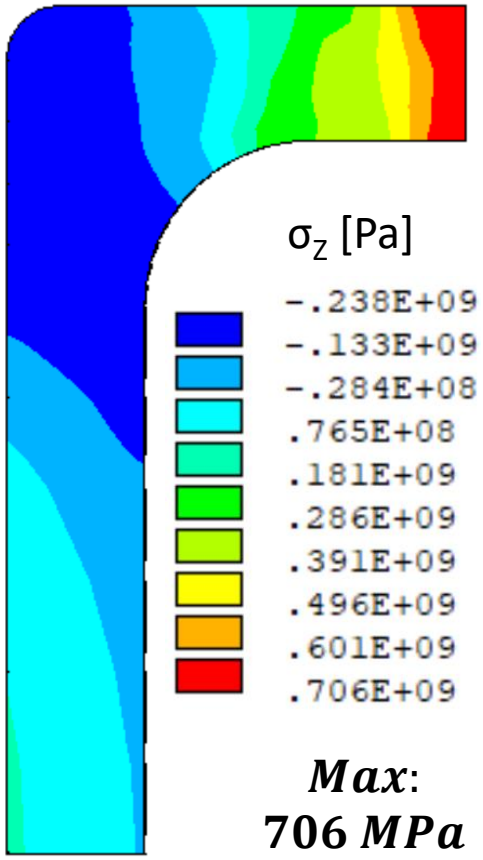
Max: 683 MPa

$P = 5000\ W$



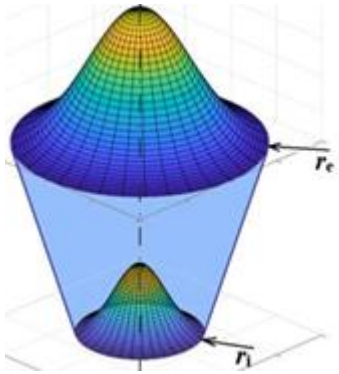
Max: 694 MPa

$P = 6000\ W$



Max: 706 MPa

4. Sensitivity study



Laser beam size

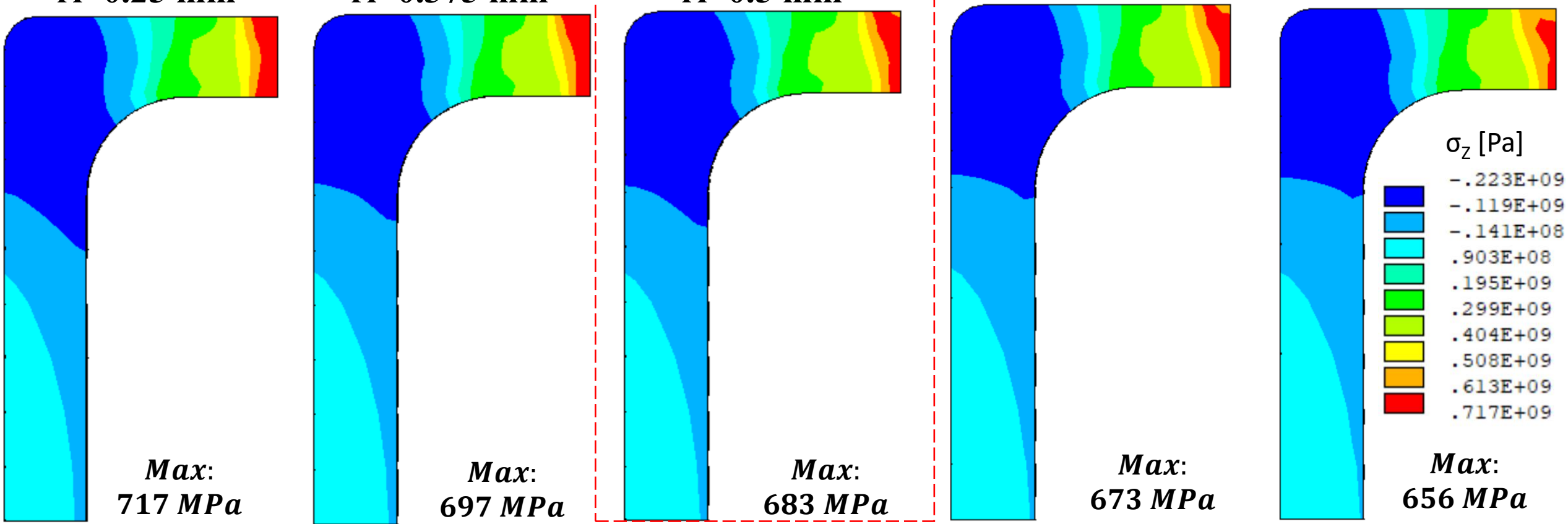
(× 0.5)
re=0.75 mm
ri=0.25 mm

(× 0.75)
re=1.125 mm
ri=0.375 mm

(× 1)
re=1.5 mm
ri=0.5 mm

(× 1.25)
re=1.875 mm
ri=0.625 mm

(× 1.5)
re=2.25 mm
ri=0.75 mm



Max:
717 *MPa*

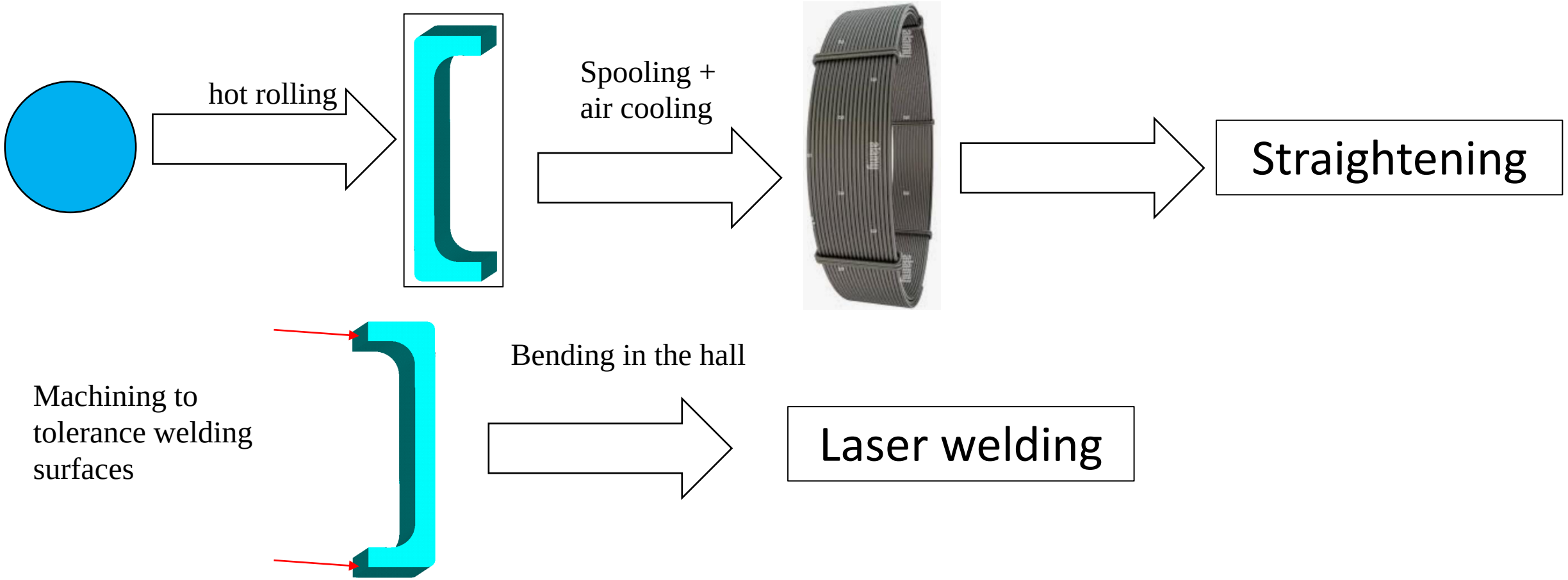
Max:
697 *MPa*

Max:
683 *MPa*

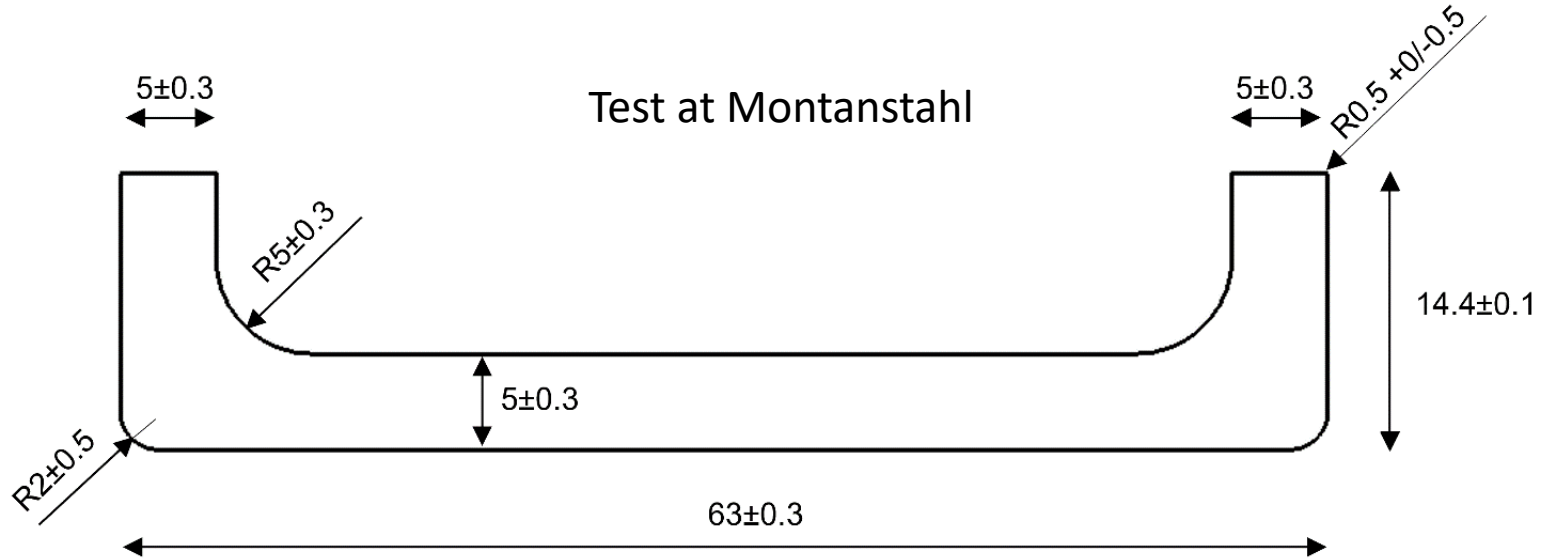
Max:
673 *MPa*

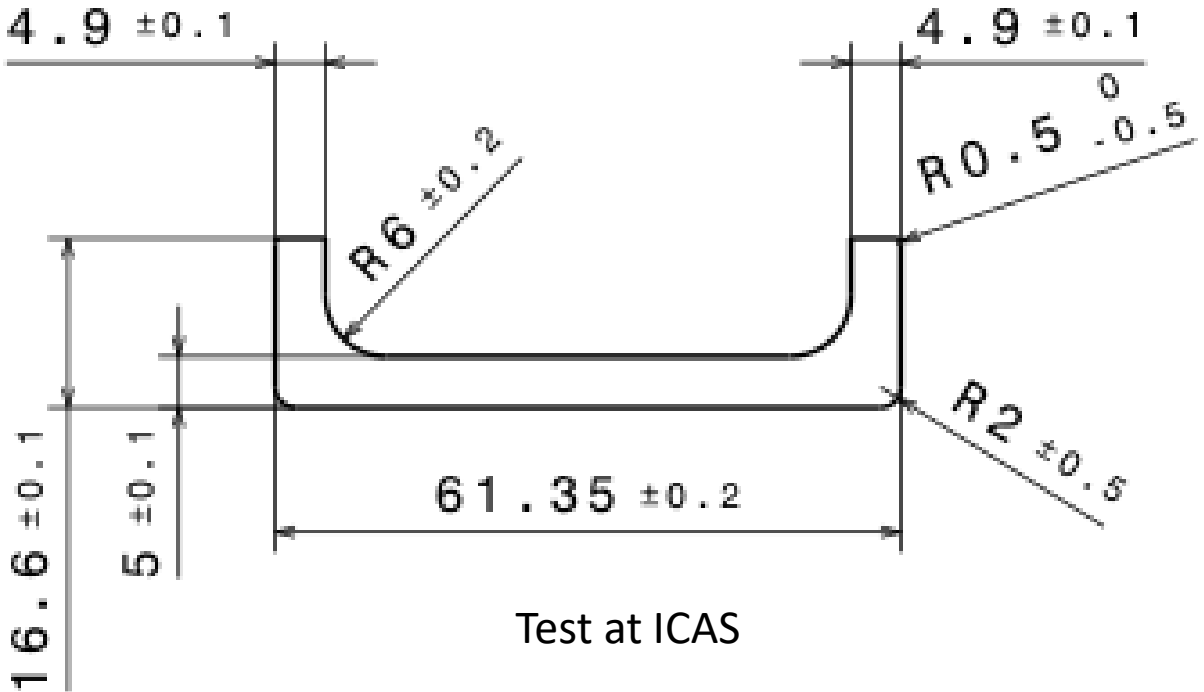
Max:
656 *MPa*

5. Welding trial (July 2025) – lessons learned



5. Welding trial (July 2025) – lessons learned





Test at ICAS

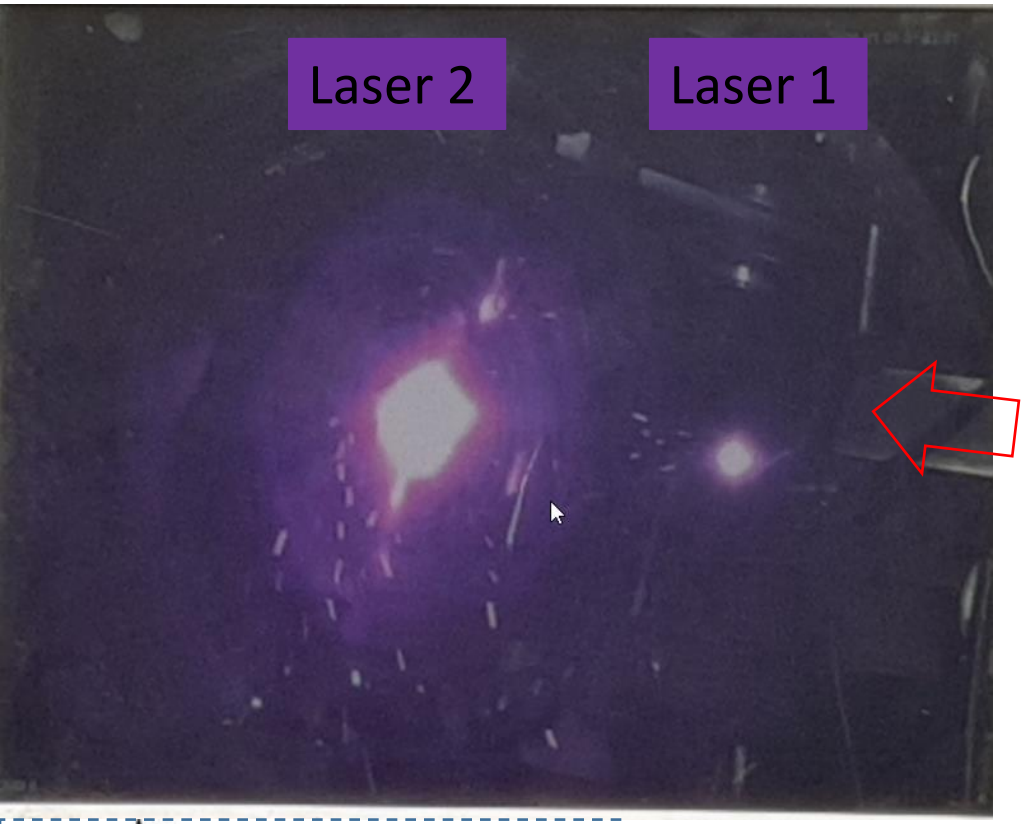
5. Welding trial (July 2025) – lessons learned

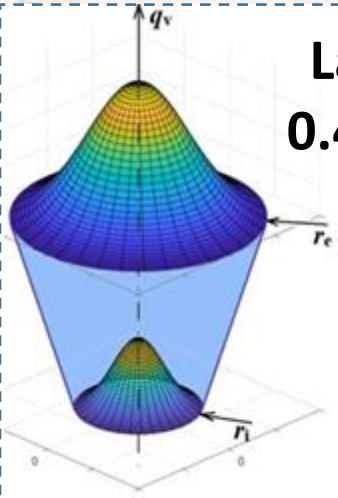
5. Welding trial (July 2025) – lessons learned

Vertical compression with a force of ~2.7 kN

Laser welding

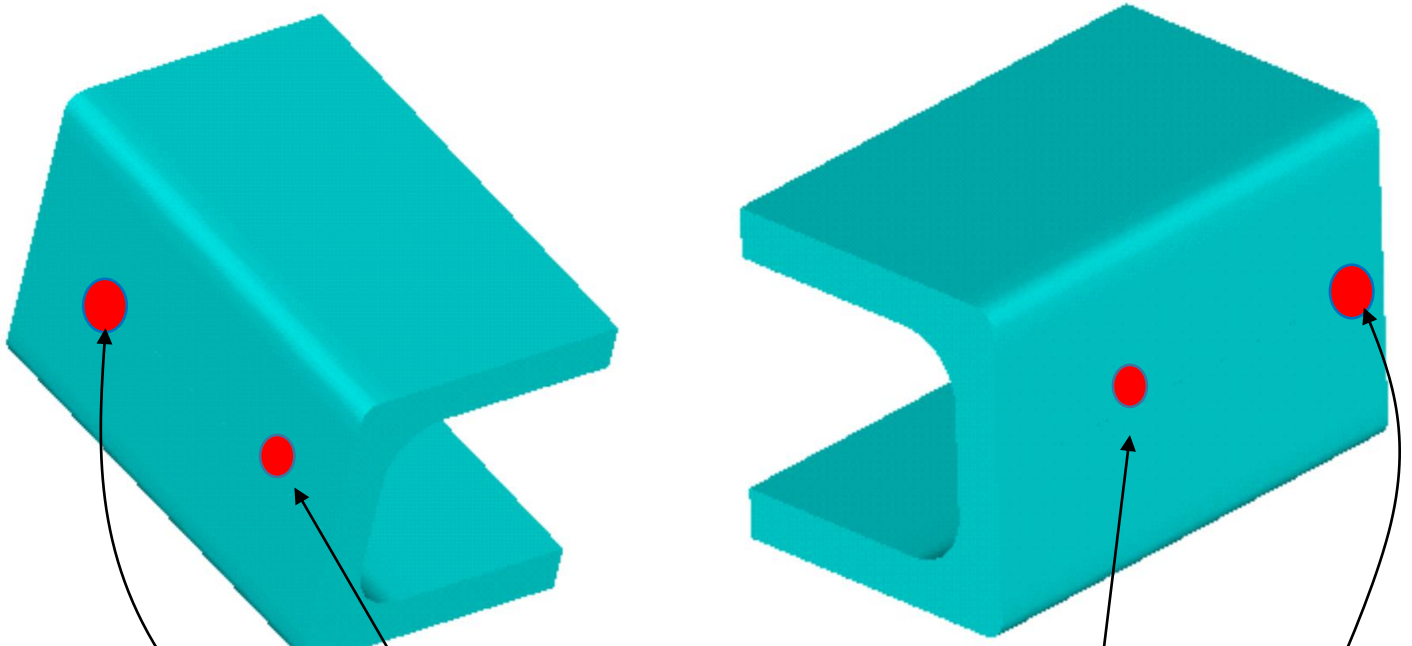
5. Welding trial (July 2025) – lessons learned





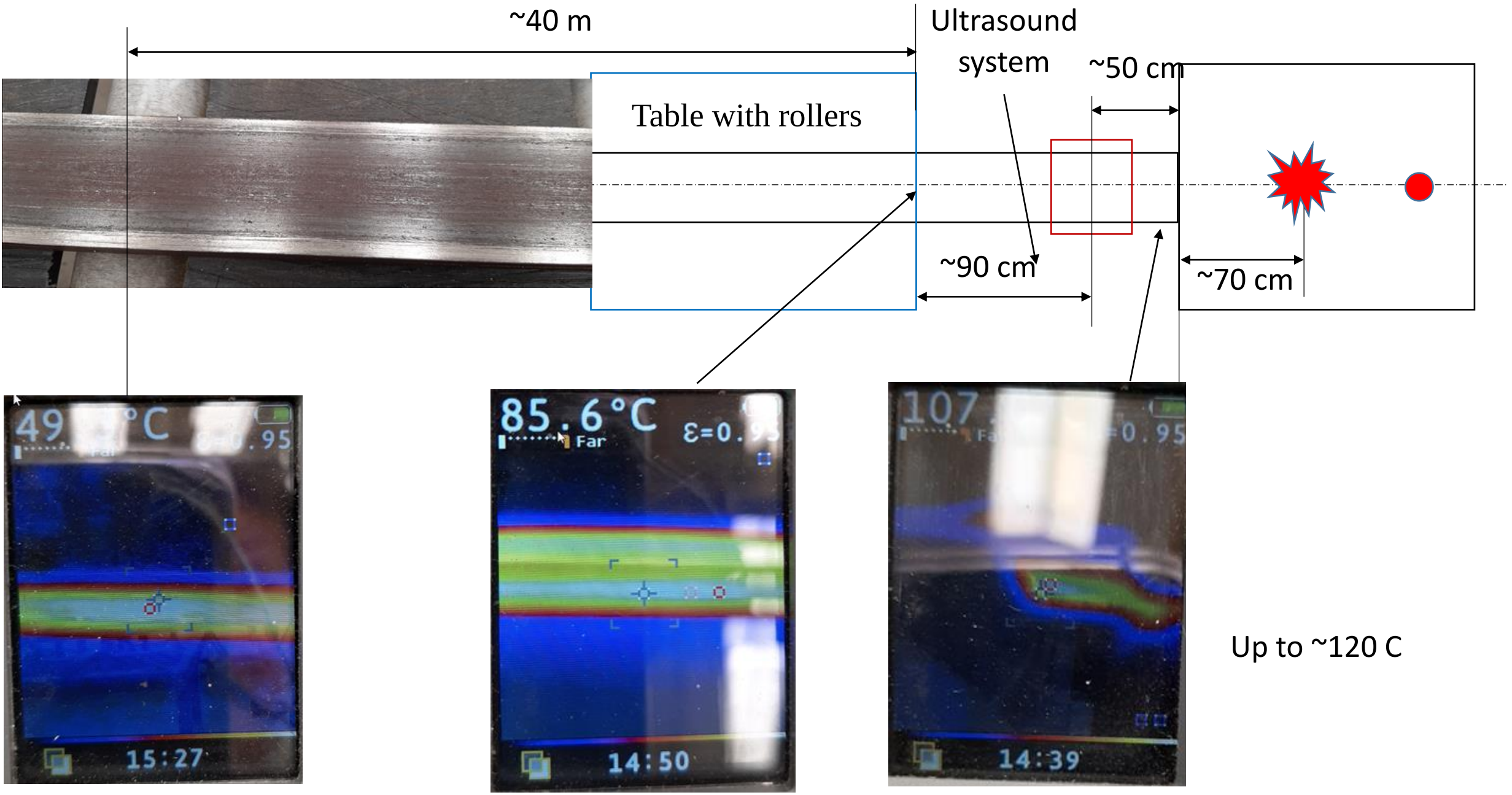
Laser size
0.4-0.5 mm

Laser velocity
2 m/min



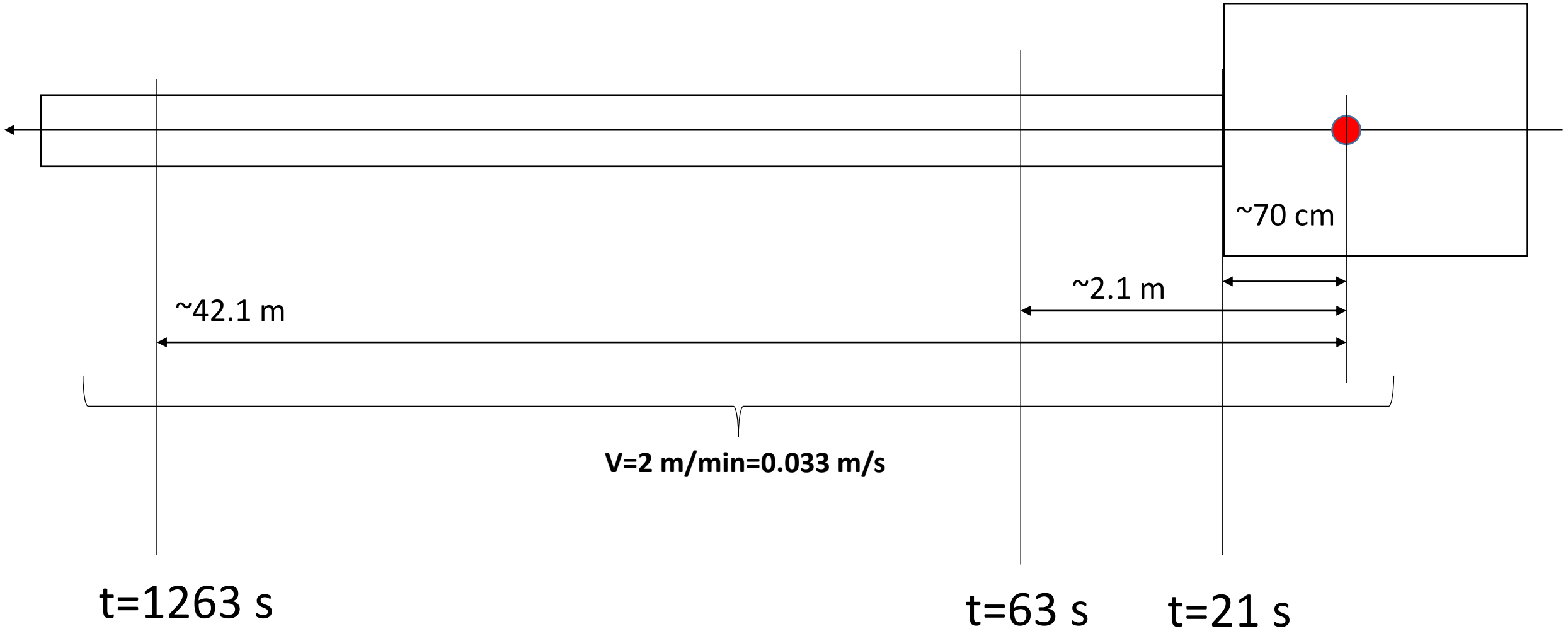
Laser 2	Laser 1
1000 W	1500 W
3300 W	3700 W

5. Welding trial (July 2025) – lessons learned

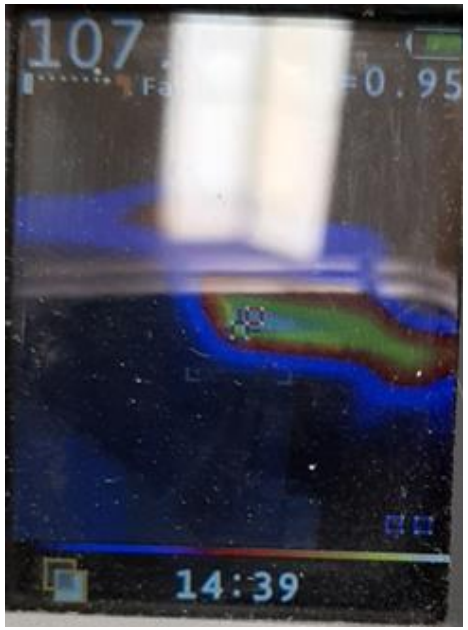


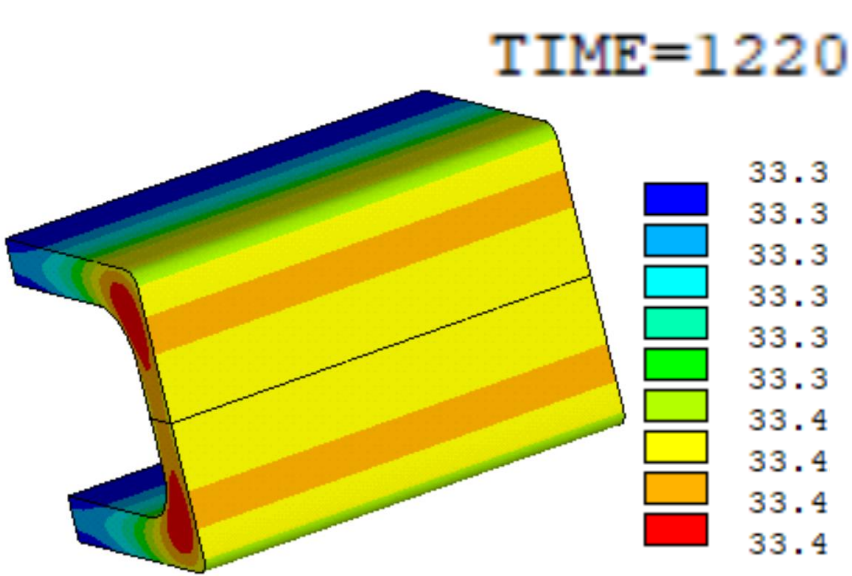
Up to ~120 C

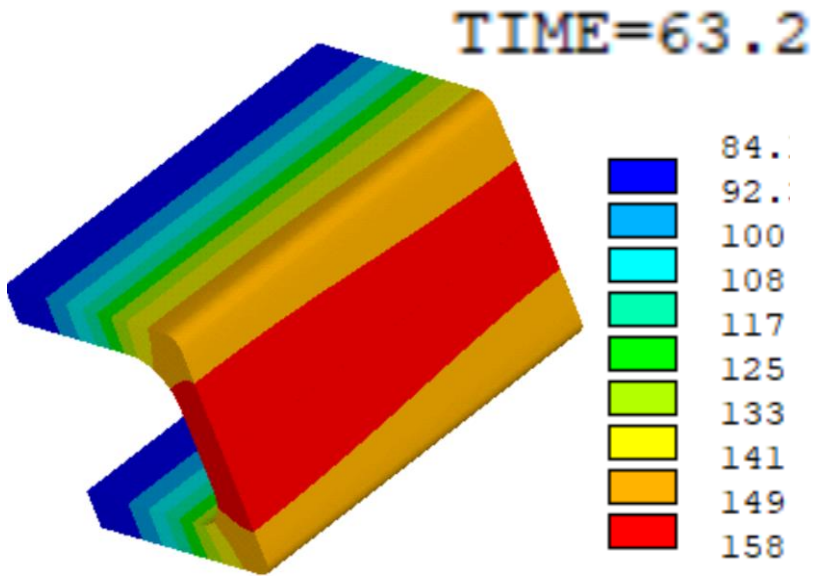
5. Welding trial (July 2025) – lessons learned

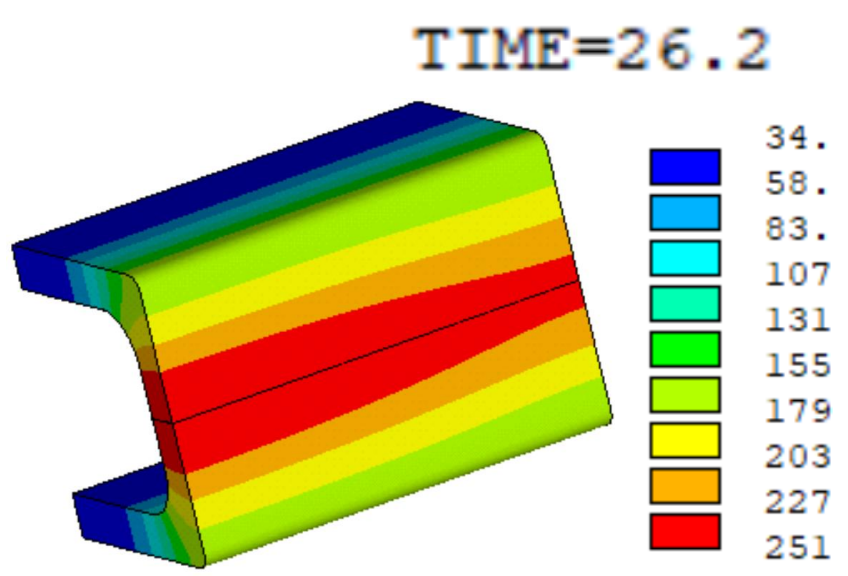


5. Welding trial (July 2025) – lessons learned

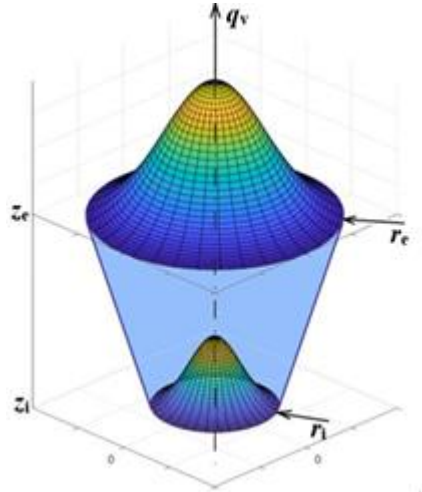




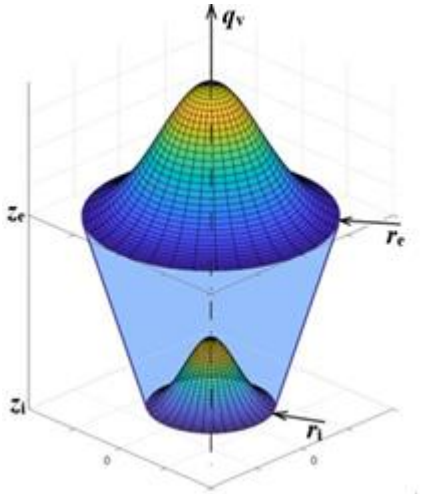




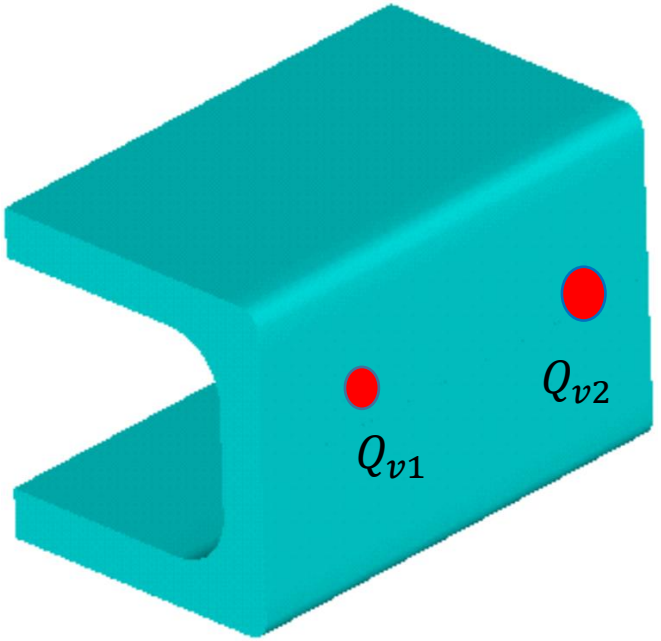
6. New thermal model



$$Q_{v1} = \frac{9P_1}{\pi(z_e - z_i)(1 - e^{-3})\left(r_e^2 + r_e r_i + r_i^2\right)} e^{\left(-\frac{3\left[x^2+[y-vt]^2\right]}{\left[r_e-\frac{(r_e-r_i)}{(z_e-z_i)}(z_e-z)\right]^2}\right)}$$



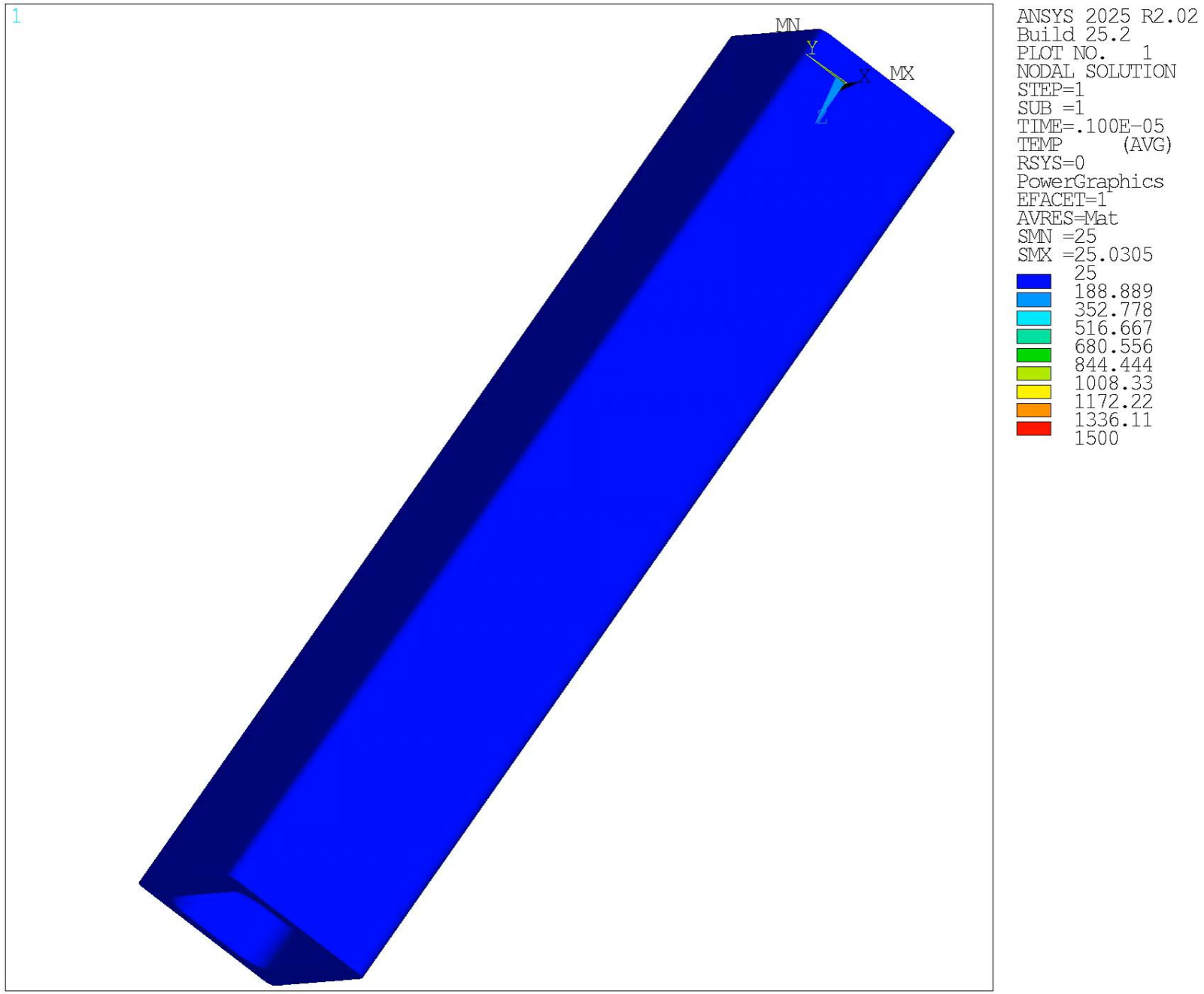
$$Q_{v2} = \frac{9P_2}{\pi(z_e - z_i)(1 - e^{-3})\left(r_e^2 + r_e r_i + r_i^2\right)} e^{\left(-\frac{3\left[x^2+[y-(y_0+vt)]^2\right]}{\left[r_e-\frac{(r_e-r_i)}{(z_e-z_i)}(z_e-z)\right]^2}\right)}$$



$$Q_v = Q_{v1} + Q_{v2}$$

6. New thermal model

200 mm long piece (4x longer than the previous model)

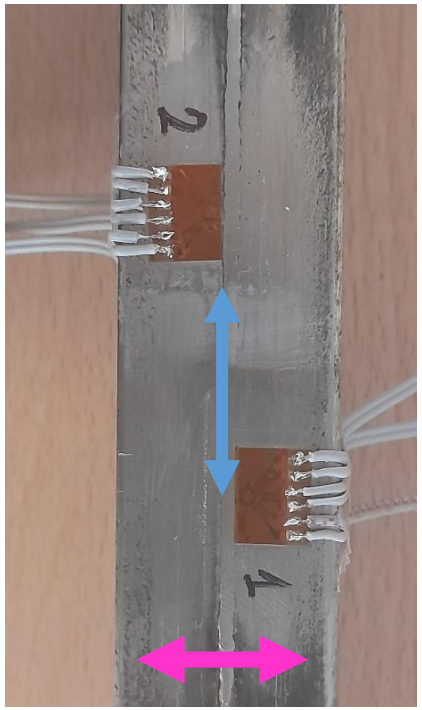


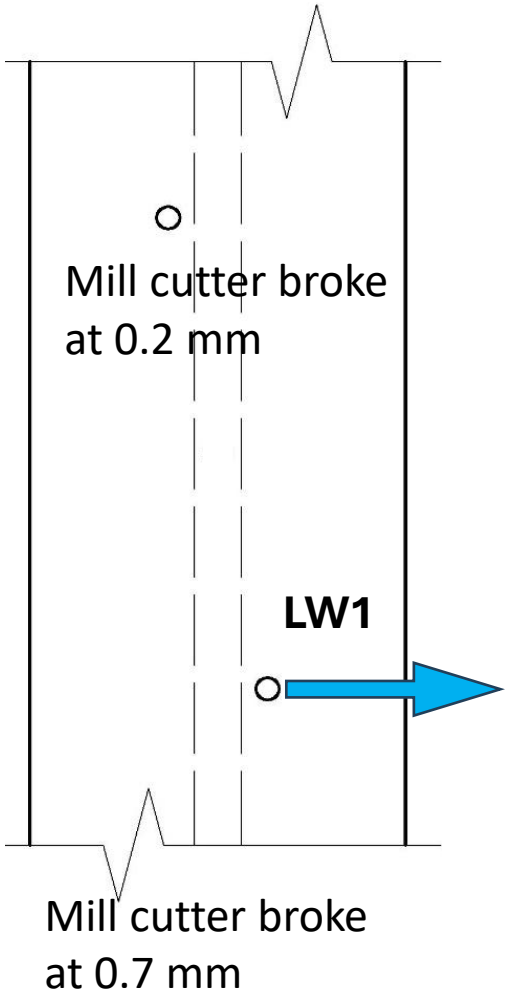
re=1.2e-3

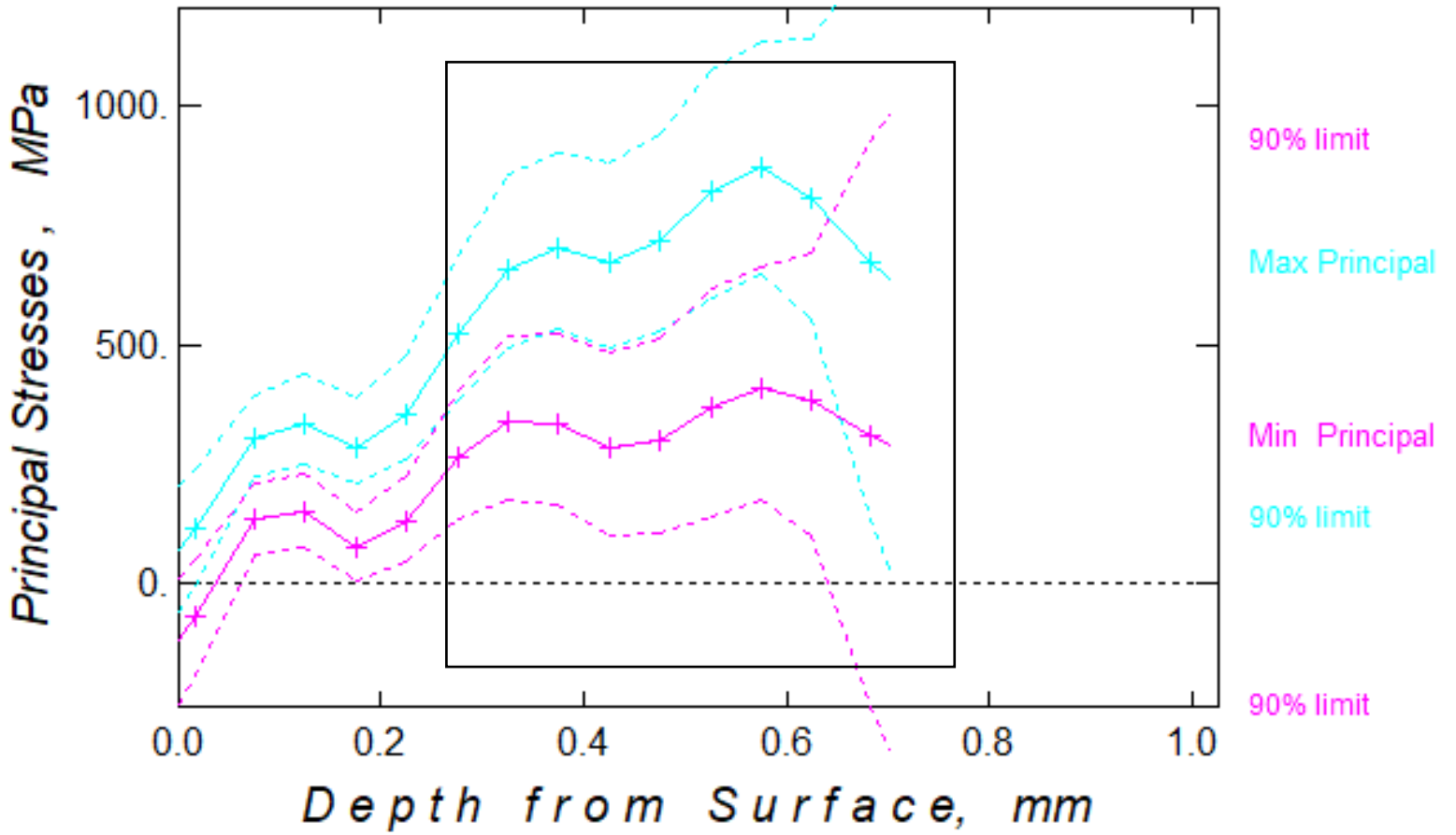
ri=0.5e-3

75% power on the sample

7. Residual stress measurements



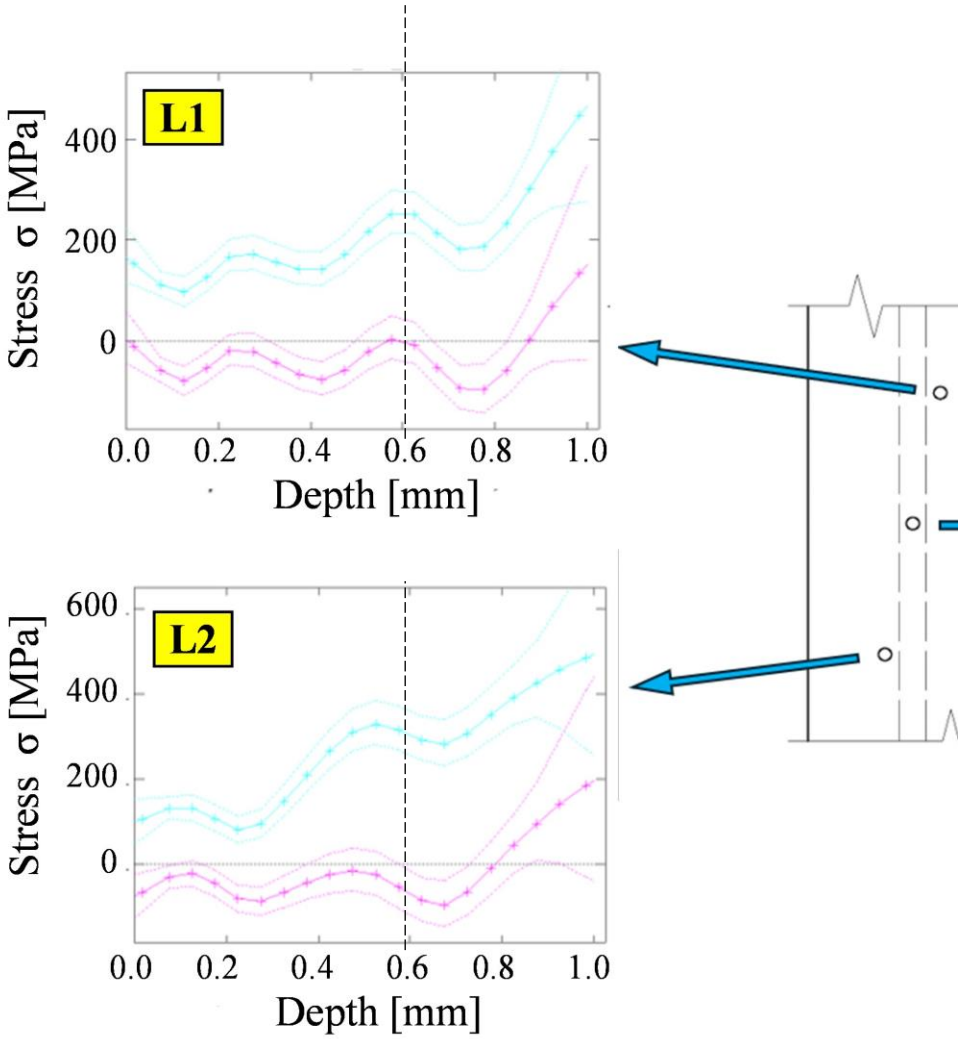


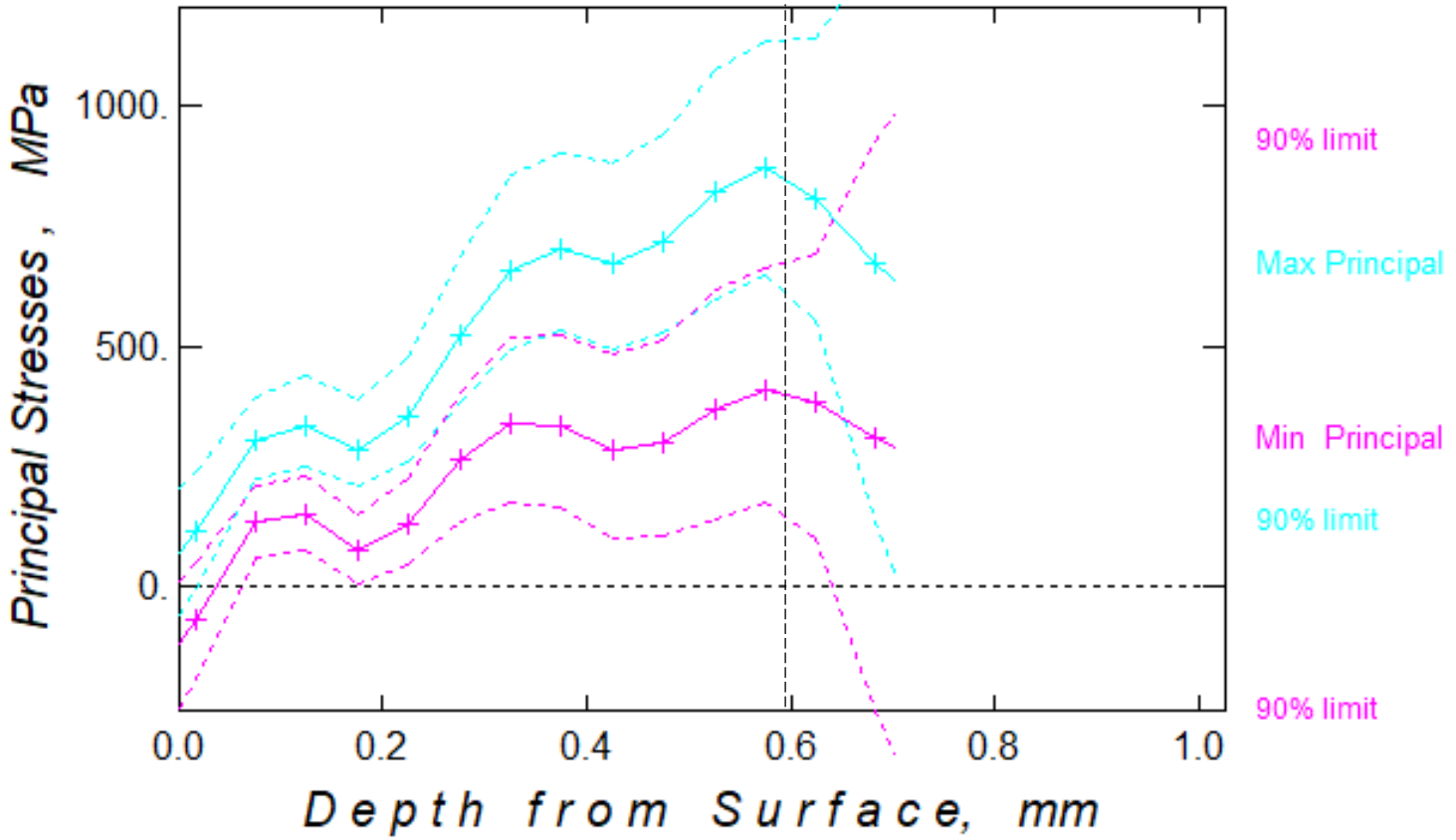


Stresses in both directions are positive (tensile),
which are more dangerous than compressive

7. Residual stress measurements

After welding by ICAS:





After welding by Montanstahl

Possible reason:
Work hardening of the material due to hot rolling and bending before welding, causing higher yield stress

8. Conclusions and next steps

For this task:

1. Performing mechanical analysis for the Montanstahl like set-up
2. Including higher heat transfer coefficient
3. Including the vertical pressure from the rollers

Future work:

1. Thermal simulation of the full RW conductor, to see the values of temperatures and the potential for damage.
2. Measuring mechanical properties of the welded material (316L) at high temperatures -> to better calibrate the model