Thermo-mechanical analyses and tests of the laser welding process

SP1 and SP2 conductor jackets

Jakub Tabin, Rafał Ortwein

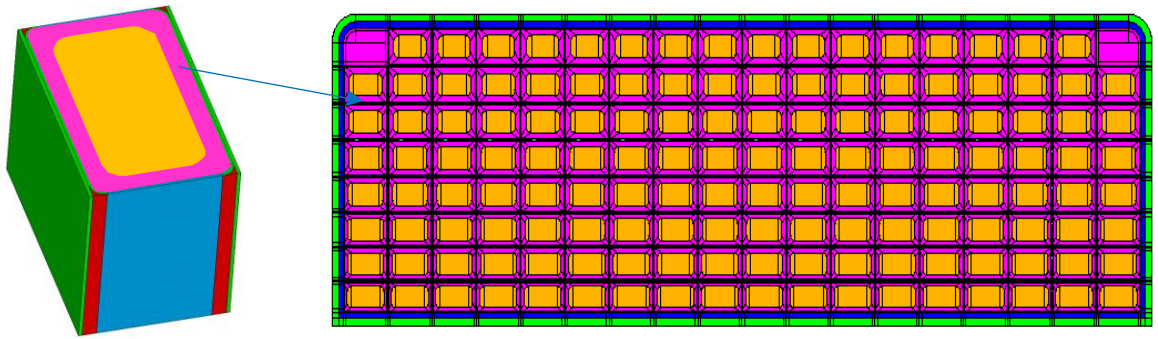
Acknowledgements: Xabier Sarasola (SPC), Tomasz Ślązak (WAT), Katarzyna Zielińska (IPPT), Adam Szyszko (IPPT)

EU–CN meeting, 28–29 October 2026

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Motivation and research objectives

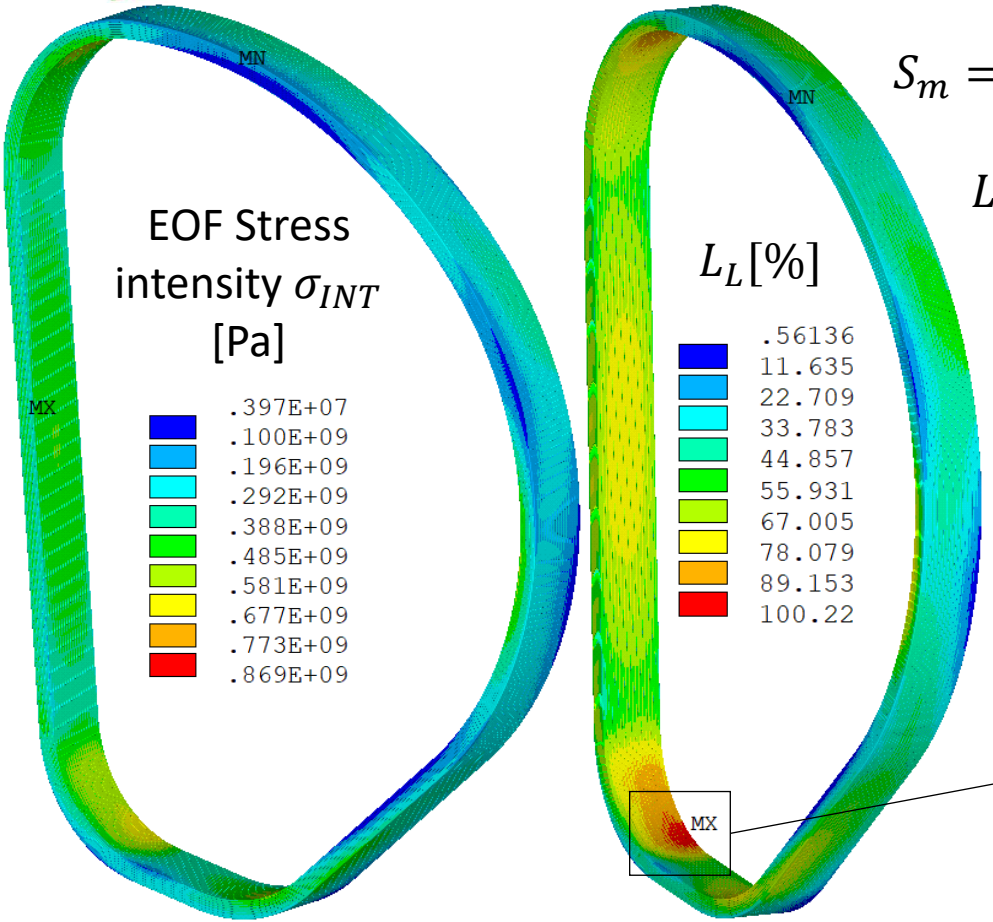
Mechanical analysis of the DEMO winding packs (2023)

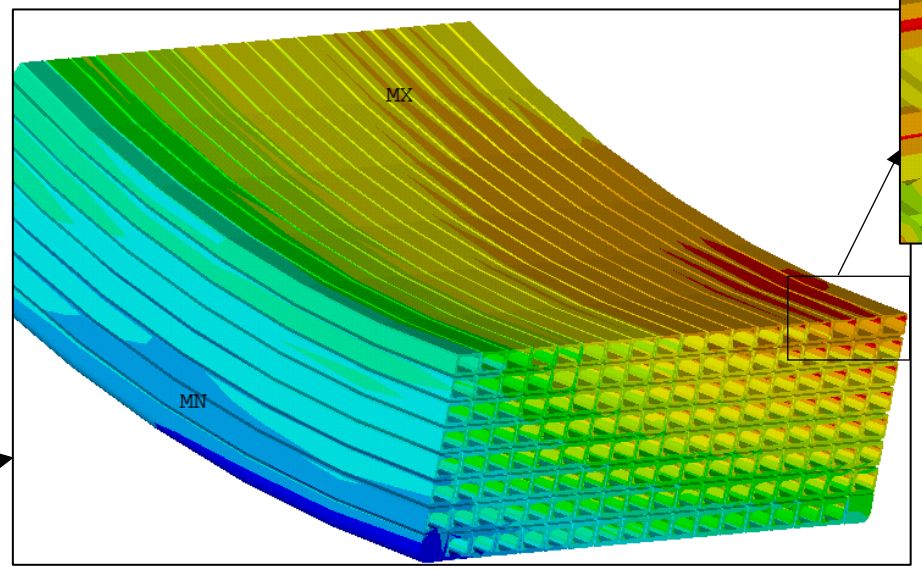


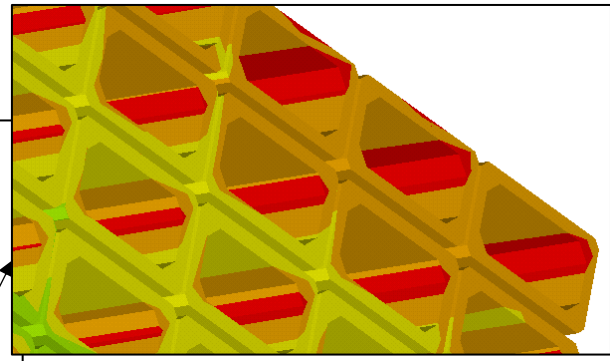
Context: Allowable stress in the winding-pack analysis: 667 MPa.
Hypothesis: Welding residual stresses may reduce local stress margins.
Objective: Compare local properties, residual stresses and cryogenic tensile response in SP1 and SP2.

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

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







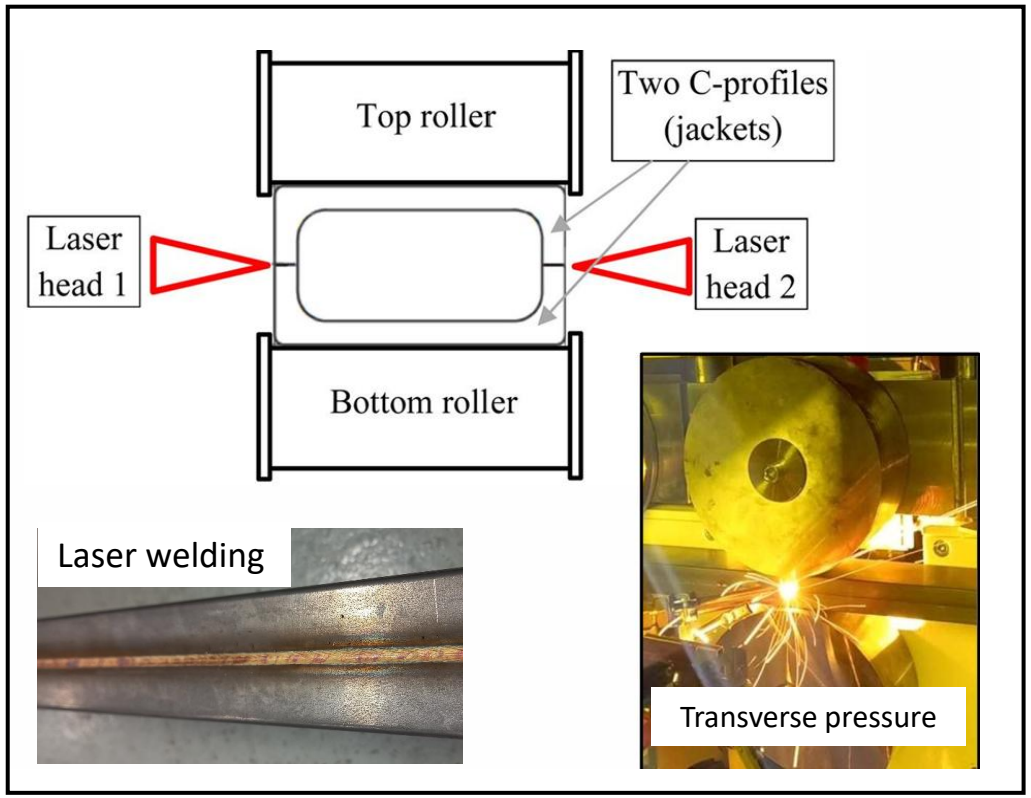
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SP1 and SP2: manufacturing and welding routes

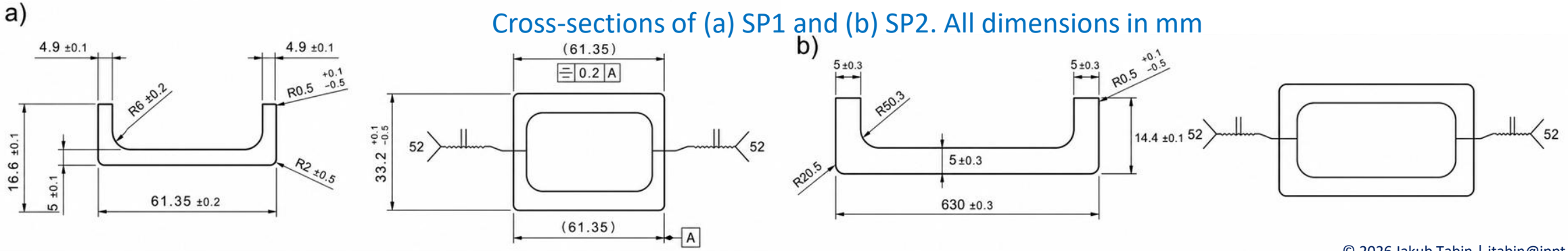
Single-pass and two-pass longitudinal laser welding

Parameter	SP1: ICAS (2022)	SP2: Montanstahl (2025)
Material	316L (1.4404)	316L (1.4404)
Welding sequence	Single pass	Two passes
Laser heads	One synchronized pair	One pair per pass
First pass	3.5–4.0 kW Final weld	≈1.0 kW Gap closure
Second pass	Not applicable	≈3.7 kW Full penetration
Welding speed	0.8–1.2 m/min	2 m/min
Transverse pressure	During welding	During first pass
Transverse joining	Manual TIG butt welds	Not reported

React & Wind conductor jacket assembly



Cross-sections of (a) SP1 and (b) SP2. All dimensions in mm



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FEM model of welding

Coupled thermo-mechanical FEM analysis:
Transient thermal model + mechanical model

Laser heat source model

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

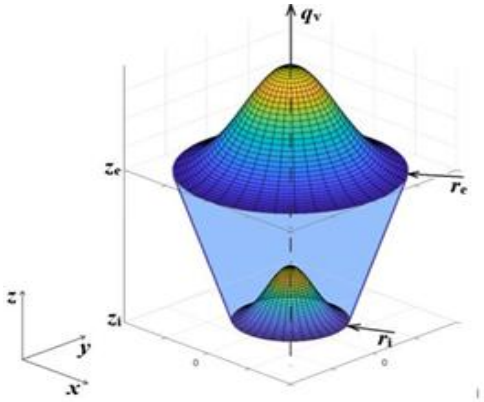
$$\frac{\partial \sigma_{ij}}{\partial x_i} + b_j = 0 \qquad \sigma_{ij} = C_{ijkl}\left(\varepsilon_{kl} - \varepsilon^p_{kl} - \varepsilon^t_{kl}\right)$$

$$\varepsilon_{kl} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right) \qquad f^{yield} = \sigma_{eqv} - \sigma_y(\boldsymbol{T})$$

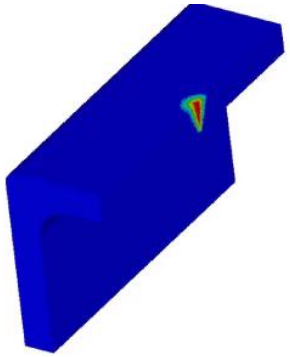
$$\varepsilon^t_{kl} = \alpha(\boldsymbol{T})(\boldsymbol{T} - T_0)$$

Model includes annealing effect at $T>T_{ANN}$

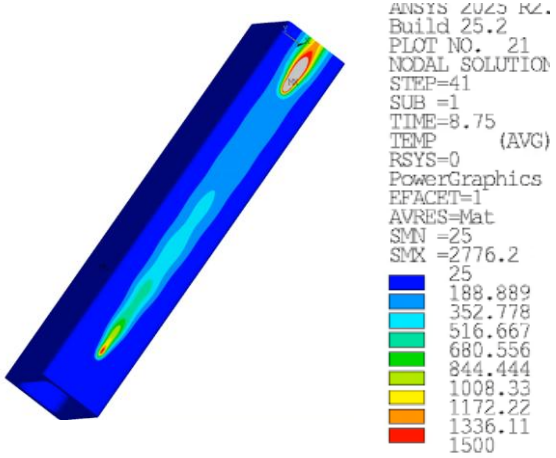
Conical heat source model

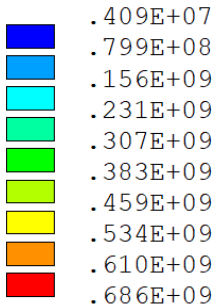


Moving heat source

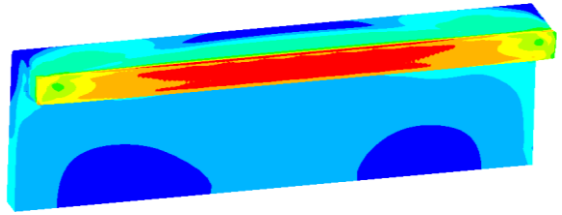


Model with 4 lasers
(as in Montanstahl set-up)





Von Mises residua stress [Pa]



Model solved with Ansys Mechanical APDL software

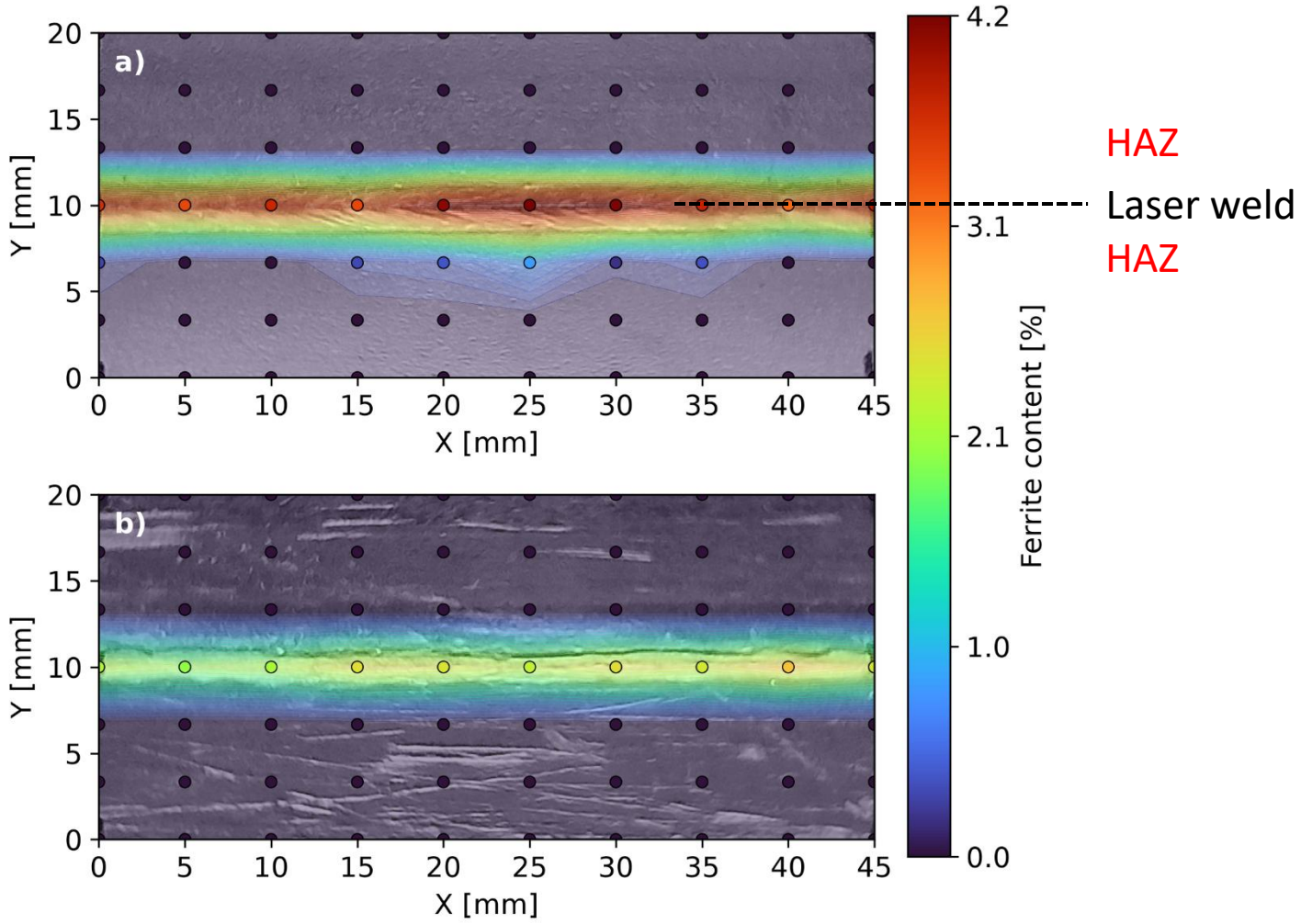
Models documented in the reports:
MAG-S.01.04-T019-D002-Thermo-mechanical analyses of residual stresses due to welding in a conductor jacket (2S8W5Y v1.1) (2025)
MAG-S.01.04-T022-D001 - Thermo-mechanical analyses and tests on laser welding process (2SV9Y9 v1.1) (2026)

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SP1 shows higher ferrite readings in the weld

SP1

SP2



Ferrite content maps of the laser weld and heat-affected zone (HAZ) in (a) SP1 and (b) SP2.

Mean weld readings (±SD)

SP1: 3.7 ± 0.3 Fe%

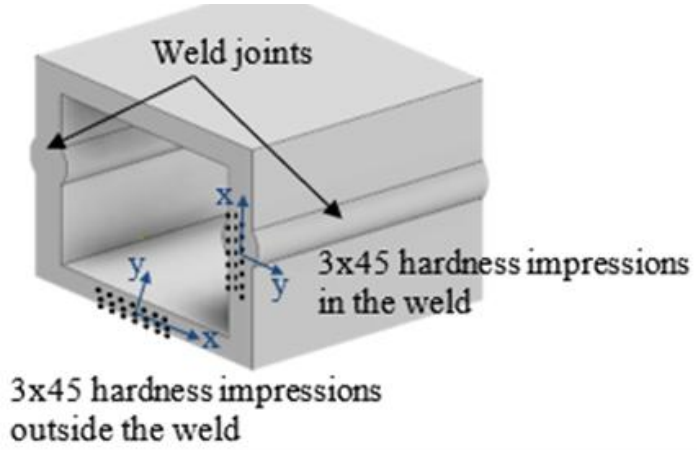
SP2: 2.3 ± 0.2 Fe%

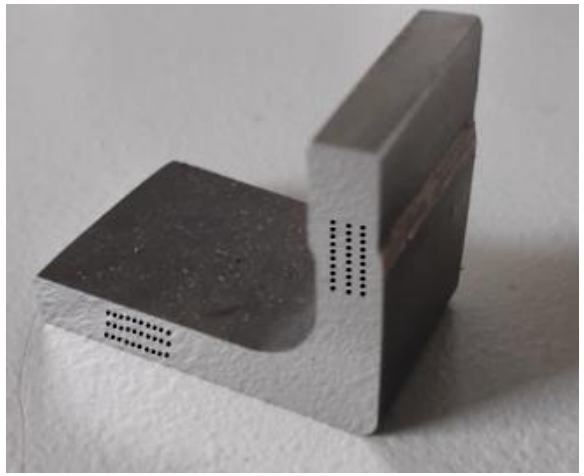


Fischer DMP30 with FGAB1.3-Fe probe
Feritscope readings detect ferromagnetic phases.

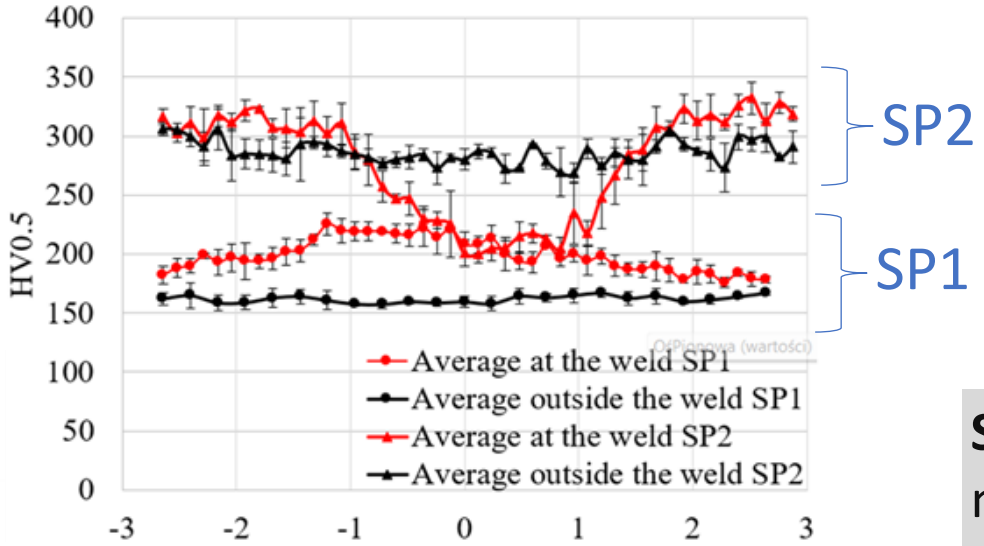
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Weld hardening in SP1 contrasts with softening in SP2

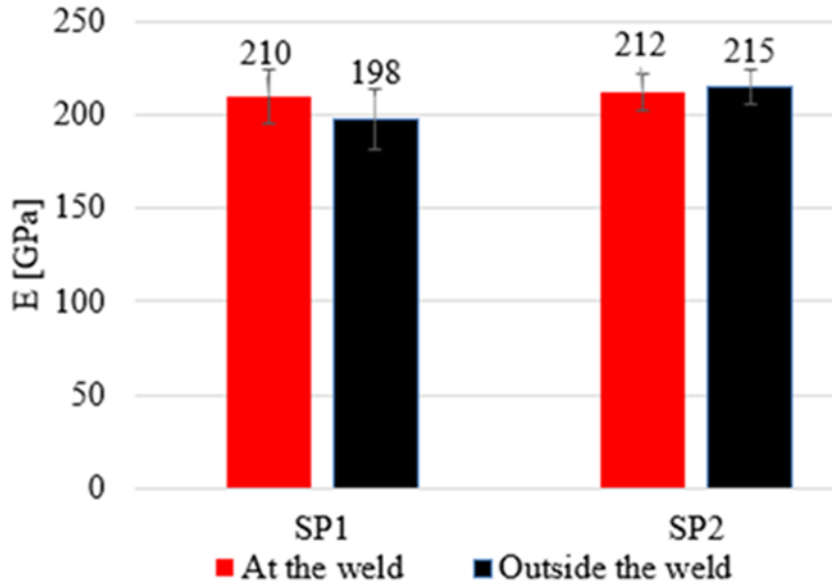




Vickers indentation: 0.5 N, 15 s



Modulus E from the Oliver–Pharr method



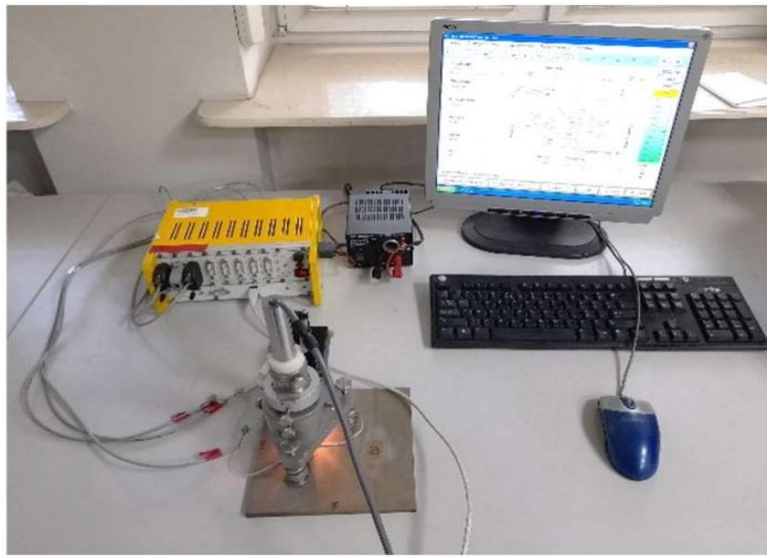
SP1: ≈160 HV in the base material, rising to ≈225 HV in the weld.

SP2: ≈290 HV in the base material, falling to ≈200 HV in the weld.

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HDM indicates higher tensile residual stresses in SP2

Hole-drilling method (HDM)





Vertical force applied during welding SP2

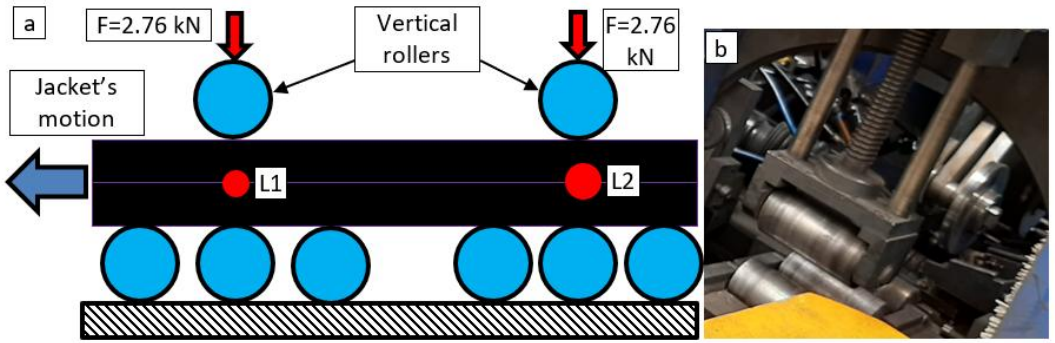
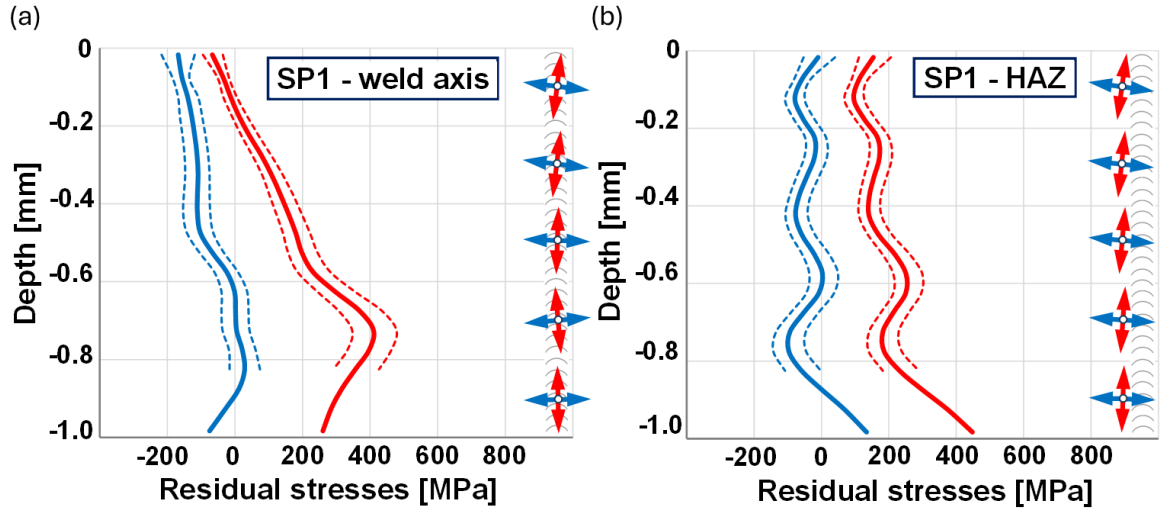


Fig. 48. Vertical force applied during welding – a scheme; b) Photograph near the laser L1

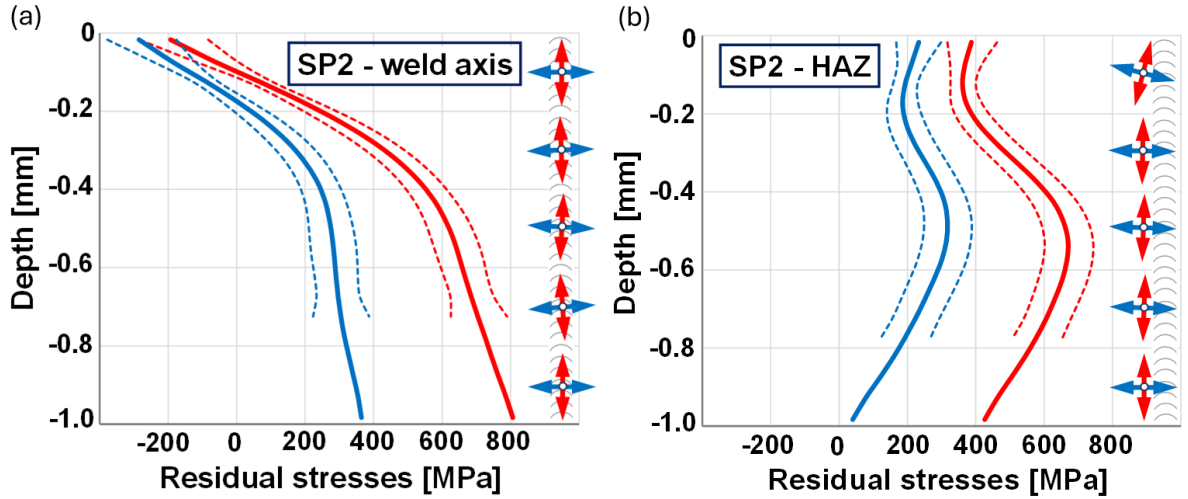
SP1: weld and HAZ

SP1



SP2: weld and HAZ

SP2

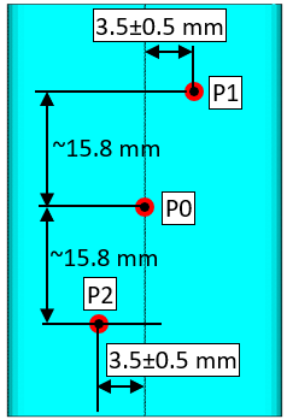


SP2: calculated σmax > 600 MPa.

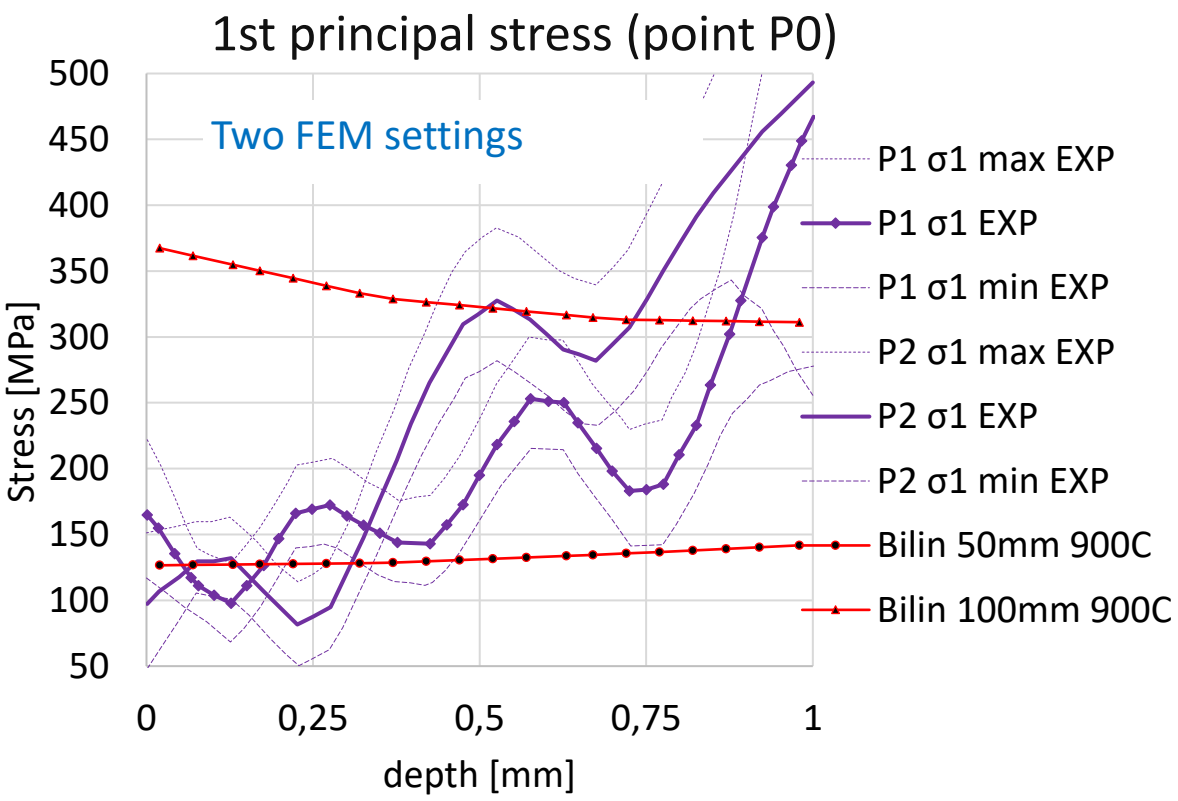
Elmesalamy, A.S. et al. (2016). *Measurement and modelling of the residual stresses in autogenous and narrow gap laser welded AISI grade 316L stainless steel plates. International Journal of Pressure Vessels and Piping, 147, 64–78.*

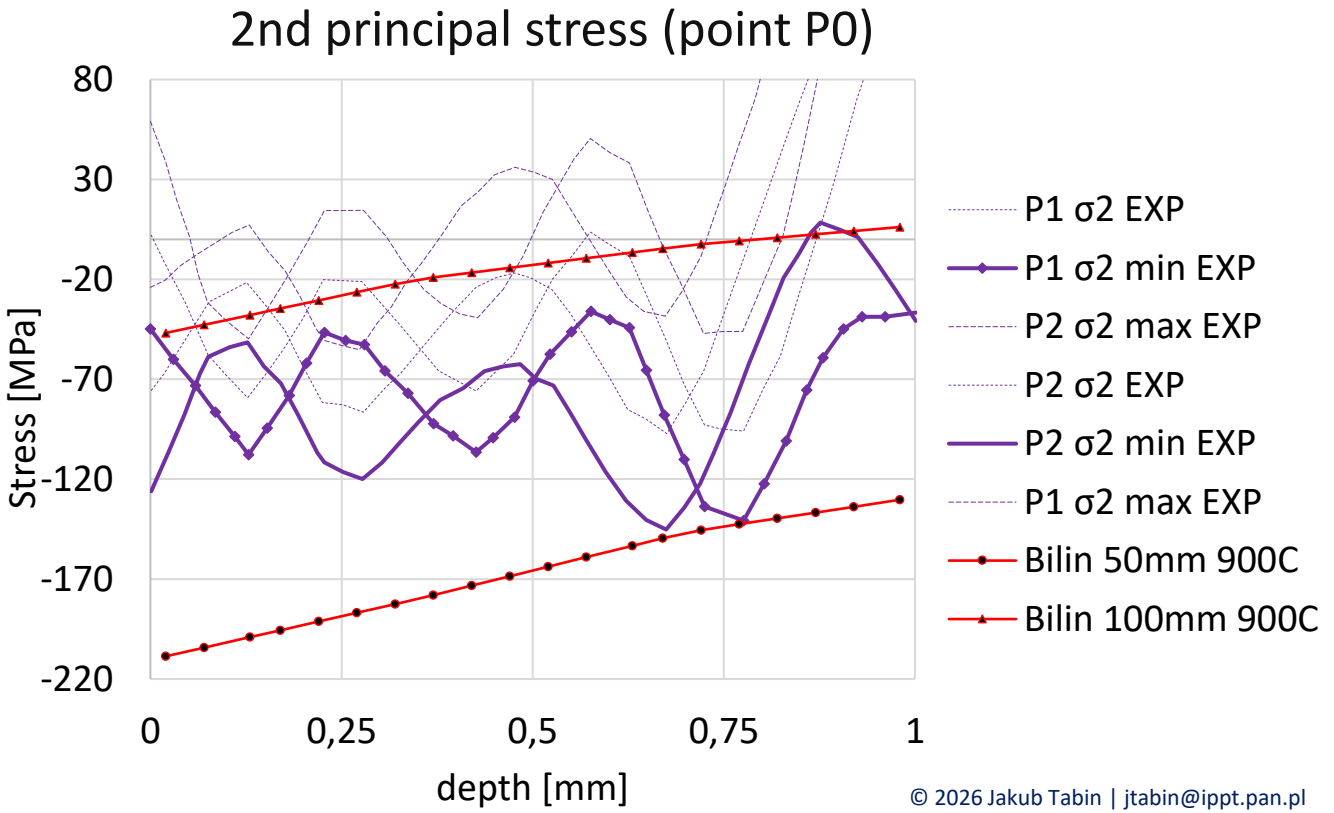
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Preliminary FEM–HDM comparison for SP1



FEM predictions (red) and hole-drilling measurements (violet): Agreement varies with depth and model settings. Surface preparation is a possible contributor to the discrepancy. Quantitative validation and measurement-point labels require verification.

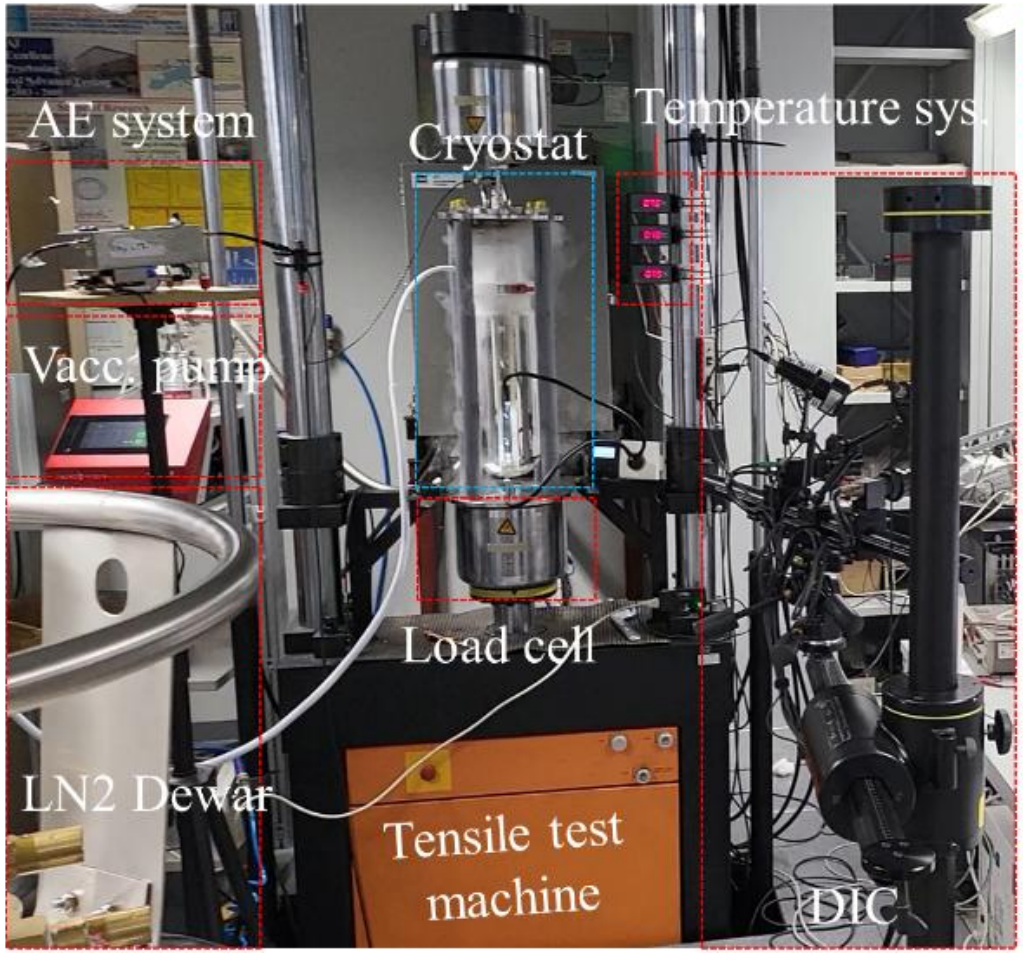


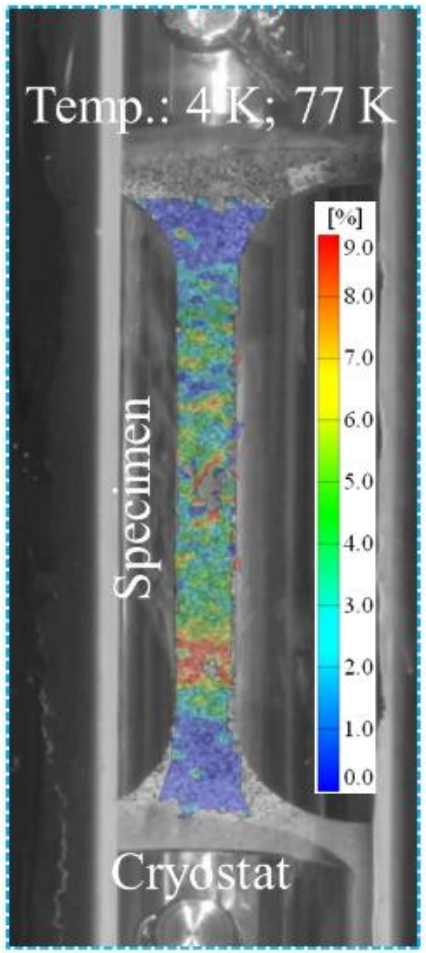


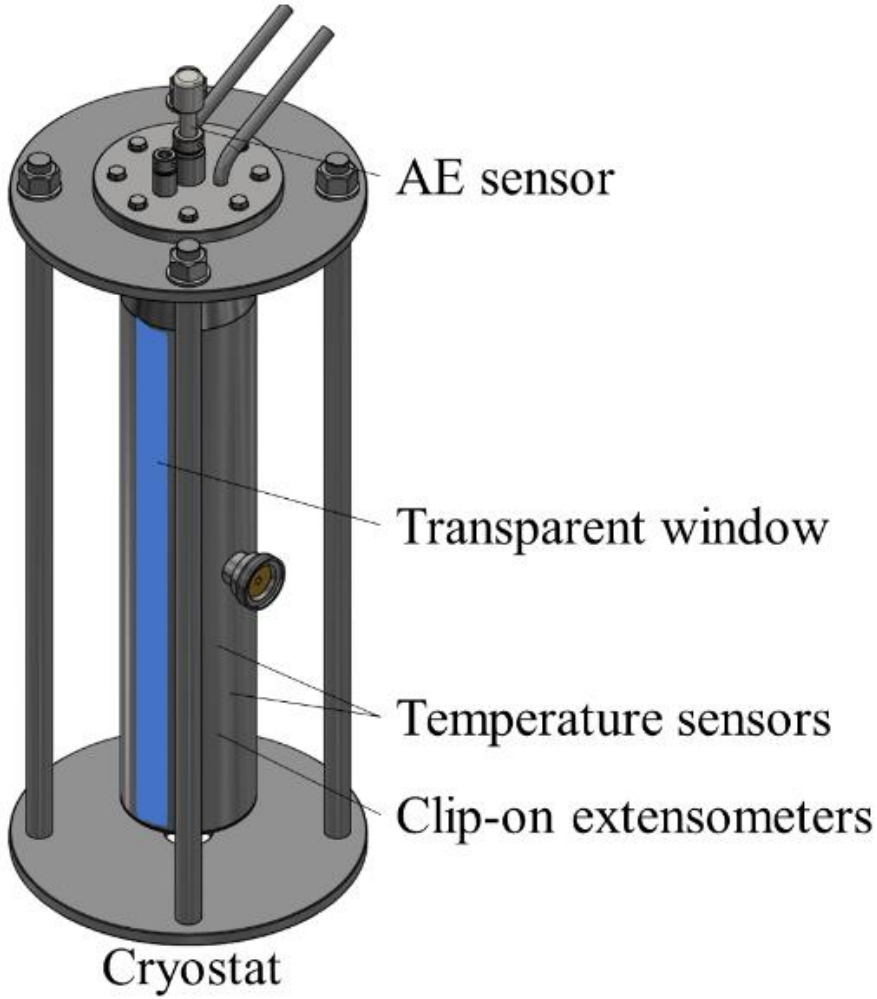
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Cryogenic tensile testing: experimental platform

Uniaxial tensile tests at 77 K and 4 K
crosshead displacement rate 1.0 mm/min



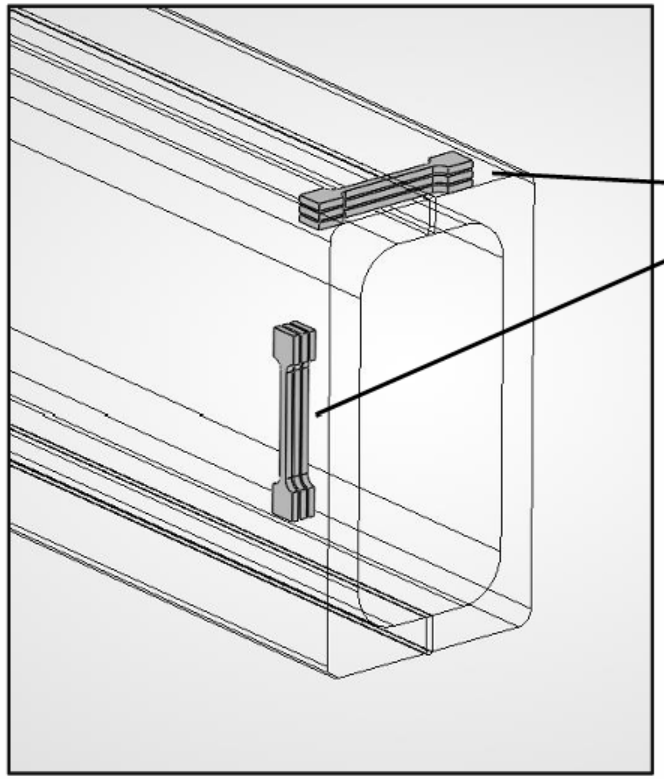




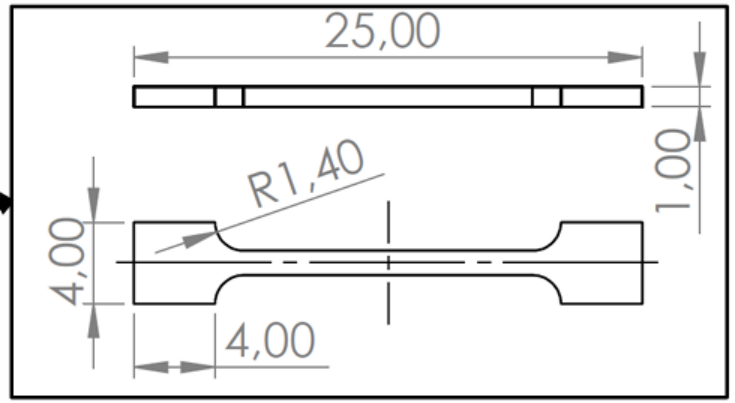
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Uniaxial tensile test at 77K and 4K

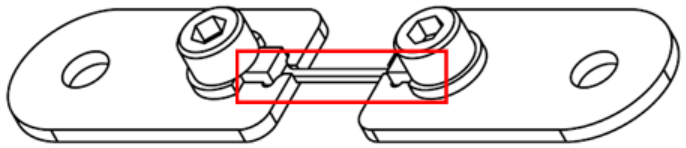
Miniature specimen for tensile testing at cryogenic temperatures



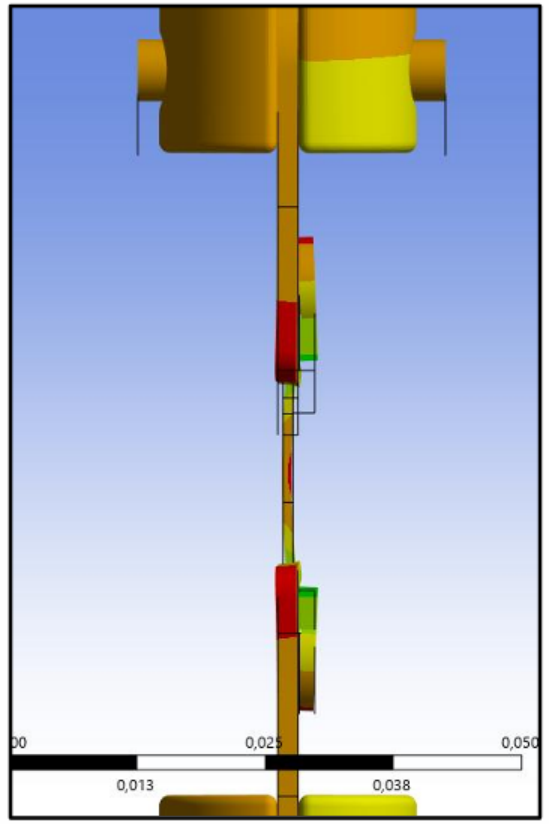
EDM cut Mini samples from weld area and referencial wall area at multiple depths



Mini samples based on Kammrath and Weiss DDS4 mini sample testing equipment



Developed mini sample grip for tensile testing in Cryostat

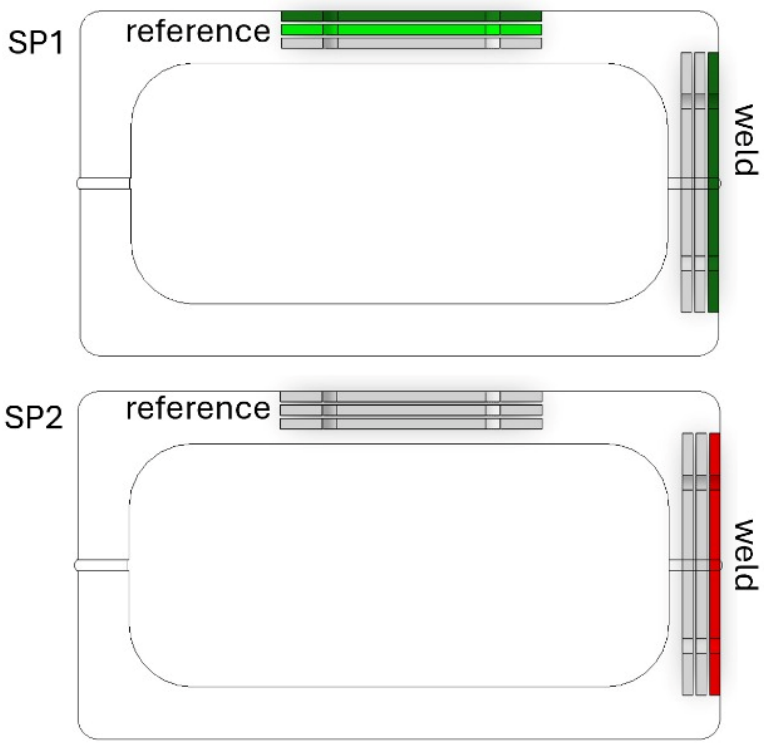


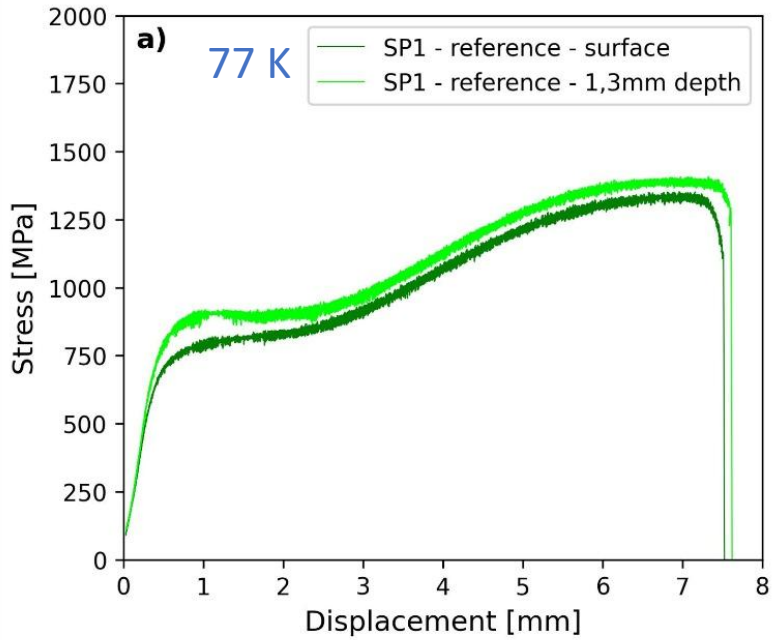
FEM analisys of mini sample grip

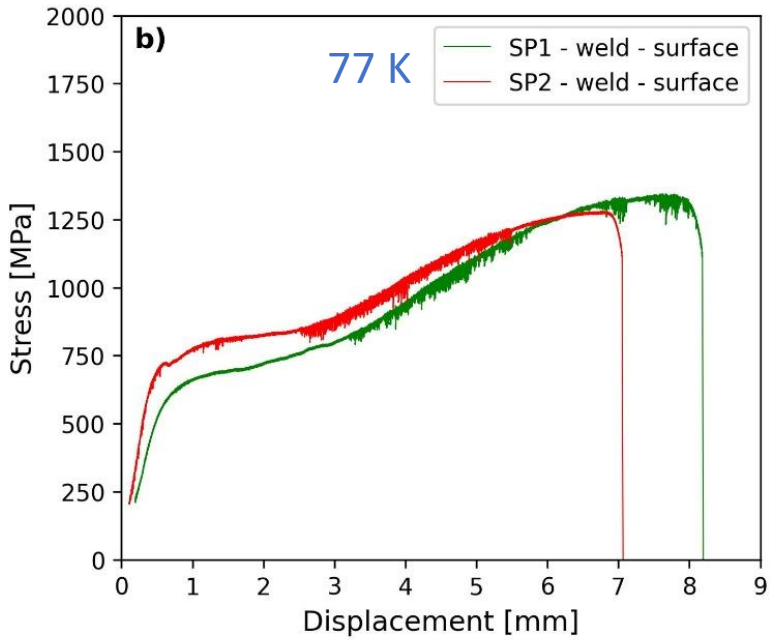
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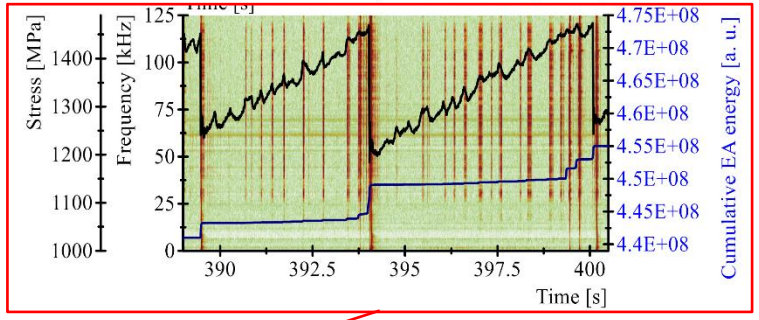
Uniaxial tensile test at 77K and 4K

Kinematically controlled uniaxial tensile test at 77 K and 4 K

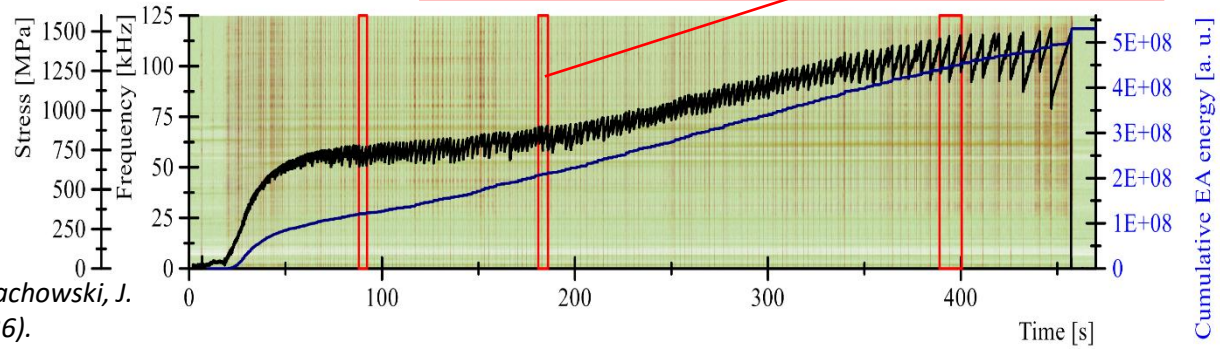


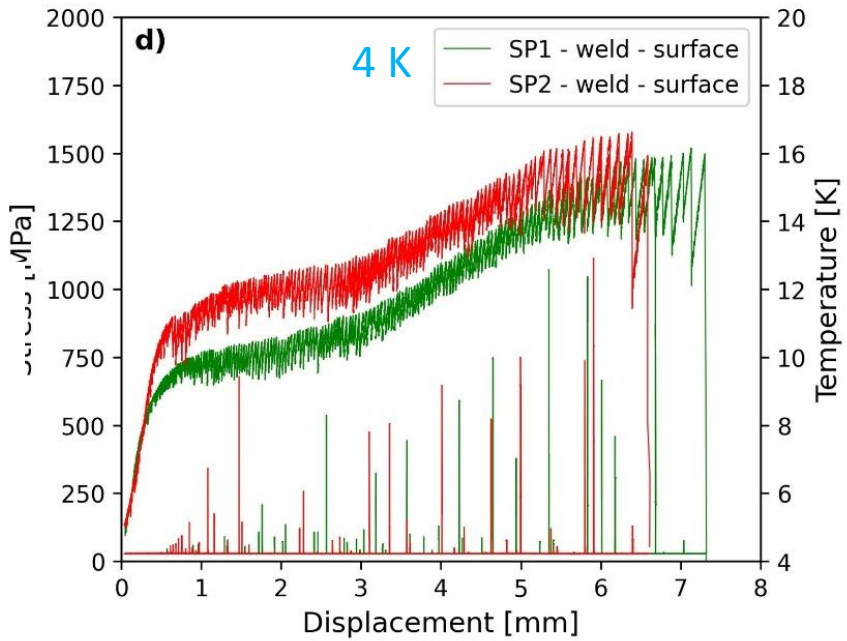






AE during kinematically controlled uniaxial tensile testat 4 K





J. Tabin, H. Nejman, A. Szyszko, Z. Ranachowski, J. Kawałko,, Metall. Mater. Trans. A (2026).

Conclusions

- **Ferrite readings:** SP1 shows higher mean weld readings than SP2: 3.7 ± 0.3 versus 2.3 ± 0.2 Fe%.
- **Local hardness:** The weld is harder than the base material in SP1 (≈160 to ≈225 HV), but softer in SP2 (≈290 to ≈200 HV).
- **Residual stresses:** HDM indicates higher tensile residual stresses in SP2, exceeding 600 MPa. Restrained thermal contraction provides a physically justified explanation, with welding sequence and restraint conditions as potential contributors.
- **Cryogenic response:** Temperature peaks appear earlier in SP2 during tensile testing at 4 K.
- **Assessment implications:** The jackets exhibit different local properties and residual-stress states. Nominal material designation alone does not establish mechanical equivalence.

To Do:

- **Microstructure and texture:** Combine EBSD with ultrasonic measurements to investigate local microstructure and assess texture variations over larger jacket regions.
- **Acoustic emission:** Develop an AE monitoring system to detect and characterize dissipative events during deformation of jacket materials.
- **Weld characterization:** Adapt the Wirotest system to the jacket geometry and calibrate its response for assessing ferrite content in laser welds.

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3. J. Tabin, T. Ślęzak, K. Zielińska, D. Kukla, R. Ortwein, X. Sarasola, K. Grzelak, Microstructure, mechanical properties and residual stress of welded stainless-steel jackets for React & Wind conductor in EU-DEMO, Fusion Eng. Des. 222 (2026) 115503. https://doi.org/10.1016/j.fusengdes.2025.115503.
4. MAG-S.01.04-T019-D002-Thermo-mechanical analyses of residual stresses due to welding in a conductor jacket (2S8W5Y v1.1) (2025)
5. MAG-S.01.04-T022-D001 - Thermo-mechanical analyses and tests on laser welding process (2SV9Y9 v1.1) (2026)
6. MAG-S.01.04-T013-D001 - Mechanical analysis of the DEMO winding packs (2023)

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