

Mechanical properties of pre-hydrogenated (600 – 5000 wppm) cladding segments

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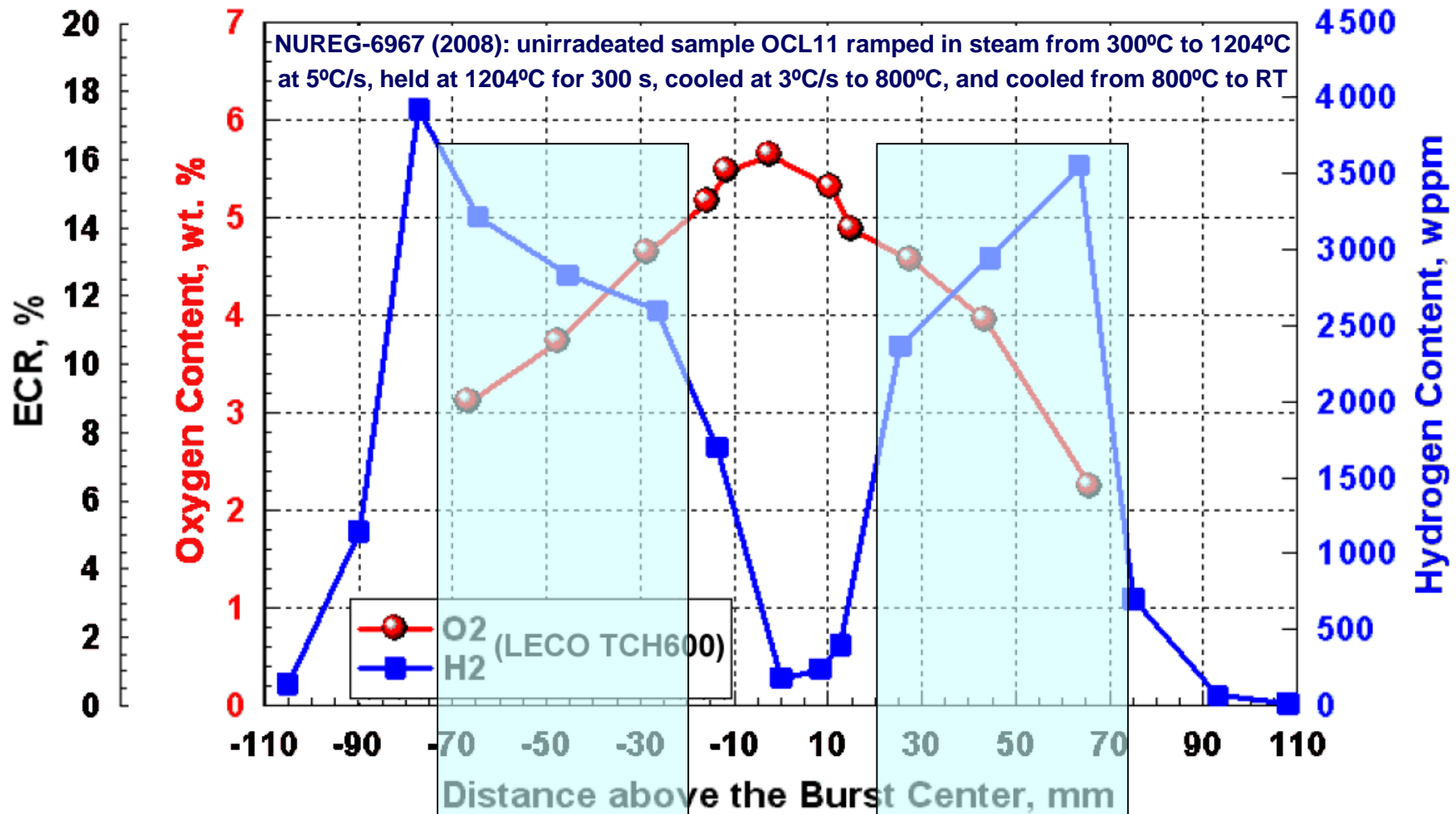
Institute for Materials Research



Objectives

- **Preparation of hydrogenated samples for mechanical tests**
- **Hydrogen uptake under hydrogen starvation conditions to achieve axial hydrogen gradient in the cladding**
- **Tension and ring compression tests with hydrogenated samples**

Short term secondary hydrogenation after ballooning and burst: hydrogen uptake increased rapidly up to 4000 ppm (significant higher than ductility limit of 500 ppm)



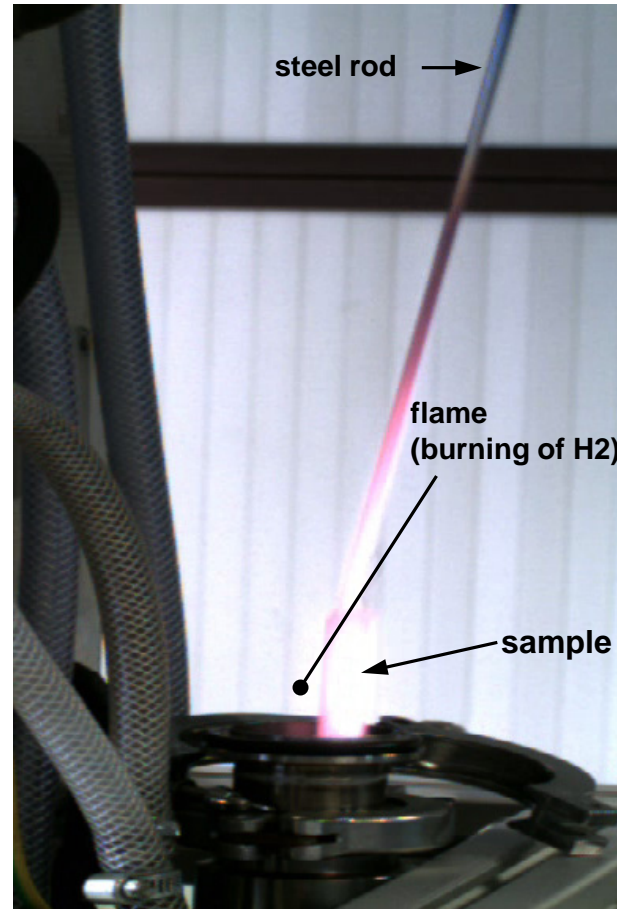
sample OCL11 (Zircaloy-2):



Hydrogenation facility



vertical 3-zones tube furnace LORA
(height 60 cm)



sample extraction
at furnace top



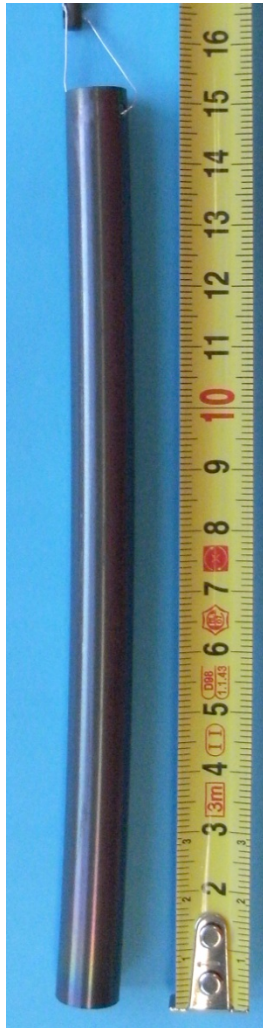
sample
15 cm

Test matrix

| sample | temperature | H2 partial pressure | hydrogenation duration | dissolved hydrogen (weight gain) | hydrogen solubility limit |
|--------|-------------|---------------------|------------------------|----------------------------------|---------------------------|
| # | °C | mbar | min | wppm | wppm |
| H11Z4 | 700 | 90 | 2 | 2473 | 16770 |
| H12Z4 | 700 | 90 | 6 | 5417 | 16770 |
| H13 Z4 | 700 | 37 | 2 | 681 | 10820 |
| H14 Z4 | 700 | 37 | 4 | 1819 | 10820 |
| H15 Z4 | 700 | 37 | 6 | 2746 | 10820 |
| H16 Z4 | 700 | 37 | 8 | 4810 | 10820 |
| H18 Z4 | 800 | 37 | 2 | 827 | 5150 |
| H19 Z4 | 800 | 37 | 4 | 1625 | 5150 |
| H20 Z4 | 800 | 37 | 8 | 2783 | 5150 |
| H21 Z4 | 800 | 37 | 16 | 4420 | 5150 |
| H29Z4 | 900 | 37 | 1 | 400 | 2770 |
| H31Z4 | 900 | 37 | 4 | 1215 | 2770 |
| H33Z4 | 900 | 37 | 8 | 1689 | 2770 |

Post-test sample appearance:

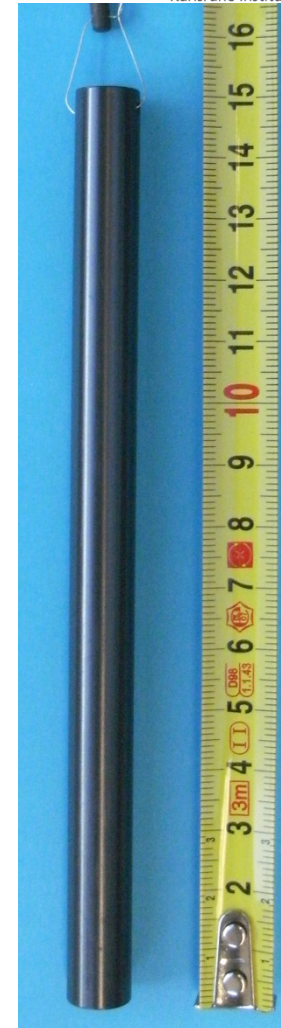
sample bending at $T < 800^\circ\text{C}$ due to phase transition $\alpha\text{-Zr}$ to $\beta\text{-Zr}$



H14Z4: annealed at 700°C
with H_2 (37 mbar); $\Delta t = 240$ s
 $\Delta m_{\text{H}} = 1800$ wppm

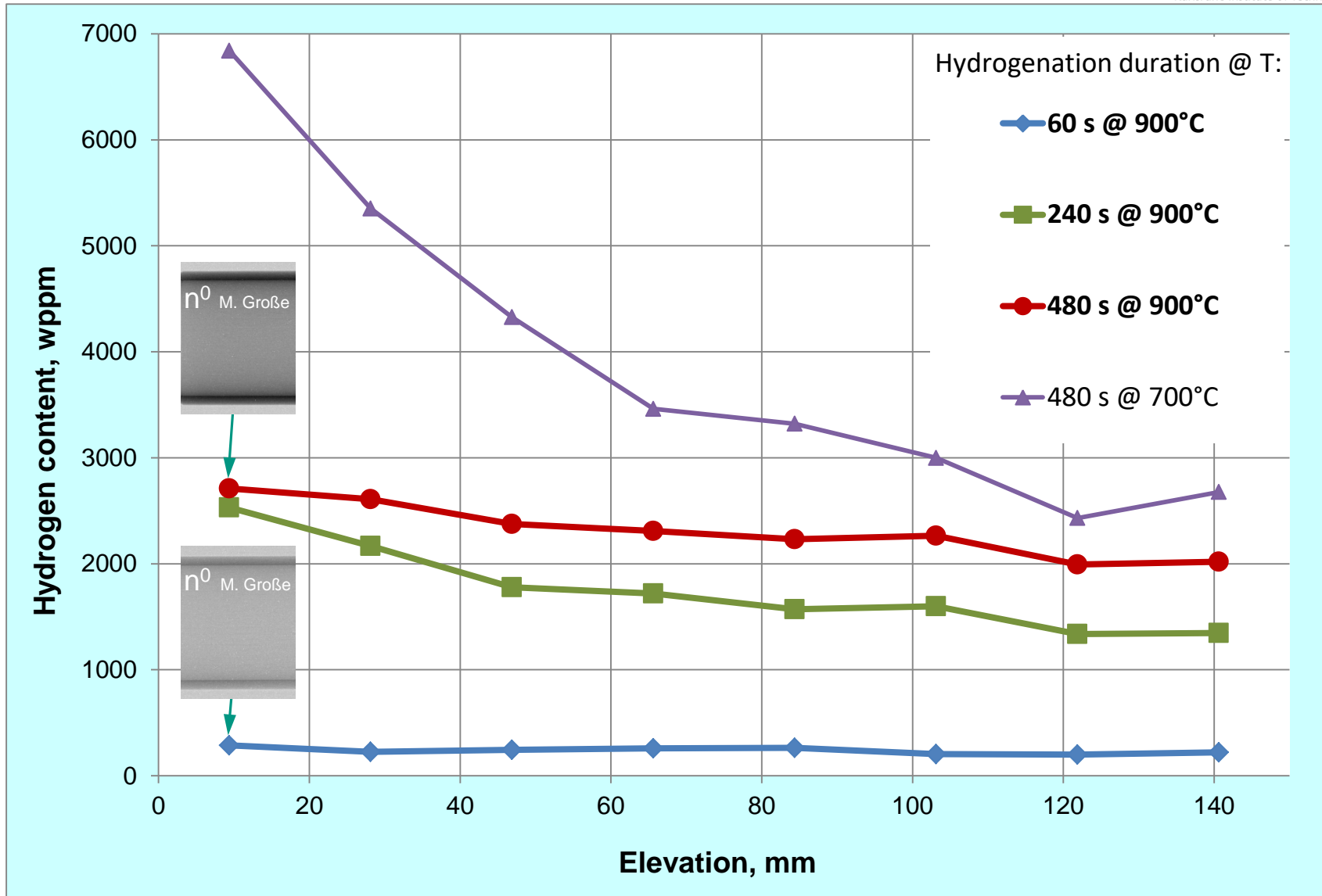


H19Z4: annealed at 800°C
with H_2 (37 mbar); $\Delta t = 240$ s
 $\Delta m_{\text{H}} = 1600$ wppm

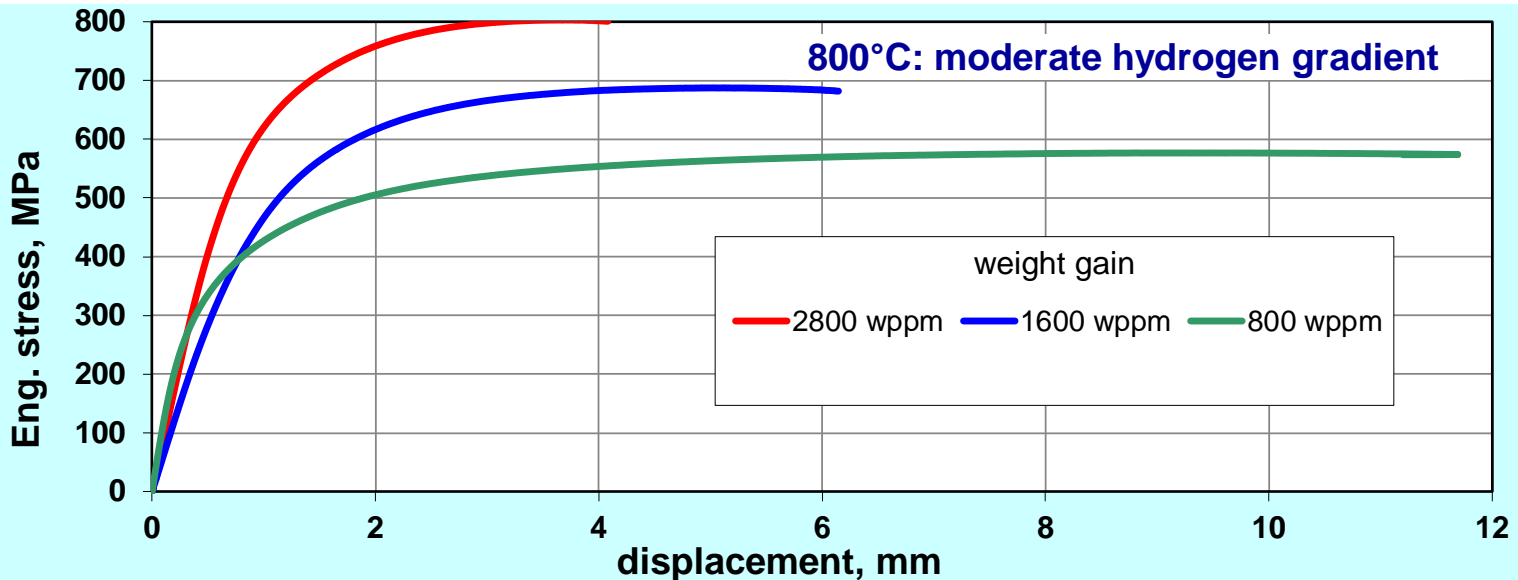
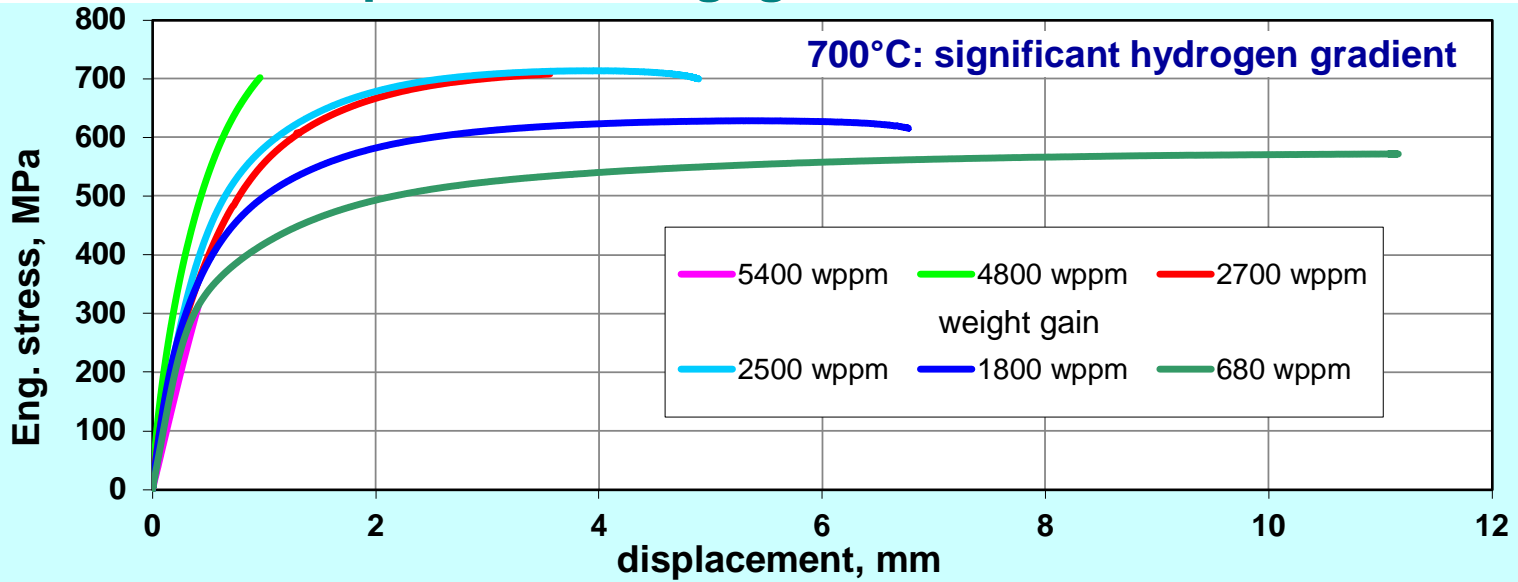


H33Z4: annealed at 900°C
with H_2 (37 mbar); $\Delta t = 480$ s
 $\Delta m_{\text{H}} = 1700$ wppm

Axial distribution of hydrogen content measured by neutron radiography

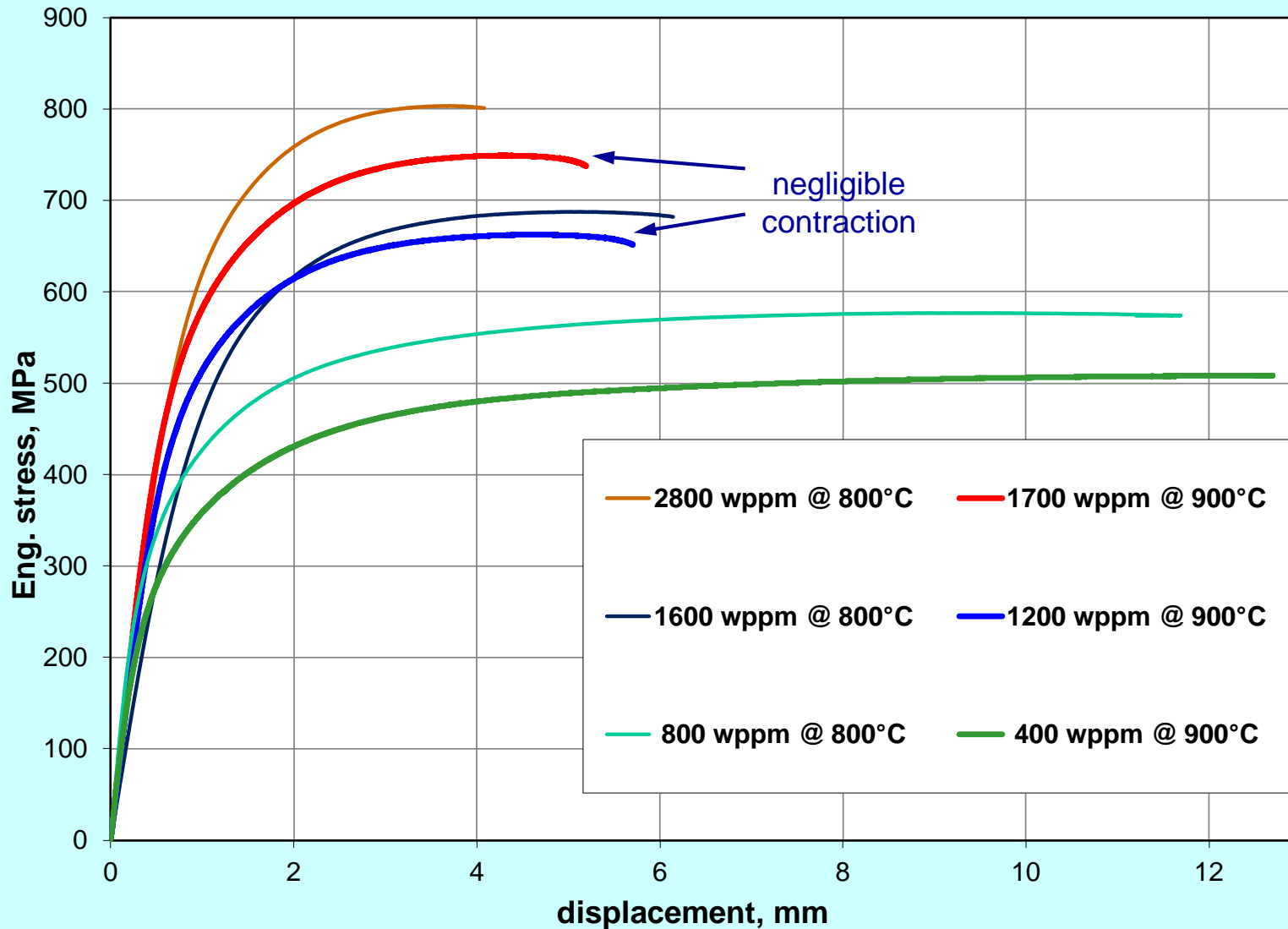


Tension tests with samples hydrogenated at 700 and 800°C: rupture with negligible contraction



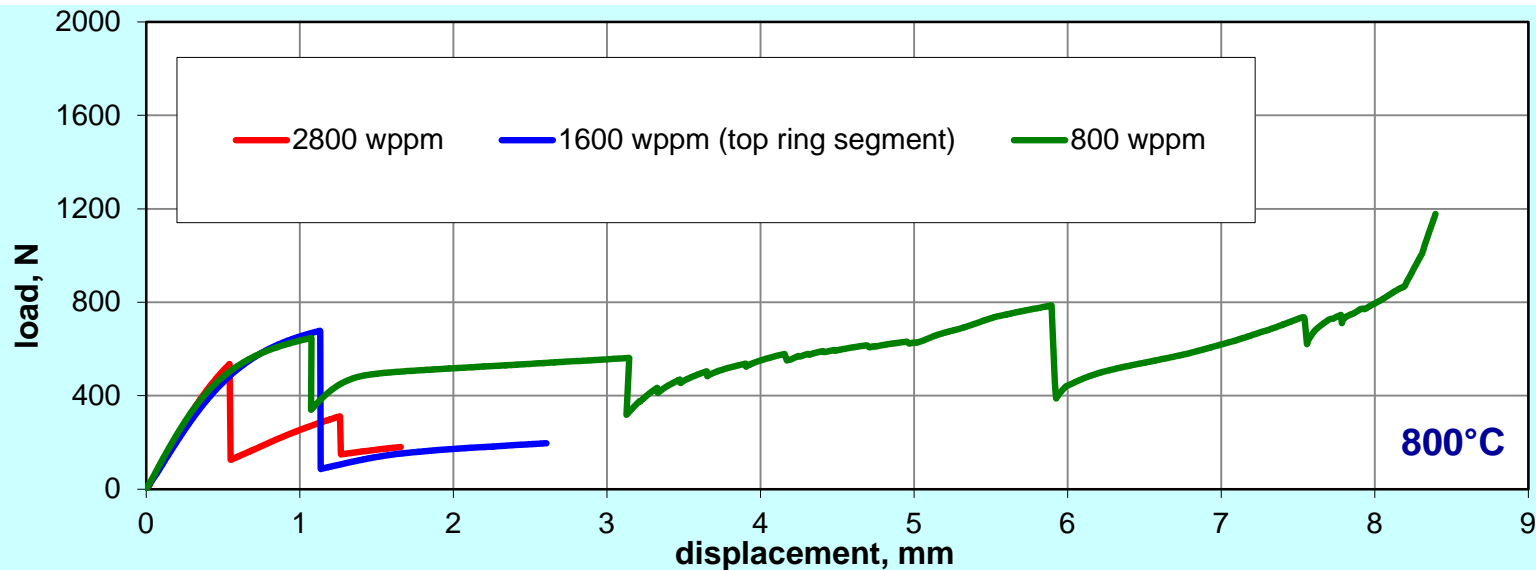
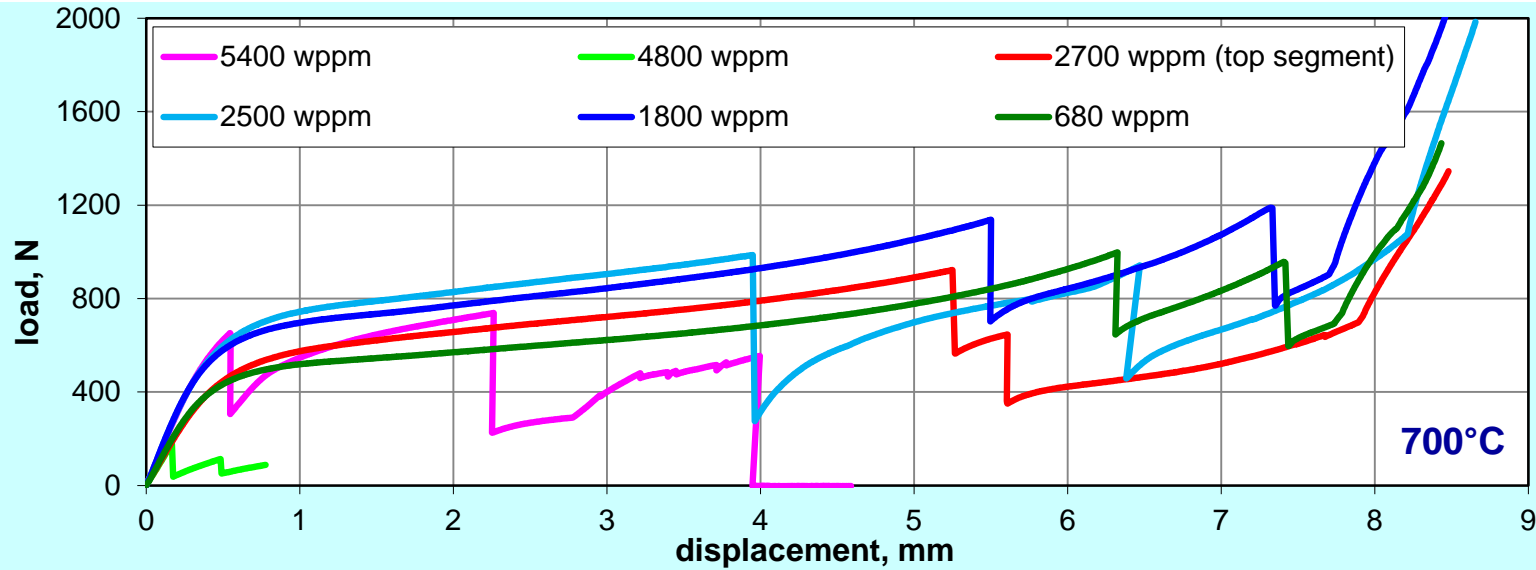
ductile not hydrogenated sample with pronounced contraction

Tension tests with samples hydrogenated at 800°C (moderate H gradient) and 900°C (small gradient)

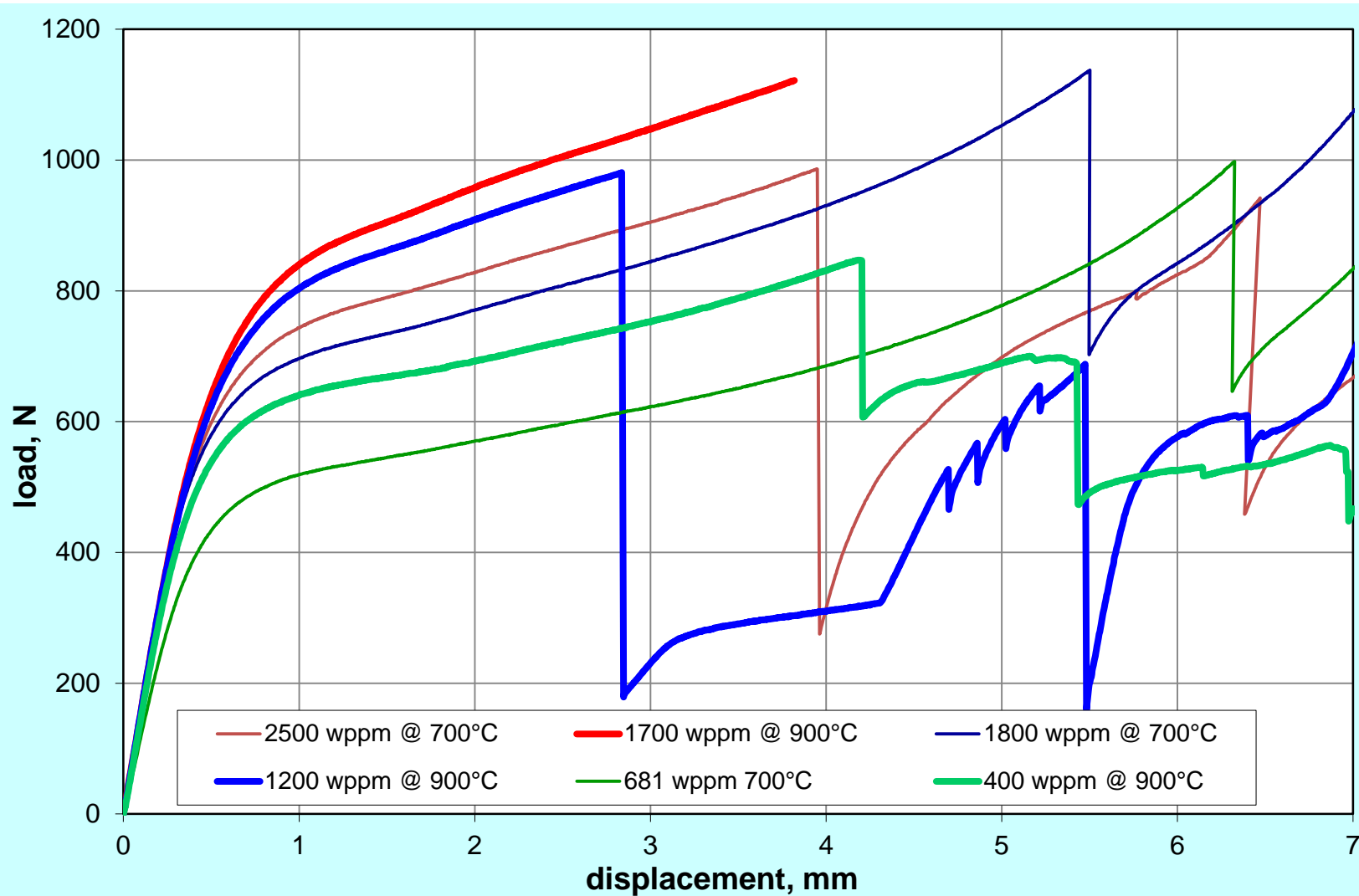


ductile not hydrogenated sample with pronounced contraction

Compression tests with rings from bottom of samples hydrogenated at 700 and 800°C



Compression tests with rings from bottom of samples hydrogenated at 700 and 900°C: hardening and embrittlement increase at higher annealing temperature



Summary

- **Twelve Zry-4 cladding specimens with length of 150 mm were hydrogenated in Ar + H₂ atmosphere at temperatures 700, 800 and 900°C**
- **Average hydrogen content was measured with sample weighing between 600 and 5000 wppm. Axial hydrogen distribution was measured by neutron radiography.**
- **No macroscopic hydrides were observed by means of optical microscopy.**
- **Tension and ring compression tests showed clear hardening and embrittlement increase with increased hydrogen content and annealing temperature.**

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Thank you for your attention