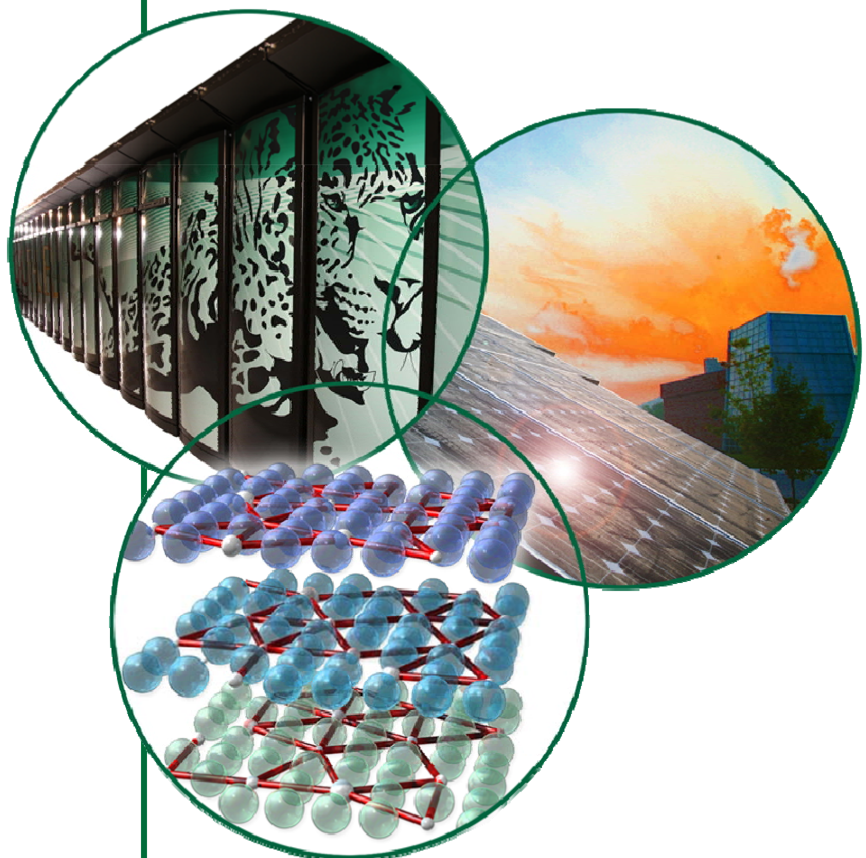
Creep-Fatigue-Oxidation Interactions: Predicting Alloy Lifetimes under Fossil Energy Service Conditions

2016 NETL Crosscutting Research Review Meeting
April 18-22 2016, Pittsburgh



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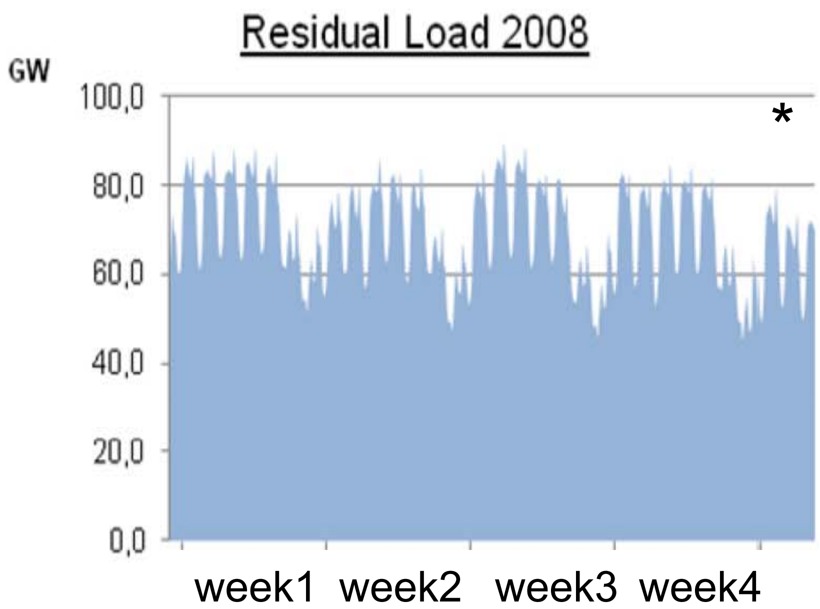
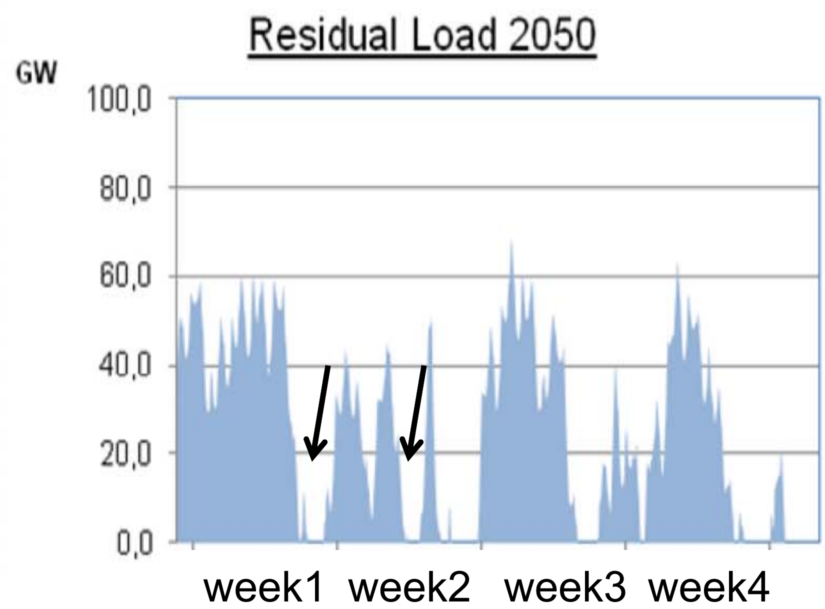
Power Plants Will Need to be Capable of Flexible Operation



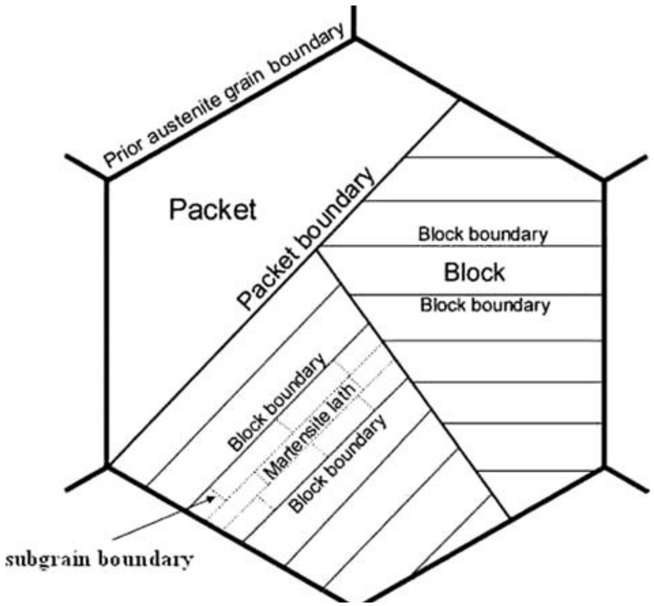


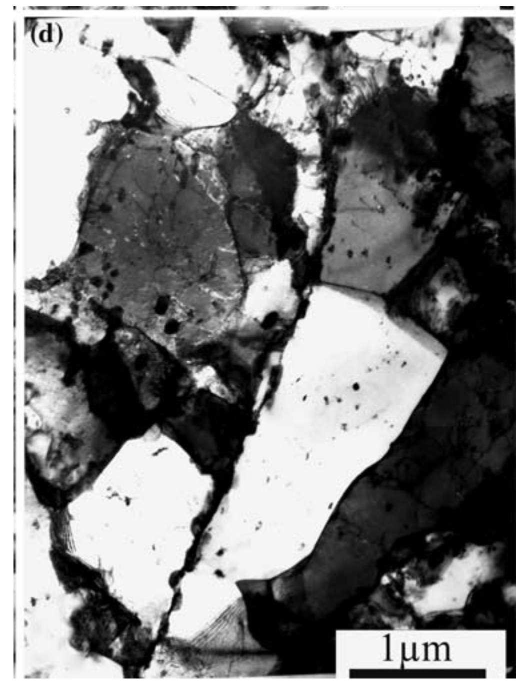
- Frequent (~daily) load cycling will result in significant creep-fatigue interaction
- Project will focus on:
    - Long term creep fatigue testing and lifetime modeling
    - Study of microstructurally small cracks under creep-fatigue loading
    - Interactions among creep fatigue and oxidation

* Ralf Mohrmann, Proceedings Liege conference 2014

Creep-Fatigue Behavior of Gr.91 Steel

- Gr.91 creep performance is significantly affected by cyclic loading due to microstructure changes (Fournier et al. 2008)





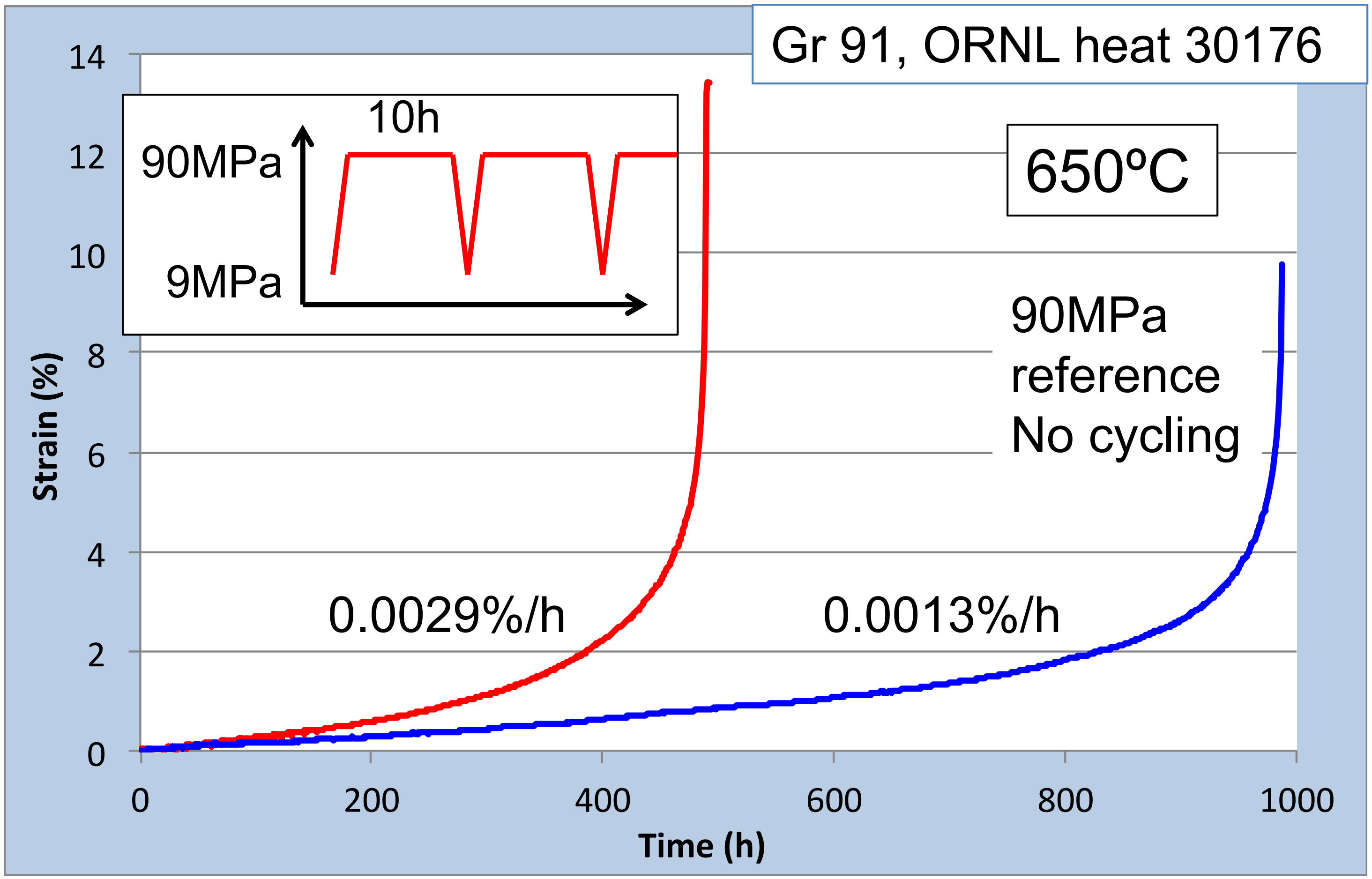
- sub grain coarsening
- dislocation density decrease

As Received

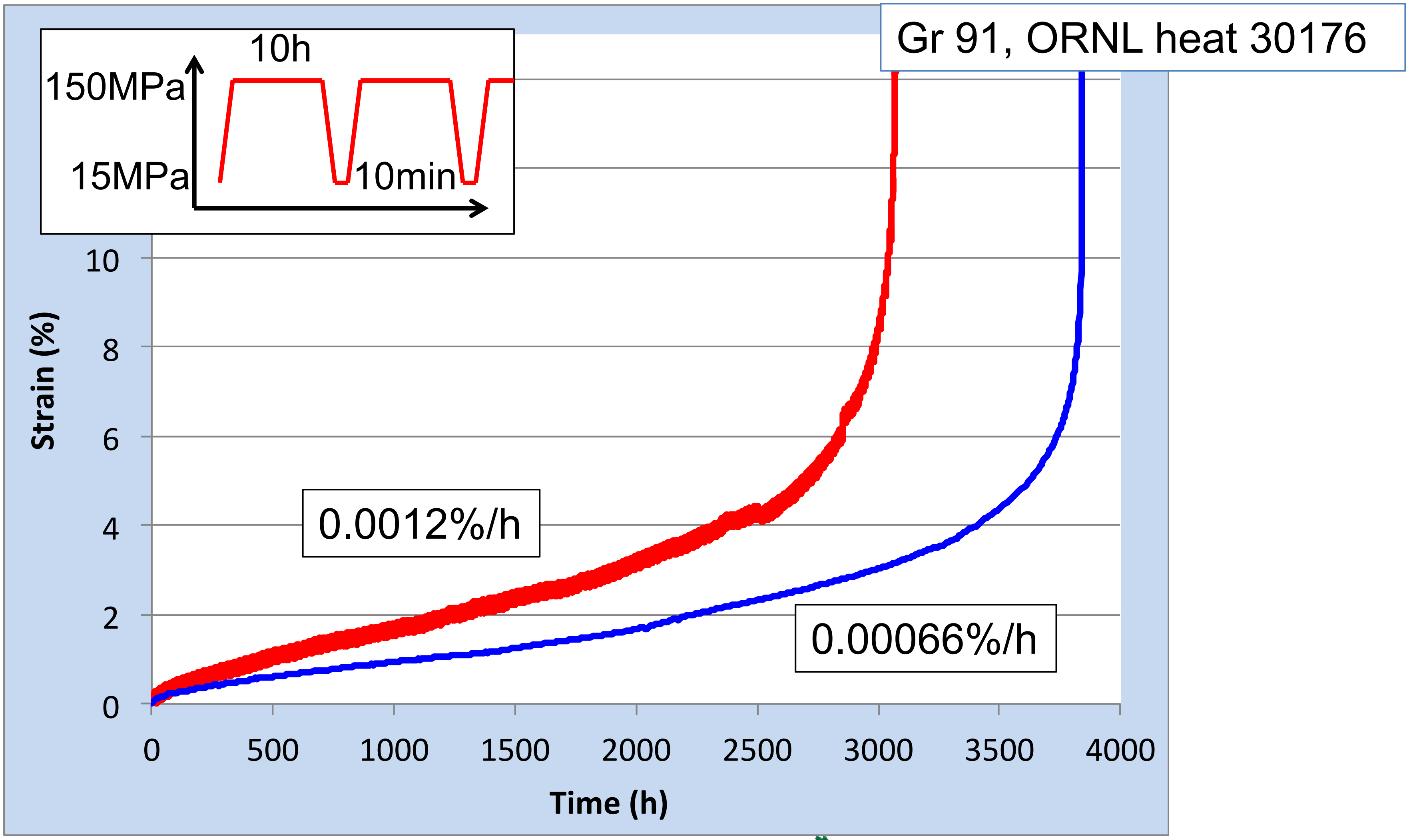
Creep-Fatigue Tests at 550ºC

- No significant effect of cyclic creep (unloading/loading) due to limited cyclic strain (3500h, ~50 cycles)

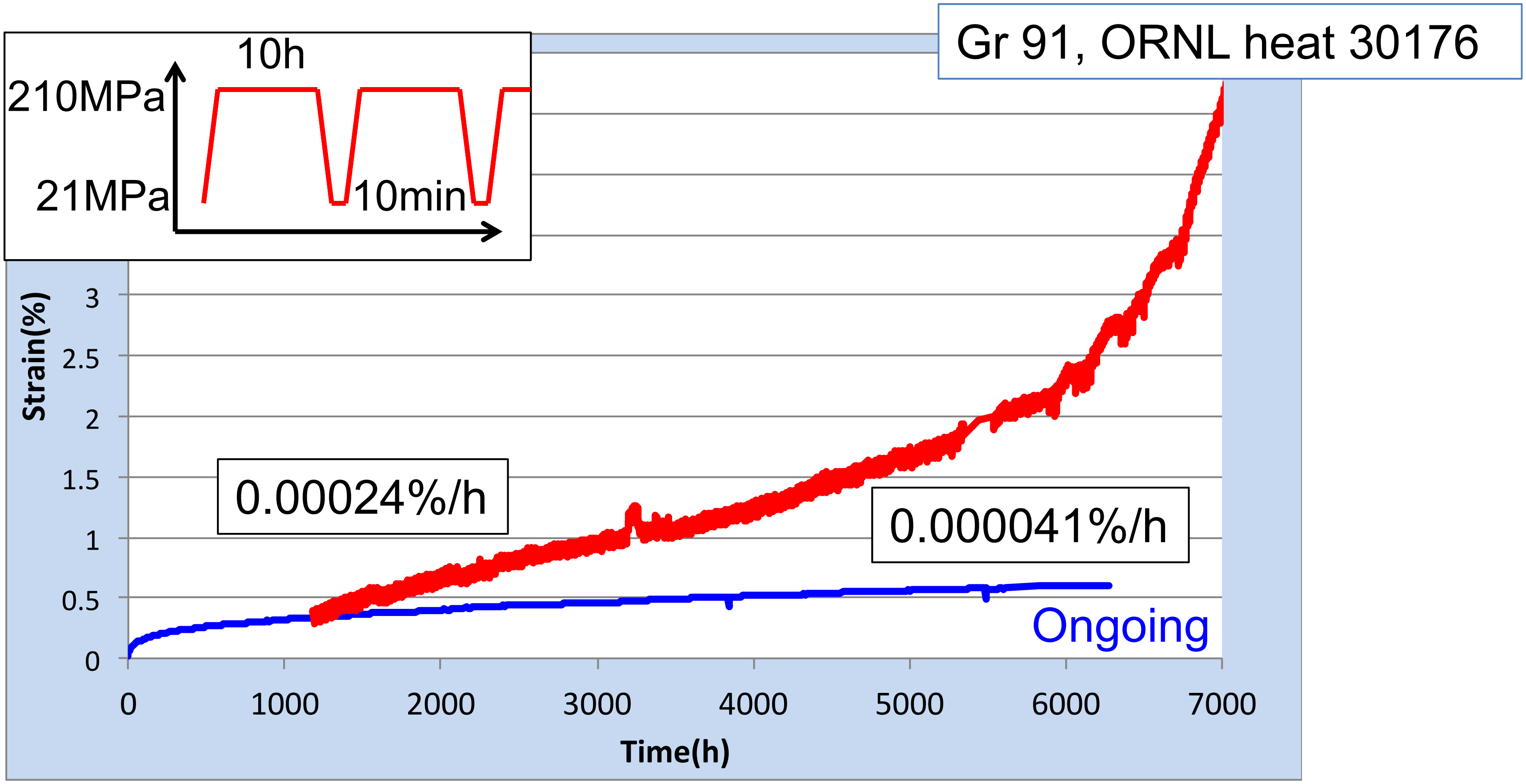
Decrease of lifetime at 650ºC, 90MPa with 10h cycle



Increase of creep rate at 600ºC, 150MPa with 10h cycle



Significant increase of creep rate at 550ºC, 210MPa with 10h cycle



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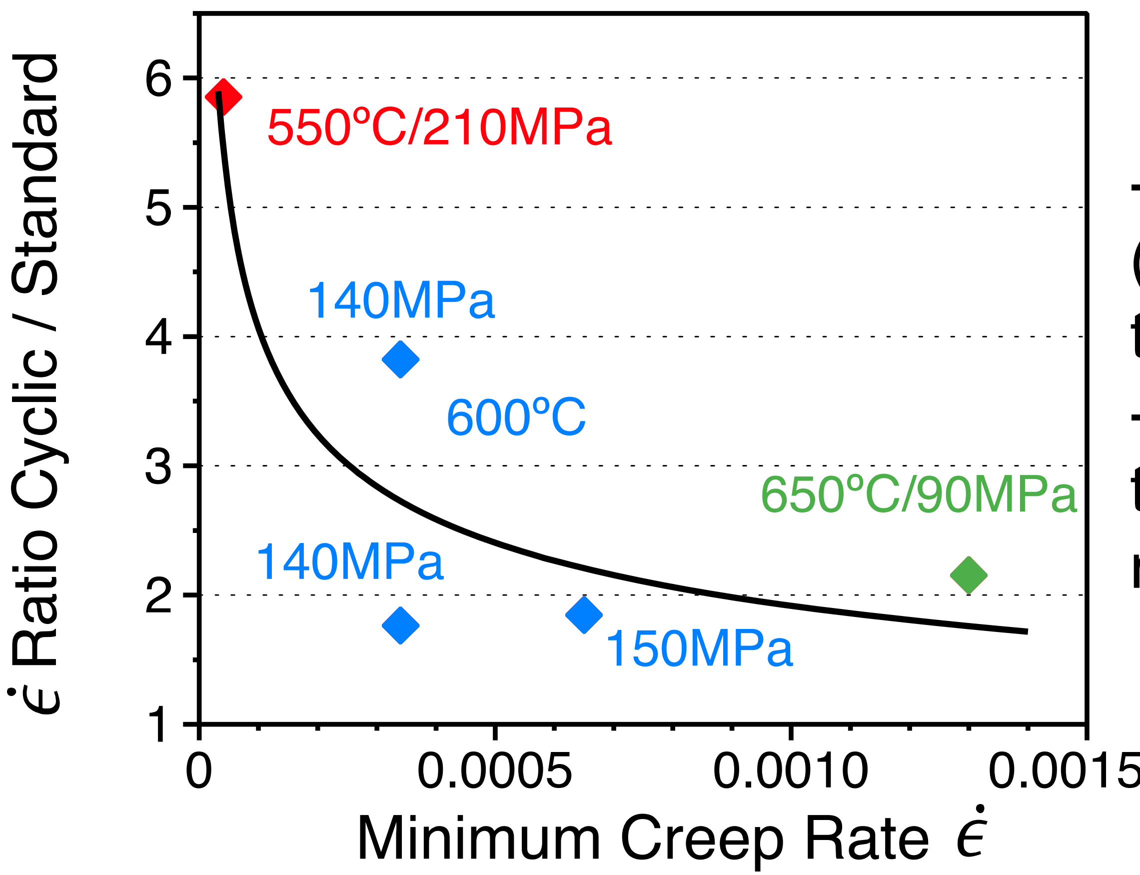
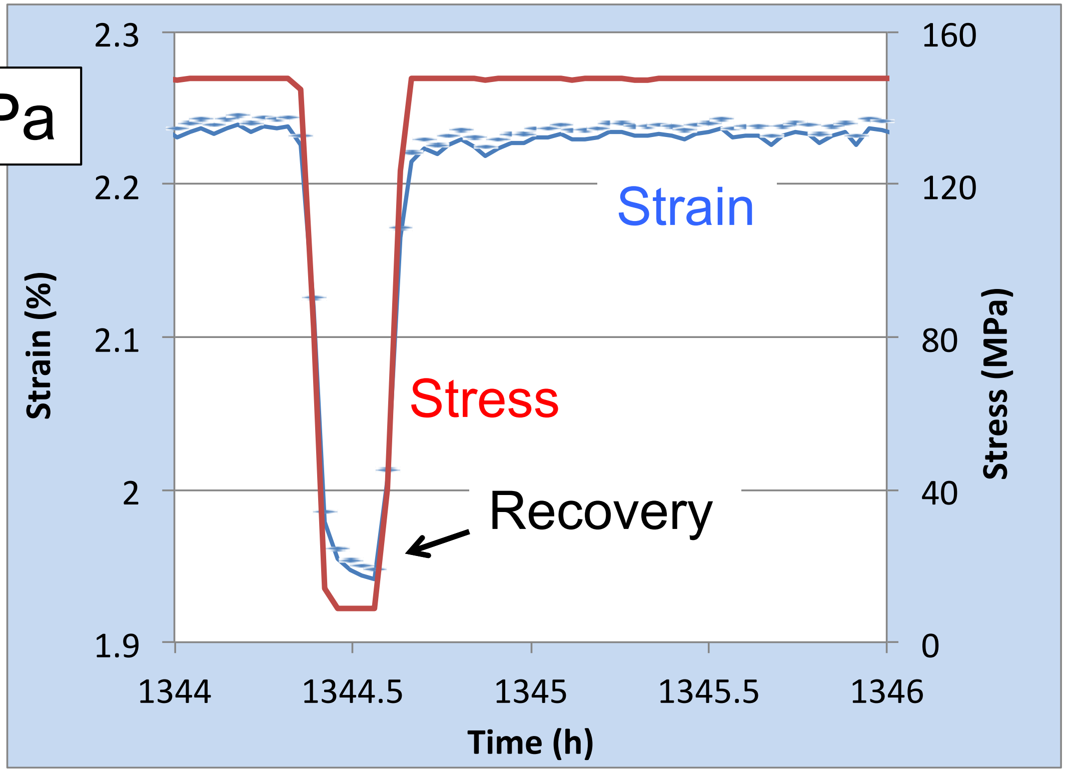
Significant Increase of Creep Rate for Longer Creep Tests



- Systematic increase (~X2) of creep rate due to cycling
- Need to focus on long term test / low creep rate

Recovery Observed During Unloading at Each Cycle

600ºC/150MPa



Decrease of dislocation density?
Coarsening of sub-grain structure?

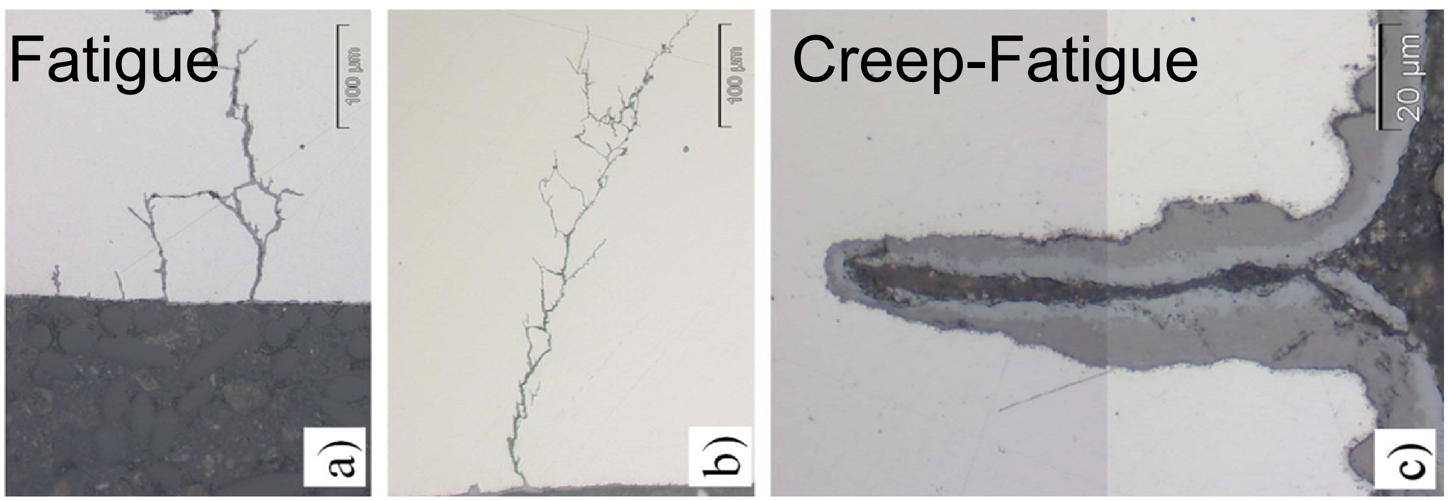
Creep-Fatigue Behavior of Gr.91 Steel

- Decrease of cycle to rupture with hold time

- No cavity observed after testing

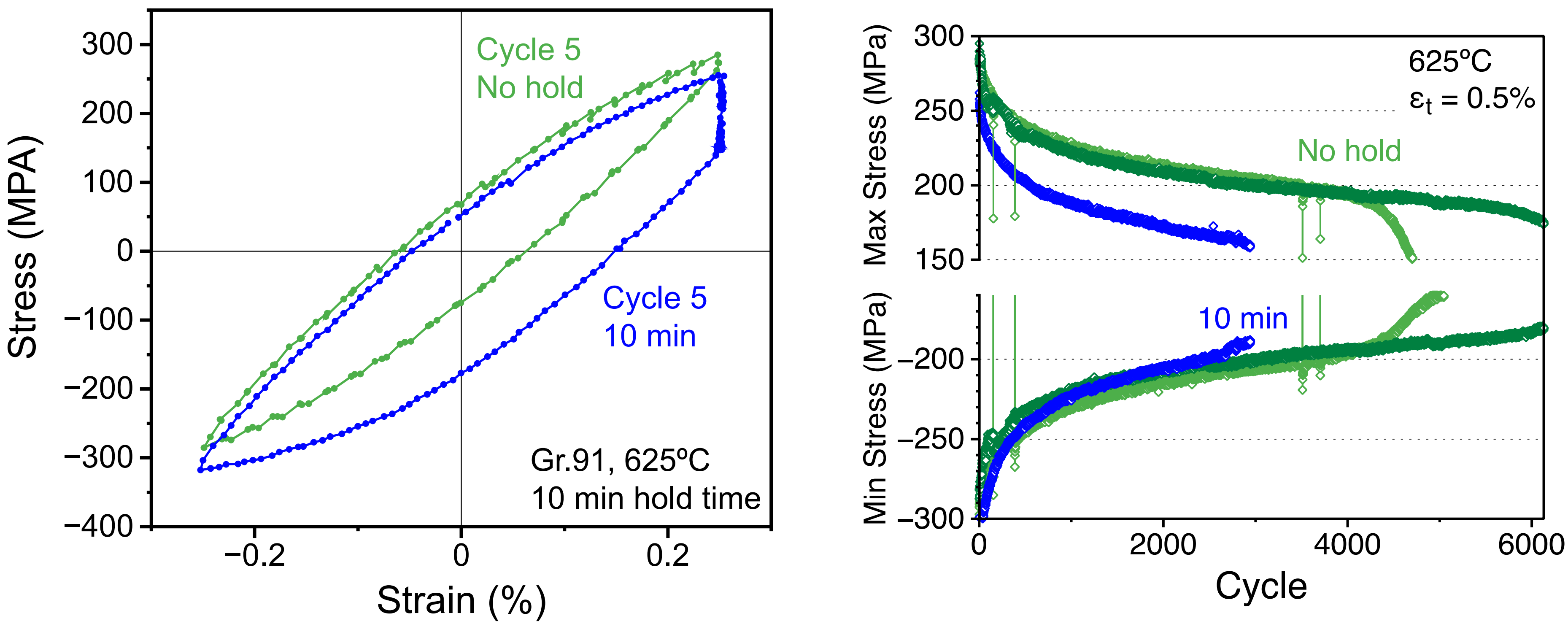
- Main effect of hold time is related to the formation of multi-layer thick scale vs thin scale on pure fatigue specimens

- **Need for longer creep fatigue test duration**



Fournier et al. (2008)

Decrease of N_f with Hold Time for Creep-fatigue Tests at 625ºC, ±0.25%



Faster softening due to 10min hold time (500h test)

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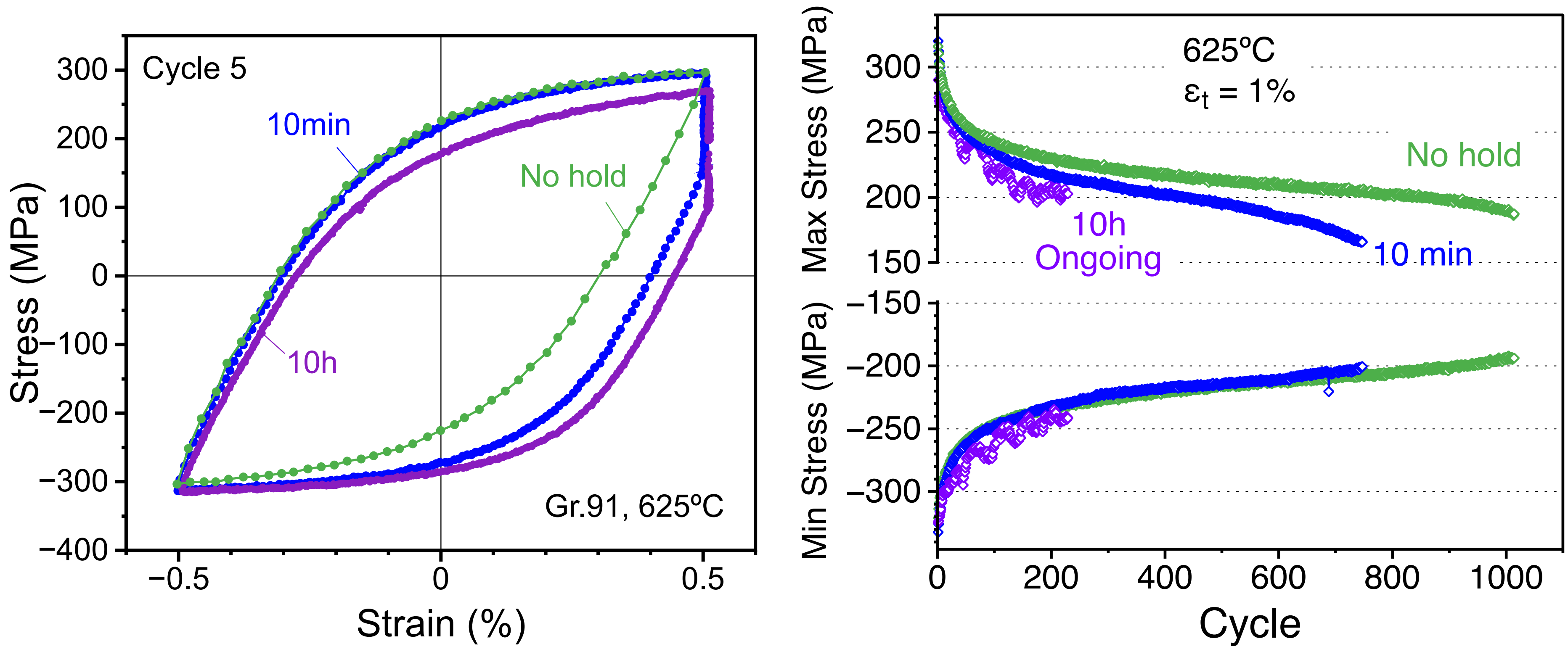
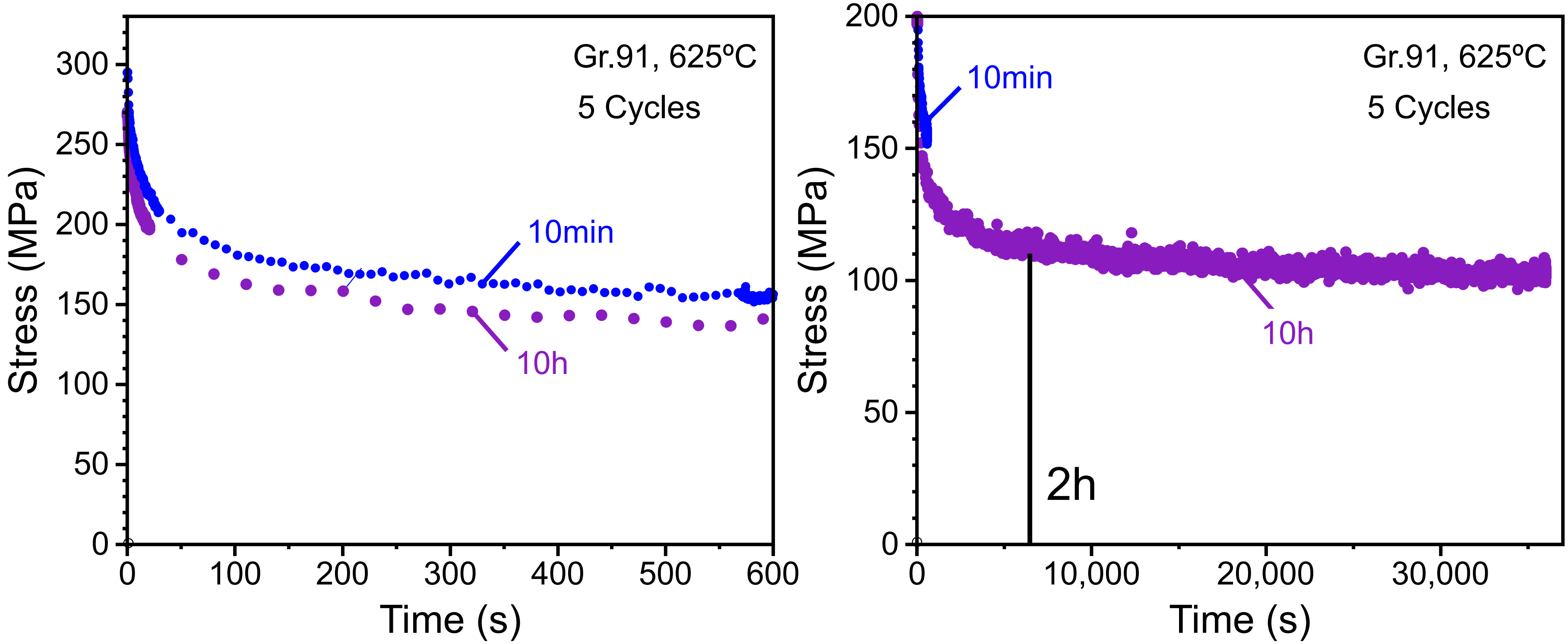
Decrease of Nf with Hold Time for Creep-fatigue Tests at 625ºC, ±0.5%?



-Faster softening due to hold time but not as drastic as for ±0.25%

-Increase of noise for 10h hold test (>2100h)

Significant Decrease of Stress During 10h Hold Time



- Close to a steady stress after ~2h
- Creep lifetime at 625ºC, 100MPa ~ 5000h

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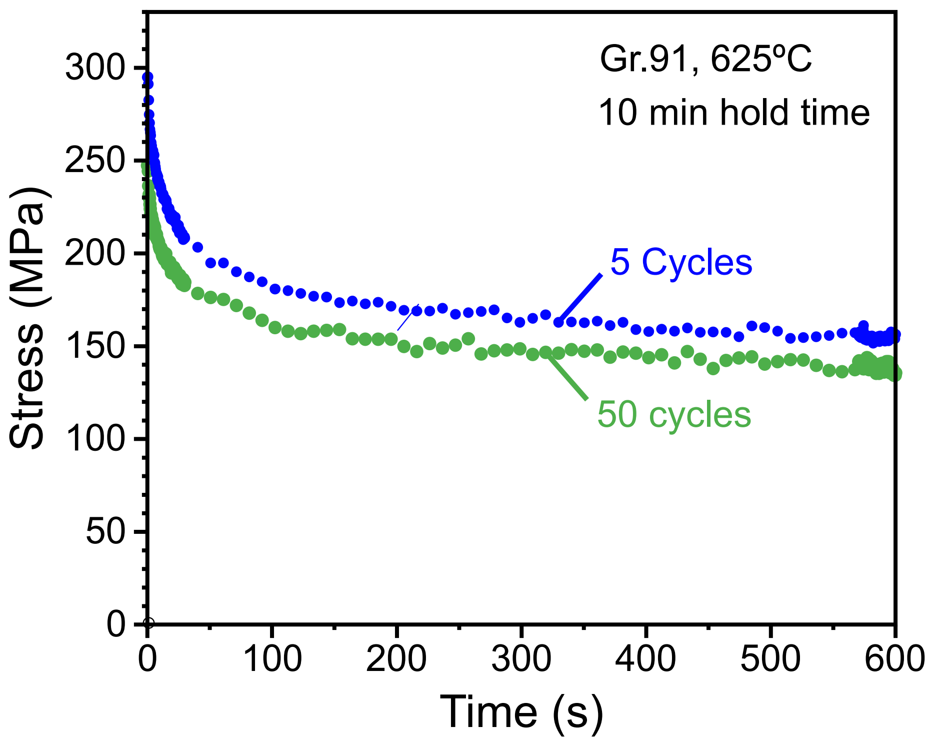
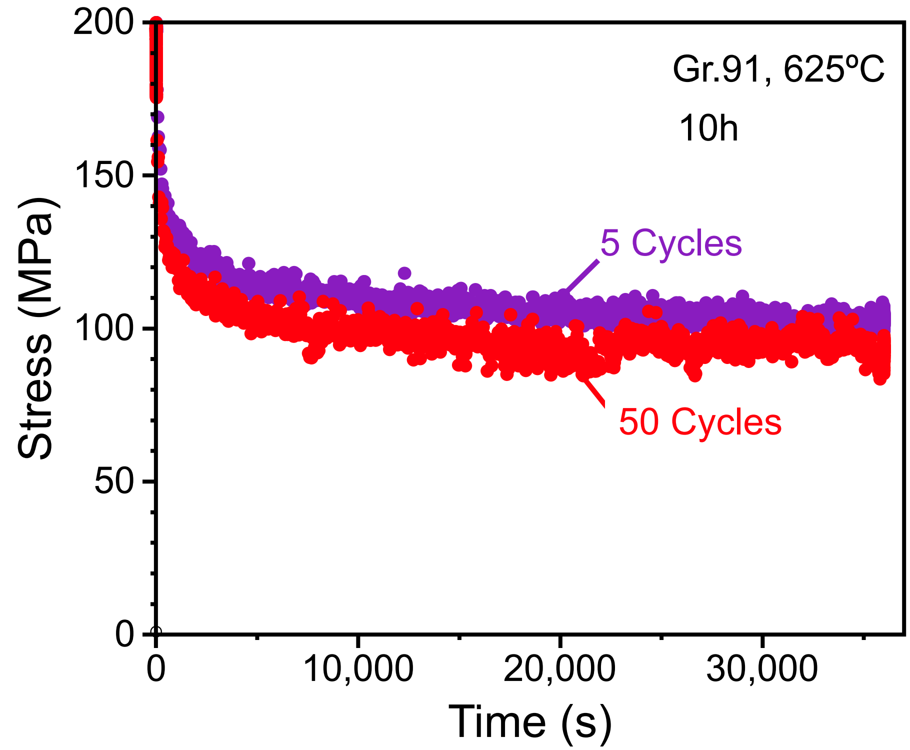
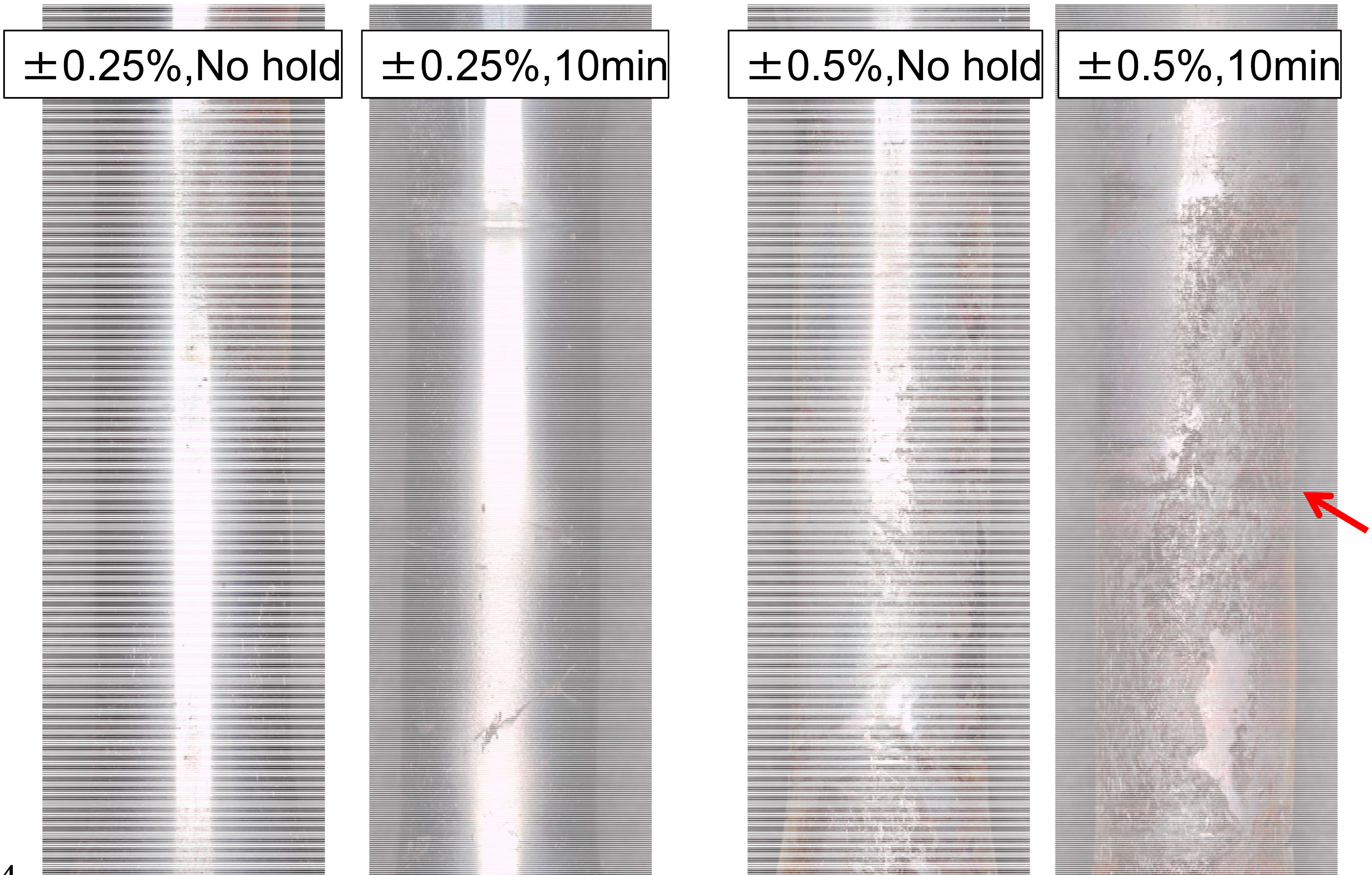
Slow Evolution of "Steady Stress" for 10h Hold Time Test

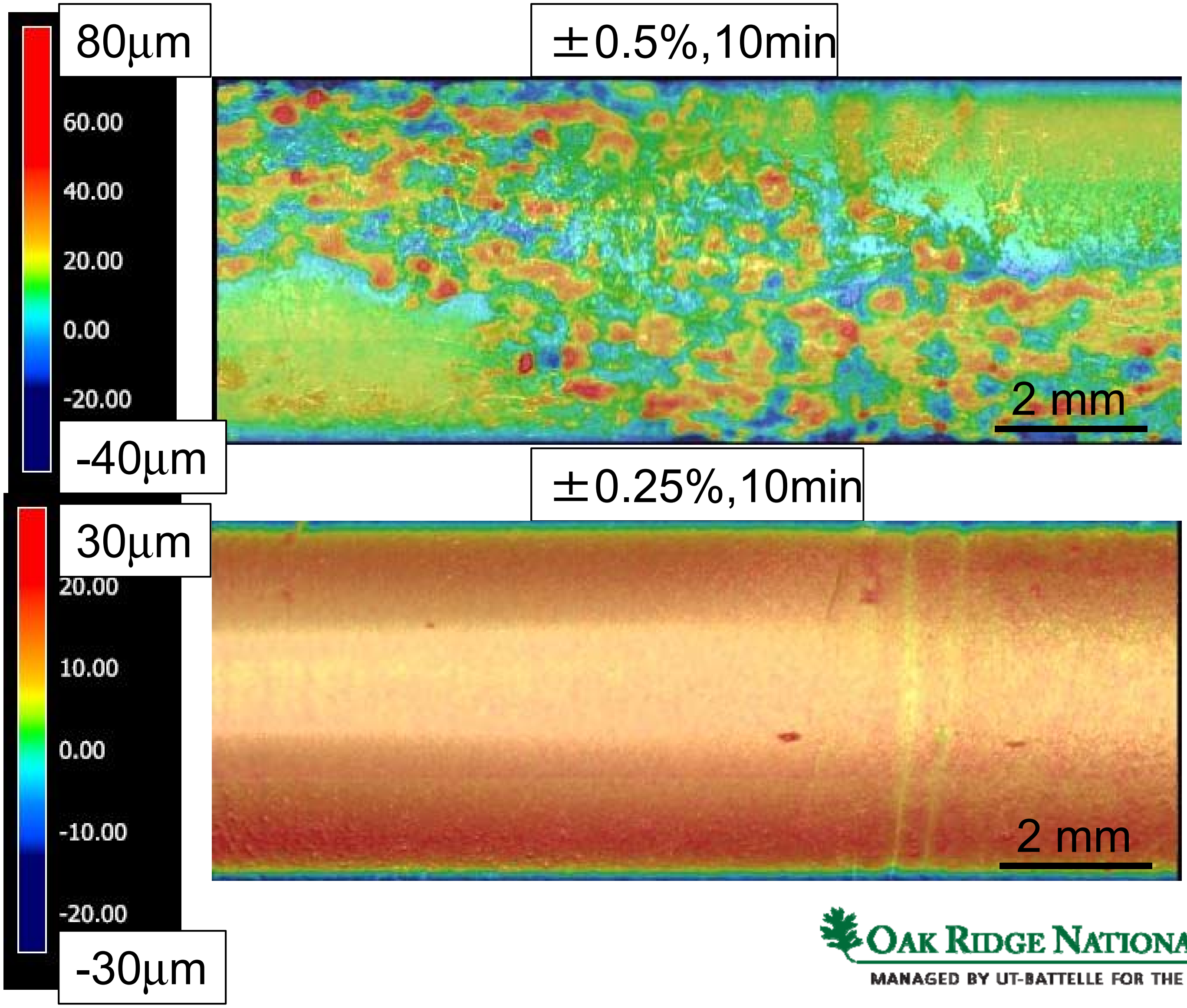




Thicker Oxide Scale for Tests Performed at ±0.5%, 10min Hold Time

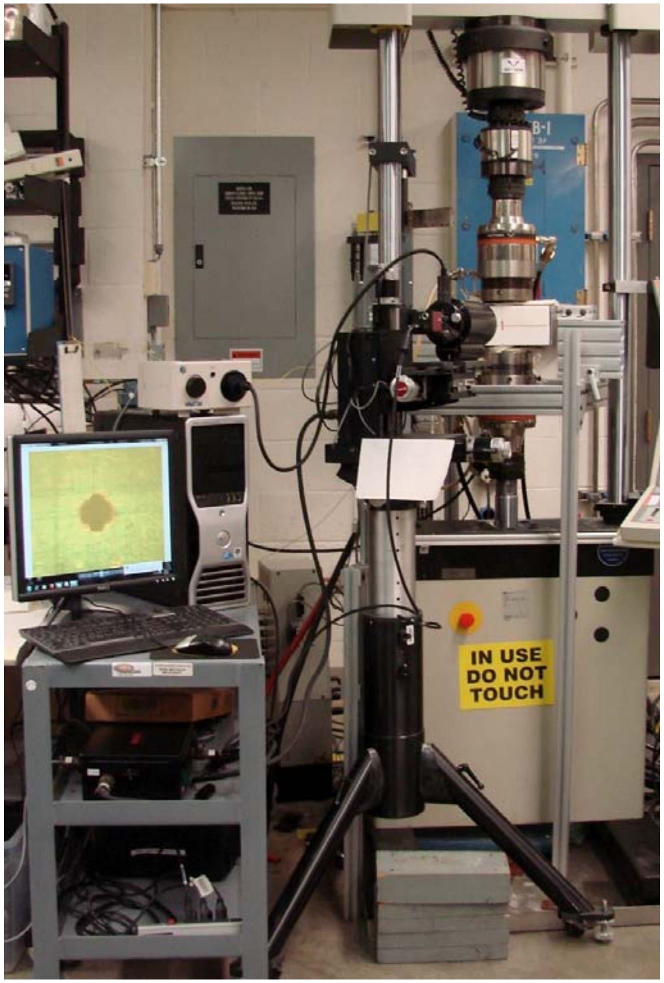


Higher Strain Leads to Oxide Scale Cracking and Re-oxidation

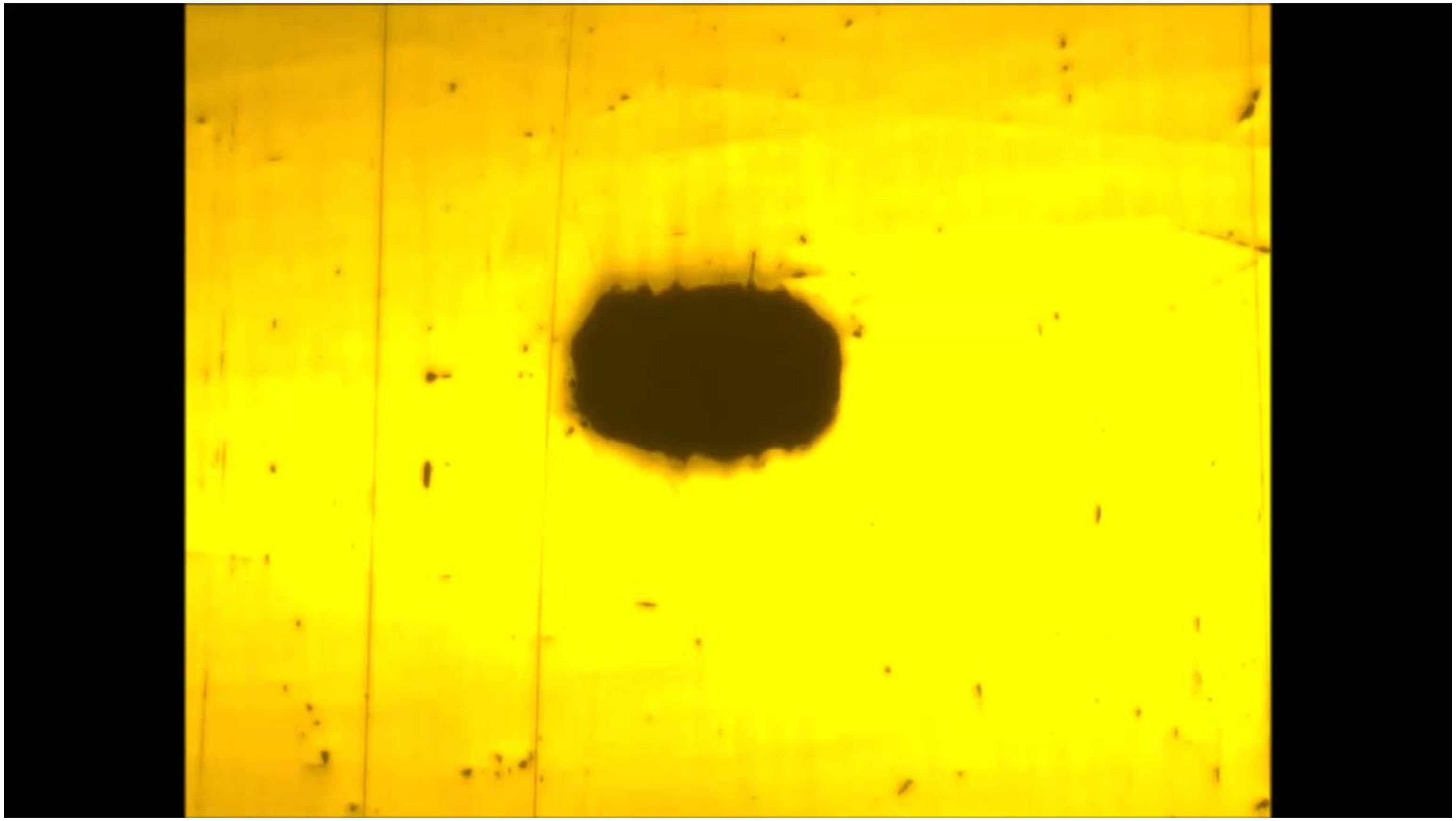


New Set up to Study Microstructurally Small Crack Growth at High T°C

- Sumit Bahl's work (Indian Institute of Science)
- Slower propagation for small cracks
- Fournier et Al.(2008)
  - - Initiation: Tanaka and Mura model
  - - Propagation: Tomkins model
- Crack initiation at room temperature
- High cyclic Fatigue & Creep Fatigue Testing
- In Situ imaging of crack propagation
- Tests conducted at Room and 550°C

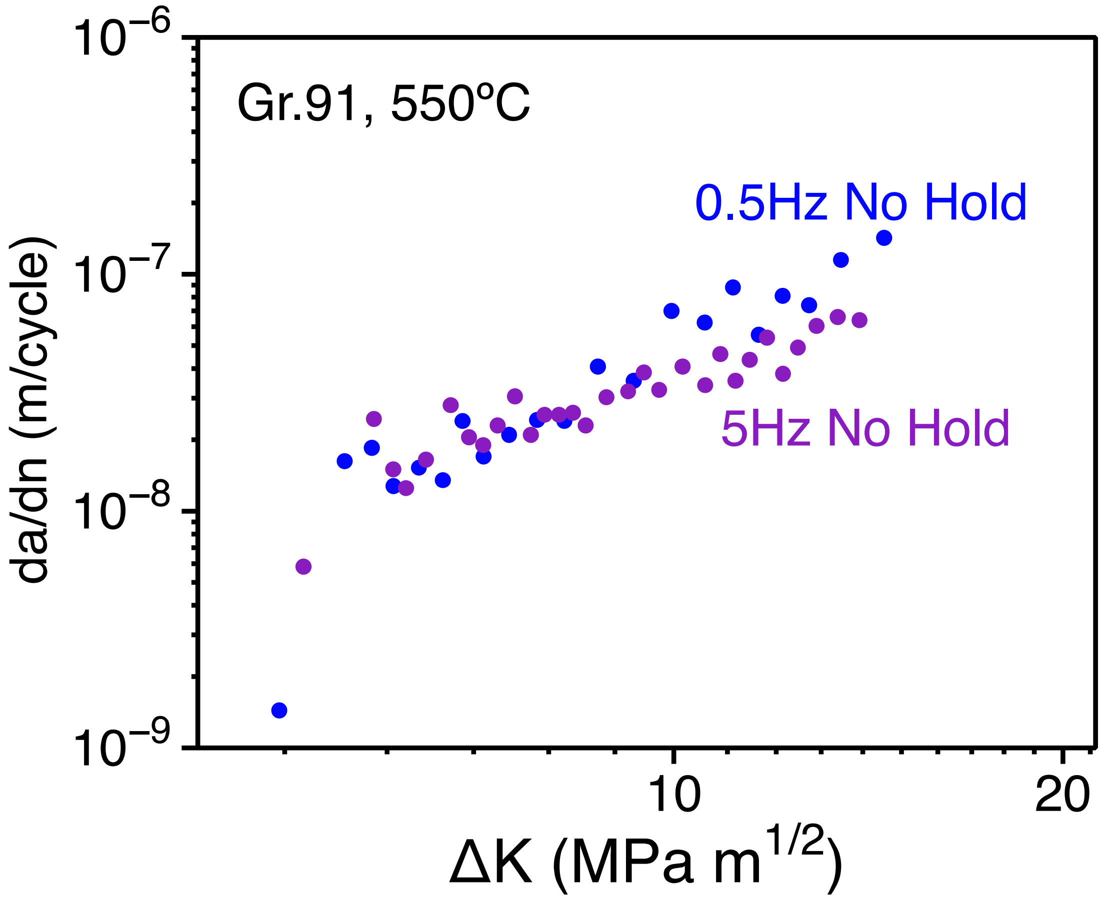


Crack Growth Imaging at Room T°C

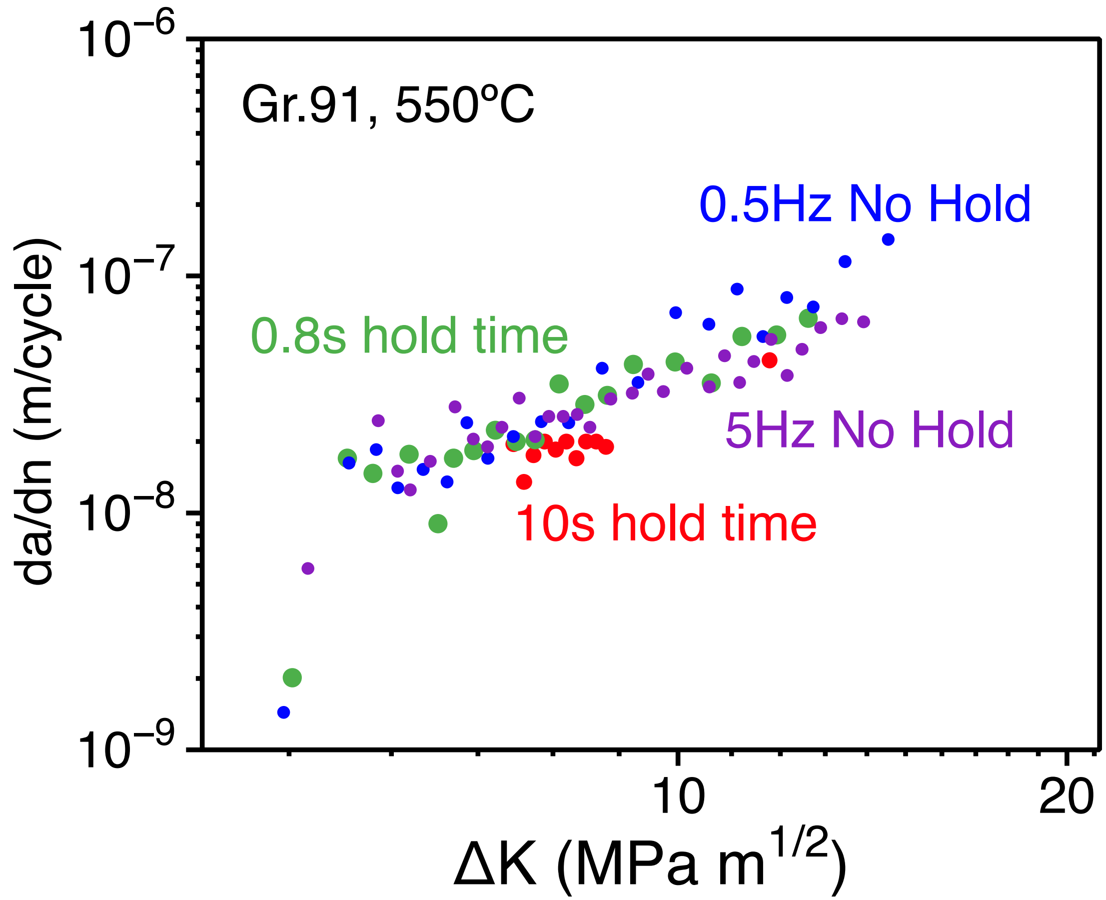


300μm

No Frequency Effect on Crack Propagation



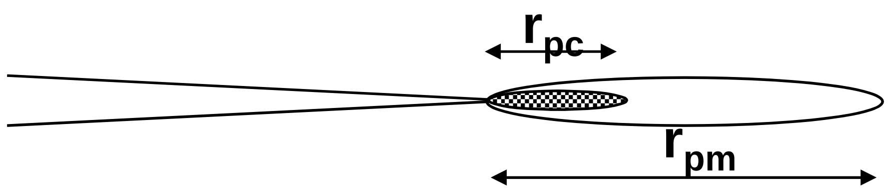
No Effect of Hold Time on Crack Propagation



Test initiated with 10min hold time

Results consistent with decrease of dislocation density at crack tip

BCS* Theory Crack Growth Characterization



$$r_{pm} = a\left[\sec\left(\frac{\pi}{2}\frac{\sigma_{max}}{\sigma_{ys}}\right) - 1\right]$$

Monotonic Plastic Zone Size*

Monotonic and Cyclic Plasticity are Related by Load Ratio

Substitute $\sigma_{max} \rightarrow \sigma_{max} - \sigma_{min} = \sigma_{max}(1\text{-}R)$ and $\sigma_{ys} \rightarrow 2\,\sigma_{ys}$

Cyclic Plastic Zone Size

$$r_{pc} = a\left[\sec\left(\frac{\pi}{2}\frac{\sigma_{max}(1-R)}{(2\sigma_{ys})}\right) - 1\right] = a\left[\sec\left(\frac{\pi}{4}\frac{\sigma_{max}(1-R)}{\sigma_{ys}}\right) - 1\right]$$

R = -1, $r_{pc} = r_{pm}$; R > 0, $r_{pc} < r_{pm}$

Crack tip displacements (for distribution of edge dislocations at crack tip)**

$$\phi_m = \frac{8\sigma_{ys}(1-\nu^2)a}{\pi E}\ln\left(\sec\left(\frac{\pi\sigma_{max}}{2\sigma_{ys}}\right)\right)$$

Monotonic Crack Tip Displacement

$$\phi_c = \frac{16\sigma_{ys}(1-\nu^2)a}{\pi E}\ln\left(\sec\left(\frac{\pi\sigma_{max}(1-R)}{4\sigma_{ys}}\right)\right)$$

Cyclic Crack Tip Displacement

*** Bilby BA, Cottrell AH, Swinden KH. Proc Royal Soc A 1963;272:304.**

**** Weertman J. "Dislocations Based Fracture Mechanics"**

Small Fatigue Crack Growth Model

Number of cycles to failure ➔ $$\Delta N = \frac{\phi_{cr}}{f\phi_c}$$

Crack extension at failure ➔ $$\Delta a = \alpha \phi_m \sigma_{ys}$$

Crack-extension force on dislocations in monotonic plastic zone

$$\frac{da}{dN} = \mu \phi_c \phi_m \sigma_{ys}$$

where $$\mu = \frac{f\alpha}{\phi_{cr}}$$

ϕ_c – cyclic crack-tip displacement

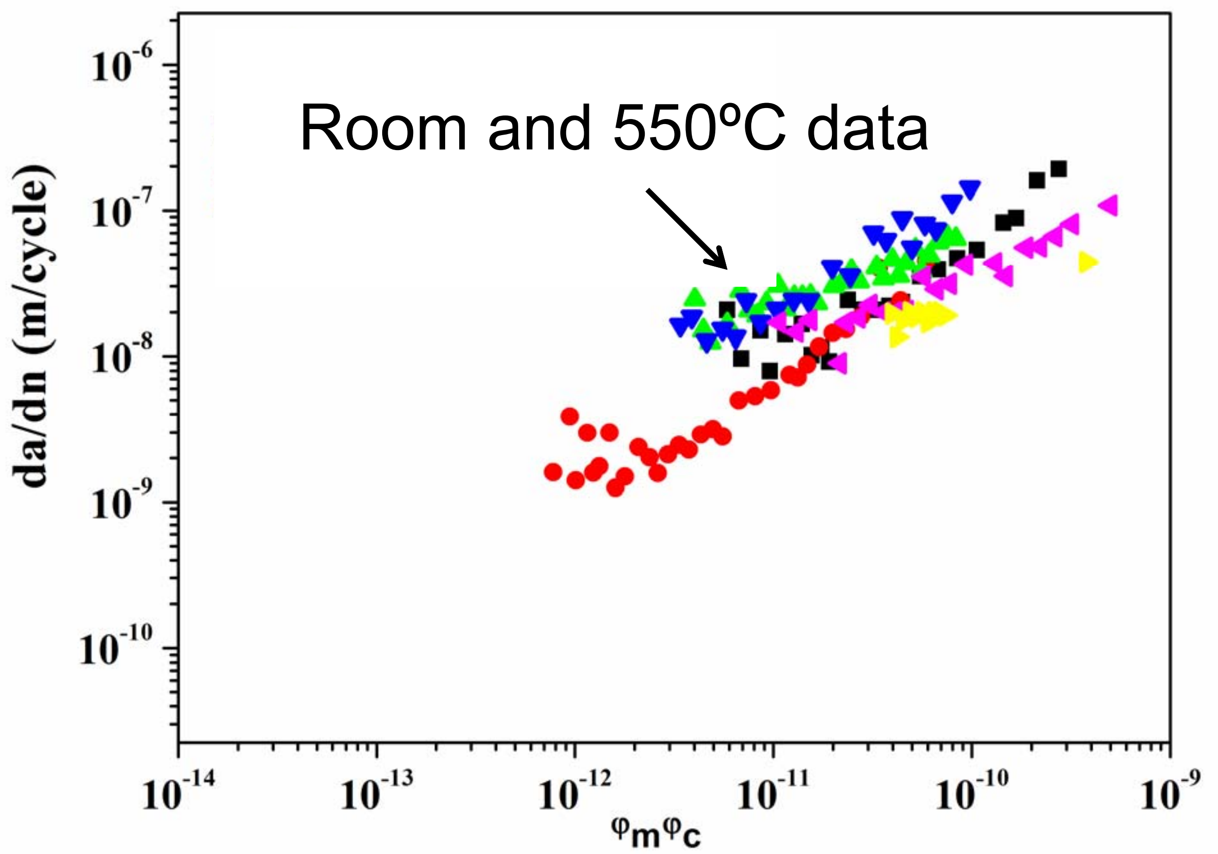
ϕ_m – monotonic crack-tip displacement

f – slip irreversibility factor

ϕ_{cr} – critical opening displacement

α – geometric factor

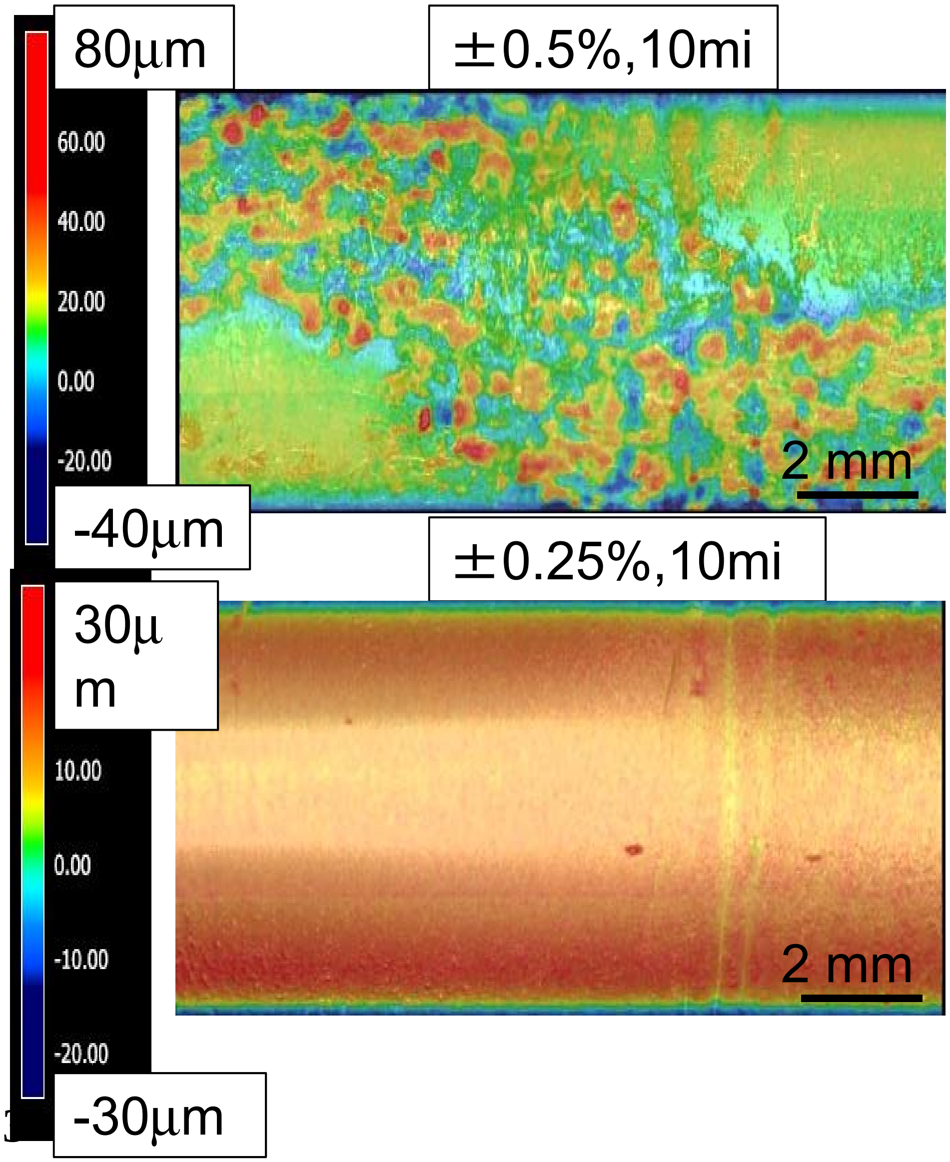
Results at room and 550ºC Consistent with Crack Growth Model



Tensile testing at different deformation rates

Microstructure characterization to evaluate dislocation density

Creep-Fatigue-Oxidation Interaction in Steam?



In Air:
From protective scale to non-protective scale due to cracking and re-oxidation
In Steam:
Effect of strain on Non-protective scale?

Martensitic Gr. 91 and fully ferritic 9Cr alloys creep tested at 650ºC in air and steam

Alloys	Fe	Cr	Mo	Si	Mn	V	C
Gr.91-1	Bal.	8.31	0.9	0.13	0.34	0.26	0.08
Gr.91-2 (or 9Cr)	Bal.	8.61	0.89	0.11	0.27	0.21	0.08

Similar composition but different microstructures:

-Gr.91-1 = standard commercial heat treatment

Normalization: 1040ºC and Tempering: 730-760ºC

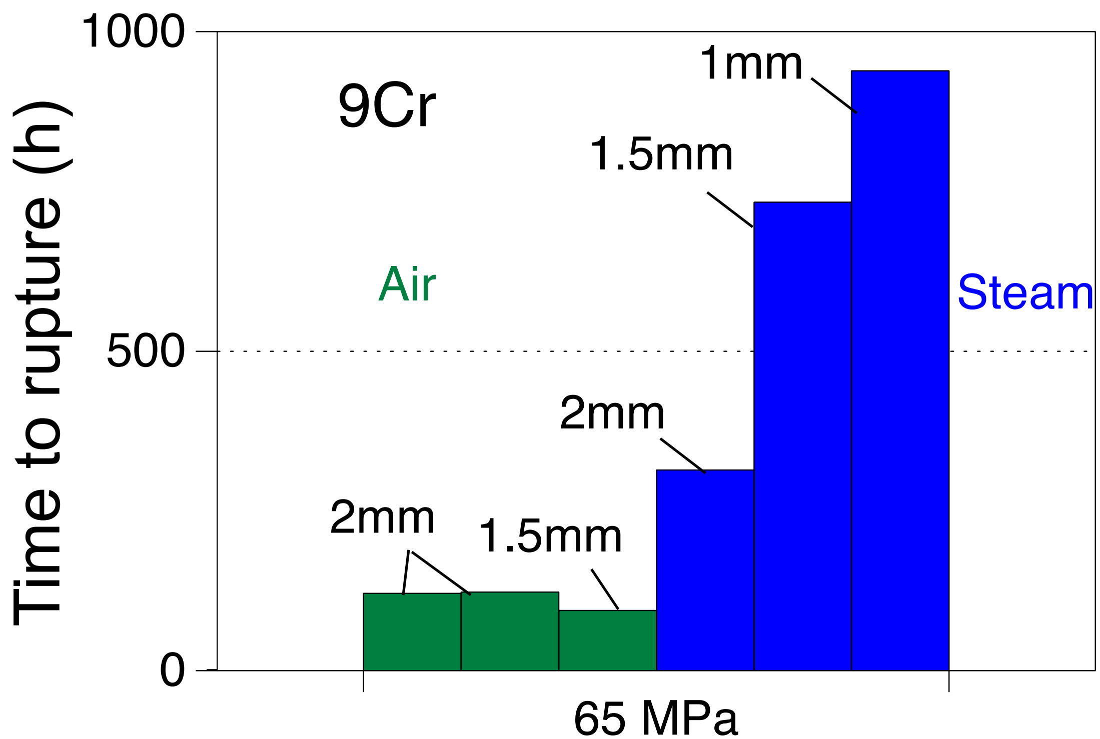
- Gr.91-2 = standard commercial heat treatment

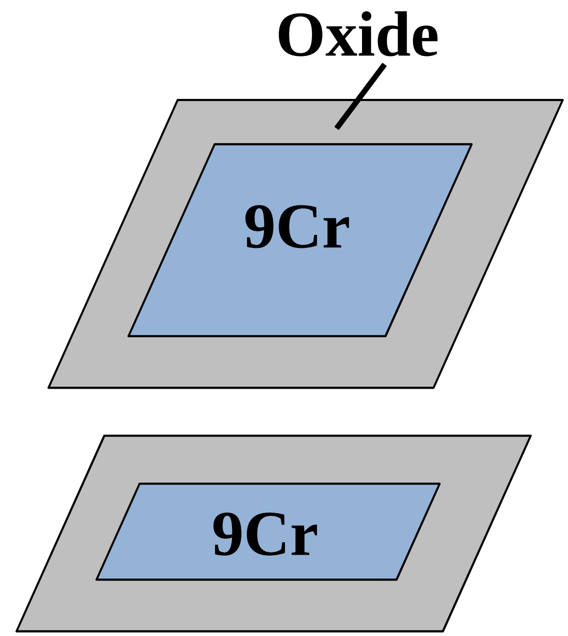
Normalization: 1080ºC and Tempering: 760ºC

- 9Cr = Non heat treated material

Fully ferritic as-fabricated microstructure

Effect of Load-Bearing Scale for Thin 9Cr Specimens





$$F = \sigma_{oxide}\frac{S_{oxide}}{S} + \sigma_{9Cr}\frac{S_{9Cr}}{S}$$

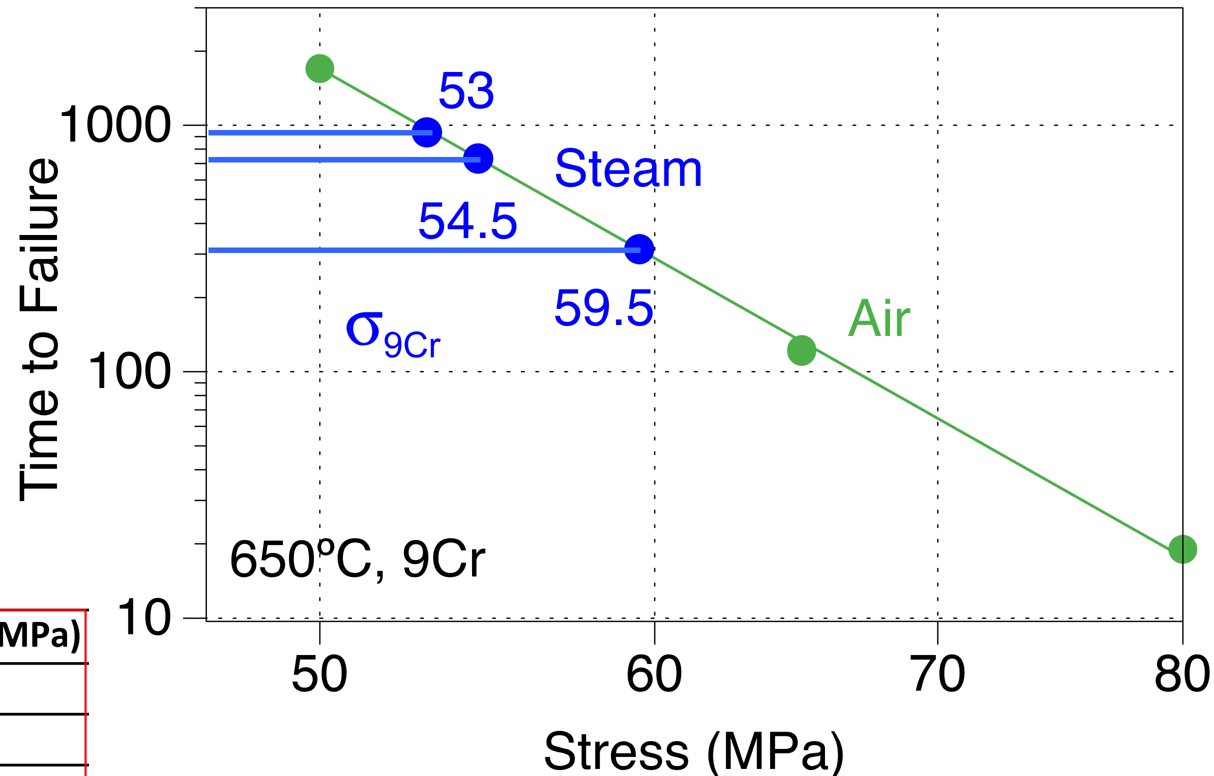
- Thinner specimen to increase the volume to surface ratio

Stress Calculation Is Very Consistent With Load Bearing Scale

$$F_{Applied} = \sigma_{oxide} \cdot S_{oxide} + \sigma_{9Cr} \cdot S_{9Cr}$$

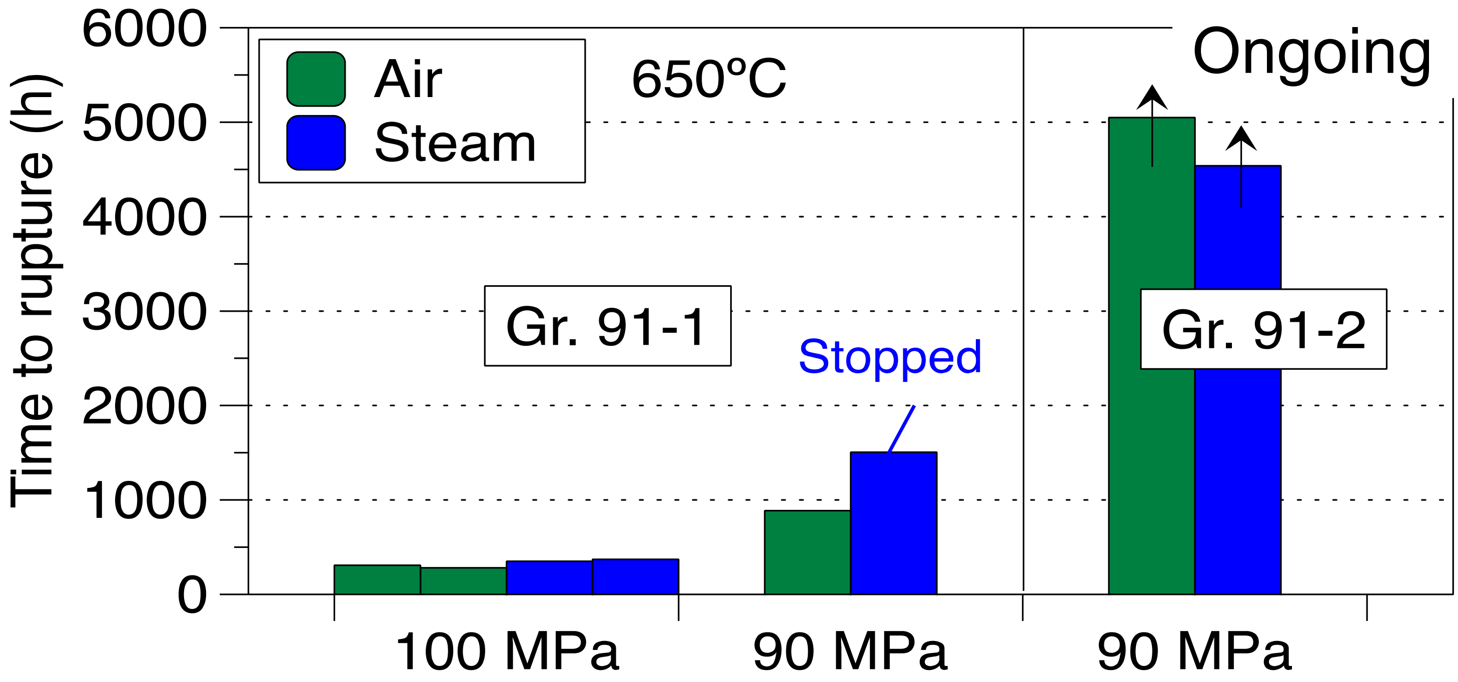
– σ_{9Cr} estimated from lifetime in steam

- Average oxide scale based on parabolic growth to calculate S_{oxide} and S_{9Cr}



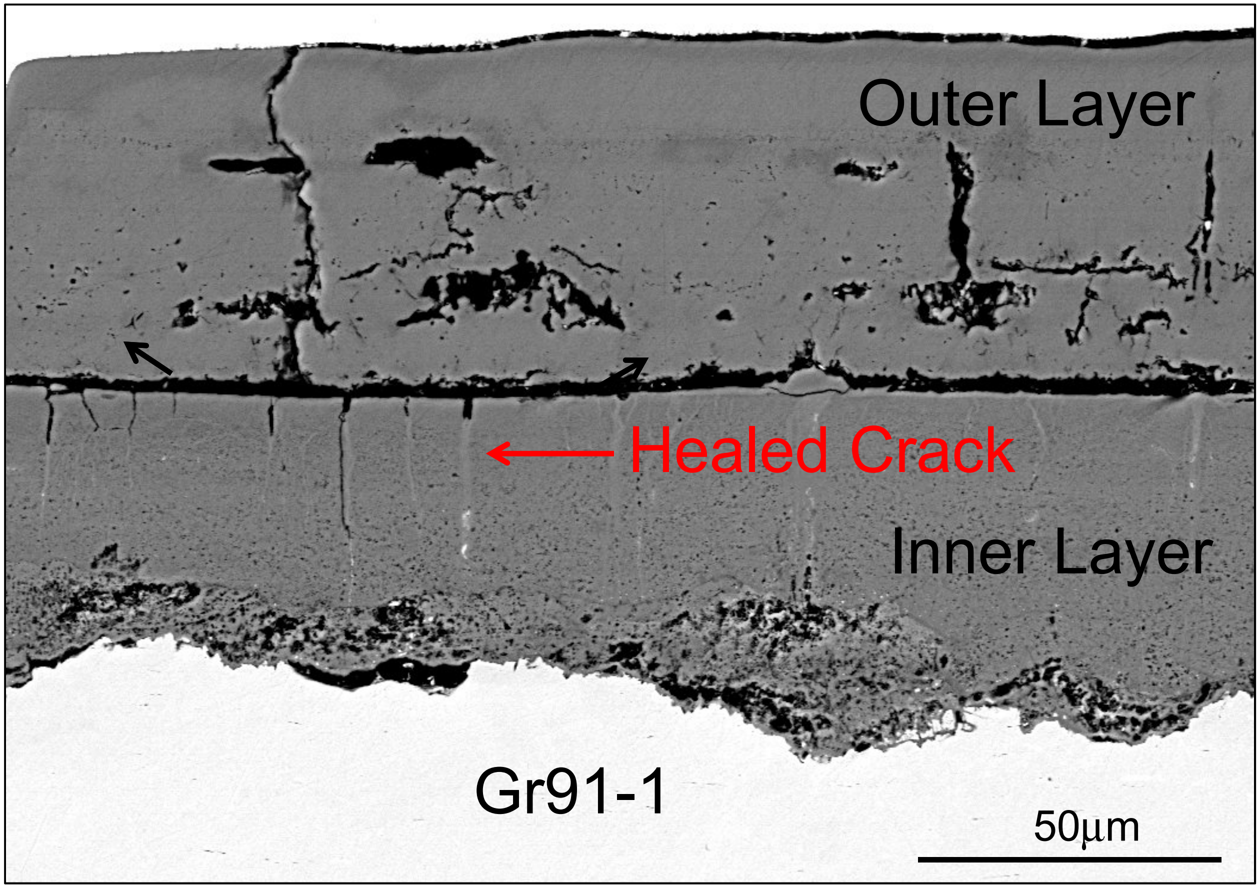
Thickness		
Specimen (mm)	Scale (μm)	σ oxide (MPa)
2	38	127
1.5	62	132
1	51	134

No Effect or Small Increase of Lifetime in Steam vs Air for Gr.91 Alloys



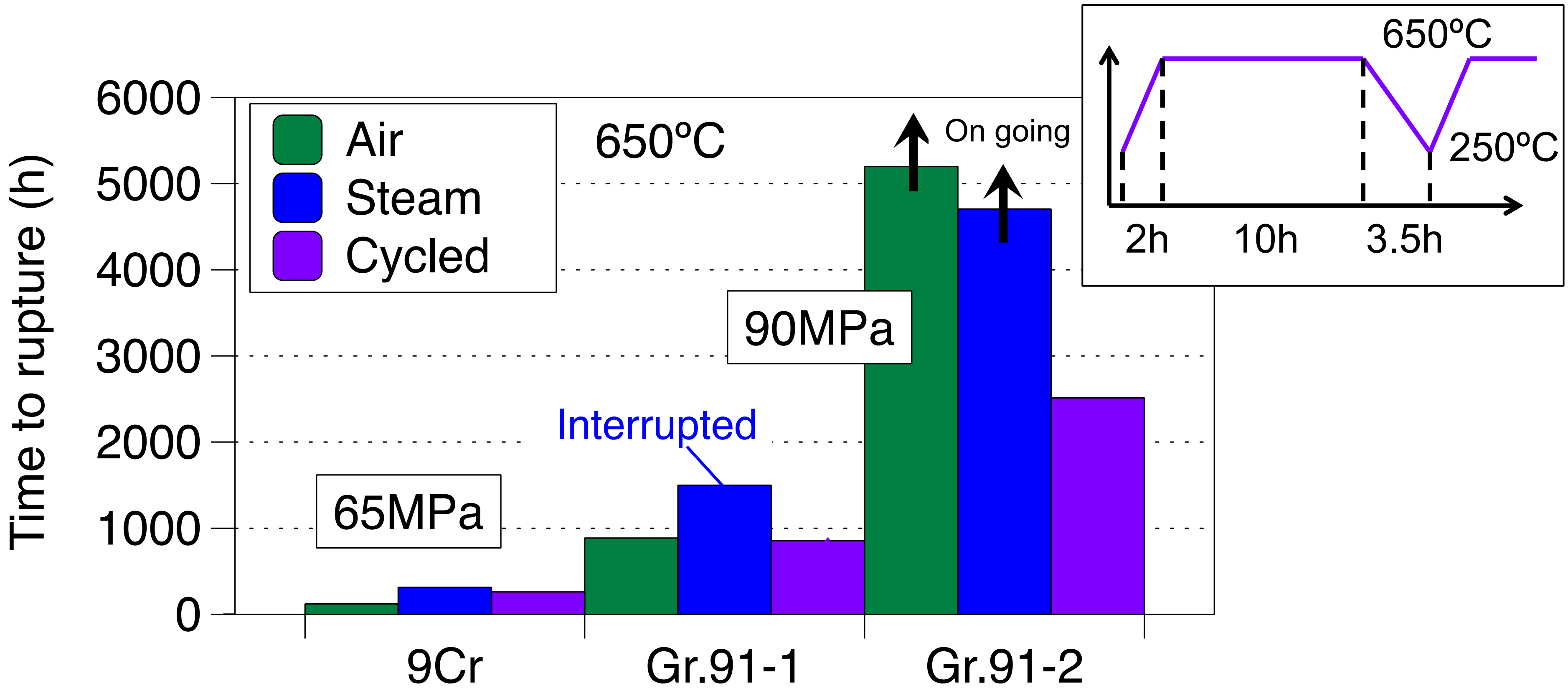
- Again consistent with Load-Bearing Scale compensating for metal loss

Healed cracks lead to a Continuous Bearing Inner Oxide scale

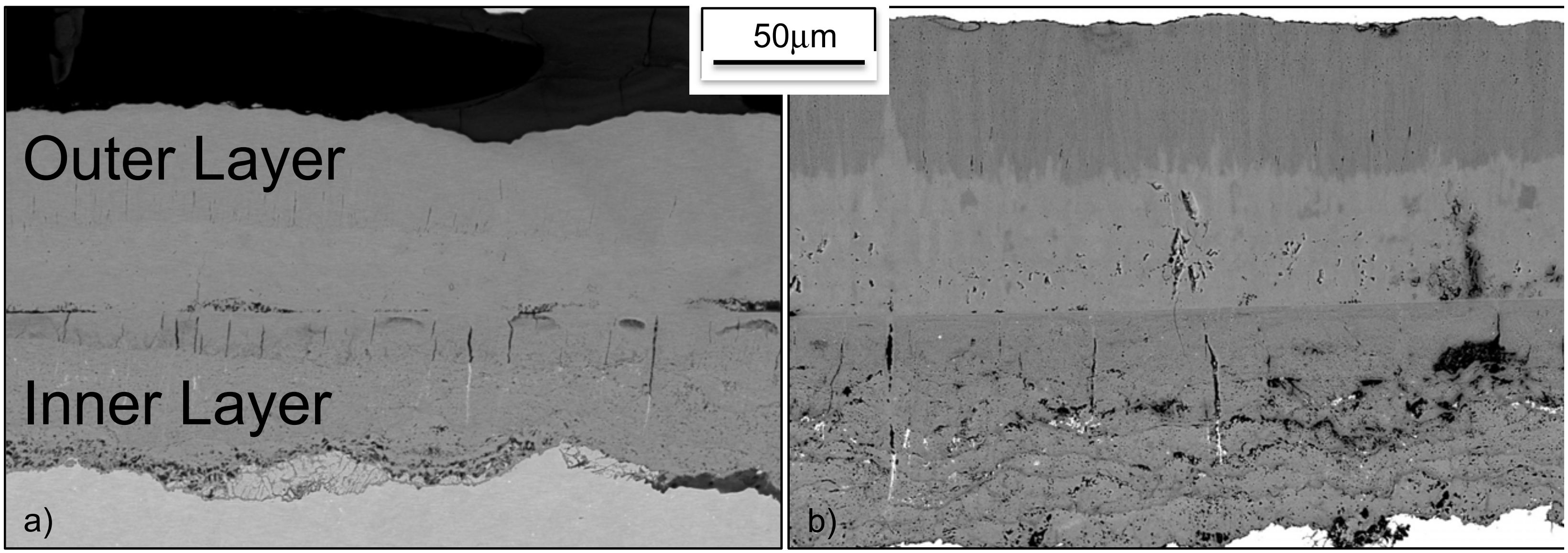


Gr91-1, Steam, 350h,100MPa

Decrease of Lifetime in Steam due to Thermal Cycling



Similar Oxide Scale Microstructure for Specimens Thermally Cycled



Gr.91-1, 855h Gr.91-2, 2512h

- Local cracking of the scale leads to sudden increase of stress and rupture?
- Ongoing cyclic air test to verify Gr.91 microstructure is not affect by thermal cycling

Future Activities

- Conduct microstructure characterization of cyclic creep, creep fatigue and fatigue crack growth specimens
    - Sub grain coarsening
    - Decrease of dislocation density
    - Cavity formation
- Continue long-term tests
- Conduct fatigue and creep-fatigue testing in steam.
    - Design is Ready
    - Effect of cyclic loading on a thick non protective scale?

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