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

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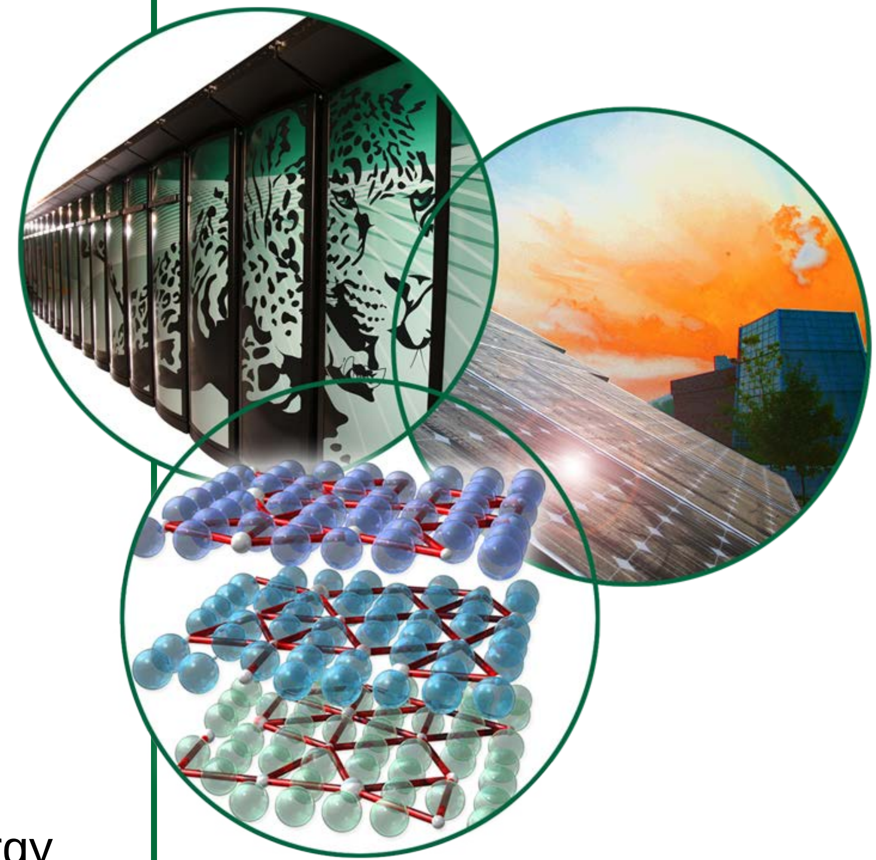

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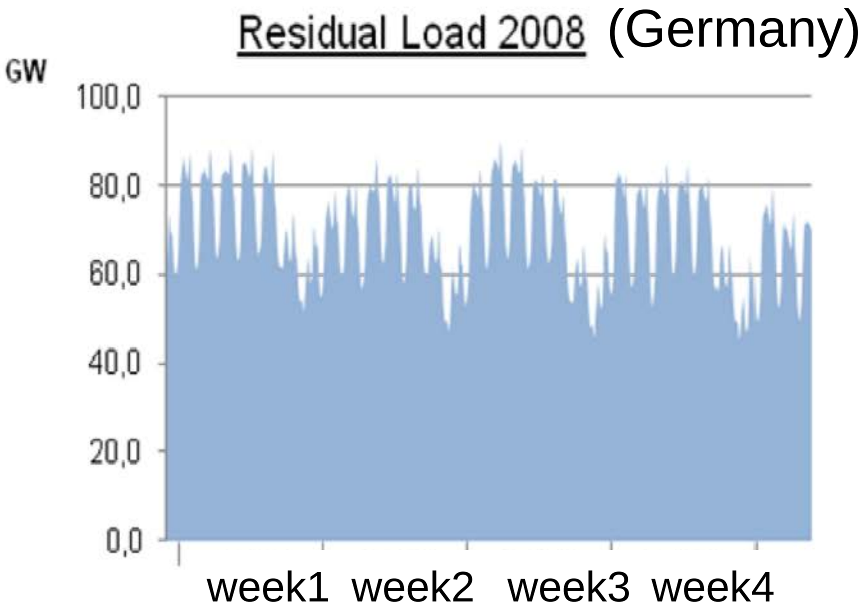
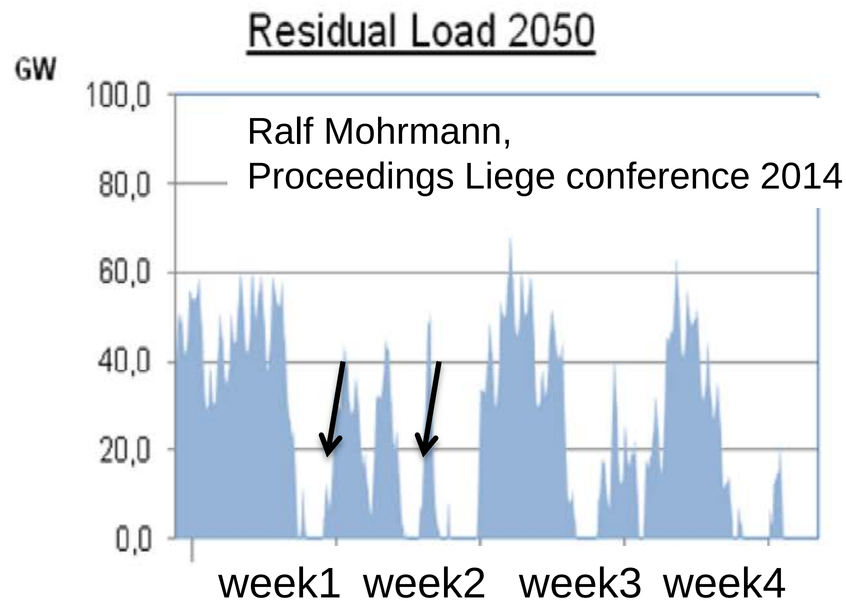
Power Plants Will Need to be Capable of Flexible Operation





- Frequent (~daily) load cycling will result in significant creep-fatigue interaction

Project focus on 3 key areas

- Long term creep fatigue testing and lifetime modeling

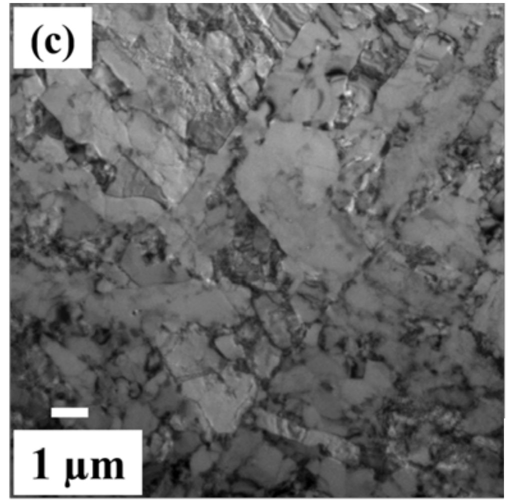
- Interactions among creep fatigue and oxidation

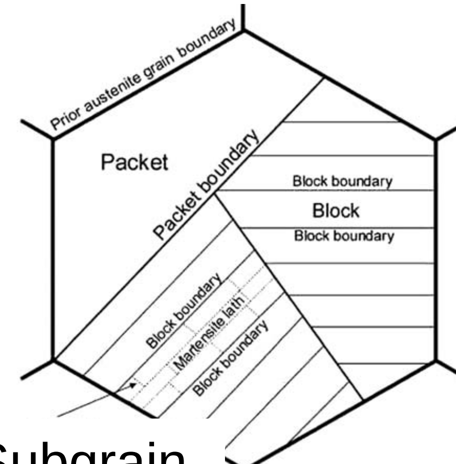
- Study of microstructurally small cracks under creep-fatigue loading

Interaction of Creep & Fatigue Damages in Gr.91

Sub grain coarsening / Dislocation density decrease

Creep performance significantly affected by strain cycling*



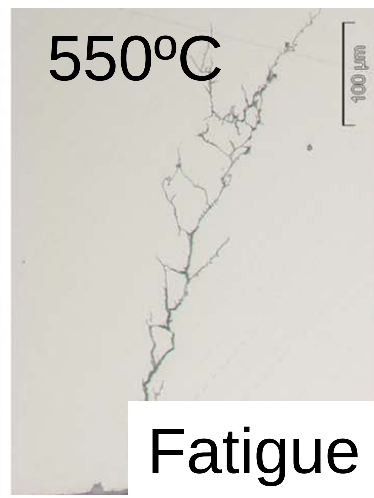


Subgrain boundary

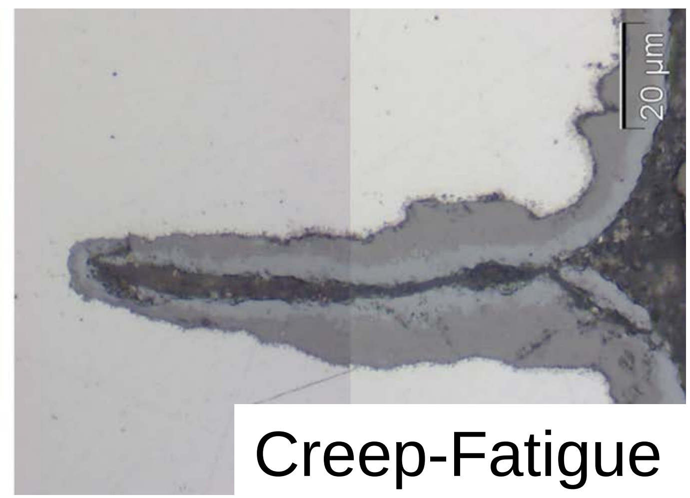
Effect of oxidation on crack initiation during Creep-Fatigue

- **Fast crack initiation due to cracking of the scale & propagation in the alloy**
- **Much thicker non protective scale in air due to cracking**

550ºC



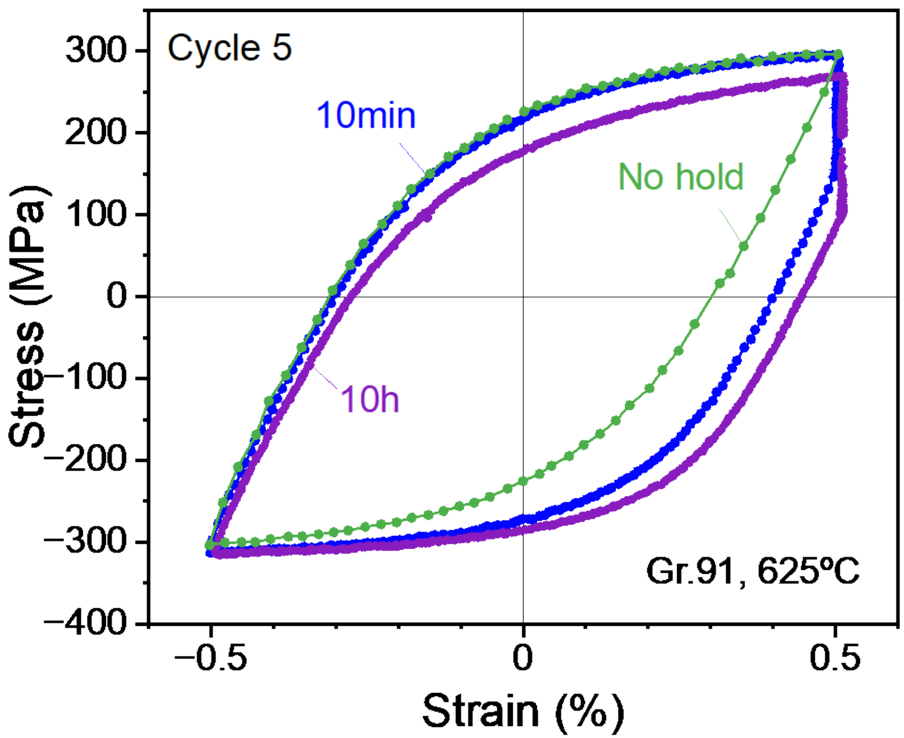
Fatigue

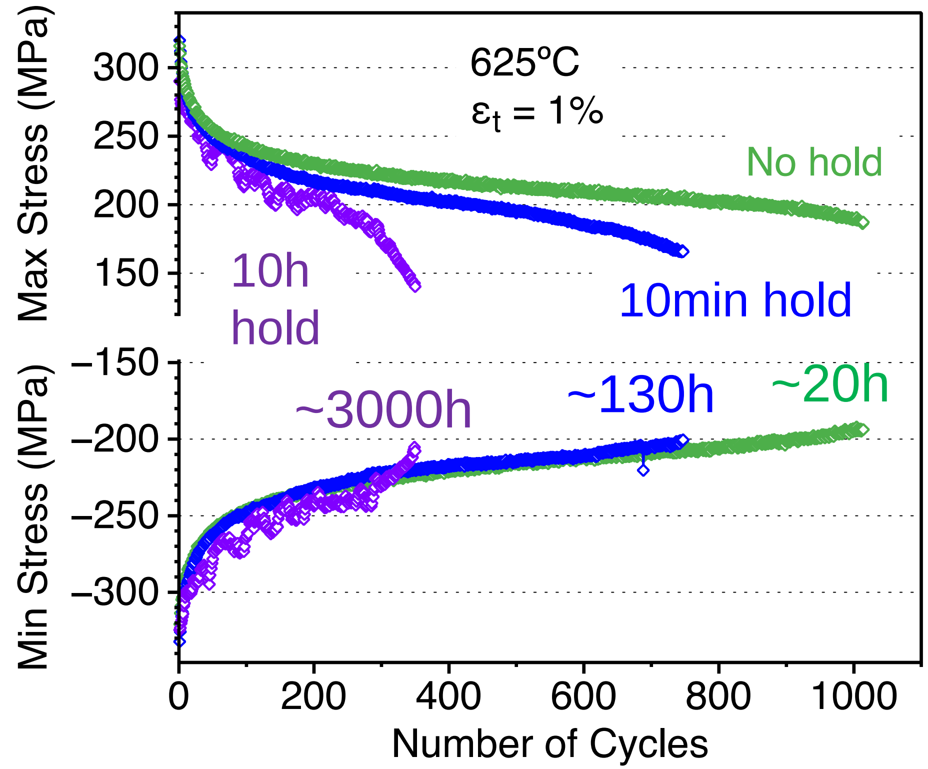


Creep-Fatigue

*Fournier et al., Int. J. Fatigue 2008, M&M Trans A 2009

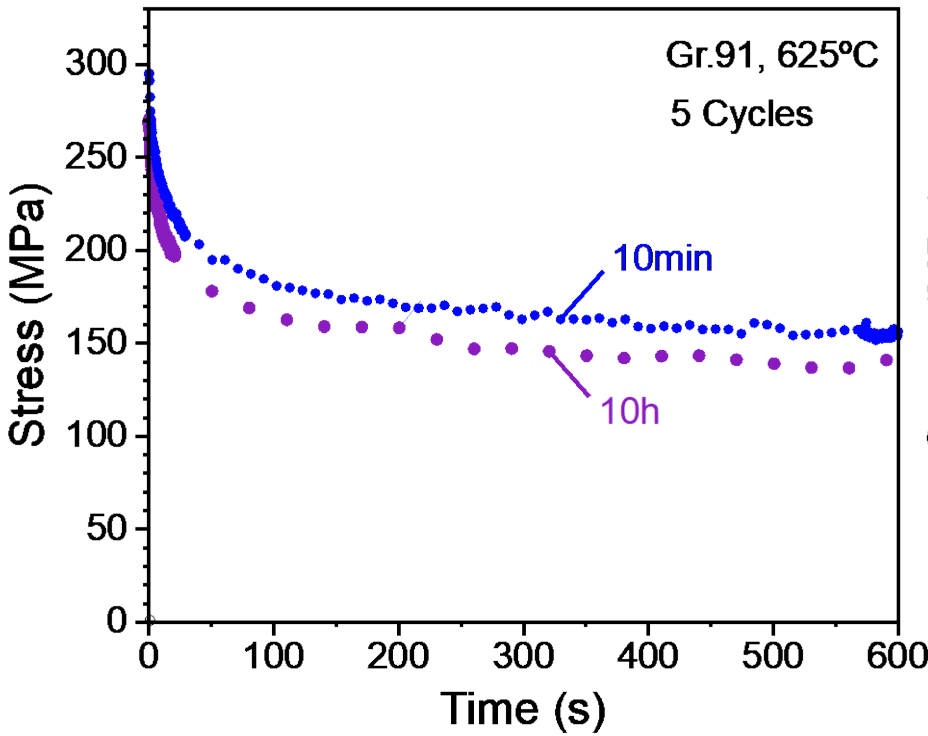
Decrease of N_f with Hold Time for Creep-fatigue Tests at 625ºC, ±0.5%

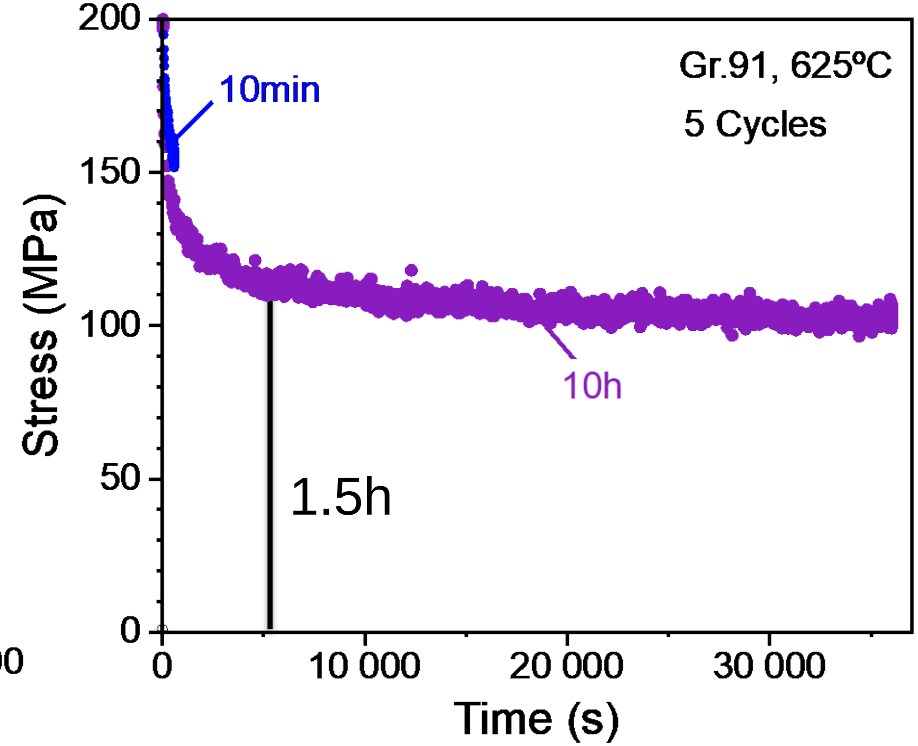




- Faster softening with increasing hold time
- Significant decrease of number of cycles to failure with longer hold time (>3000h test)

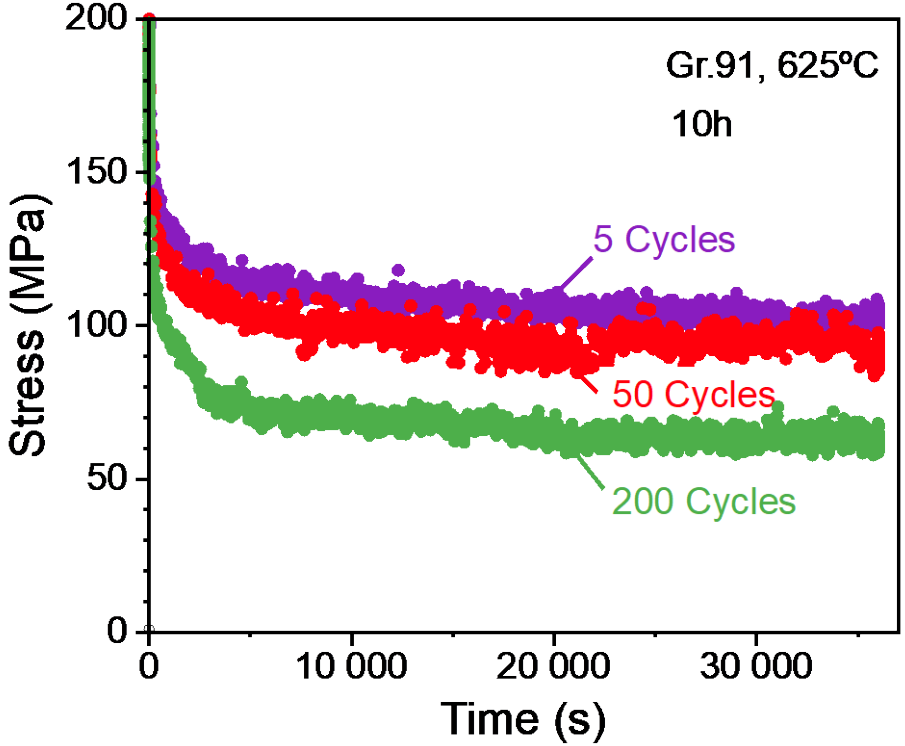
Significant Stress Relaxation During 10h Hold Time

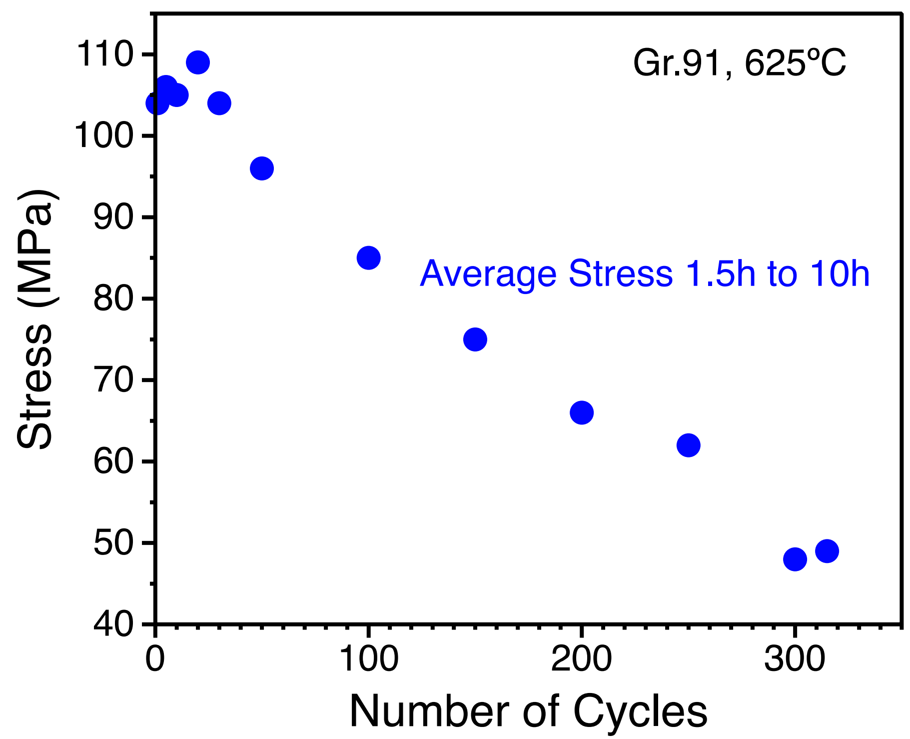




- Need ~ 1.5h to reach a nearly steady state stress
- Creep lifetime at 625ºC, 100MPa ~5000h

Linear Decrease of "Steady Stress" for 10h Hold Time Test After ~30 cycles





Significant softening due to cycling

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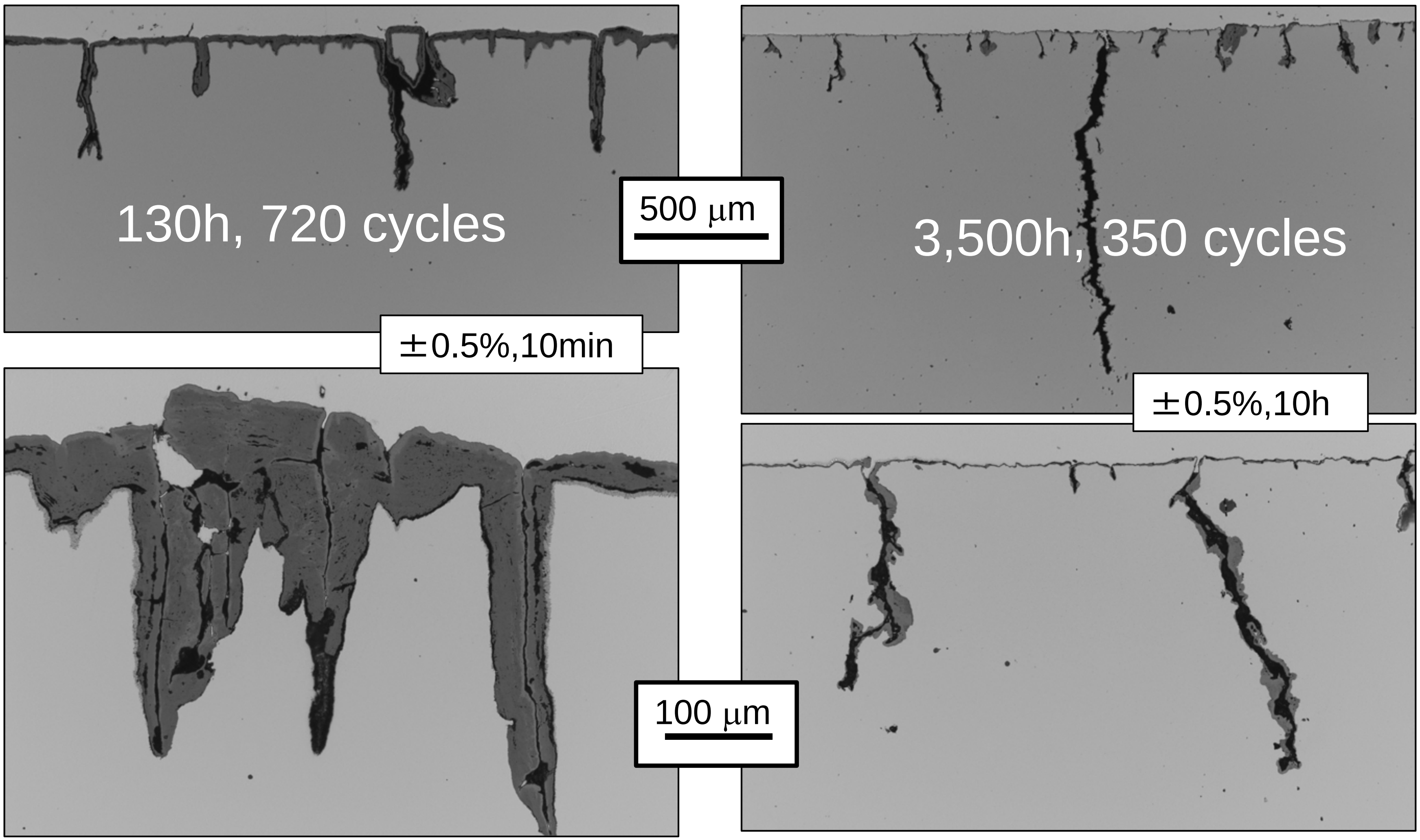
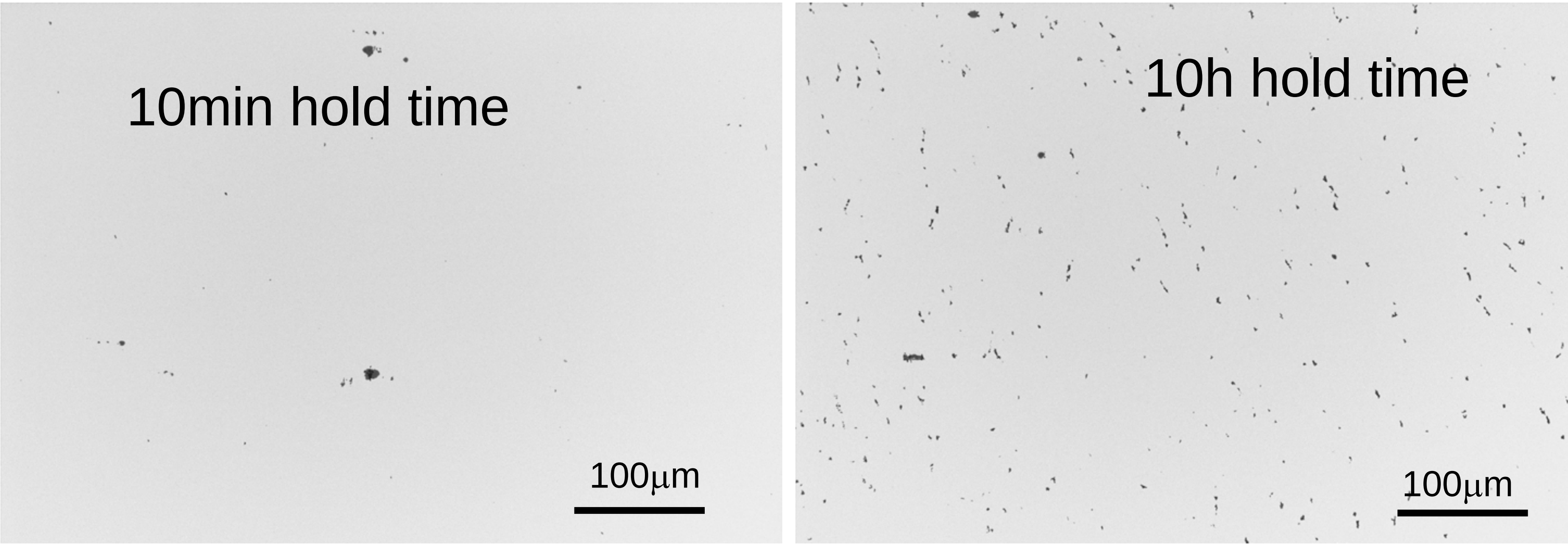
Significant Effect of Frequent Cycling on Oxide Scale Growth in Air



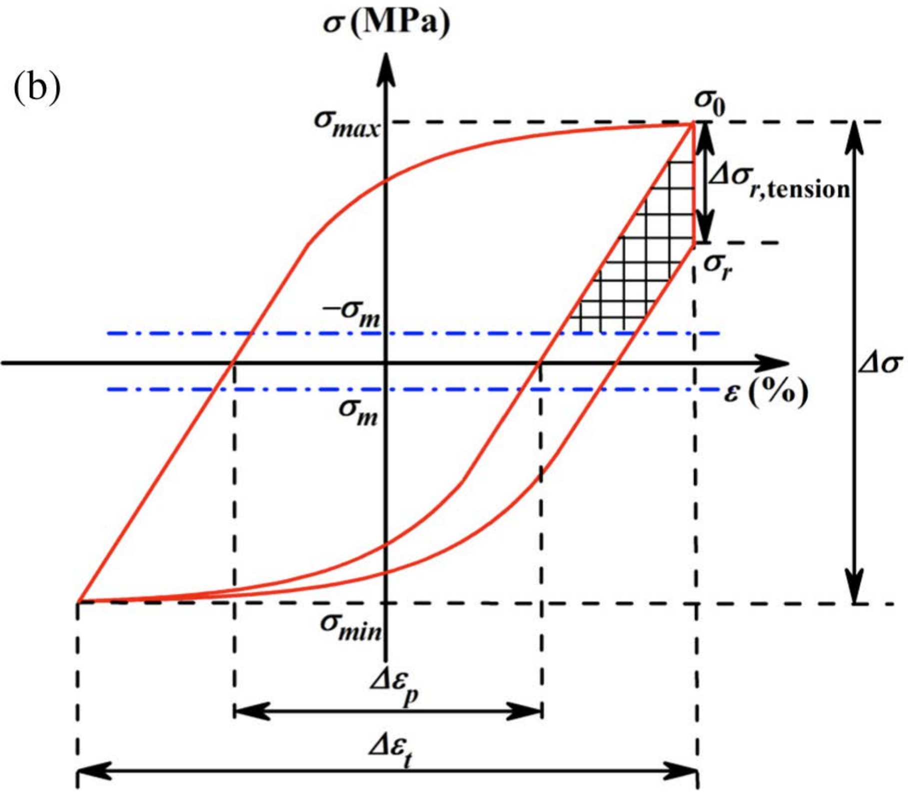
Interaction Between Crack Propagation & Creep Cavitation for ±0.5%, 10h Hold

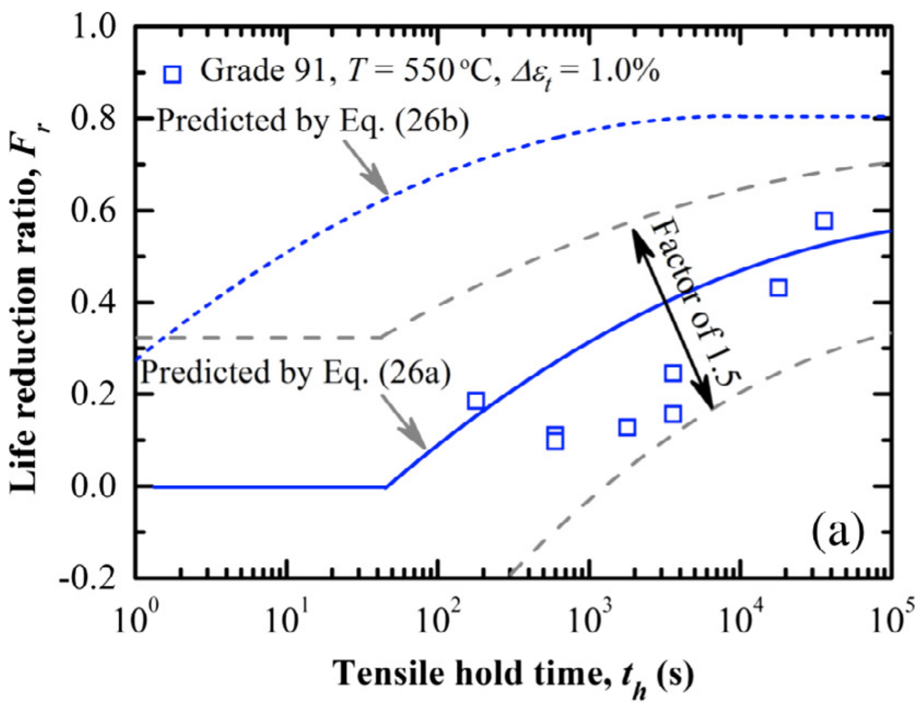


- Effect of creep cavitation on crack propagation?

Creep-Fatigue Damage Models

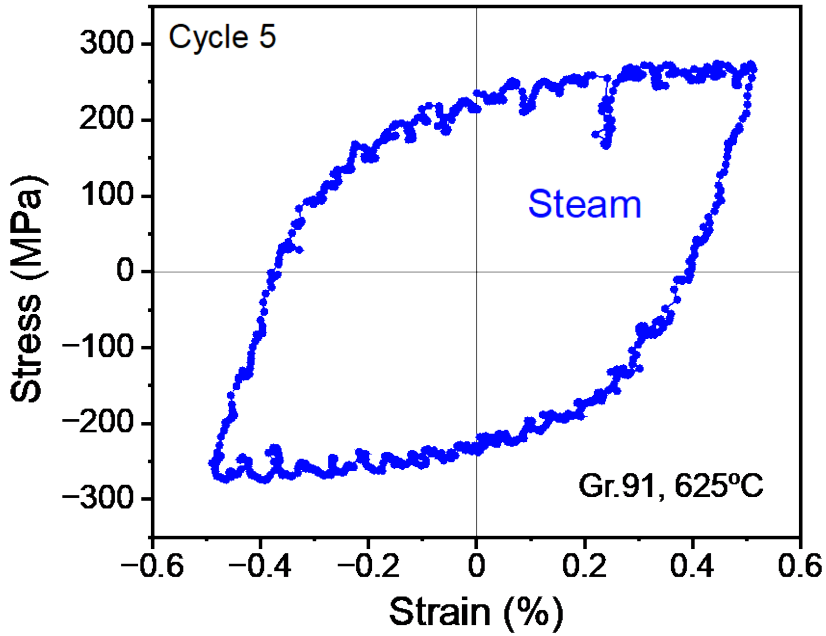
Modified strain energy density exhaustion model, Wang et al. 2016, Int. J. Fatigue



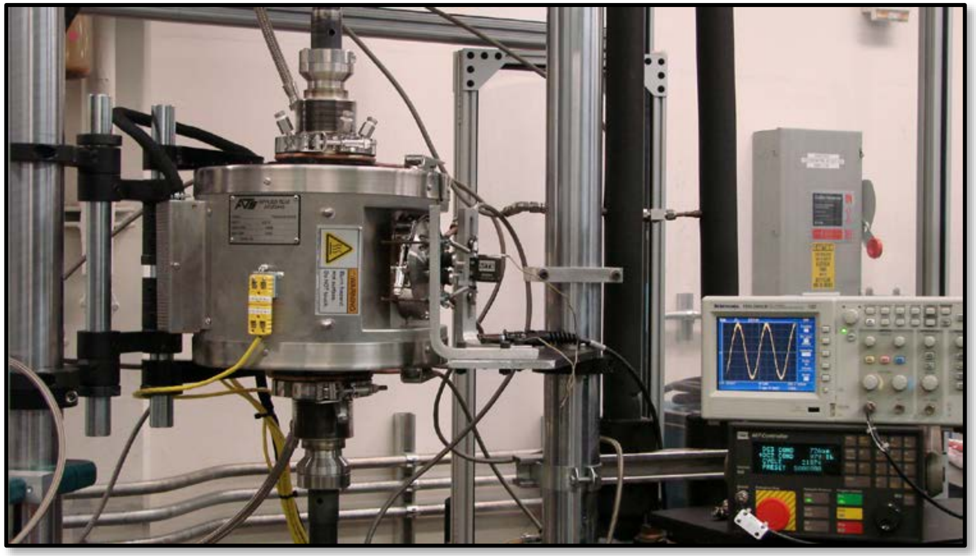


Ductility exhaustion is based on theories of grain-boundary void growth and matrix creep

New Test Facility to Evaluate LCF Resistance in Aggressive Environments

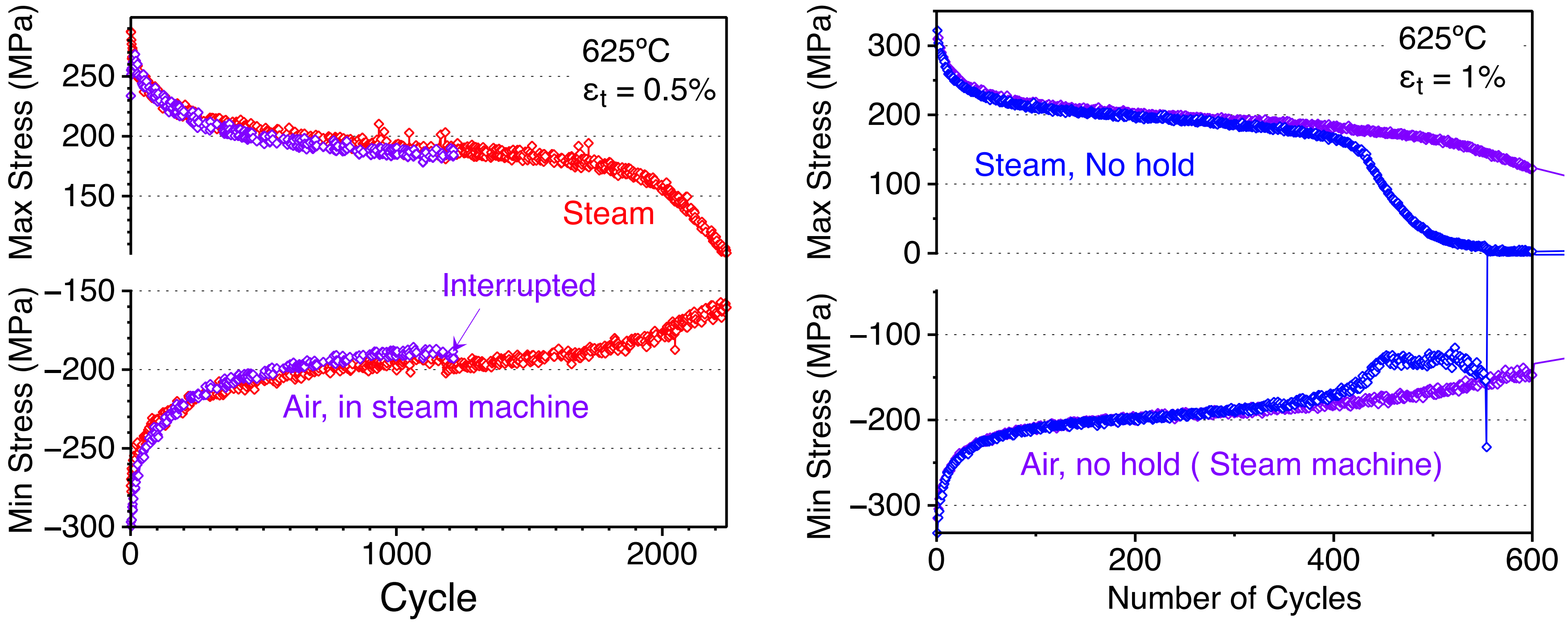


Stress-strain curve, 9Cr-1Mo ferritic steel, 625ºC, fully reversed 1% total deformation, Steam



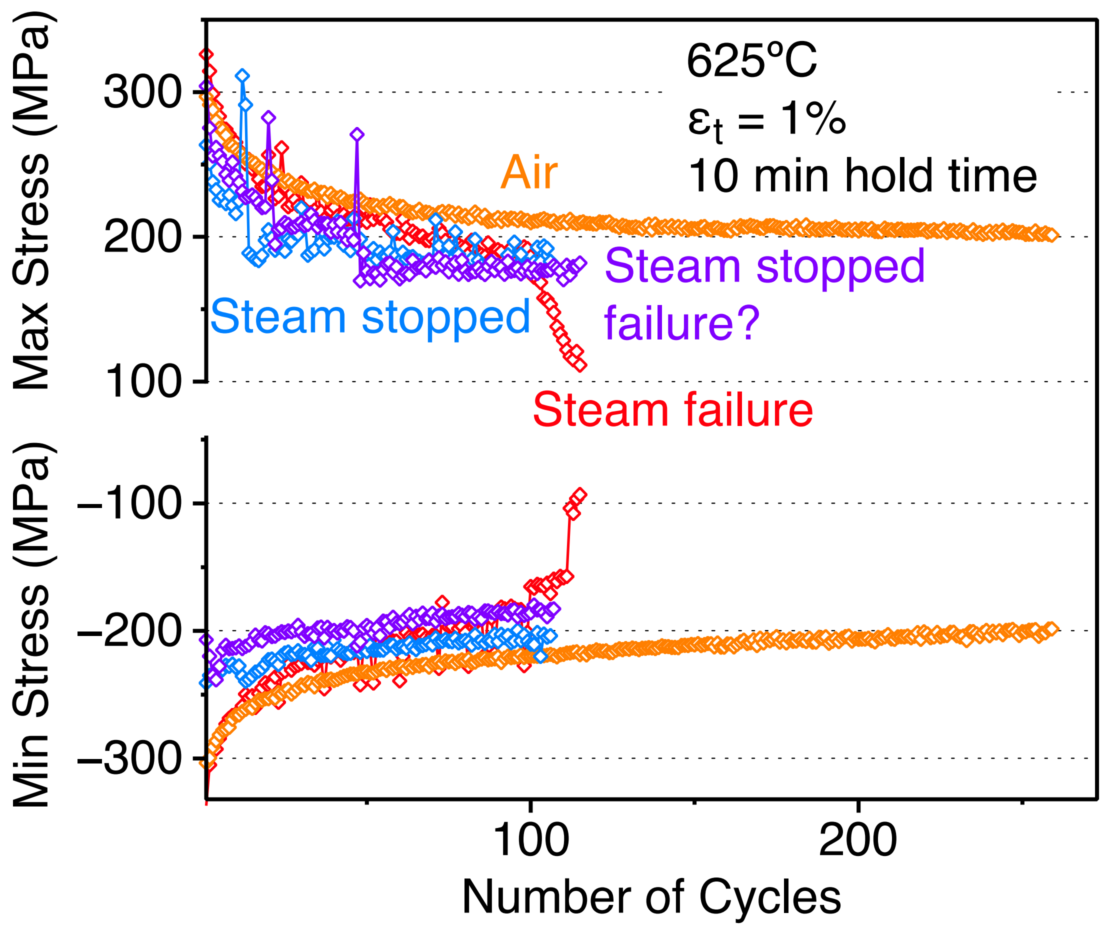
Sealed chamber inside furnace and extensometer to provide feedback signal for system operation under strain control

Limited Effect of Steam on the HCF Behavior of Gr.91



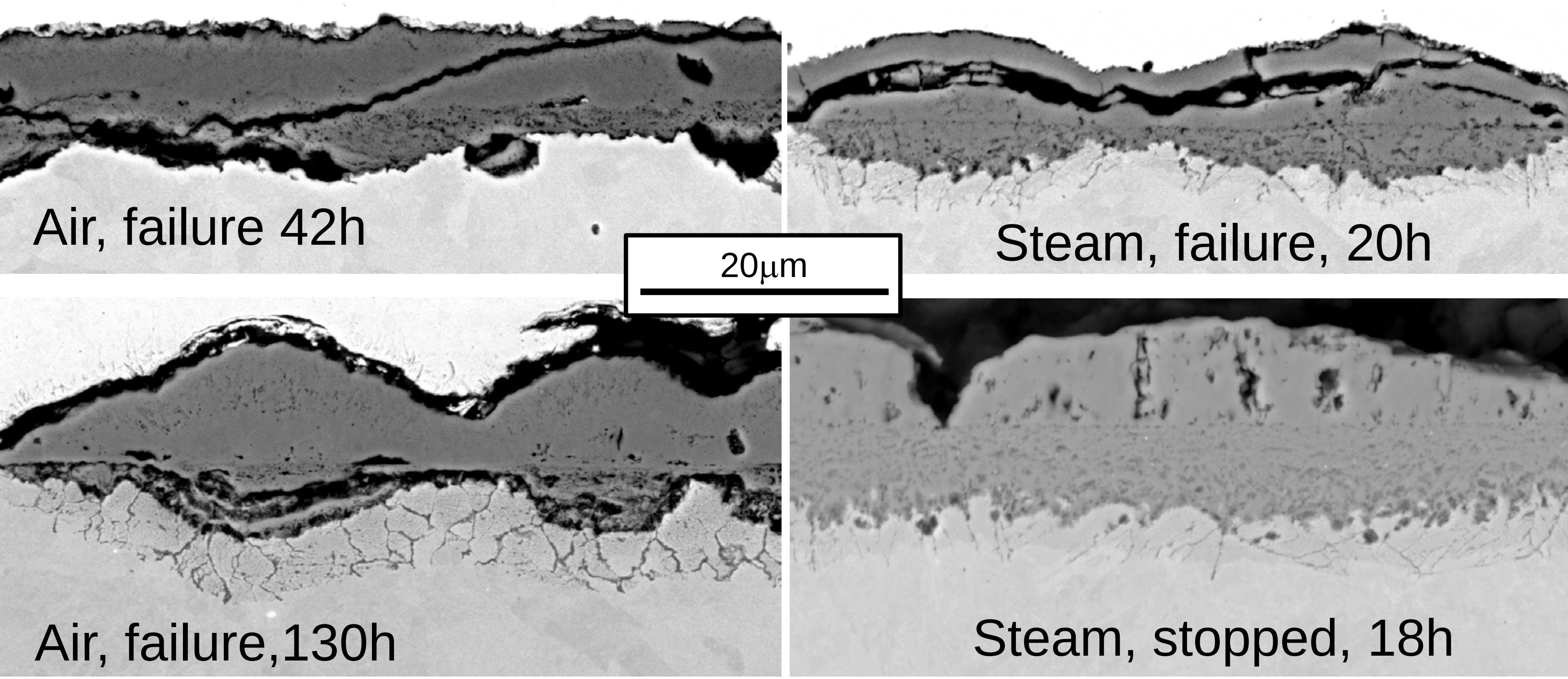
- Very similar softening in air and steam
- Gr91 oxidation rate is known to be drastically affected by H_2O
- New batch of Gr.91 alloy showing lower N_f

Decrease of Nf for Creep-Fatigue Test in Steam with 10min hold time



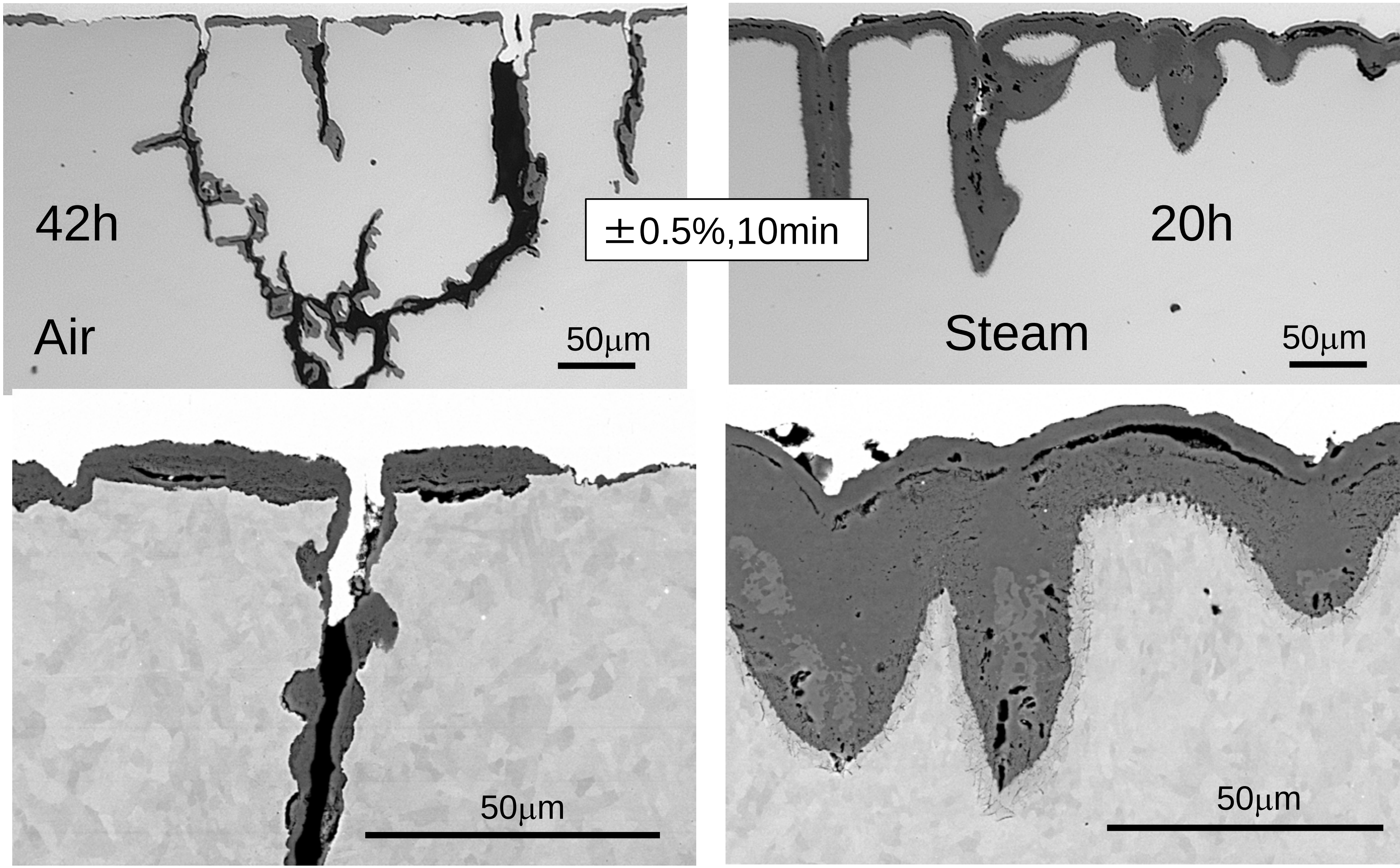
Continuous improvement of the Fatigue Steam Rig

Thicker Oxide Scale in Steam Away from Cracks?



Cr-rich few microns thick oxide scale expected in air without cyclic loading

Very Oxidized Cracks in Steam
Steam effect on crack formation?



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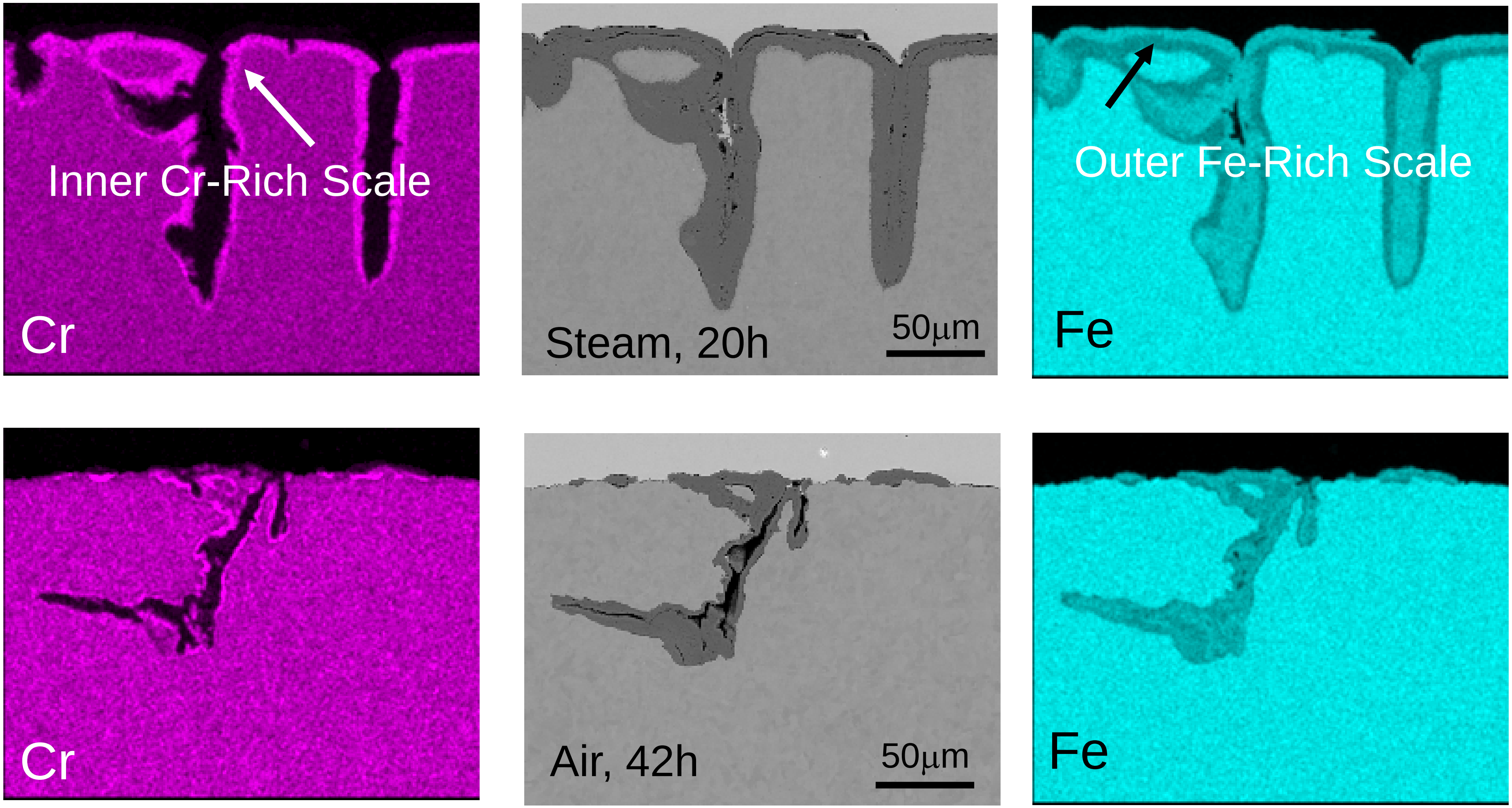
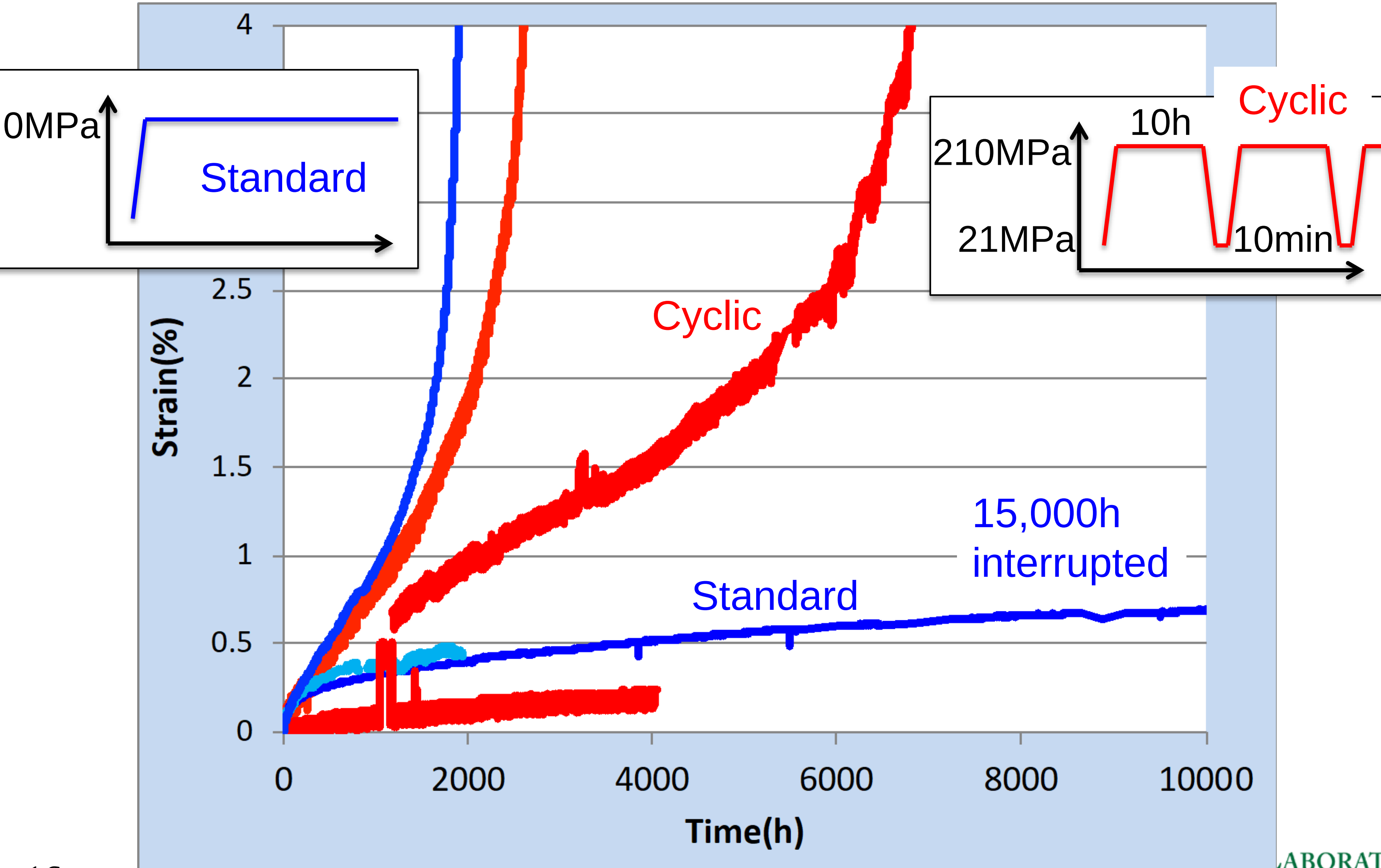
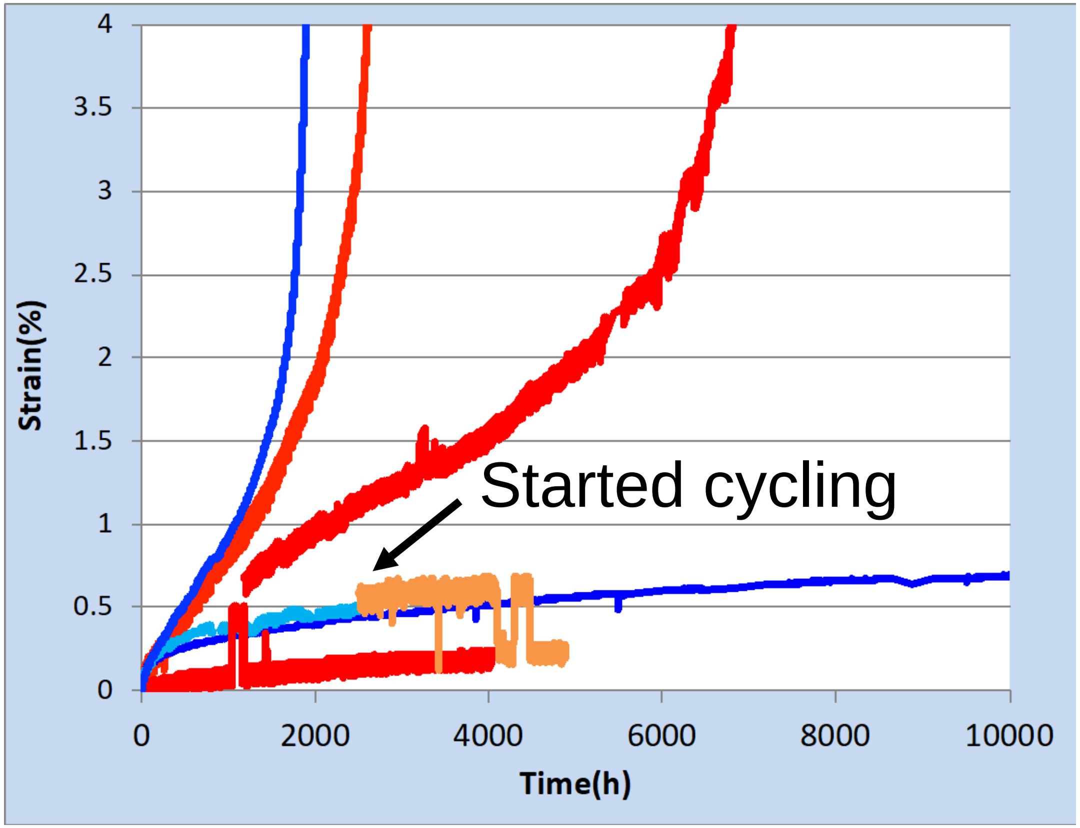
Similar Scale Composition in Air and Steam



Limited Effect of Load Cycling on Gr.91 Creep Properties



Switching from Standard to Cyclic Testing Does Not Impact Creep Rate



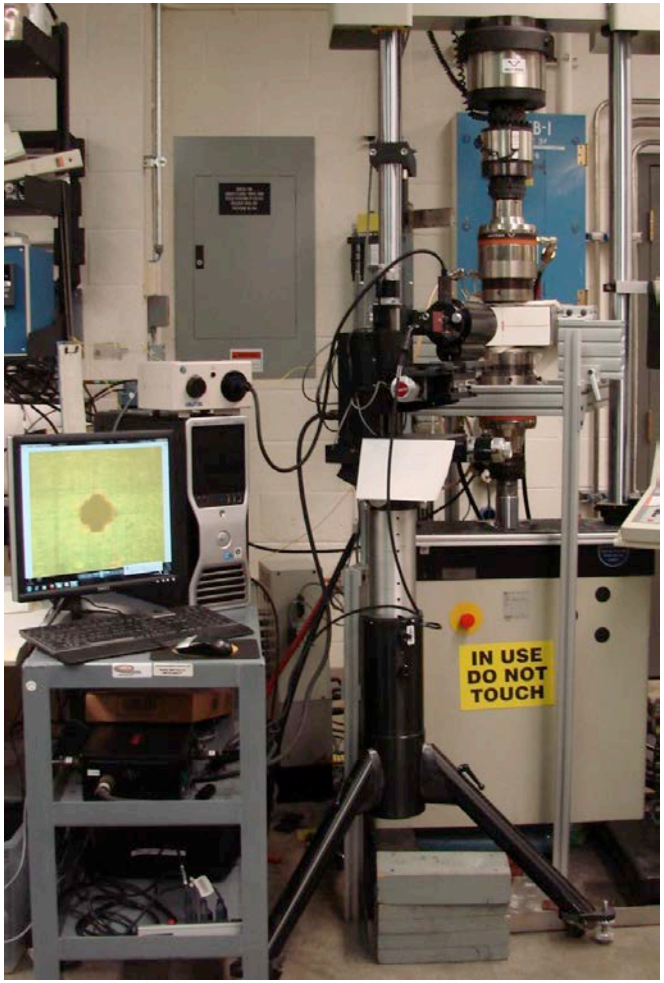
Standard, 7.4 x10^{-5} %/h

Cyclic 7.1 x10^{-5} %/h

- No effect of load cycling: cyclic damage requires strain cycling
- Best testing conditions would be fully reverse creep-fatigue testing using electro-mechanical testing machines

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

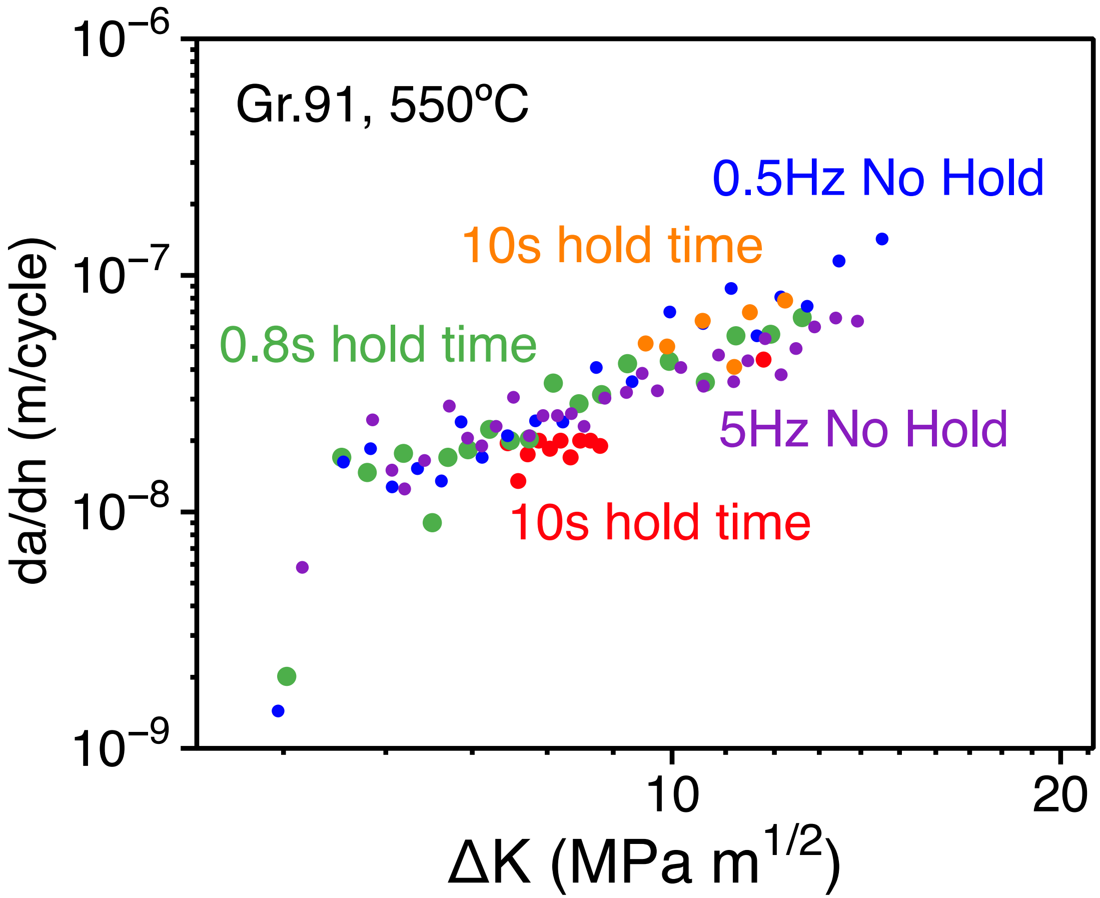
- Sumit Bahl's work (Indian Institute of Science)
- Slower propagation for small cracks
- Crack initiation at room temperature
- High cyclic fatigue & creep fatigue testing
- In Situ imaging of crack propagation
- Tests conducted at Room and 550°C



Crack Growth Imaging at Room T^{o}C

300µm

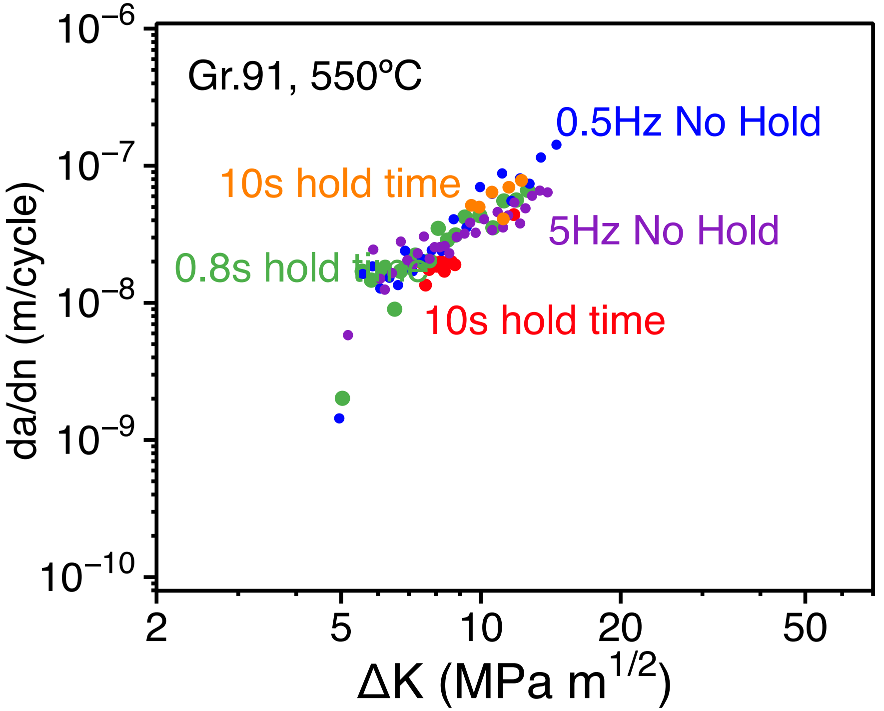
No Effect of Frequency & Hold Time on Small Crack Propagation

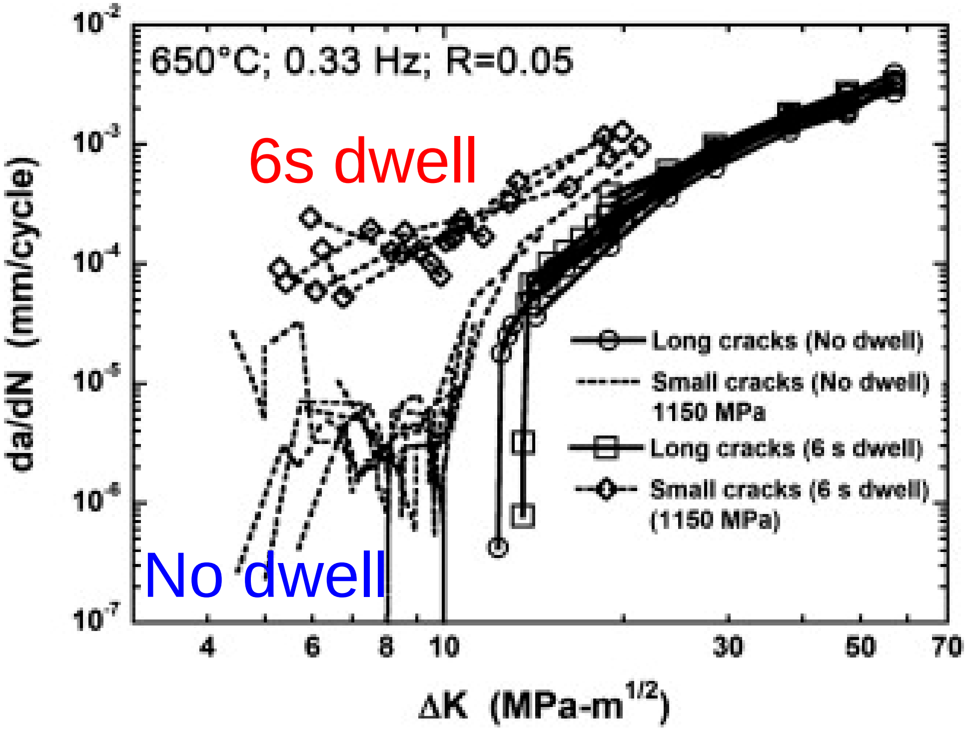


Crack arrest with 100s or 10min hold time

Effect of oxidation or decrease of dislocation density at crack tip?

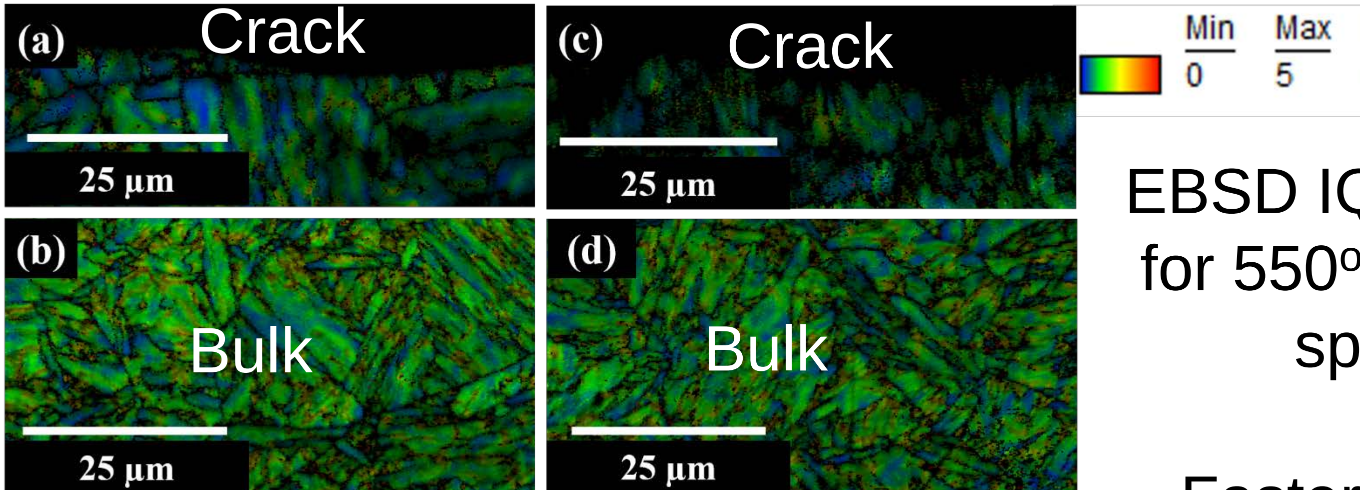
No Acceleration or Retardation & Arrest of Crack Growth in Grade 91 Steel is Unusual





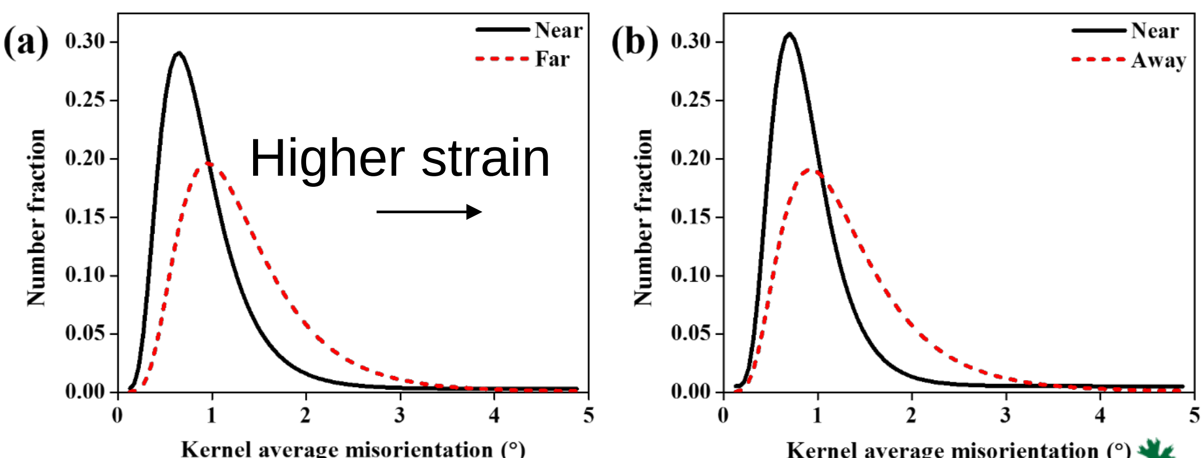
Jha and Caton, Int J Fatigue 2010
Strong effect of dwell time (6 s) in IN100

Near the fracture surface the dislocation densities are lower (cyclic softening)



No Hold

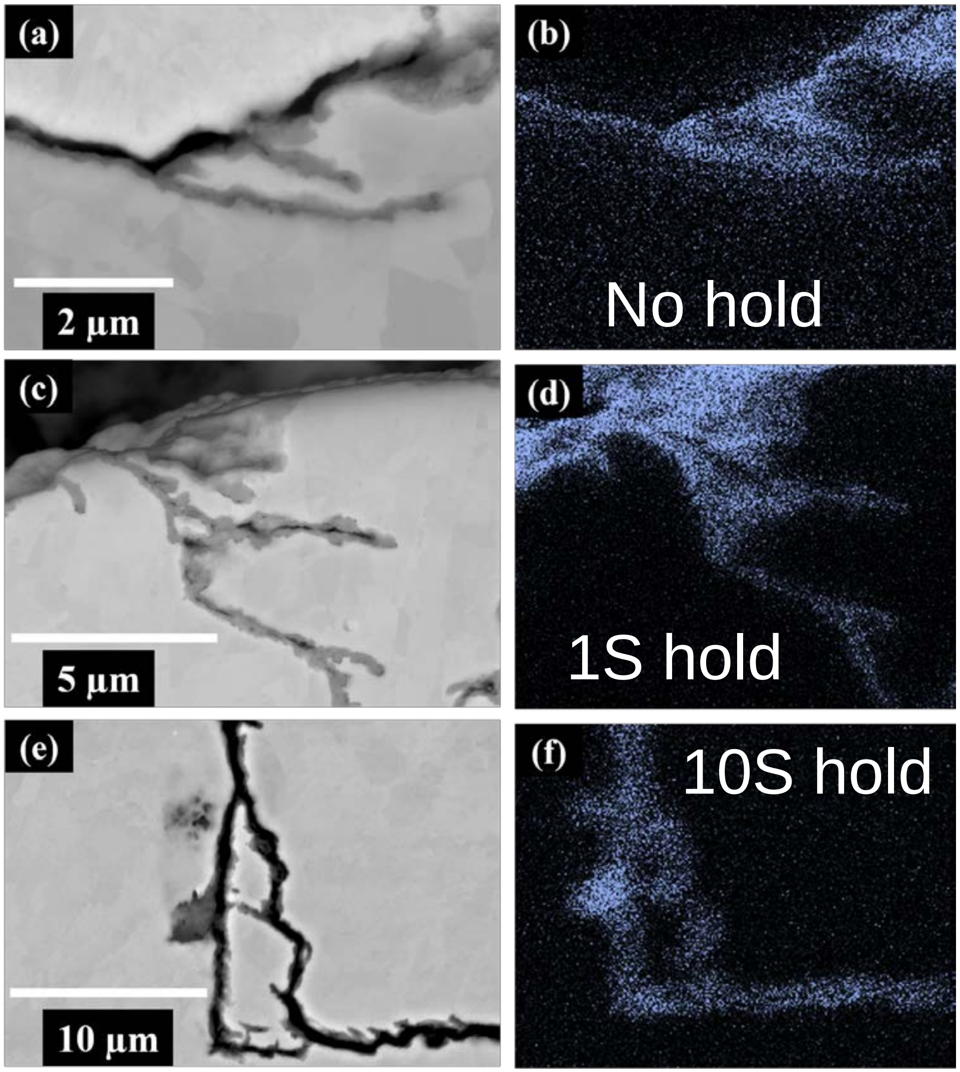
1s hold time



EBSD IQ + KAM maps for 550°C FCG tested specimens

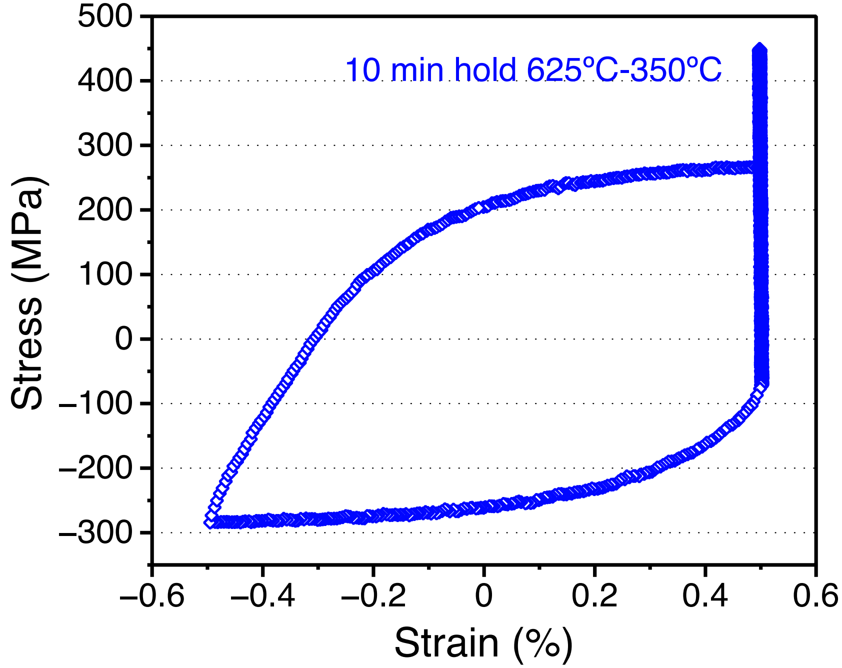
Faster decrease of dislocation density at crack tip for creep-fatigue specimens? Bahl et al. Mat Trans 2018

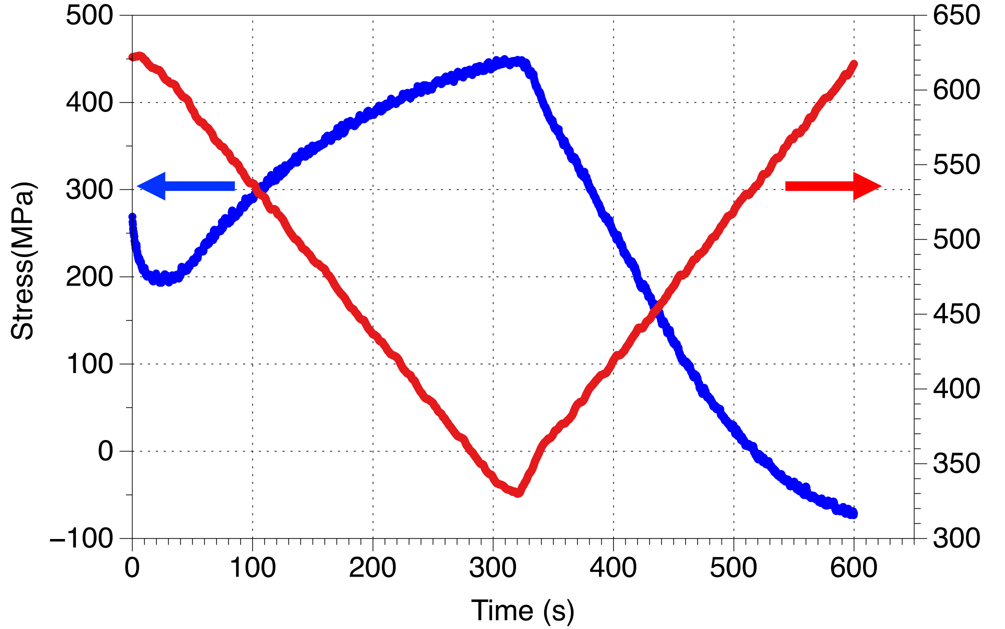
Significant Oxidation at the Crack Tip During Testing



Depending on the scale (Fe or Cr-rich), oxidation at 550ºC can be very fast
Oxidation-induced crack closure?

Thermo-Mechanical Fatigue Testing of Gr.91 Between 625ºC and 350ºC





- Cycle to rupture decreased by factor 2 compared to creep-fatigue tests at 625ºC
- Guidance from plant operators will be required to determine a test procedure relevant to power plant operation

Conclusion

- Significant effect of hold time on Gr.91 fatigue lifetime

- Continuous improvement of creep-fatigue models

- Relevant long-term creep-fatigue testing will require strain-controlled electro-mechanical machines

- Complex synergy between strain cycling and oxide scale growth Need to generate more data in relevant environments to determine degradation mechanisms and develop lifetime models
- TMF is likely to impact component lifetime for power plants requiring flexible operation