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

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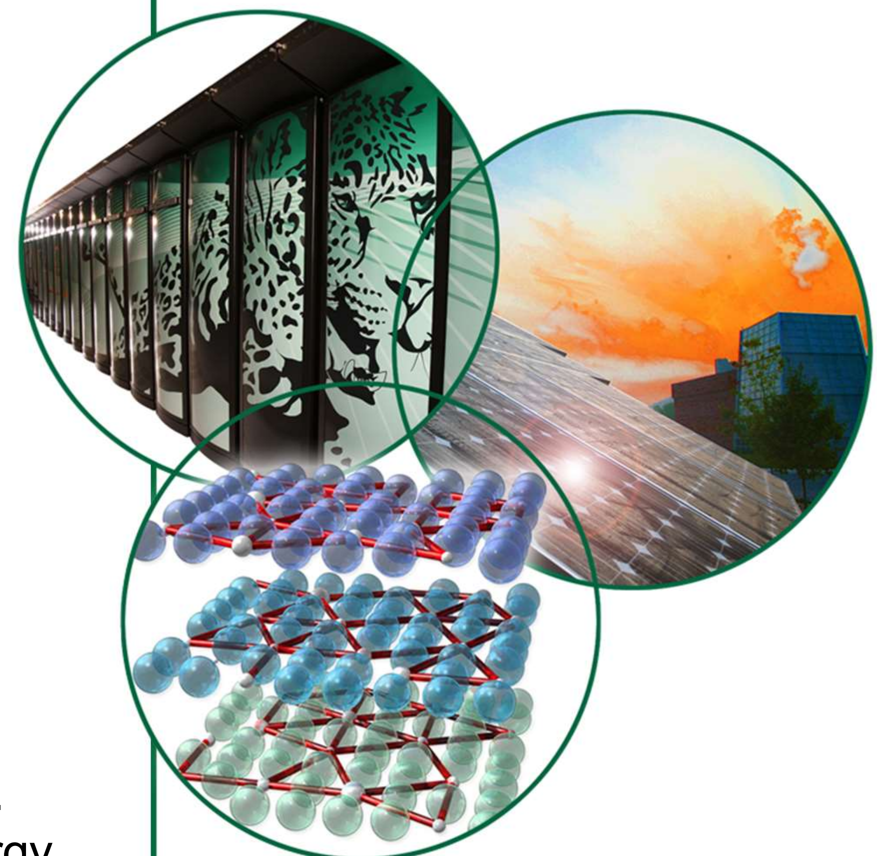

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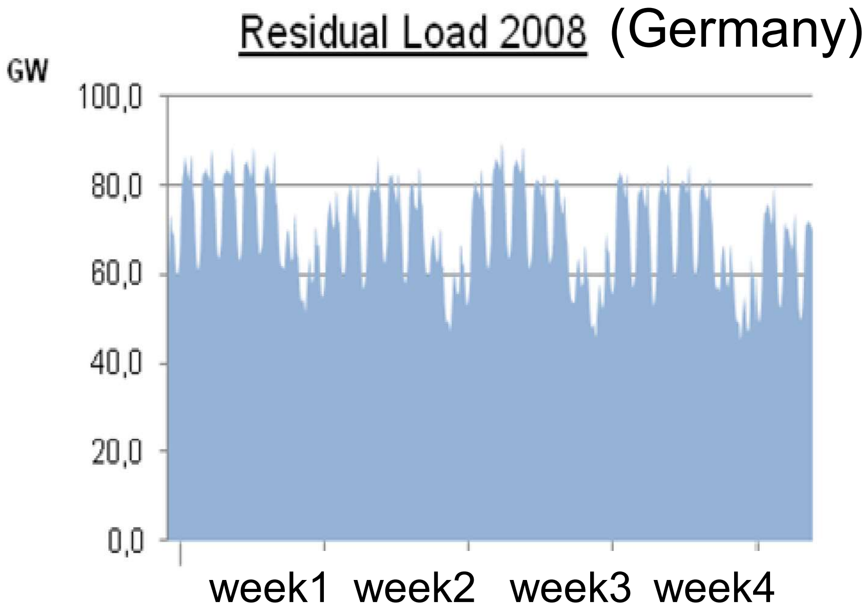
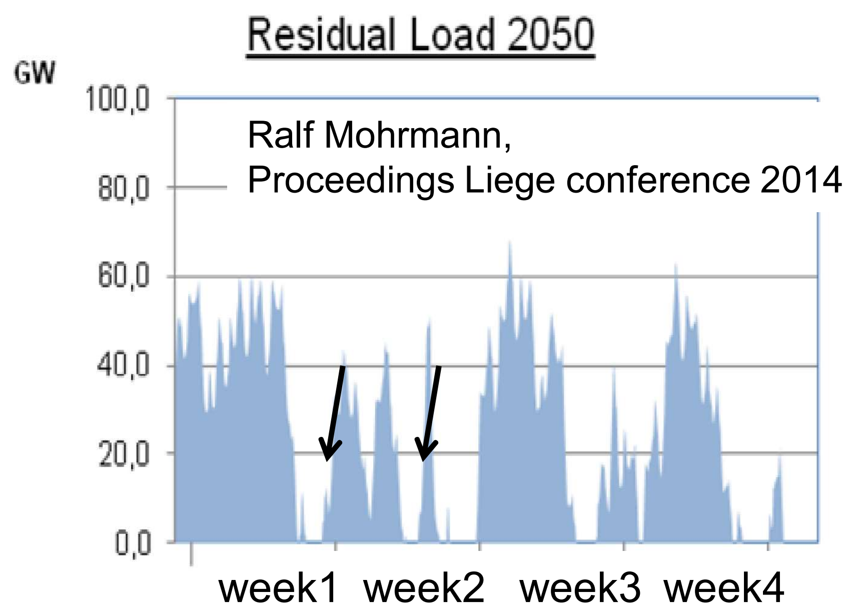
Power Plants Will Need to be Capable of Flexible Operation





- 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

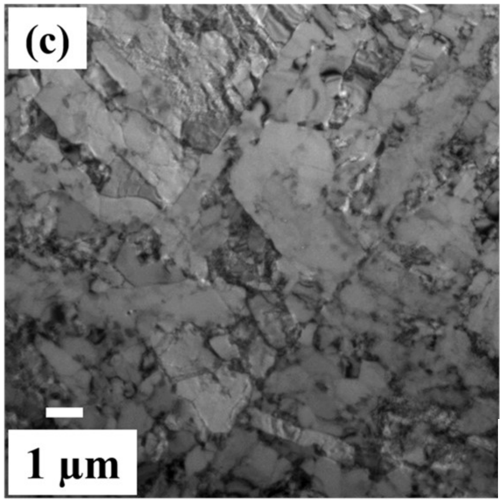
- Interactions among creep fatigue and oxidation

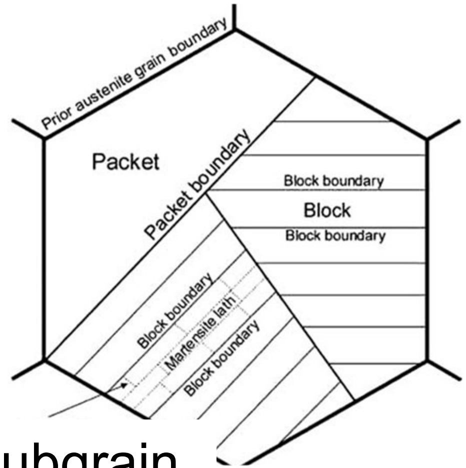
- Study of microstructurally small cracks under creep-fatigue loading

Interaction of Creep & Fatigue Damages in Gr.91

Sub grain coarsening / Dislocation density decrease

Creep performance significantly affected by strain cycling*

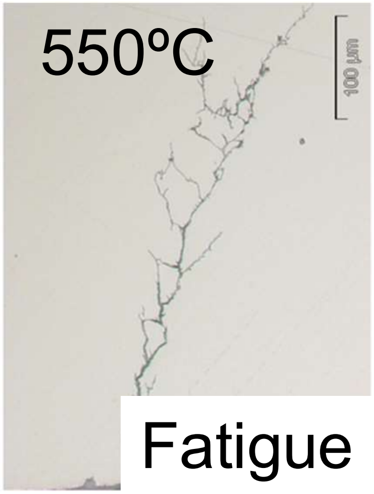




Subgrain boundary

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**

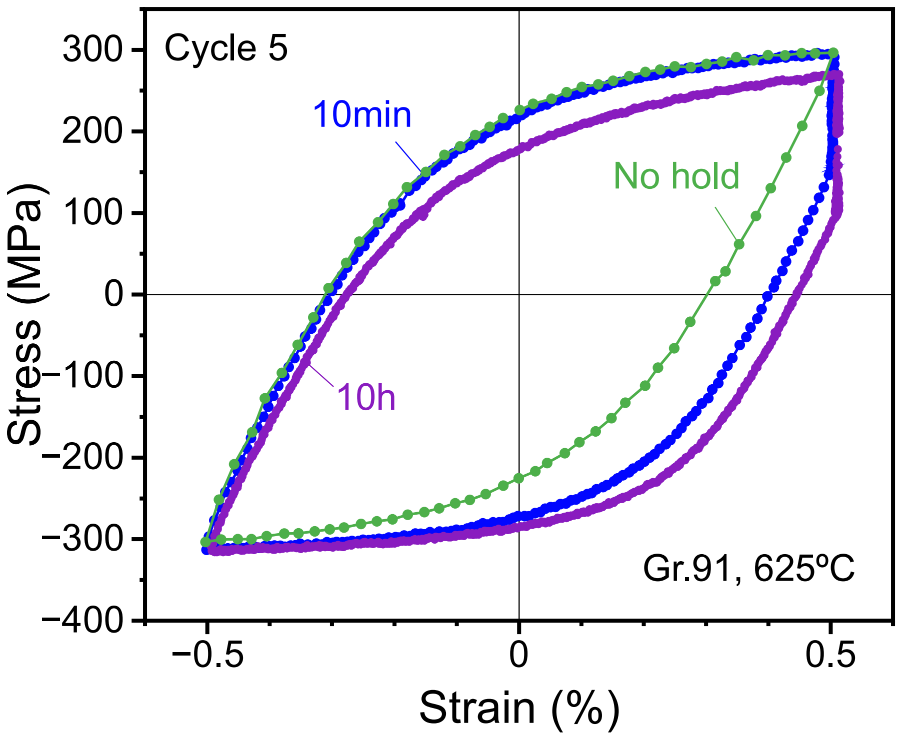


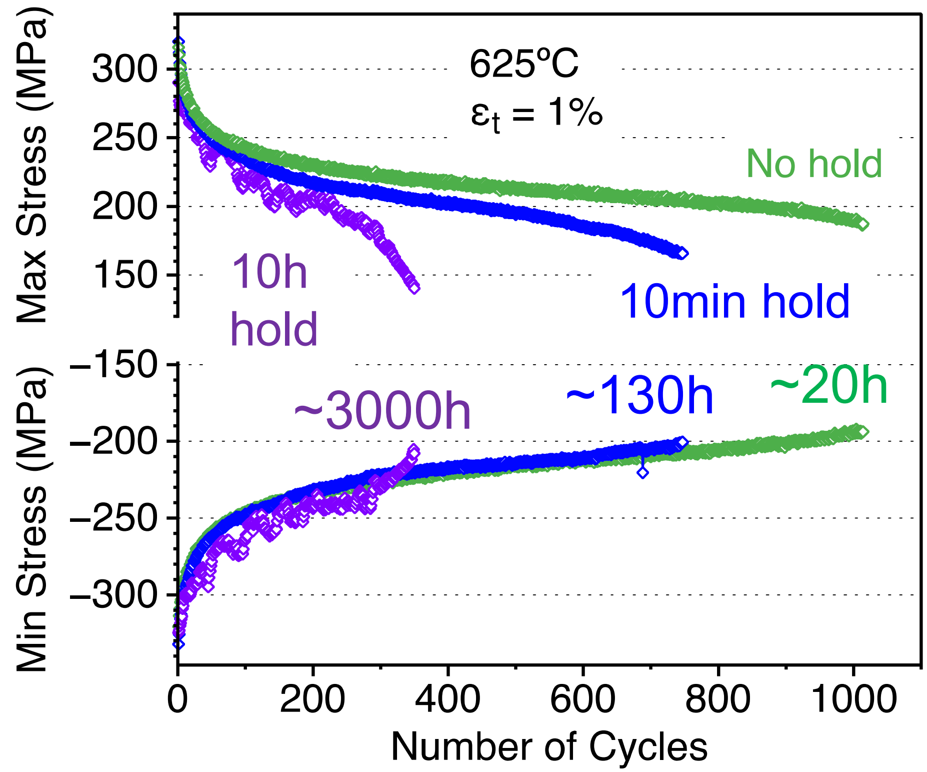
Fatigue

Creep-Fatigue

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

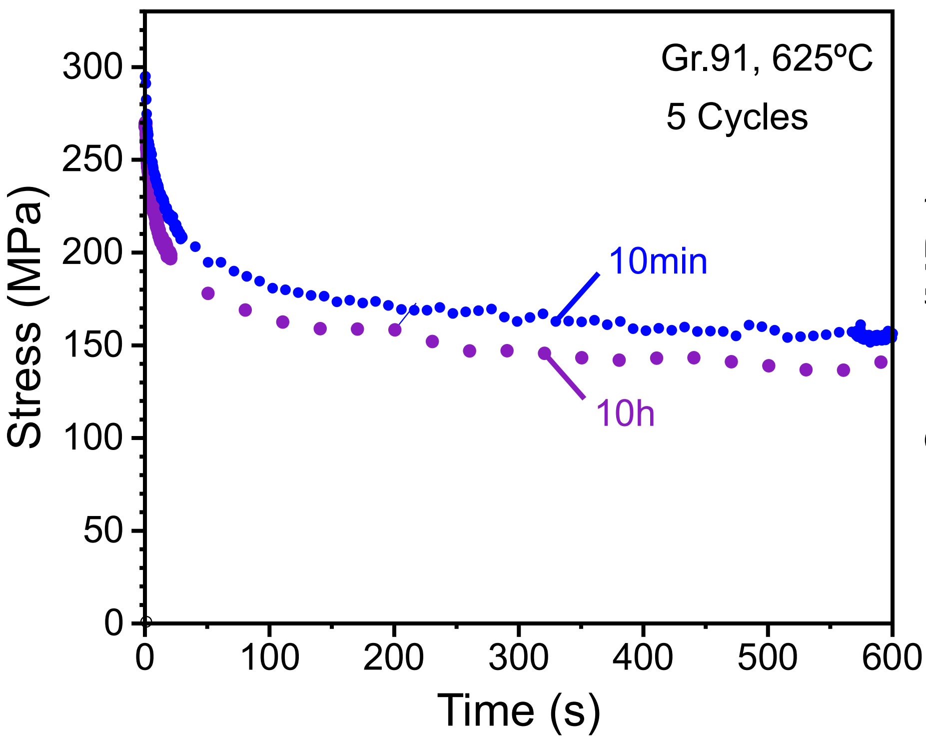
Decrease of N_f with Hold Time for Creep-fatigue Tests at 625ºC, ±0.5%

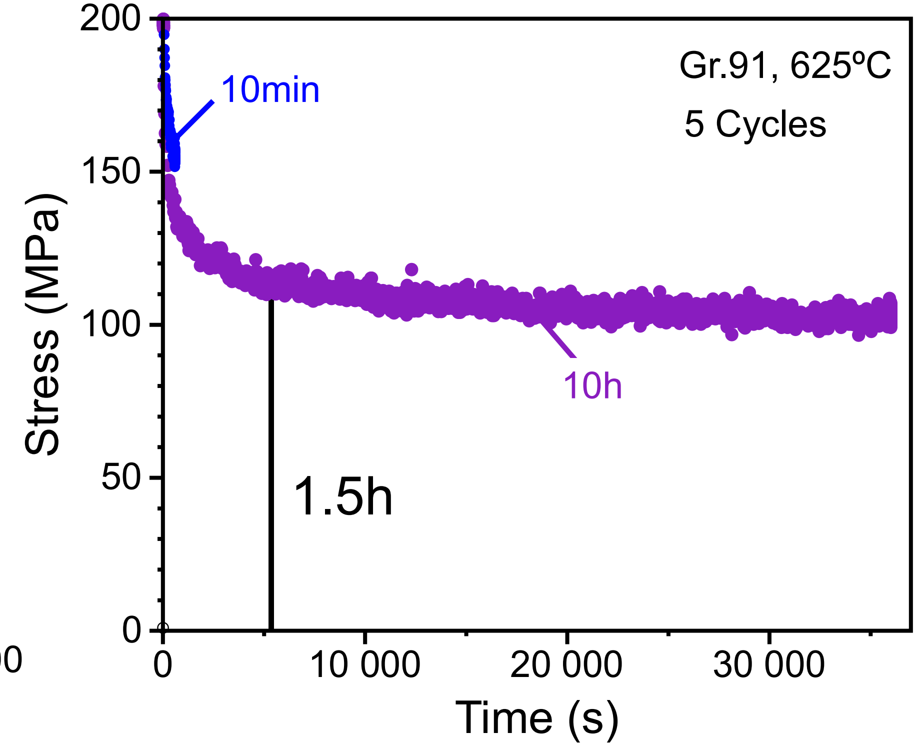




- Faster softening with increasing hold time
- Significant decrease of number of cycles to failure with longer hold time (>3000h test)

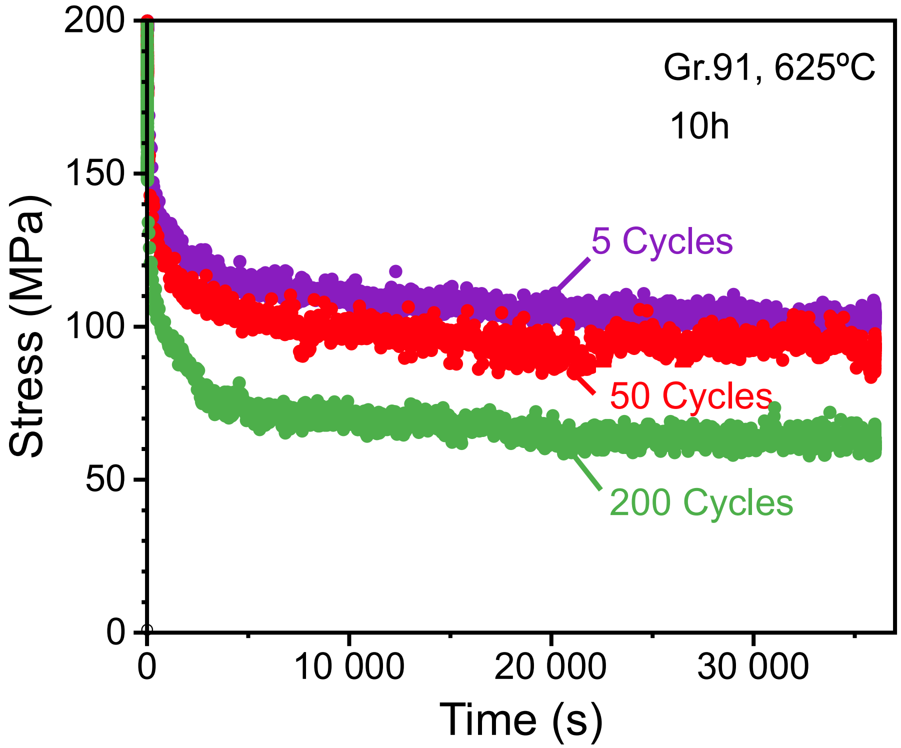
Significant Stress Relaxation During 10h Hold Time

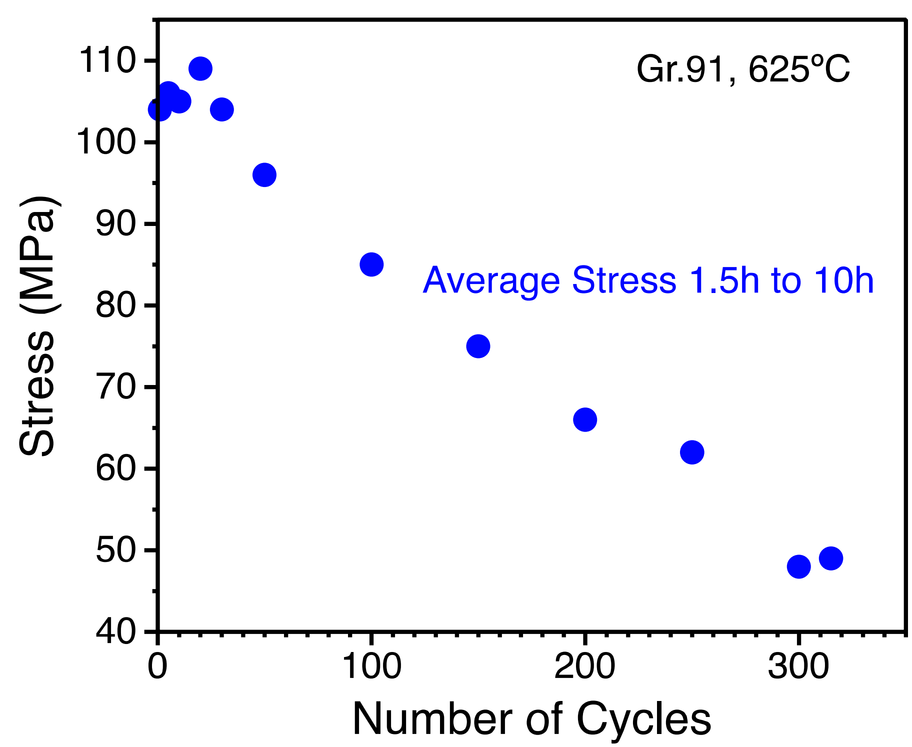




- Need ~ 1.5h to reach a nearly steady state stress
- Creep lifetime at 625ºC, 100MPa ~5000h

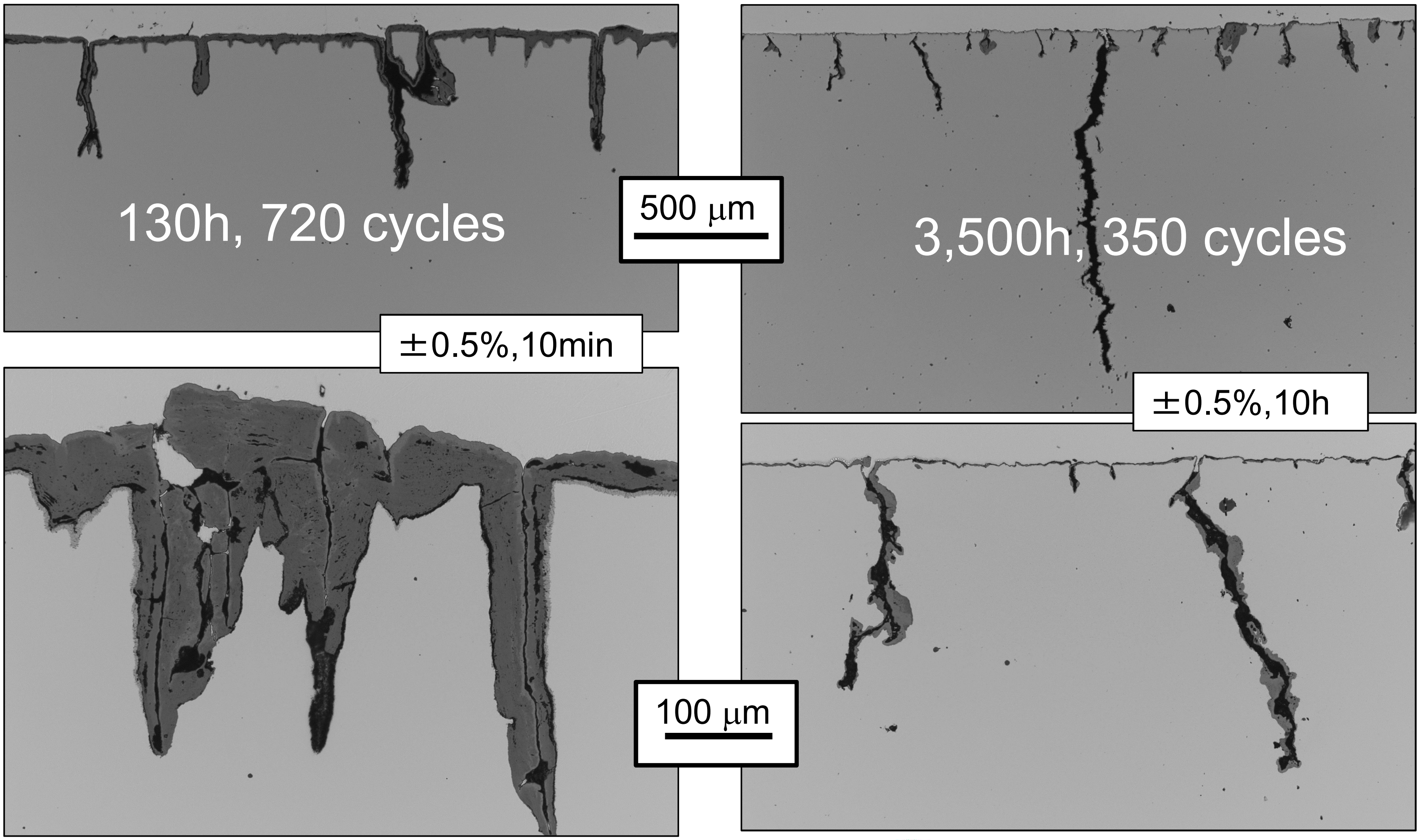
Linear Decrease of “Steady Stress” for 10h Hold Time Test After ~30 cycles



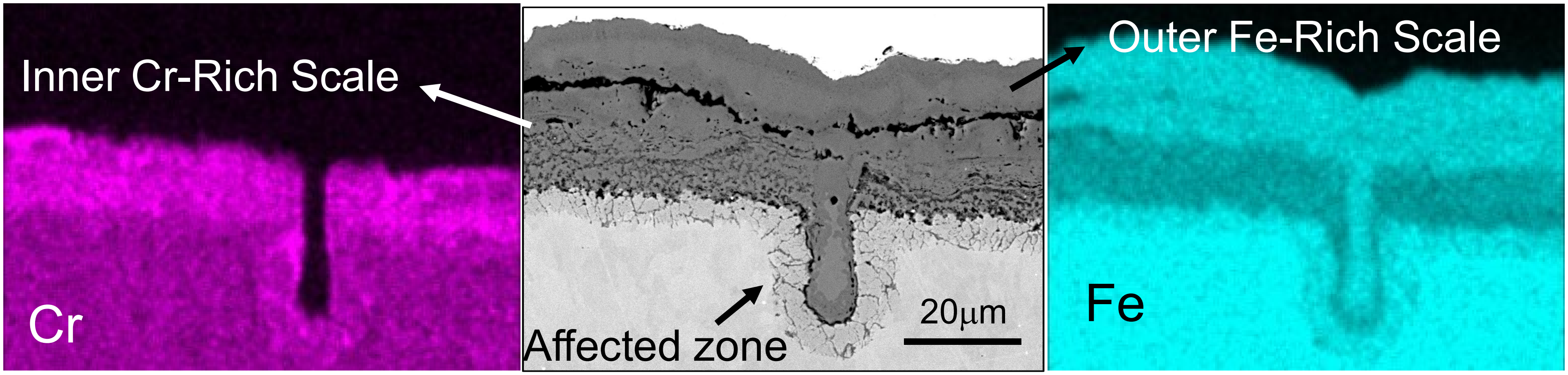


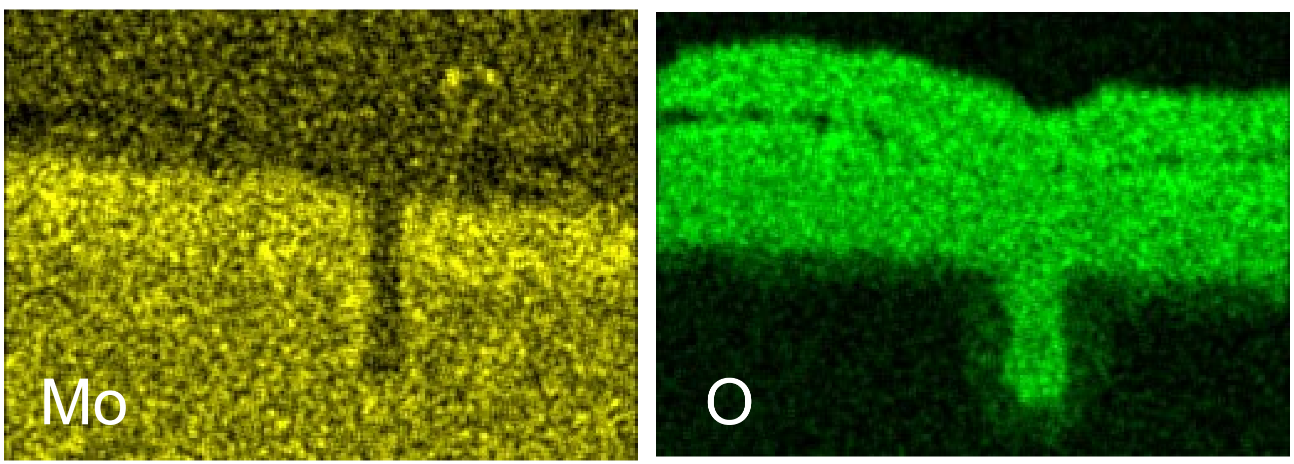
Significant softening due to cycling

Significant Effect of Cycling on Scale Growth



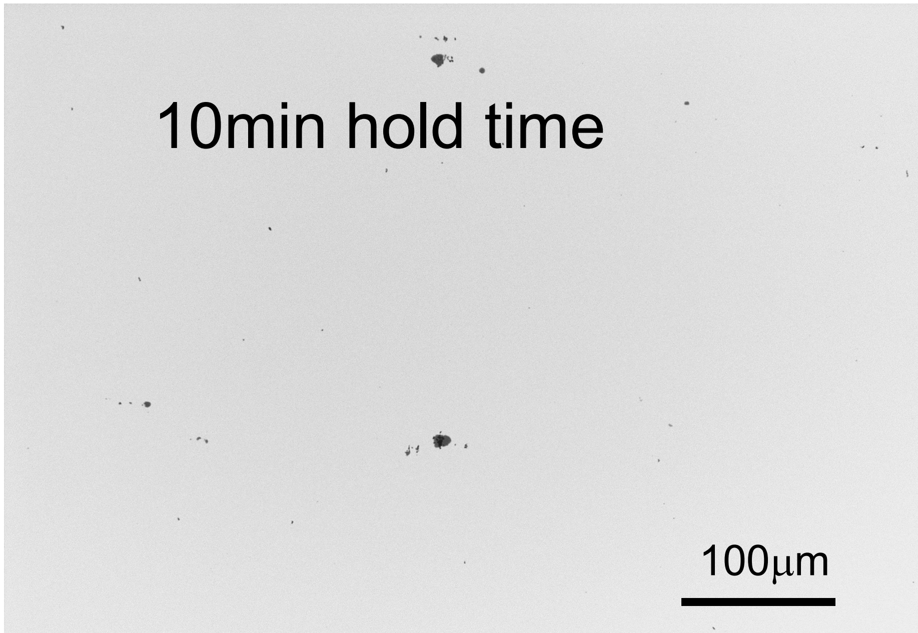
Multi-Layer Oxide Scale for 10min Hold Time Test

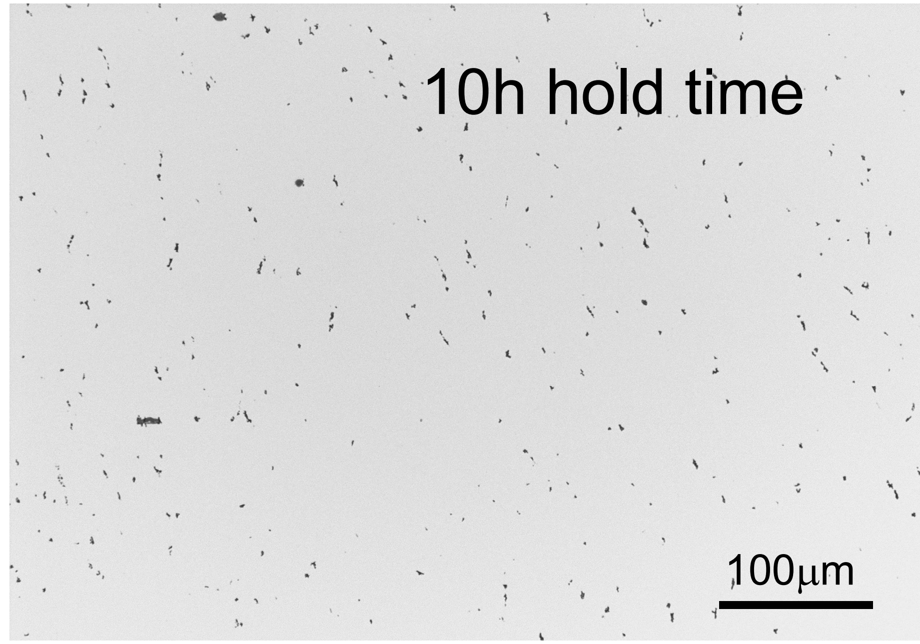




Oxide scale at specimen surface

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

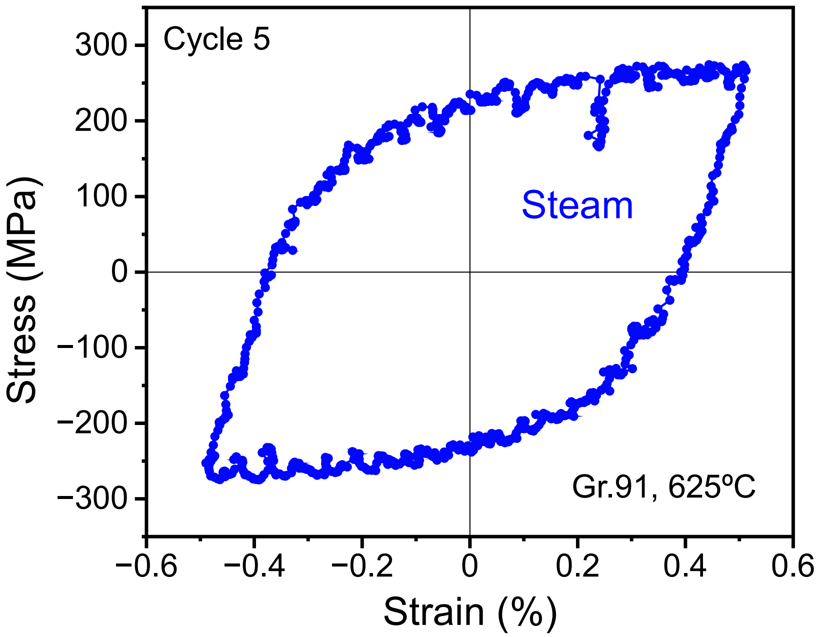




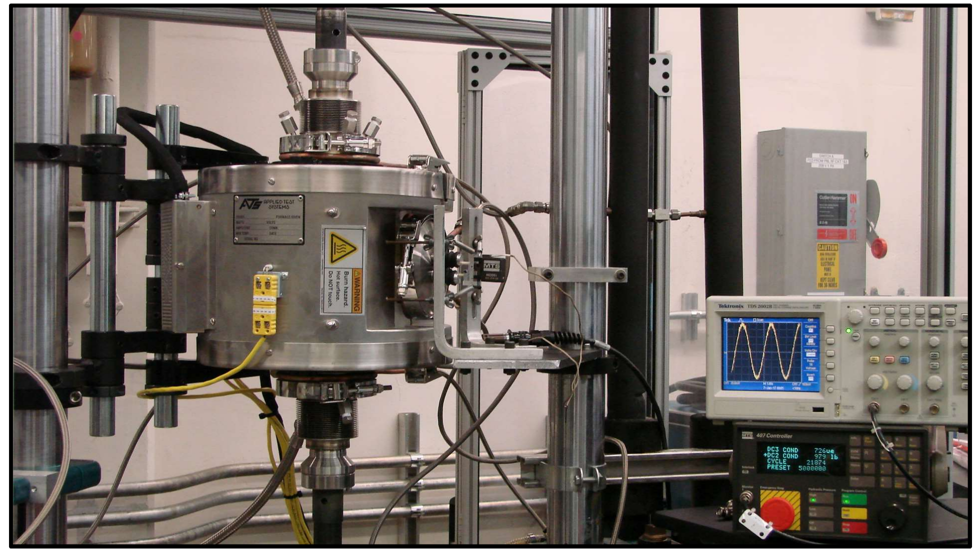
Lower cycle to failure for 10h hold time test is likely due to

- Fast crack initiation due to oxide scale cracking
- Effect of creep cavitation on crack propagation

New Test Facility to Evaluate LCF Resistance in Aggressive Environments

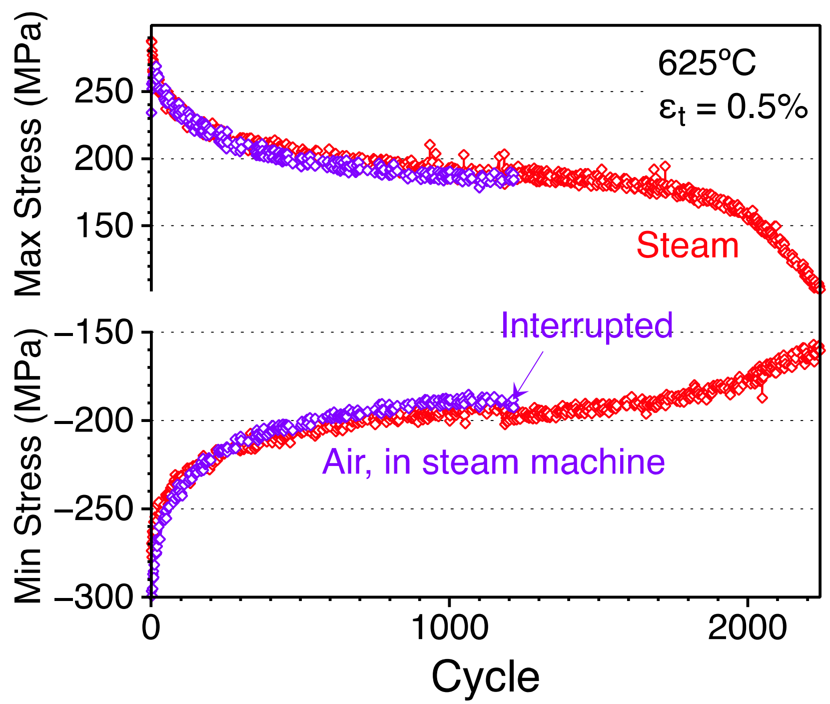


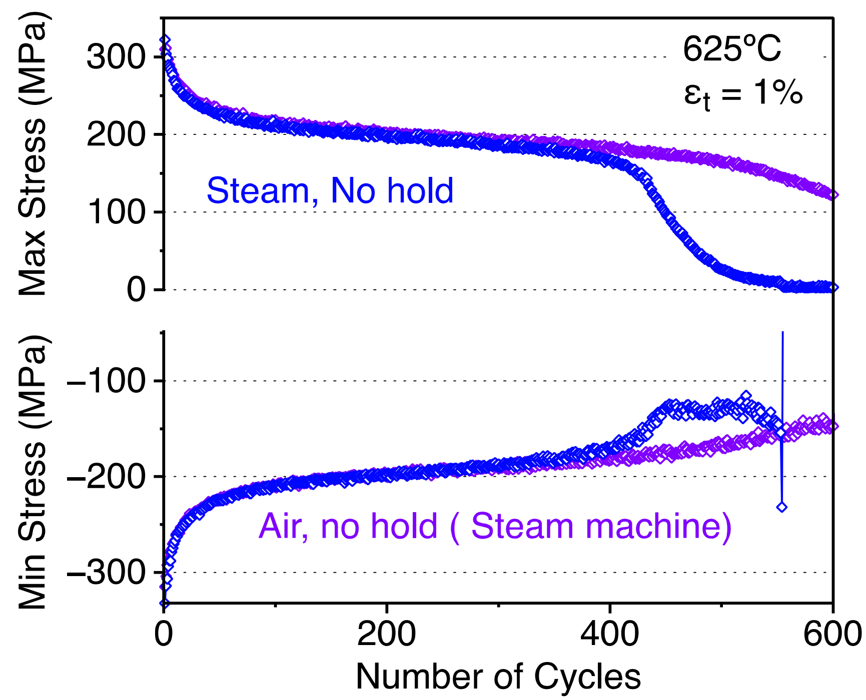
Stress-strain curve, 9Cr-1Mo ferritic steel, 625ºC, fully reversed 1% total deformation, Steam



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

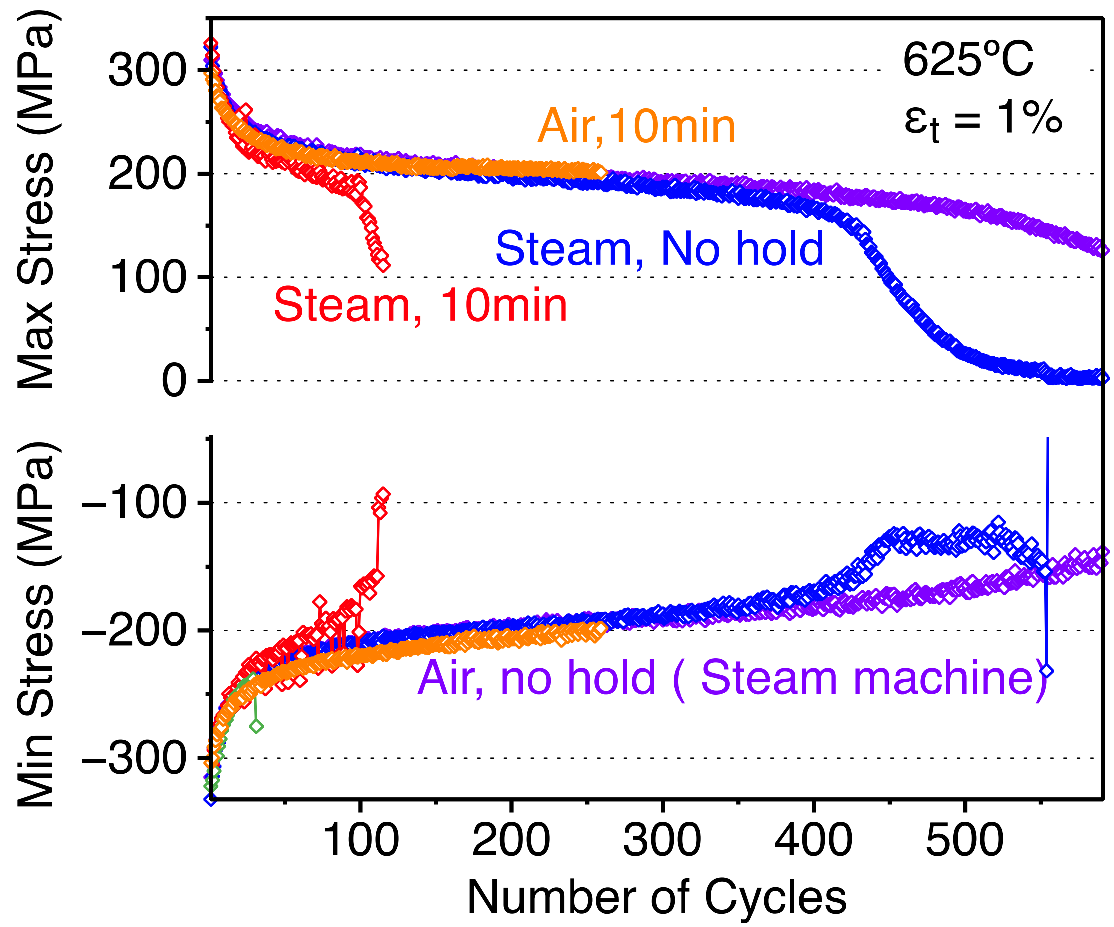
Limited Effect of Steam on the HCF Behavior of Gr.91





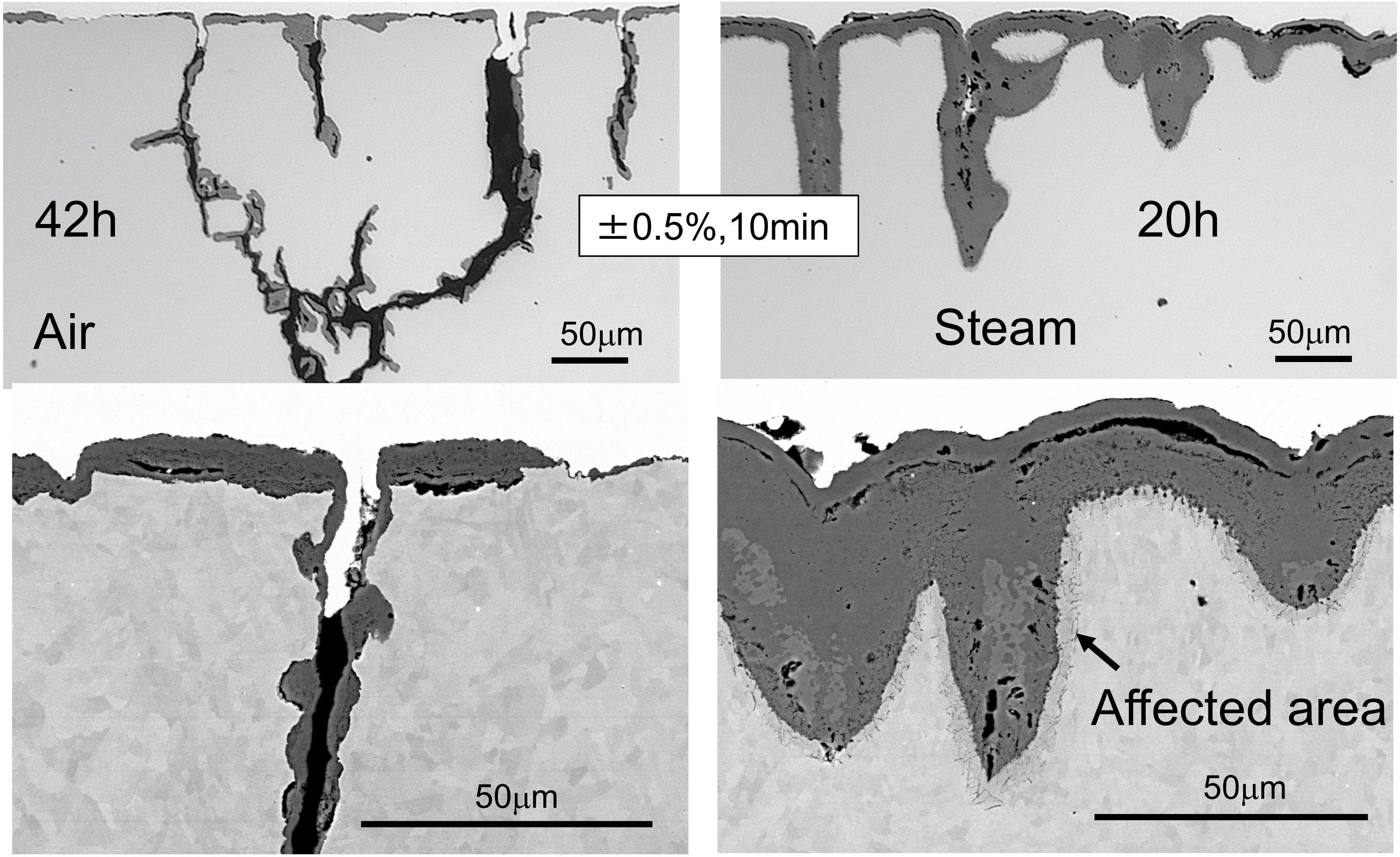
- Very similar softening in air and steam
- Gr91 oxidation rate is known to be drastically affected by H_2O
- New batch of Gr.91 alloy showing lower N_f

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

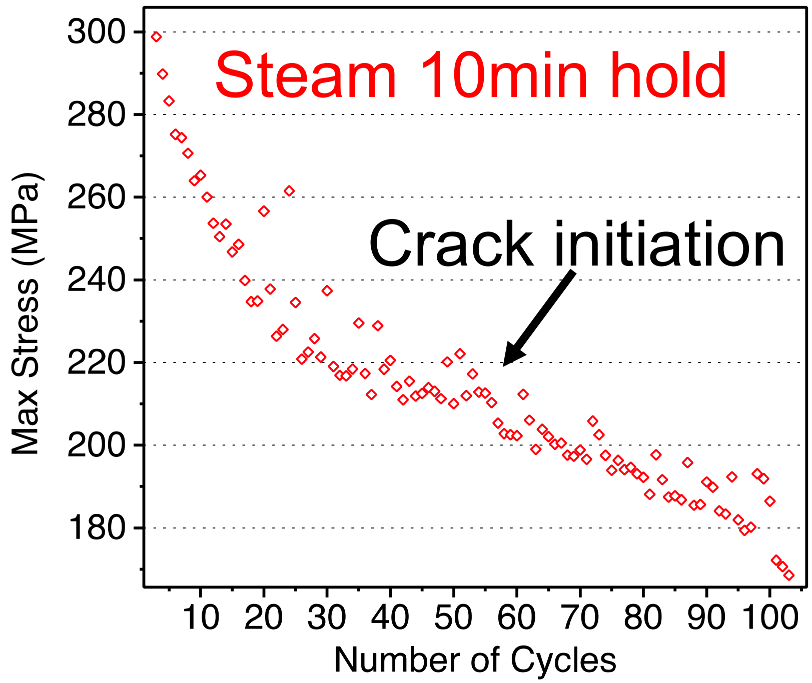


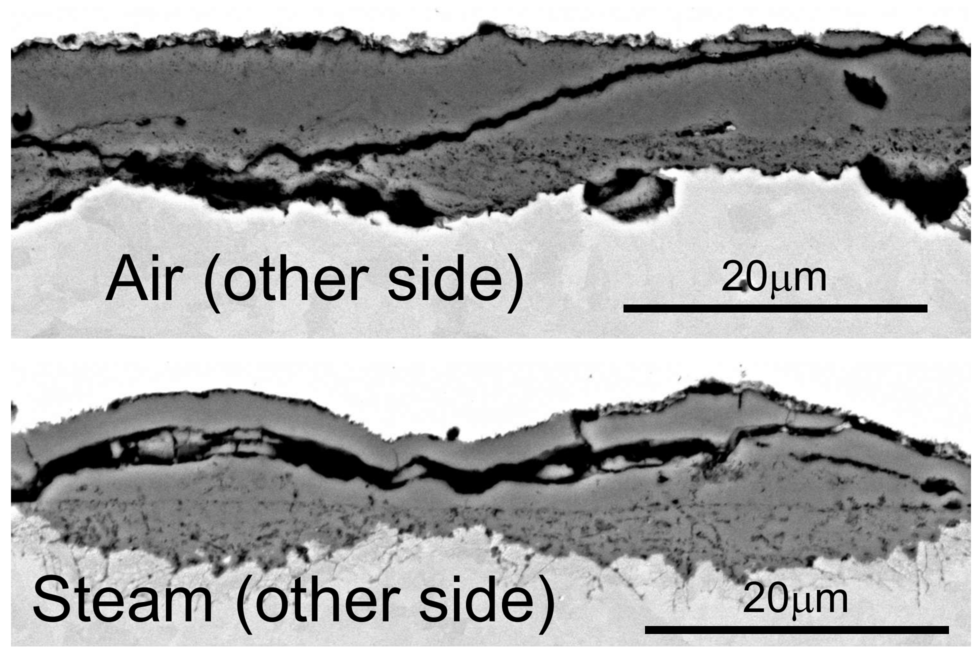
Still working on testing procedure to improve post test microstructure characterization

Very Oxidized Cracks in Steam



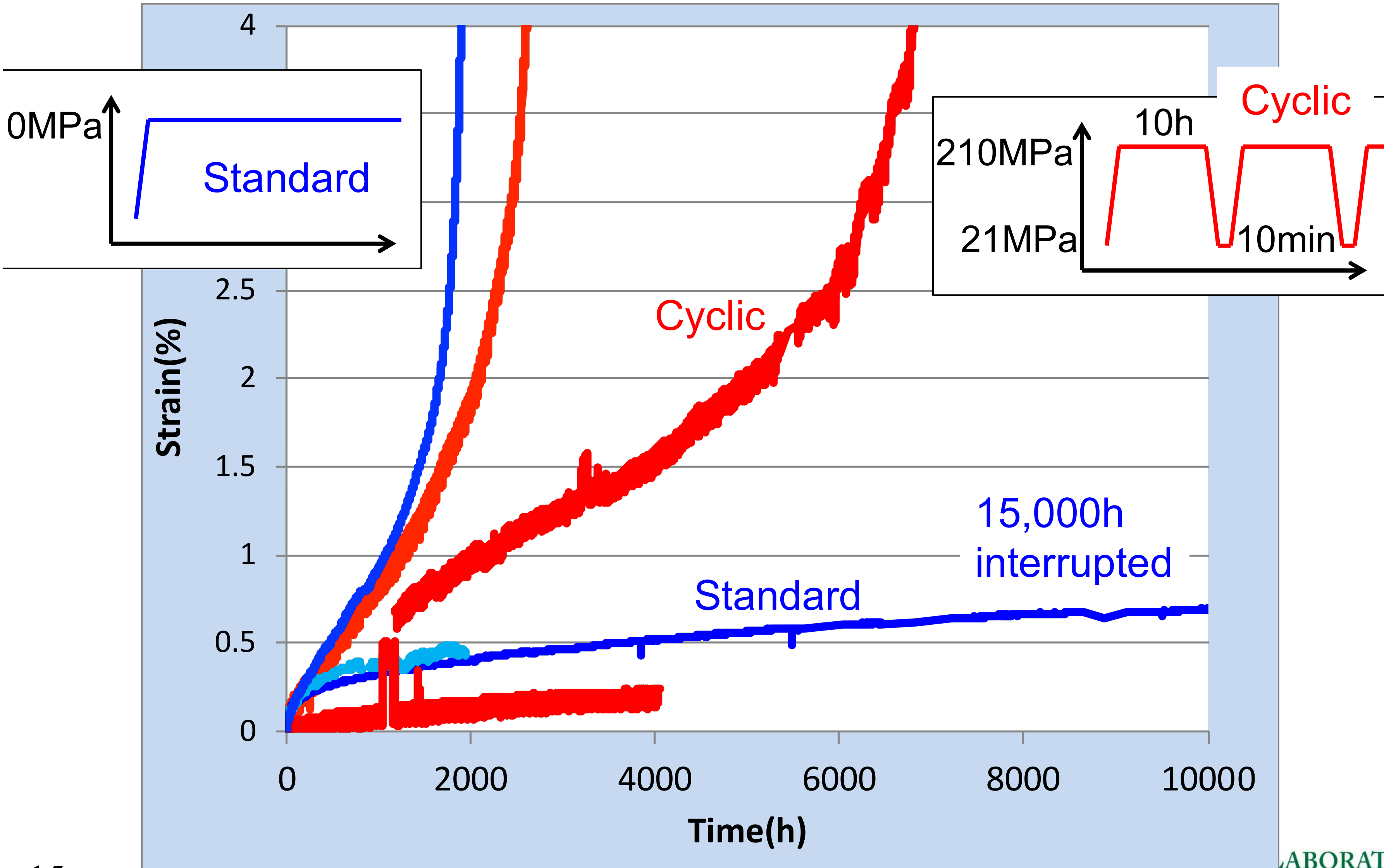
Further Curve Analysis + Upgrading the Steam Rig



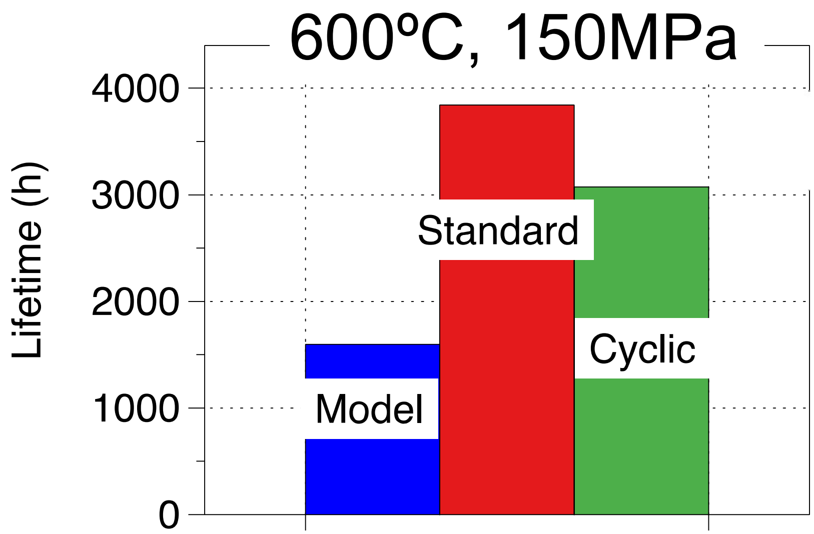


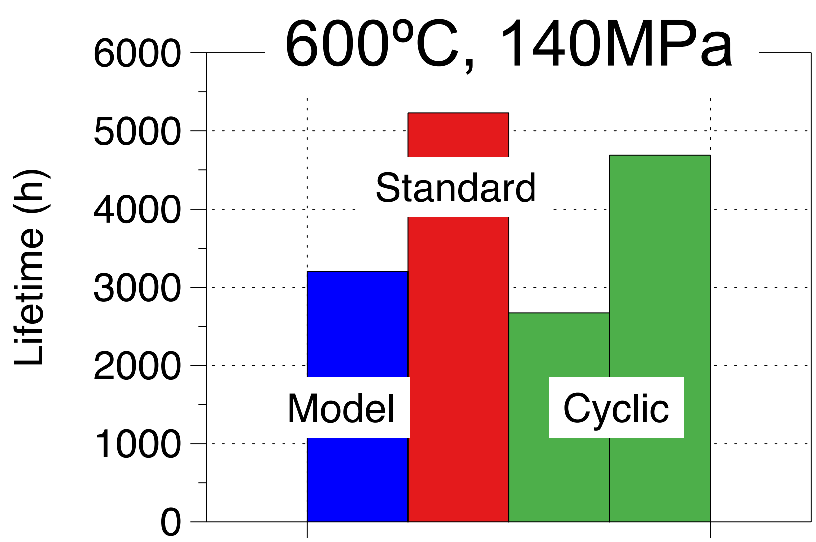
- Scale growth depends on environment and cycling time
- Fournier et al. simple assumption that crack initiates at t=0 when thicker scale is observed
- Crack initiation leads to more complex stress state
- Lowering noise + Making the steam rig operator-friendly

Limited Effect of Load Cycling on Gr.91 Creep Properties



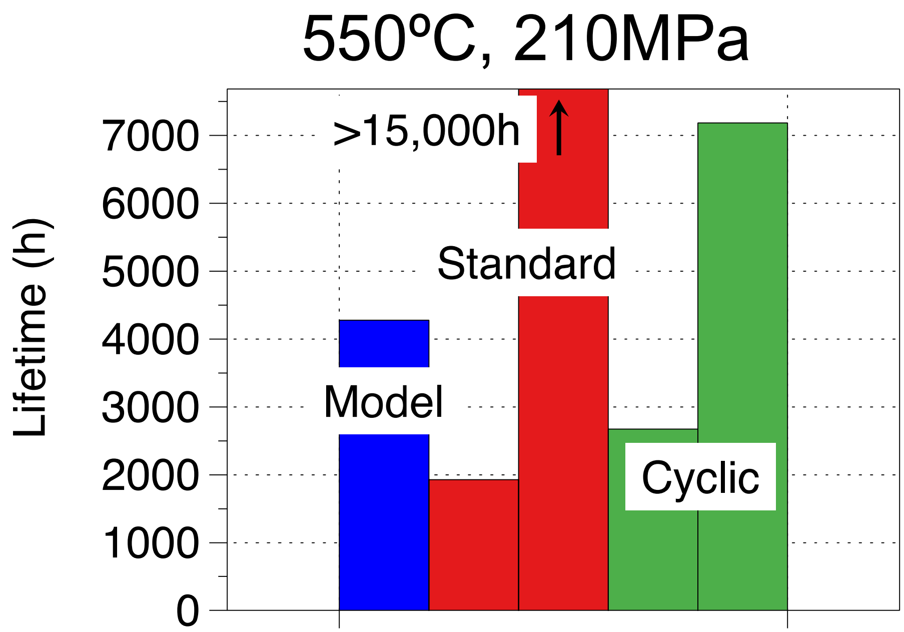
Significant Variation of Gr.91 Creep Properties





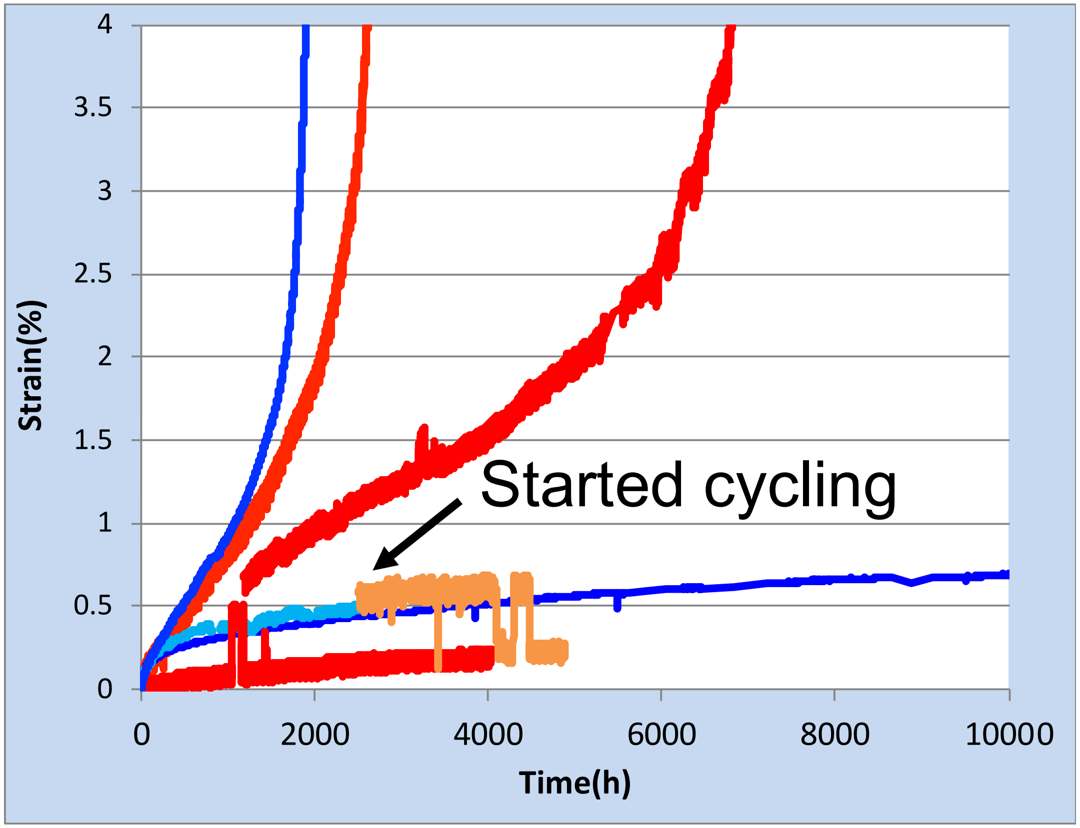
ORNL Gr.91 development program

$$\log t_r = C_h - 0.0231\delta - 2.385 \log \sigma + 31{,}080/T,$$



Leftover specimens from original Gr. 91 program

Switching from Standard to Cyclic Testing Does Not Impact Creep Rate



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

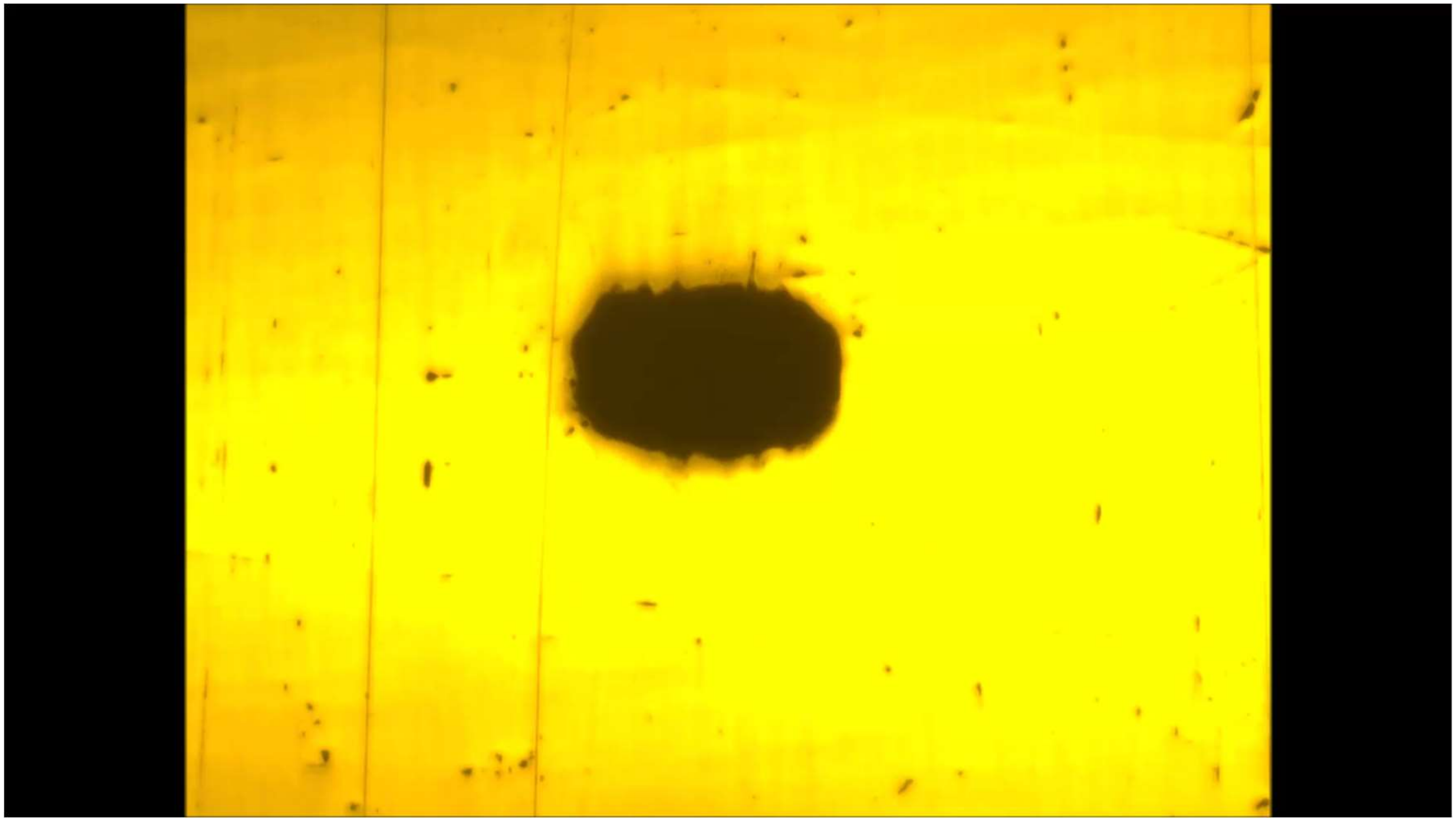
Cyclic 7.1 x10^{-5} %/h

- No effect of load cycling: cyclic damage requires strain cycling
- Best testing conditions would be fully reverse creep-fatigue testing using thermomechanical machines
- Ongoing microstructure characterization

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

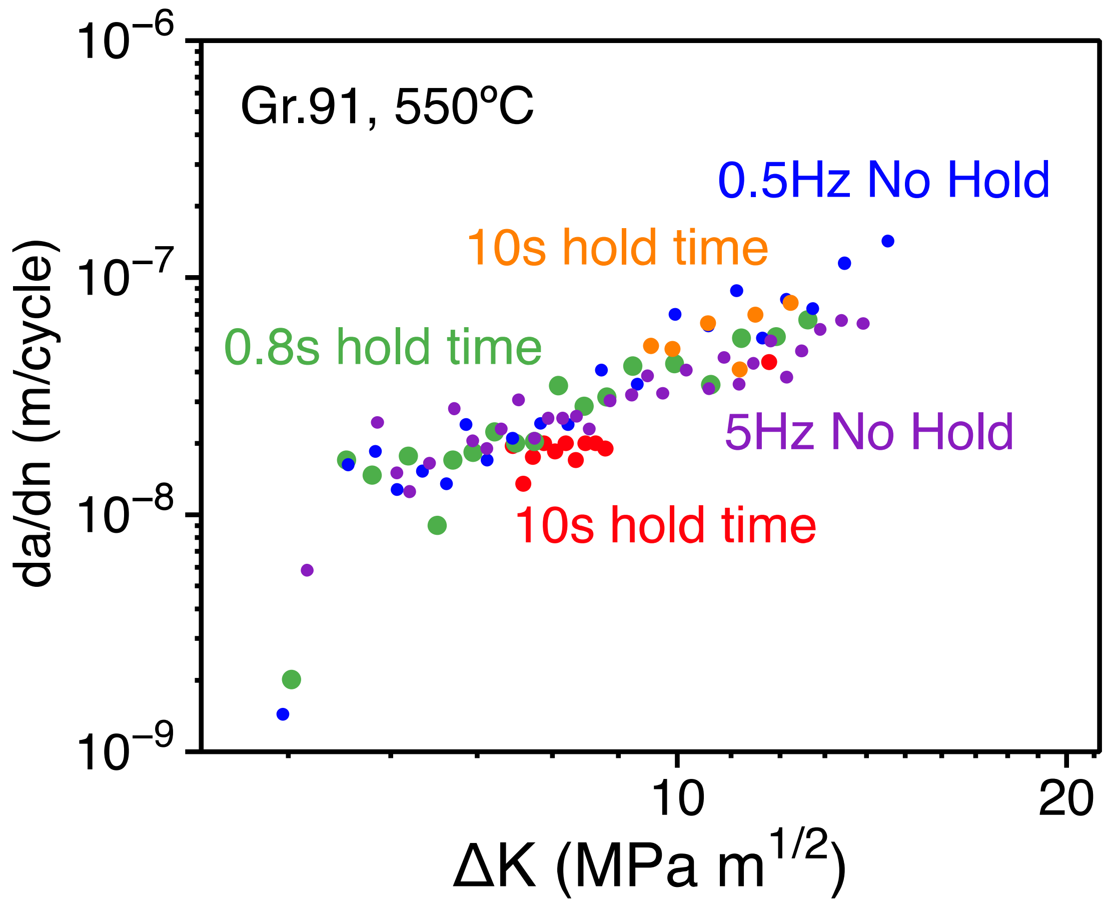
- Sumit Bahl's work (Indian Institute of Science)
- Slower propagation for small cracks
- Crack initiation at room temperature
- High cyclic fatigue & creep fatigue testing
- In Situ imaging of crack propagation
- Tests conducted at Room and 550°C

Crack Growth Imaging at Room T°C



300μm

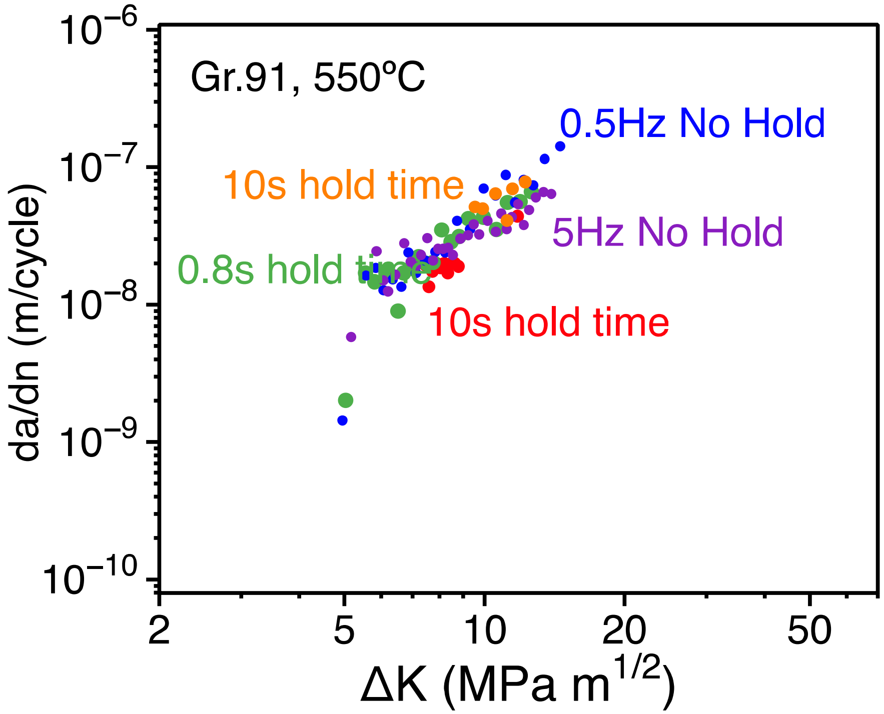
No Effect of Frequency & Hold Time on Small Crack Propagation

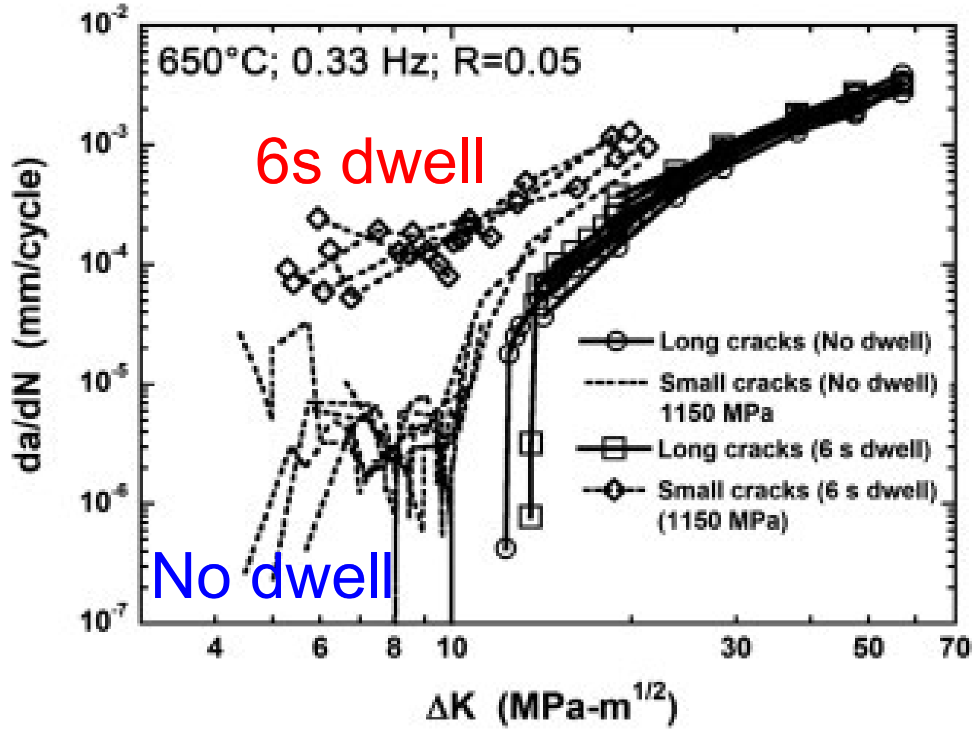


Crack arrest with 100s or 10min hold time

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



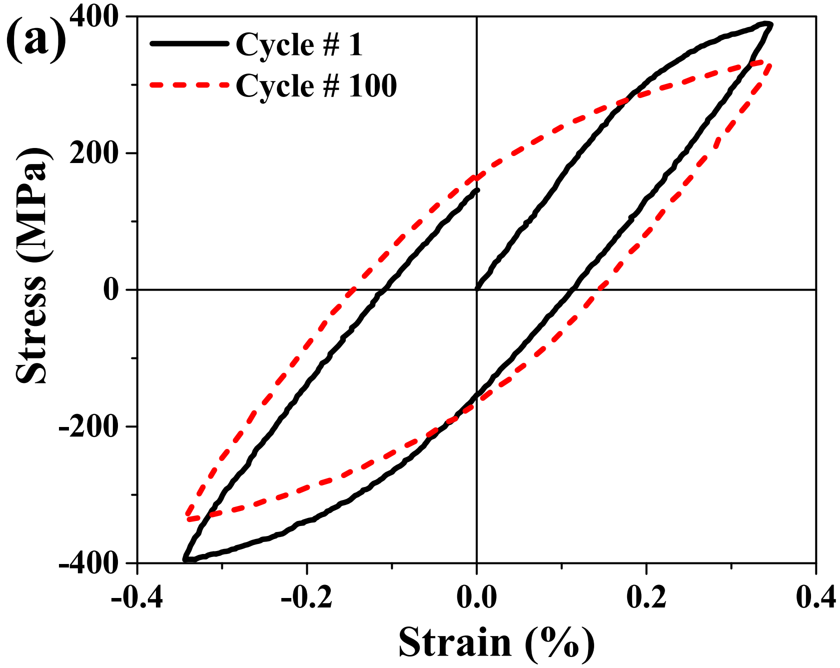


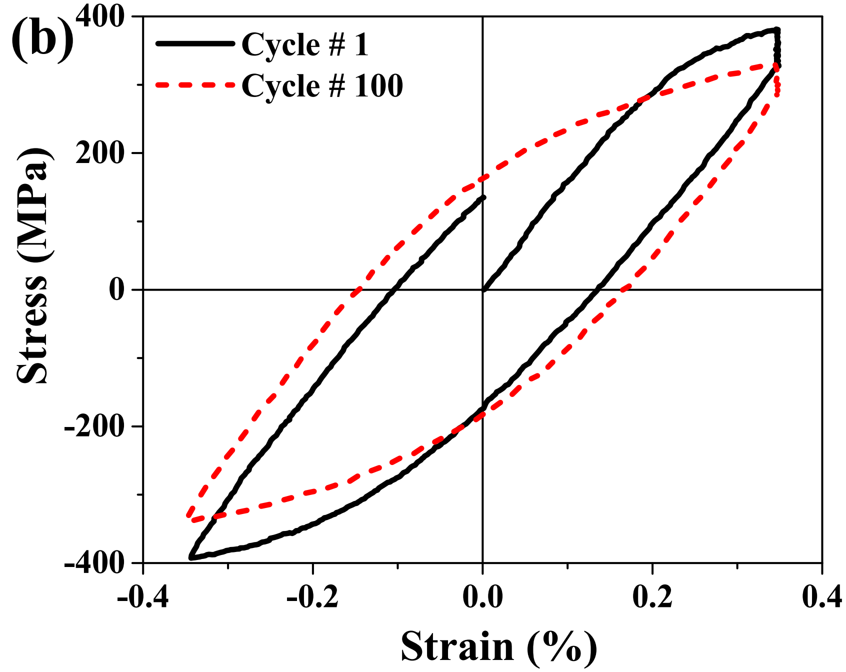
Jha and Caton, Int J Fatigue 2010
Strong effect of dwell time (6 s) in IN100

Plastic Relaxation at the Crack-tip a Possible Mechanism?

Low cycle fatigue

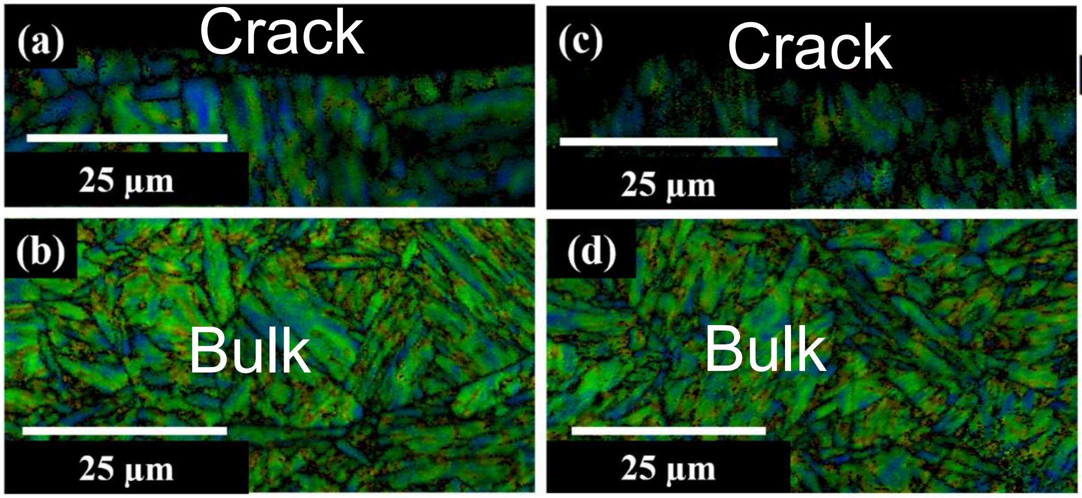
Low cycle creep-fatigue (10 s hold time)





All high temp data at 550°C

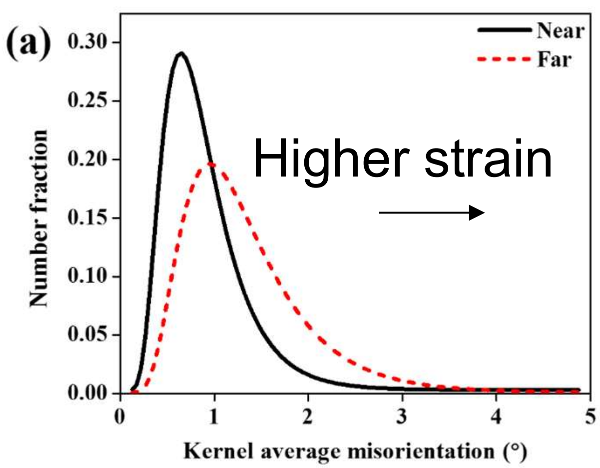
Near the racture surface the dislocation densities are lower (cyclic softening)

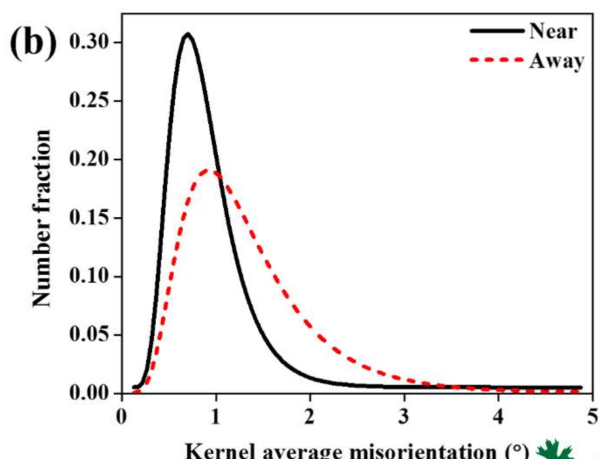


EBSD IQ + KAM maps for 550^{o}C FCG tested specimens

No Hold

1s hold time





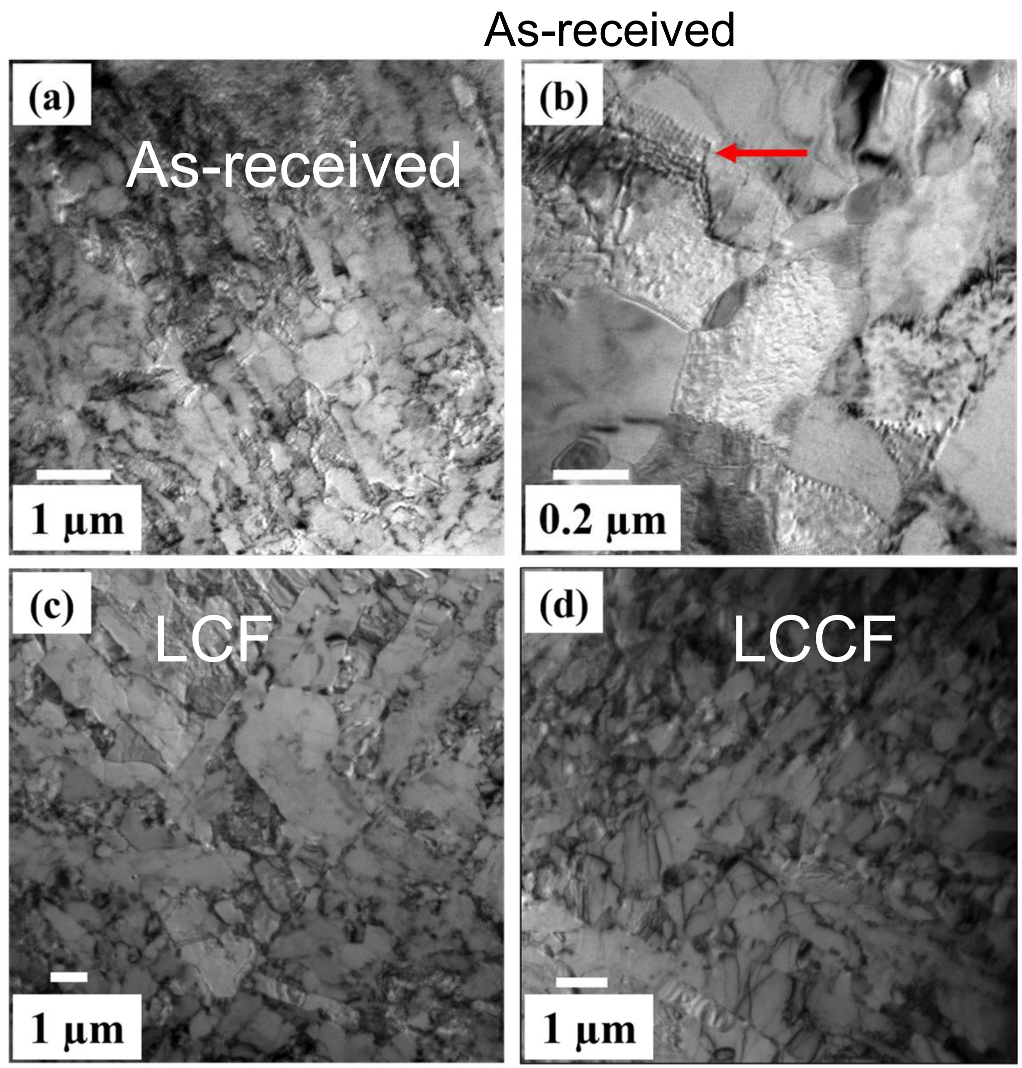
Faster decrease of dislocation density at crack tip for creep-fatigue specimens?

The average sub-grain size measured using the TEM micrographs for the as-received, low cycle fatigue and low cycle creep-fatigue tested specimens (10 sec hold time) are

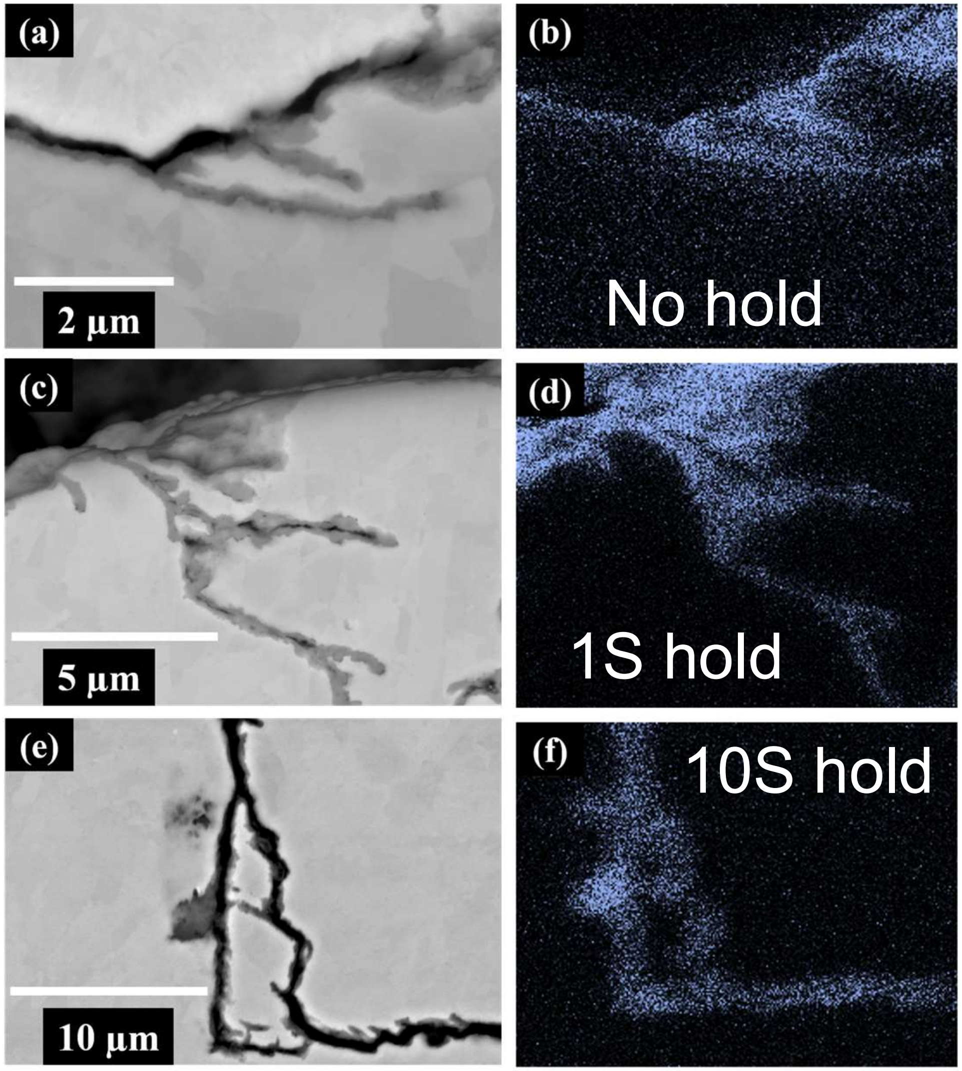
220 ± 80 nm,

310 ± 130 nm and

360 ± 120 nm.

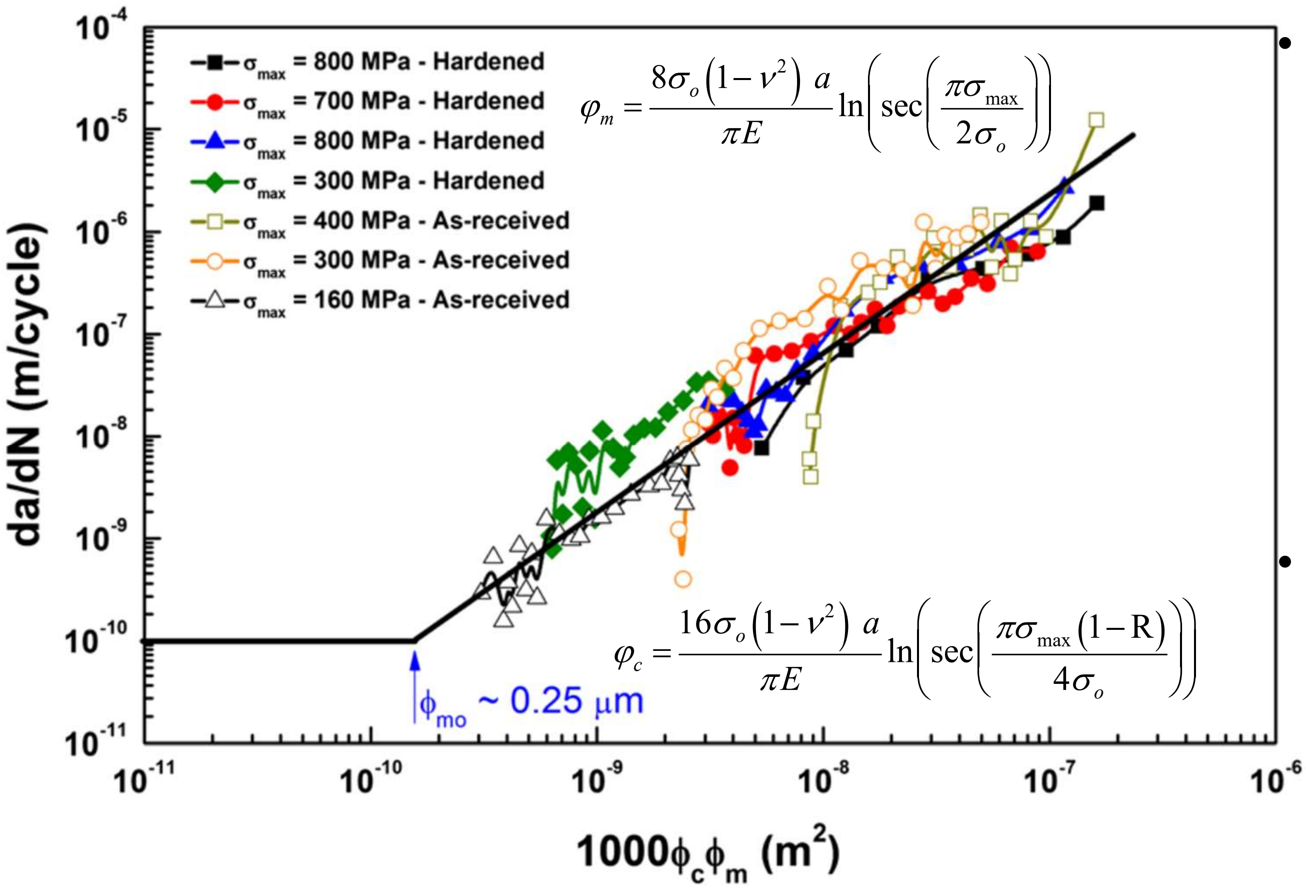


Significant Oxidation at the Crack Tip During Testing



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

Modeling can show why 3 factors are important



- Stress relaxation may reduce monotonic crack tip displacement, oxide scale may wedge the crack and microstructural coarsening may reduce the crack tip displacement density
- All three mechanisms lead to reduction of monotonic and cyclic crack tip displacements that can lead to retardation and/or arrest

* Shyam et al. FFEMS 2014 for tool steels

Conclusion

Significant effect of hold time on Gr.91 fatigue lifetime

- Fast crack initiation due to oxide formation and cracking

Combined effects of strain cycling and environment. No existing model?

- Interaction between cavity formation & crack propagation

Collaboration with FEAA118 (next presentation) on modeling microstructure evolution and its effect on cavity formation

Long term cyclic creep has limited effect on Gr.91 creep strength

Relevant testing requires strain-controlled cycling with electro-mechanical machines

No effect of hold time on small crack growth

Demonstrated thermo-mechanical testing

Temperature variation during hold time