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

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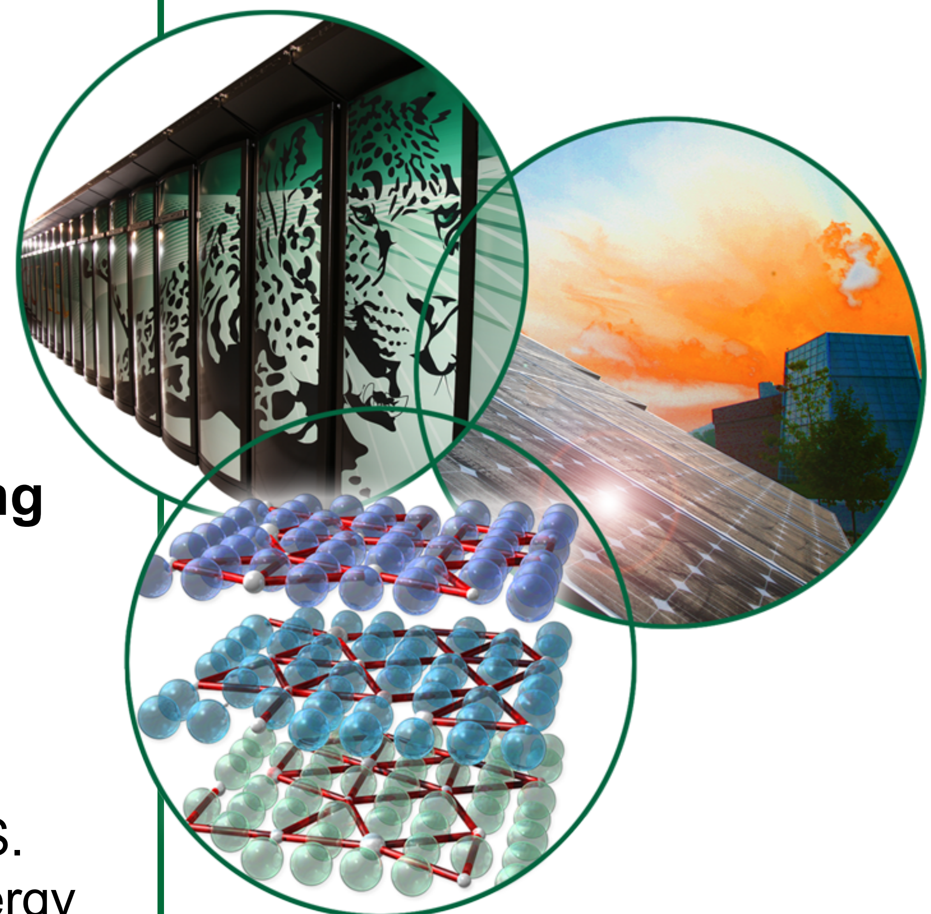

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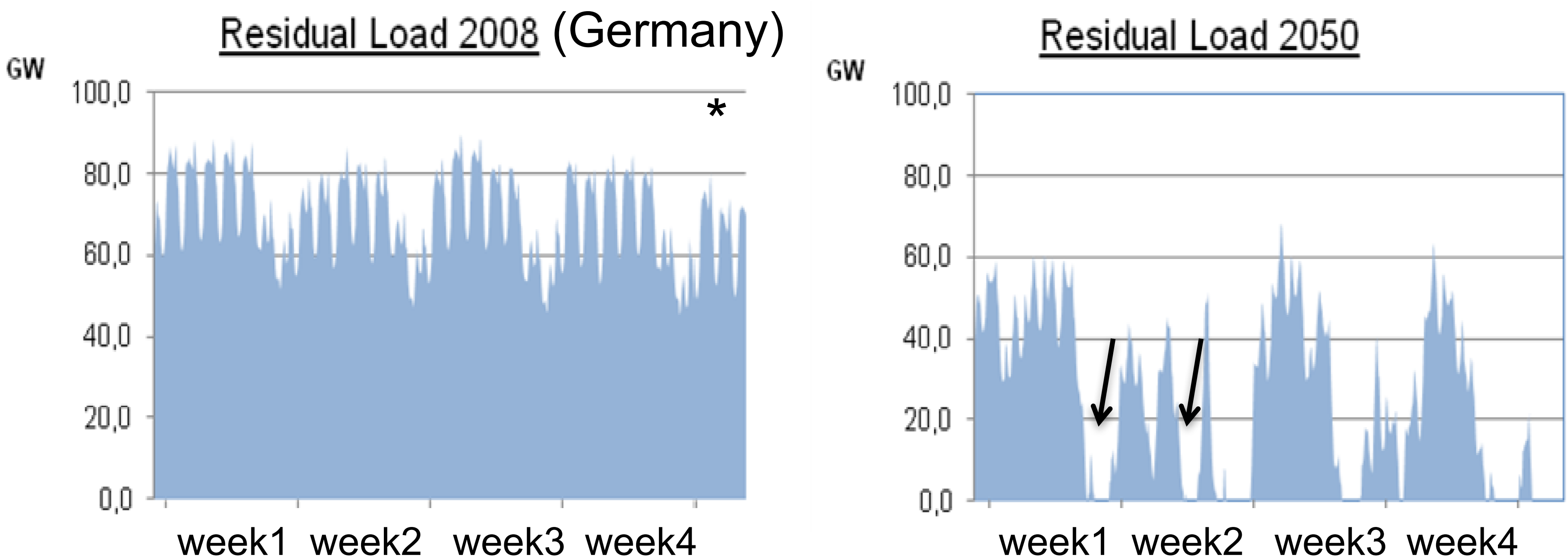
Projects Goals & Objectives

- **Long term creep fatigue testing and lifetime modeling**
- **Interactions among creep fatigue and oxidation**
- **Study of microstructurally small cracks under creep-fatigue loading**

- Submit an open-literature paper on the development and propagation of microstructurally small cracks **03/31/17 met**
- Perform at least three strain-controlled creep-fatigue tests in steam **02/15/17 met**
- Develop a creep-fatigue lifetime model in air based on long term data + small cracks **06/31/17 and steam In progress**
- ICME scheme based on the lifetime models developed to accelerate the design of creep-fatigue resistant alloys **In progress**
- Conduct at least three thermo-mechanical tests **09/31/17**

Power Plants Will Need to be Capable of Flexible Operation

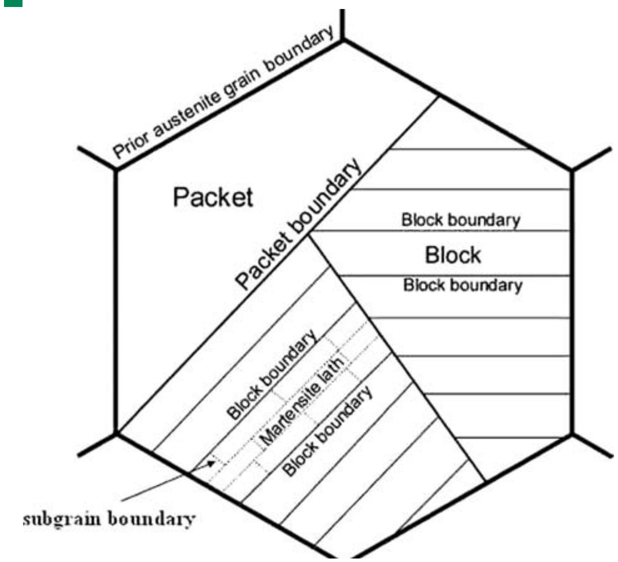


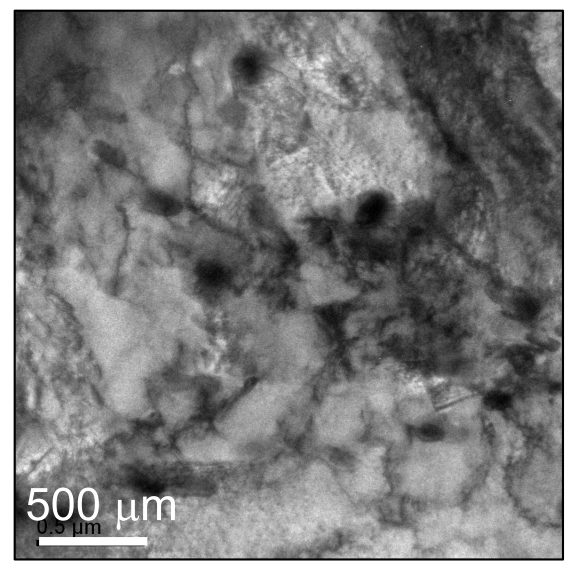
- Frequent (~daily) load cycling will result in significant creep-fatigue interaction

* Ralf Mohrmann, Proceedings Liege conference 2014

Microstructural Creep Damage for Gr.91 9Cr-1Mo Steel

- Subgrain coarsening 1-5
- Decrease of Dislocation Density 1-5
- Particle coarsening (MX, $M_{23}C_6$) 1-5
- Cavitation at GB 4-5
- Lave/Z phase formation 3
- Depletion of solid-solution elements 1
- Oxidation?





1 Semba et al. MHT (2008), 2 Orugandi et al. Acta Met (2011),3 Sawada et al. MSE (2011), 4 Gaffard et al. Int jour Fat (2011), 5 Yadav et al. MSE (2016)

Interaction of Creep & Fatigue Damages

- Sub grain coarsening / Dislocation density decrease.

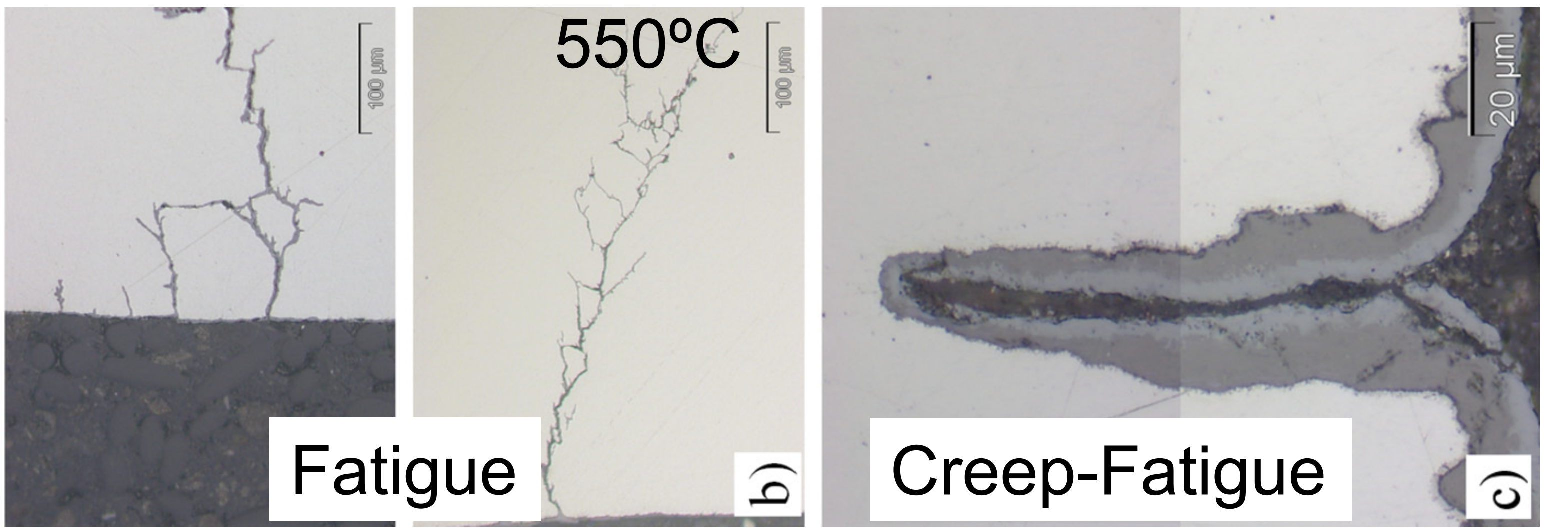
Creep performance significantly affected by strain cycling*

- Effect of oxidation on crack initiation during Creep-Fatigue

Fast initiation due to cracking of the scale and propagation in the alloy*

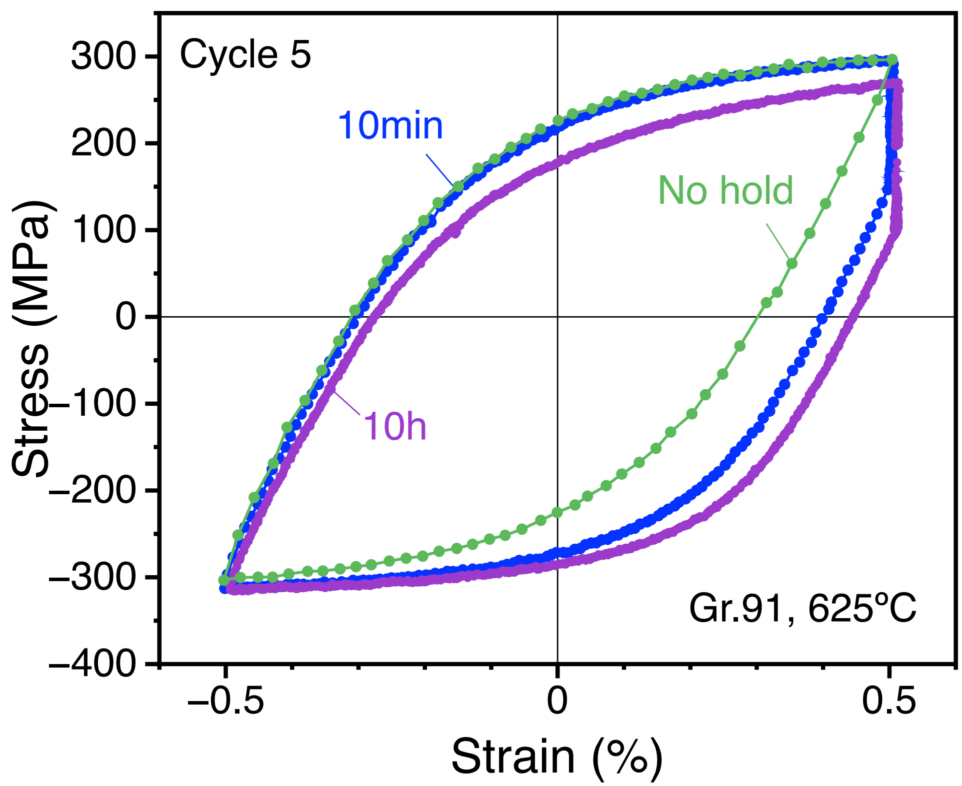
Much thicker non protective scale in air sue to cracking

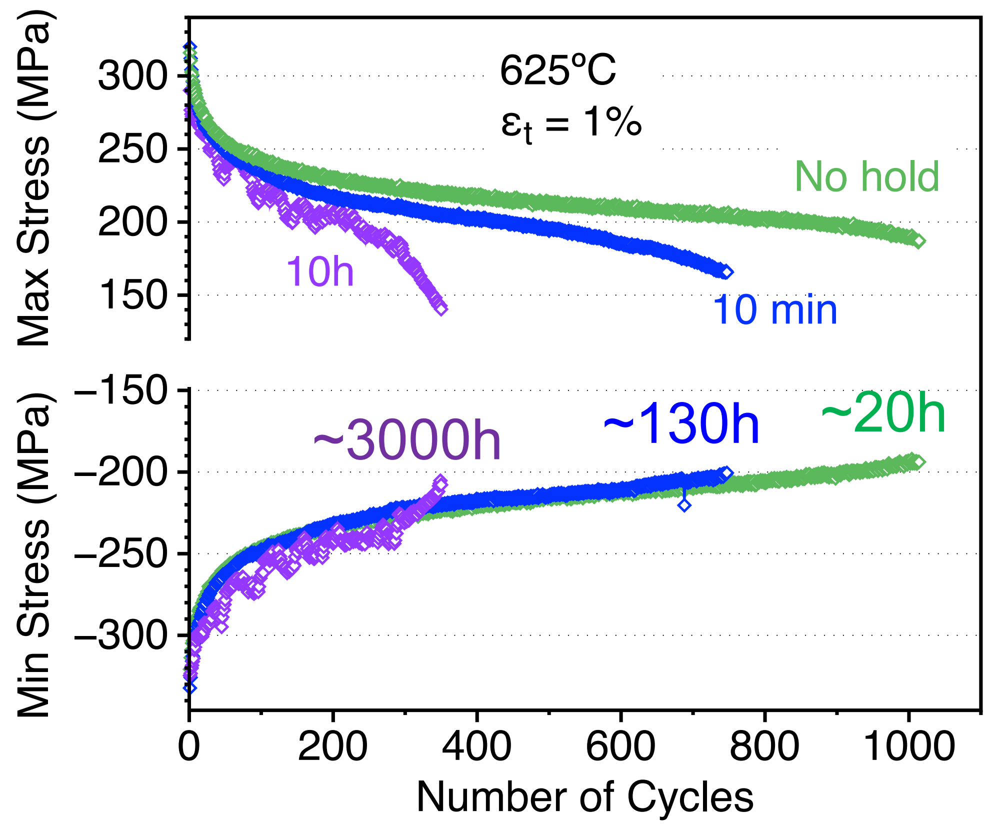
- No obvious effect of oxidation/hold time on crack propagation?



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

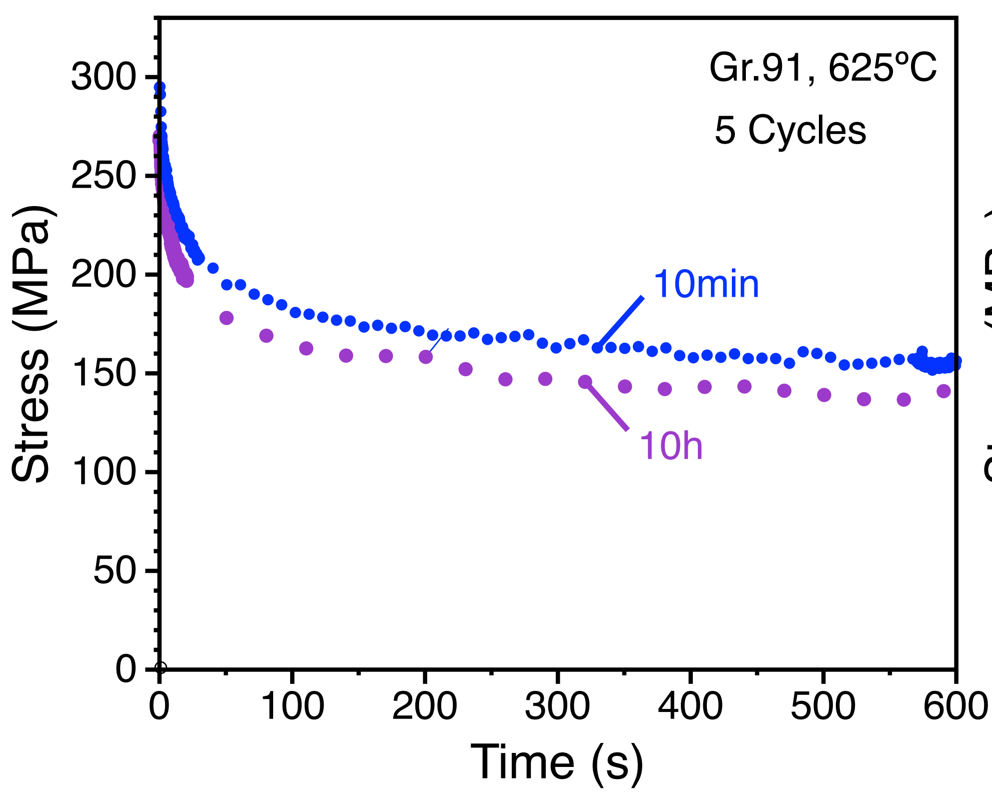
Decrease of N_f with Hold Time for Creep-fatigue Tests at 625ºC, ±0.5%

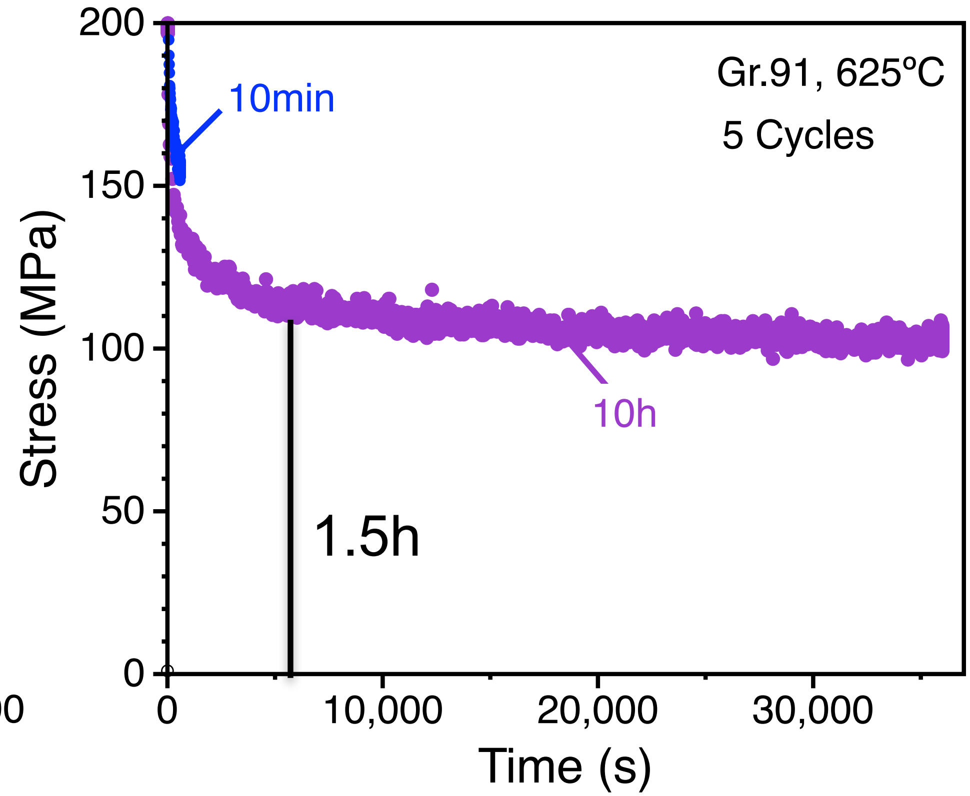




- Limited effect of hold time on softening rate
- Significant decrease of number of cycles to failure with longer hold time (>3000h test)

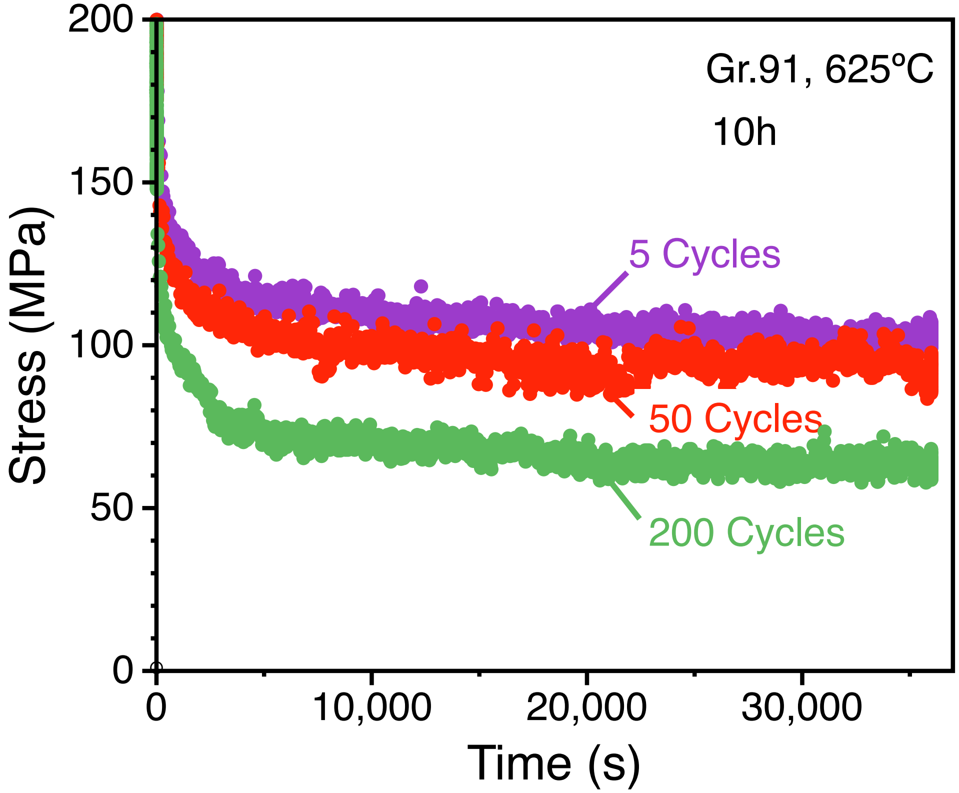
Significant Stress Relaxation During 10h Hold Time

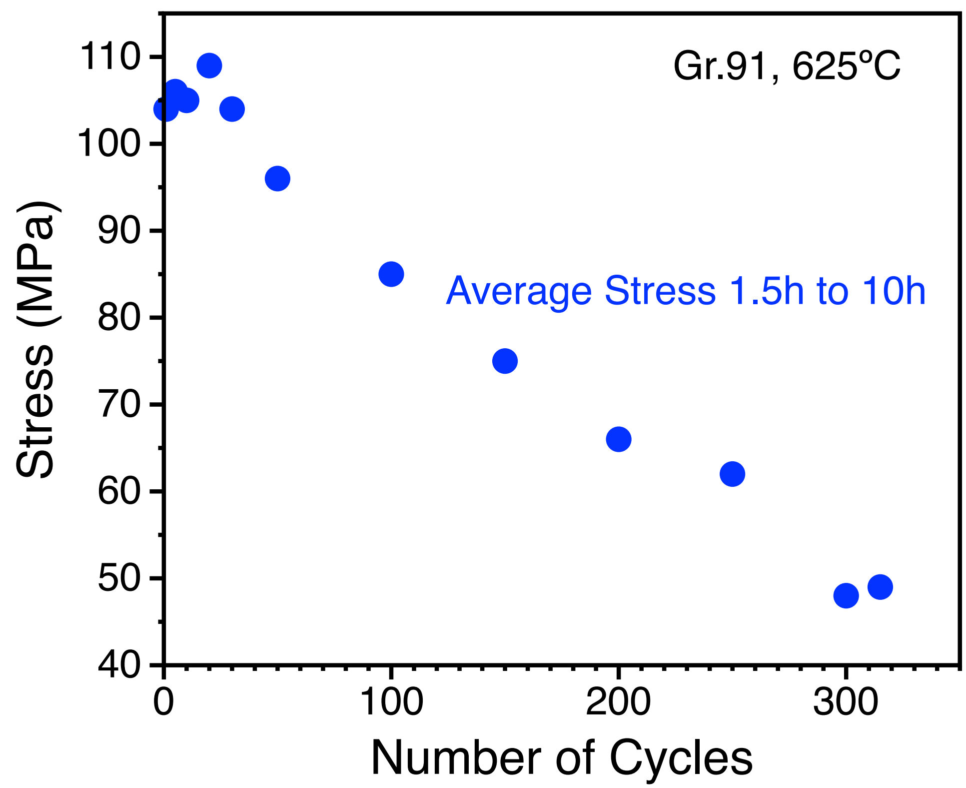




- Need ~ 1.5h to reach a nearly steady state stress
- Creep lifetime at 625ºC, 100MPa ~5000h

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





Significant effect of cycling on alloy creep behavior

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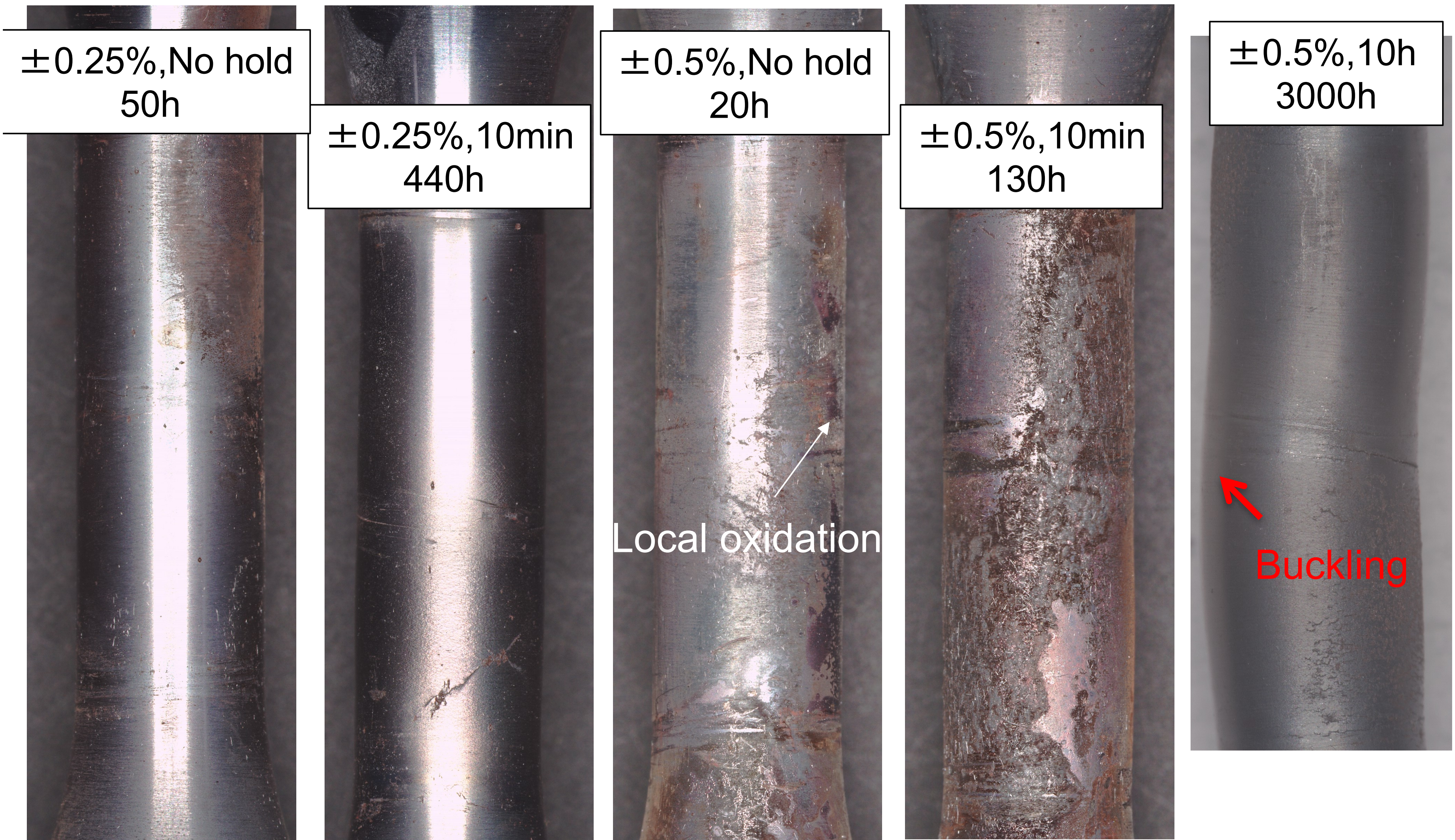
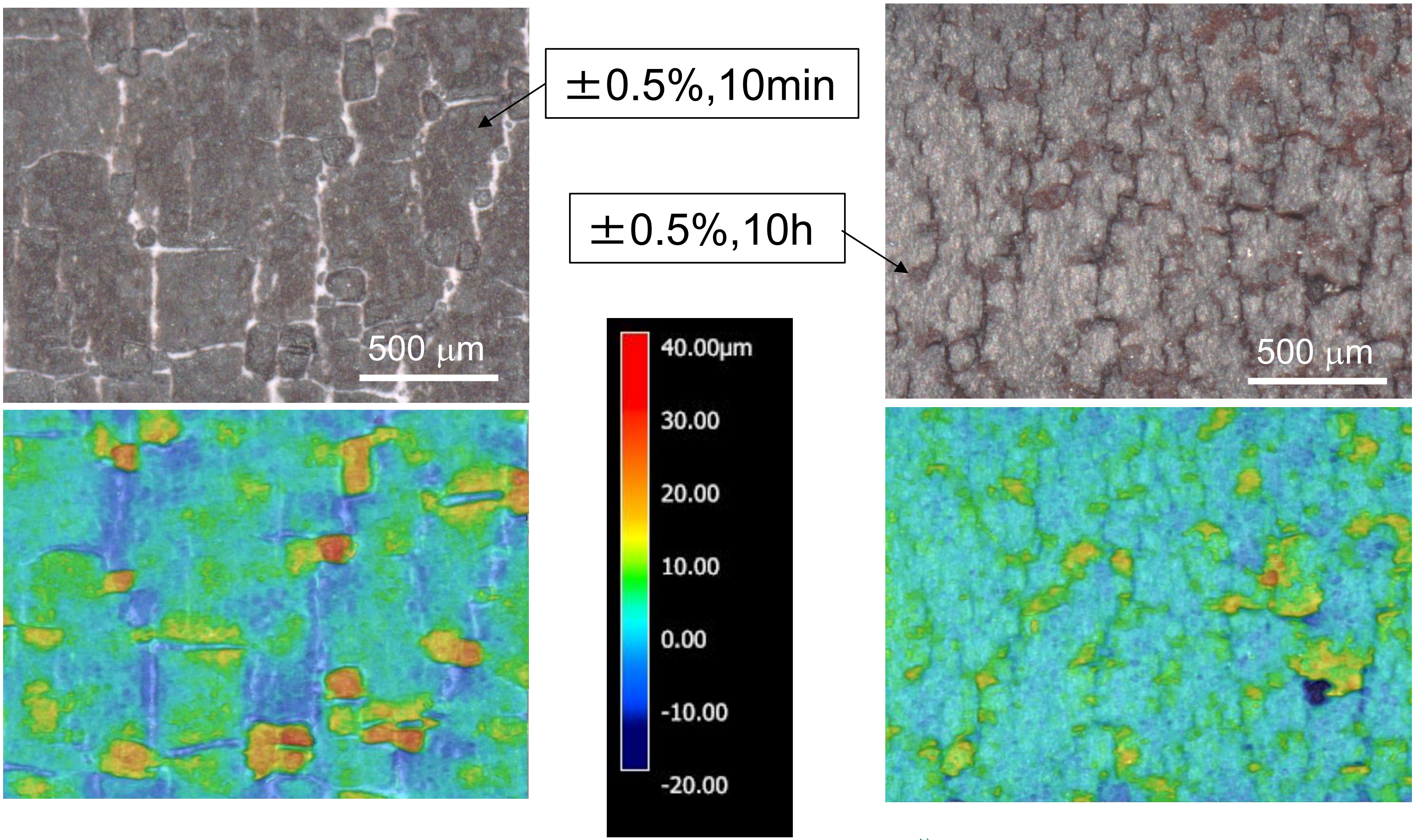
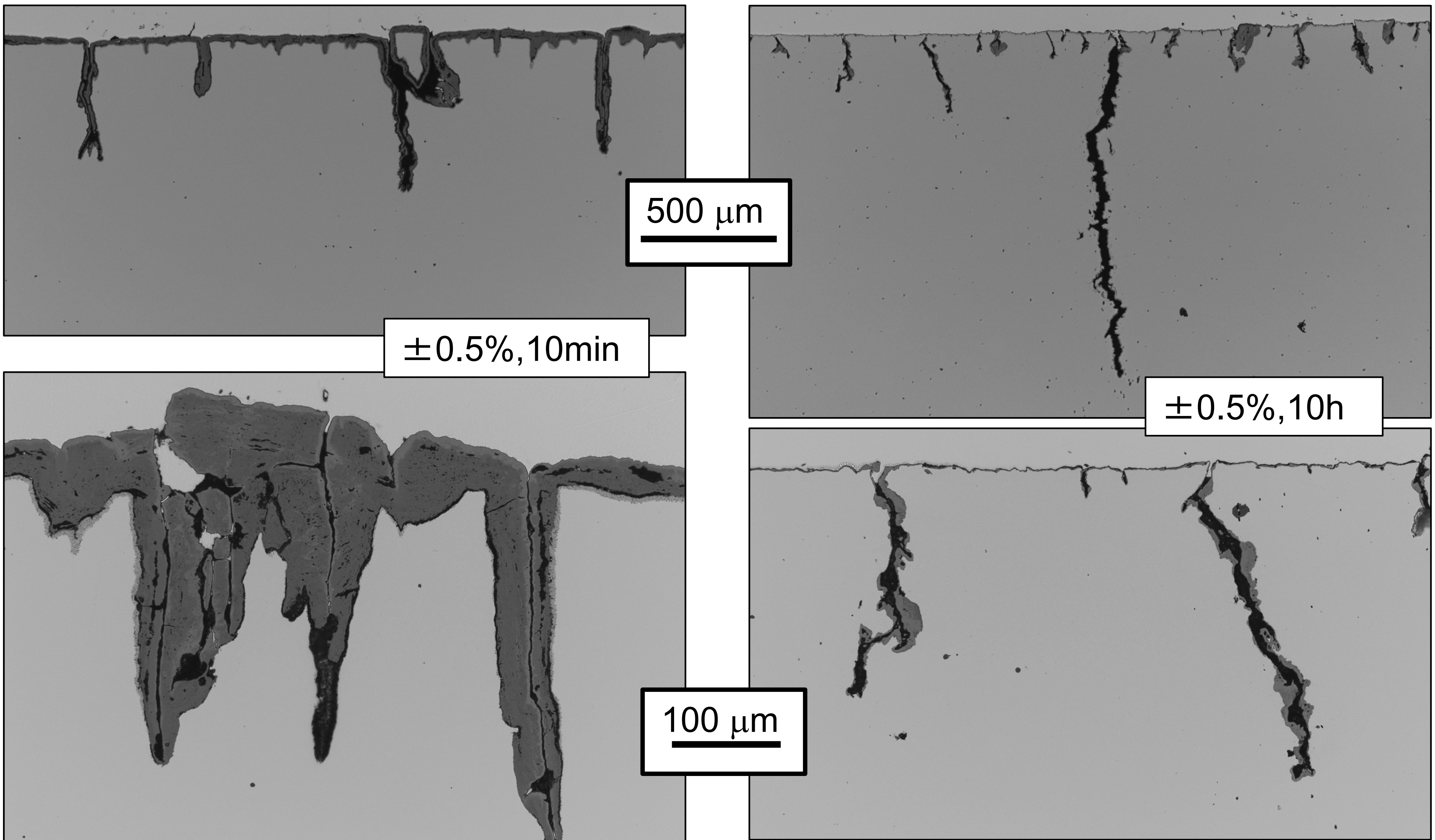
Thicker Oxide Scale for Tests in Air With ±0.5%, 10min and 10h Hold Time



Crack Pattern at 10min & 10h specimen surface. Thicker scale for 10min test

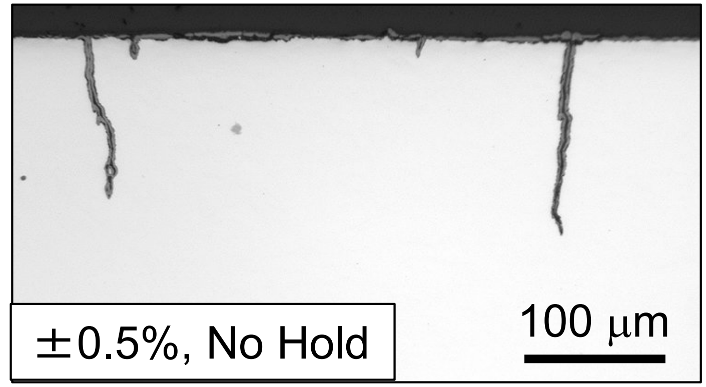


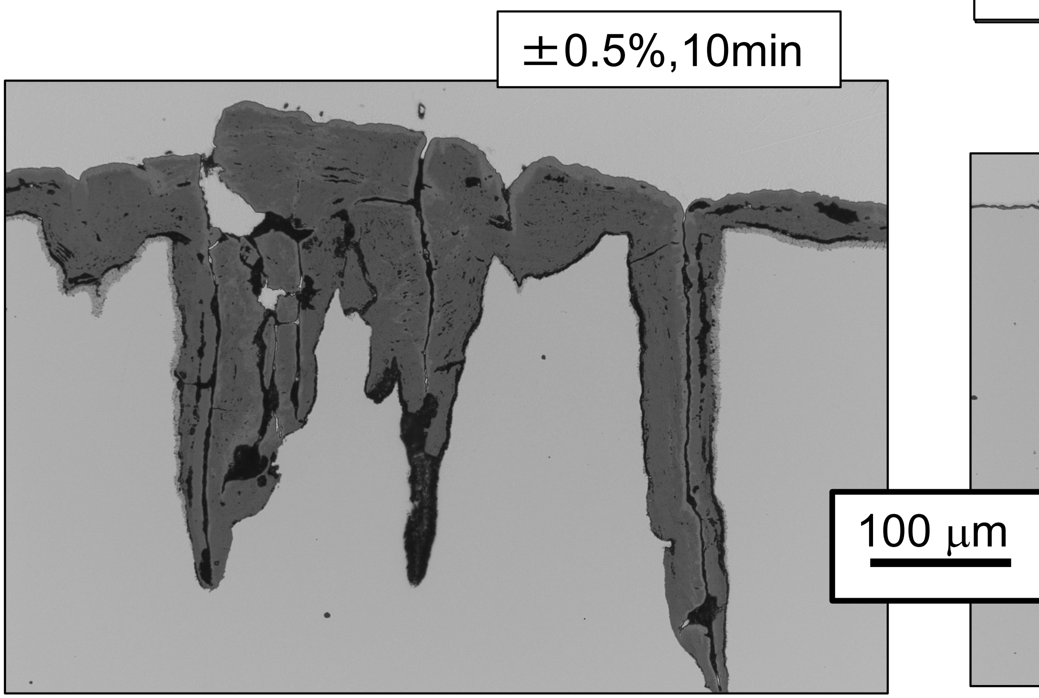
Numerous Oxidized Cracks for 10min and 10h Hold Time Tests

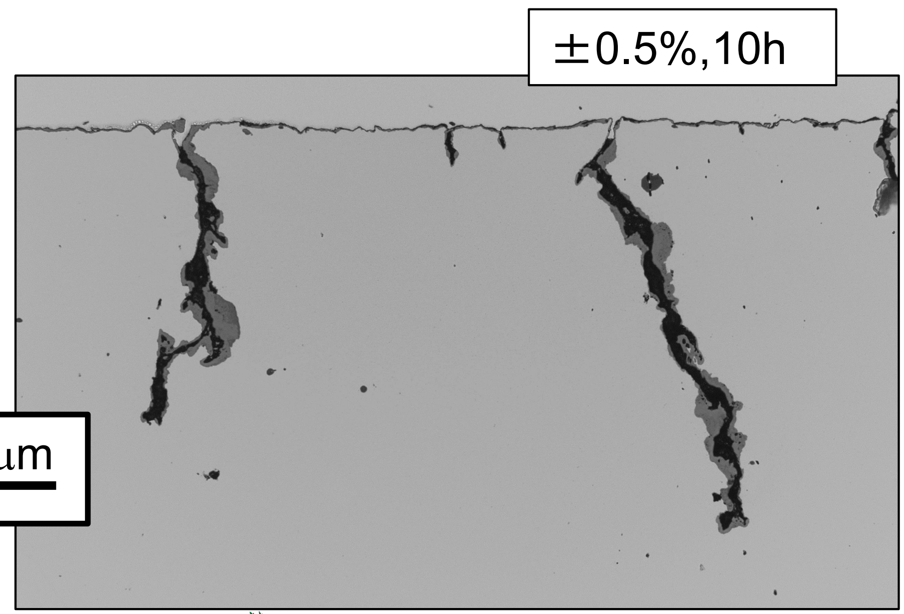


Thicker Oxide Scale for 10min Hold Time Test

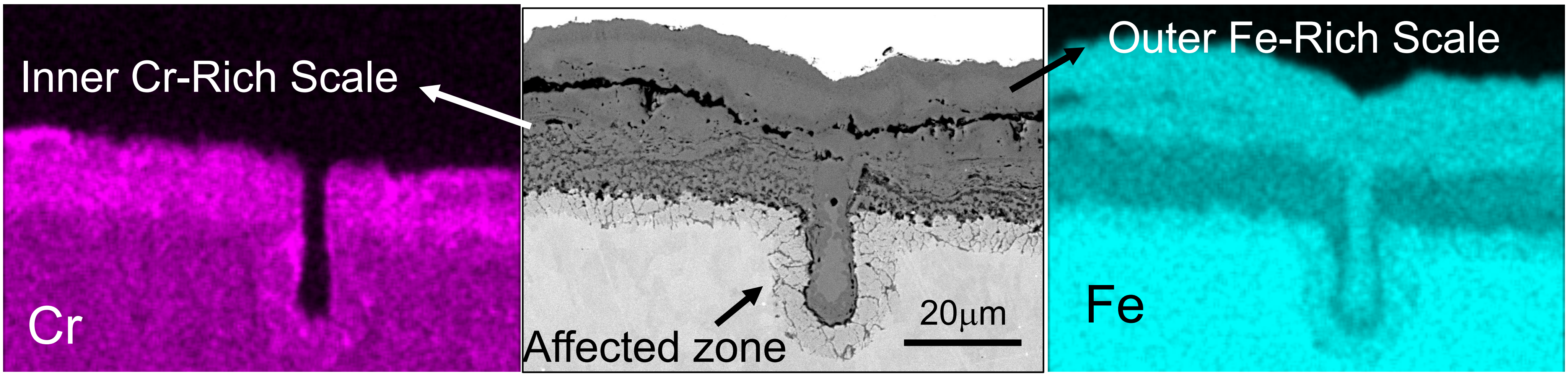
Few Localized Oxidized Cracks for Test without Hold

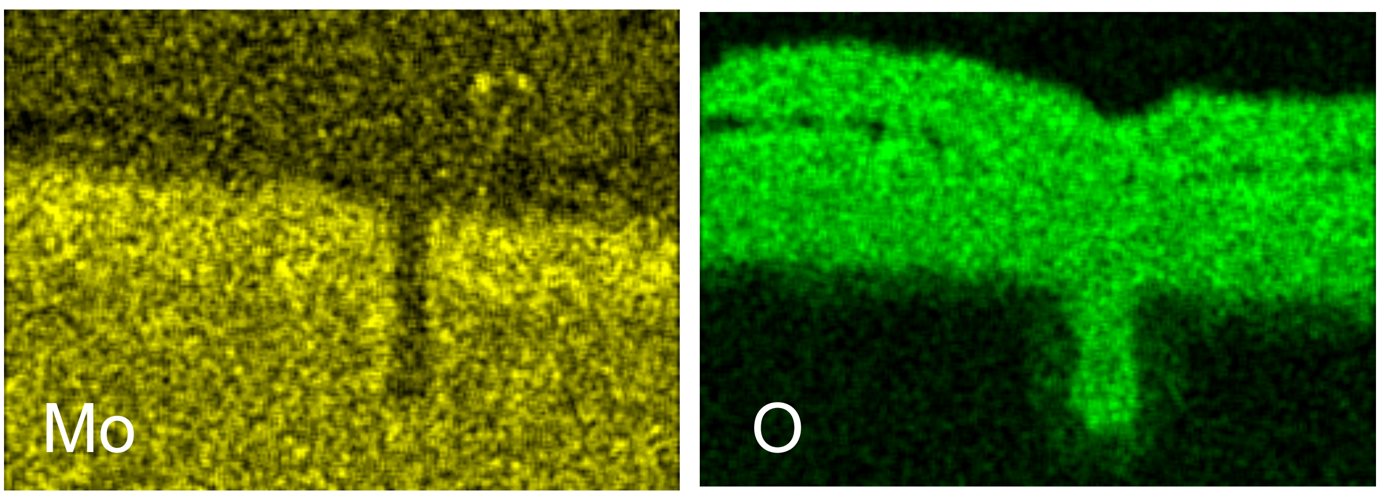






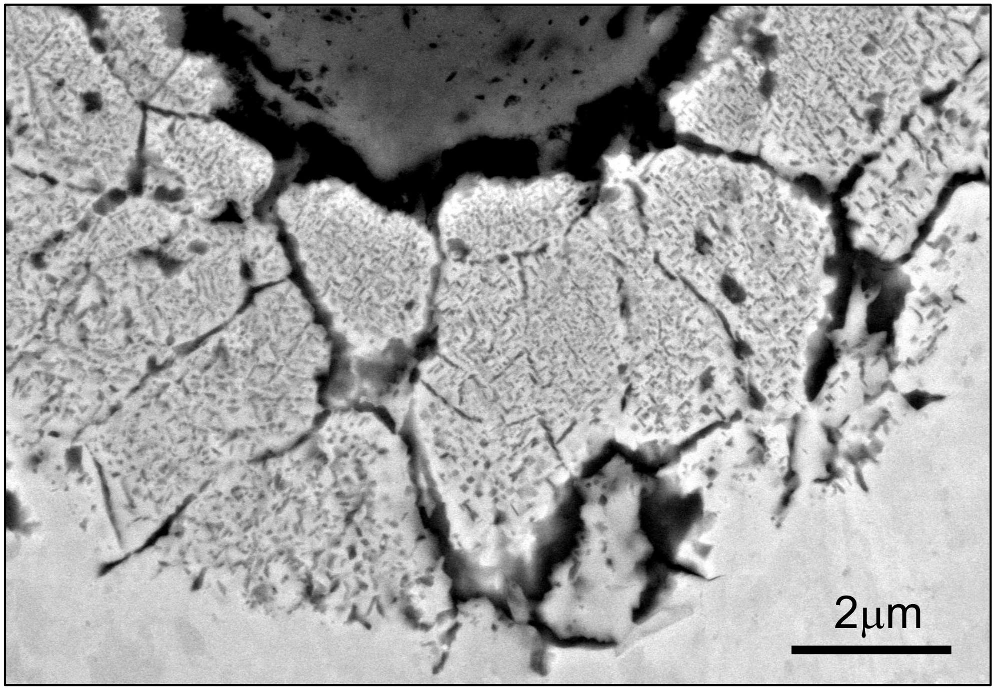
Multi-Layer Oxide Scale for 10min Hold Time Test

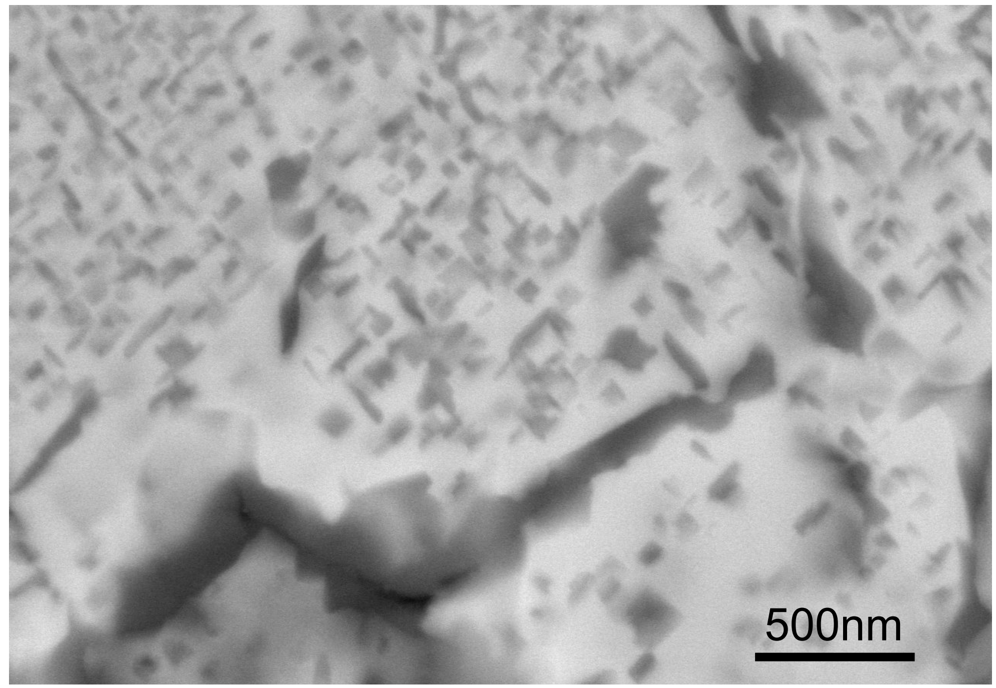




Oxide scale at specimen surface

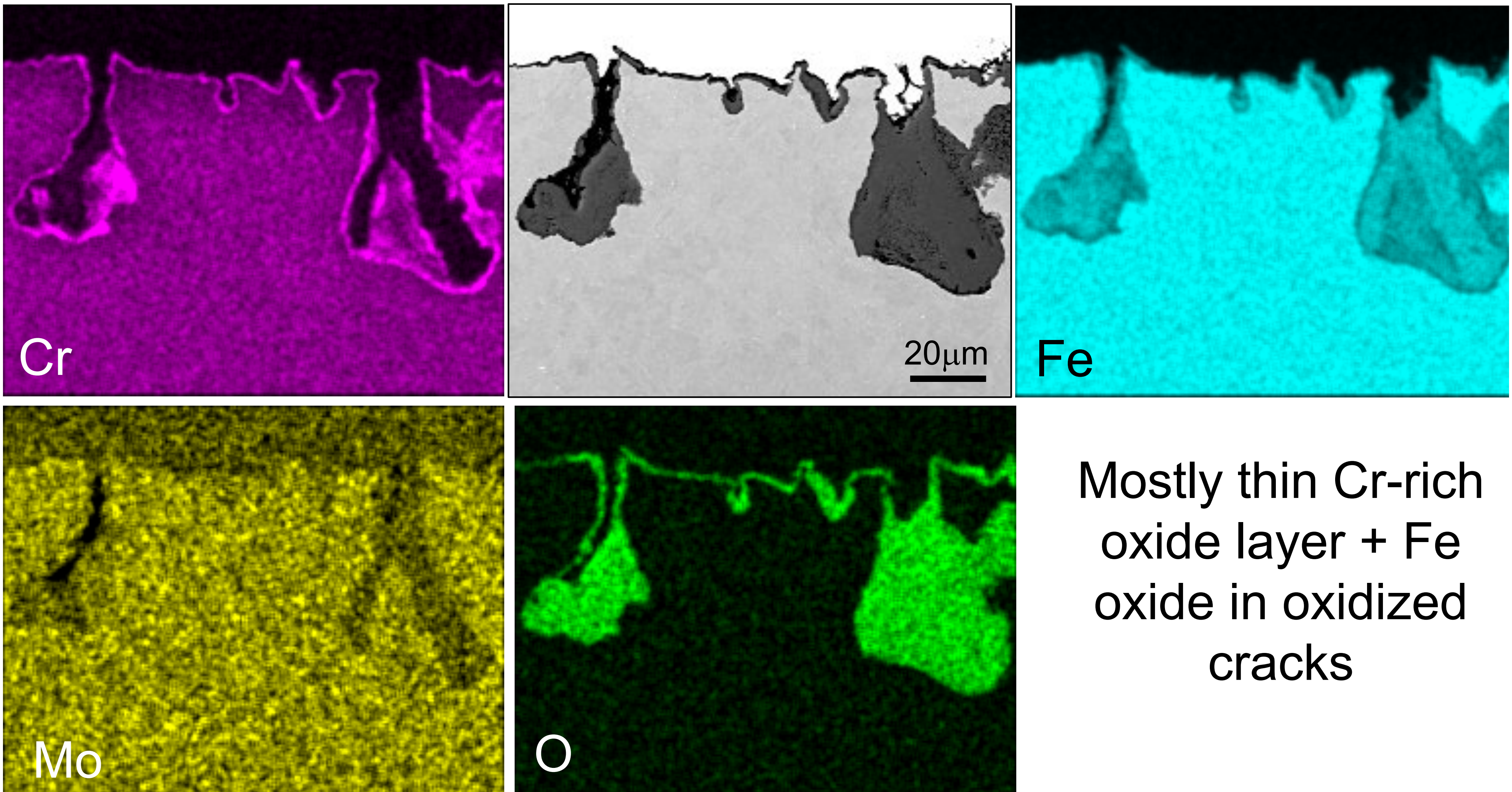
Presence of Fine Precipitates in the Affected Zone. Internal Oxidation?





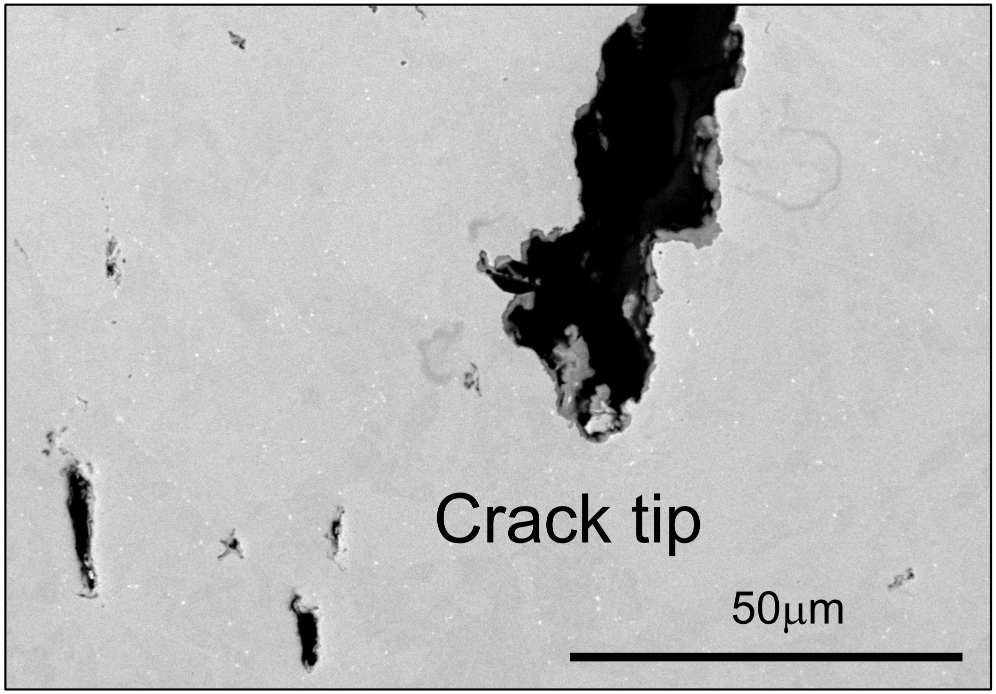
- Need TEM characterization to identify precipitates

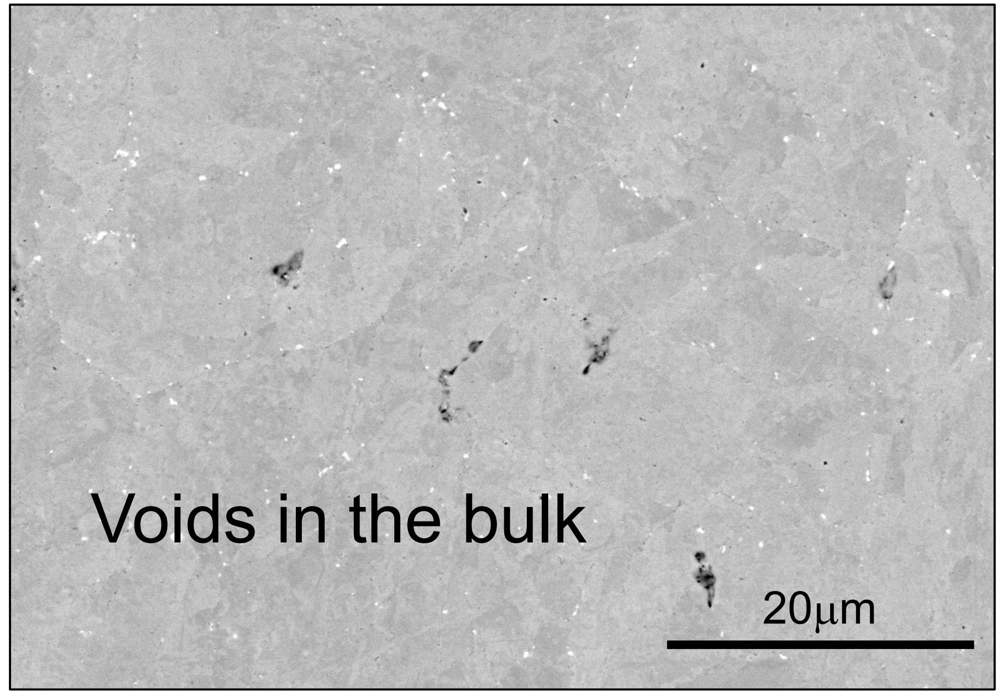
Thinner Oxide Scale for Tests Performed at ±0.5%, 10h Hold Time



Mostly thin Cr-rich oxide layer + Fe oxide in oxidized cracks

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

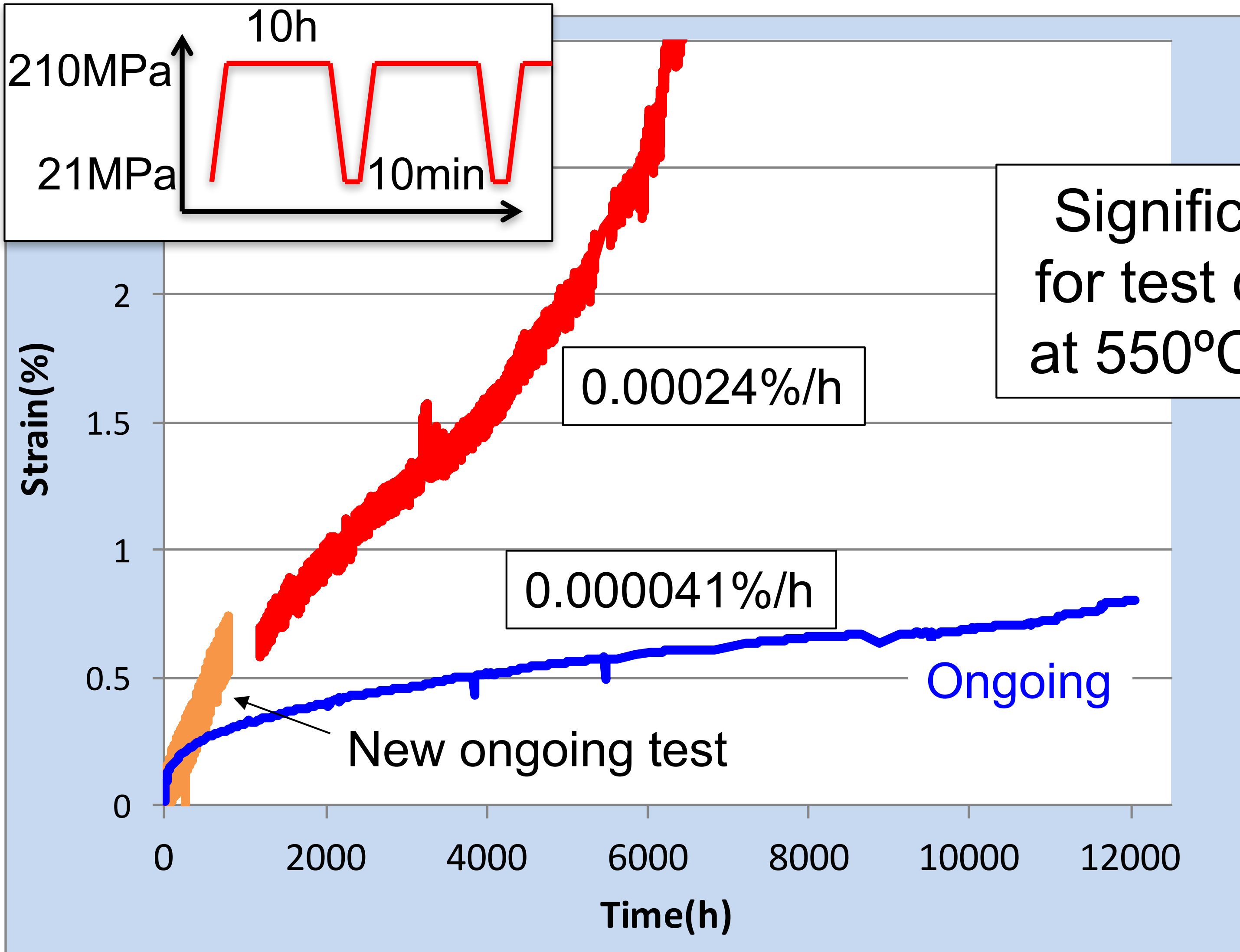




Lower cycle to failure for 10h hold time test is likely due to

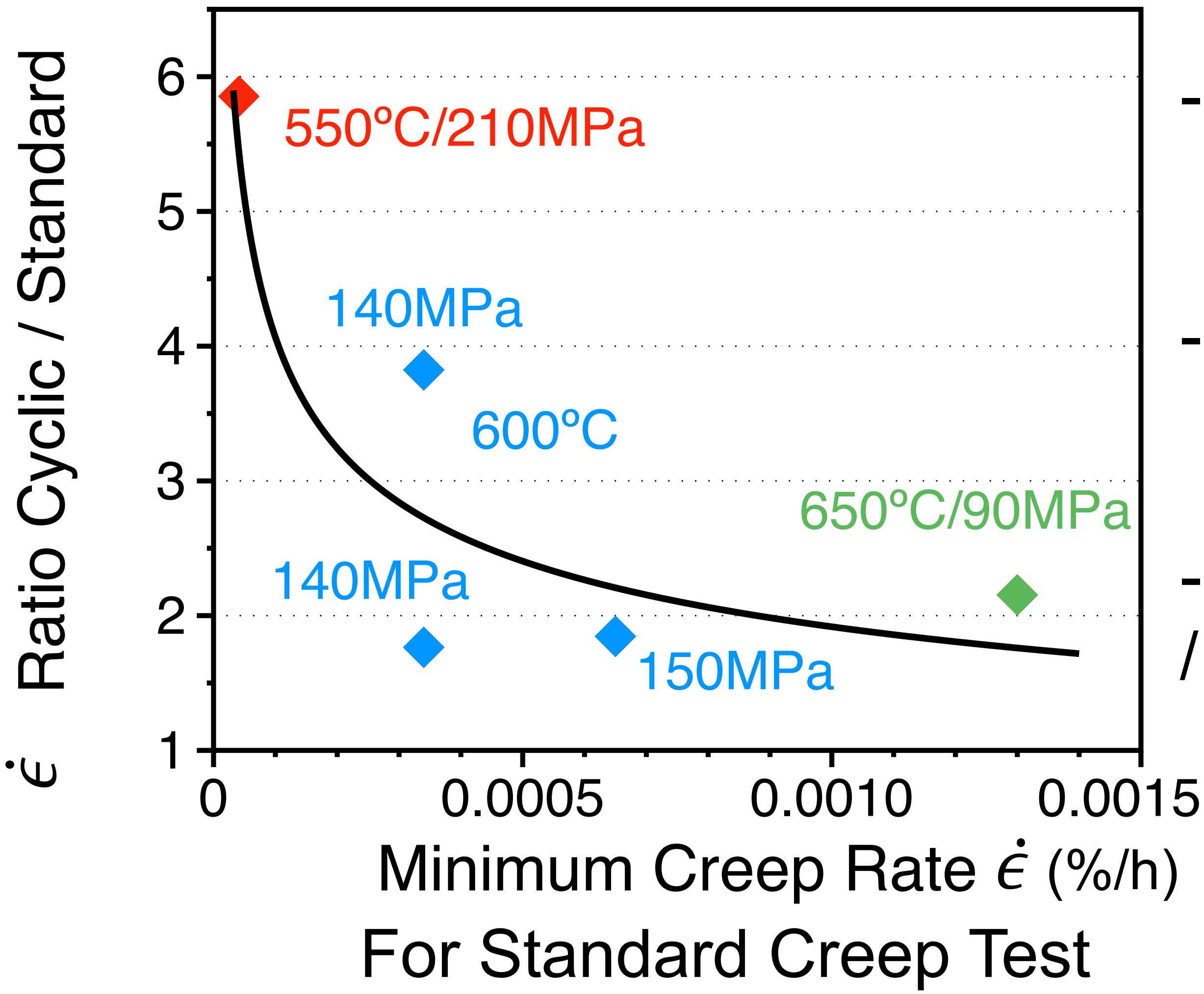
- Fast crack initiation due to oxide scale cracking
- Effect of creep cavitation on crack propagation

Effect of Load Cycling on Gr.91 Creep Properties



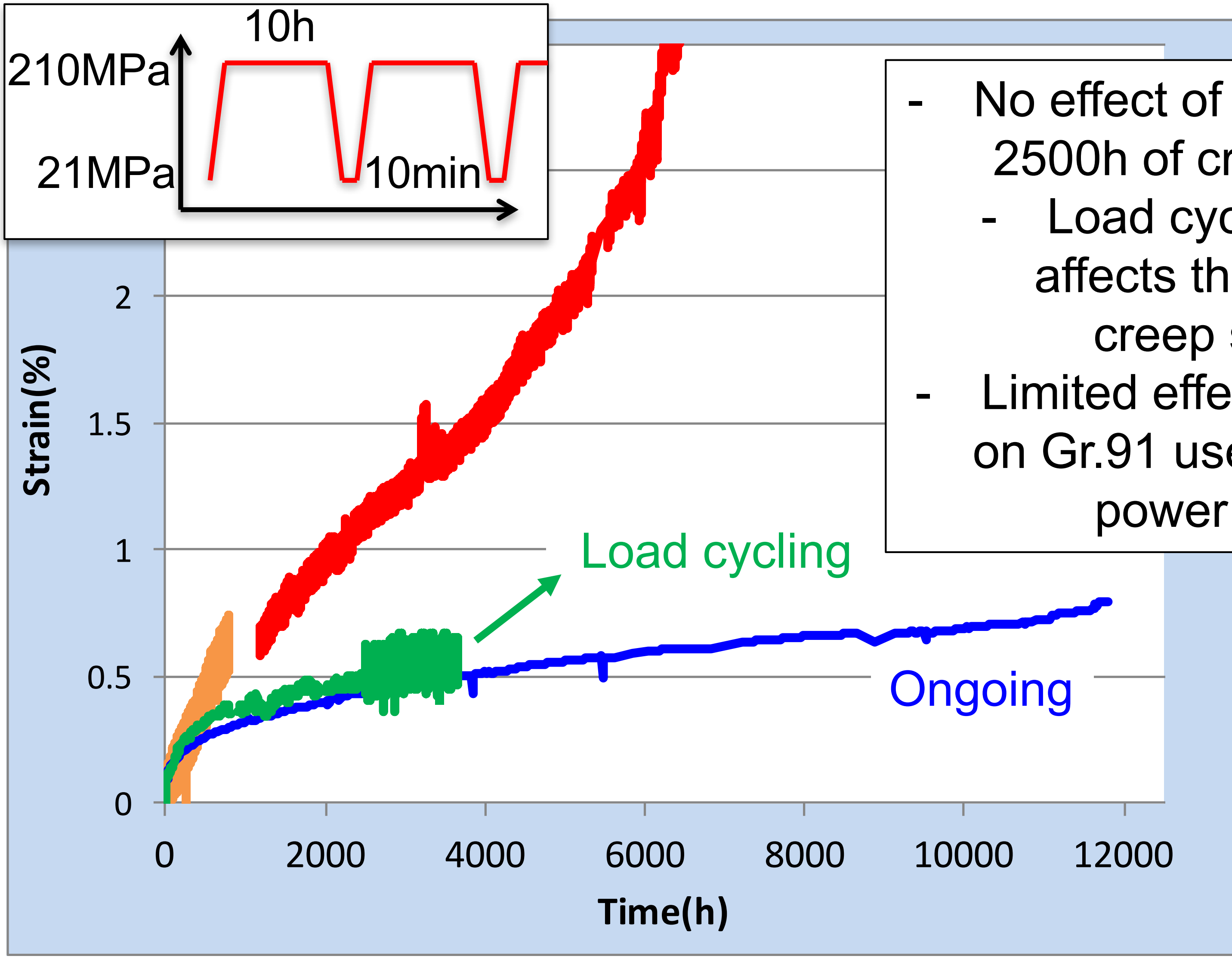
Significant effect for test conducted at 550ºC, 210MPa

Significant Increase of Creep Rate for Longer Creep Tests



- Systematic increase (~X2) of creep rate due to cycling
- Significant variation from one test to another
- Focus on long term test / low creep rate

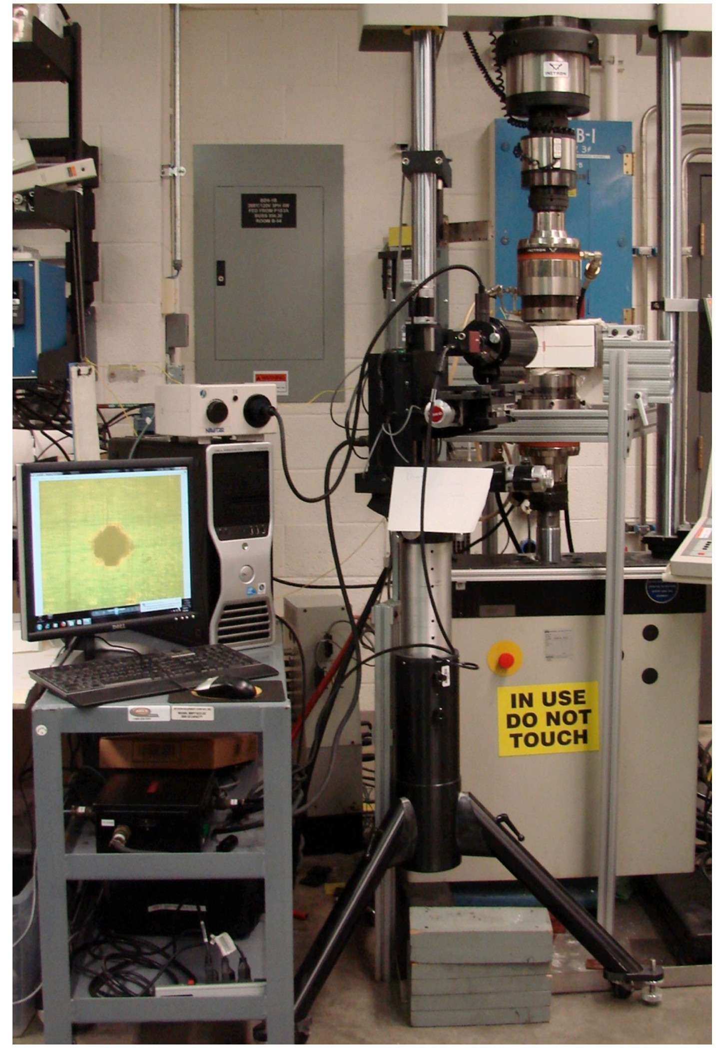
New Test With Load Cycling Initiated After ~2500h of Creep Testing



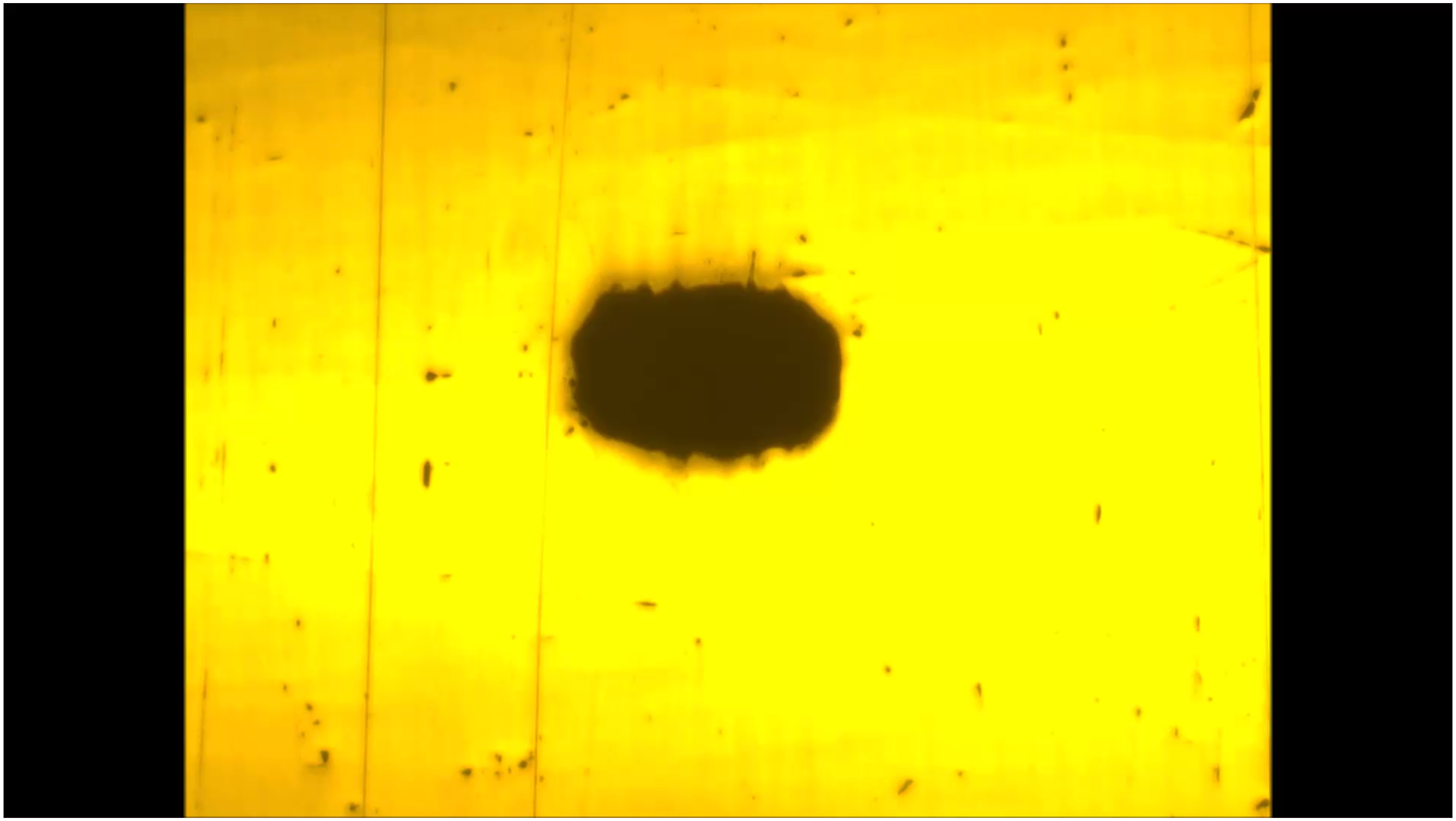
- No effect of cycling after 2500h of creep testing
  - Load cycling only affects the primary creep stage?
- Limited effect of cycling on Gr.91 used in current power plant?

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

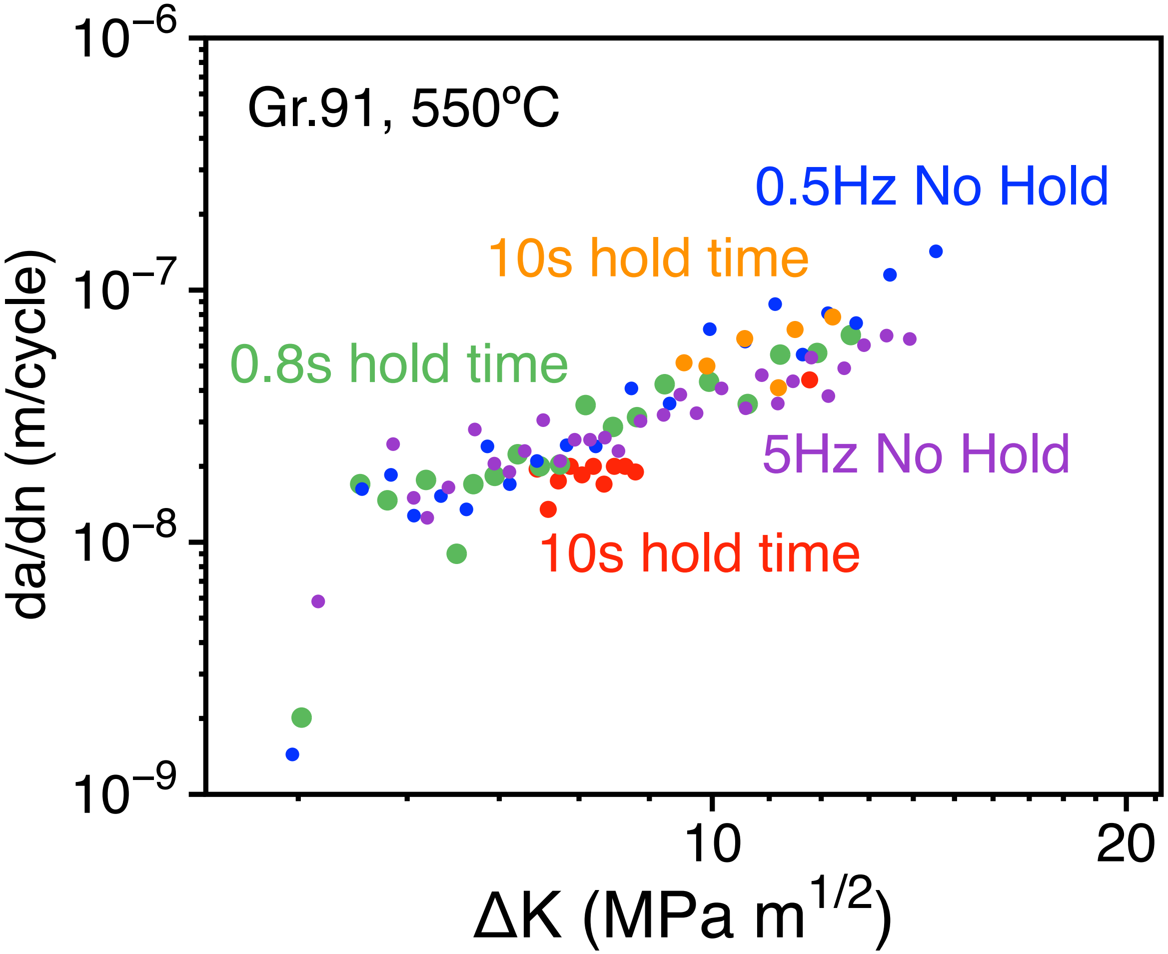


Crack Growth Imaging at Room T°C



300μm

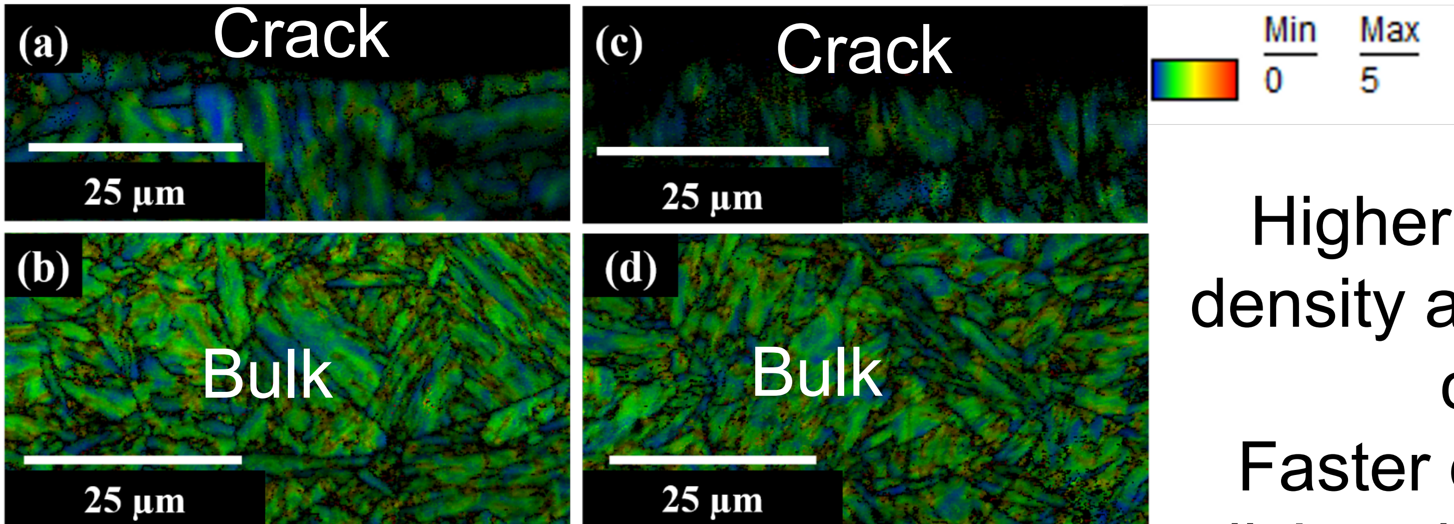
No Effect of Frequency & Hold Time on Small Crack Propagation



No crack propagation with 100s or 10min hold time

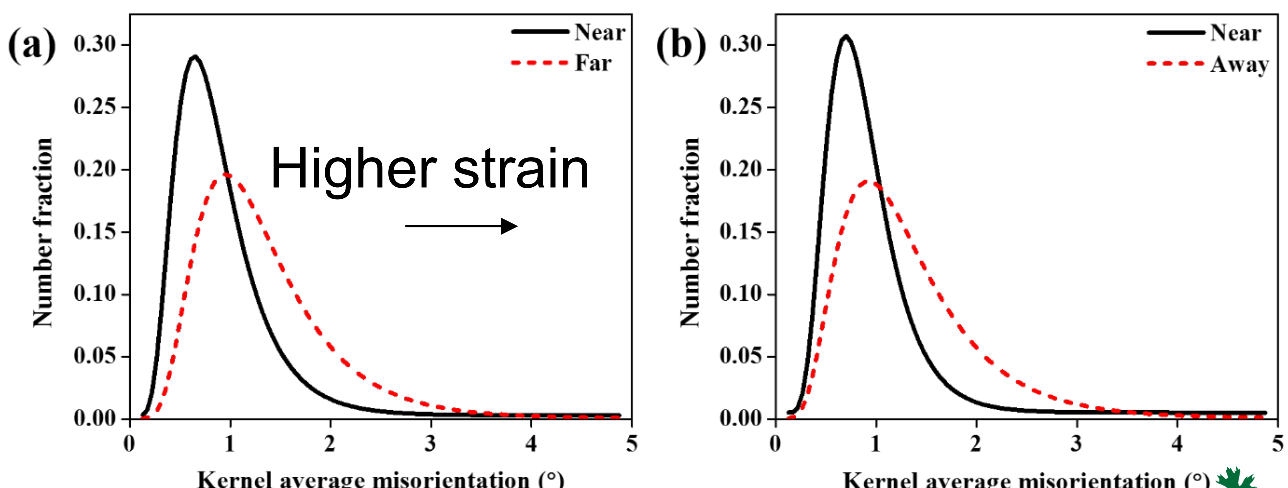
Effect of oxidation or decrease of dislocation density at crack tip?

EBSD Measurements to assess strain/dislocation density



No Hold

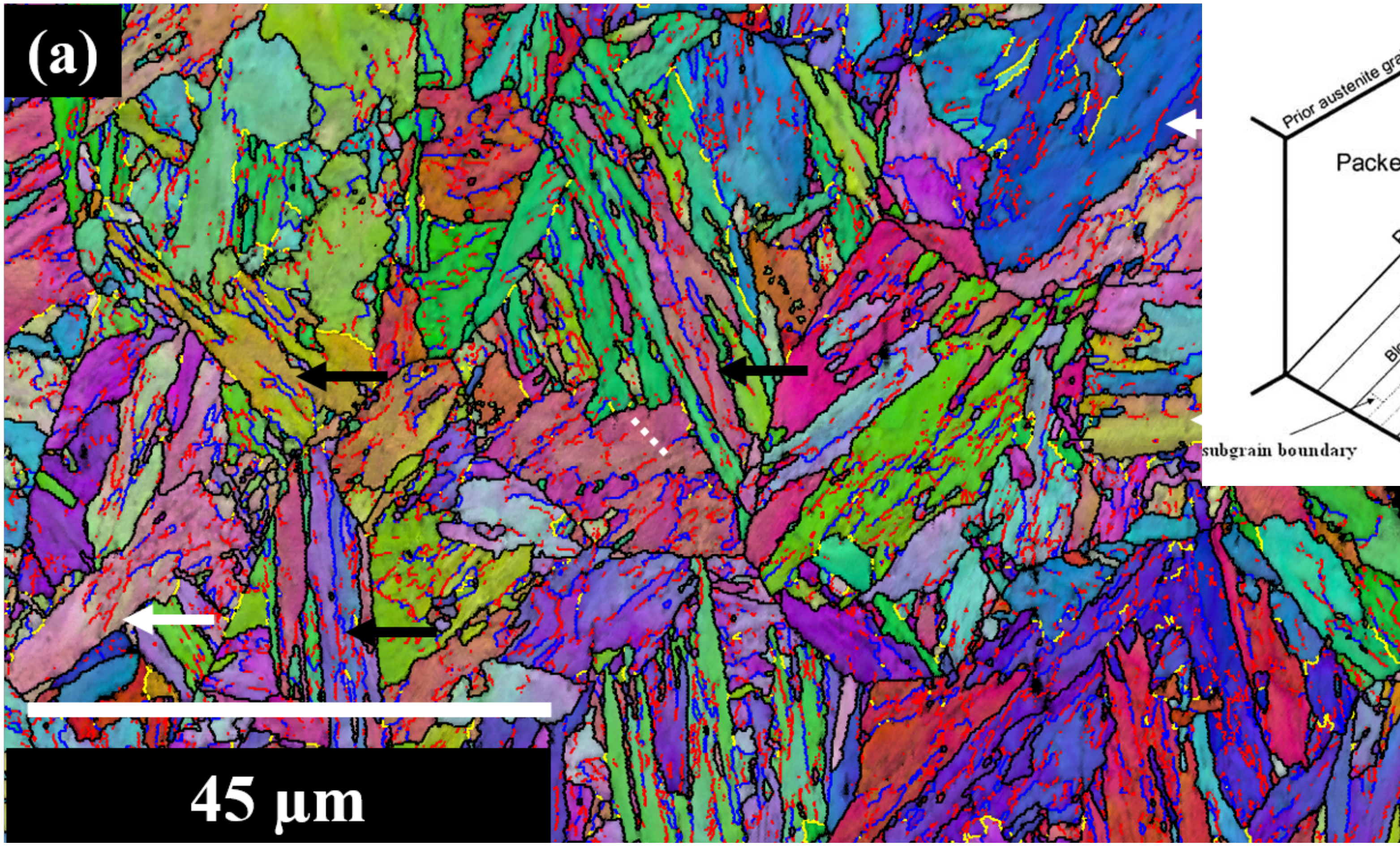
1s hold time

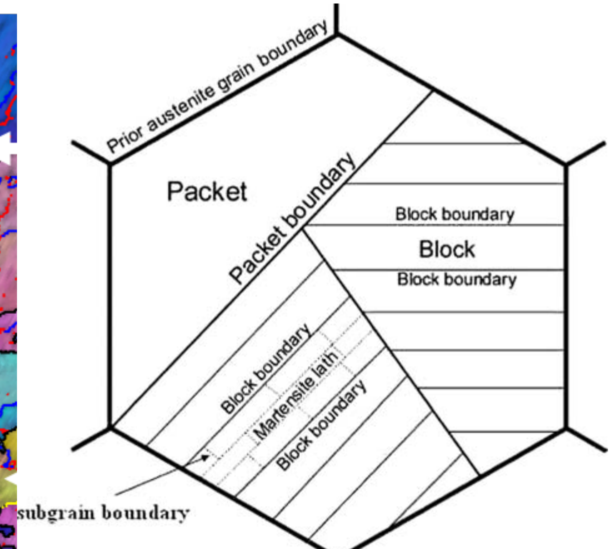


Higher dislocation density away from the crack

Faster decrease of dislocation density at crack tip for creep-fatigue specimens? Depends on Gr91. ductility

Extensive Characterization of Boundaries Misorientation

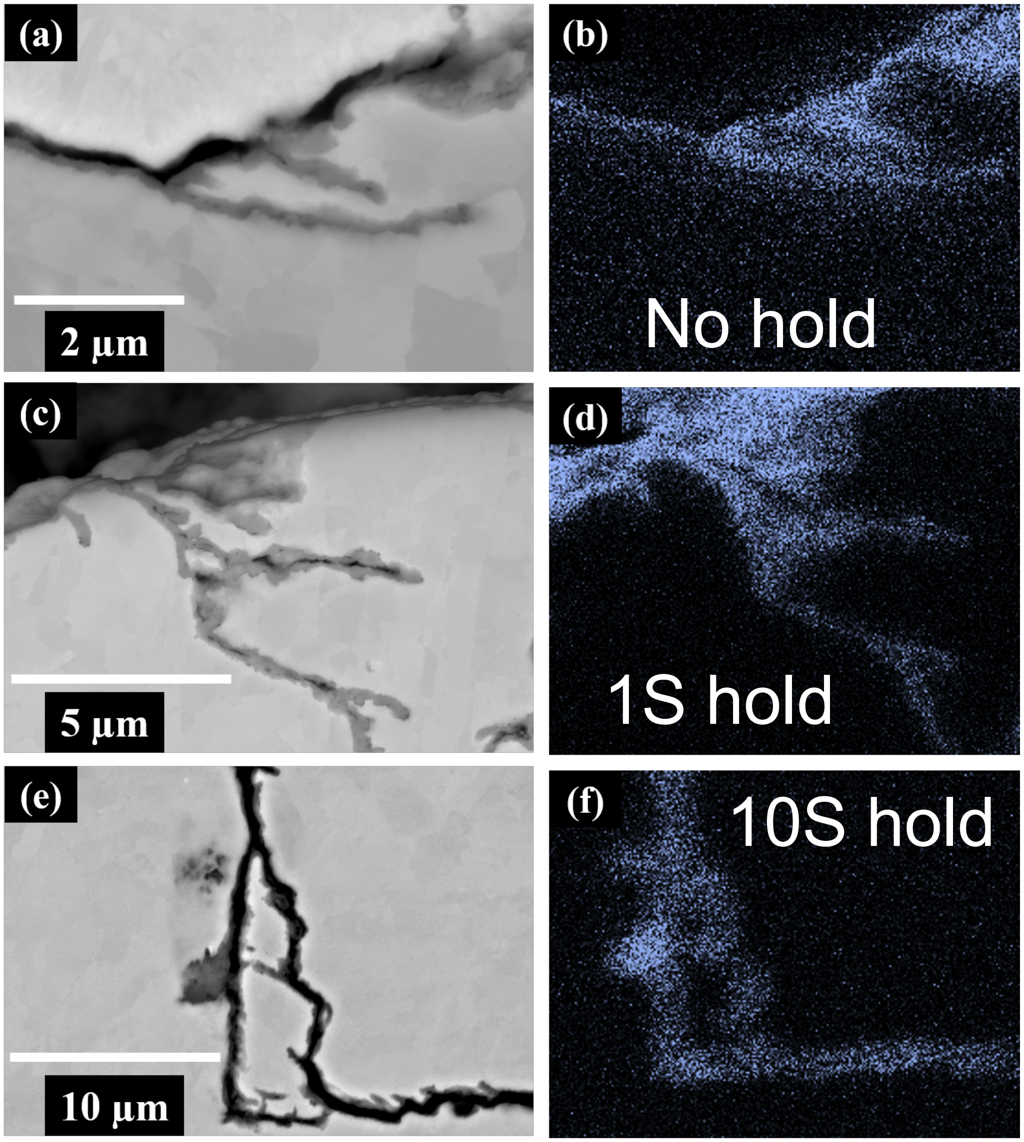




	Min	Max
Red	2°	5°
Blue	5°	10°
Yellow	10°	15°
Black	15°	65°

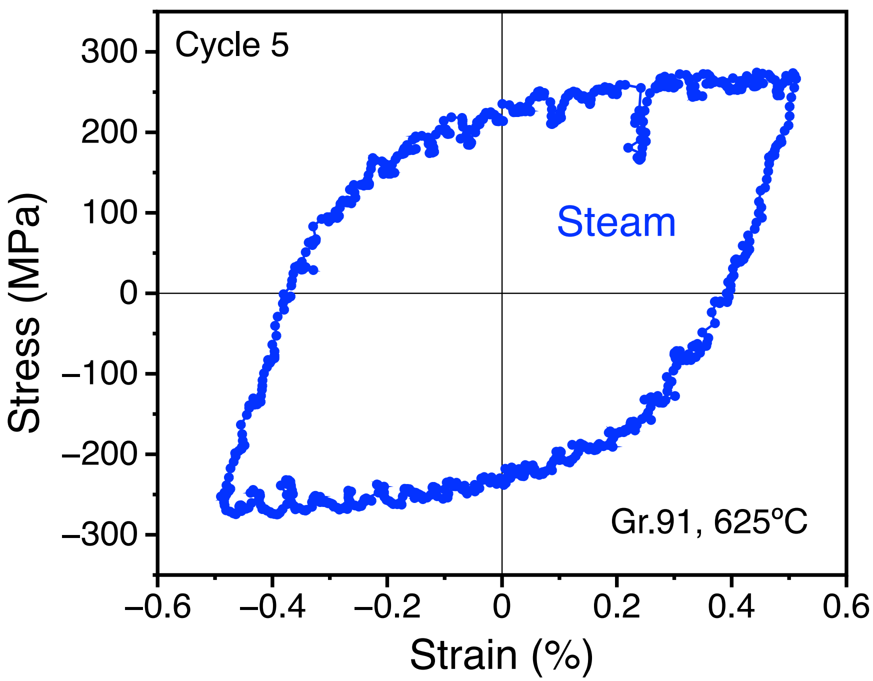
Misorientation between the sub-grains boundaries or block boundaries increased due to hold time

Significant Oxidation at the Crack Tip During Testing

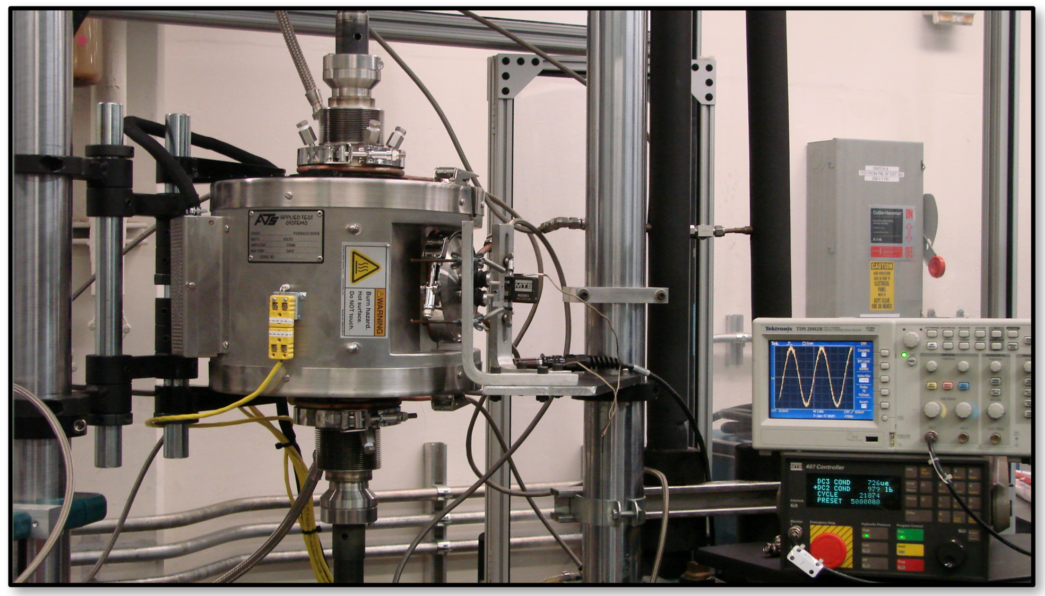


Higher dislocation density away from the crack
Faster decrease of dislocation density at crack tip due to hold time?

New test facility to evaluate LCF resistance in aggressive environments

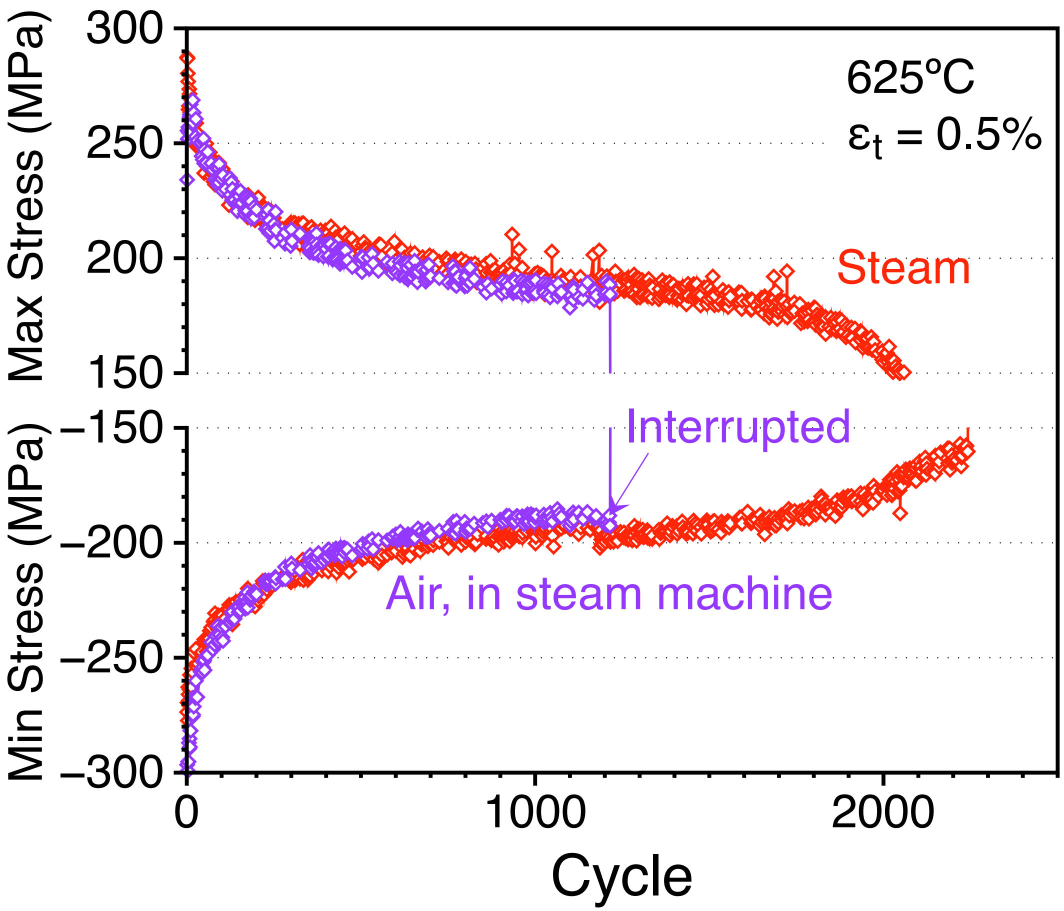


Stress-strain curve, 9Cr-1Mo ferritic steel, 625ºC, fully reversed 1% total deformation, Steam



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

Similar Min-Max Curves In Air and Steam, 625ºC, 0.5% Strain, No Hold



- But issue with specimen buckling and signal stability
- Machine alignment is ongoing

Conclusion

- Significant effect of hold time on Gr.91 fatigue lifetime
    - Fast crack initiation due to oxide formation and cracking
    - Interaction between Cavity formation & crack propagation
- Will improve creep-fatigue lifetime modeling based on experimental data in collaboration with 3FEAA118 (Xinghua)
- Long term cyclic creep affects Gr.91 primary creep stage
- Longer hold time lead to small crack propagation arrest
- New rig to conduct LCF testing in corrosive environments
- Future work: Focusing on key industry needs