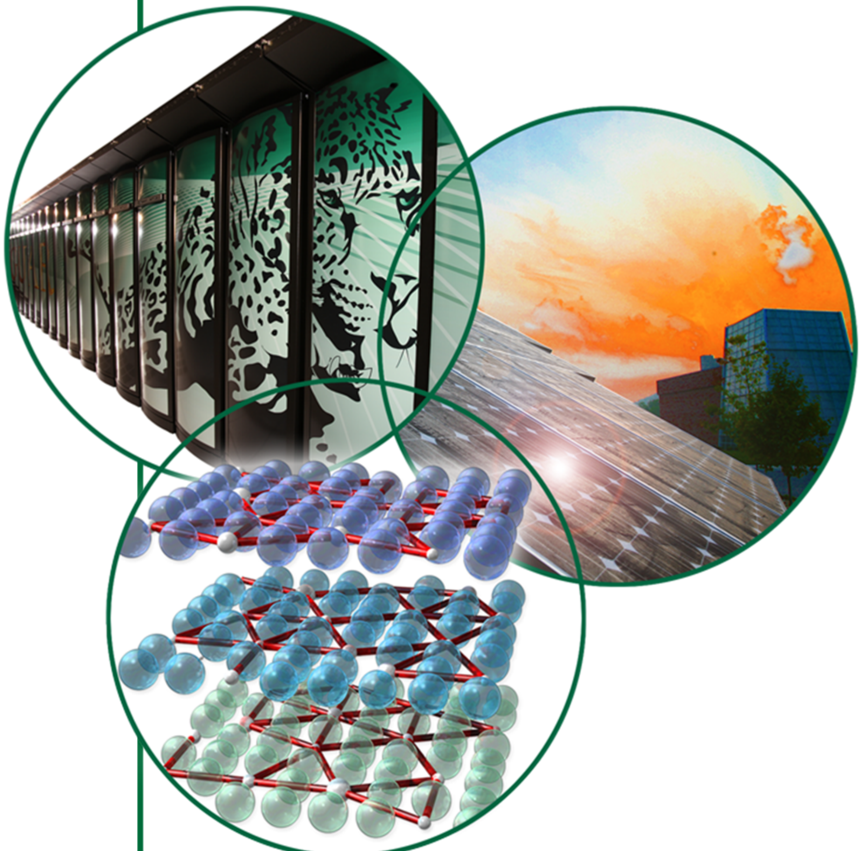
Creep-Fatigue-Oxidation Interactions: Predicting Alloy Lifetimes under Fossil Energy Service Conditions

2015 NETL Crosscutting Research Review Meeting

April 27-30 2015, Pittsburgh



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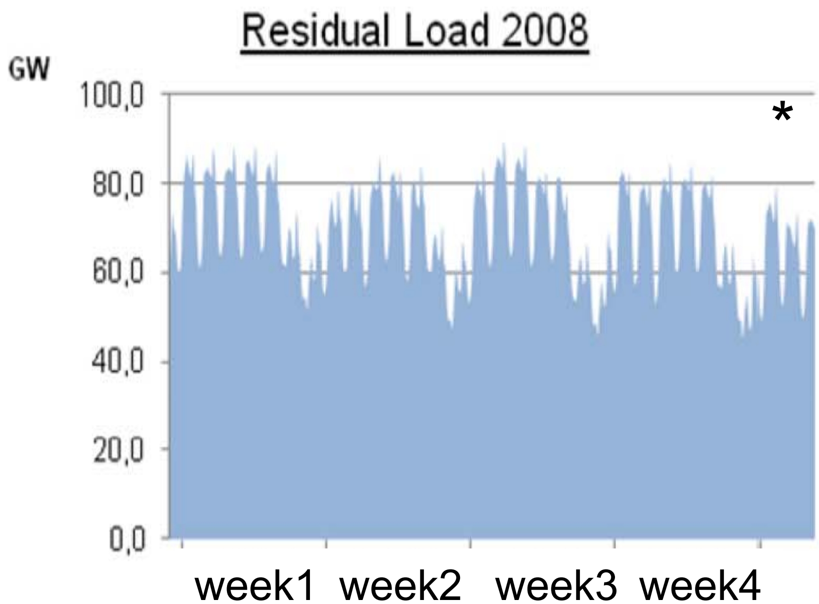
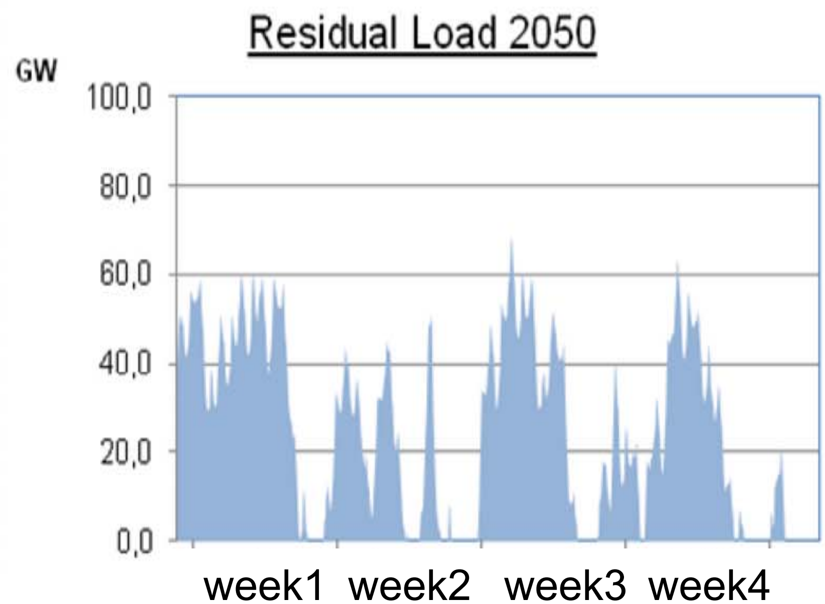
Power plants will need to be capable of flexible operation





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

* Ralf Mohrmann, Proceedings Liege conference 2014

FY15 Technical achievements

- Project initiated in FY15

- Developed two creep machines allowing automated loading/unloading sequences during testing

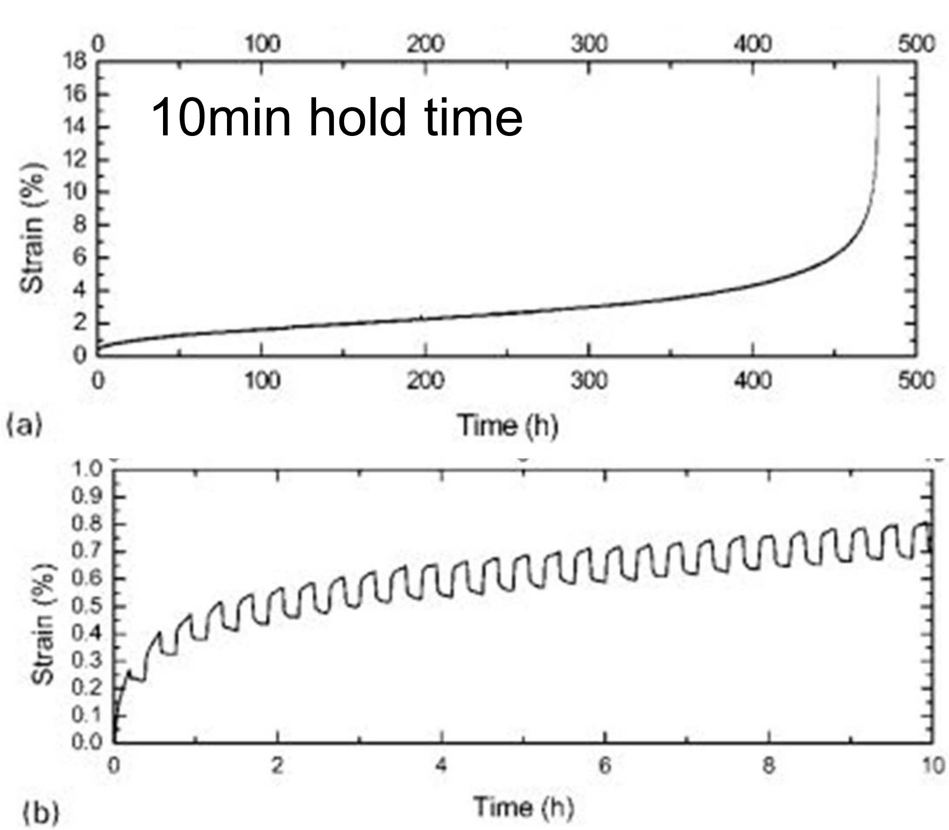
- Set up creep fatigue machine to conduct long term creep fatigue tests

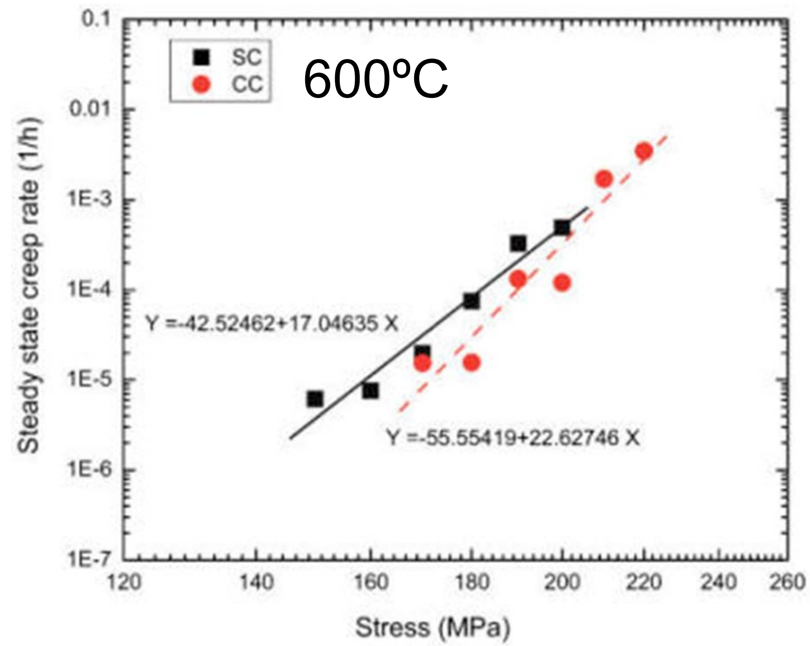
- Continued work on interaction between oxidation in steam and creep testing

Creep testing in steam with additional thermal cycling

- Project focusing on ferritic/martensitic Gr91 (9Cr-1Mo) alloy

Very limited Gr.91 cyclic creep data





Kim et al. MHT, 31, 249 (2014)

- Slight decrease of creep rate and increase of life due to cycling
- Beneficial effect of cycling due to dislocation recovery?
- Only short term data

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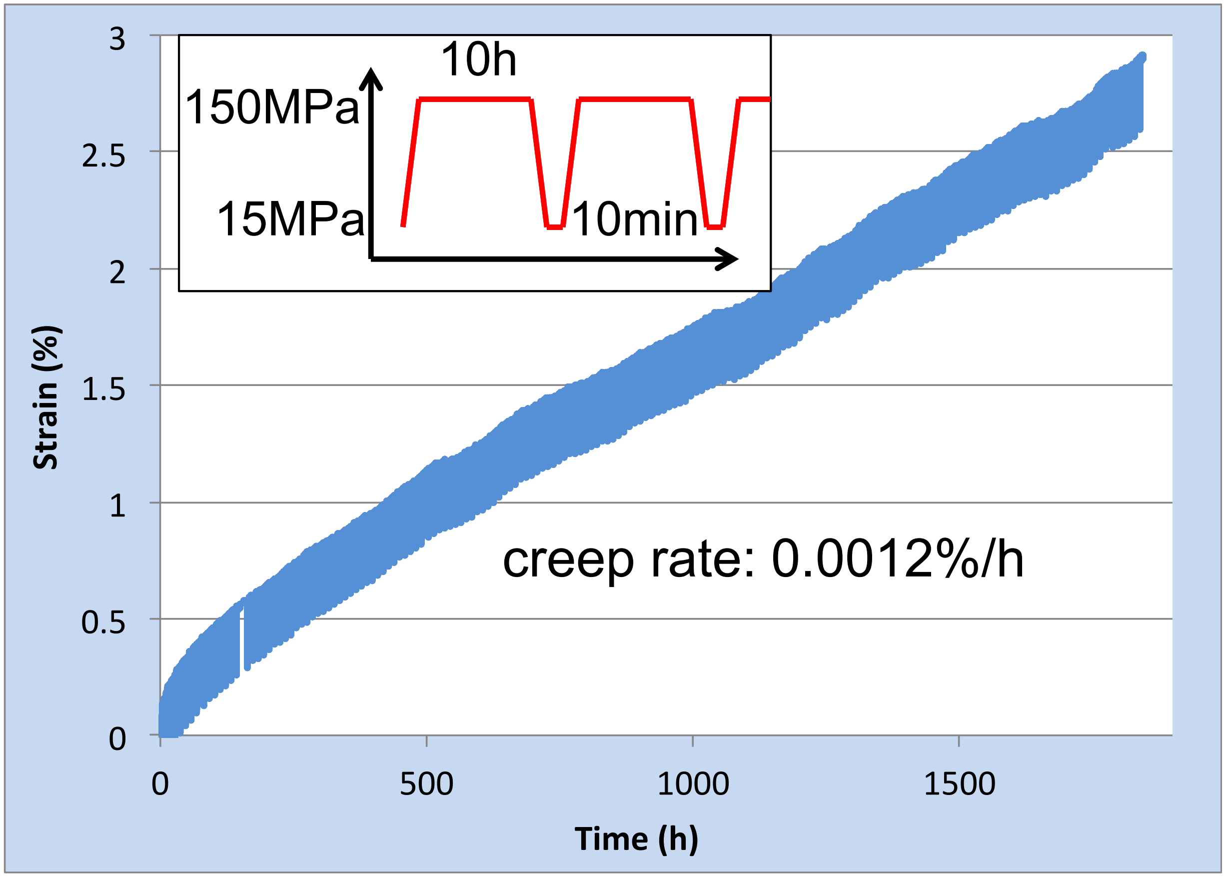
Decrease of creep rate at 600ºC, 150MPa with 10h cycle



Gr 91, ORNL heat 30176

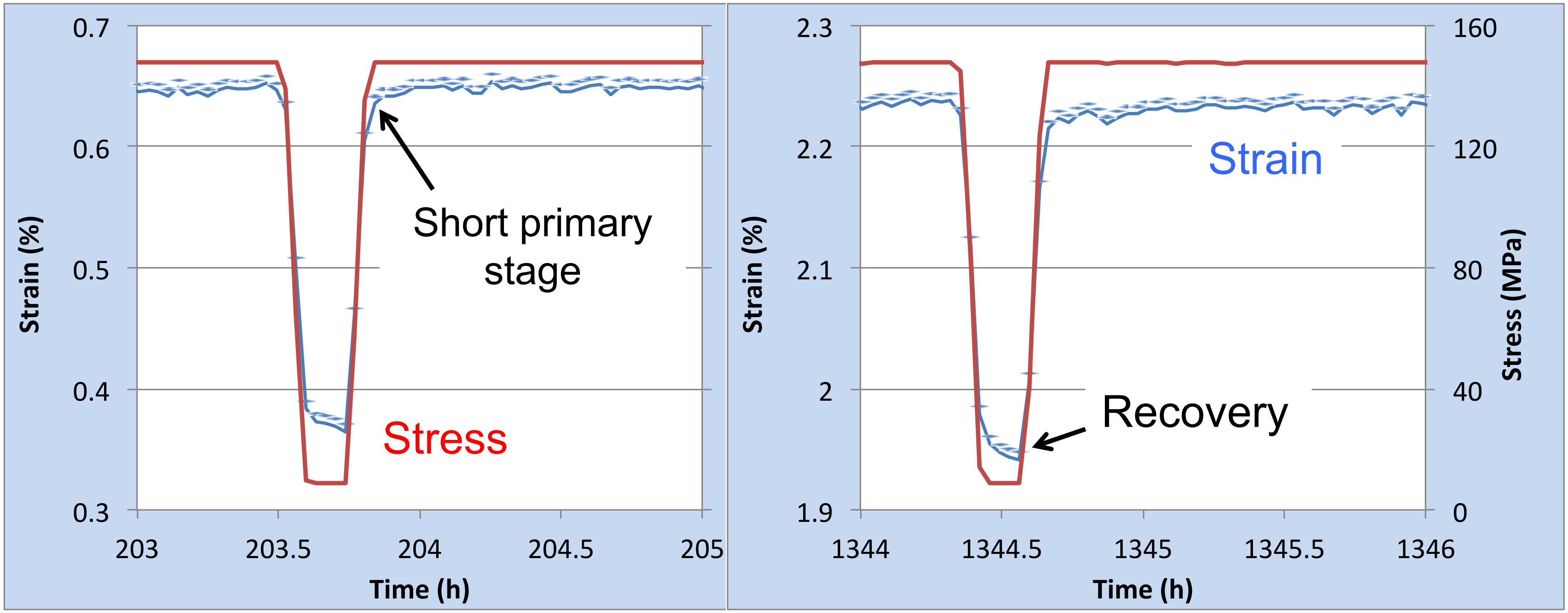
Estimate from ORNL report without cycling: (several heats)

$\dot{\varepsilon}$ =0.0026%/h
t_r = 1600h

standard creep testing was initiated

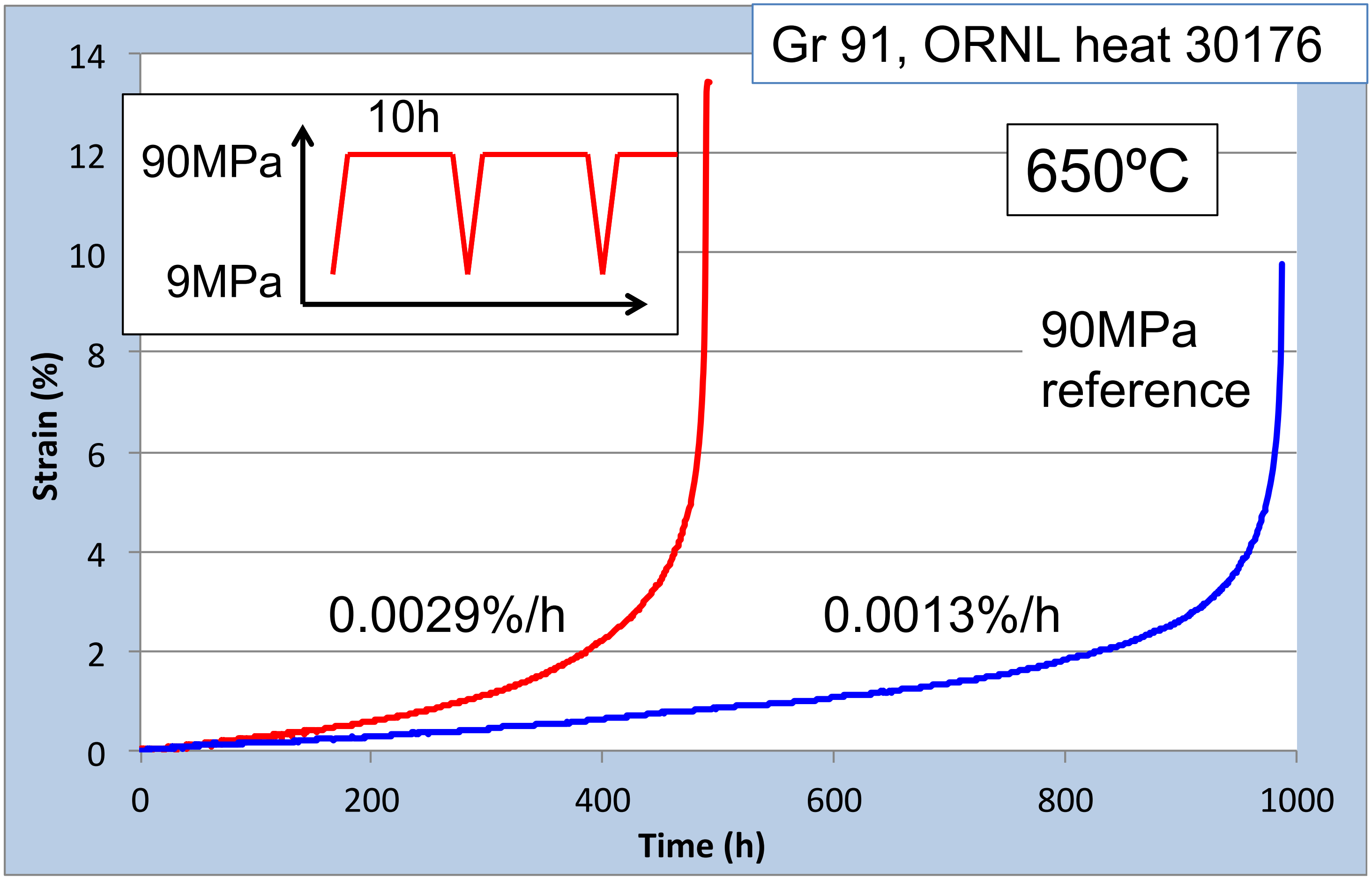
Increase of time to rupture

Recovery observed during unloading at each cycle



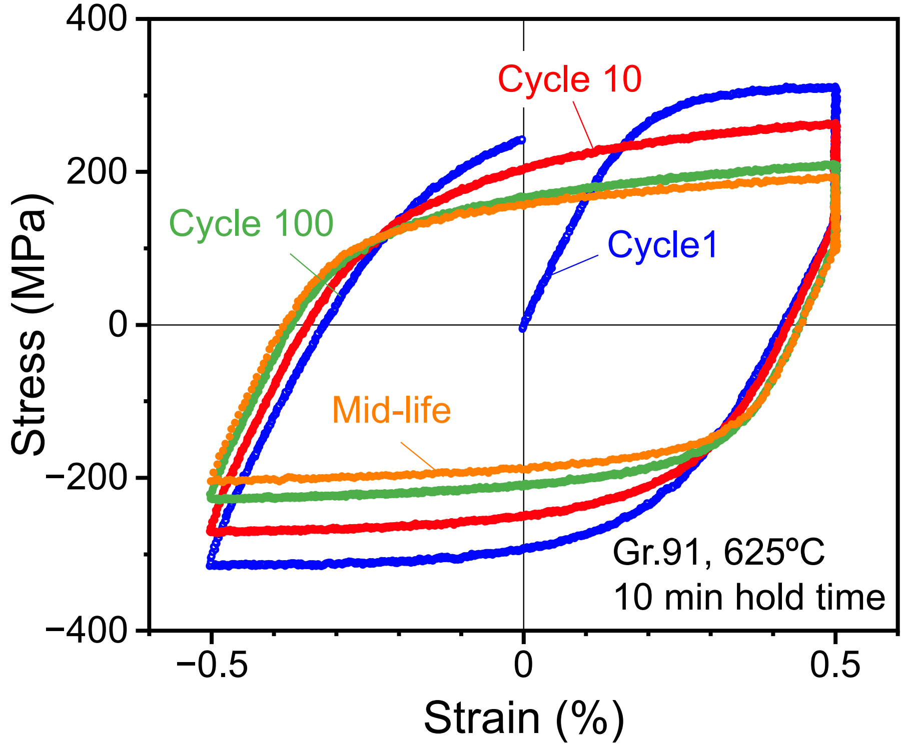
Effect of cycling on dislocation network and subgrain?
Effect of hold time during unloading?

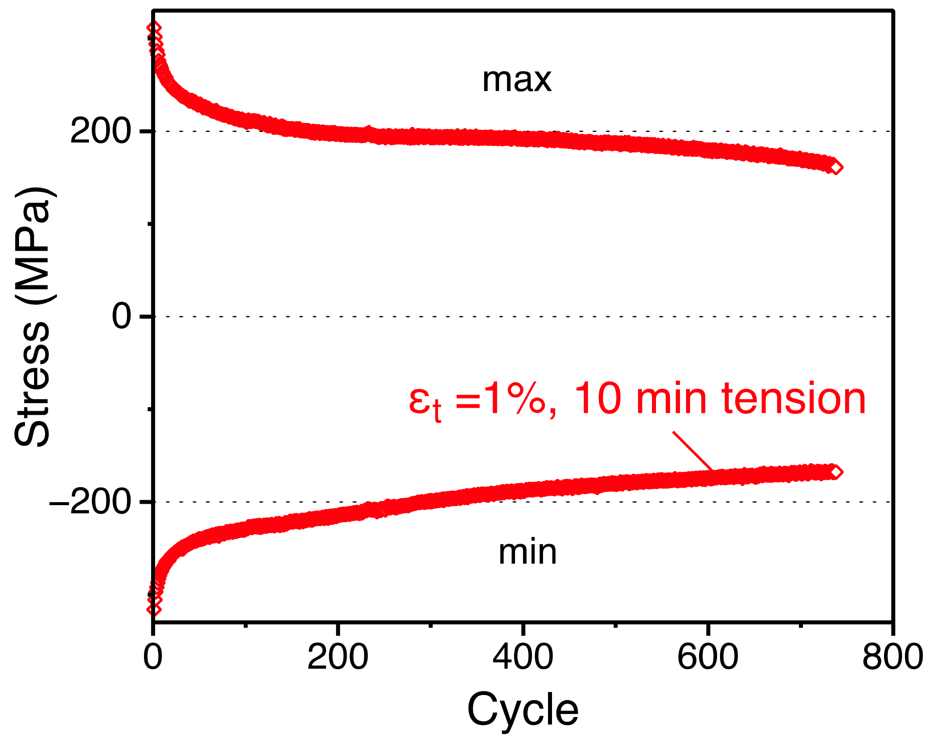
Decrease of lifetime at 650ºC, 90MPa with 10h cycle



Different microstructure evolution above and below 600ºC?

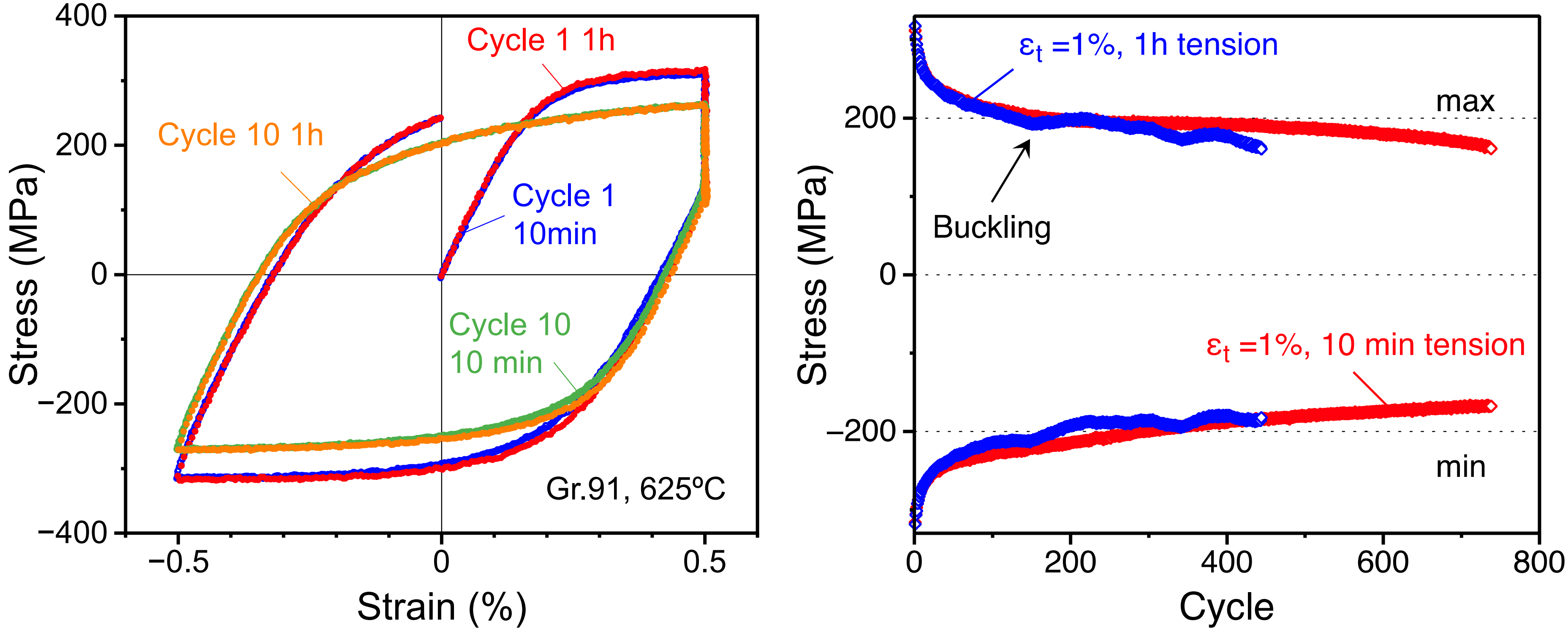
creep-fatigue 625ºC, ±0.5% results consistent with literature data





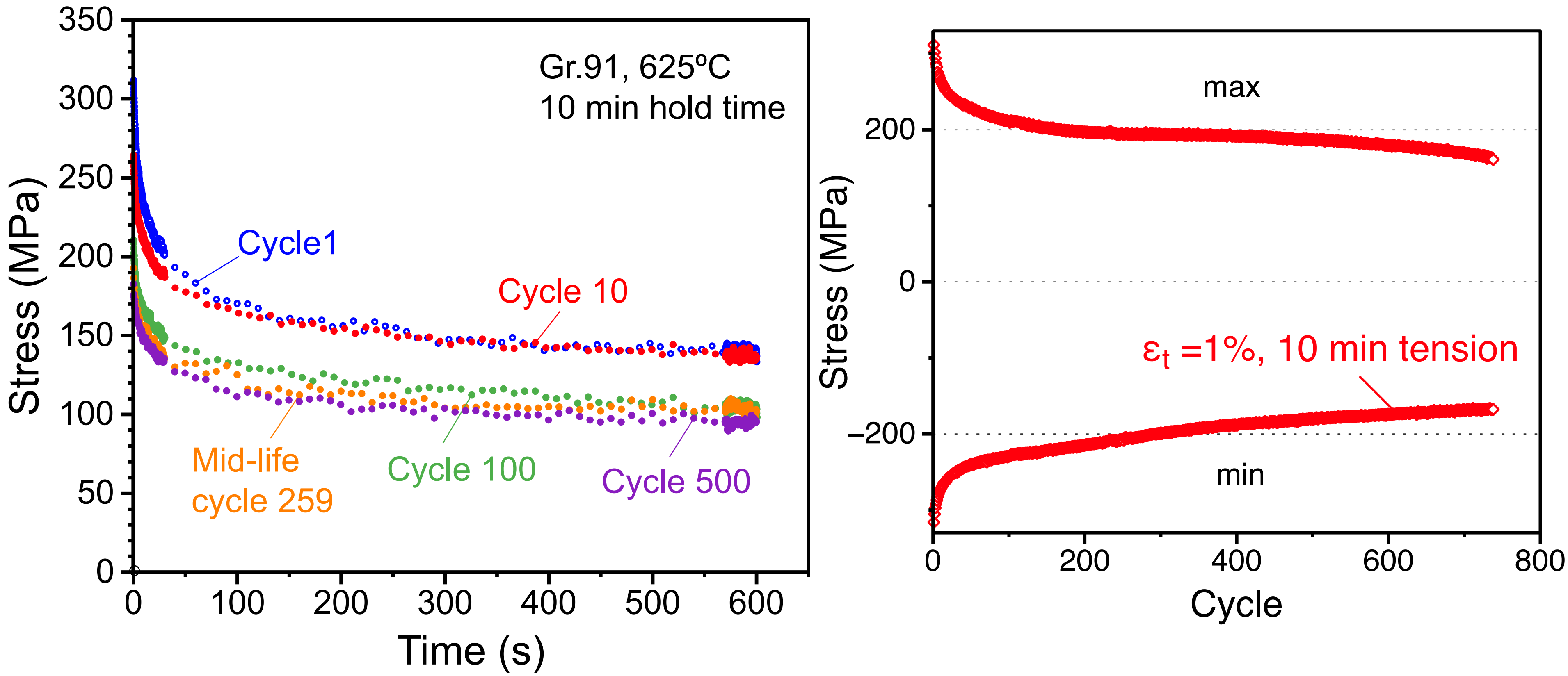
- Comparison with EPRI Round-Robin conducted at 625ºC
  "need longer hold time"
- Significant softening of the alloy at the test beginning

Similar stress strain curves with 10min and 1h hold time up to ~50 cycles



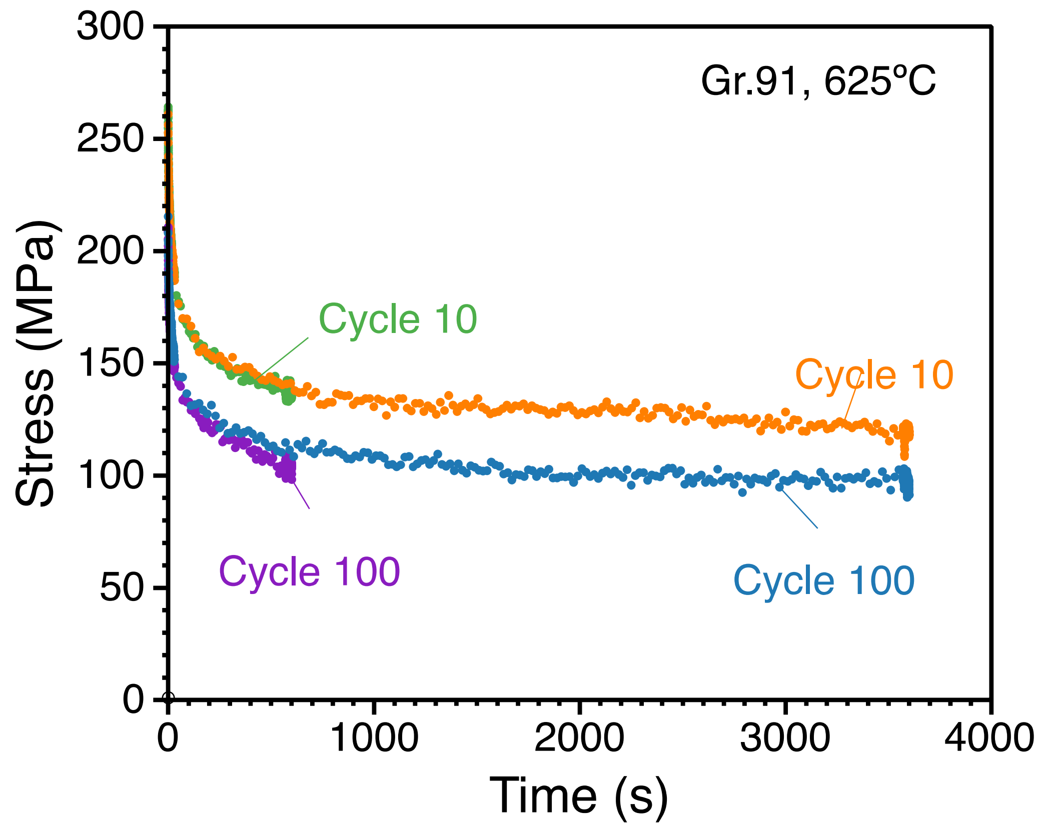
- 10min hold time (tension) test "failed" after ~519 cycles
- Buckling of 1h hold specimen. Specimen geometry has been modified to avoid buckling in future tests

625ºC, ±0.5% 10 min hold time
Fast stress relaxation during 1rst ~30s



- Stable relaxation curves after ~100 cycles

625ºC, ±0.5% Similar relaxation curves for 10min and 1h hold time



Stress plateau reached after ~30 min for 1hold time tests

625ºC, ±0.5%, Significant initial creep damage

Damage accumulation model

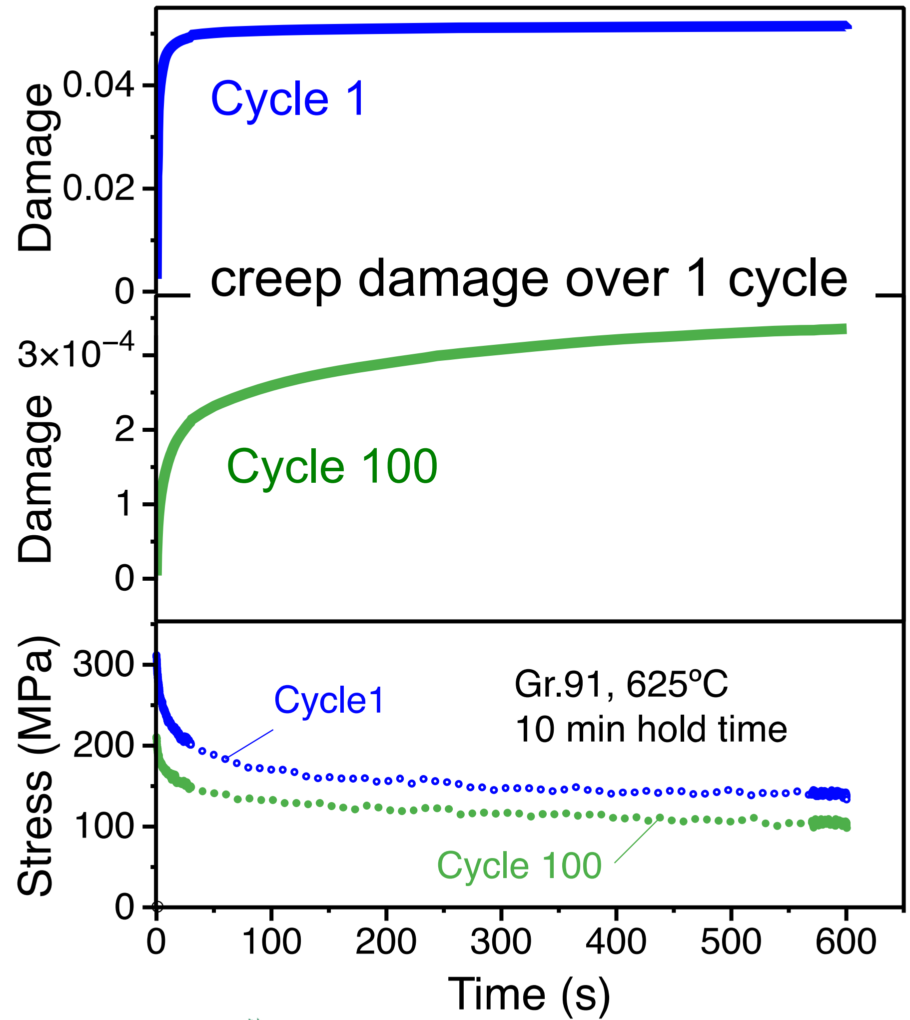
$D_c + D_F < 1$

D_f, fatigue damage
D_c, creep damage

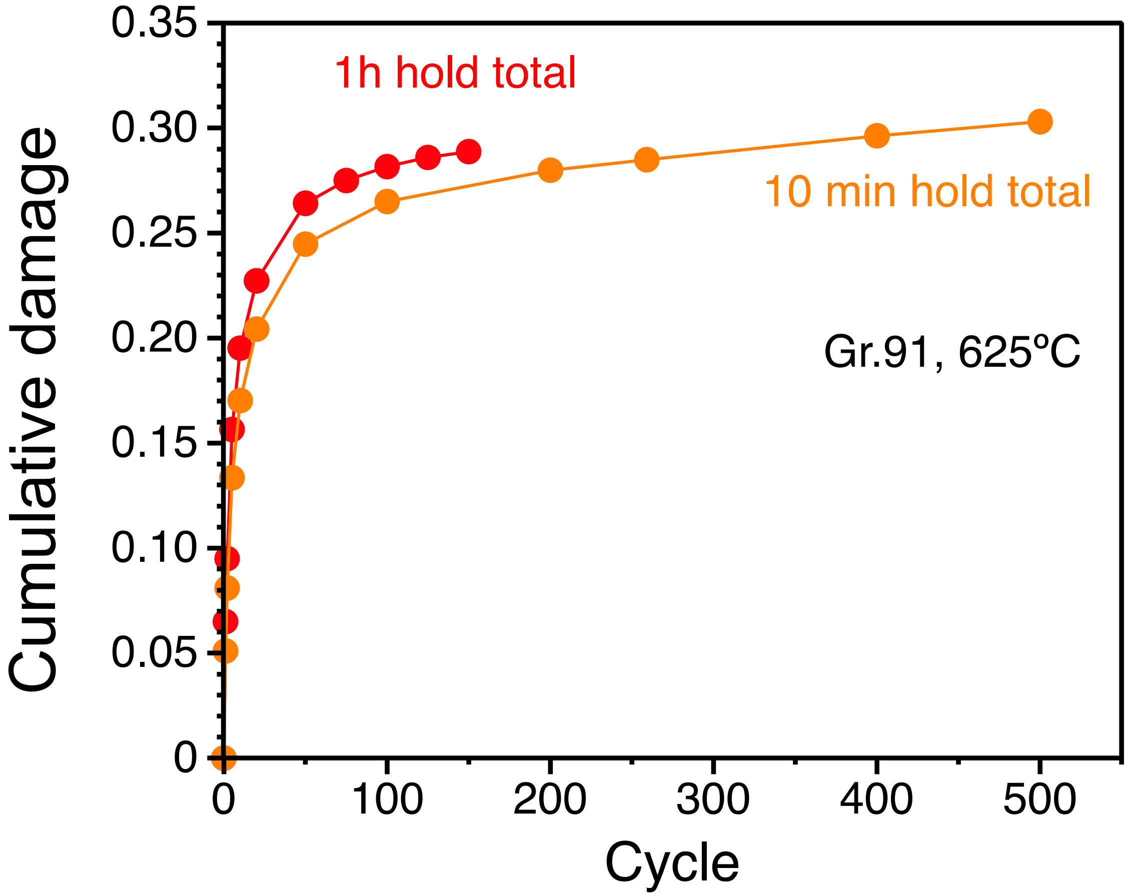
$$D_C = \sum \frac{\Delta t}{t_r(\sigma)} = \int_0^N \int_0^{t_0} \frac{dt}{t_r(\sigma)} dN_0$$

N: number of cycle
t_0 hold time

- Initial high stress leads to high creep damage

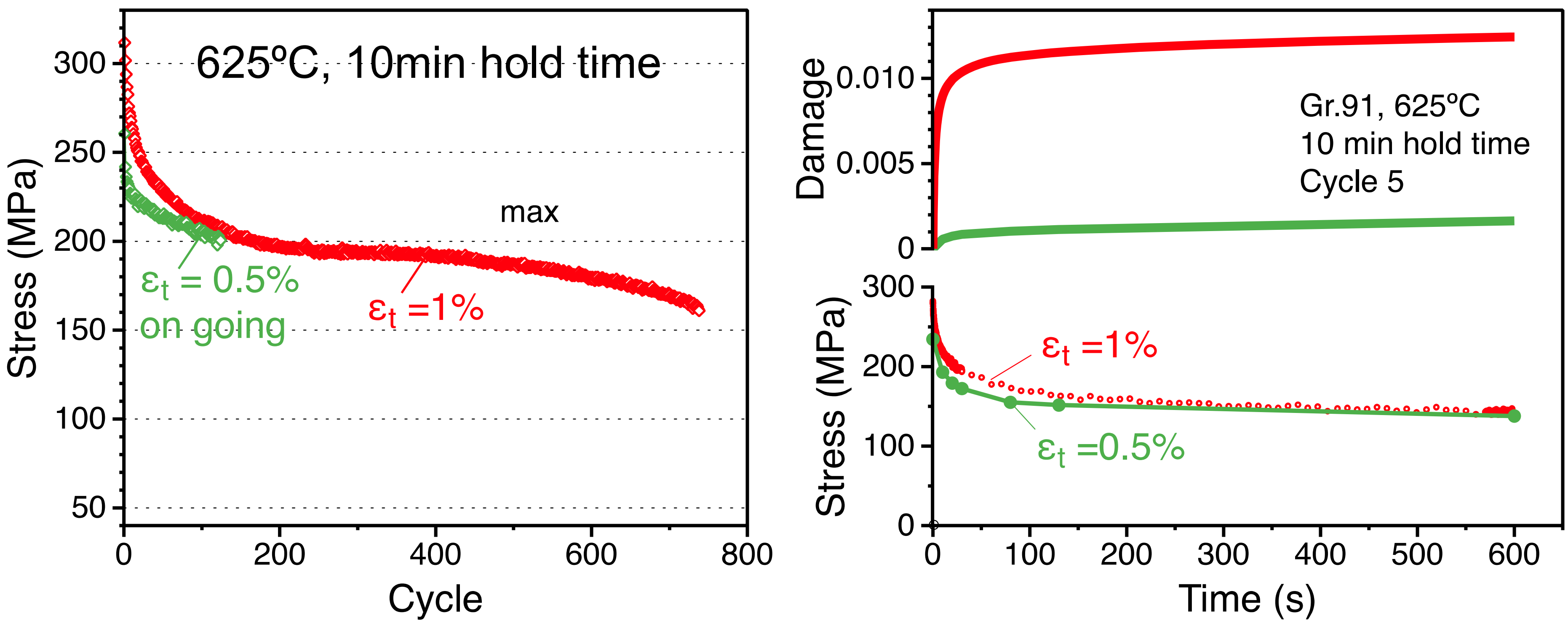


625ºC, ±0.5% Similar creep damage for the 10 min and 1h tests



Total creep damage of ~0.3

625ºC, ±0.25% strain results in limited creep damage during first cycles



Lowering strain and increasing hold time to increase creep damage

Creep-fatigue modeling needs to integrate microstructure evolution

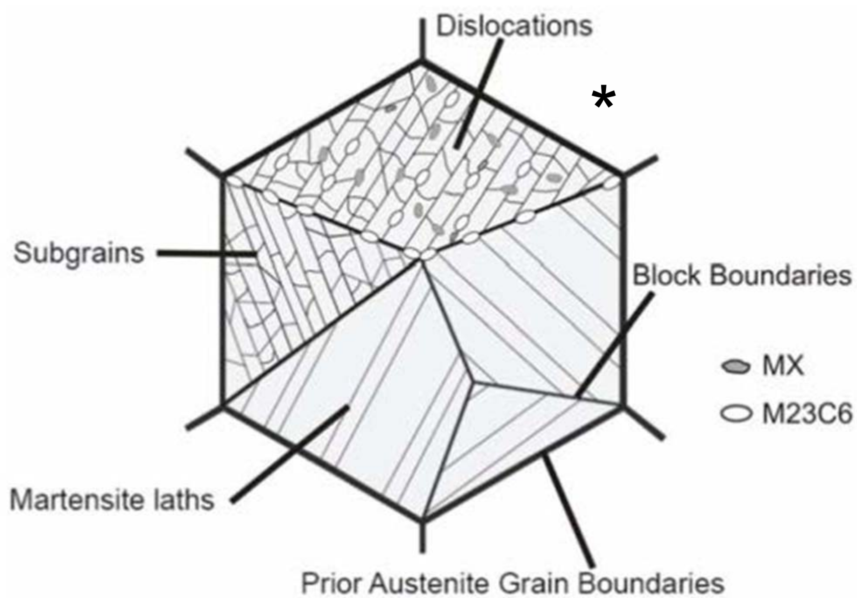
Damage accumulation model

$$\frac{D_F}{1-I_{cf}D_C} + \frac{D_C}{1-I_{fc}D_F} = 1$$

D_f, fatigue damage, D_c, creep damage

Microstructural creep damage

- Subgrain and network dislocation evolution
- Precipitate coarsening
- Cavity formation
- Depletion of solid solution elements



- Longer test duration needed to allow for microstructure change
- Lower strain to limit initial high creep damage

* Kitahara et al., acta met 54, 1279 (2006).

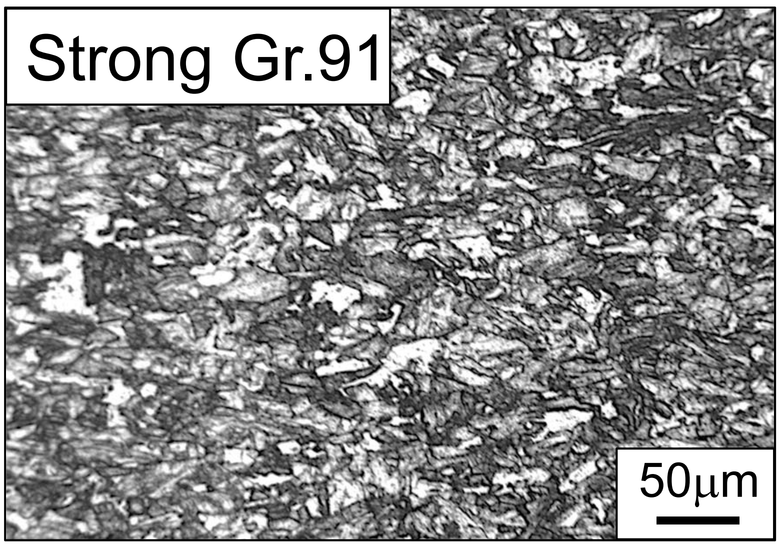
Ferritic/martensitic Gr. 91 and fully ferritic 9Cr alloys creep tested at 650ºC in air and steam

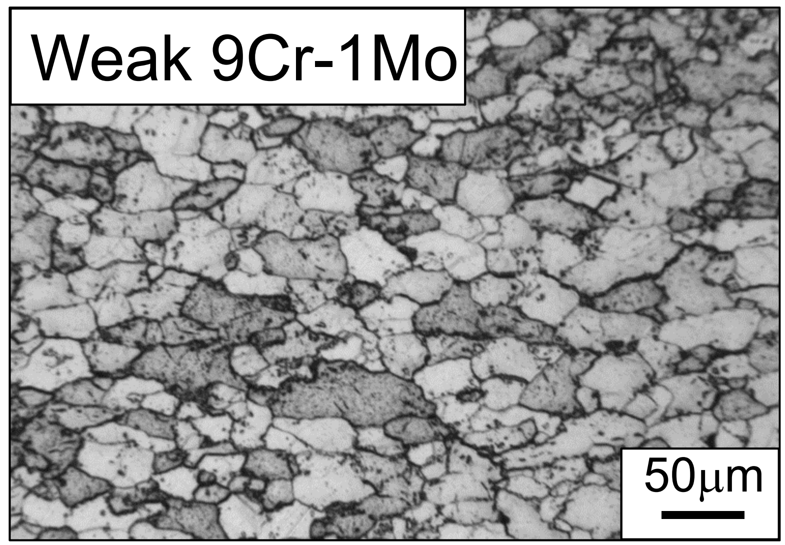
Wt%	Fe	Cr	Mo	Si	Mn	V	C
gr.91	base	8.31	0.9	0.13	0.34	0.26	0.08
9Cr	base	8.61	0.89	0.11	0.27	0.21	0.08

Similar composition but different microstructures:

-Gr.91 = standard commercial heat treatment (normalized and tempered)

- 9Cr = Non heat treated material





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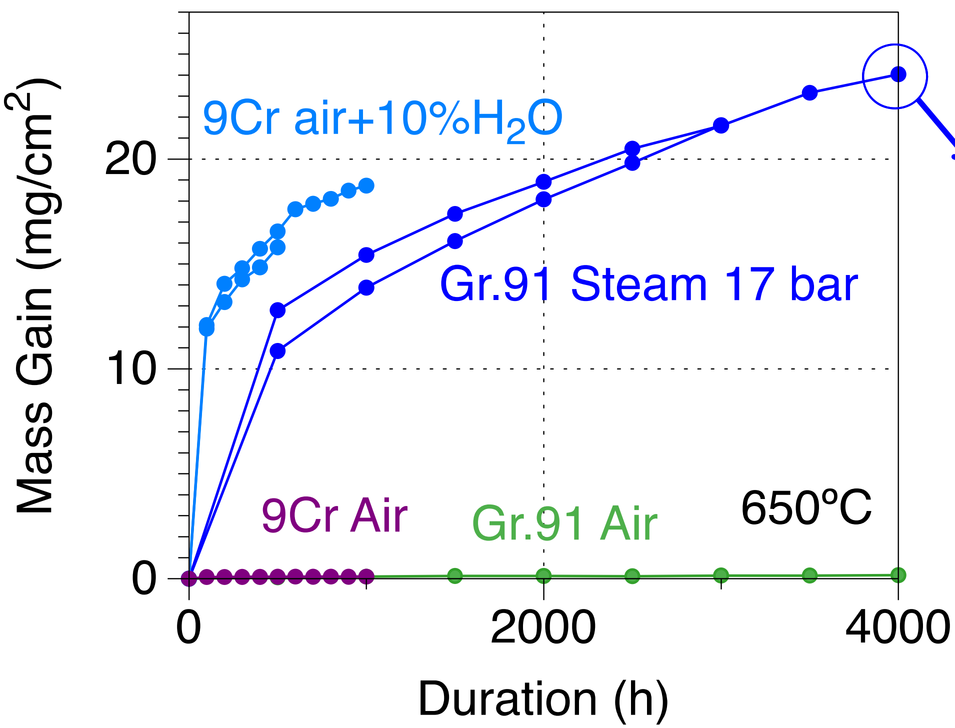
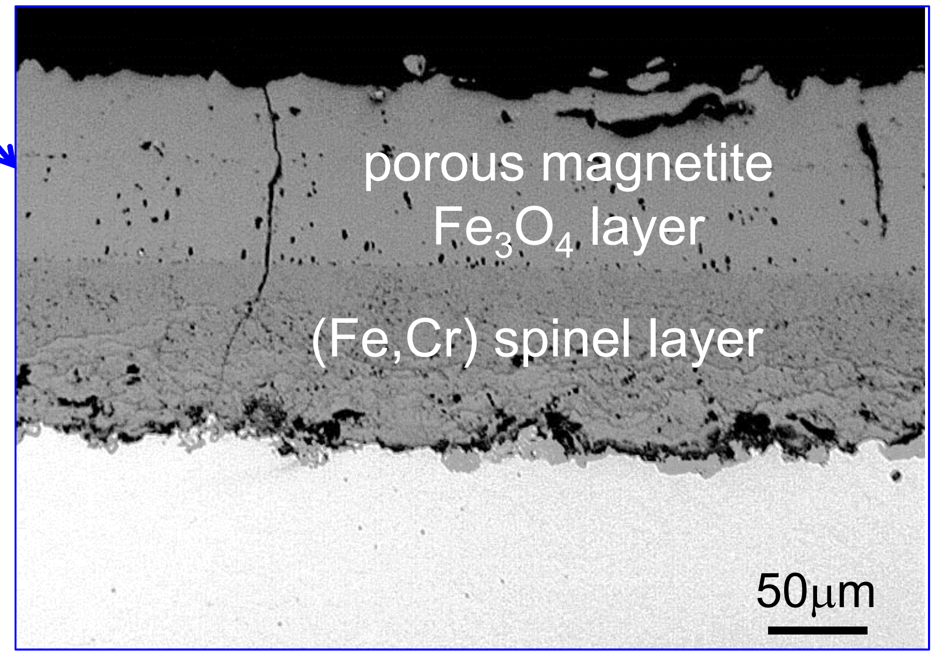
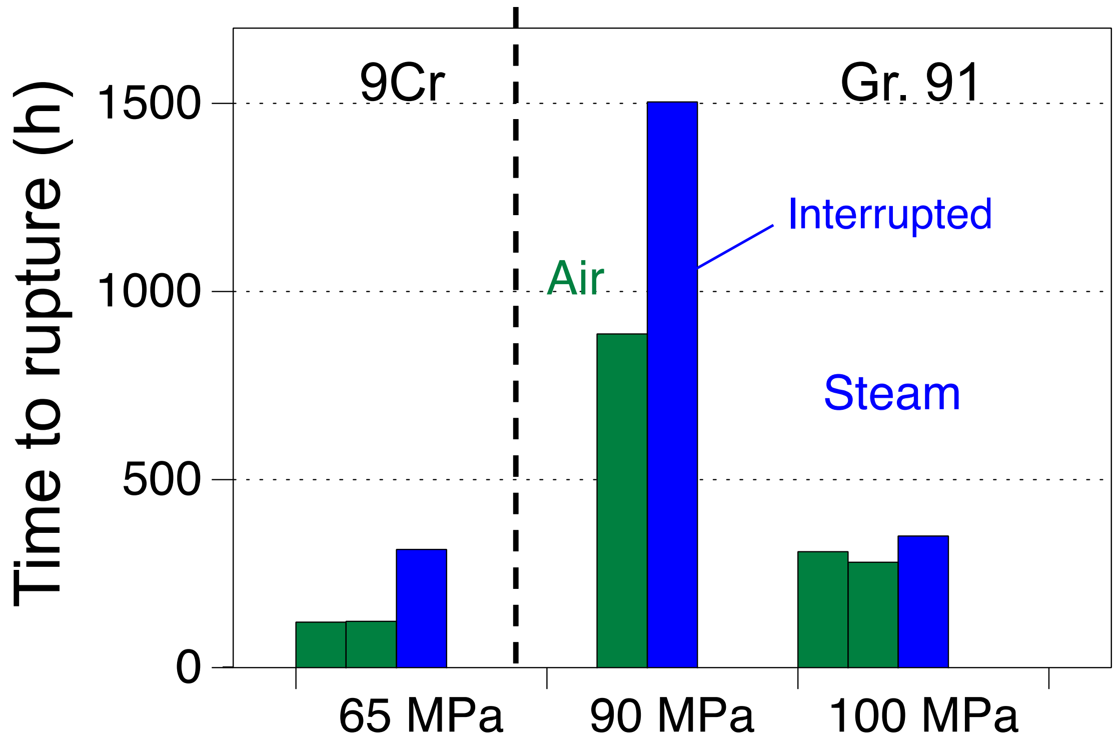
Asses the effect of oxide scale and metal loss on gr.91 creep properties

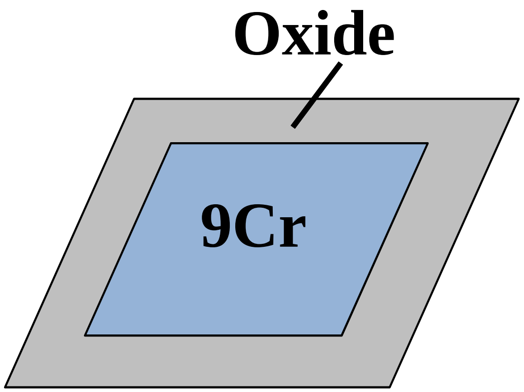




Loss of metal = decrease of load bearing section?
*C*omposite behavior with scale bearing some load?

Lifetime X3 in steam for 9Cr alloy due to load-bearing scale

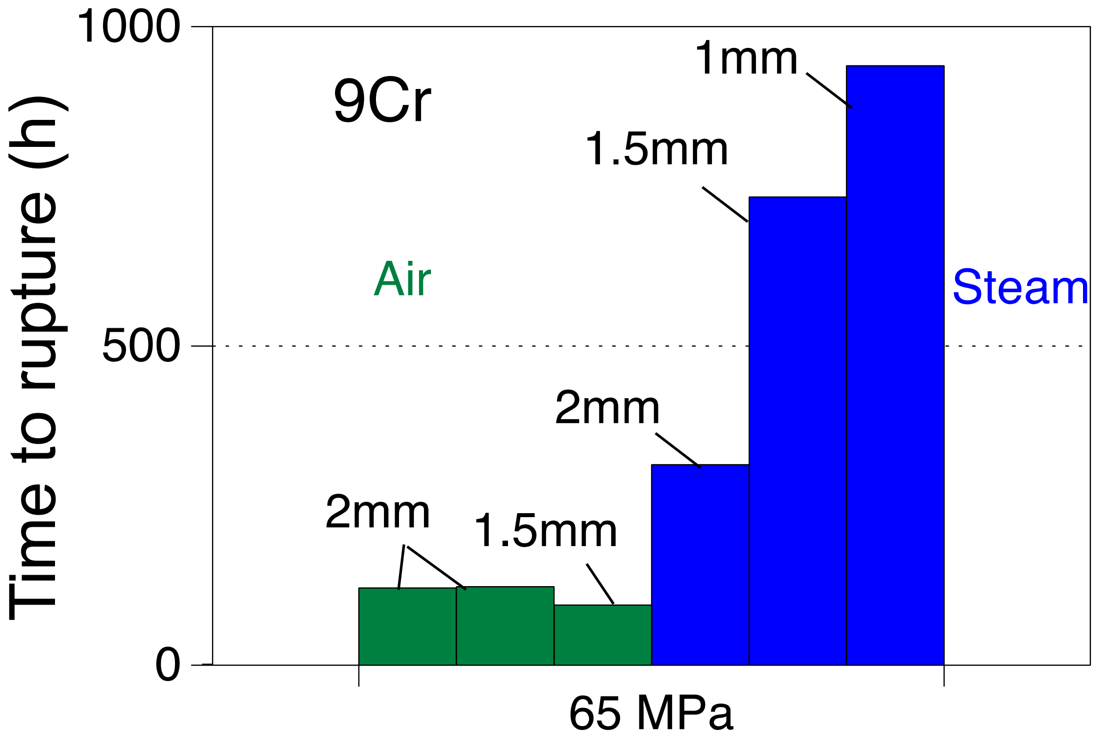


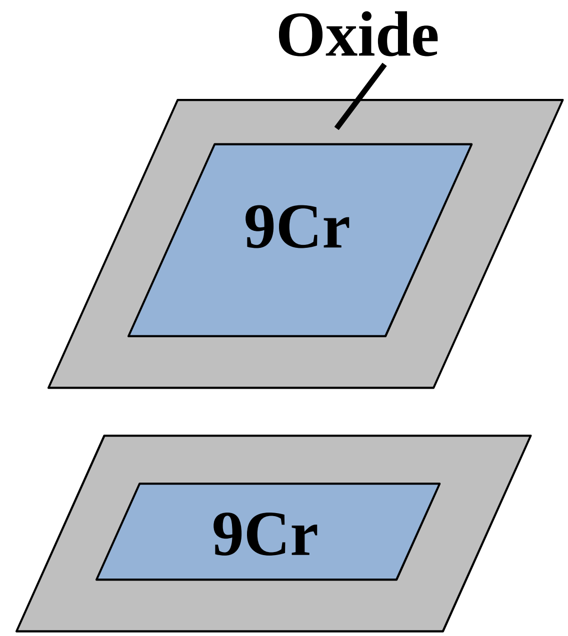


$$F = \sigma_{oxide} \frac{S_{oxide}}{S} + \sigma_{9Cr} \frac{S_{9Cr}}{S}$$

- Load-bearing oxide scale has a significant impact on weak 9Cr

Higher effect of load-bearing scale for thin specimen

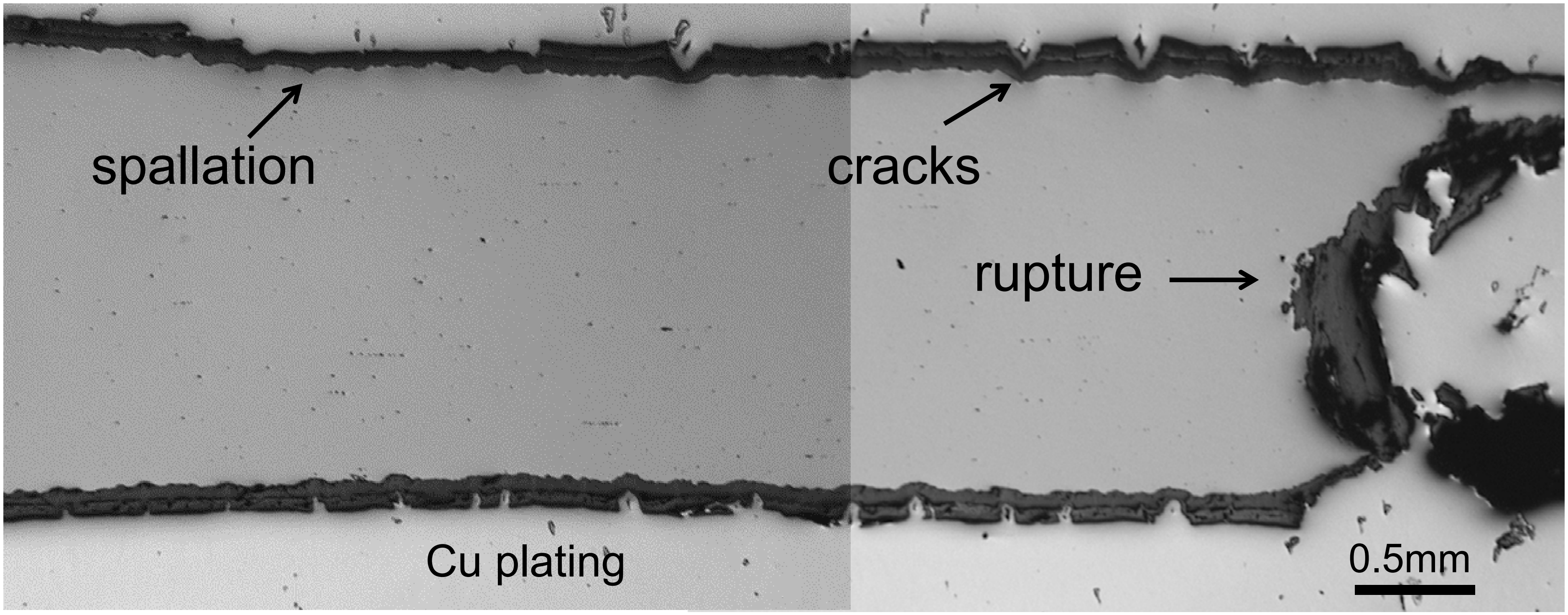




$$F = \sigma_{oxide}\frac{S_{oxide}}{S} + \sigma_{9Cr}\frac{S_{9Cr}}{S}$$

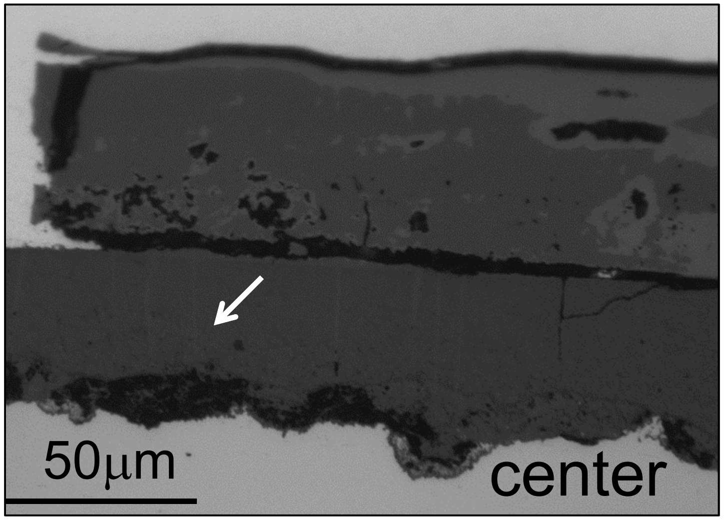
- Thinner specimen to increase the volume to surface ratio

Cracking/debonding of the outer oxide layer but continuous inner layer

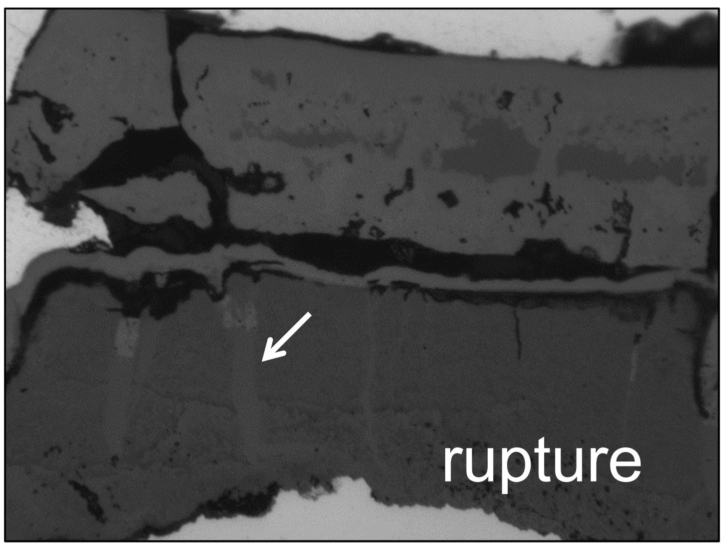


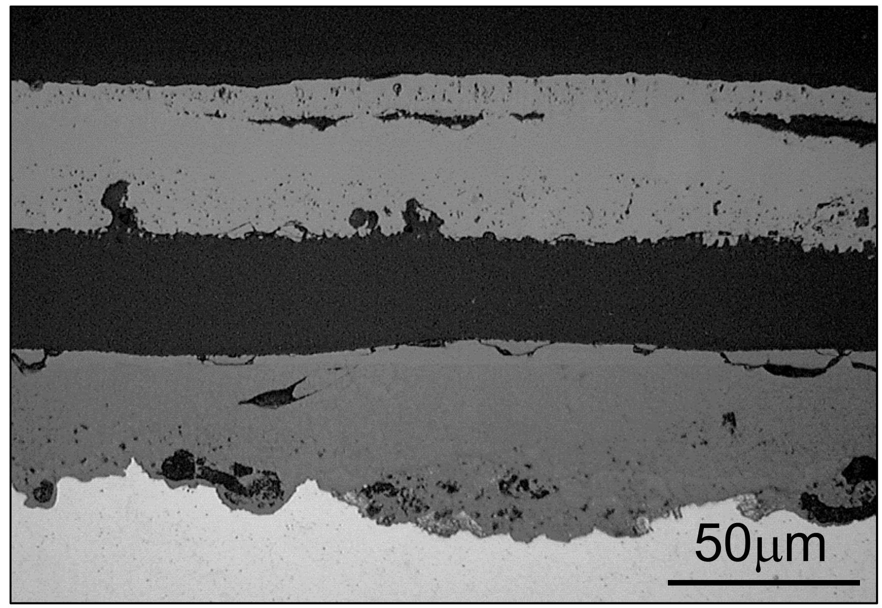
Gr91, Steam, 350h,100MPa

“Similar” oxide scale with and without stress except for healed cracks



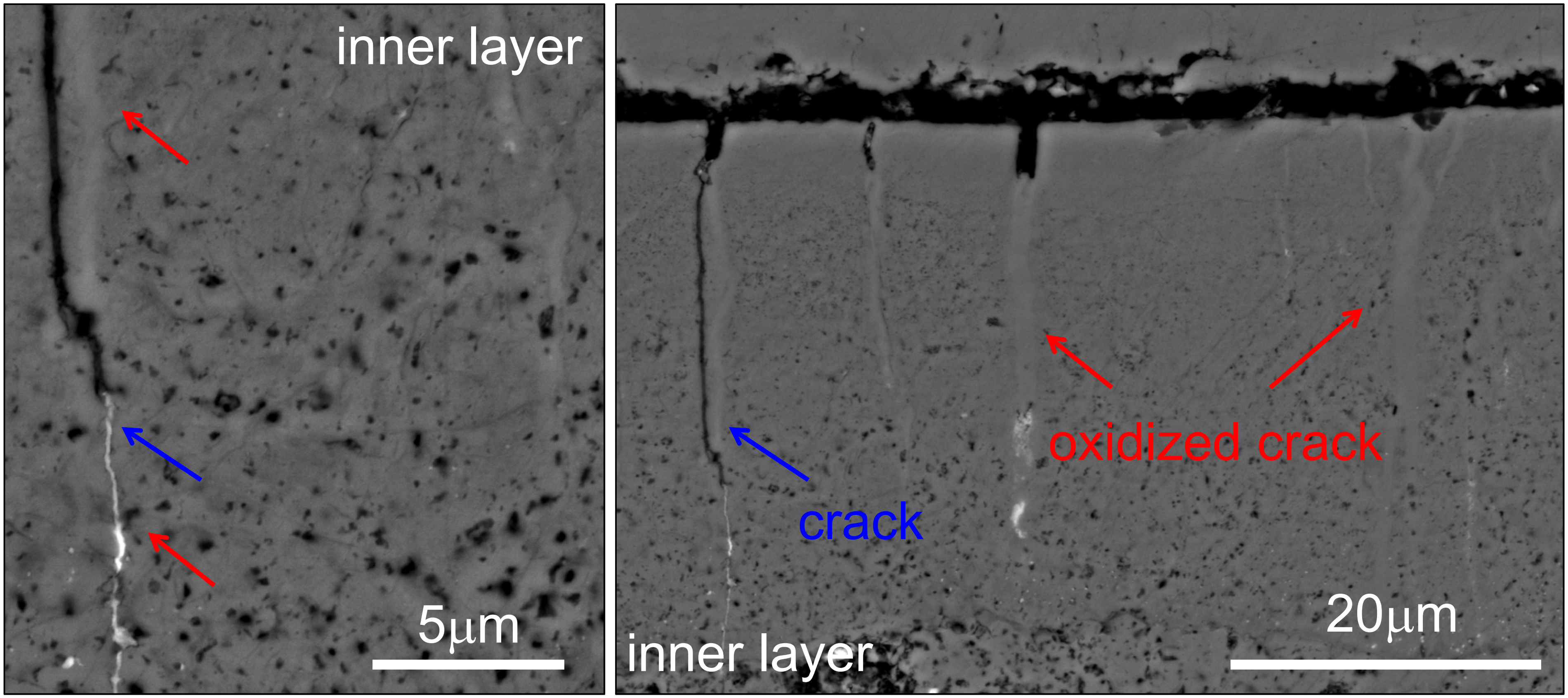
Gr91, Steam, 350h,100MPa





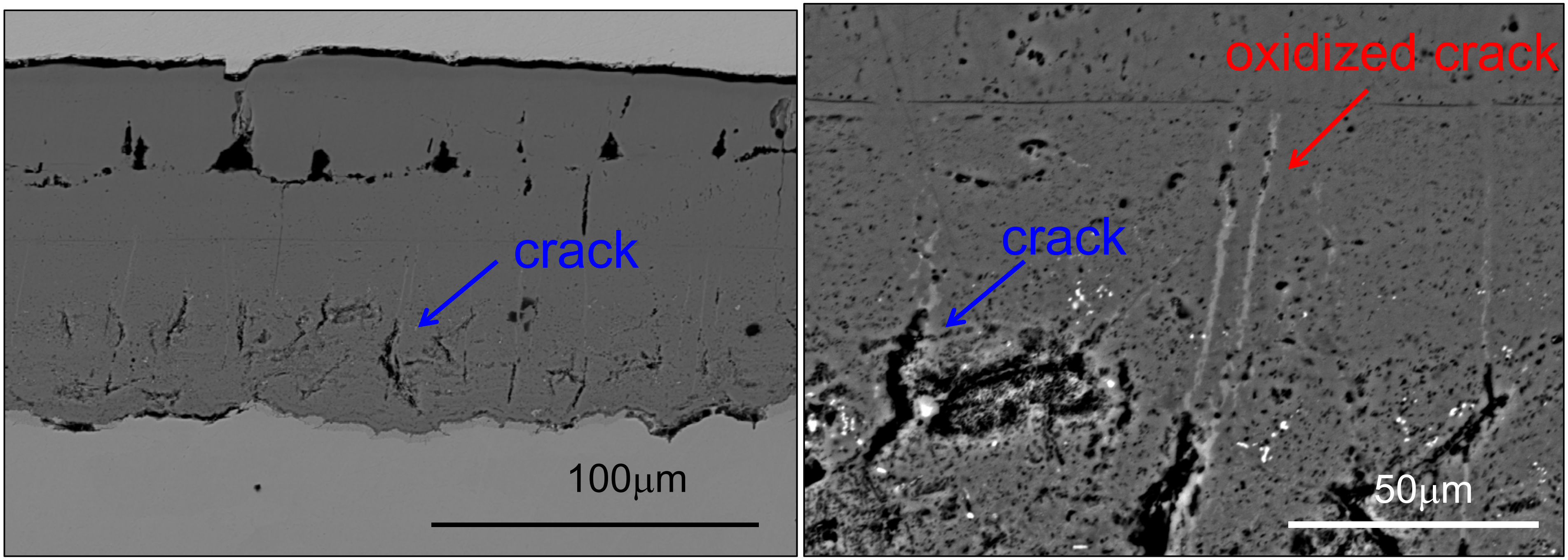
500h in steam at 650ºC no load

Cracks in the inner oxide scale seems to heal by formation of new oxides



Gr91, Steam, 350h,100MPa

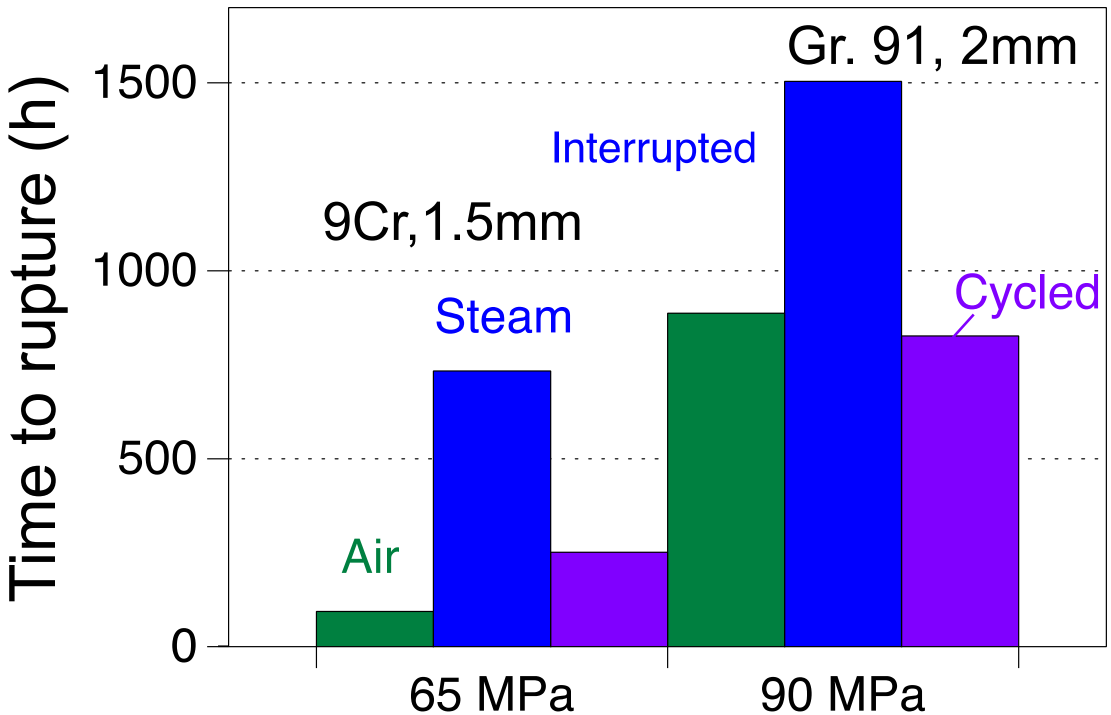
Similar continuous inner layer with oxidized cracks for 9Cr alloy



9Cr, Steam, 314h,65MPa

Small cracks close to the alloy/inner oxide interface

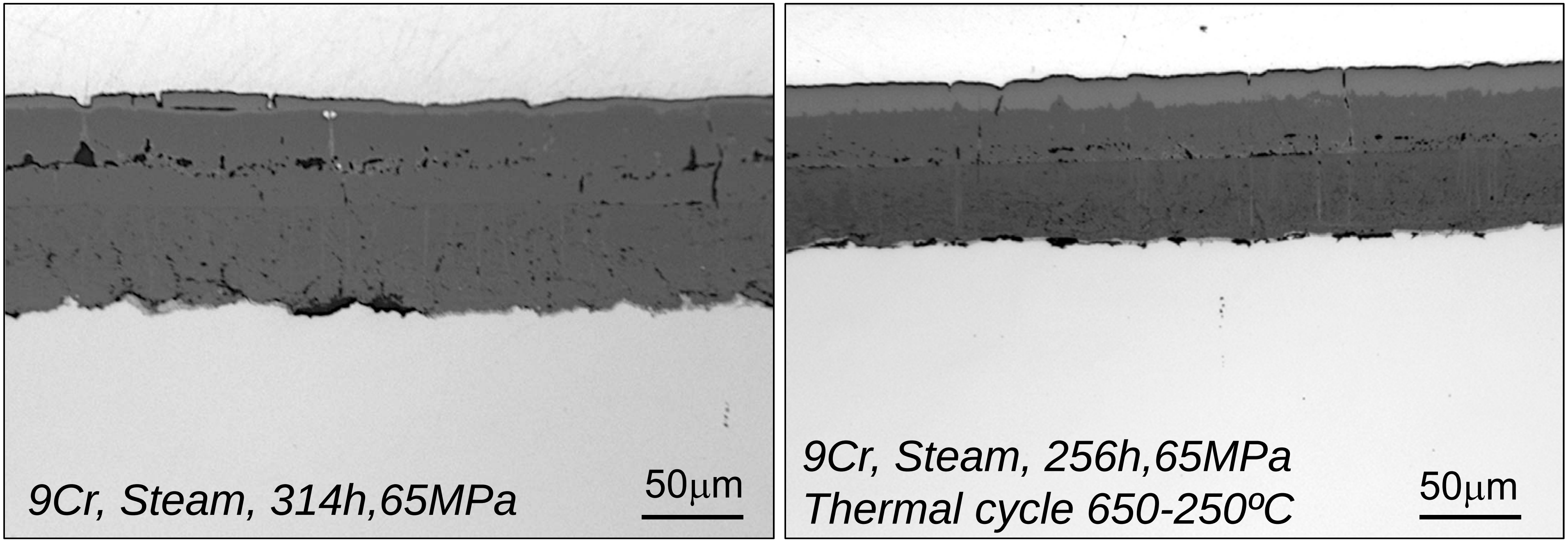
Addition of thermal cycling during creep testing in steam



Cycle:
- 10h at 650ºC
- ~3.5h cooling down to 250ºC
- 5min at 250ºC
- 2h heating to 650ºC

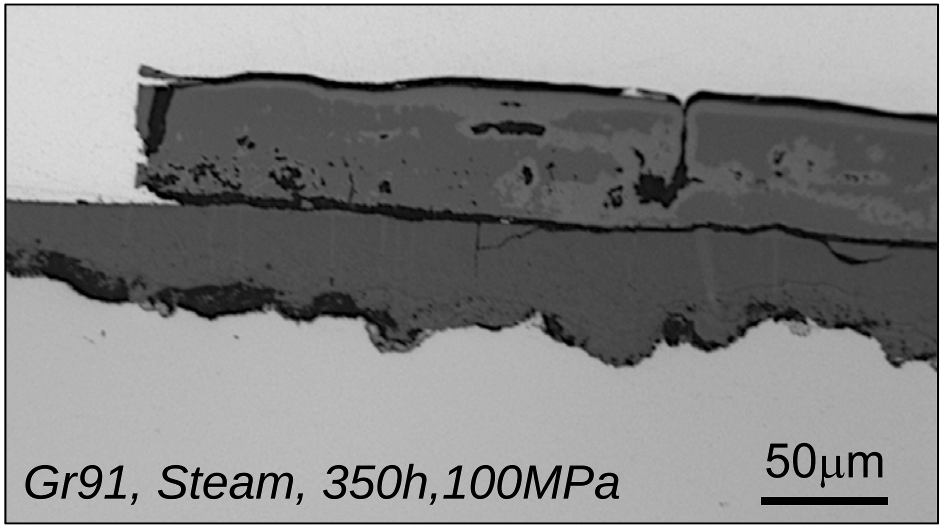
- Cycling resulted in lifetime decrease in steam for 9Cr and gr91 alloys

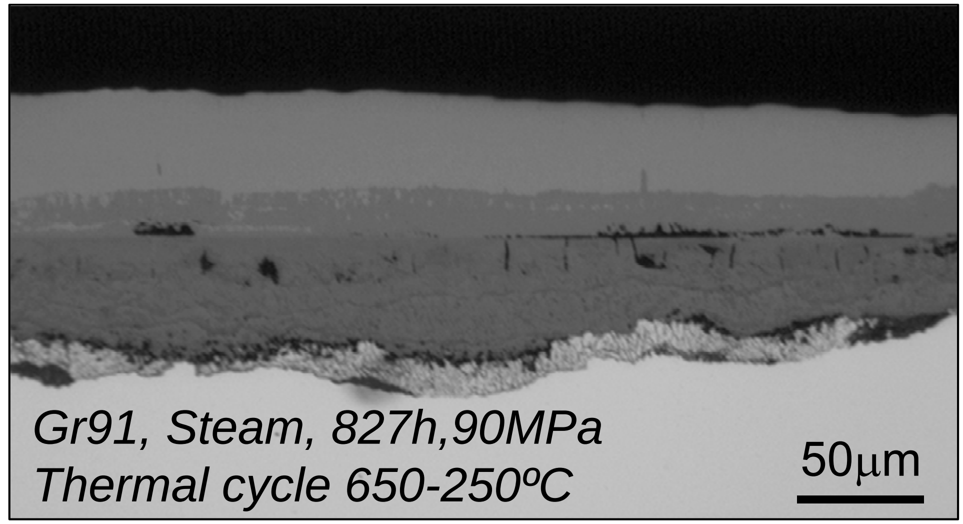
No scale degradation due to thermal cycling for 9Cr alloy



- Thinner scale for thermally cycled specimen

No scale degradation due to thermal cycling for Gr.91 alloy

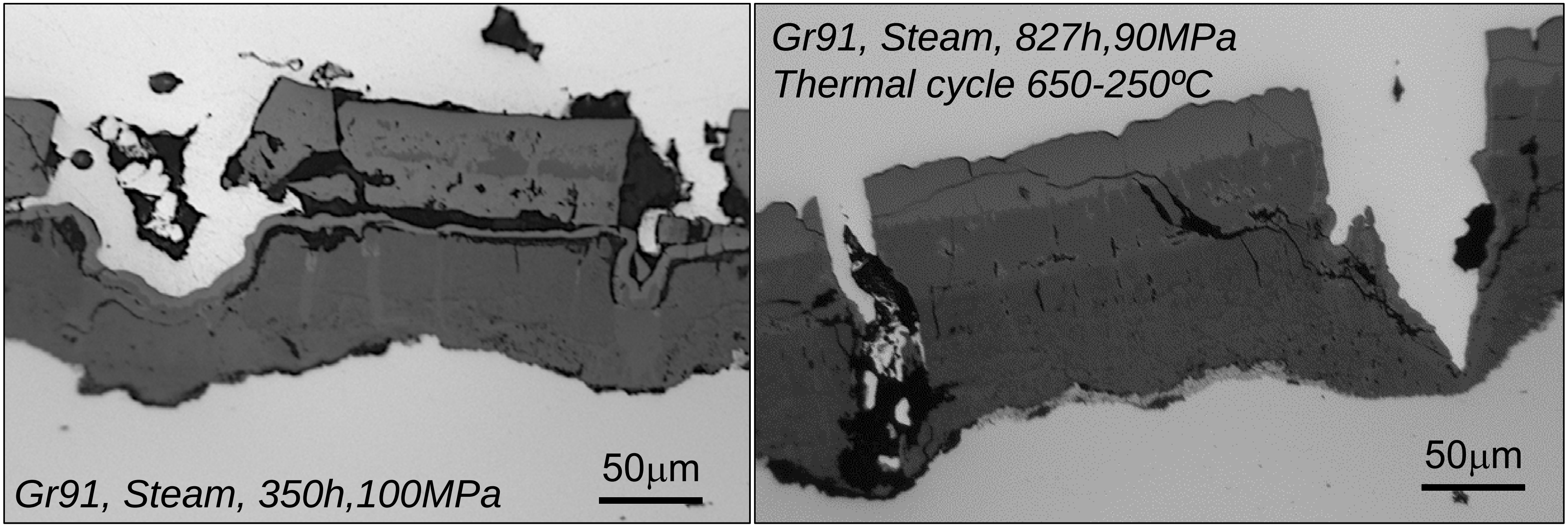




center

- Difference in scale composition?
- No clear explanation for lower lifetime with thermal cycling

Localized effect of thermal cycling during creep testing in steam?



- Will assess the effect of cycling on Gr.91 and 9Cr microstructure

FY15 Milestones

- Perform five creep-fatigue tests in humid atmosphere

  - need to conduct 3 more tests

- Initiate five long-term creep-fatigue tests

  - done

- Submit an open-literature paper on creep-fatigue of ferritic-martensitic steel

  - on track

Future Activities

- Start assembling a new creep-fatigue machine

- Design a set up for creep-fatigue testing in steam

- Compare the performance of different creep-fatigue models based on damage accumulation

- Focus on gr. 91 to develop a microstructure-based model

Acknowledgements

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