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Report on Resolution of Regulatory Issues for VHTR Materials: Notch Effects

M. McMurtrey

March 2017

Idaho National Laboratory

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M. McMurtrey

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Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

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M. McMurtrey
Idaho National Laboratory

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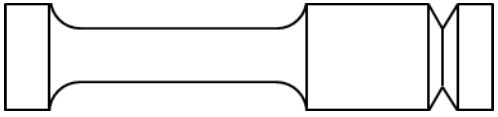
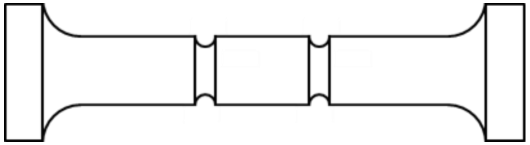
High Temperature Gas Reactor (HTGR)

- A better understanding of the high temperature behavior of Inconel 617 is needed in order to resolve NRC licensing concerns.
- Extensive characterization of uniaxial creep behavior has been performed, in preparation for addition of Alloy 617 to the high temperature section of the ASME Boiler and Pressure Vessel Code (rules for design and construction).
- The current work continues this effort and examines the effects of discontinuities and multi-axial stress states on creep of 617 at high temperatures.

Specimen design

- The circumferential notch is present in all specimens.
- V-notch test specimen contains both a straight bar gauge section and a notch, with equal diameters to test notch weakening/strengthening behavior.
- U-notch test specimens used to analyzed multi-axial creep deformation response.





Ni	Cr	Co	Mo	Al	Ti	Fe	Mn	Cu	Si	C	S	B
54.1	22.2	11.6	8.6	1.1	0.4	1.6	0.1	0.04	0.1	0.05	<0.002	<0.001

Test conditions

- Test conditions chosen to result in reasonable test times and compare with prior work at INL.

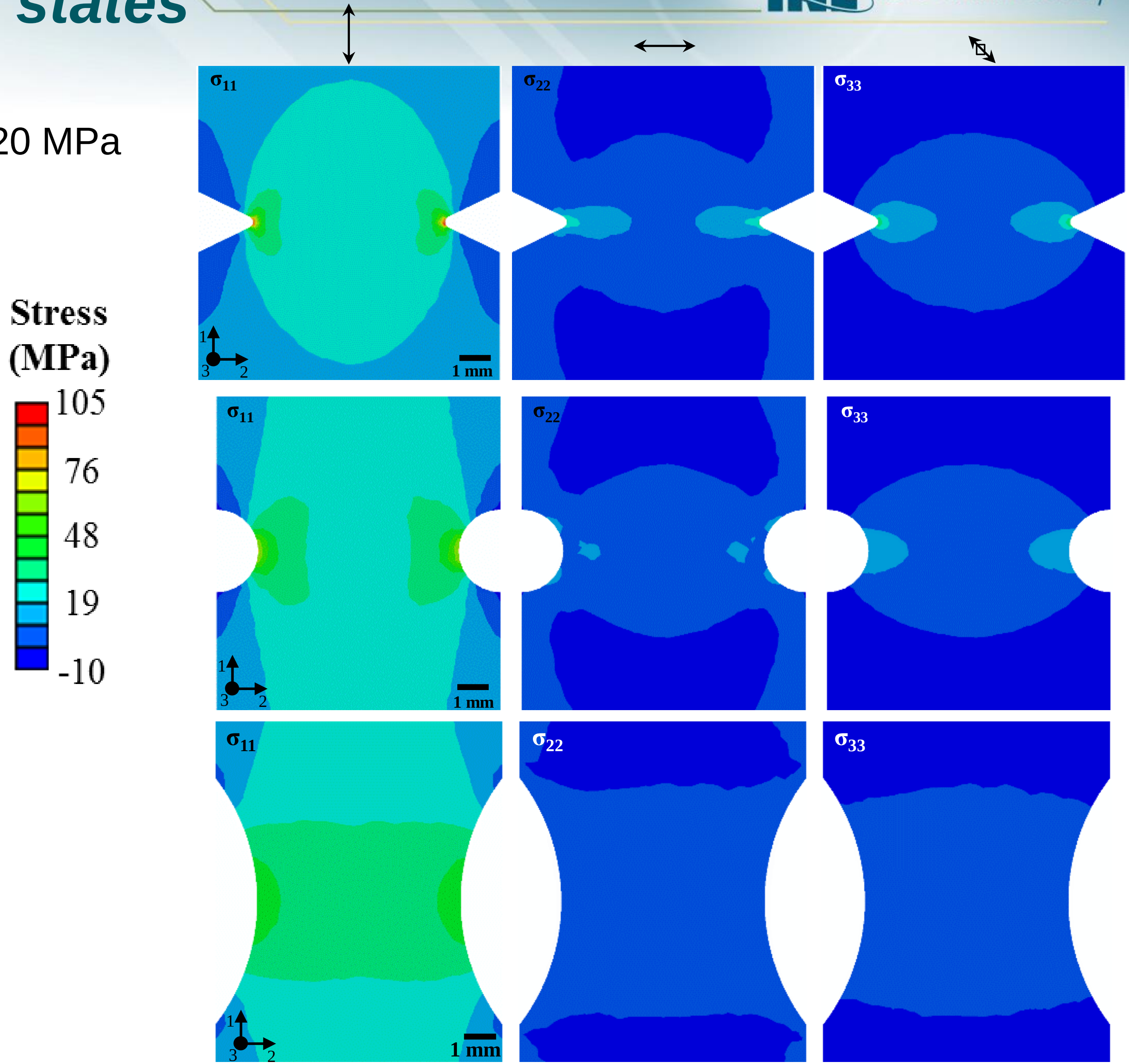
Temperature (°C)	1000	900	800	750
Stress (MPa)	20	36	80	145

- Temperatures 800 – 1000°C, at these stresses, are expected to have a life around 1200 hours.
- The rupture life at 750°C, 145 MPa is expected to be ~2500 hours.

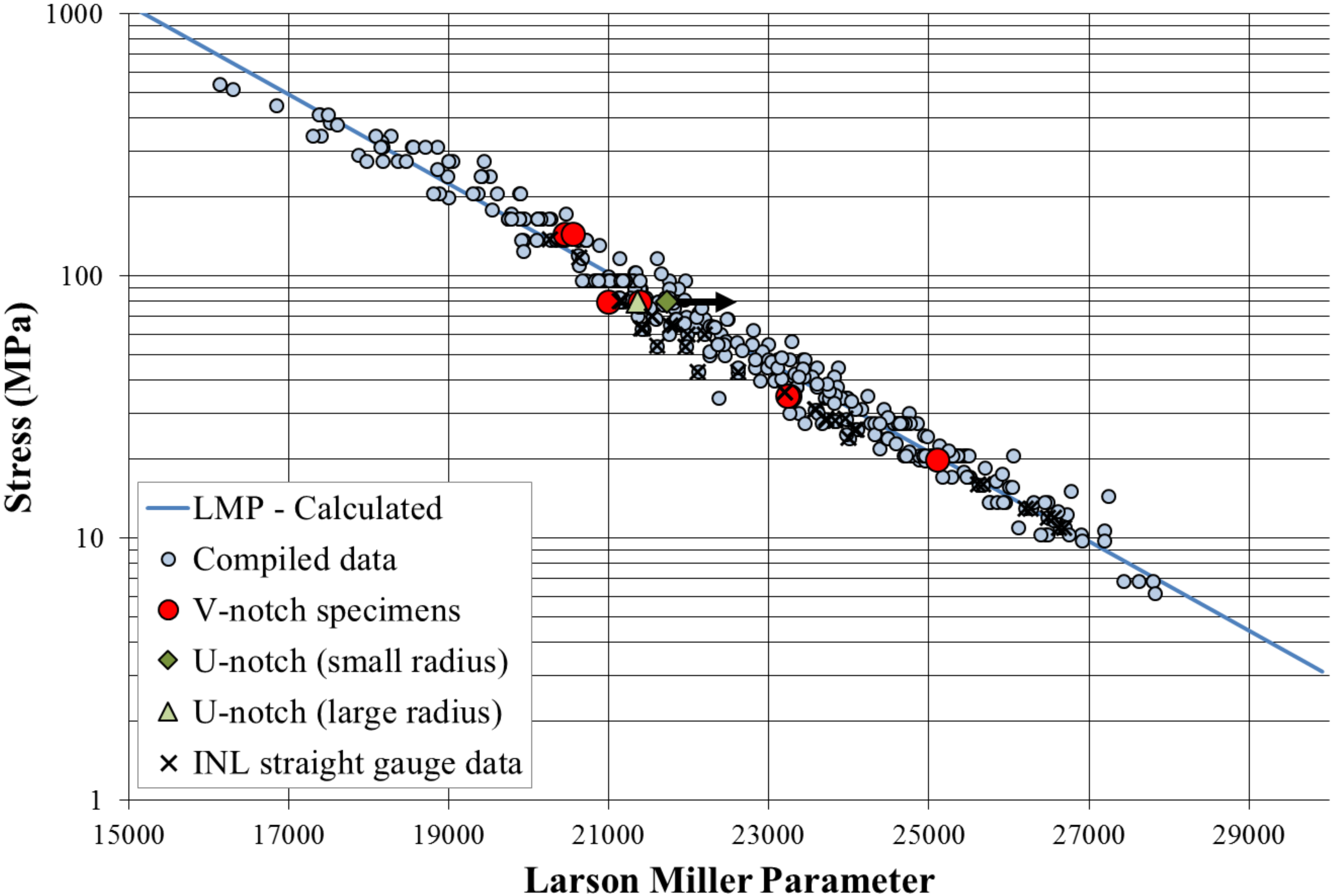
V-notch **U-notch Small radius** **U-notch Large radius**

Initial stress states

Stress states for 20 MPa applied stress

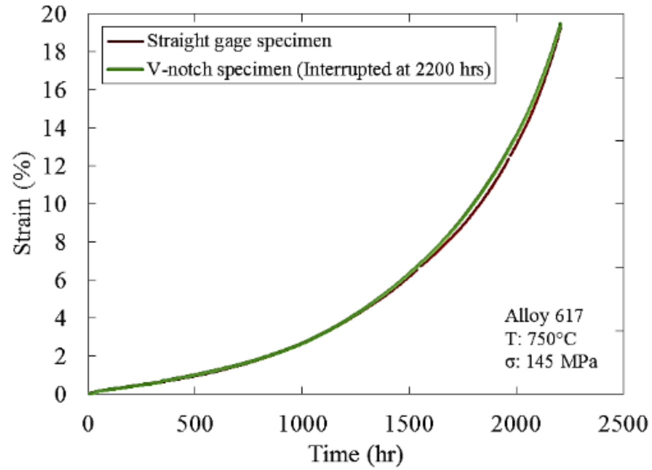


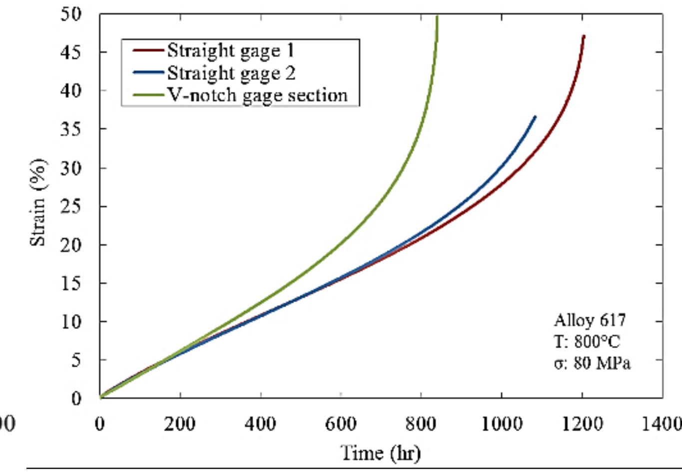
Comparison of rupture life (LMP)

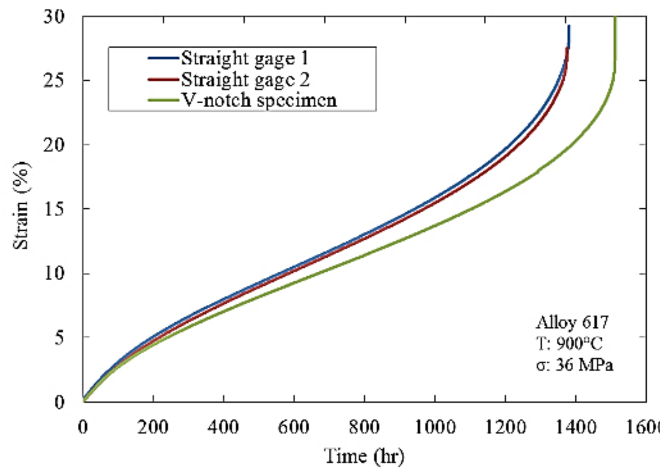


Creep V-notch testing (straight gauge measurements)

Displacement measured across the straight gauge

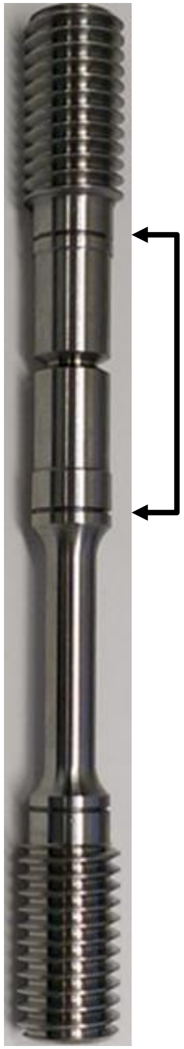




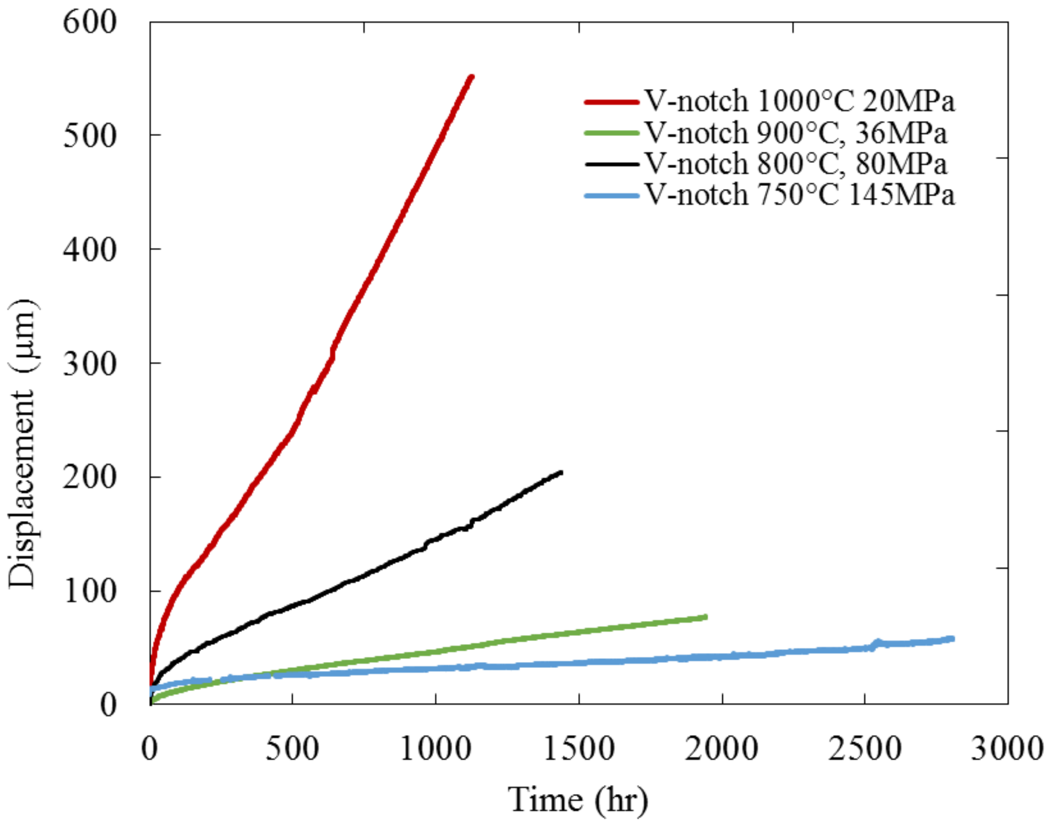


Creep results for V-notch specimens with extensometers over the straight gauge section and tested at 750, 800, and 900°C.

V-notch testing (notch displacement measurements)

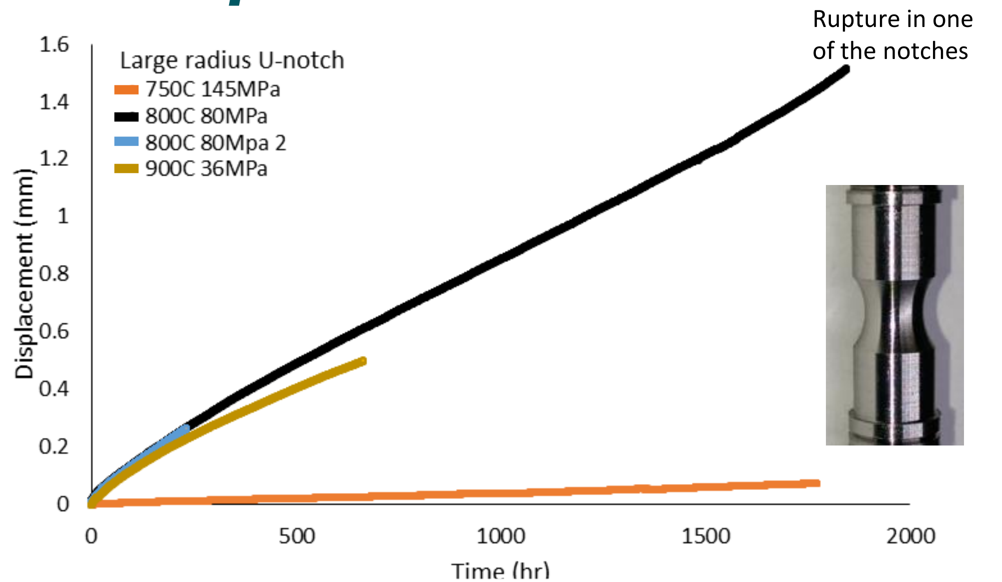


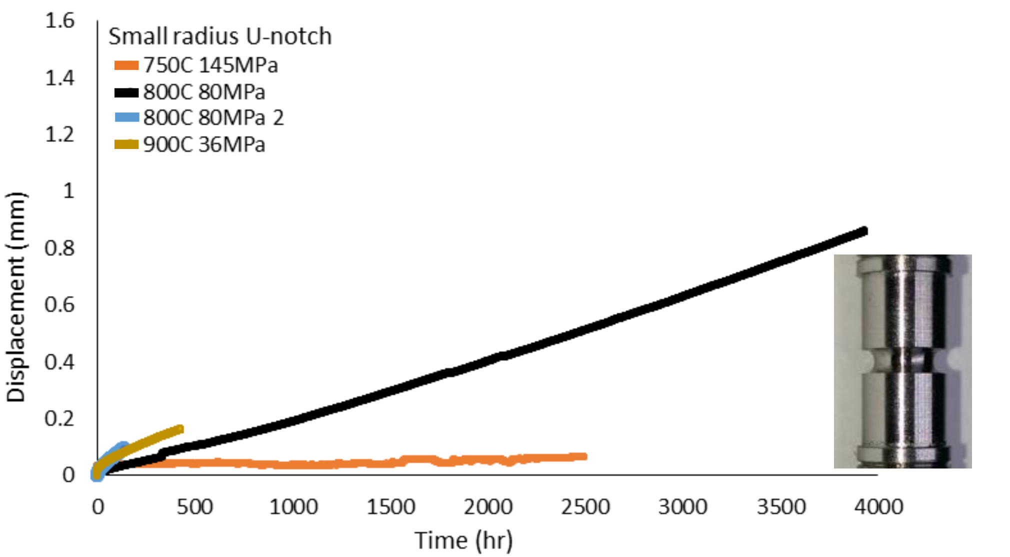
Displacement measured across the V-notch



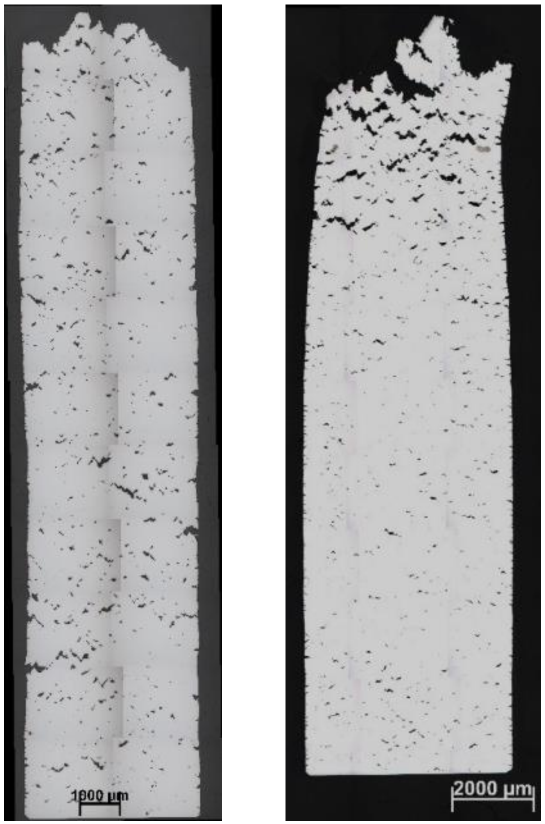
Testing of U-notch specimens

- Limited results – only a single test has finished.
- Life of straight gauge specimens tested at INL for these conditions was ~1200 hrs for all but the 750°C, 145 MPa tests, which had a life of ~2500 hours.
- Currently running large and small radius U-notch at 900°C, 36 MPa, 750°C, 145 MPa and replicate 800°C 80MPa tests.

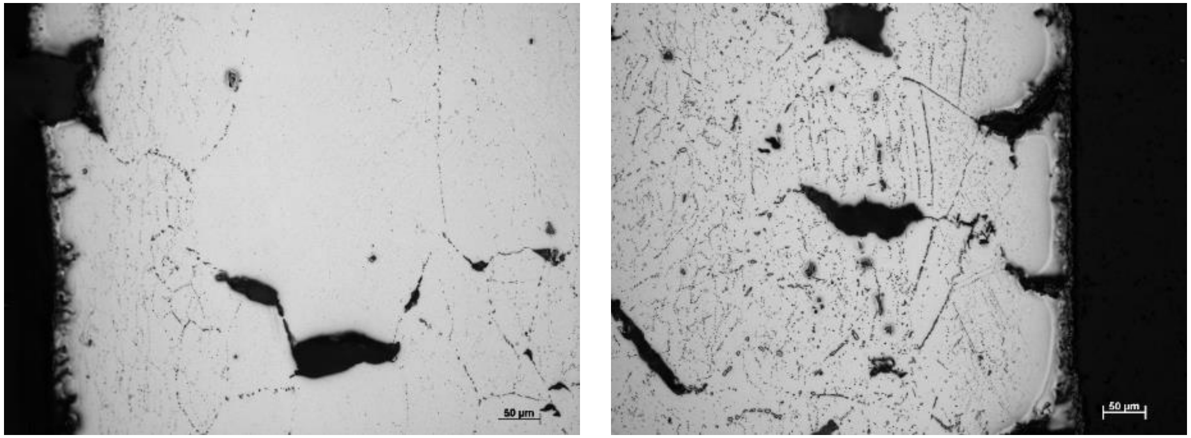




Damage in straight gauge section

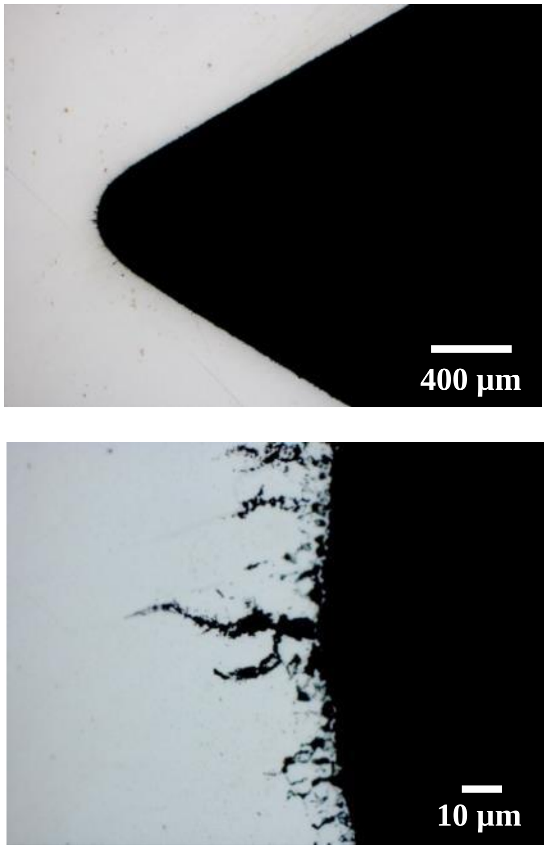


Optical micrographs showing fractured gauge section tested at 800°C (left) and 900°C (right)

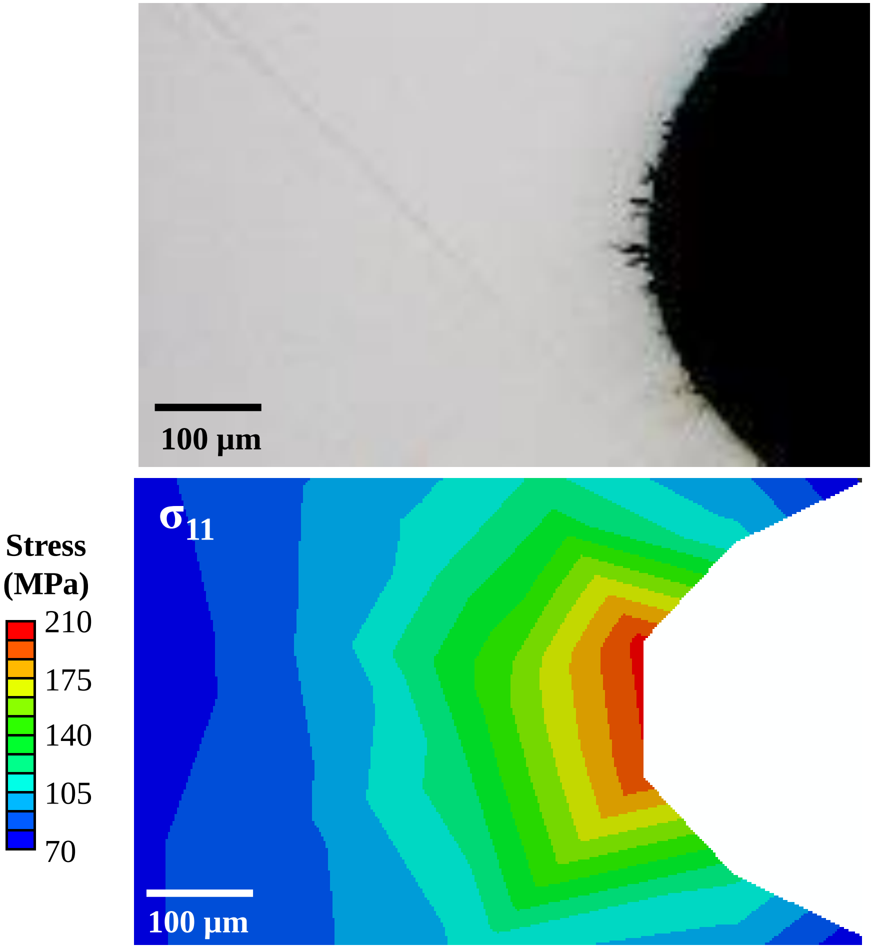


Optical micrographs after electrochemical etch showing cracking occurring at the grain boundaries for both (left) the 800°C and (right) the 900°C tests.

Plasticity and damage at notch tip

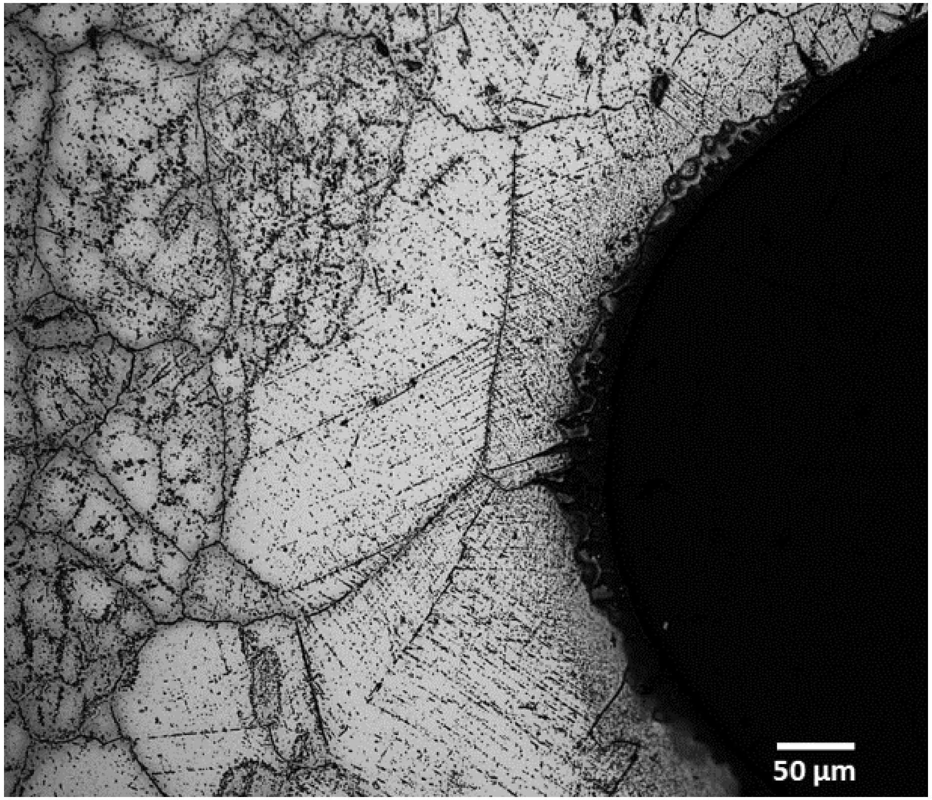


Optical micrographs from the V-notch (800°C, 80 Mpa)



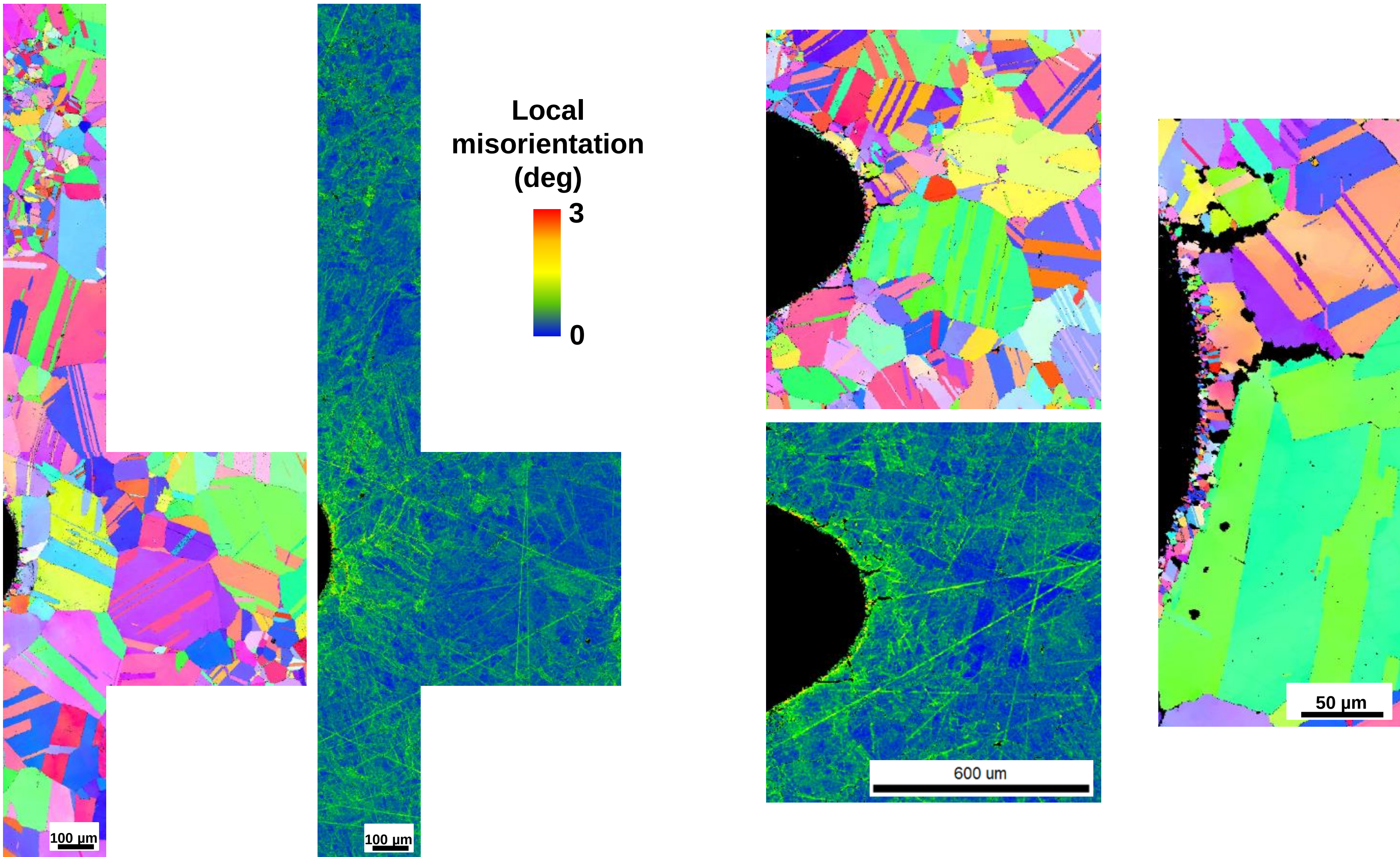
FEA model of stress in the loading axis and optical micrograph showing the tip of the V-notch, (applied stress 80 MPa at 800°C).

Plasticity and damage at notch tip

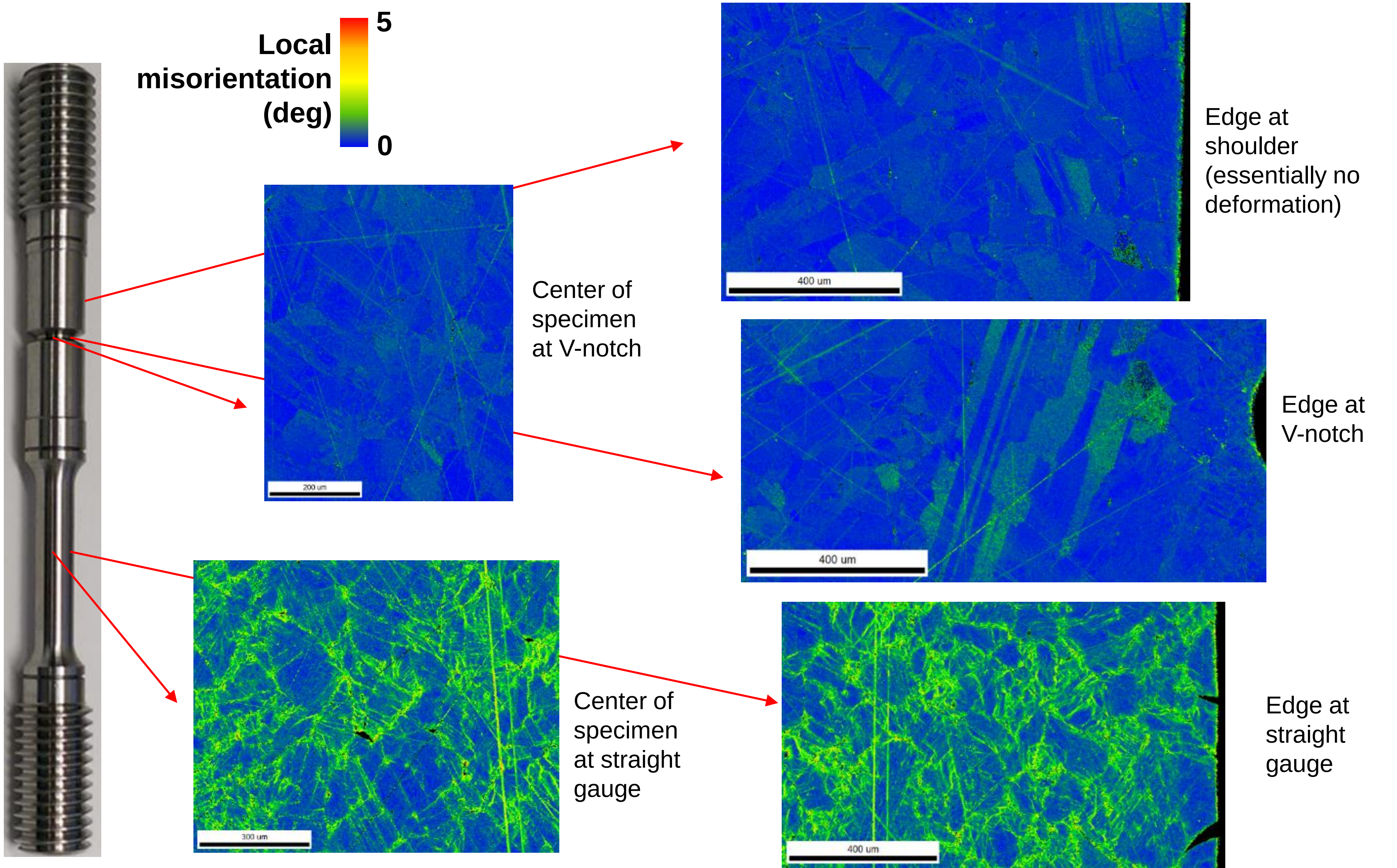


Optical micrographs after electrochemical etch of the V-notch (800°C, 80 Mpa)

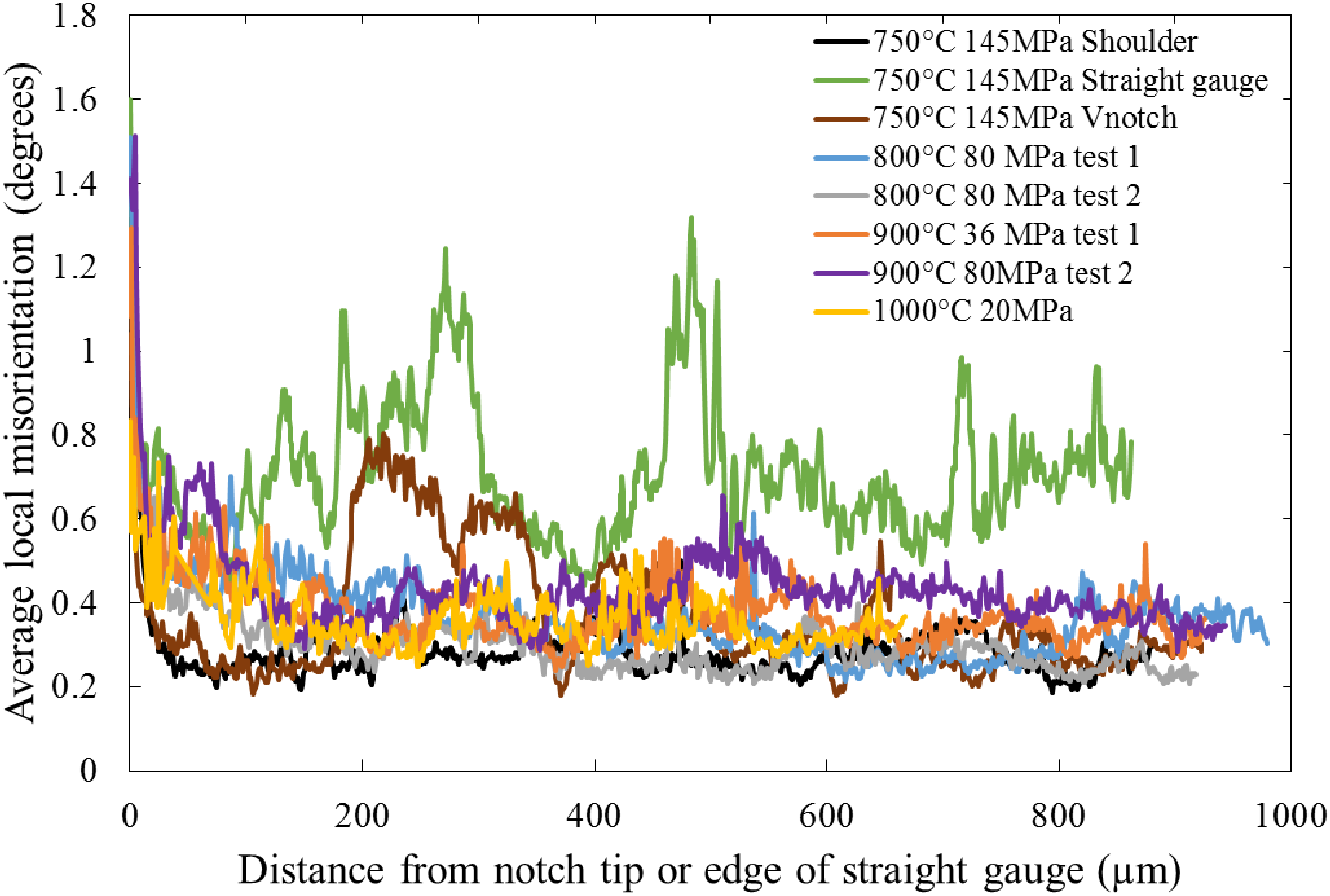
EBSD from 800ºC 80MPa (left) and 900ºC 36MPa creep test (right)



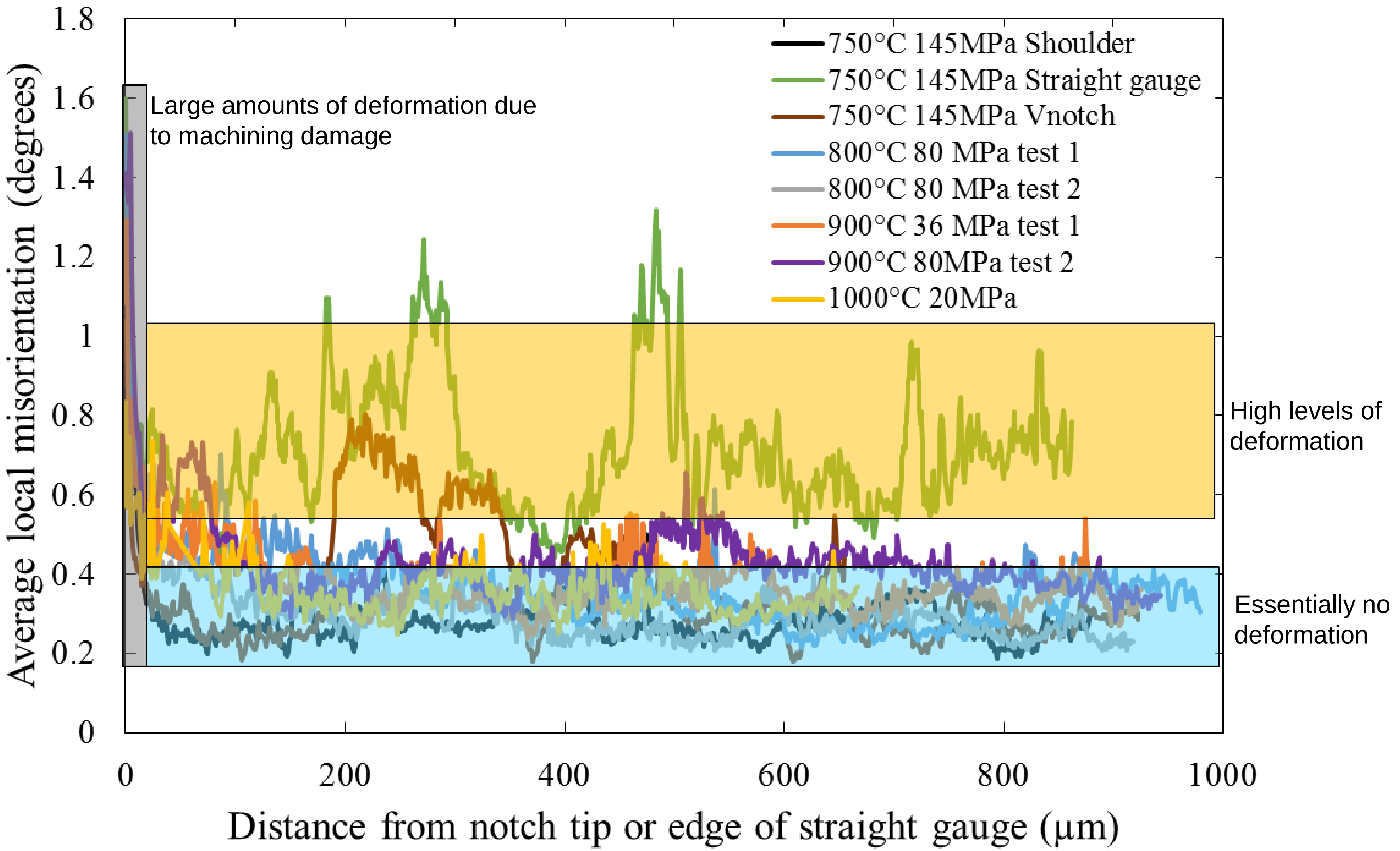
Interrupted test (750^{o}C, 145 MPa, 2200 hrs)



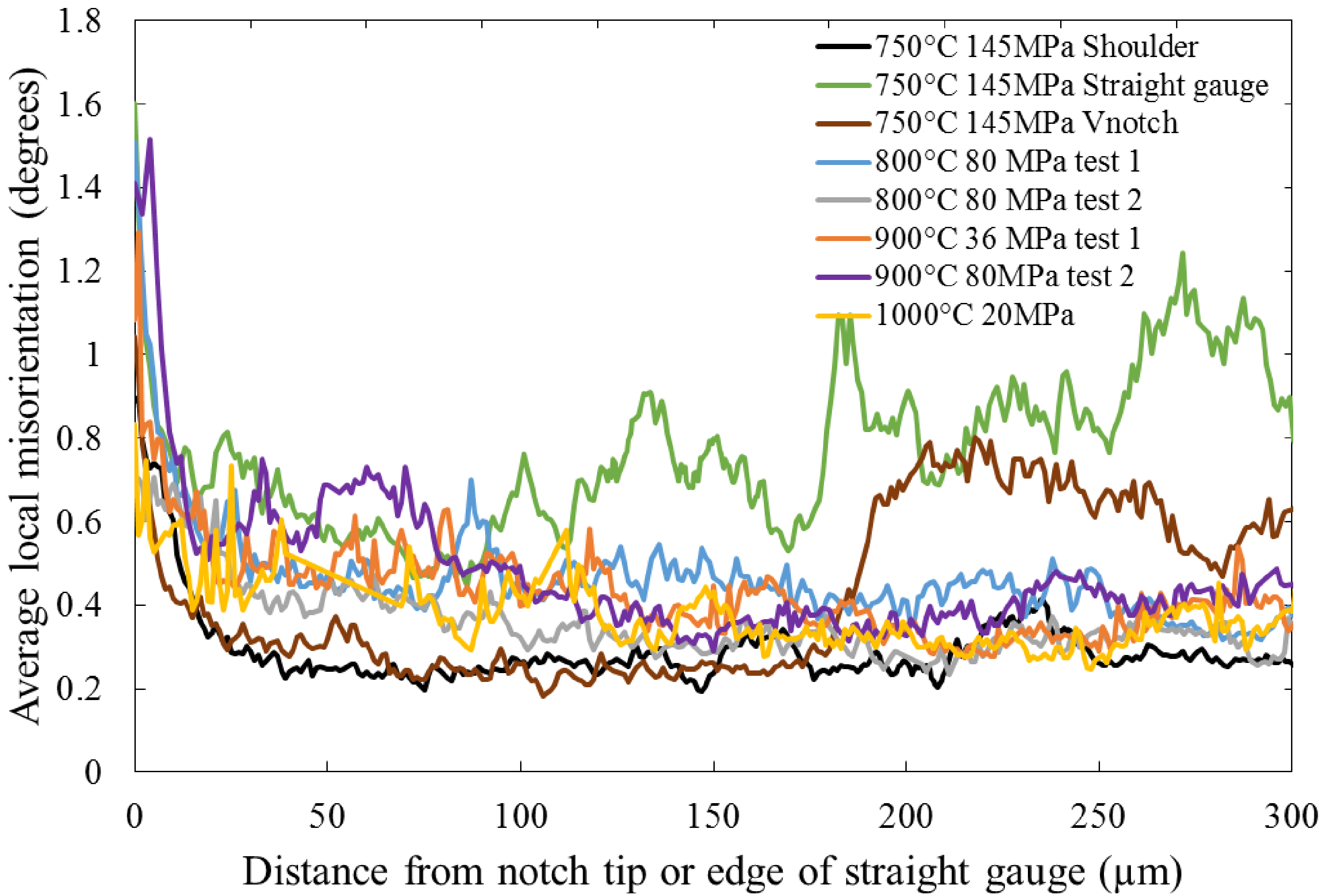
Deformation in V-notch specimens



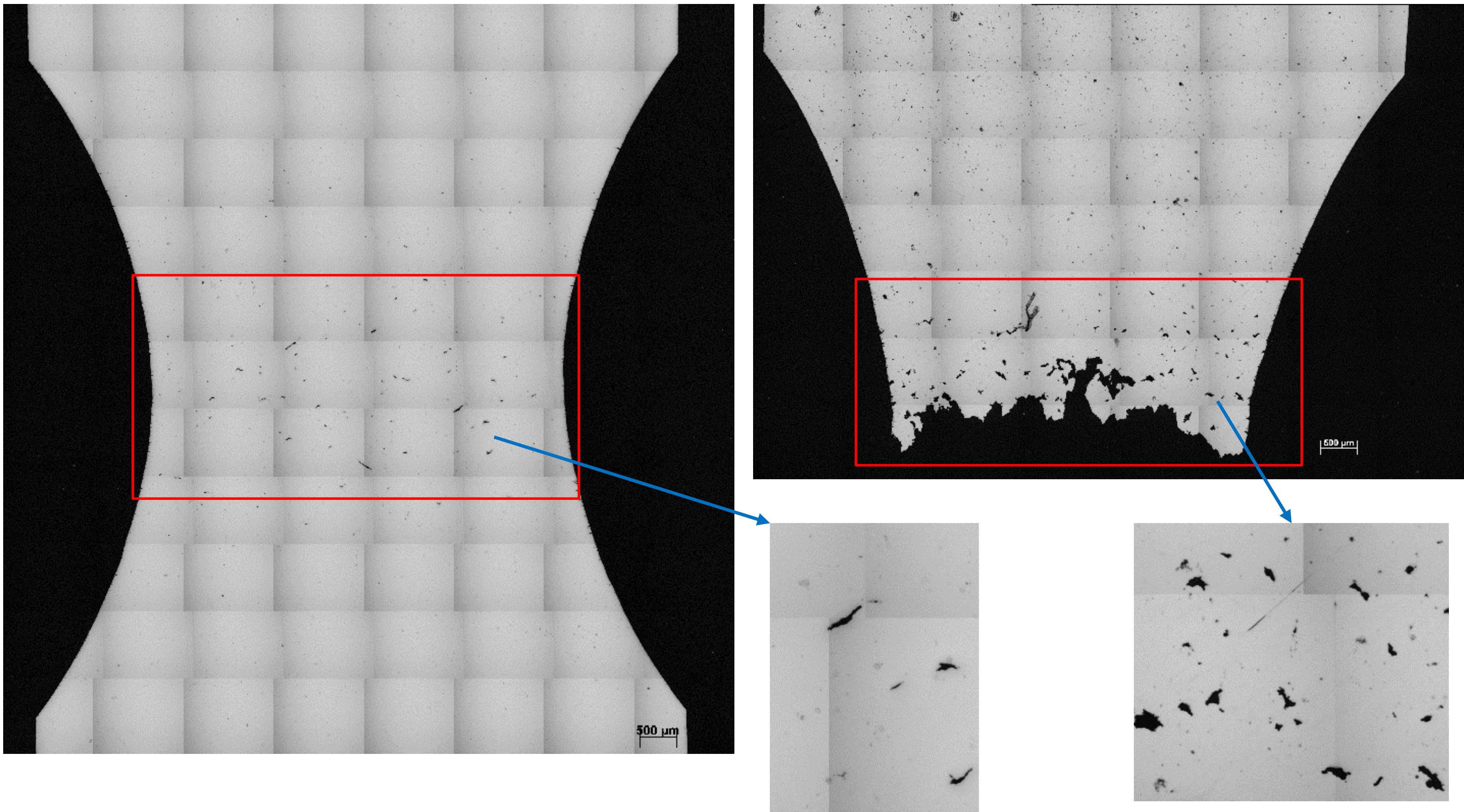
Deformation in V-notch specimens



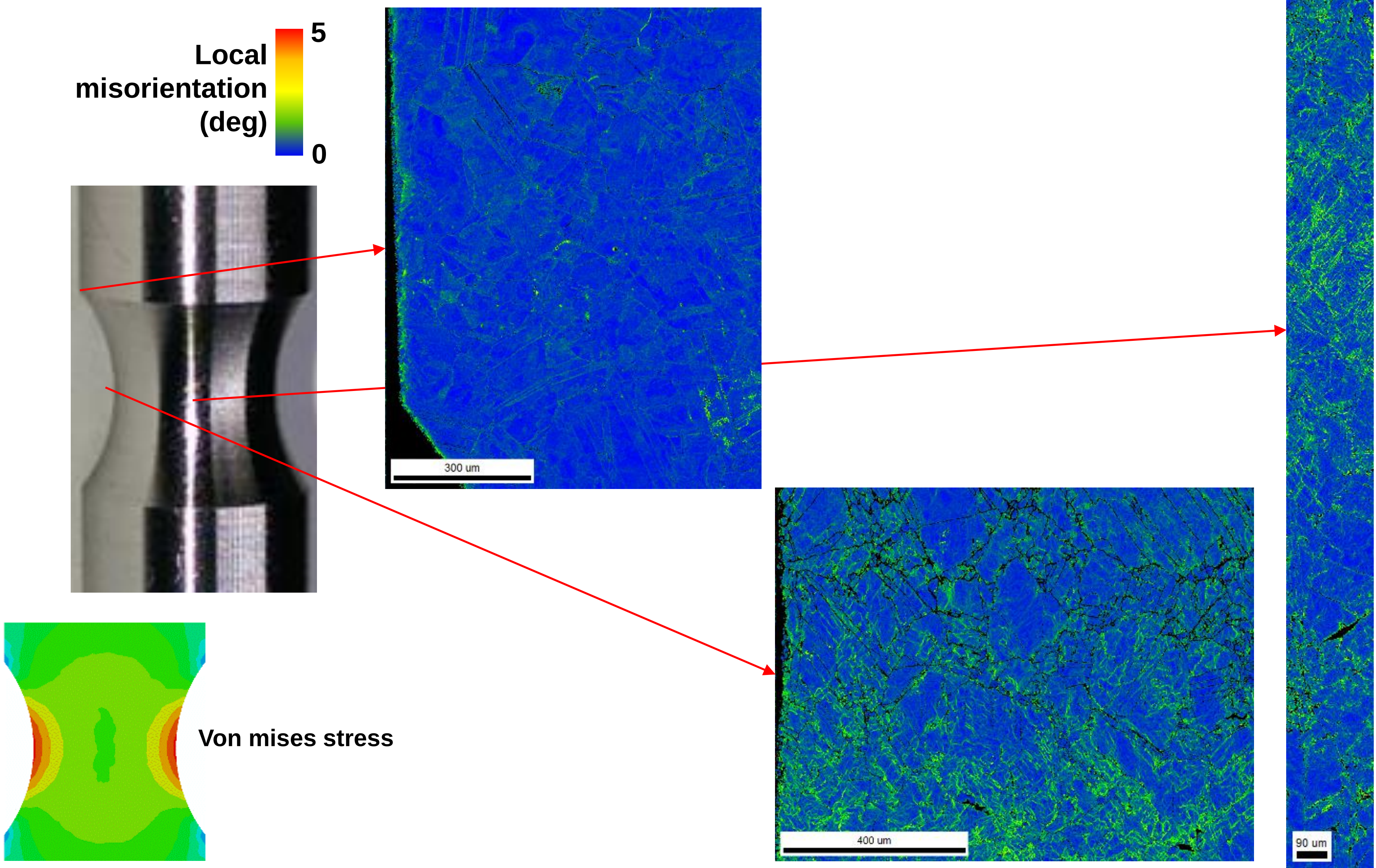
Plasticity at V-notch tip



Damage in large radius U-notch specimen (800℃, 80 MPa)



Deformation in large radius U-notch specimens



Conclusions

- Alloy 617 is notch strengthening at temperatures between 750-1000^{o}C and short lifetimes (~1000-2500 hours)

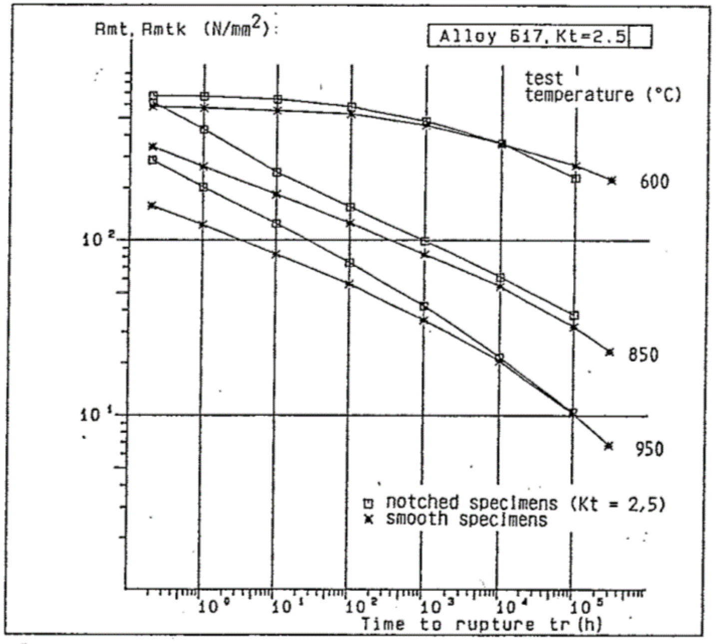
- Notch strengthening effect is due to restrictions on plastic deformation, very little evidence deformation is noted beyond ~150µm from the notch tip.

- Initial testing suggests that multi-axial stress states do not shorten creep rupture life compared to laboratory uniaxial creep measurements, and in some cases, increase the rupture life.

- It is possible that the small radius U-notch tests experience notch strengthening effects as well as multi-axial stress states

Upcoming work

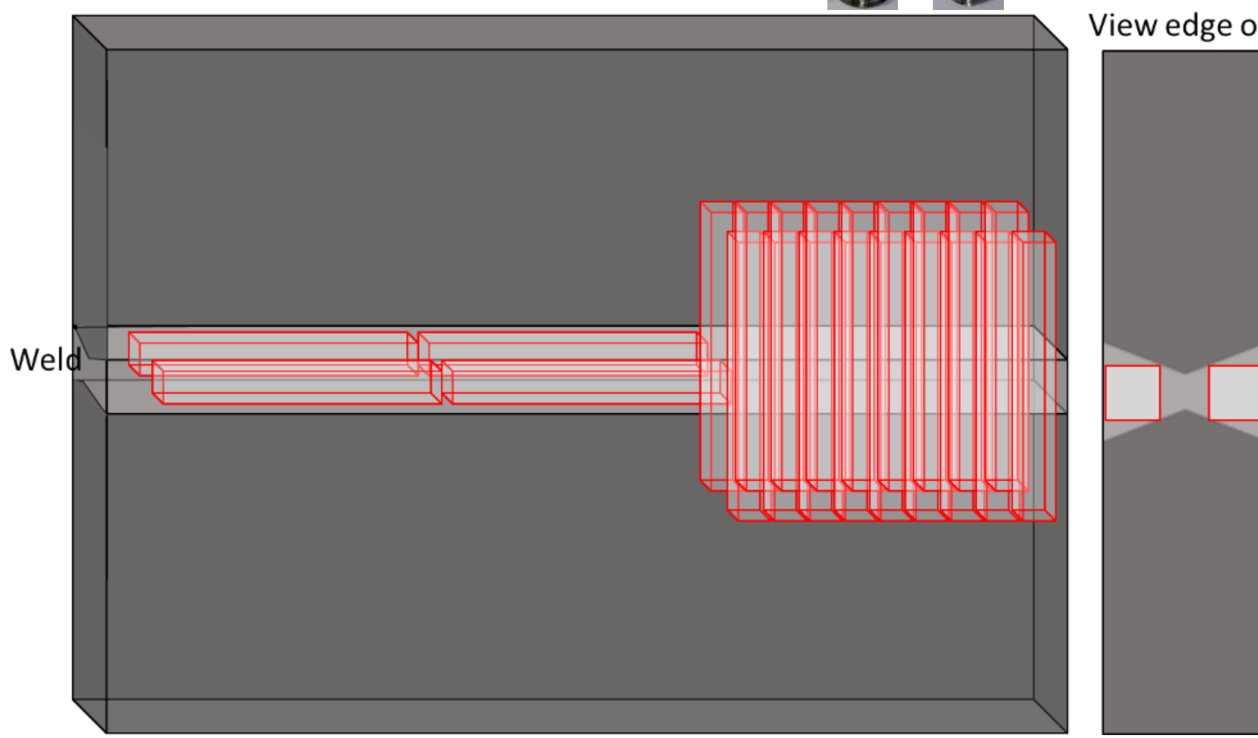
- Finish U-notch test matrix
- Long term V-notch strengthening/weakening tests
  - Test at 750°C 86.8MPa and test at 900°C 25.3MPa (estimated life 20,000 hrs)
- Long term U-notch test?
- Notched specimens machined from welded plate



Isothermal stress-rupture curves for notched and smooth 617 specimens (notch radius 0.5 mm)
Diehl, Sonsino, Third International Conference on Biaxial/Multiaxial Fatigue, 1989

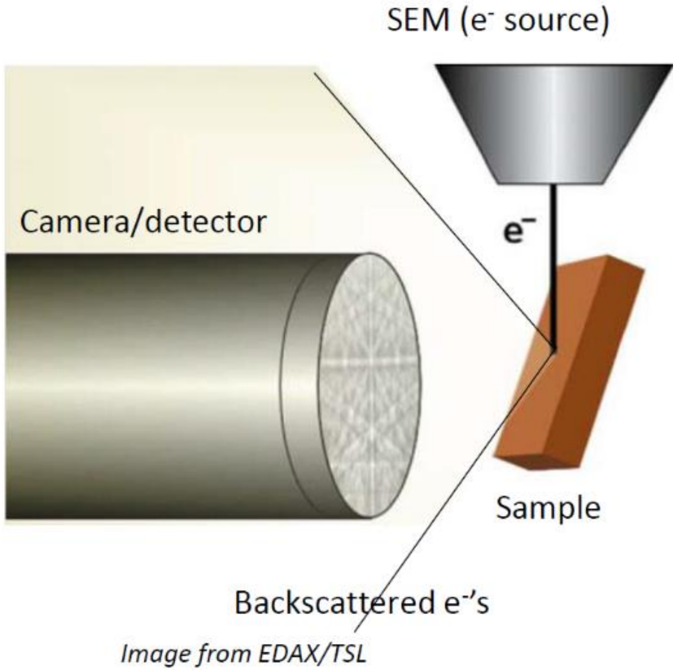
Upcoming work – welded specimens

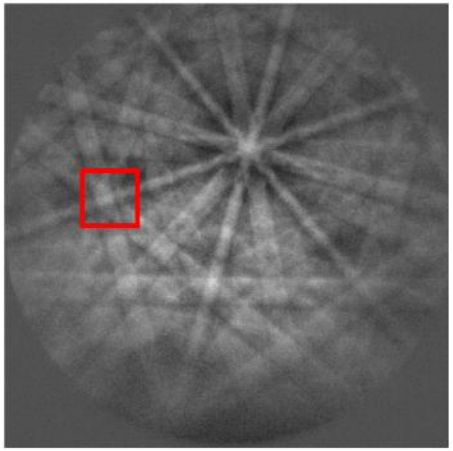
- V-notch/straight gauge specimen machined entirely within weld
- Single notch U-notch specimens machined so that notch is contained within weld and the rest of the specimen is in the base material



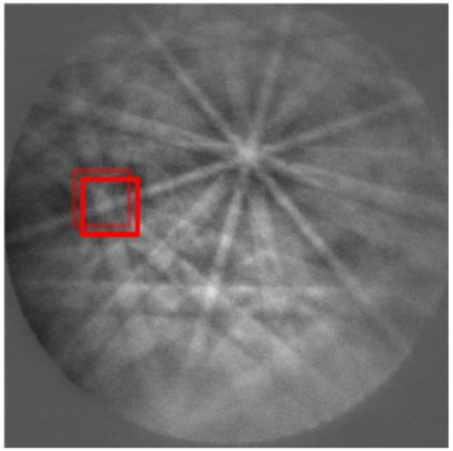
Backup slides

EBSD





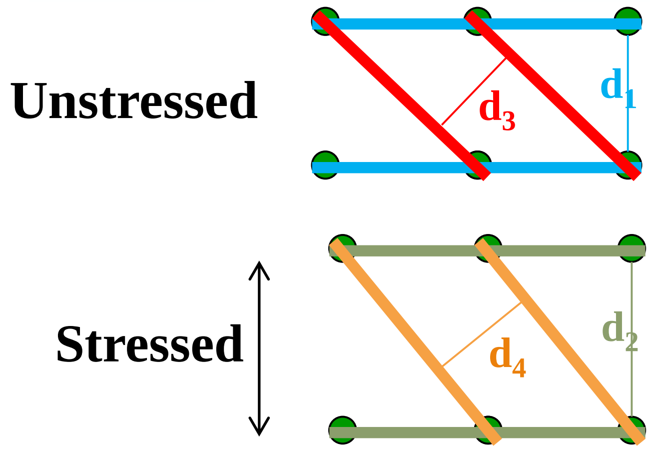
Pattern from unstressed lattice



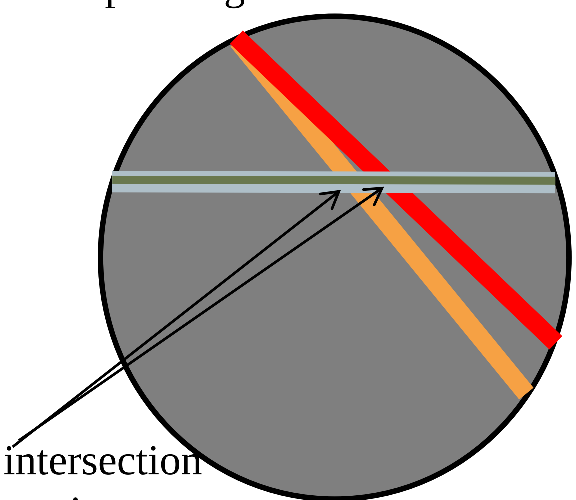
Pattern from stressed lattice

Stress and strain measurements via EBSD analysis

- Measures changes the Kikuchi pattern to determine changes in the crystal lattice.
- High resolution measurements require a reference pattern at a zero strain state.
- Cross correlation gives higher resolution than Orientation Image Microscopy (OIM) typically used to create grain orientation maps.
  - OIM angular resolution of 0.5°
  - High res techniques (cross correlation) are as good as 0.006° (Wilkinson *et. al*. Ultramicroscopy 2006)
- Can be used to measure distortion in the crystal lattice caused by:
  - elastic strain
  - rotation in the lattice caused by the presence of dislocations.



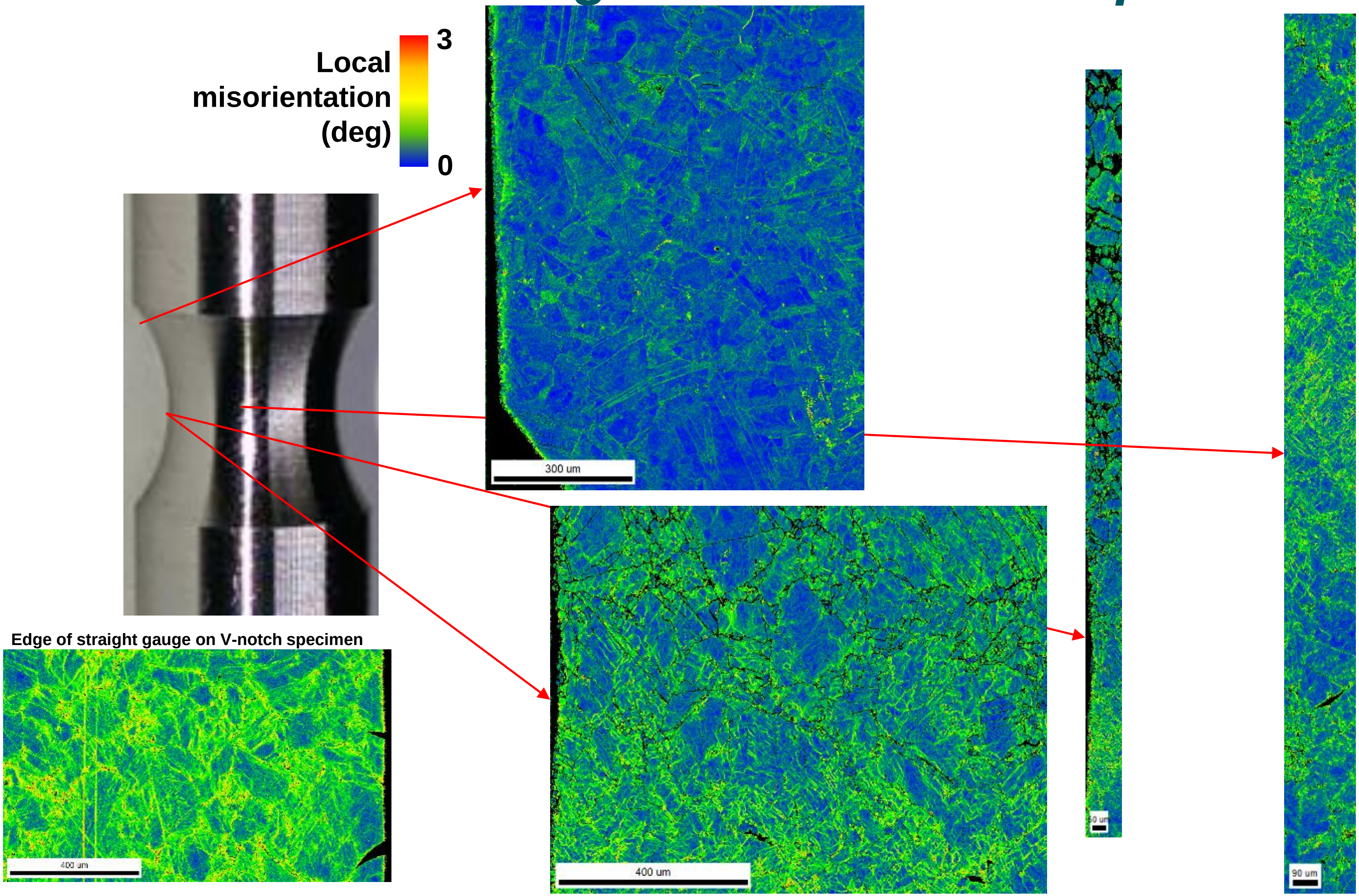
Colored lines represent lattice planes in the above diagram and the corresponding Kikuchi bands below.



Shift in band intersection due to elastic strain

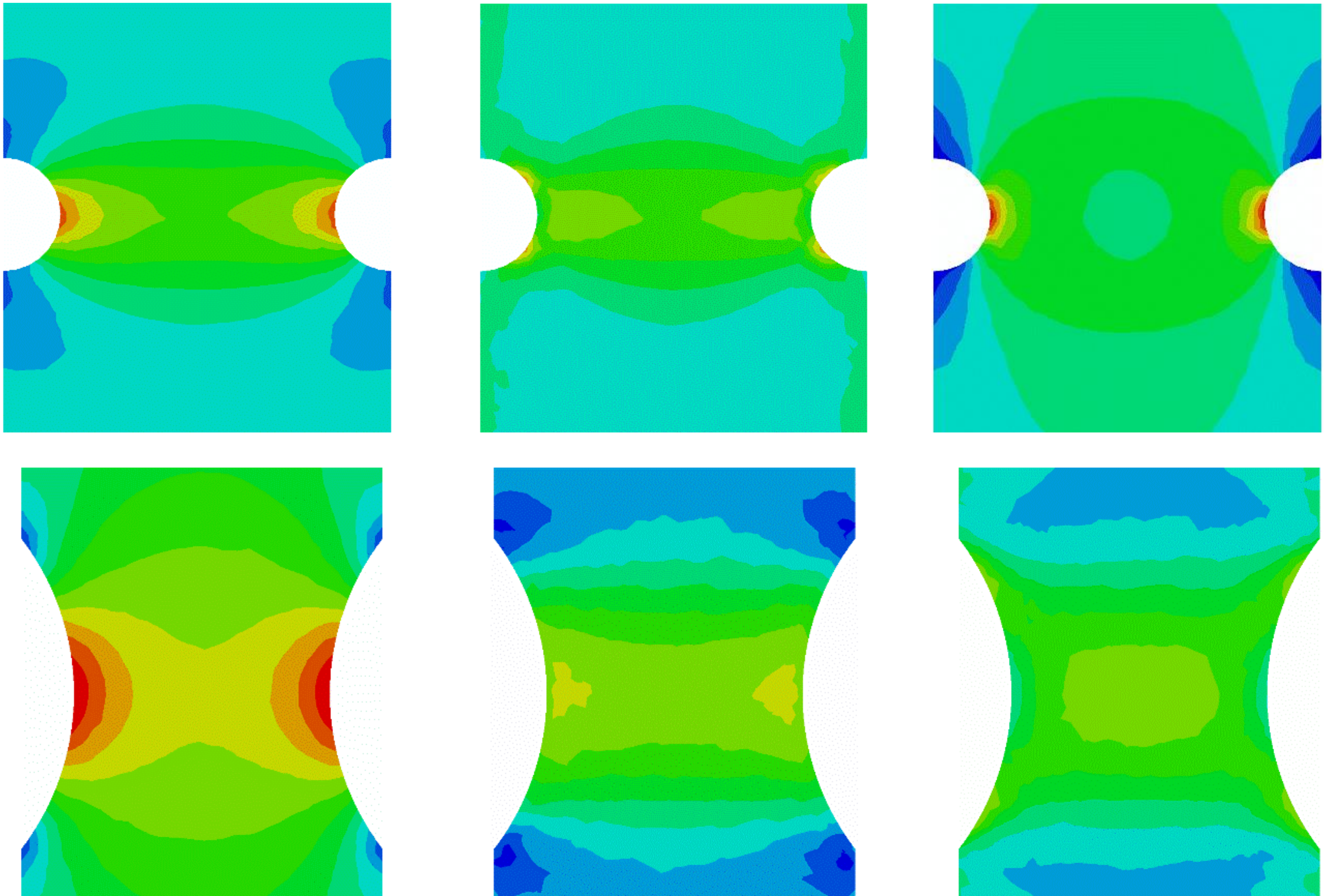
Kikuchi bands

Deformation in large radius U-notch specimens



Edge of straight gauge on V-notch specimen

Smaller color scale U-notch stresses



Advanced reactor materials issues

- The Code contains mandatory requirements, specific prohibitions, and nonmandatory guidance for construction activities and inservice inspection and testing activities. The Code does not address all aspects of these activities and those aspects that are not specifically addressed should not be considered prohibited.

  -ASME Code foreword, 2015

- NRC has listed areas of concern from assessment of the Clinch River Breeder Reactor in the late 70's and early 80's, and in the 90's, the NRC sponsored a reevaluation of the design issues for high temperature reactors. Both times, concerns for notch weakening effects were listed.

- Current versions of the Code (Section III, Division 5) address to some degree the prior regulatory concerns
  - Uniaxial creep behavior is addressed
  - Creep-fatigue for wrought products
  - Environmental effects
  - Rules for the design of welded joints
- Some concerns still not addressed by the code
  - Detailed material properties needed for cyclic finite element creep design analysis
  - More work needed to adequately cover cyclic loads in creep regime and creep fatigue-creep rupture interaction effects
  - Creep-fatigue of weldments is not well understood
  - Need to expand high temperature design work to handle additional materials, higher temperatures and creep damage mechanisms anticipated for the new reactors.
- R&D to address regulatory and licensing concerns:
  - Develop an understanding of the relationship between complex multi-axial component loading and metallurgical behavior observed in uniaxial testing under laboratory conditions.
  - Simplified strain limits and creep-fatigue bounding rules at geometric and metallurgical discontinuities.
- Multiaxial stress states can significantly affect creep and fatigue behavior.