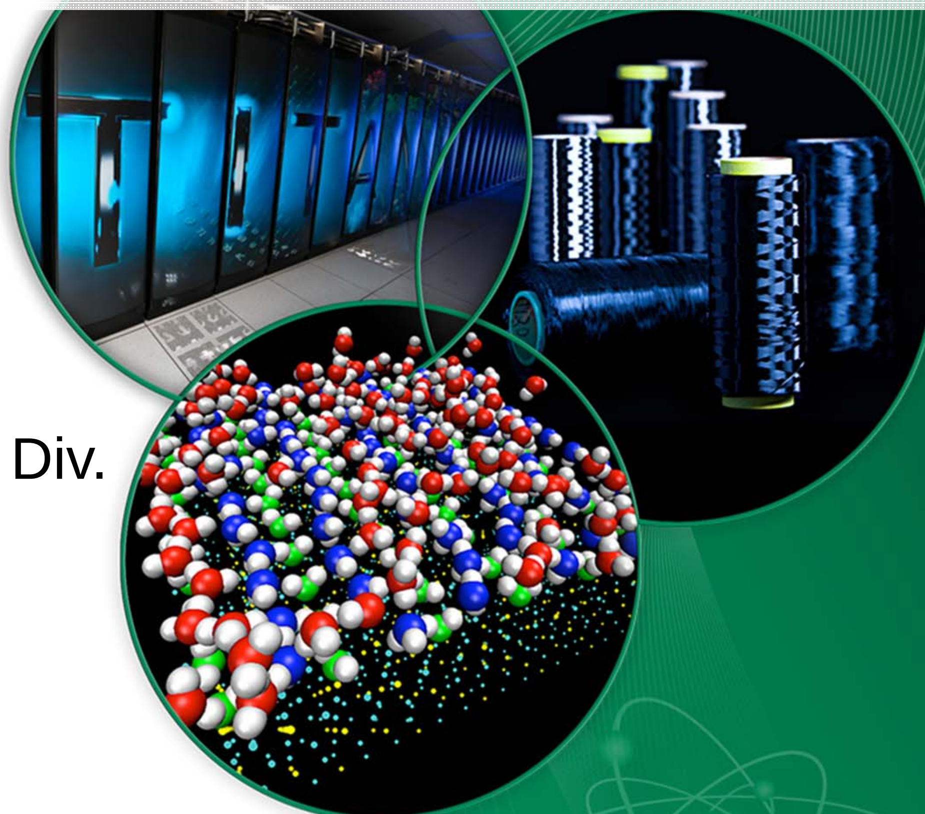
Weldability of Creep-Resistant Alloys for Advanced Fossil Power Plants



Xinghua Yu
Zhili Feng (PI)

Materials Science and Technology Div.
Oak Ridge National Laboratory

Project Manager: Vito Cedro

Objectives

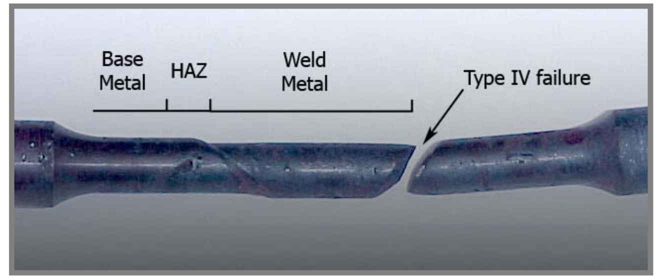
- Focus on two critical welding challenges for creep-resistant alloys for A-USC/USC
  - Reduced creep strength in the weld regions of CSEF (primary focus)
  - Joining of dissimilar metals
- Develop a modeling tool to predict local creep deformation and failure in welded structures in operation
  - Development of localized creep deformation measurement (ORNL weld creep test)
  - Understand phase transformation and failure mechanism of welded CSEF steels
  - Expand Integrated Computational Welding Engineering (ICWE) modeling capability for creep performance
  - Develop practice solutions to address weld degradation and predict life of welded structures.

Outline

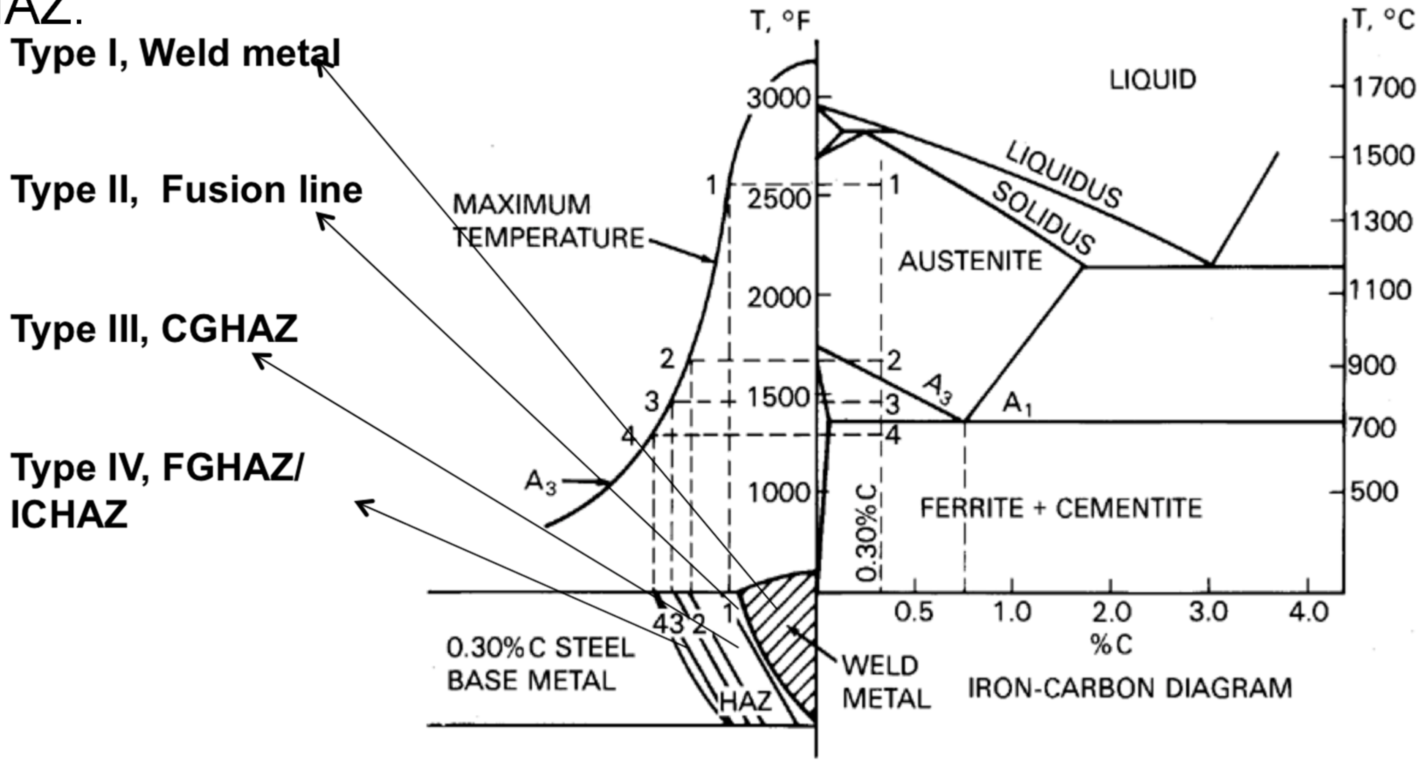
- Limitations in conventional cross-weld creep testing
- Full-field creep deformation measurement
- Failure mechanism of welded CSEF steels
- Integrated Computational Welding Engineering (ICWE) modeling capability for creep performance
- Conclusions

Type IV failure of Grade 91 steels

- **Life of weldments shorter than Base Metal.**
  - Type IV failure shortens the material life, caused by weakened microstructure at HAZ.

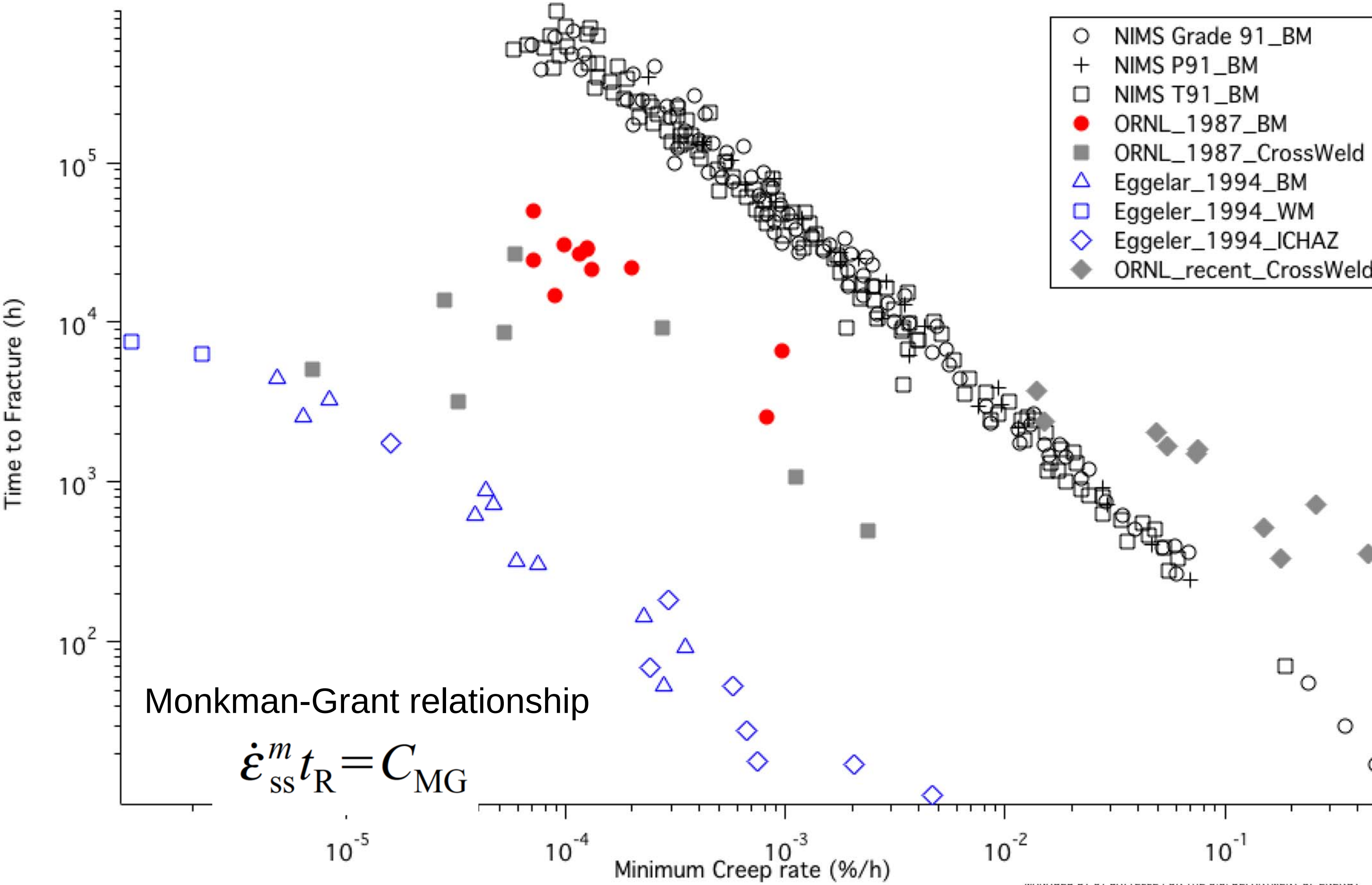


Weld Joint Strength Reduction Factors (WSRF = σ_{weld} / $\sigma_{base\ metal}$) for CSFE steels can be as low as 0.5 at ~600ºC.



Due to localized deformation, conventional cross-weld testing has limitations

Minimum Creep Rate in Cross-Weld Creep Testing



Monkman-Grant relationship

$$\dot{\varepsilon}_{ss}^{m} t_R = C_{MG}$$

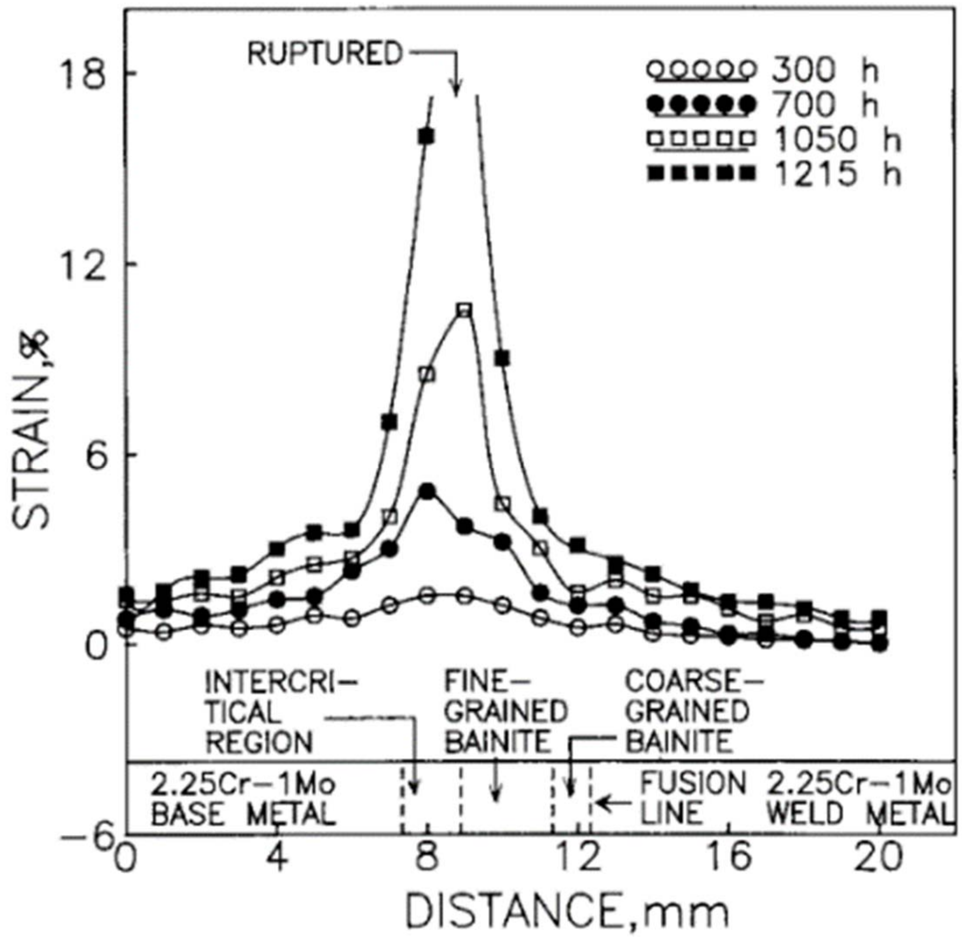
Full Field Creep Strain Mapping is Needed

- To capture creep behaviors in different regions
  - "True" weld minimum creep rate
- To obtain creep parameters in different regions for modeling
- To validate model results
- To correlate creep deformation to microstructure and mechanical properties

ORNL’s weld creep test technique

Strain Distribution Measurement in Literature

Measuring indents distance by interrupted creep tests



Time-consuming

Low accuracy

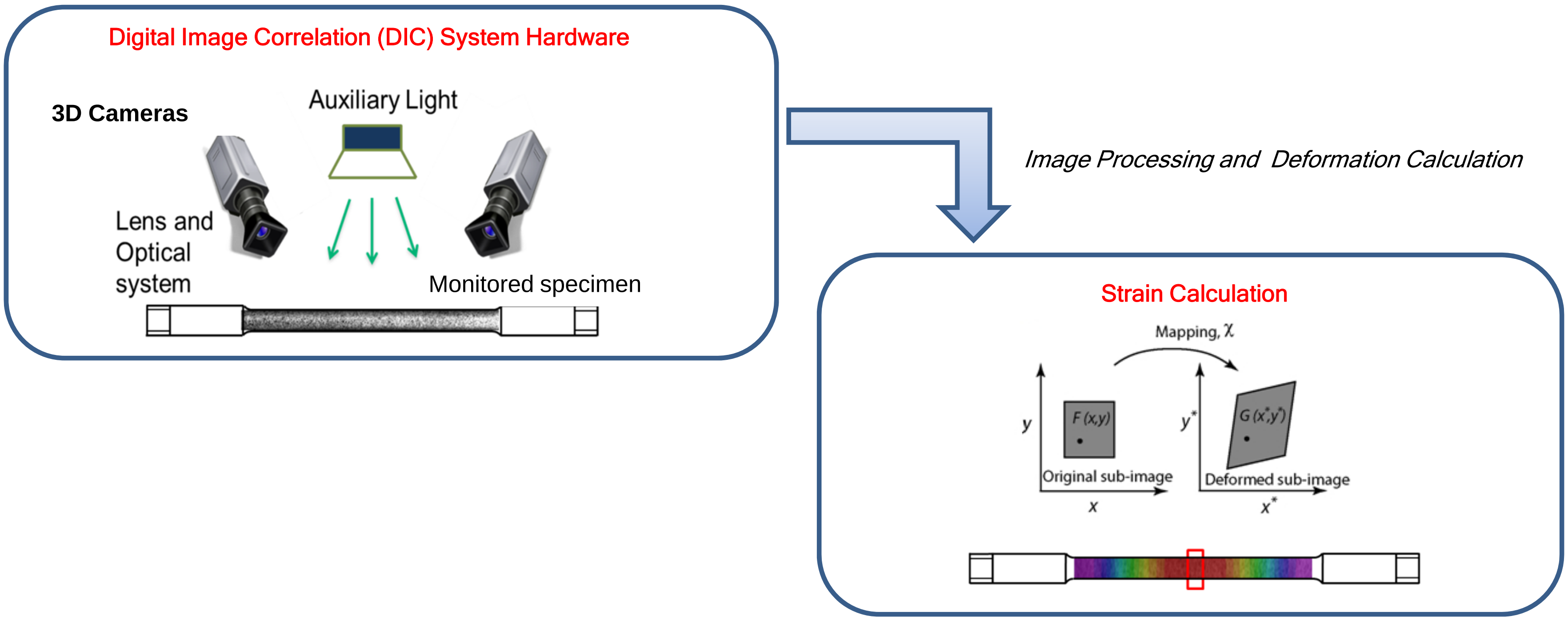
1D distribution

Indentation may affect the final result

K. Laha et al. / Int J Pressure Vessels and Piping 2000

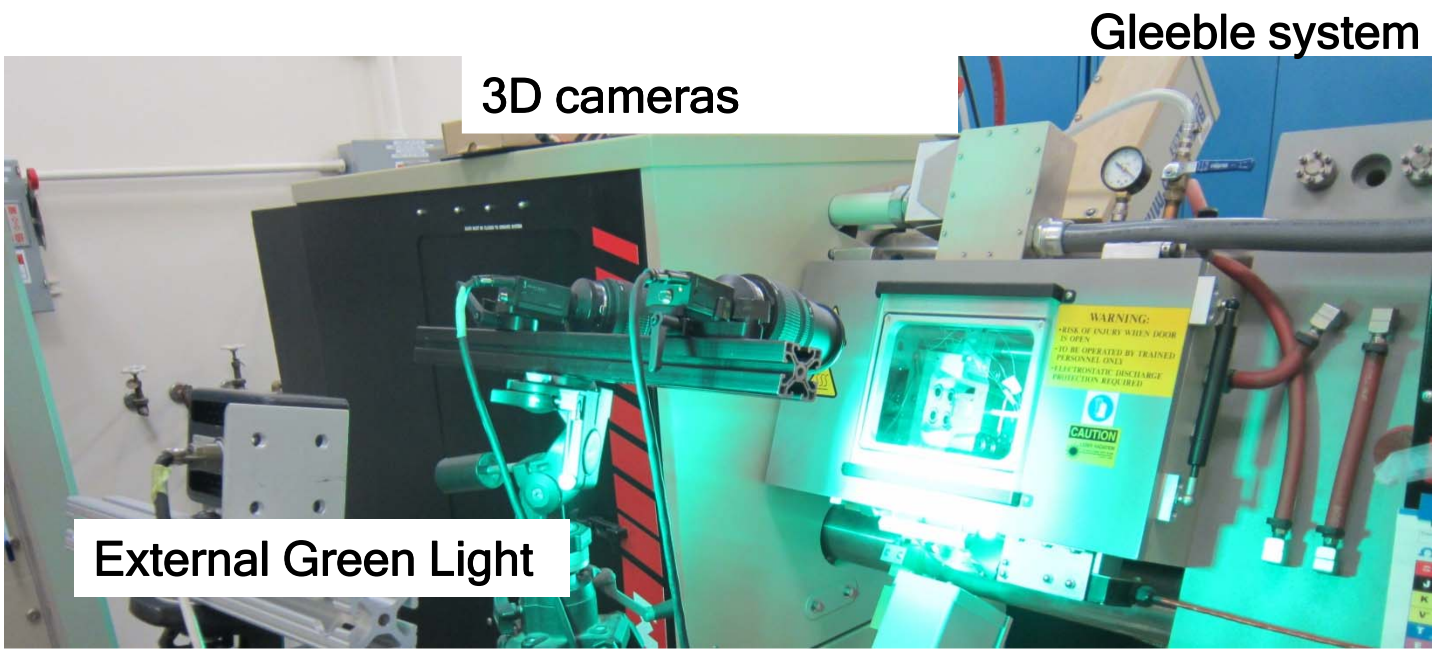
Our Approach: Digital Image Correlation (DIC)

- DIC, a full-field deformation measurement method can be applied to measure strain distribution in a cross-weld sample
- “DIC is an optical method that employs tracking and image registration techniques for accurate 2D and 3D measurements of changes in images”*



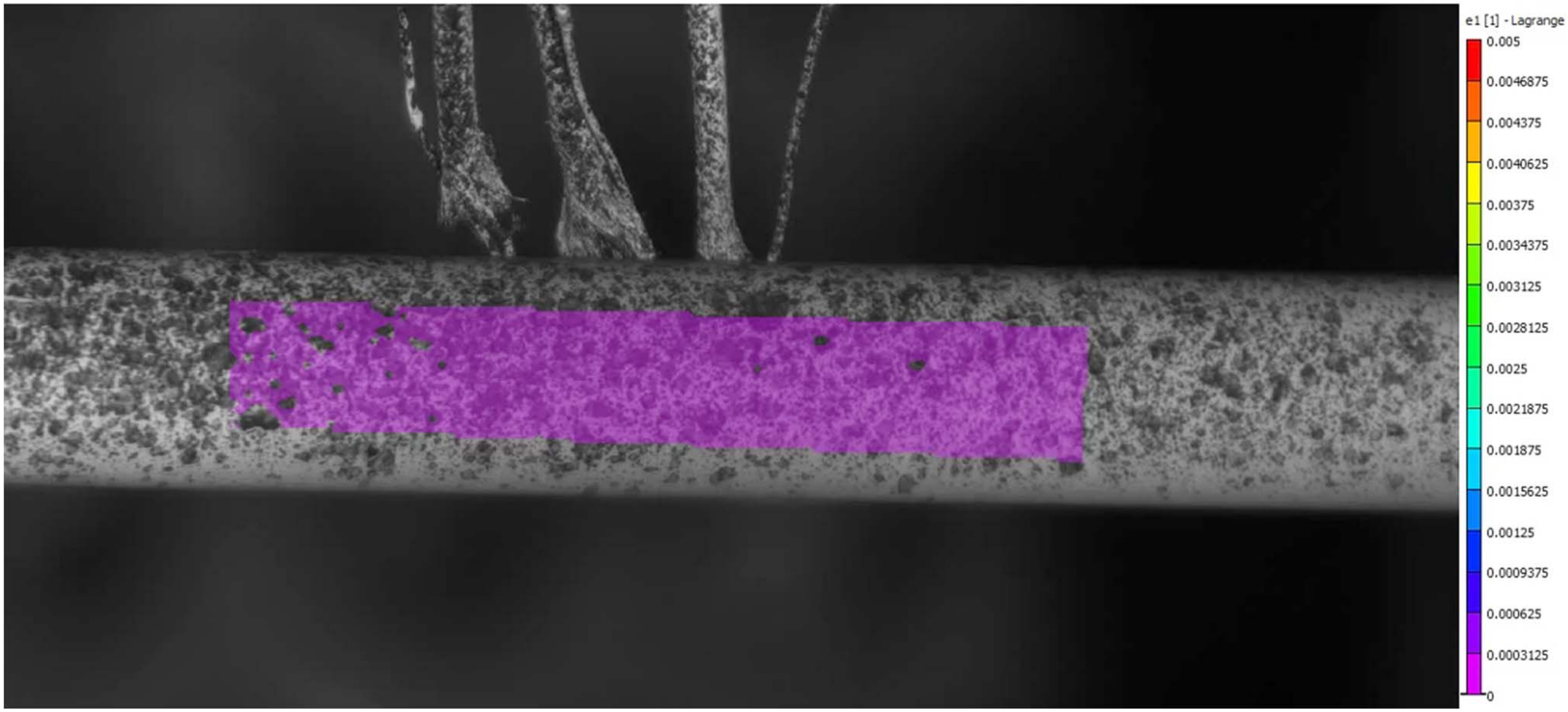
* Sutton, M. A., Orteu, J. J., & Schreier, H. W. (2009). *Springer, New York*

Experimental Setup (Gleeble + DIC)



- Samples were painted with speckles for surface strain measurement
- Images was taken 1 image/60s for the first 12 hours and 1 image/300s for the rest 78 hours.

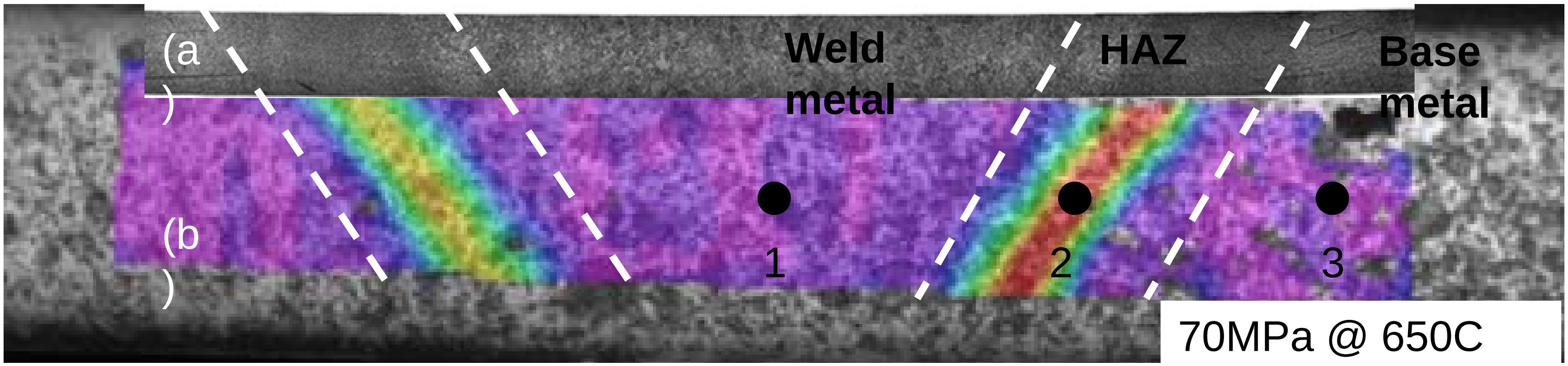
Creep Strain Evolution



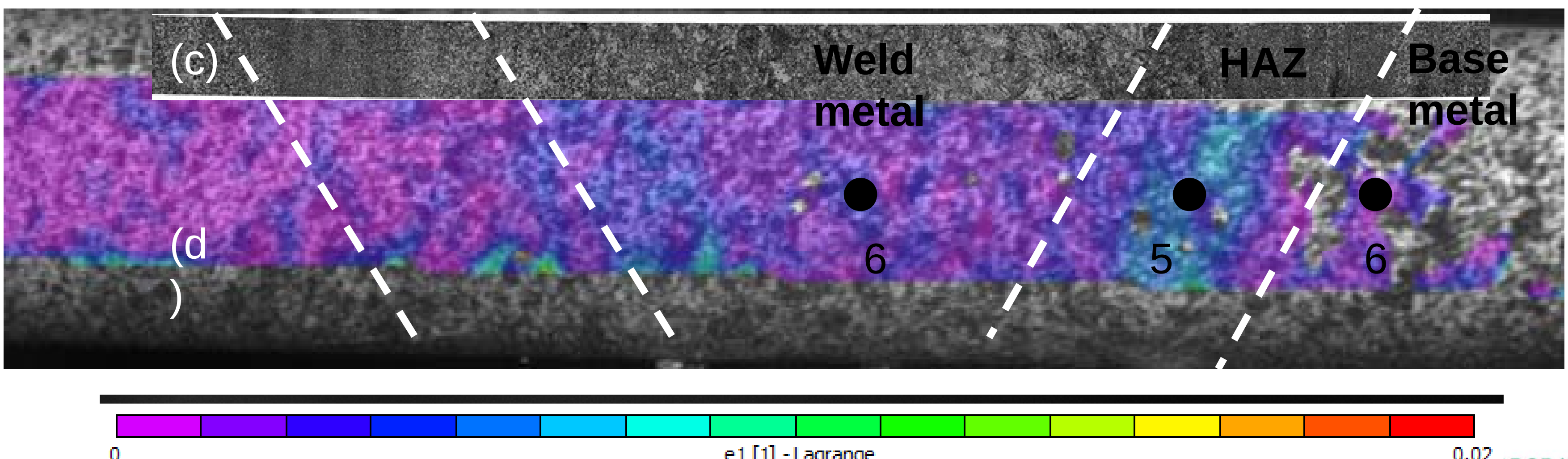
Significant strain concentration is shown after 30 hours of test

Creep Strain Distribution Comparison

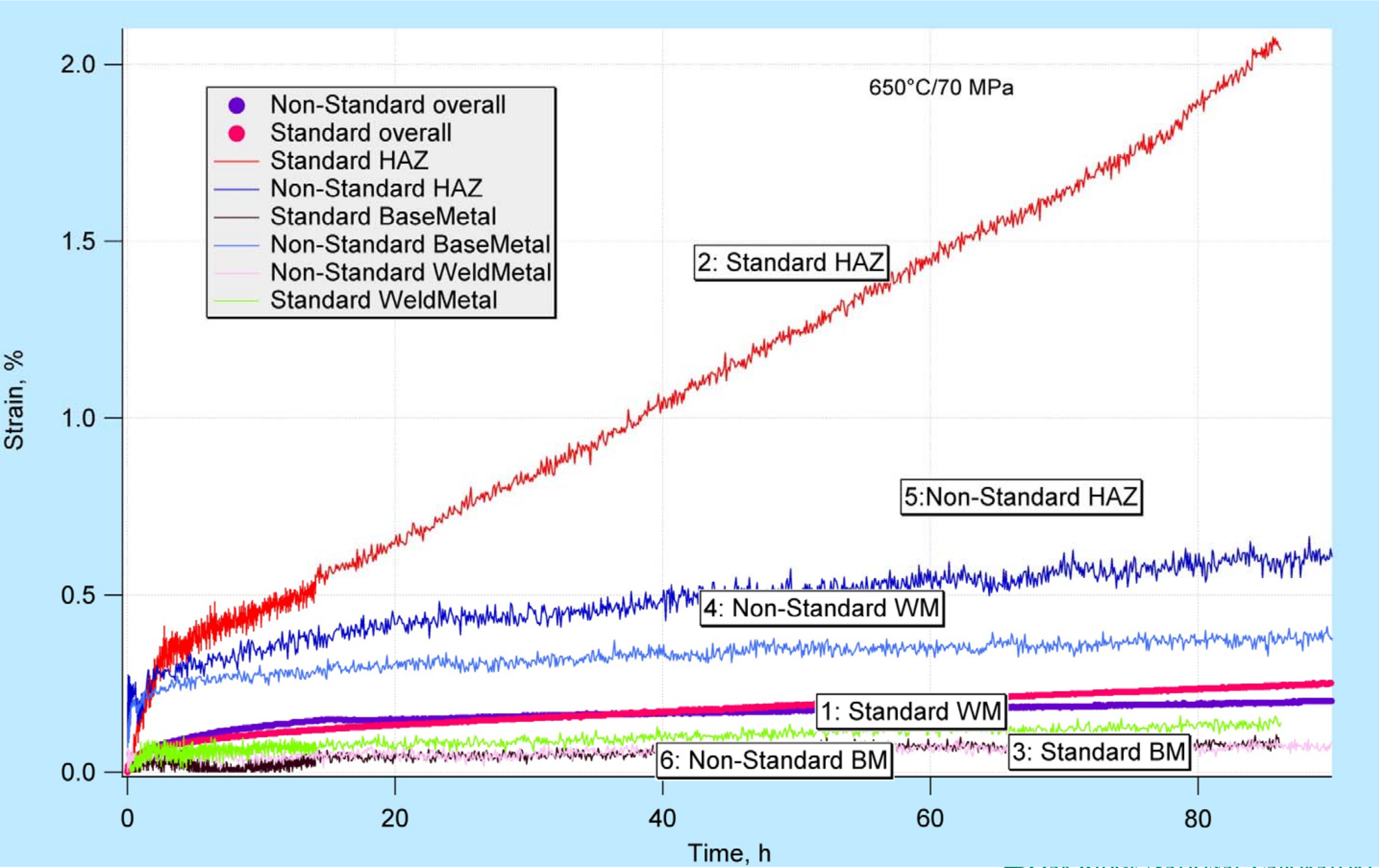
Standard heat treatment (1040/760/760), creep life:~500h



Modified heat treatment (1040/650/760) creep life:~2500h

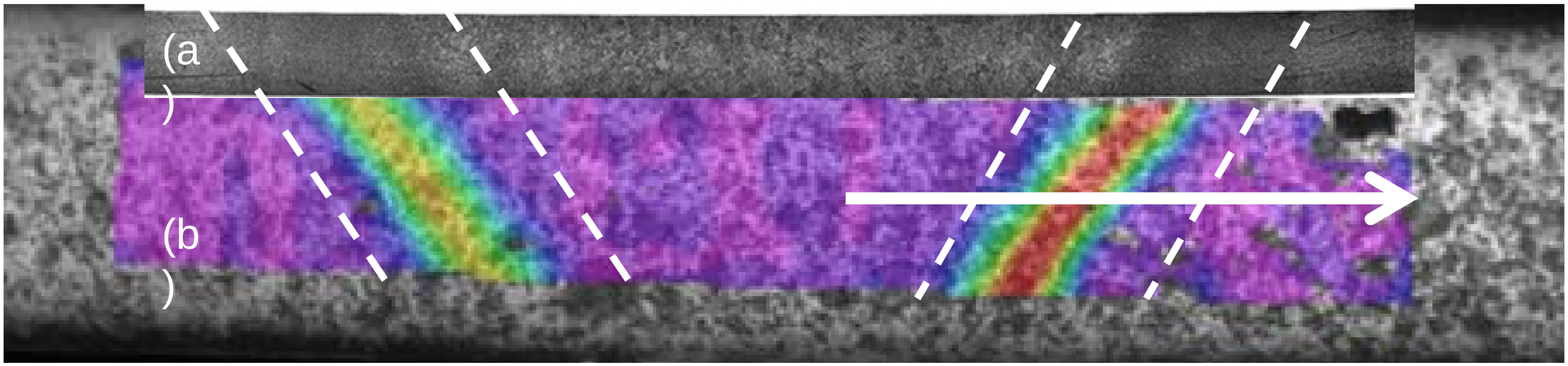


Creep deformation evolution in different locations

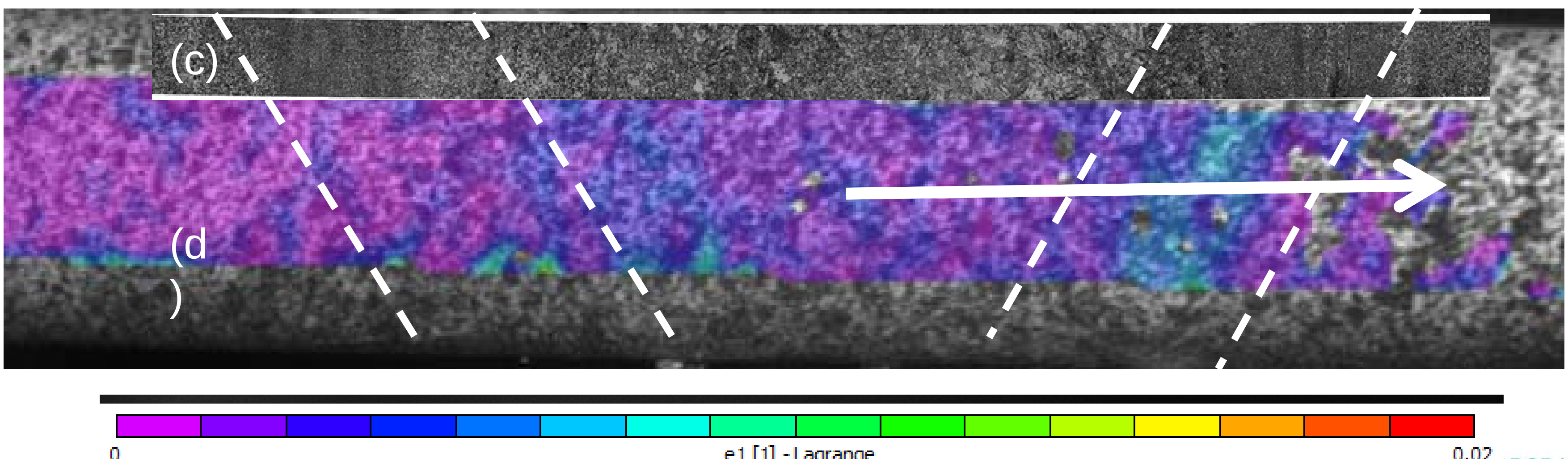


Traverse Creep Strain Distribution Comparison

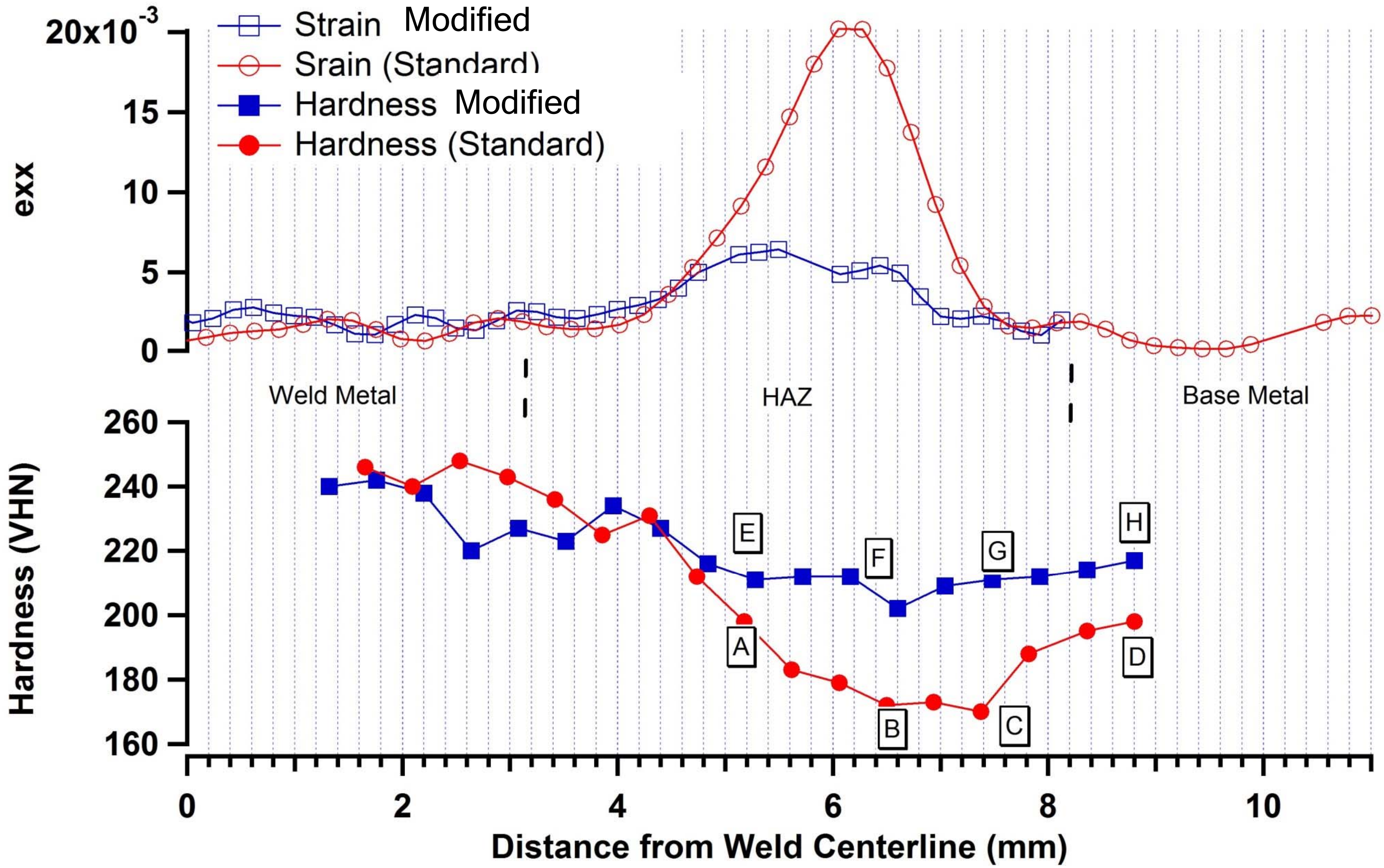
Standard heat treatment (1040/760/760)



Modified heat treatment (1040/650/760)

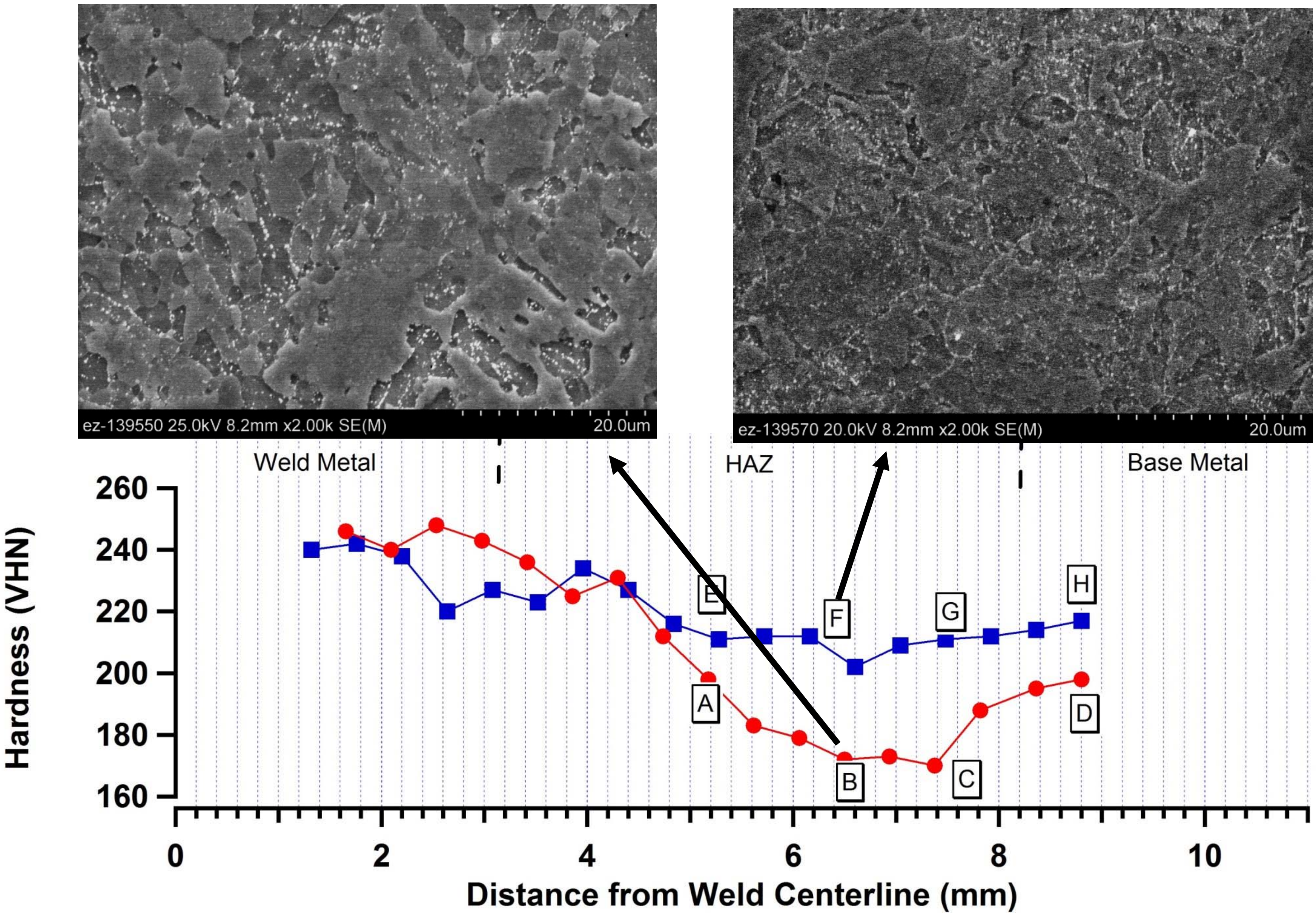


Micro-hardness vs. Creep Strain



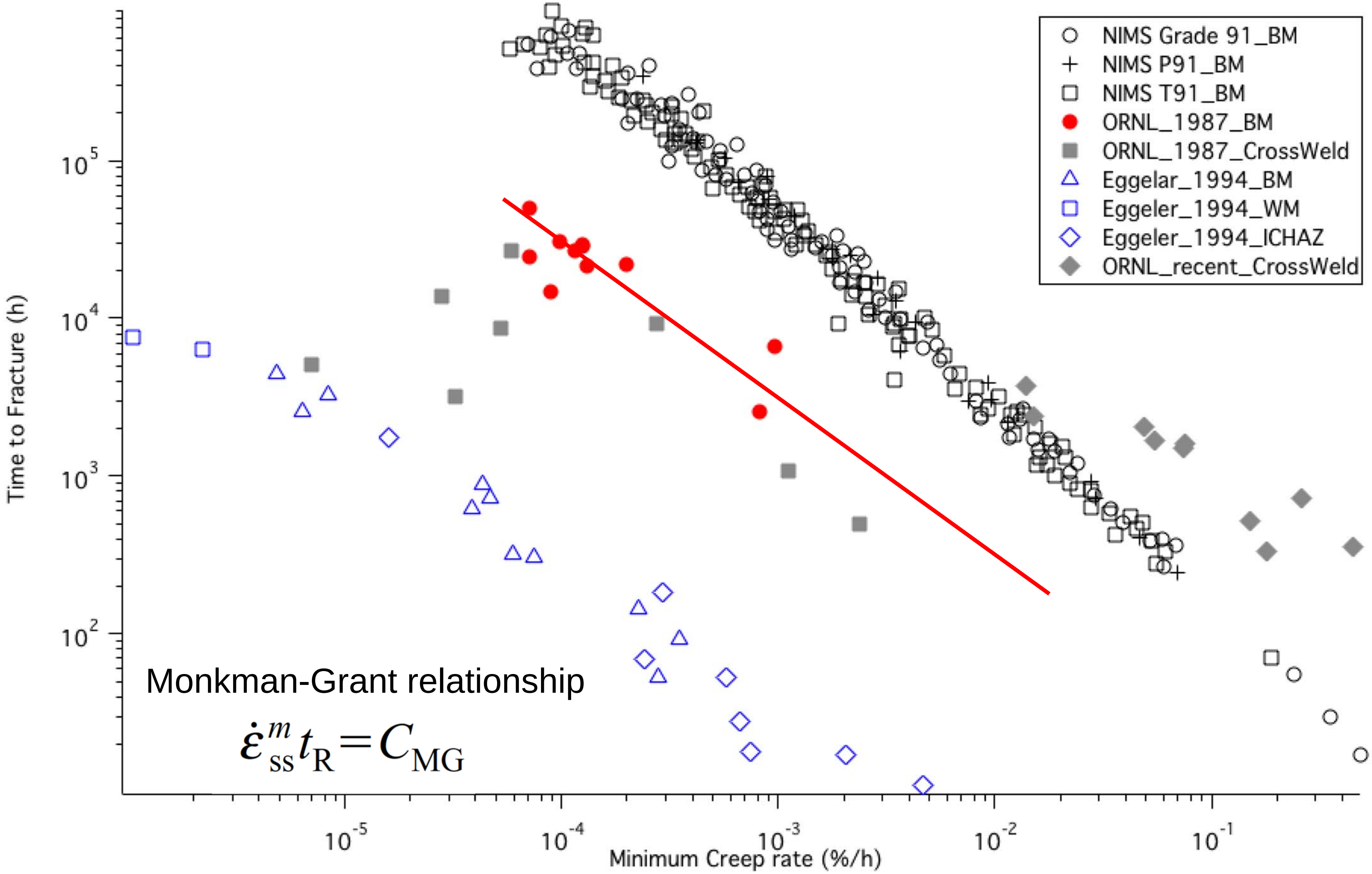
Highest creep deformation region is not the weakest.

Strain-Microstructure Correlation



Coarse carbides in “standard” weld and fine carbides in “modified” weld

Minimum Creep Rate in Cross-Weld Creep Testing



Monkman-Grant relationship

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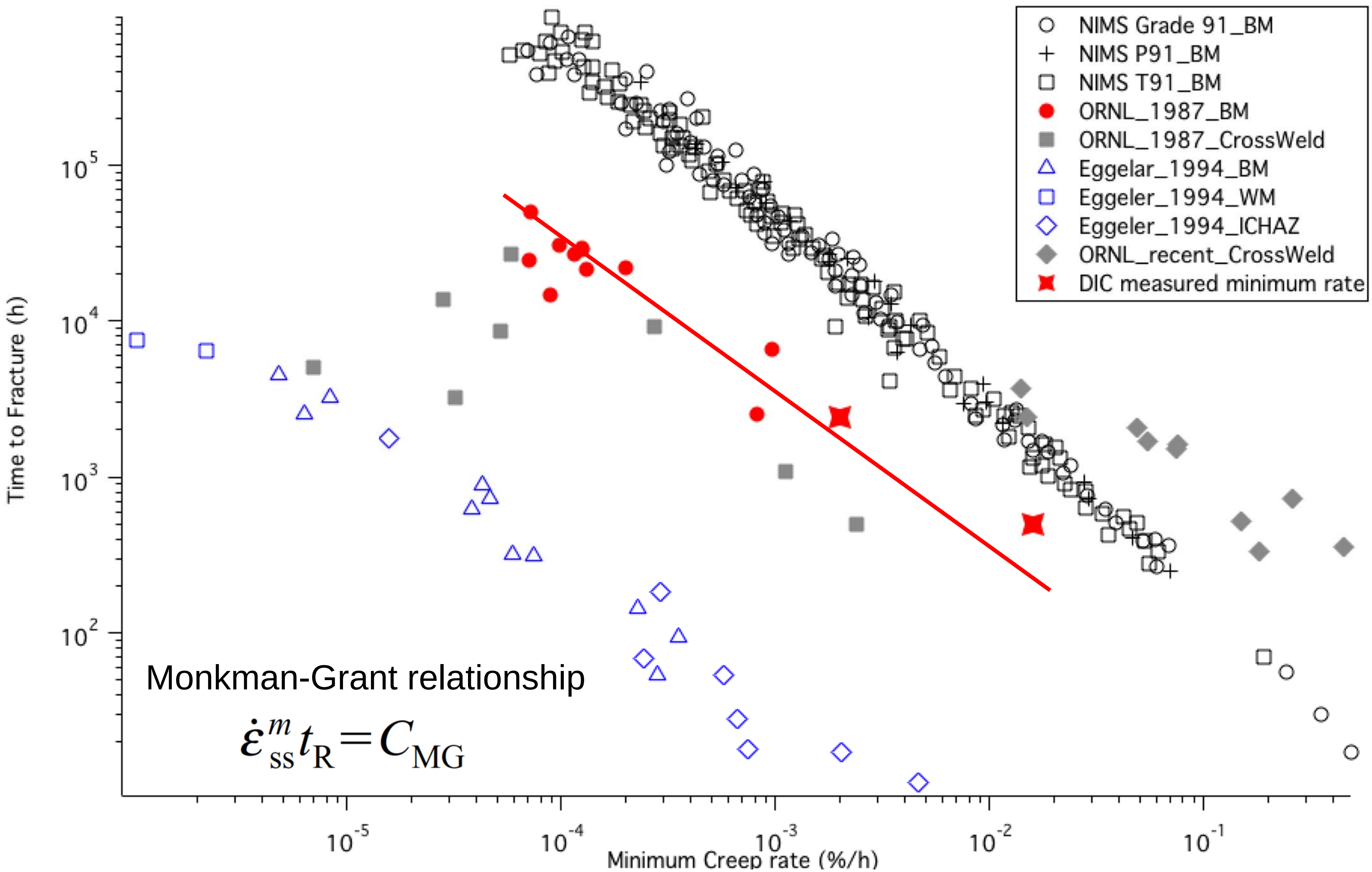
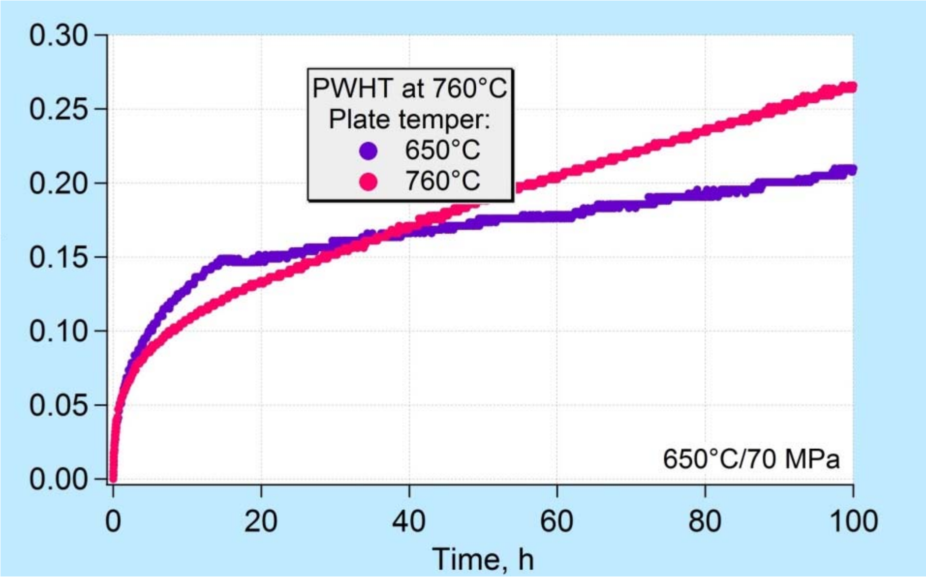
Minimum Creep Rate in Cross-Weld Creep Testing



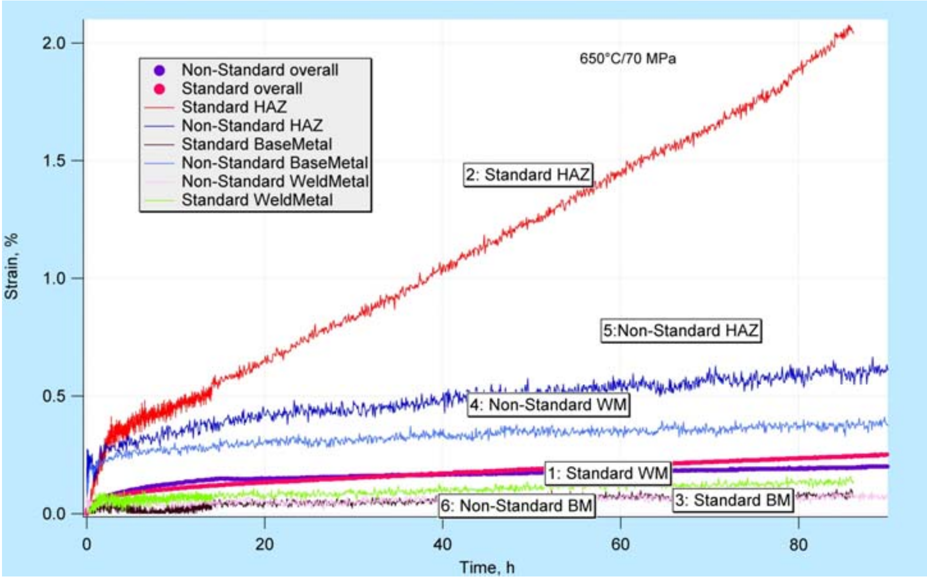
Advantages of ORNL weld creep test

- Localized creep deformation measurement

Total creep strain after 90 hours



Local creep strain after 90 hours



- Local creep strain can be easily correlated to local microstructure

Understanding Failure Mechanism of Welded CSEF Steels

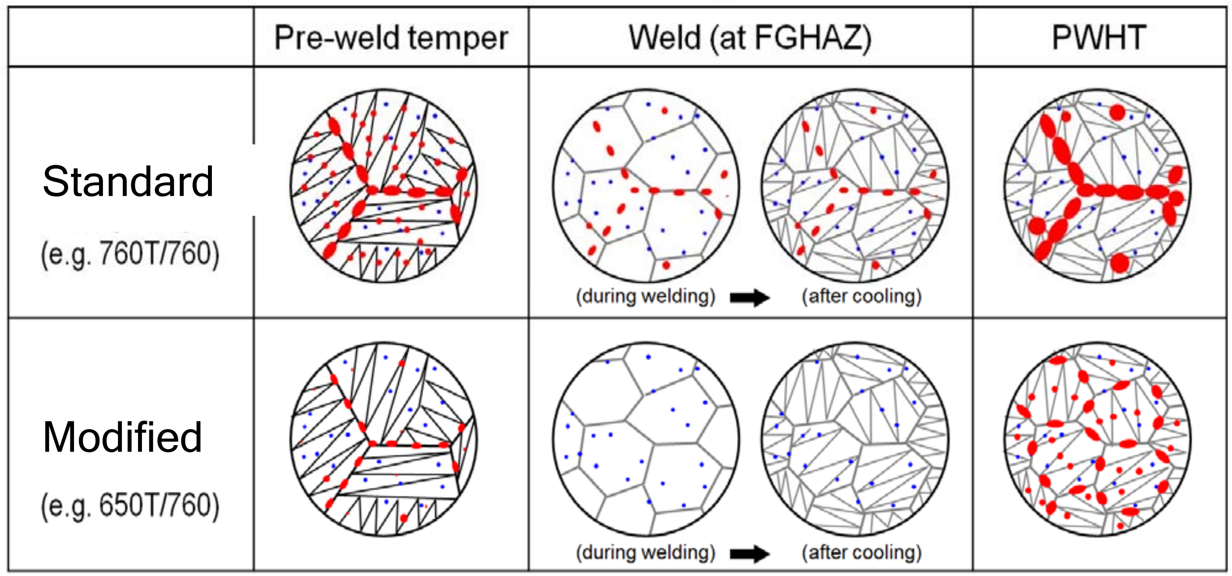
U.S. DEPARTMENT OF ENERGY

OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE U.S. DEPARTMENT OF ENERGY

Previous Study on Grade 91 Show Dispersion of Fine Carbides is the Key

o Simulated HAZ heat profile during high energy X-ray diffraction scan

Table: Microstructure evolution at fine grain heat affected zone



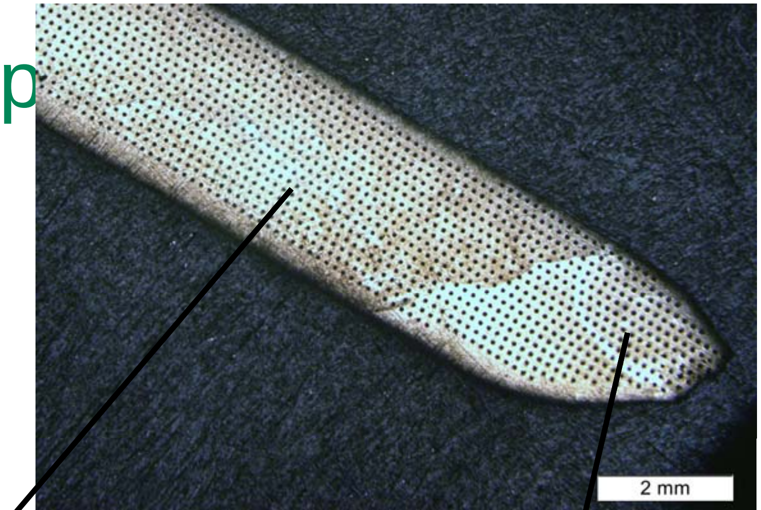
: $M_{23}C_6$ • : MX

X. Yu et al., *Acta Materialia*, vol. 61 (2013) p. 2194-2206.

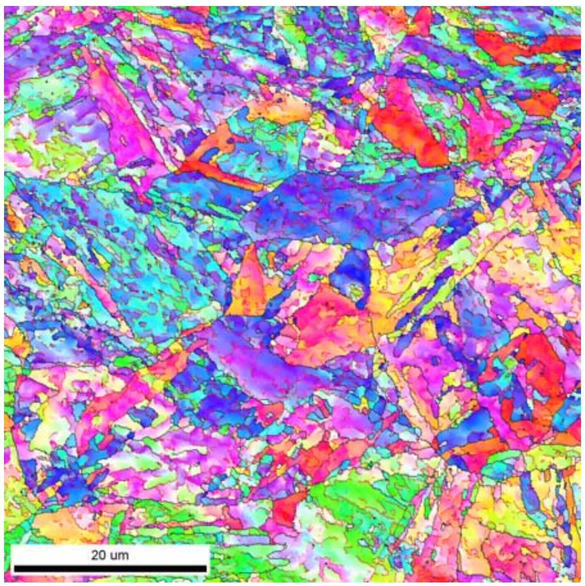
In-situ Diffraction Study at SPring-8 showed carbide evolution in FGHAZ

Does martensite sub-structure play a role in creep?

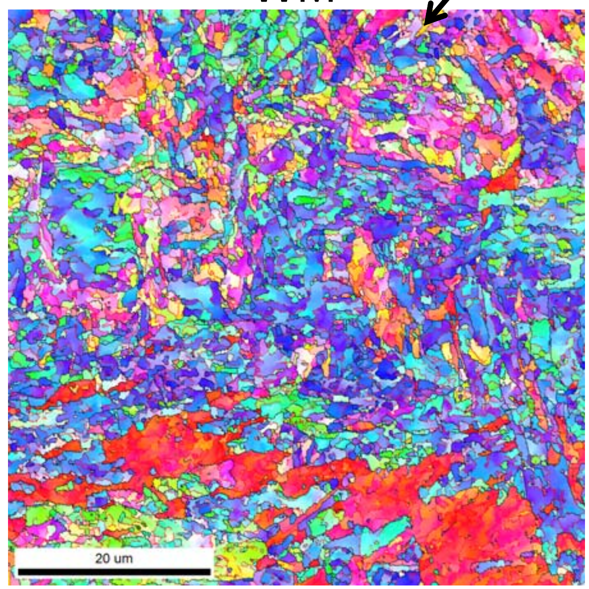
Orientation Maps of Crept Samp



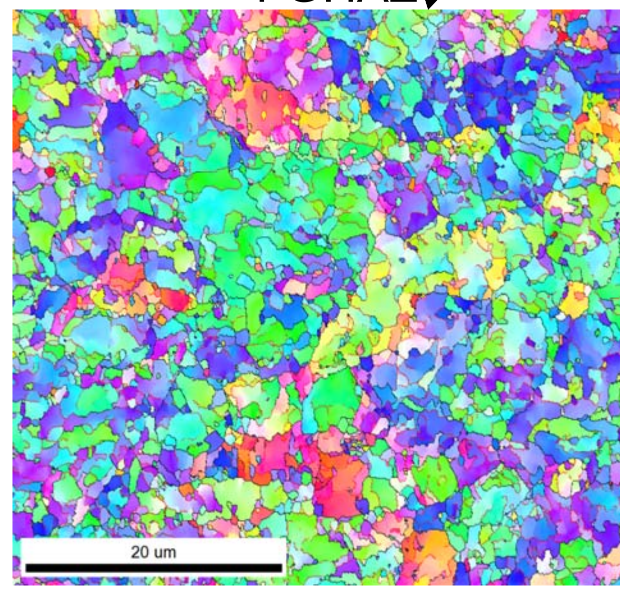
BM



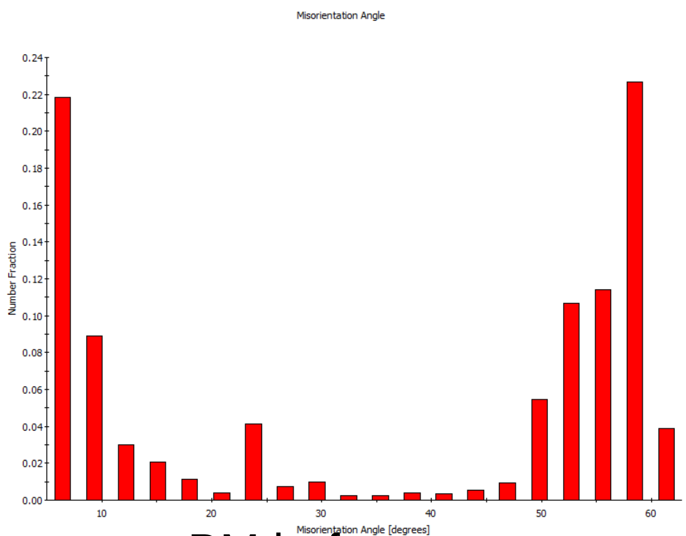
WM



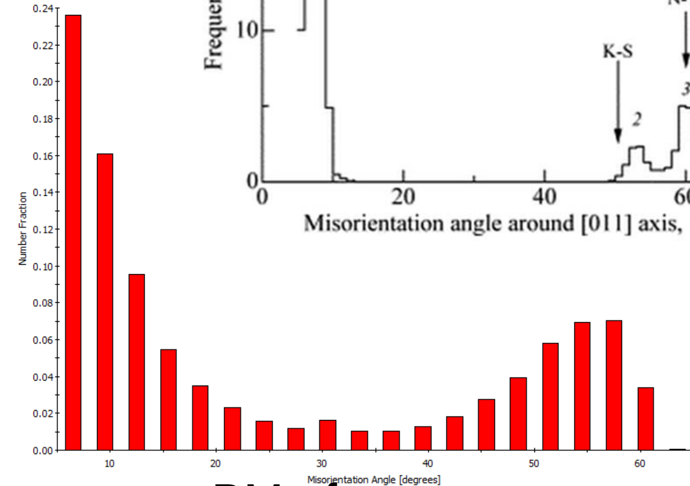
FGHAZ

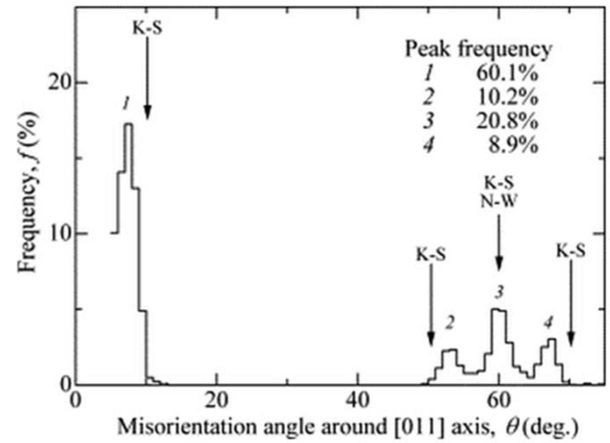


Misorientation Angles

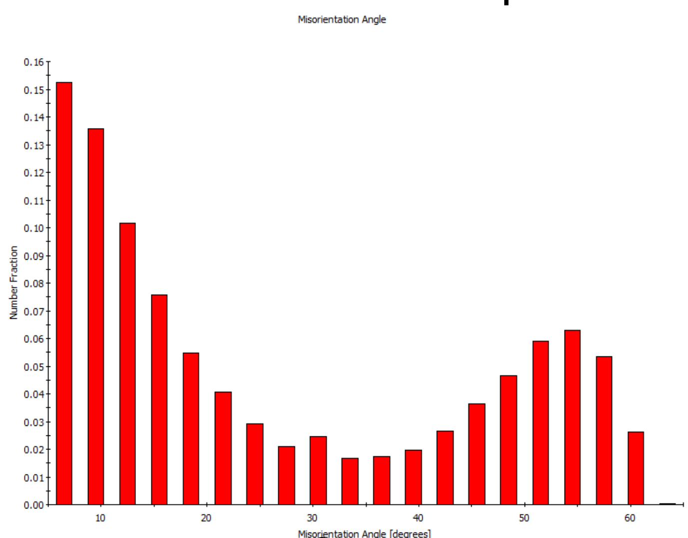


BM before creep

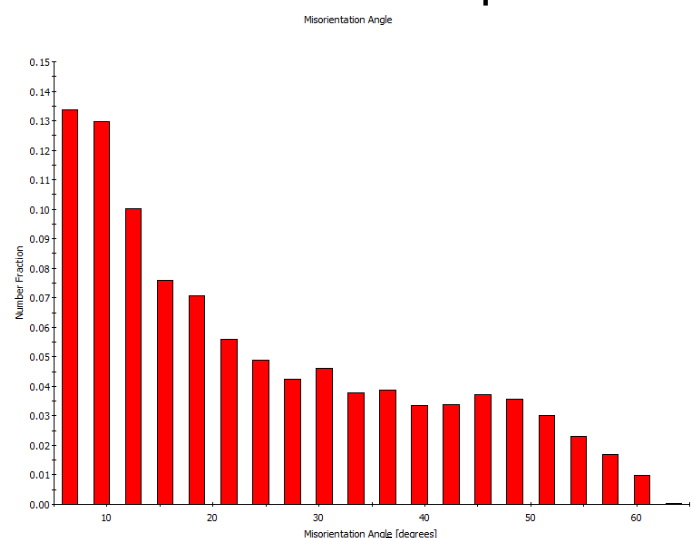




BM after creep

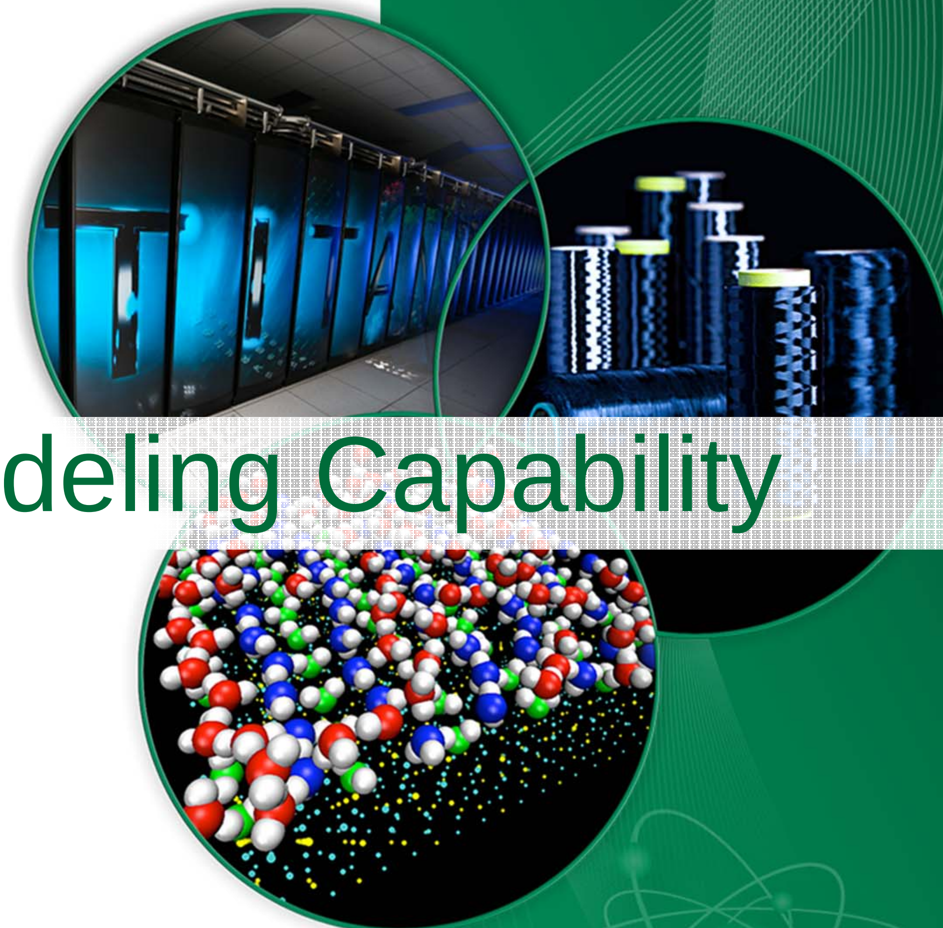


WM after creep

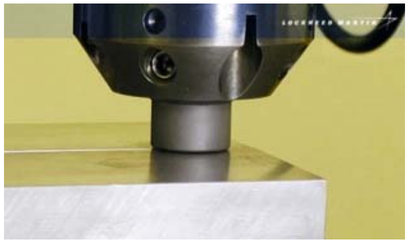
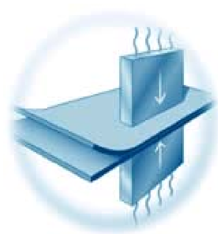


FGHAZ after creep

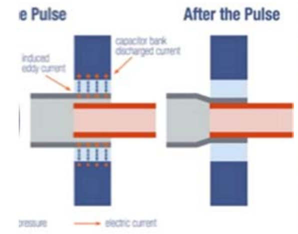
Develop ICWE Modeling Capability



Integrated Modeling of Materials, Processes and Properties





Friction stir welding:
Mechanic deformation

Ultrasonic welding:
20~50 kHz vibration

Advanced fusion welding:
Heat & melt flow

MagPulse welding:
Electromagnetic force

Process & materials → [**Fluid flow** | **Mechanics** | **Metallurgy** | **Electromagnetics** | **Heat transfer**] → Property & performance

Non-destructive evaluation

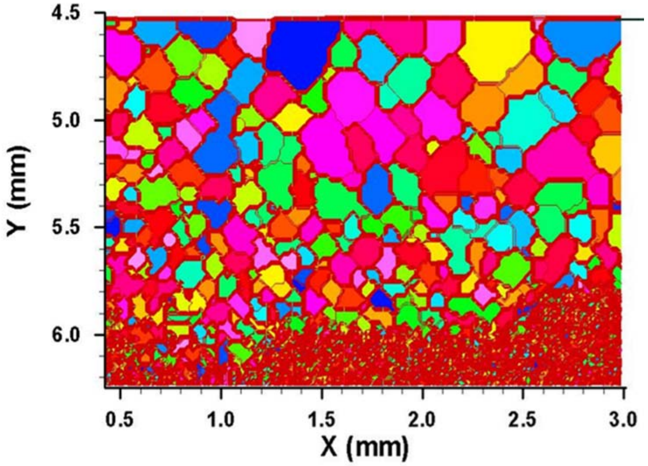
Cost modeling: Design for assembly & manufacturing

Model automation for technology transfer

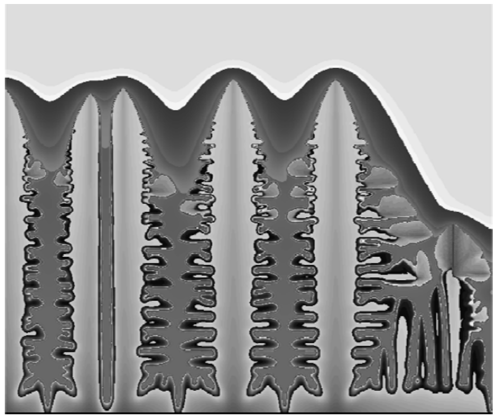
Expend our capability to cross-weld creep modeling

Modeling of Microstructure & Properties

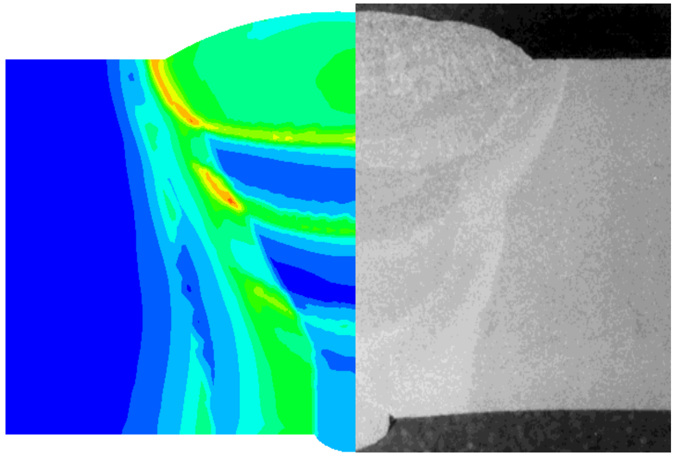
High-fidelity microstructure modeling provides insight into microstructure evolution and property heterogeneity of welds



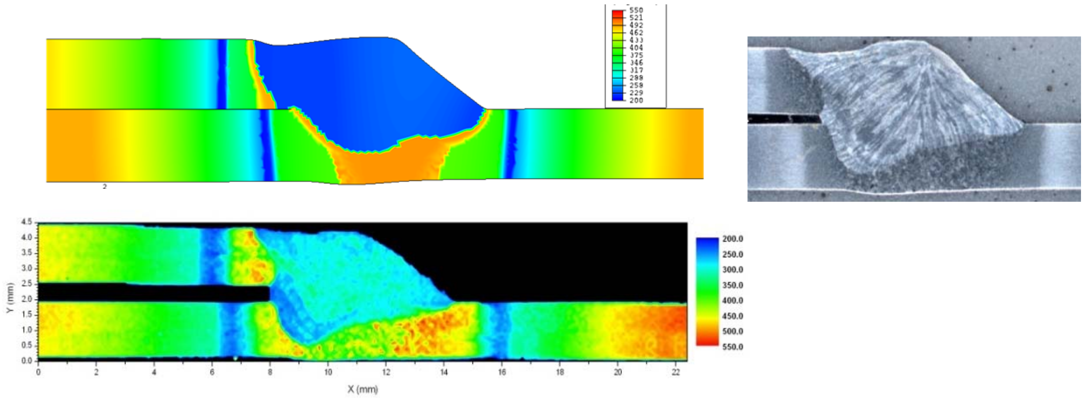
Monte Carlo simulation of grain growth



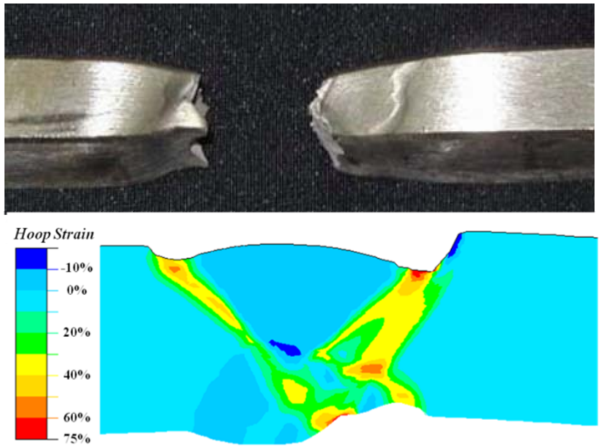
Phase field simulation of solidification



Yield strength gradient simulation in a multi-pass steel weld



Simulation of HAZ softening of a boron steel top: simulation; bottom: measurement

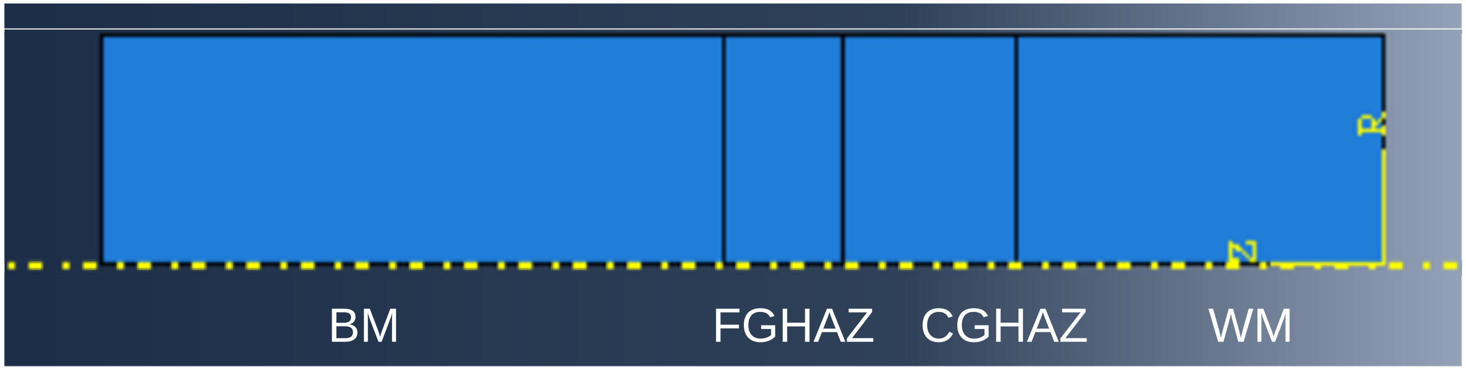


Performance simulation of a high strength steel weld

Initial FEA model

- 2-dimension axisymmetric model
- 4 distinct regions : WM, CGHAZ, FGHAZ, WM
- Power law creep

	A, $MPa^{-n} h^{-1}$	n	Young's modulus, GPa	Yield stress, MPa	Poisson's ratio
WM	$3{\cdot}37 \times 10^{-57}$	24·0	106	91	0·3
CGHAZ	$6{\cdot}97 \times 10^{-26}$	10·2	99	135	0·3
FGHAZ	$2{\cdot}80 \times 10^{-24}$	9·8	77	82	0·3
BM	$3{\cdot}76 \times 10^{-33}$	13·6	103	104	0·3



FEA model

- Initial feasibly demonstration of ICWE model to capture local creep deformation and failure in a representative cross weld tensile specimen

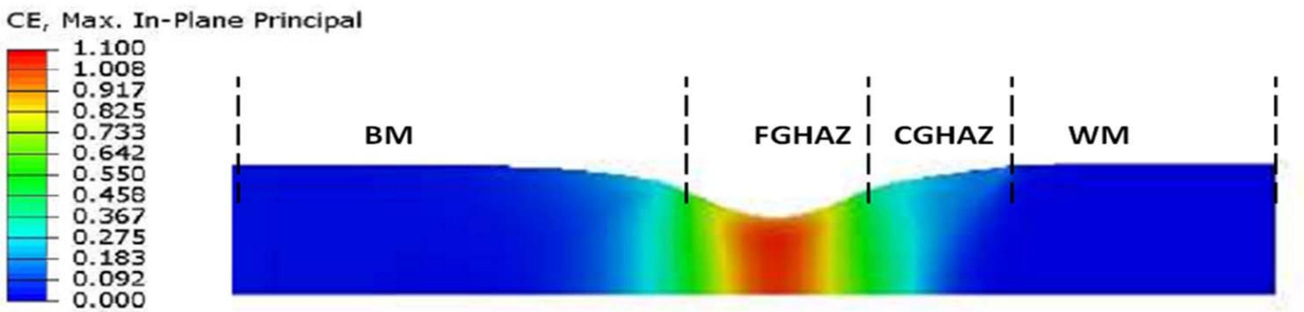
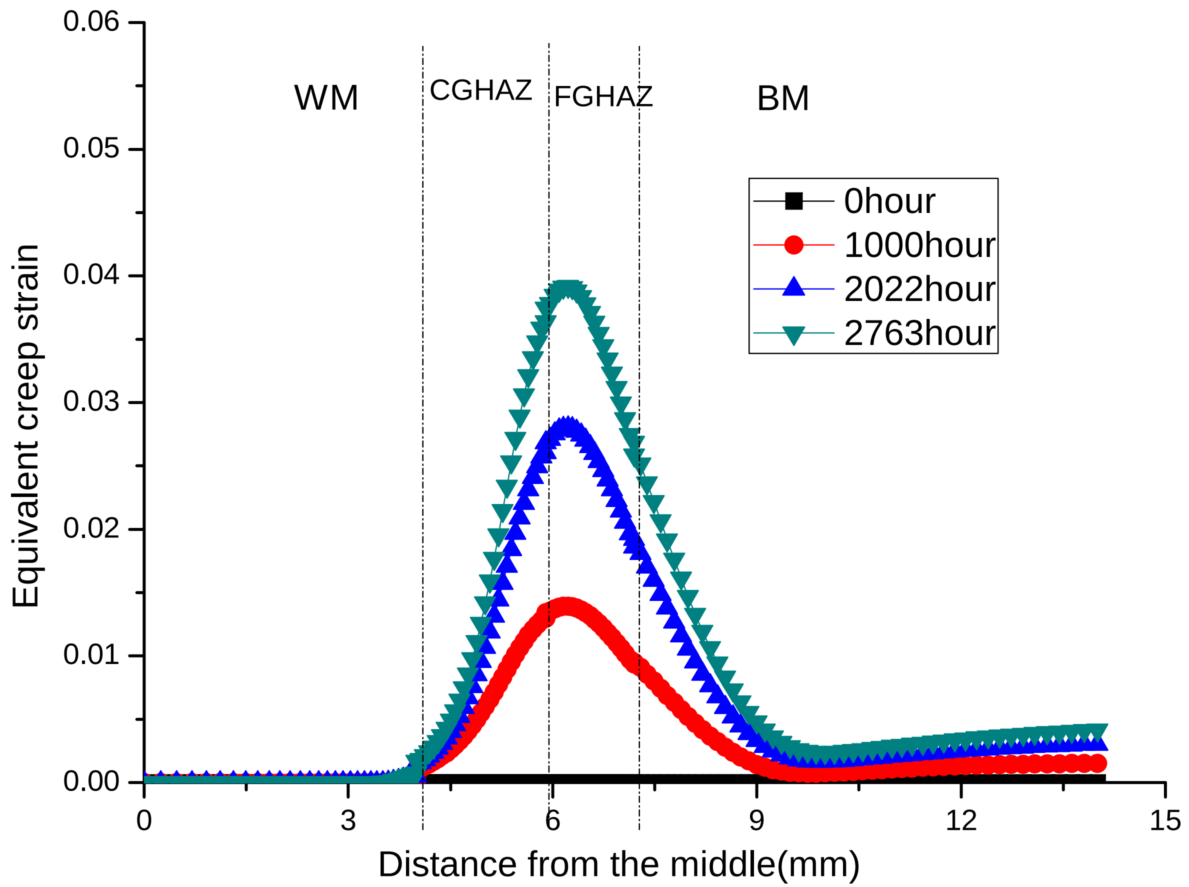


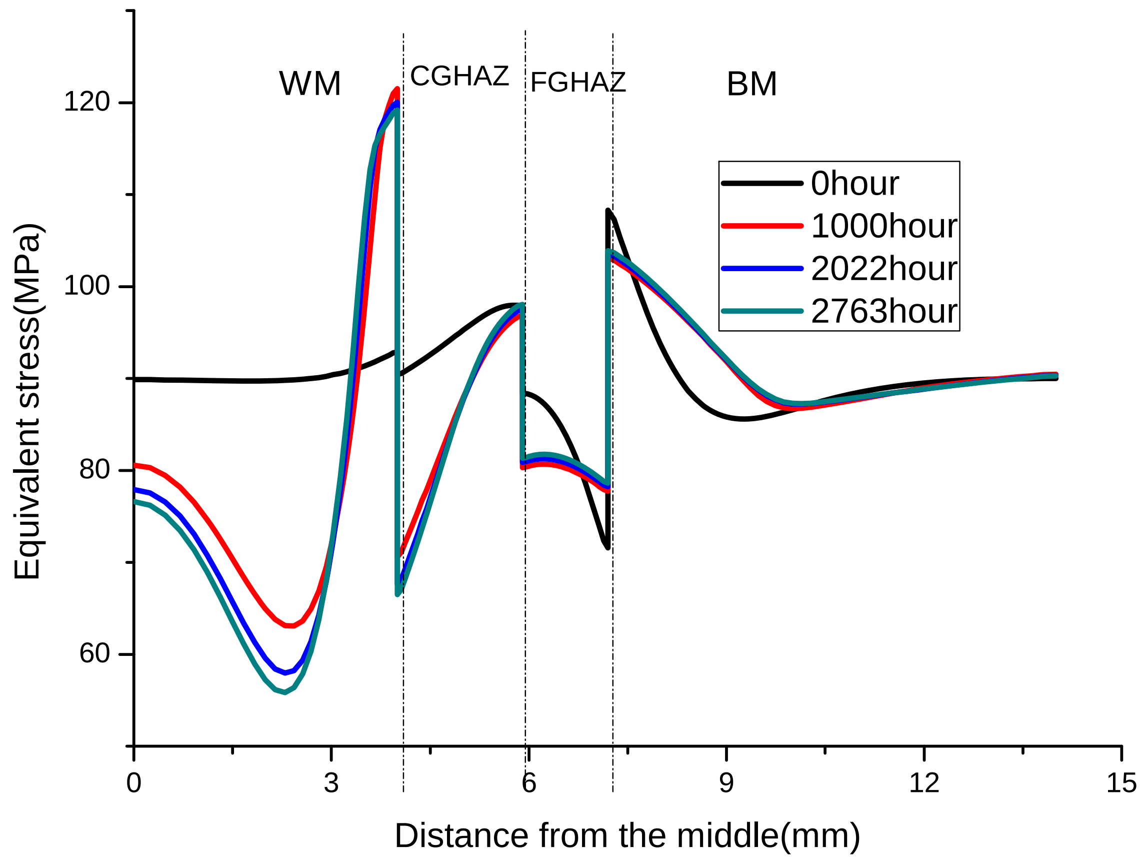
Figure 1. Maximum in-plane creep strain in a cross-weld specimen after 13000 hours creep. (CE is in-plane principal creep strain)

- Further develop and refine the creep testing technique. Design new sample geometry for creep-microstructure correlation.

Equivalent Strain Distribution



Equivalent Stress Distribution

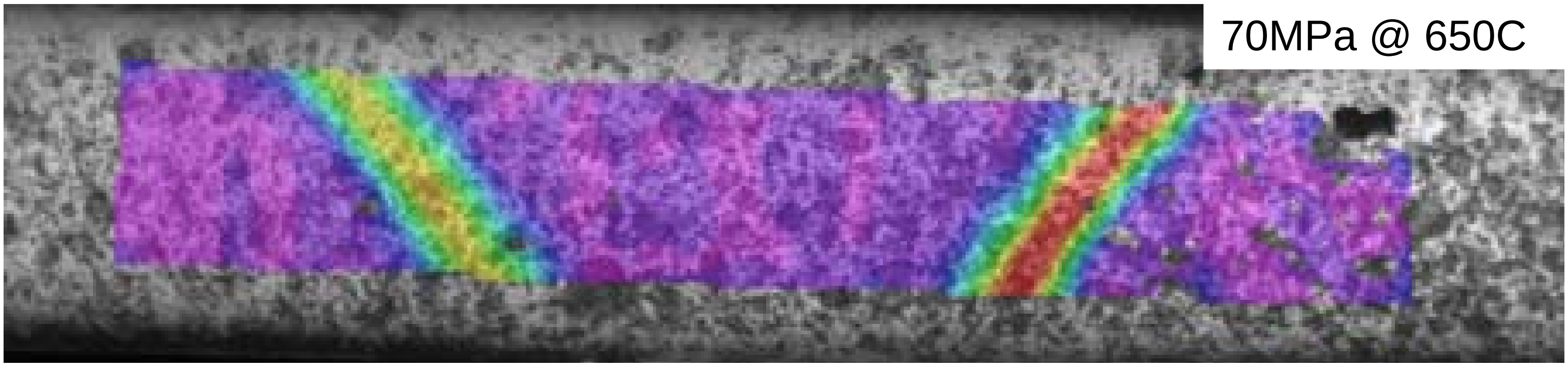


Steep stress gradient at the interface between different regions. Gradual properties transition need to be considered.

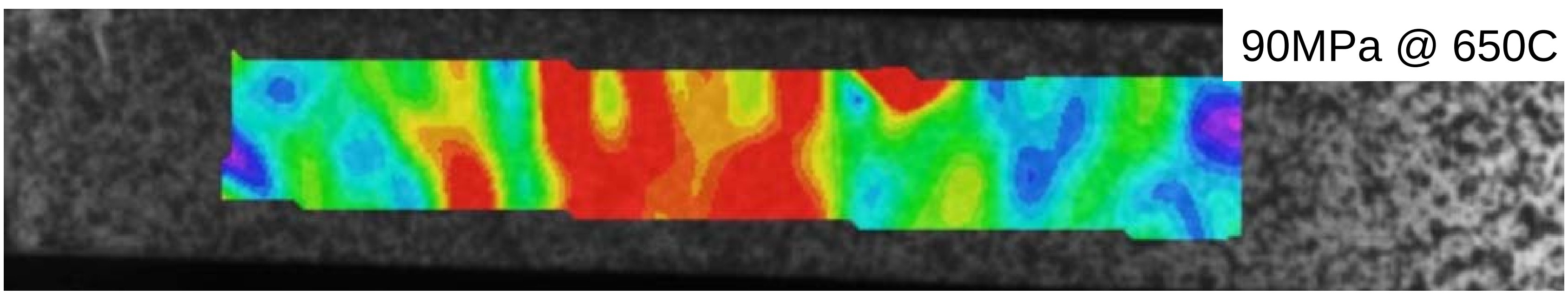
Next step model development

- Include gradual mechanical properties transition from WM to BM.
- Establish the relation between microstructure and creep properties in different region of the weld.
- The mechanical properties used in the model, especially creep properties of different regions need to be further re-evaluated by experiments.

Power Law Parameters Obtained by DIC



70MPa @ 650C



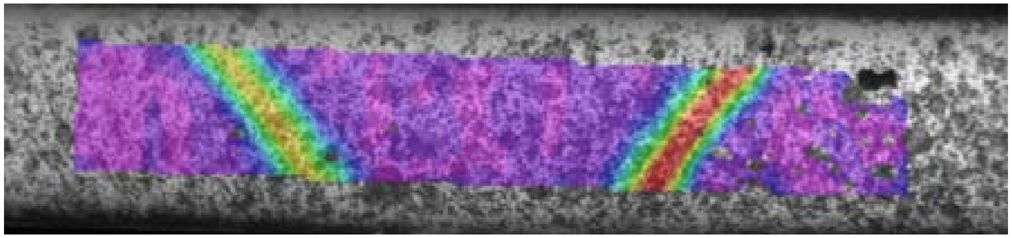
90MPa @ 650C

Strain rate can be extracted from each individual location
Creep constitutive equation parameters can be obtained

Milestones

- 9/30/14 Demonstrate ICWE modeling capability to capture local creep deformation and failure in a representative cross weld tensile ✔
- 3/31/15 Improve and standardize the ORNL weld creep test procedure and demonstrate its effectiveness to quantify the non-uniform creep deformation behavior in Grade 91 steel weldments ✔
- 6/30/15 Establish the relationship between the local microstructure/stress evolution to creep deformation in weldments in Grade 91 steels using ORNL weld creep test and in-situ neutron/synchrotron techniques. (depends on beam time allocation)
- 9/30/15 Complete next stage of ICWE model development and demonstrate its capability to predict local creep deformation and failure in ORNL weld creep test (on track)

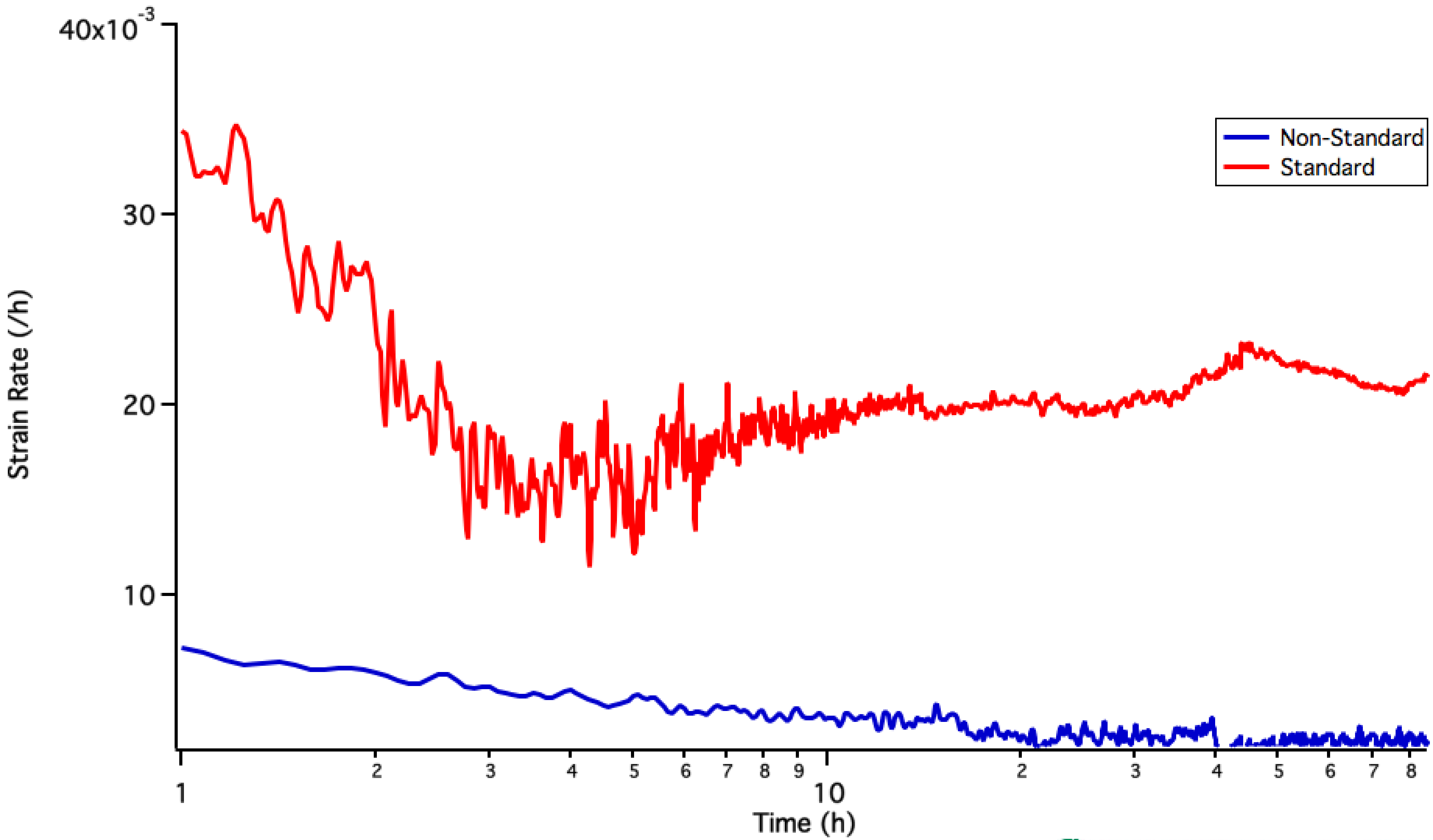
Conclusions



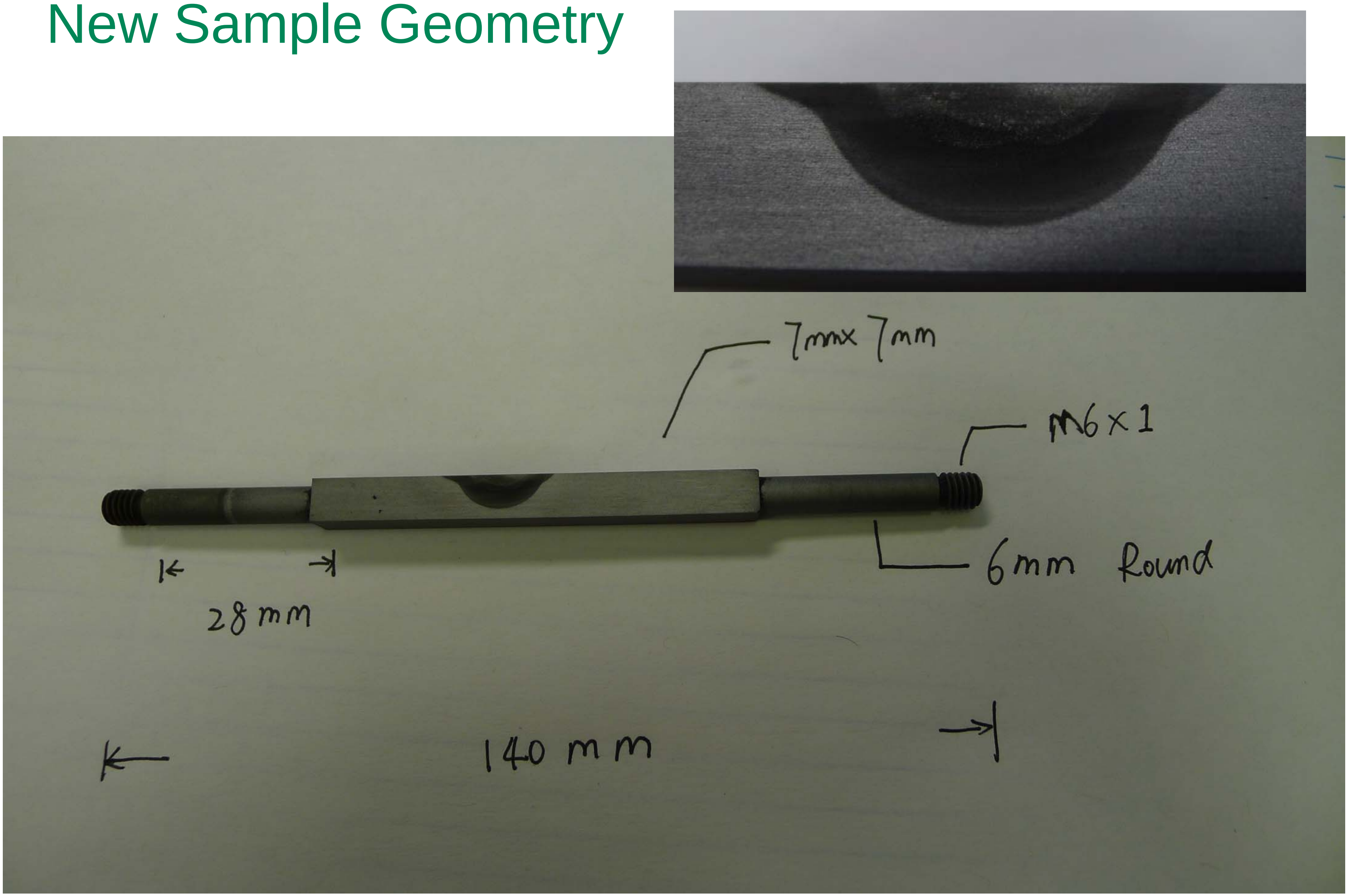
- ORNL weld creep test has successfully been used to measure localized creep deformation.
- Local strain is correlated to hardness and microstructure.
- FEA model of cross-weld sample is being established with consideration of gradual properties change
- Stability of martensite substructure and higher angle boundaries play an important role in Type IV failure

Backup Slides

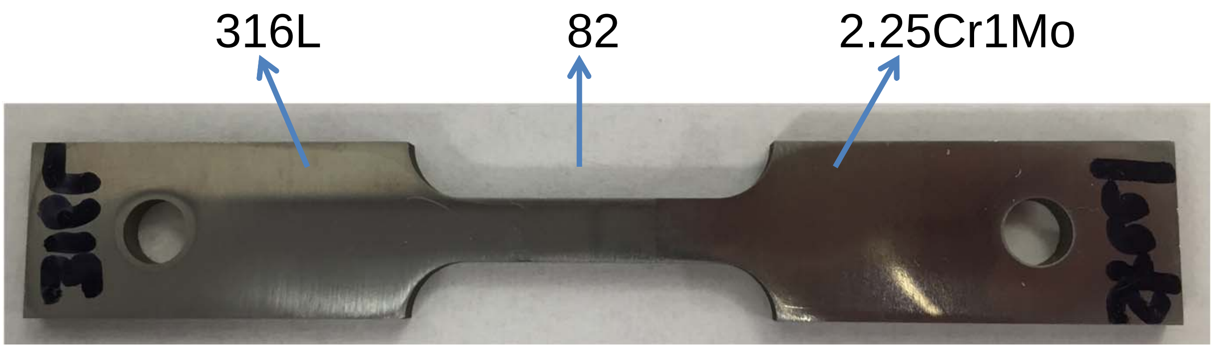
HAZ Creep Rate



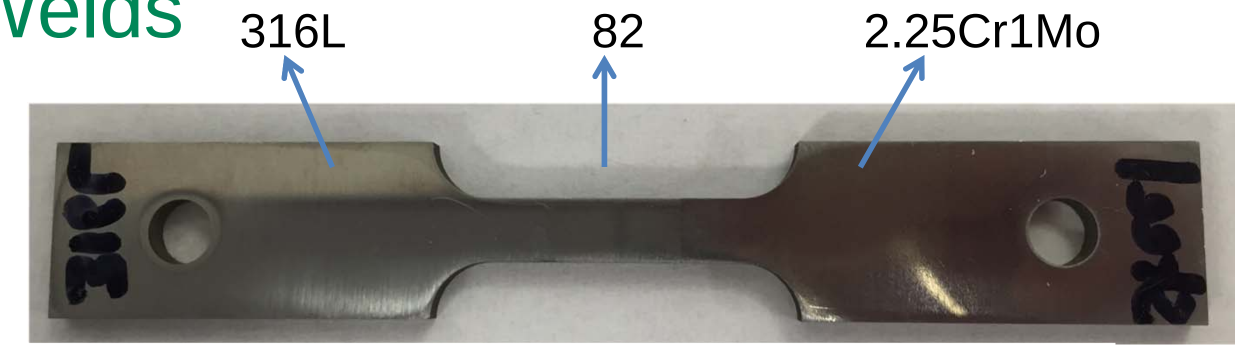
New Sample Geometry

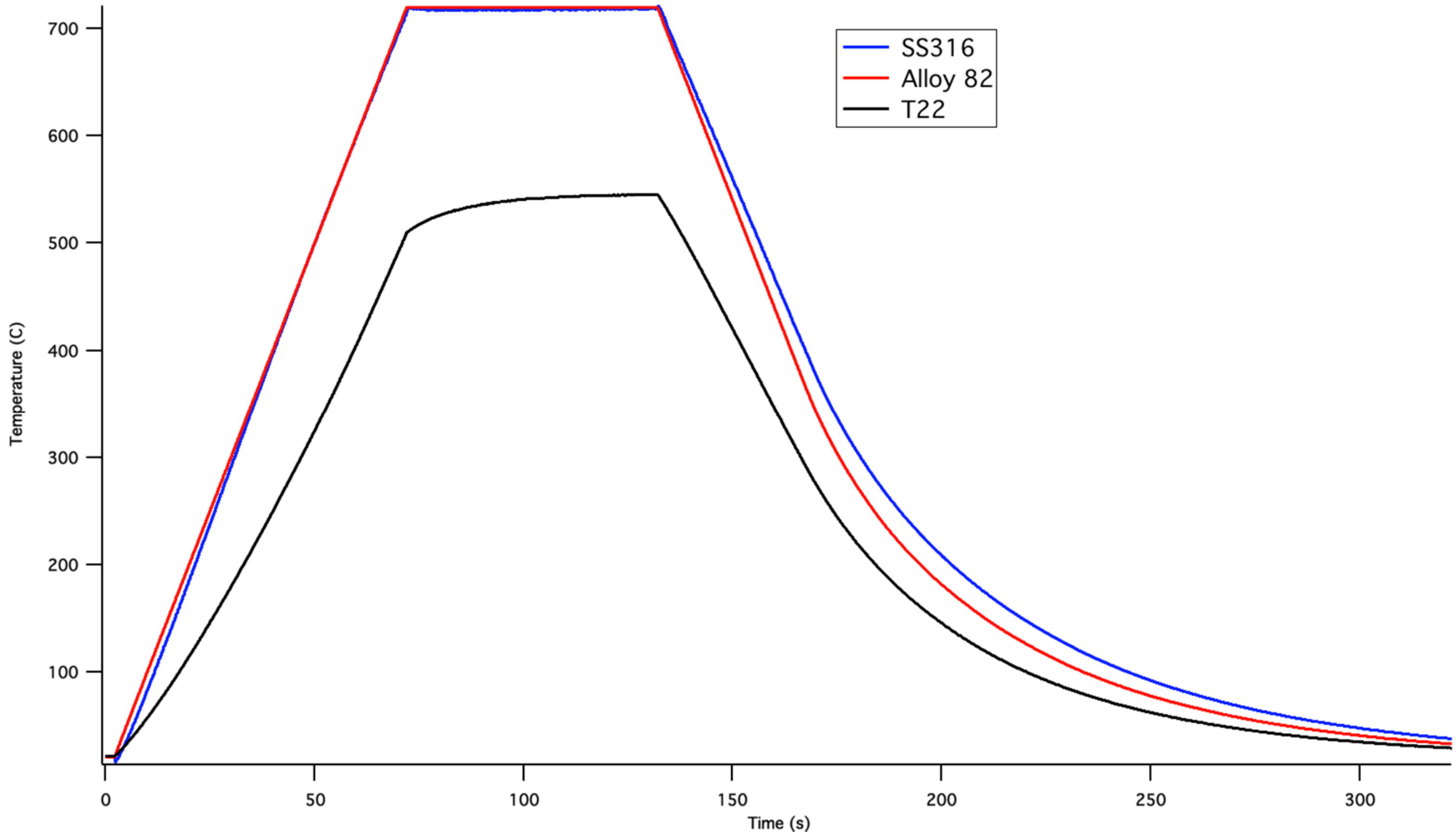


Dissimilar Metal Welds



Dissimilar Metal Welds



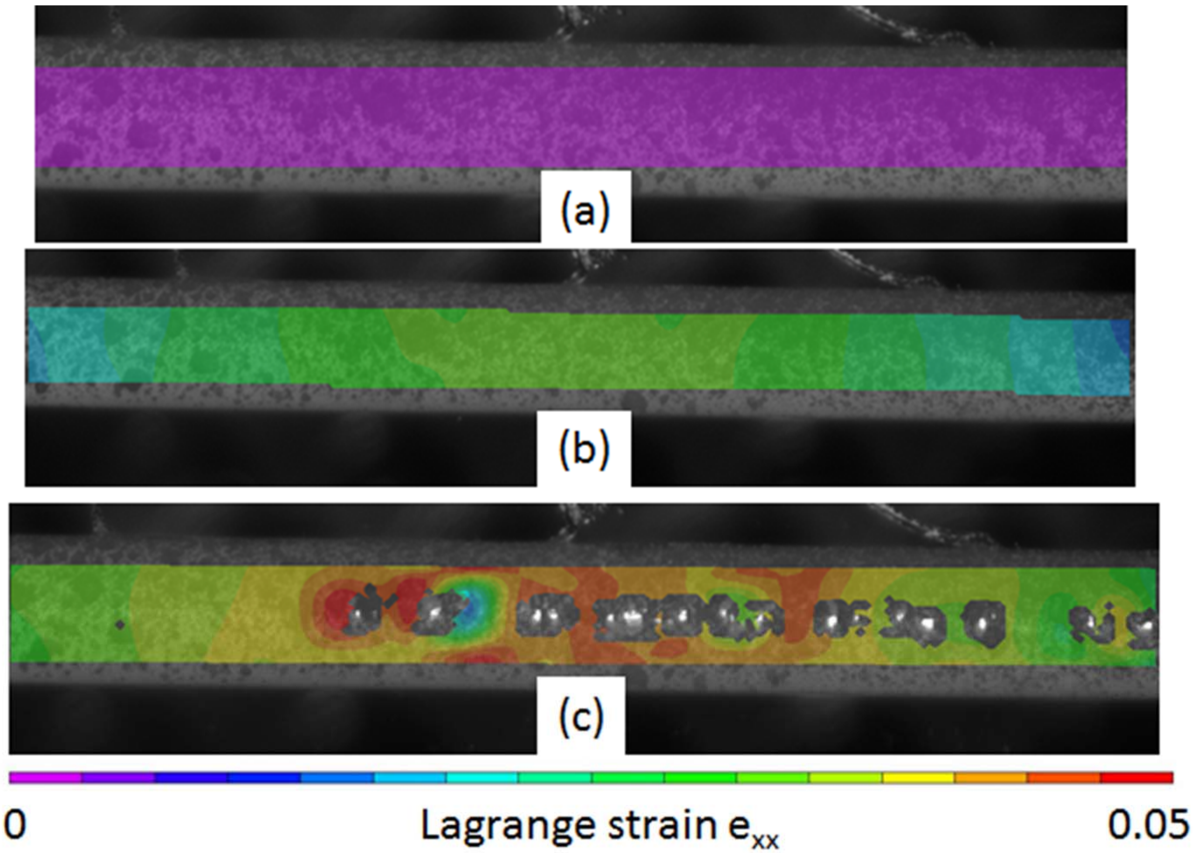


Damage prediction

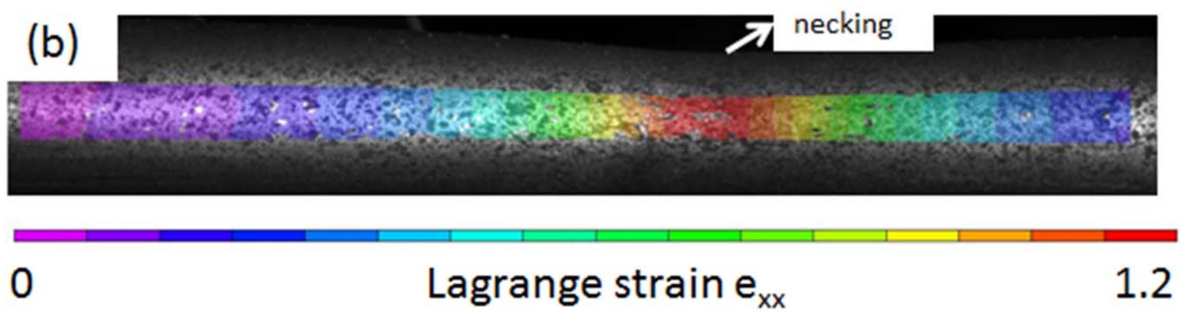
$$\frac{d\varepsilon_c}{dt} = \frac{3}{2} A \left[\frac{\sigma_{\text{eq}}}{1-\omega}\right]^n \frac{S_{ij}}{\sigma_{\text{eq}}} t^m$$

$$\frac{d\omega}{dt} = \frac{M\left[\alpha\sigma_1 + (1-\alpha)\sigma_{\text{eq}}\right]^\chi}{(1+\varphi)(1-\omega)^\varphi} t^m$$

Hot Tensile Testing



Original painting



Improved painting