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Challenges in Predicting and Observing Ductile Tearing

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Albuquerque, NM

Plasticity
January 4, 2011

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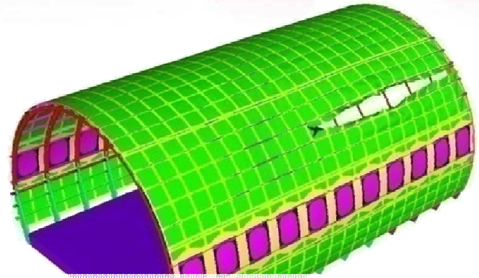
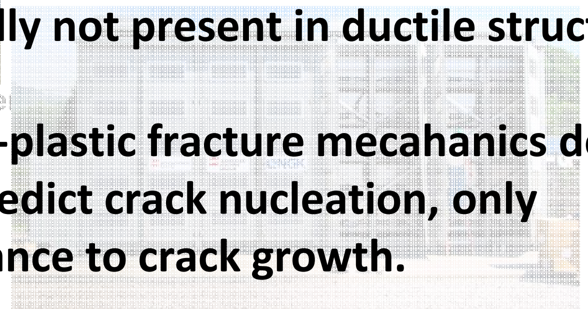
Ductile fracture (tearing) is a pervasive problem



- Linear elastic fracture mechanics only applies in cases of small-scale yielding, typically not present in ductile structures.
- Elasto-plastic fracture mecahanics does not predict crack nucleation, only resistance to crack growth.
- There are many other computational alternatives to predict ductile tearing, but none are fully mature.

Nuclear safety: operational and threat environments

An unexpected burst rocket component.



Structural survivability of electric grid.

Hydrogen storage in GM fuel cell vehicles
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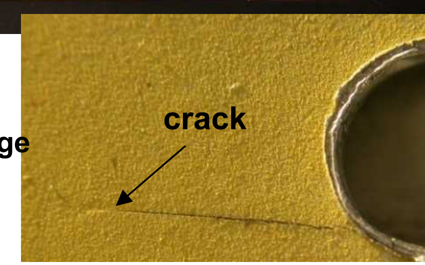
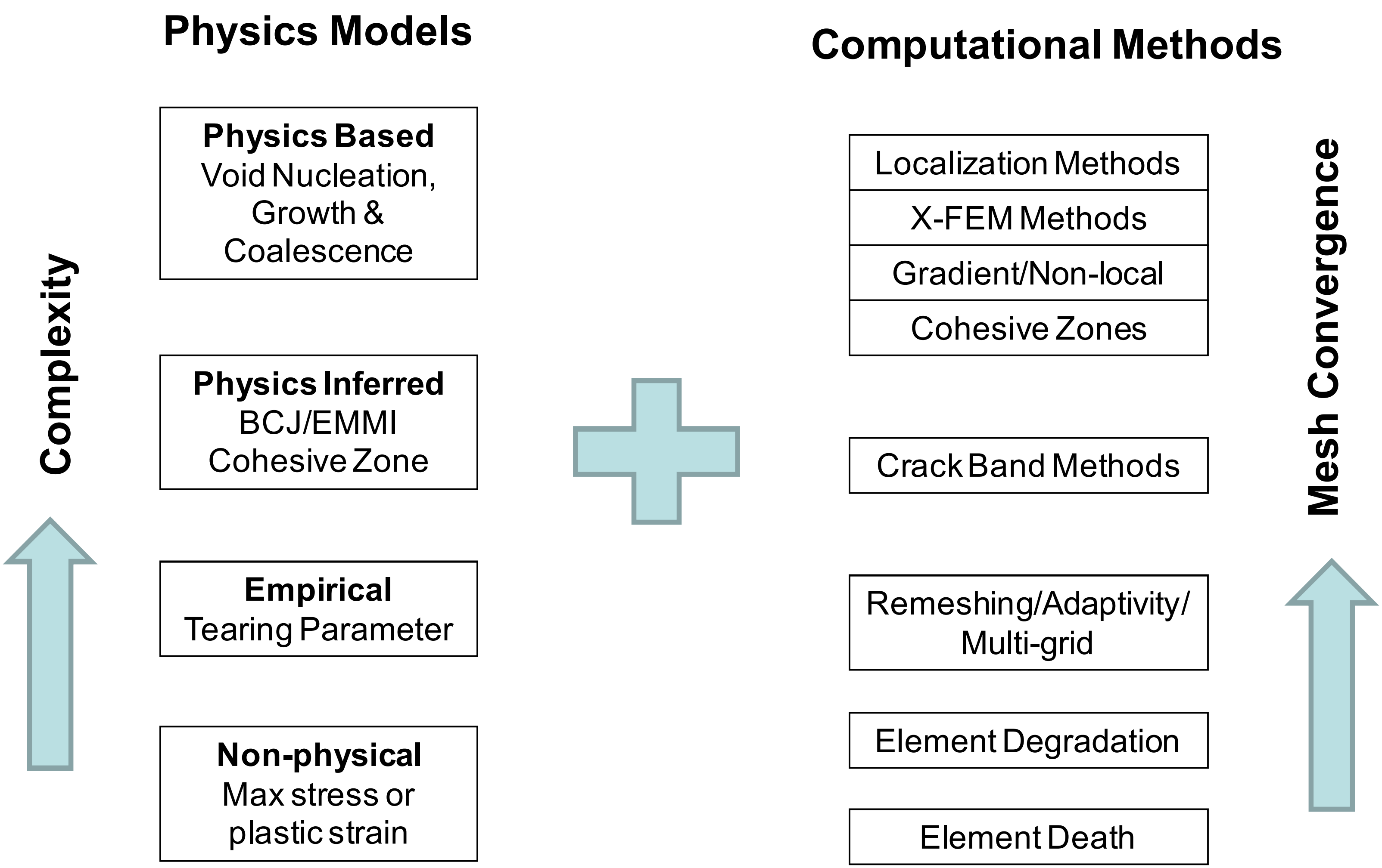


Rivet hole cracks in aircraft fuselage

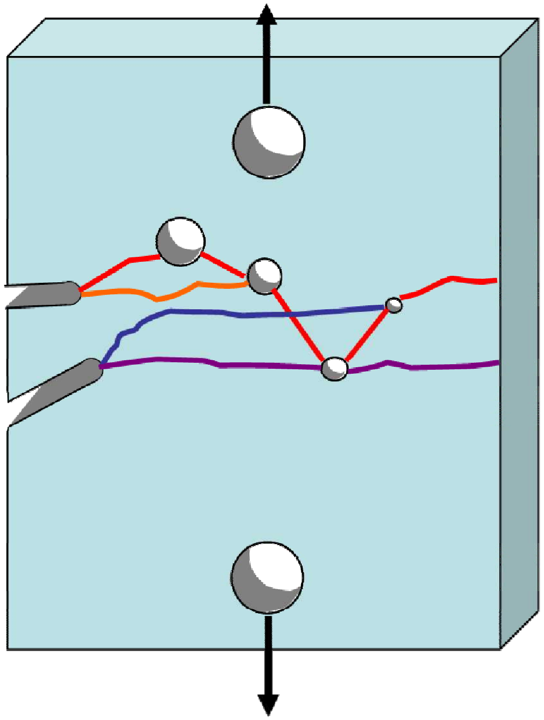
Minnesota I-35W Bridge Collapse..

B. L. Boyce

There is a rich variety of physical models and computational methods for ductile fracture



ASSESSMENT: How well do Sandia's modeling methods <u>blindly predict</u> metallic fracture in an arbitrary geometry?



"Crack-in-a-maze" Concept

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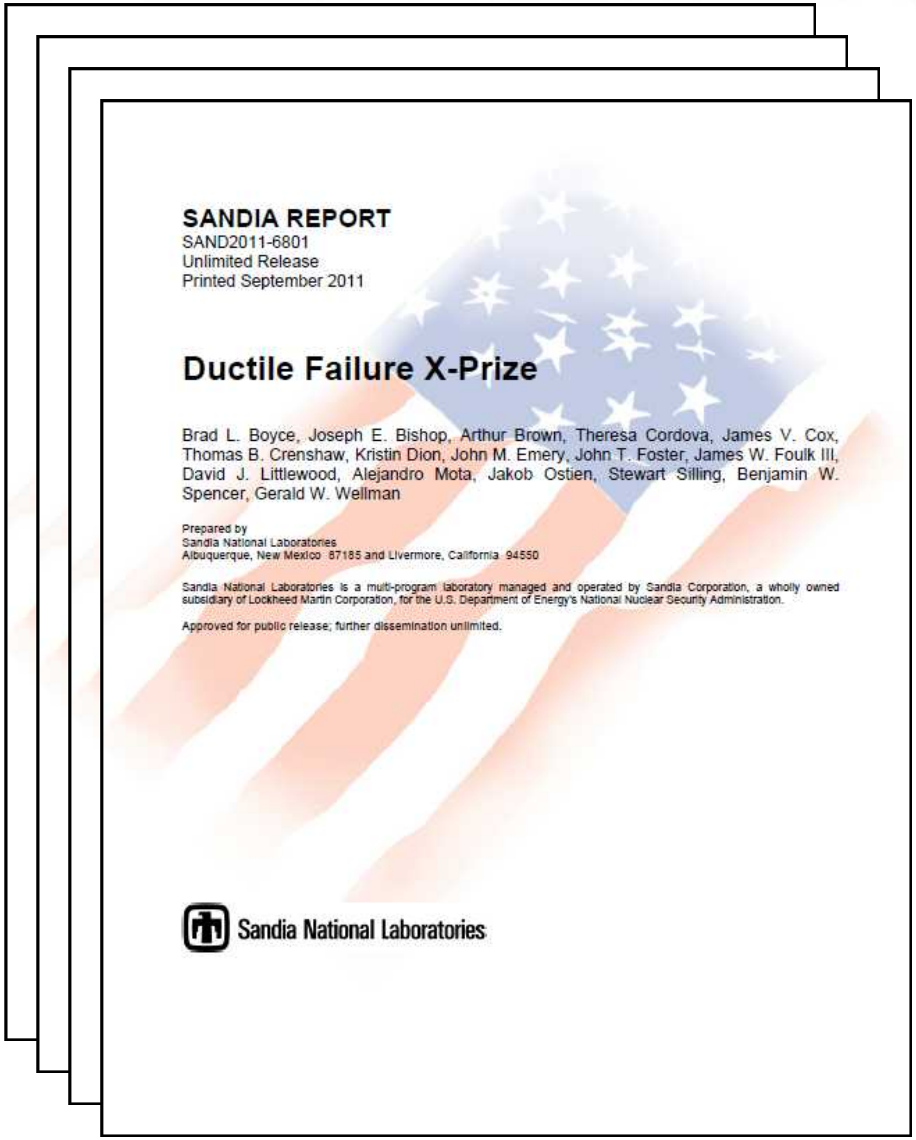
Four teams were chosen to represent the breadth of Sandia failure modeling approaches.

Team	Numerical Implementation	Crack Physics	Brief Description of Key Model Attributes	Failure Equation
Tearing Parameter				
K. Dion, G. Wellman	*Crack Band FEA*	***Tearing parameter*** *with critical crack opening strain*	An equivalent plastic strain evolution integral incorporating effects of stress triaxiality.	$T = \int_0^{\bar{\varepsilon}_f} \left\langle \frac{2\sigma_T}{3(\sigma_T - \sigma_m)} \right\rangle^4 d\bar{\varepsilon}$
Localization Elements				
J. Foulk, A. Mota, J. Emery, J. Ostien	***Localization Elements***	*BJC_mem damage model with Cocks-Ashby Void Growth*	A BCJ damage model is implemented in a regularized subgrid describing surface elements at a crack.	$\dot{\phi} = \{\frac{1}{(1-\phi)^m} - (1-\phi)\}\sinh[\frac{2(2m-1)}{2m+1}\frac{\langle\sigma_h\rangle}{\bar{\sigma}}]\dot{\varepsilon}_p$
Peridynamics				
J. Foster, J. Bishop, S. Silling, D. Littlewood	***Peridynamics***	*Critical Stretch*	Bond-node based meshless reformulation of continuum mechanics, particularly suitable for discontinuous displacement fields.	$w_\xi = \int_0^{\eta(t_{final})} \{\underline{\mathbf{T}}[\mathbf{x},t]\langle\mathbf{x}'-\mathbf{x}\rangle - \underline{\mathbf{T}}[\mathbf{x}',t]\langle\mathbf{x}-\mathbf{x}'\rangle\}\cdot d\boldsymbol{\eta}$
XFEM				
J. Cox, D. Littlewood, B. Spencer	***XFEM***	*Max Princ. Stress, EQPS, tearing parameter*	Crack-like asymptotic displacement fields and discontinuities enrich the finite element approximation. No explicit meshing of crack surfaces is needed.	$\dot{\bar{\varepsilon}}^p = \sqrt{\frac{2}{3}\dot{\varepsilon}^p_{ij}\dot{\varepsilon}^p_{ij}} = \sqrt{\frac{2}{3}}\left\{(\dot{\varepsilon}^p_{xx})^2 + (\dot{\varepsilon}^p_{yy})^2 + (\dot{\varepsilon}^p_{zz})^2 + 2\left[(\dot{\varepsilon}^p_{xy})^2 + (\dot{\varepsilon}^p_{xz})^2 + (\dot{\varepsilon}^p_{yz})^2\right]\right\}^{1/2}$

A 300-page Report is Available, Describing Methods And Results.



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Printed September 2011

Ductile Failure X-Prize

Brad L. Boyce, Joseph E. Bishop, Arthur Brown, Theresa Cordova, James V. Cox, Thomas B. Crenshaw, Kristin Dion, John M. Emery, John T. Foster, James W. Foulk III, David J. Littlewood, Alejandro Mota, Jakob Ostien, Stewart Silling, Benjamin W. Spencer, Gerald W. Wellman

Prepared by
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- Motivation & Background
- Numerical Methodologies for Four Independent Teams
- Blind Predictions
- Experimental Methods
- Comparison of Blind Predictions to Experiments
- Assessment of Sources of Error

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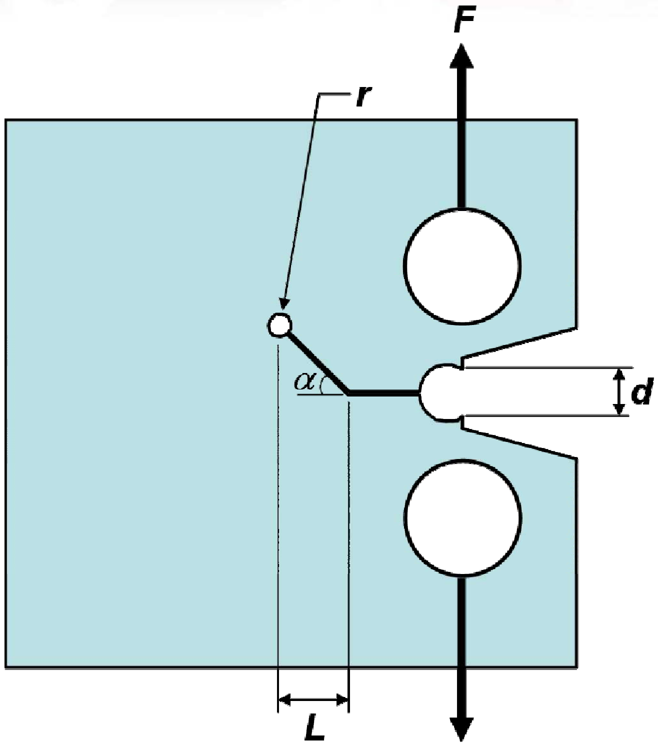
1st Challenge: Predict Crack Initiation



1. **What is the loadline displacement ∆d, needed to induce crack initiation?**

2. **What is the peak force F applied to the sample prior to crack initiation?**

   provided information: detailed engineering drawings, material specification (PH13-8Mo H950)

Crack initiation in this geometry is difficult to predict for three reasons:

(a) The pre-existing flaw is a blunt notch rather than a sharp crack.

(b) The notch is inclined resulting in significant mode mixity.

(c) The sample is relatively thin (1/8”) resulting in a constraint that is somewhere between plane-stress and plane-strain.

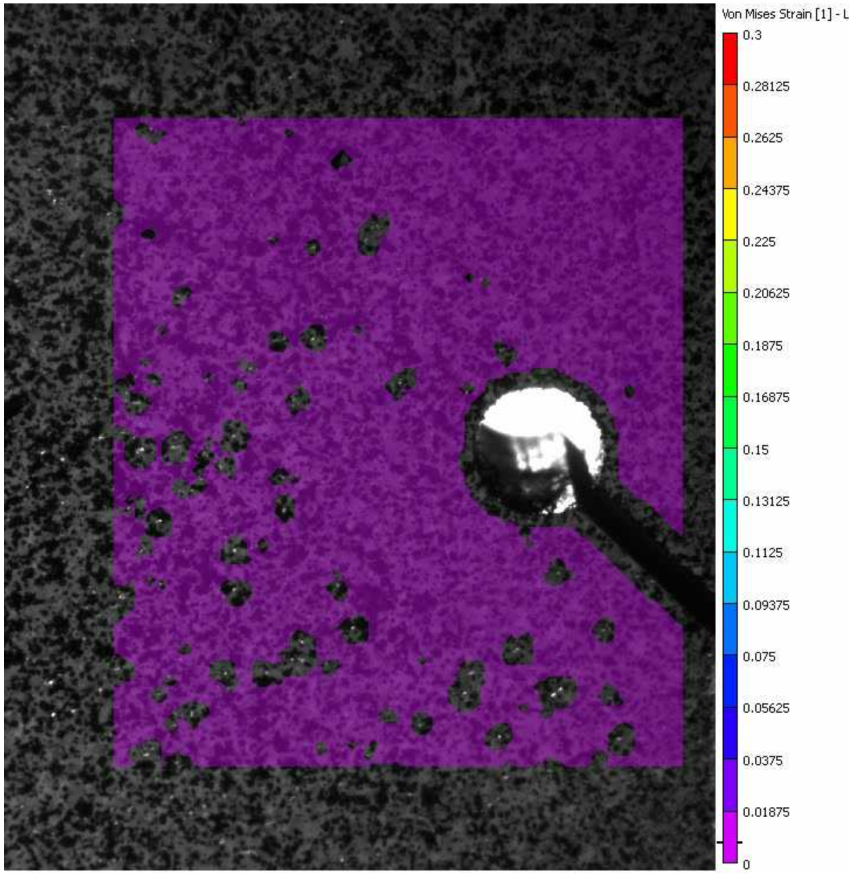
b1

Two test labs & several repeats builds confidence in expt'l results

- **Two independent mechanical test labs, each testing 6-8 samples**

- **The two labs chose very different approaches (i.e. rigid load train vs. fully-flexible load train)**

- **Yet, the quantitative results differed by <2%, confirming that Challenge 1A was repeatable and the experimental validation results were uncontroversial.**



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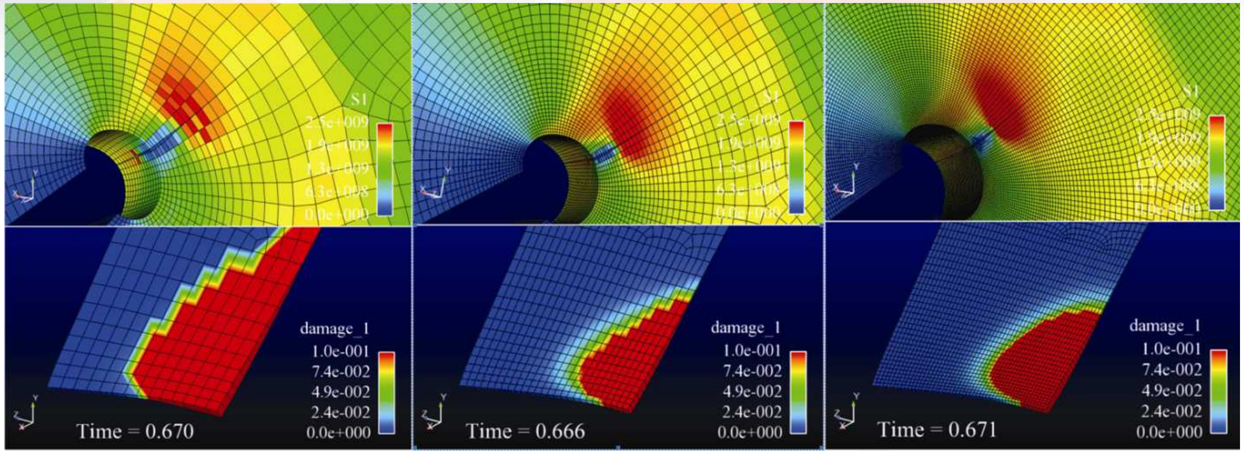
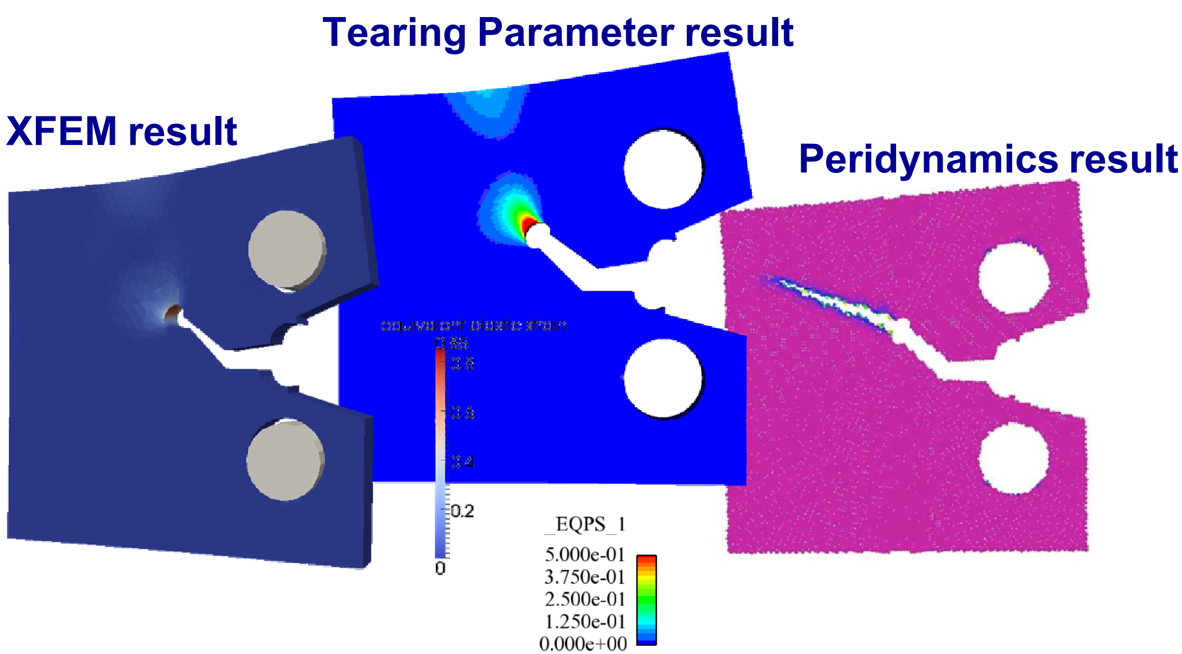
Slide 8

b1 blb, 8/3/2011

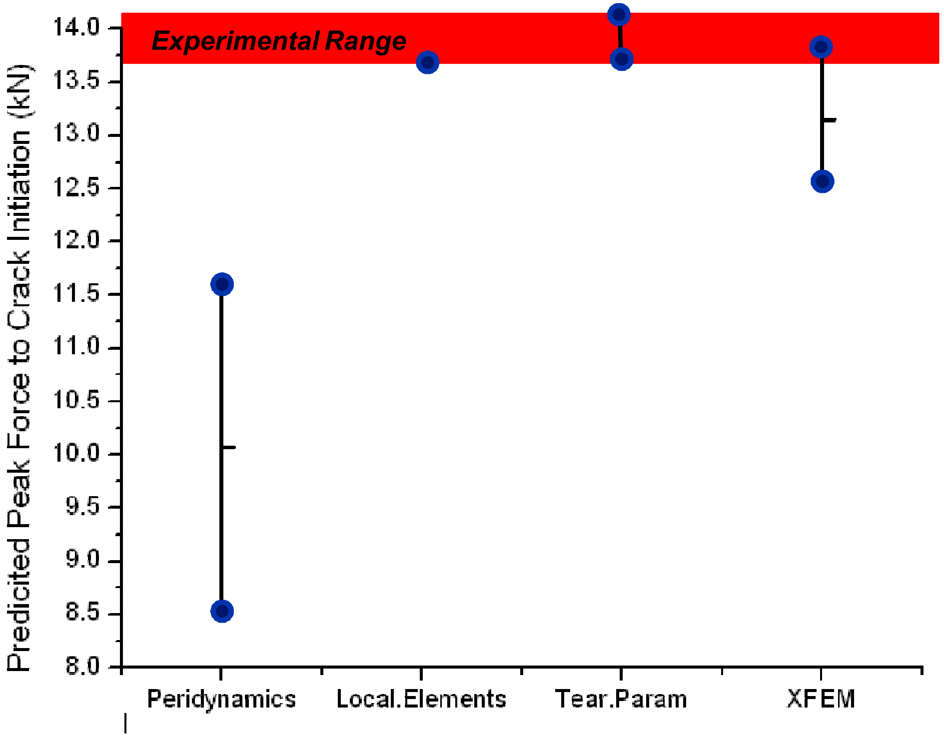
All four teams are ‘on their own’ to make predictions by the due date



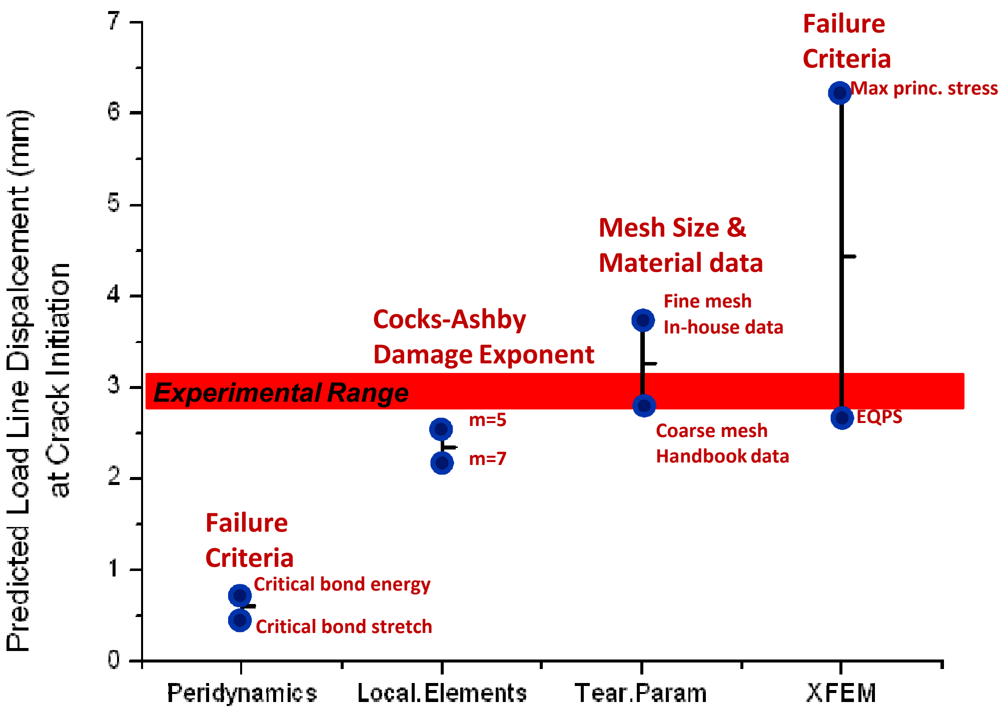
Localization elements mesh convergence study



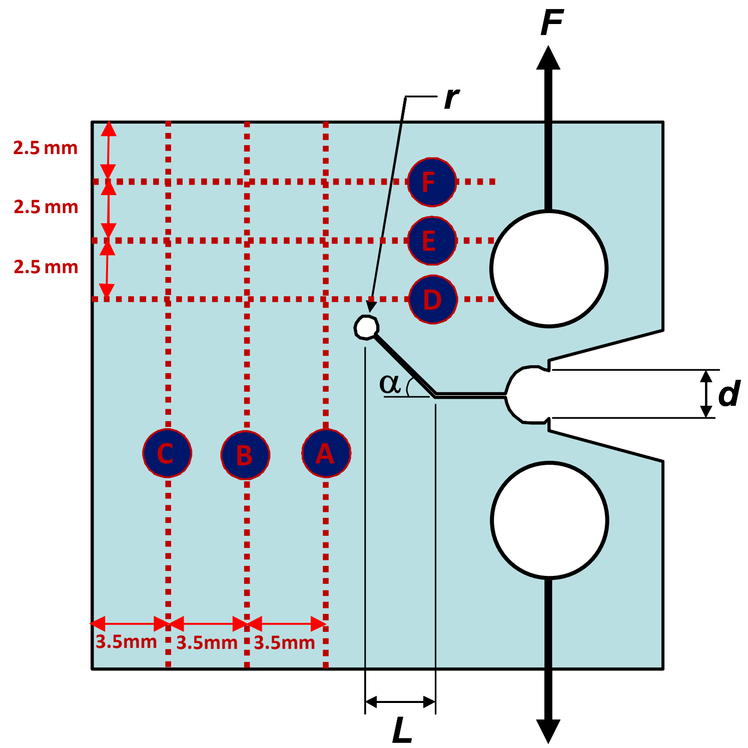
1st Challenge: Predictions Compared to Experiments



1st Challenge: Predictions Compared to Experiments



2nd Challenge: Predict Mixed-Mode Propagation



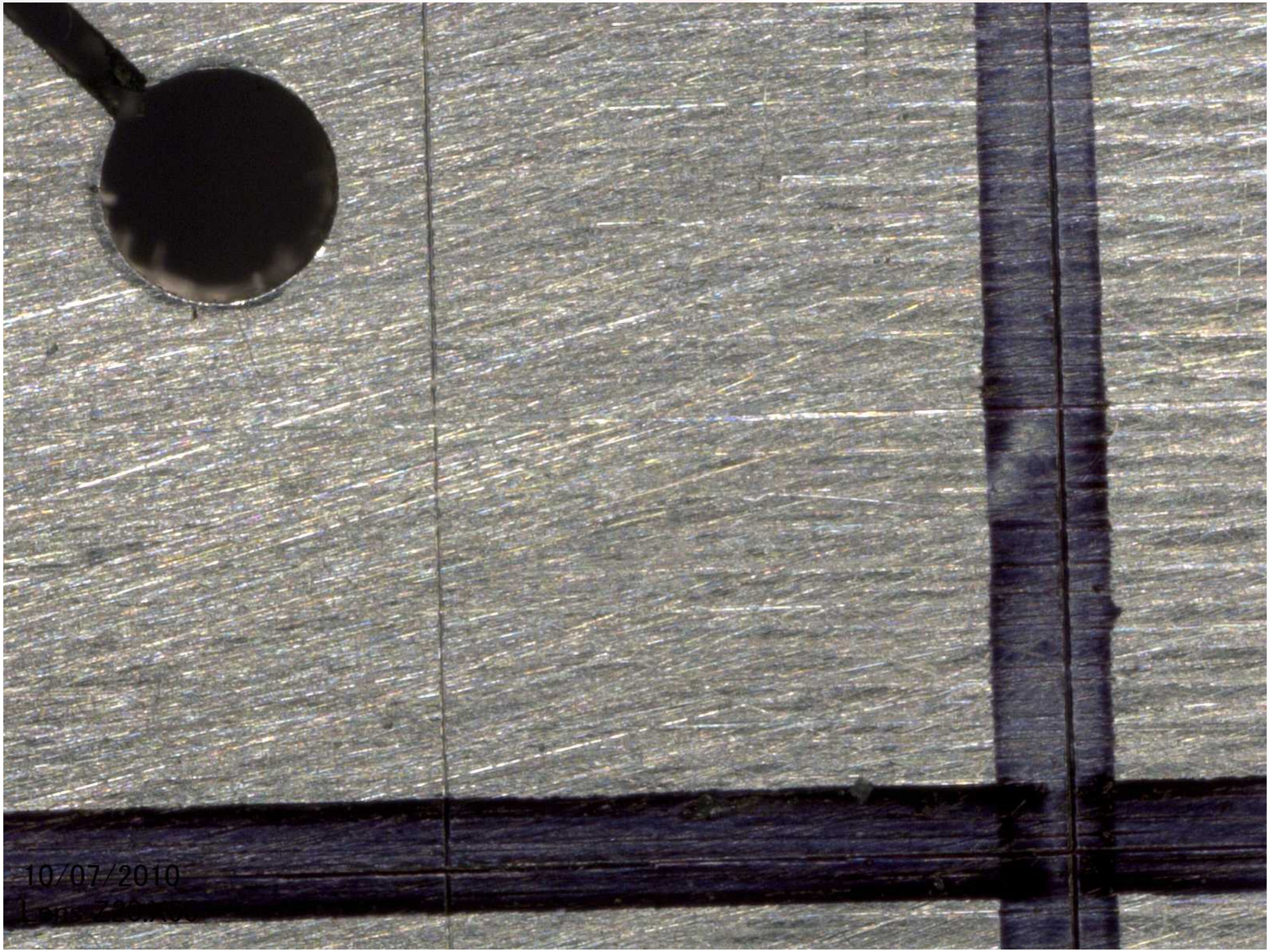
1. **For a specimen as shown on the left, with geometry defined previously, what is the loadline displacement Δd needed to induce crack initiation (in inches) in aluminum alloy 2024-T3? What is the peak force prior to crack initiation?**

2. **Six lines labeled A-G will be scribed prior to testing in the locations indicated. What is the order of crack propagation (e.g. A-B-D-C, etc.)?**

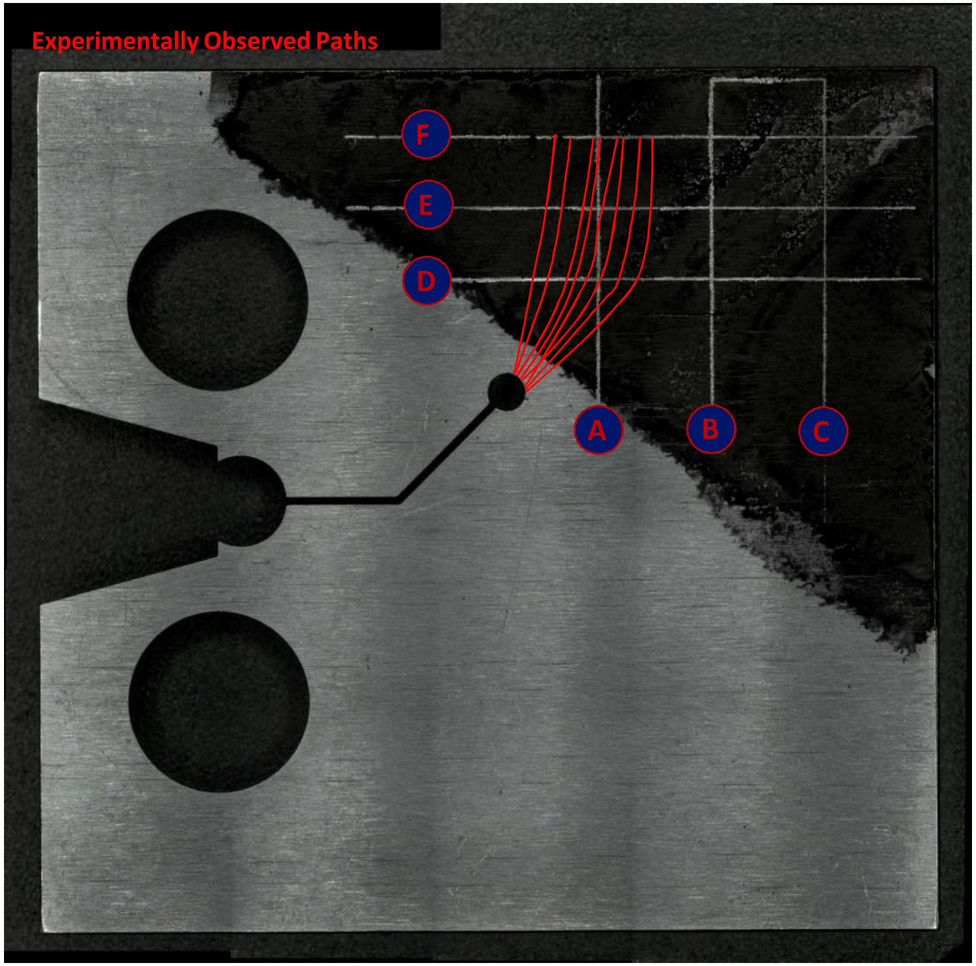
3. **What is the force and displacement at which the crack reaches the 1st line?**

4. **What is the force and loadline displacement at which the crack reaches line E (refer to previous drawing)?**

Image progression of Crack Initiation and Propagation

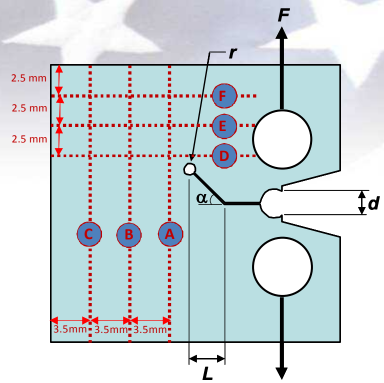


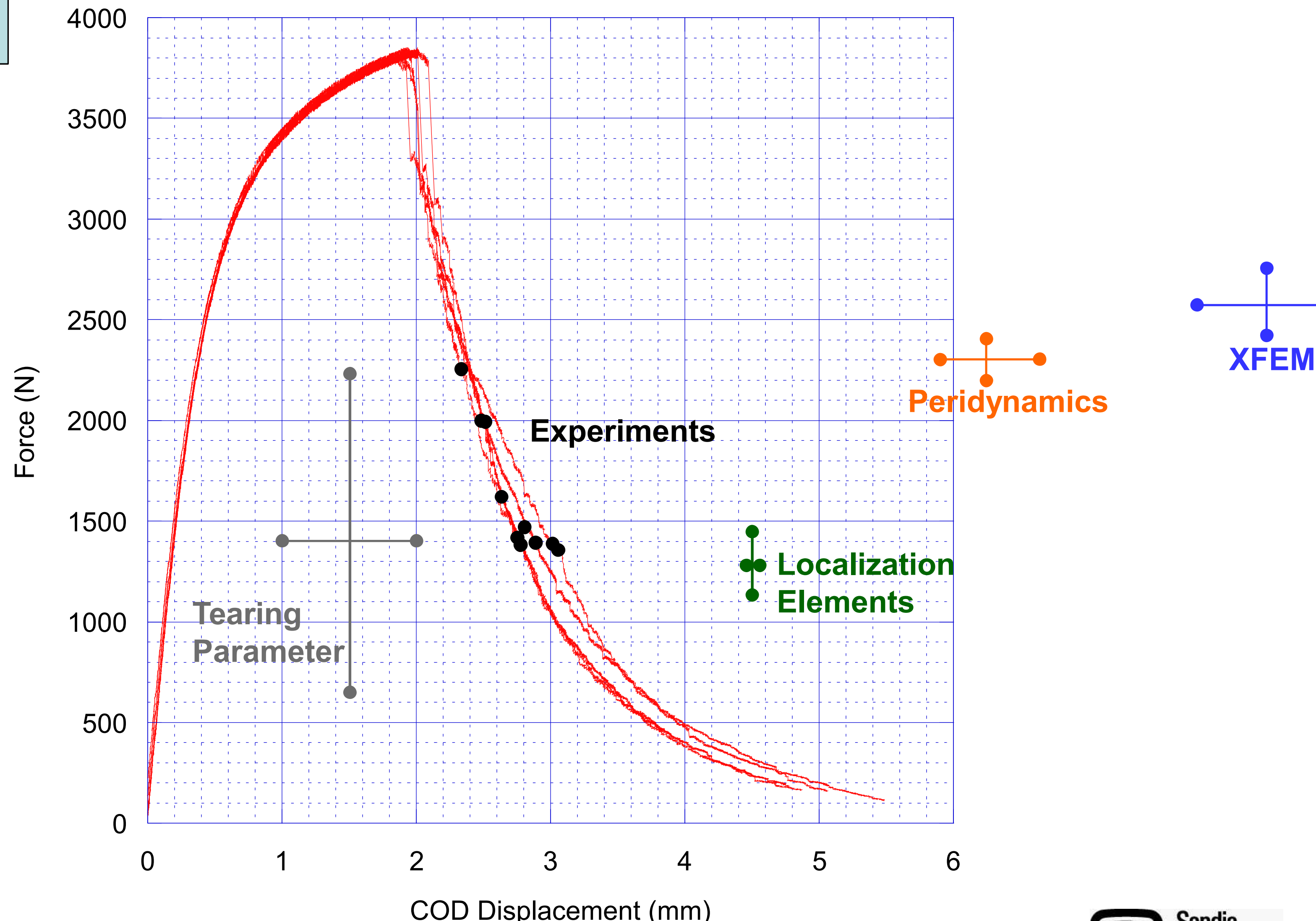
2nd Challenge: Predict Crack Path



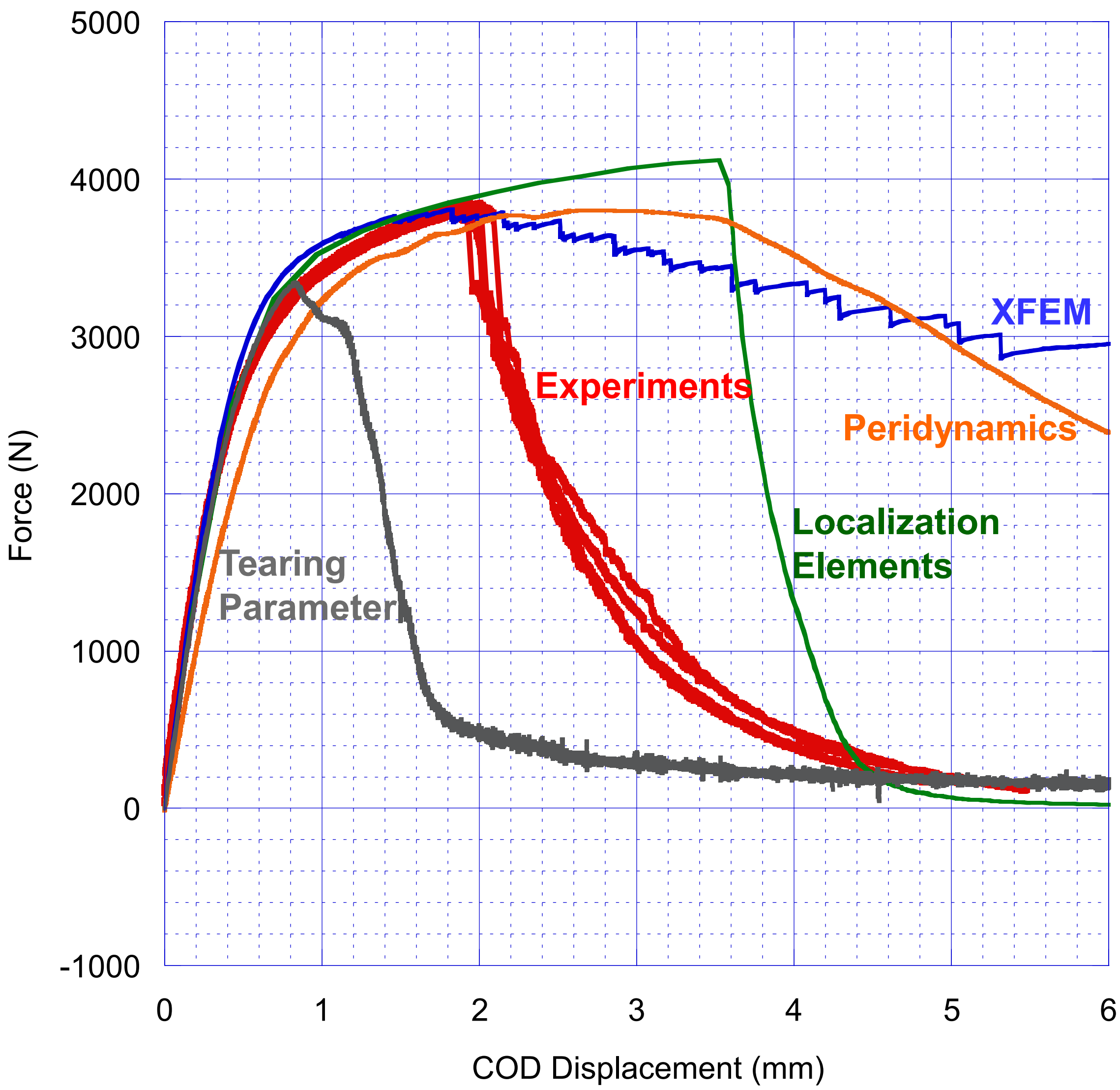
Predicted Path:	
Localiz. Elements	D-A-E-F-B
Peridynamics	D-E-A-F or D-E-F-A
Tearing Parameter	D-E-F-(A?)
X-FEM Abaqus	D-E-A-F or D-E-F-A
X-FEM Sierra	A-B-C

2^{nd} Challenge: Predict F and d as the crack crosses feduciary line D

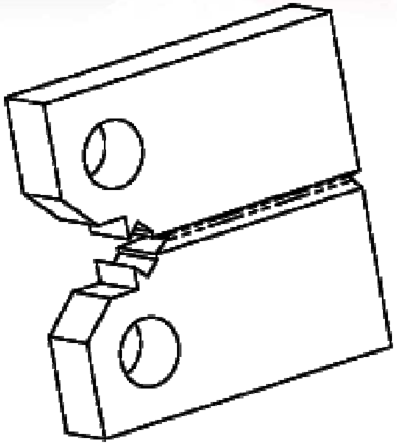


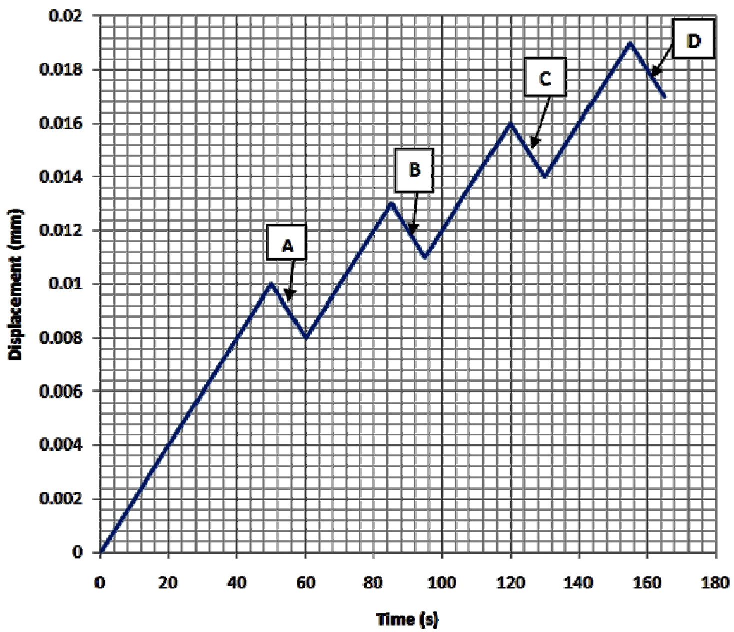


2nd Challenge: Results



3rd Challenge: Predict R-Curve Behavior

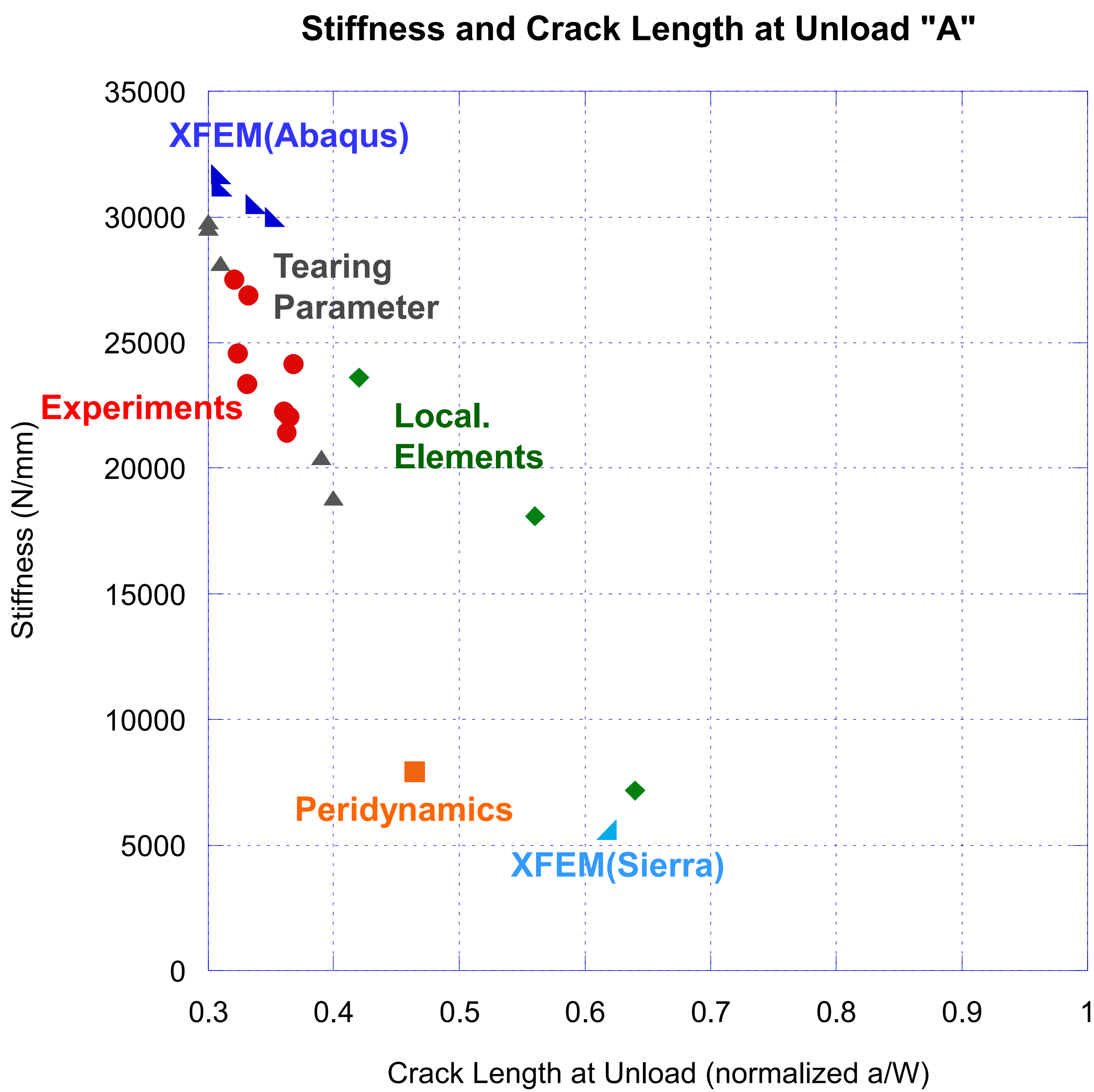




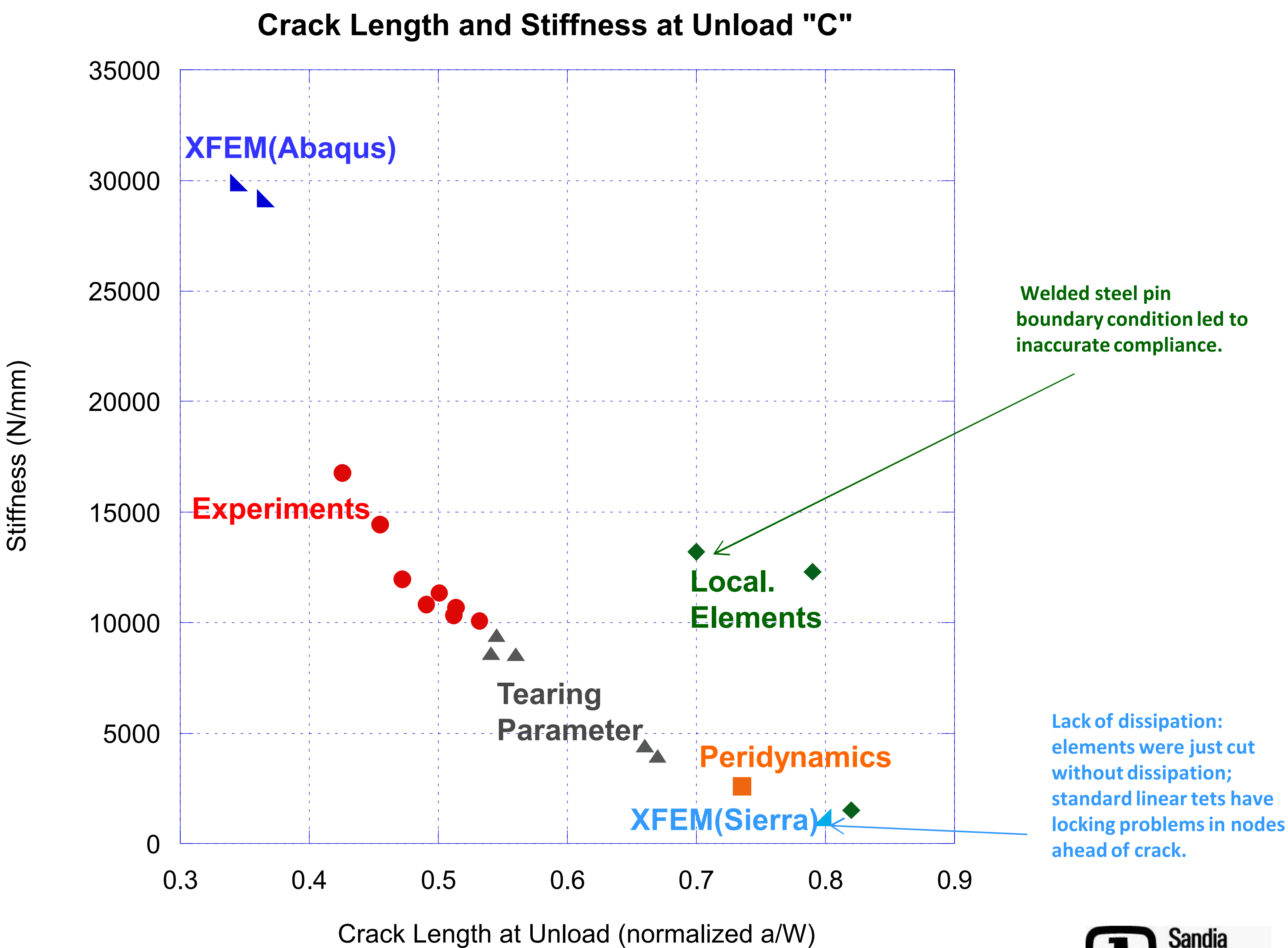
-side-grooved compact tension geometry
-aluminum alloy 2024-T3
-precracked to a crack length of a/W=0.3

For a displacement-controlled loading regimen, as shown, predict the crack length and unloading compliance for peaks labeled A-D.

3rd Challenge: Results



3rd Challenge: Results



Q: Why do these models have such difficulty in predicting ductile tearing?

A: While there are many sources of error (numerical methods, boundary conditions, poor assumptions, etc.), the most glaring is the lack of a rigorous physically-based model for ductile tearing.

Microvoid coalescence as represented by a Cocks-Ashby or Gurson-Tvergaard-Needleman model still does not capture the diversity of ductile metals response.

Don't we already know about ductile fracture via void coalesence?

Acta Metallurgica, 1978

OVERVIEW NO. 1

THE NUCLEATION OF CAVITIES BY PLASTIC DEFORMATION

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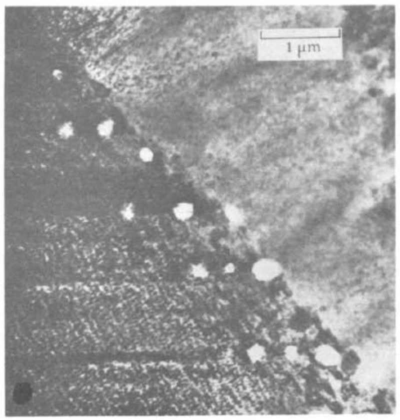

Fig. 1. The formation of cavities by the intersection of slip bands (horizontal lines) with a grain boundary in Nimonic 80A (after Dyson).

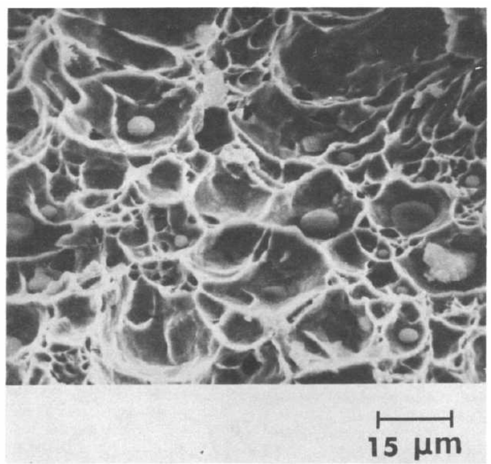

Fig. 3. Ductile fracture surface of a spheroidized steel with carbides present within the dimples (after Eiselstein).

Acta Metallurgica, 1984
(see also Gurson in late 1970's)

ANALYSIS OF THE CUP-CONE FRACTURE IN A ROUND TENSILE BAR

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and

A. NEEDLEMAN

Division of Engineering, Brown University Providence, RI 02912, U.S.A.

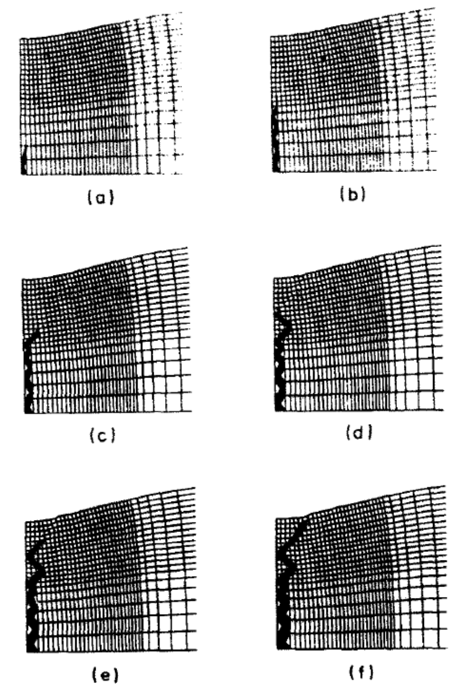
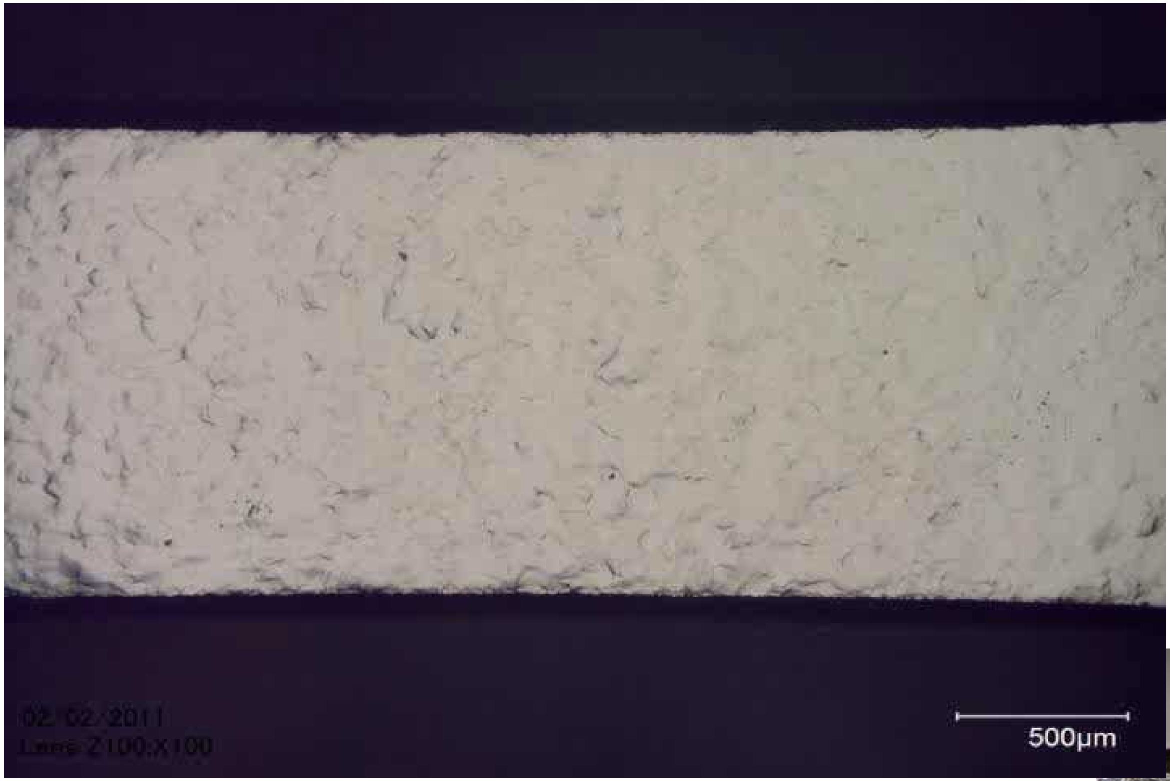
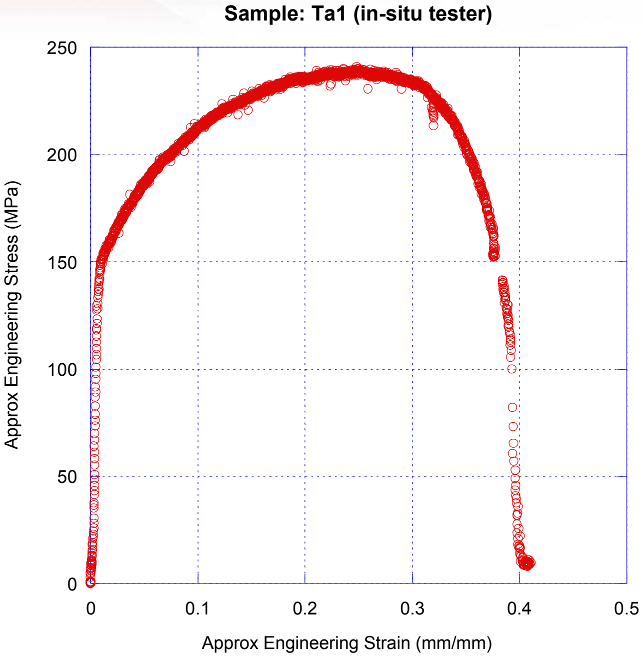
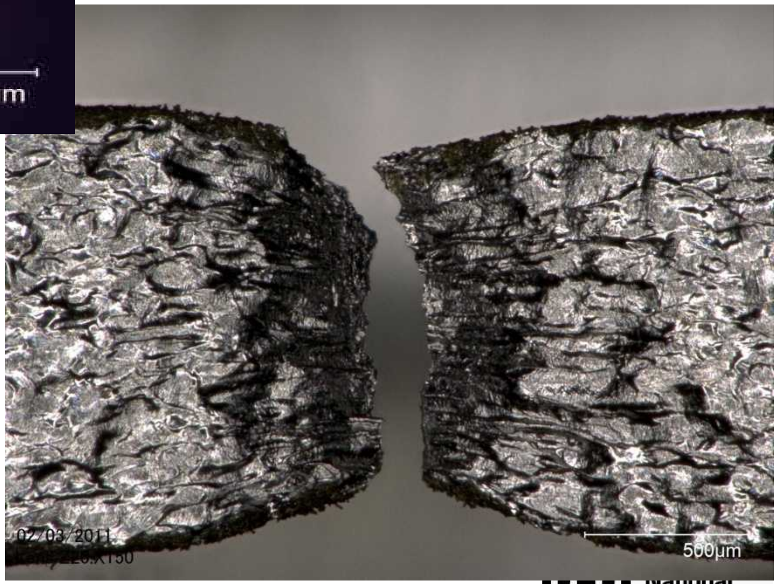


Fig. 13. Crack growth in 20×42 mesh for $L_0/R_0 = 2$. Vanished triangular elements are painted black. (a) $T/T_{max} = 0.683$, (b) $T/T_{max} = 0.565$, (c) $T/T_{max} = 0.438$, (d) $T/T_{max} = 0.249$, (e) $T/T_{max} = 0.165$, (f) $T/T_{max} = 0.032$.

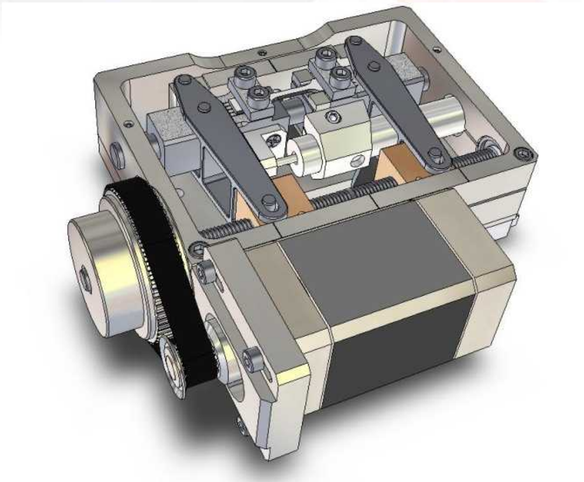
Ductile Tearing of Tantalum

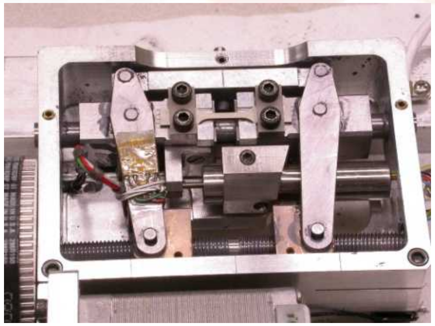


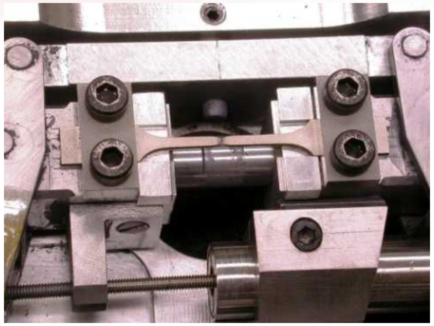


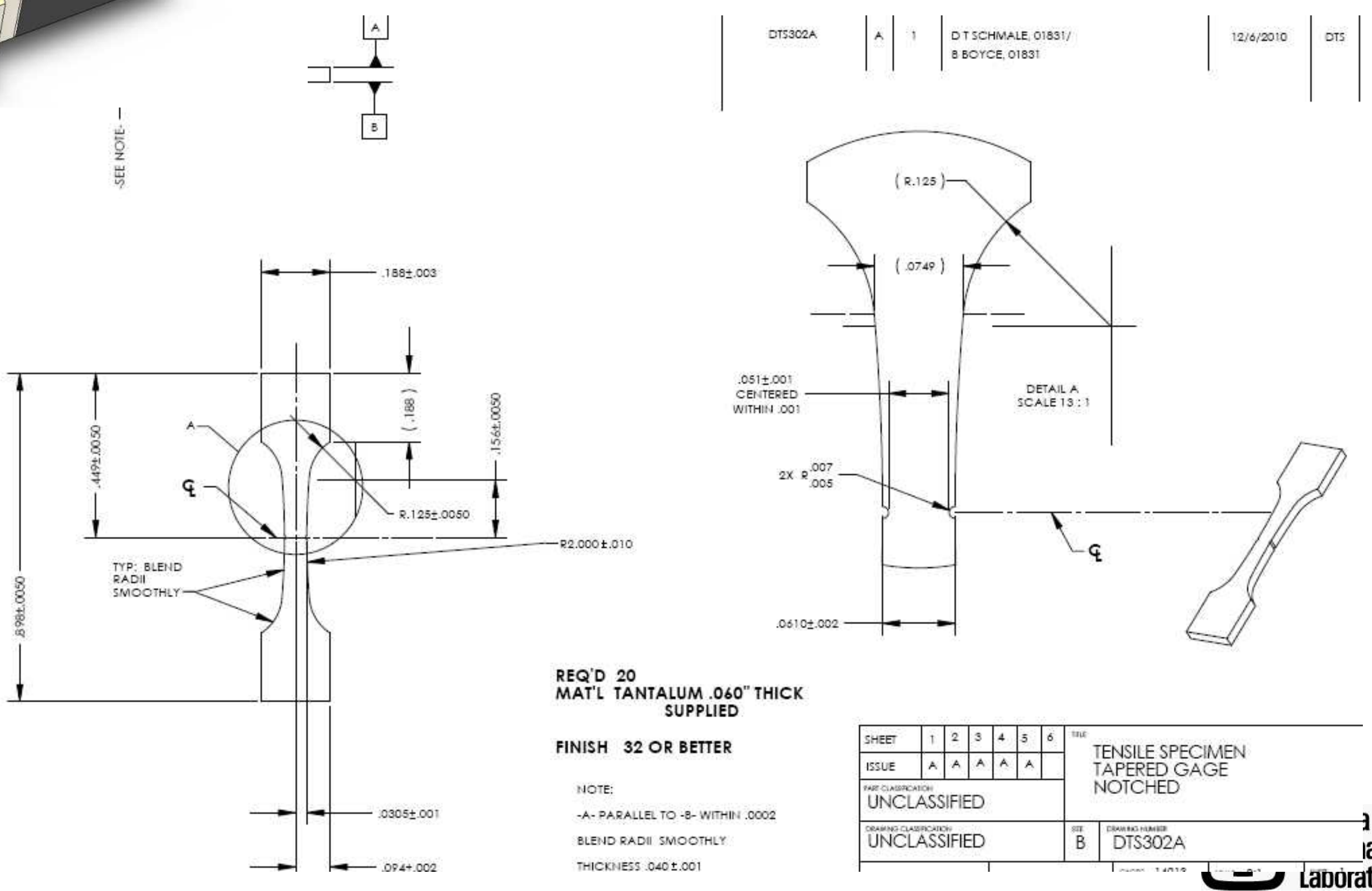


Compact In-Situ SEM / EBSD Tensile Stage with 500-lbf capacity

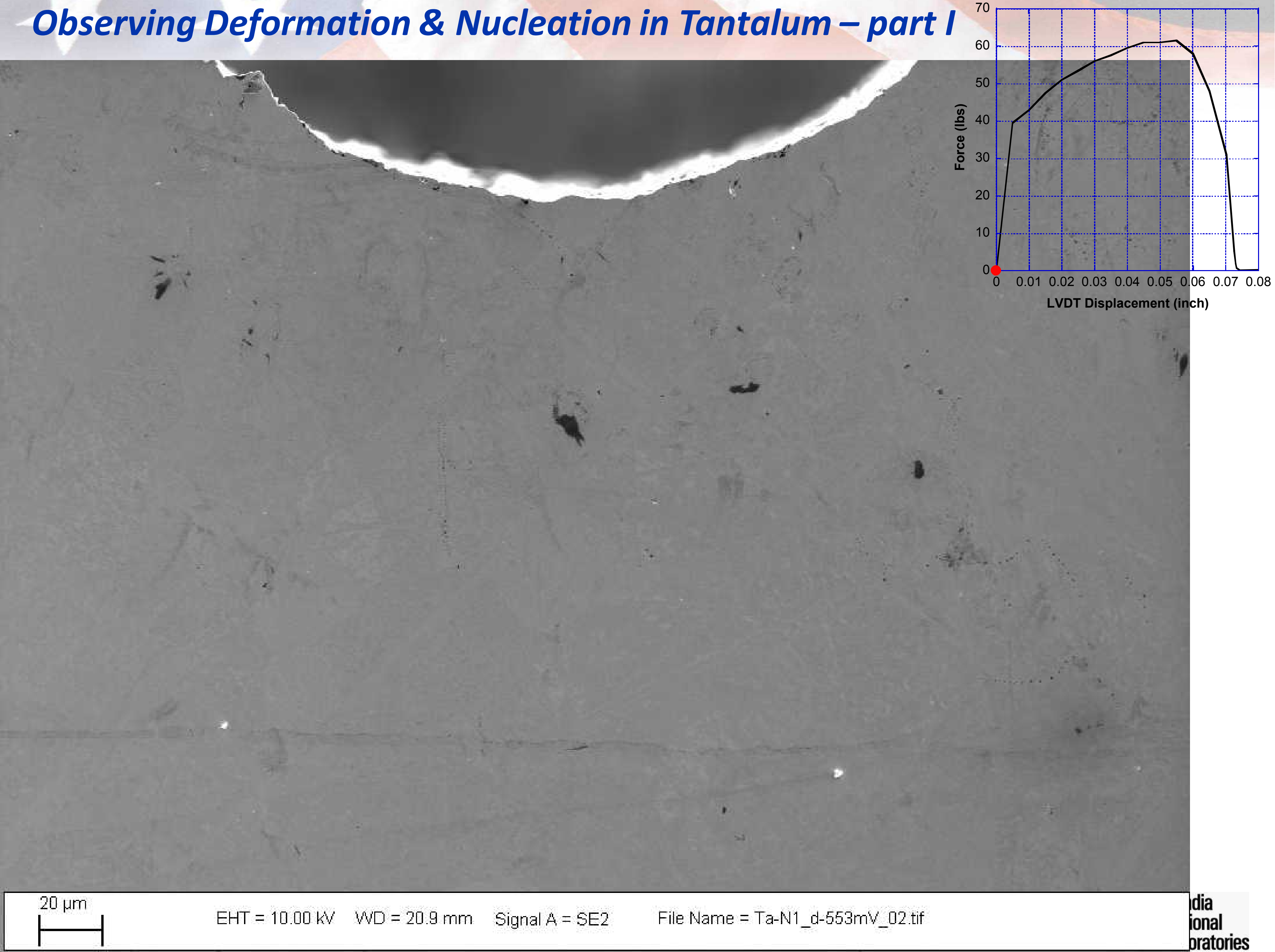








Observing Deformation & Nucleation in Tantalum – part I



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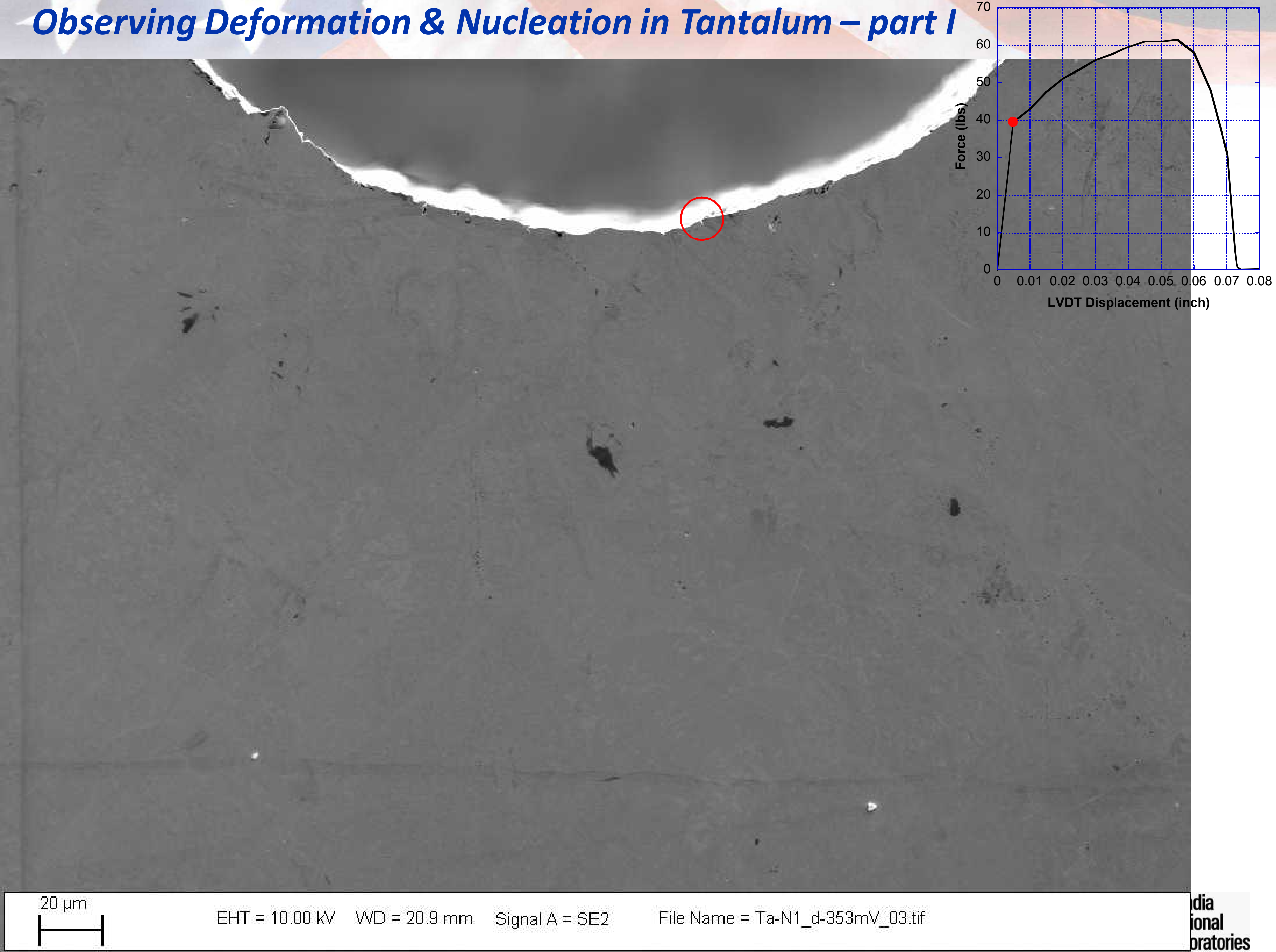

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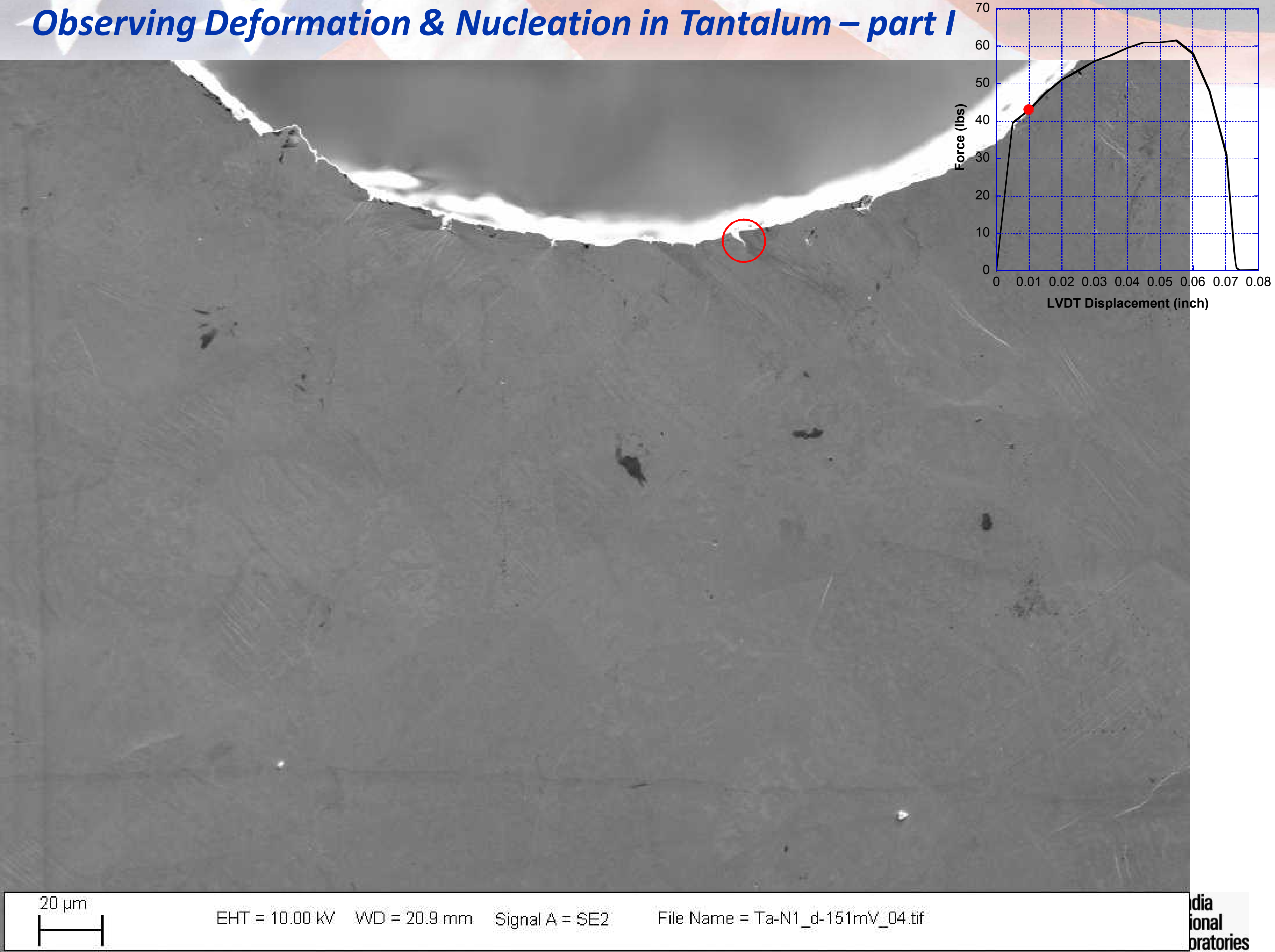

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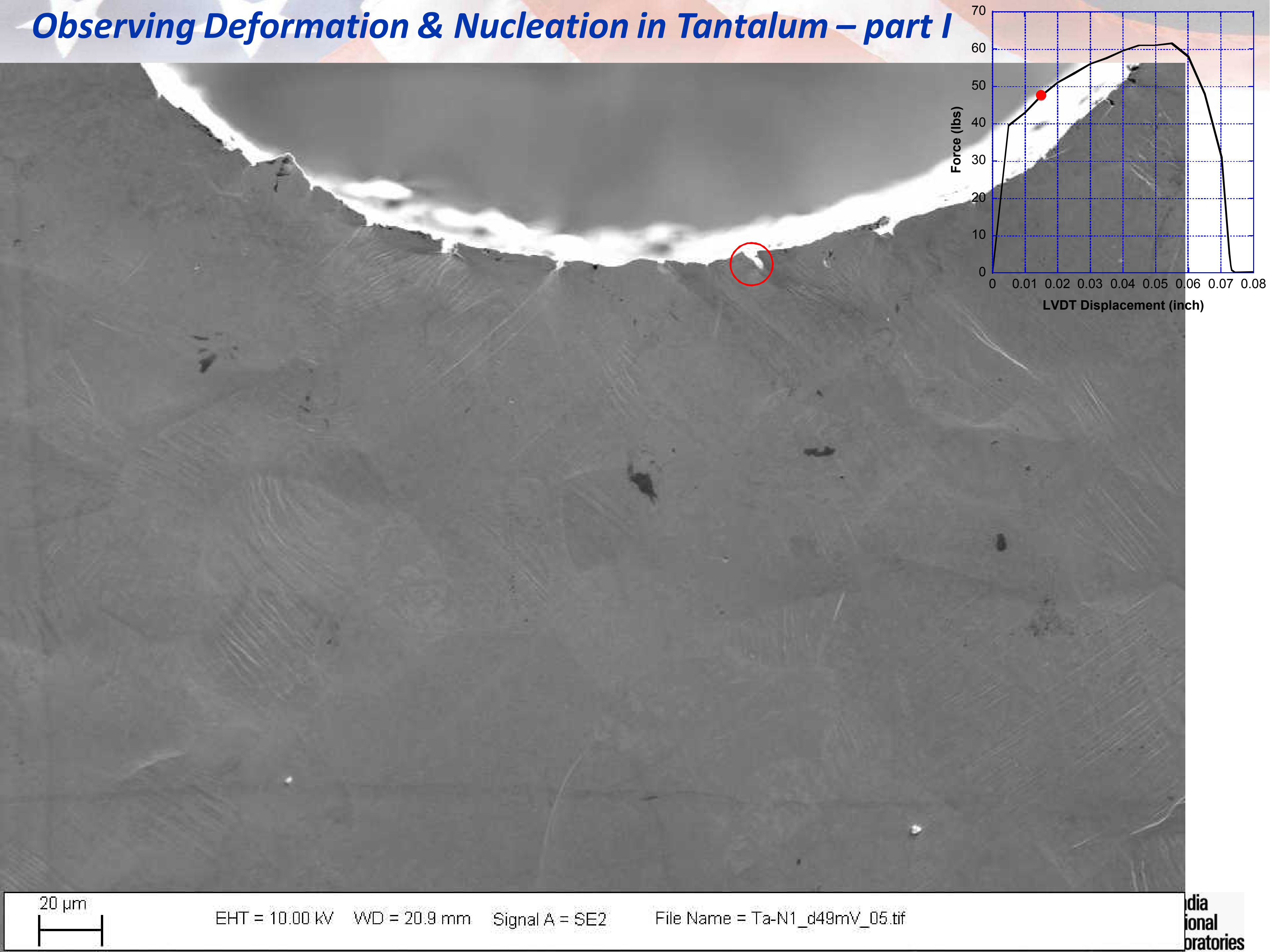

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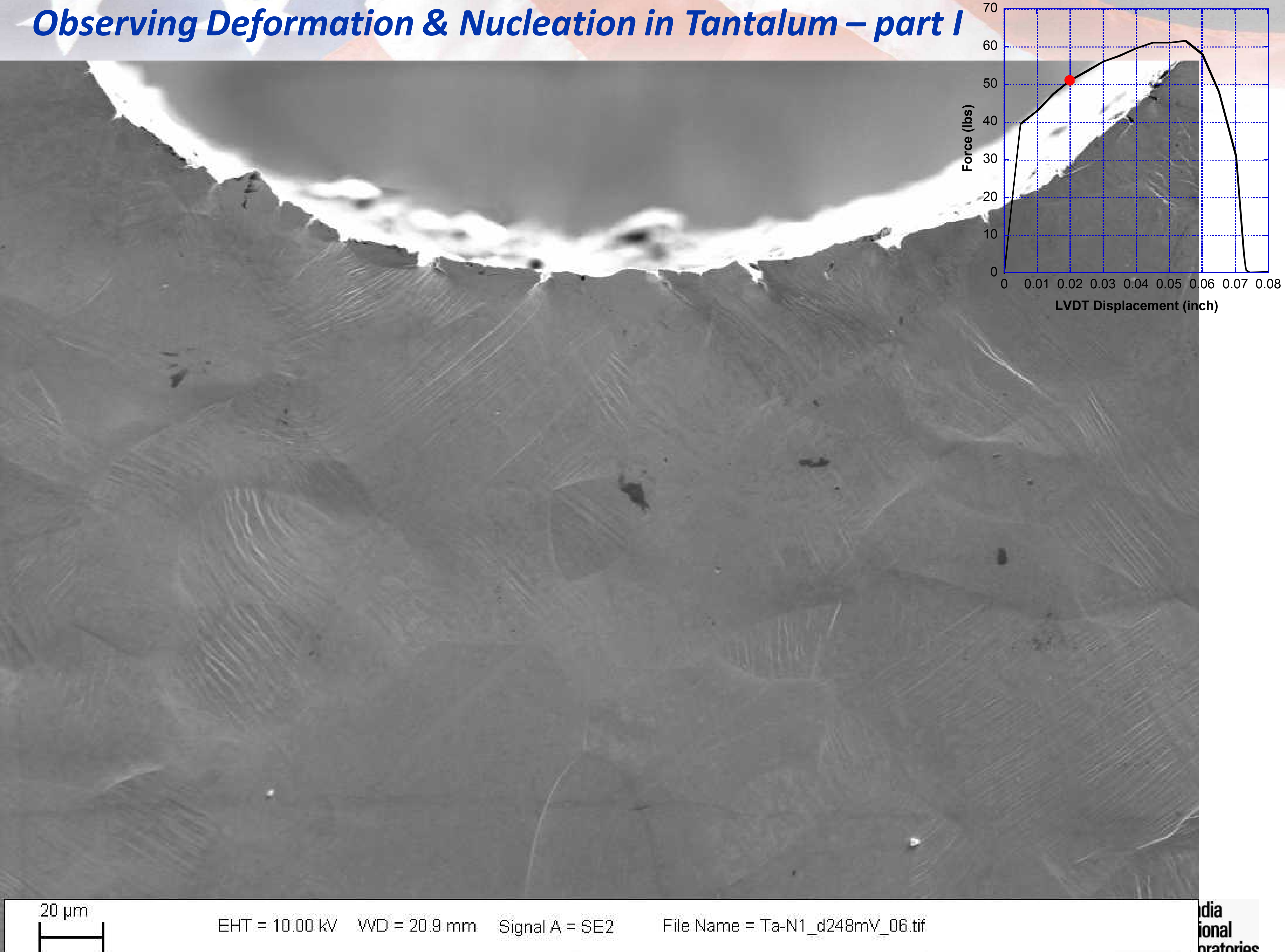

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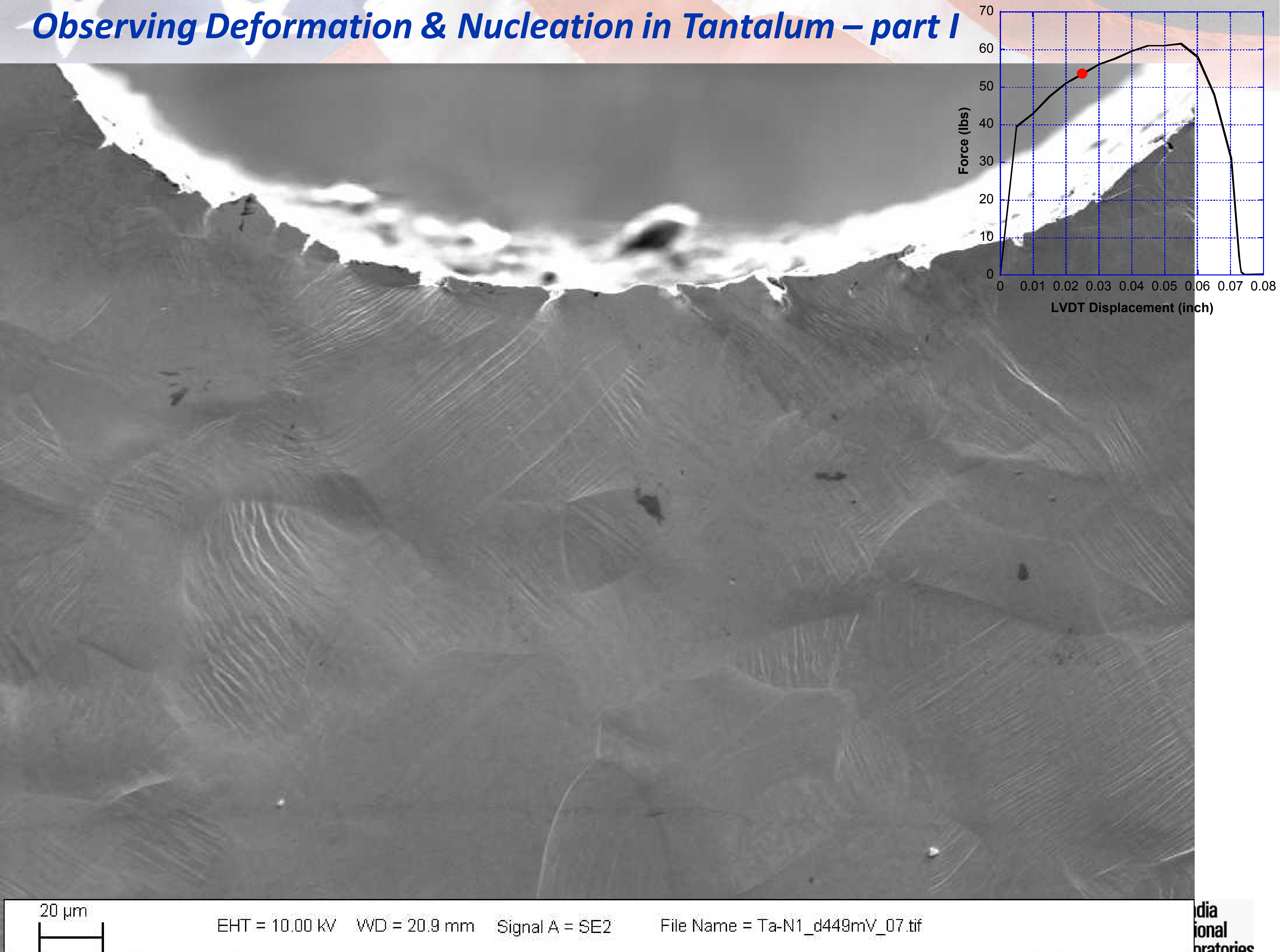

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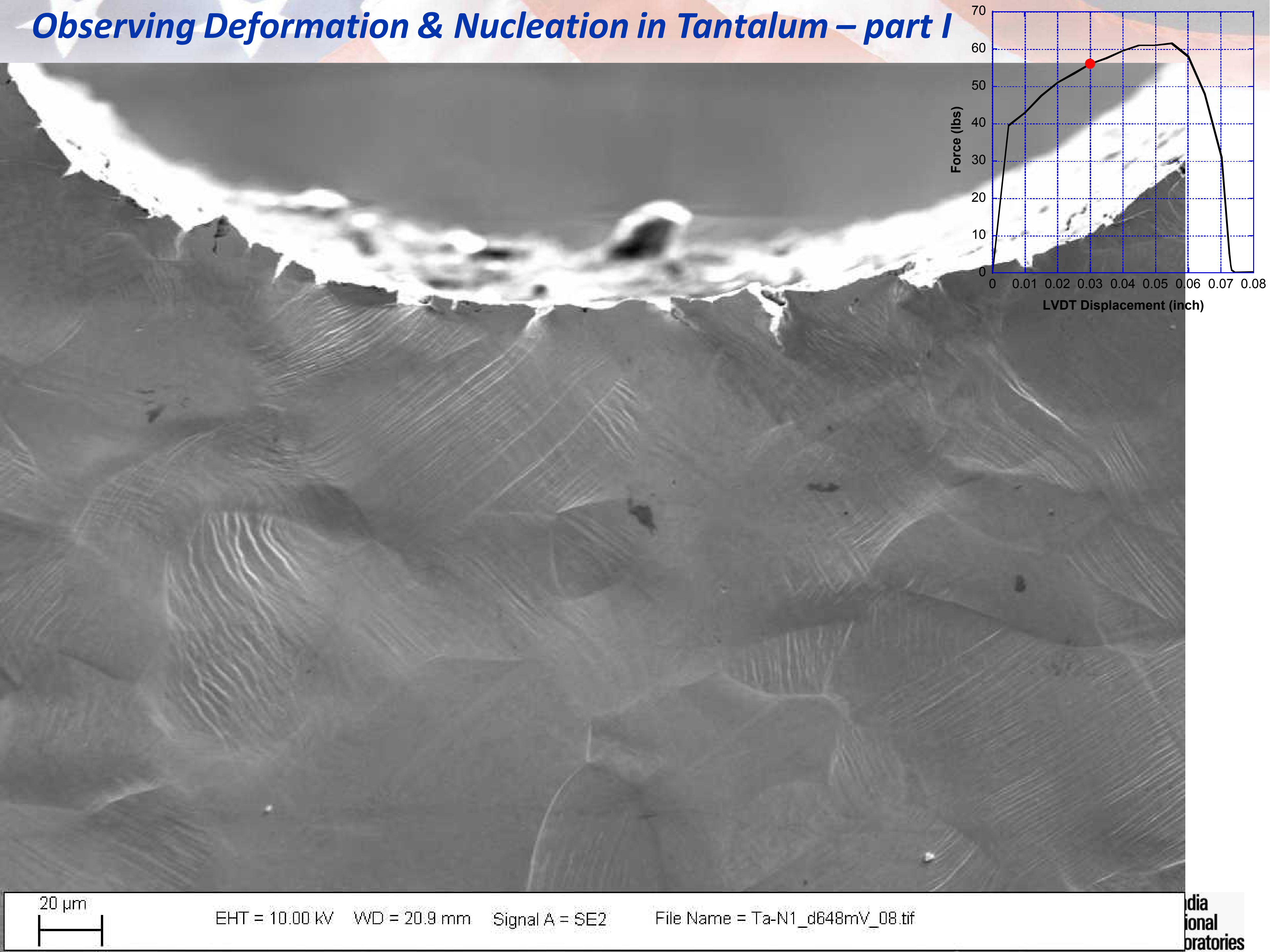

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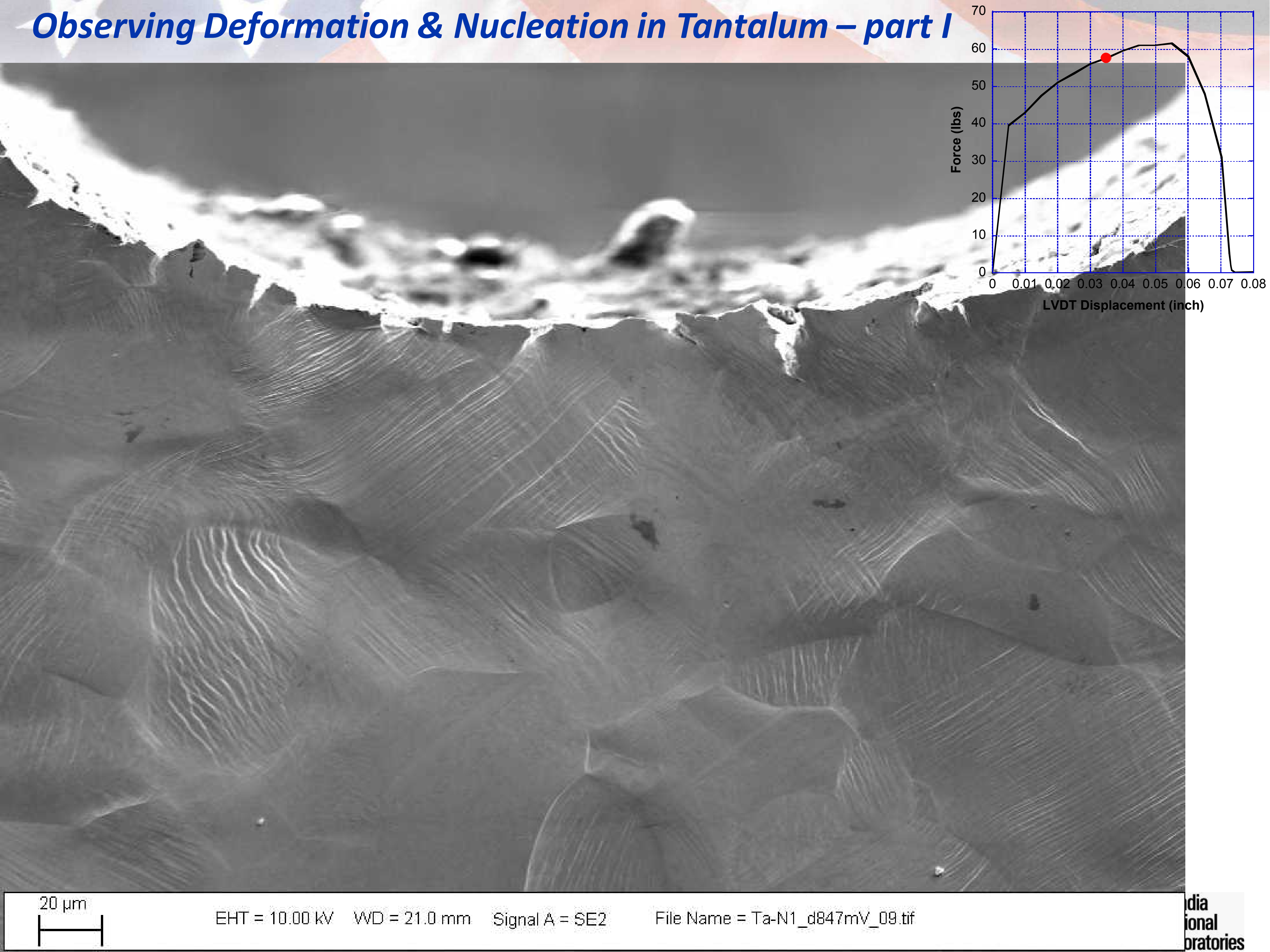

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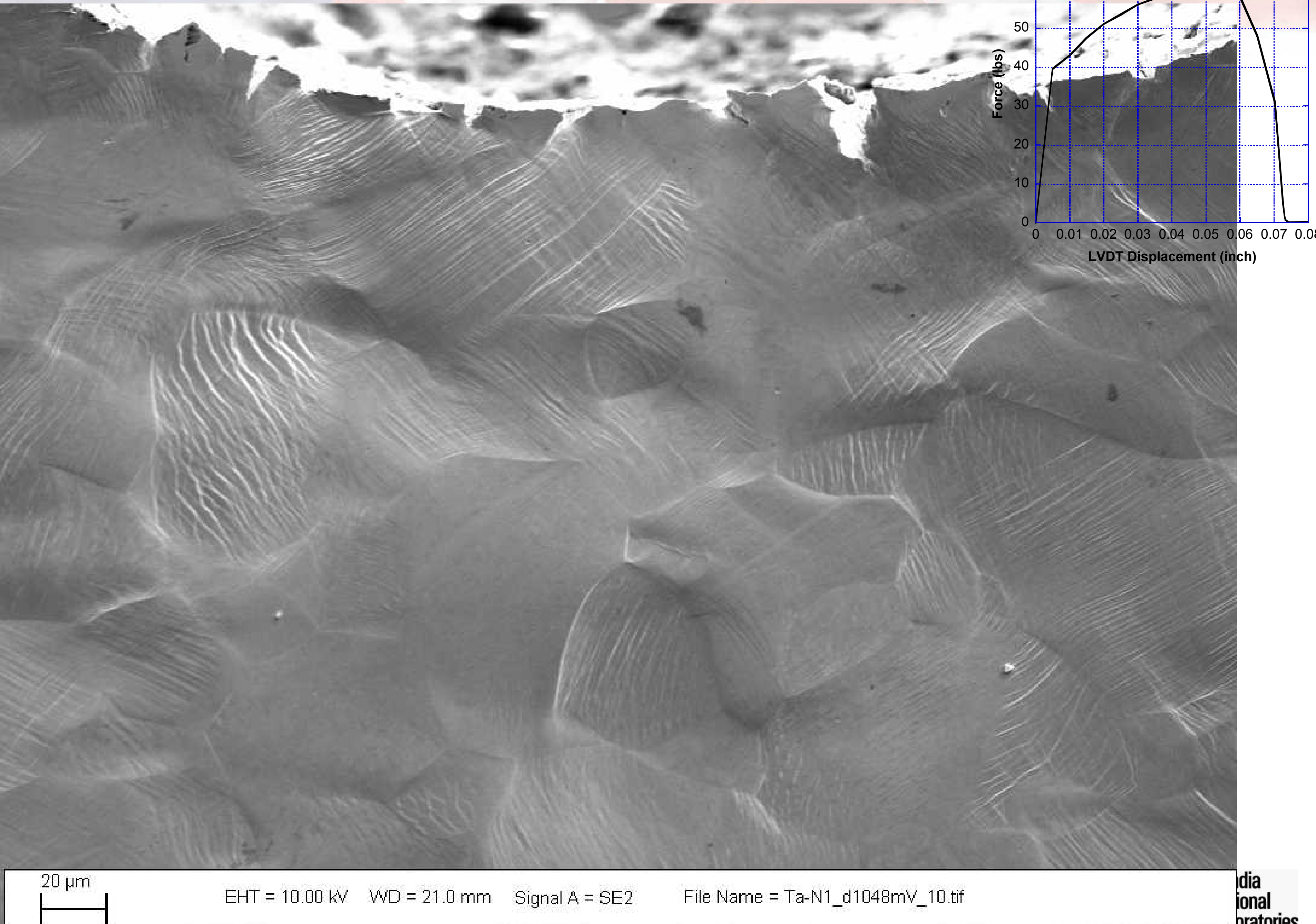
Observing Deformation & Nucleation in Tantalum – part I



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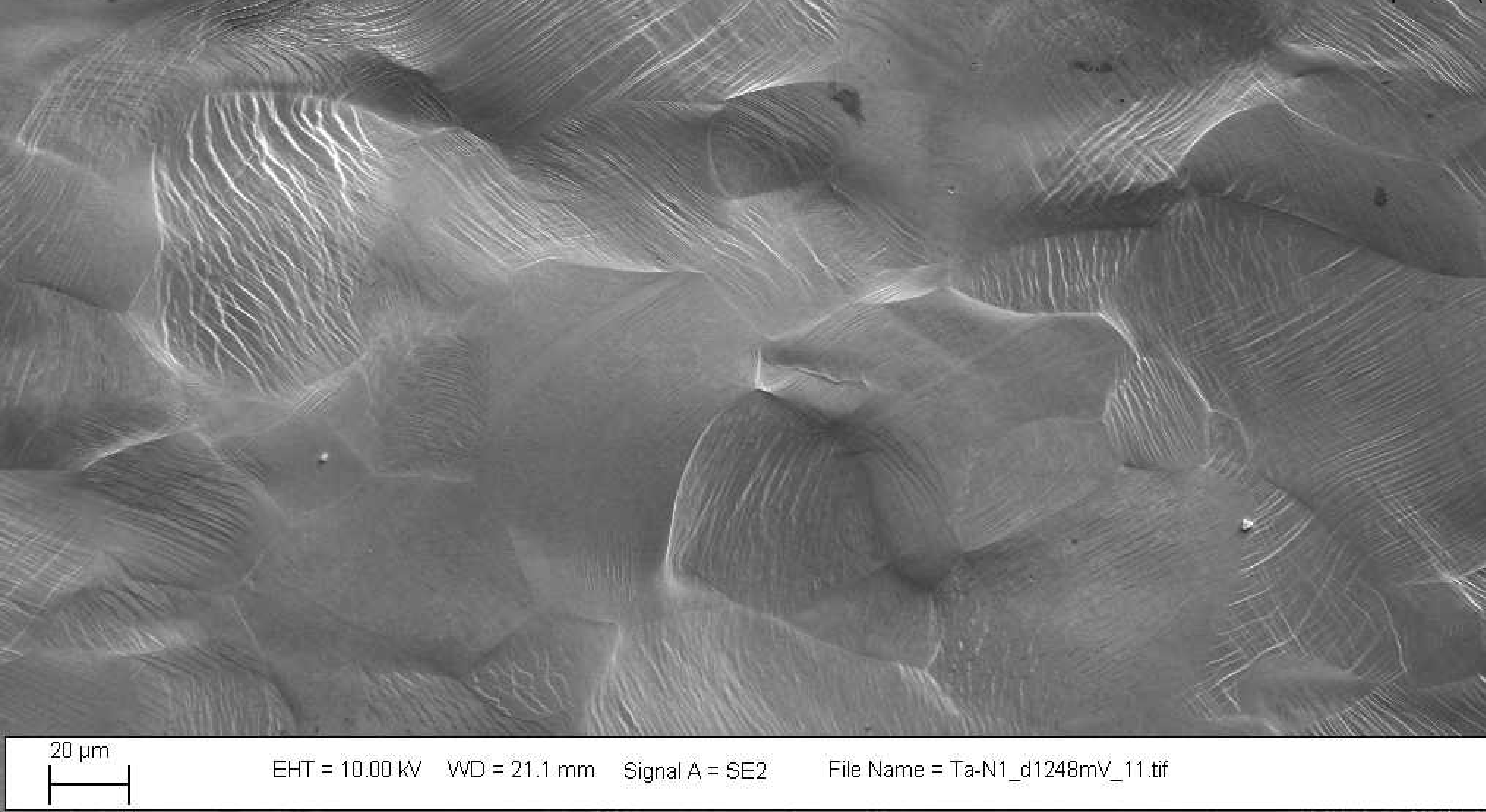

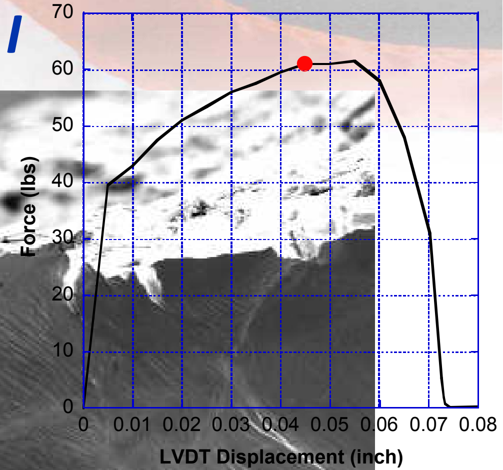

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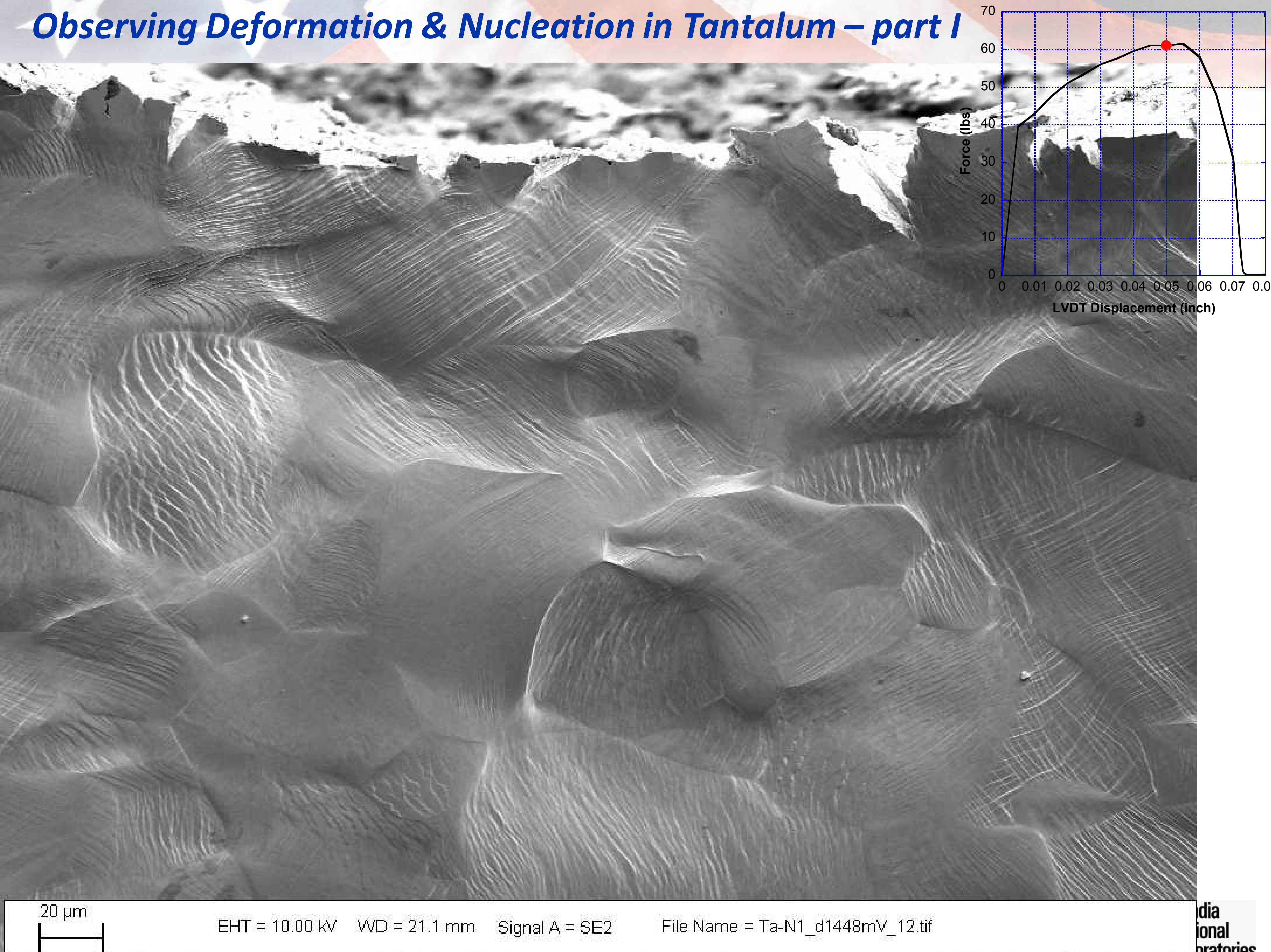

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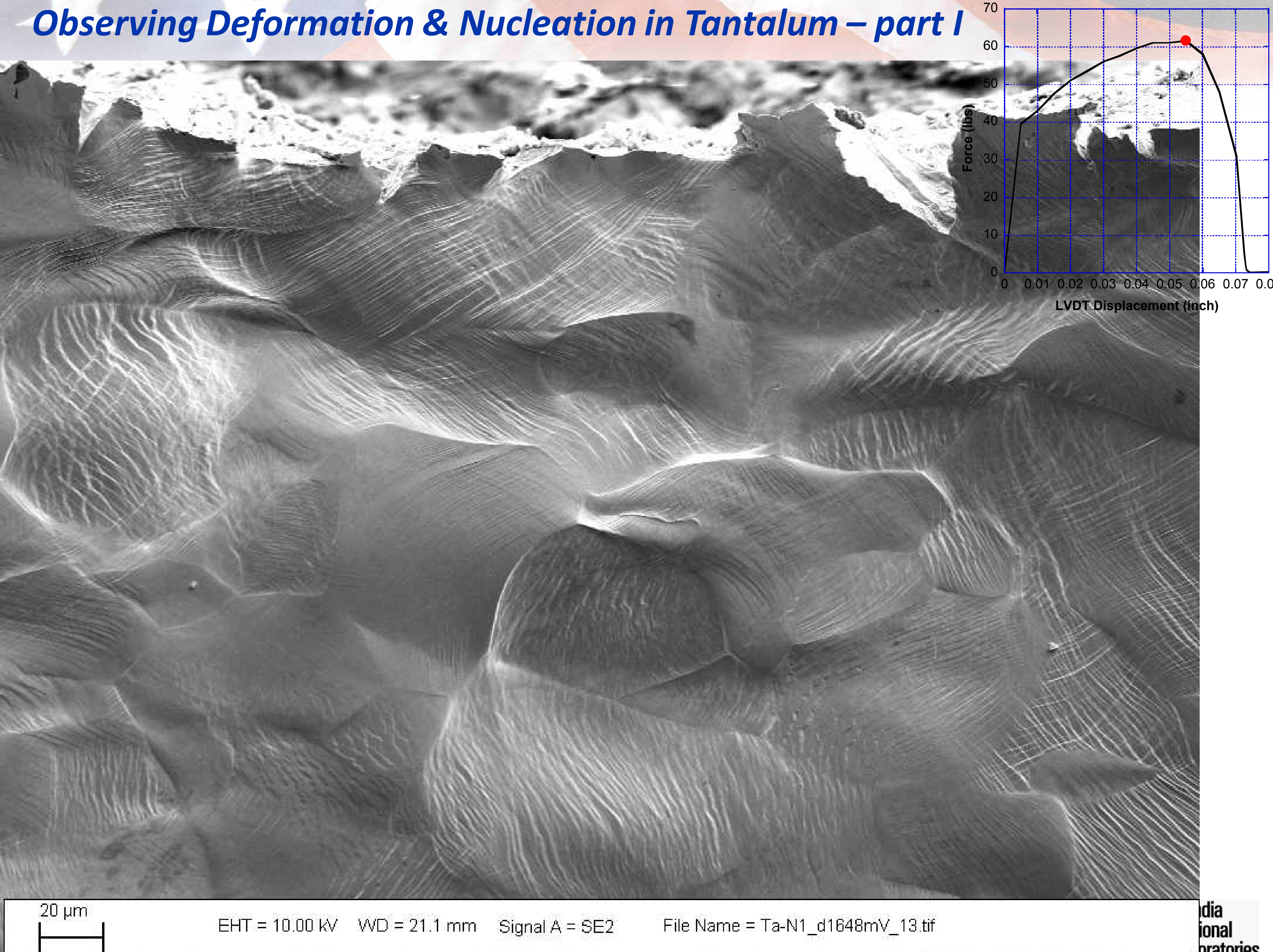

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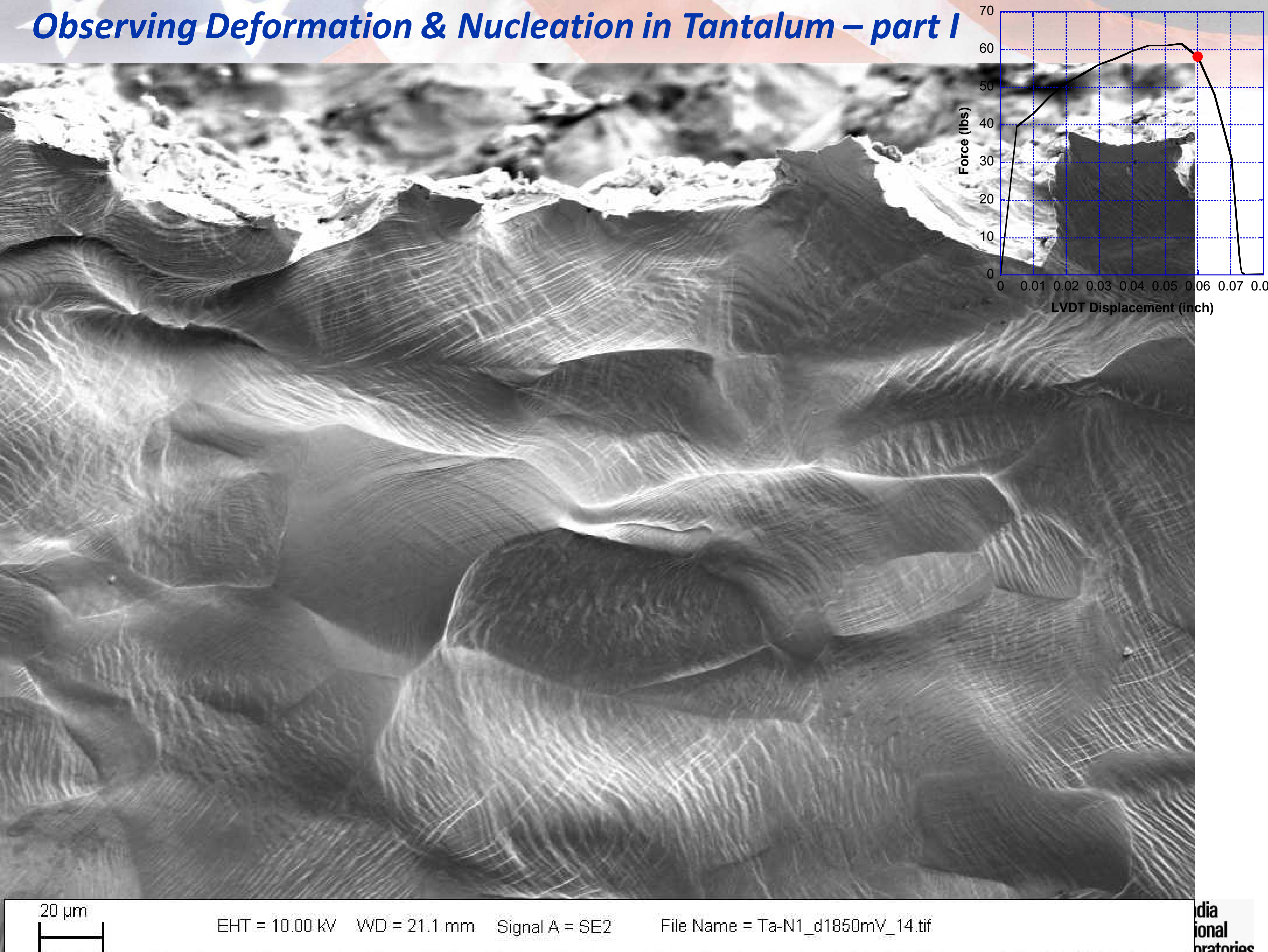

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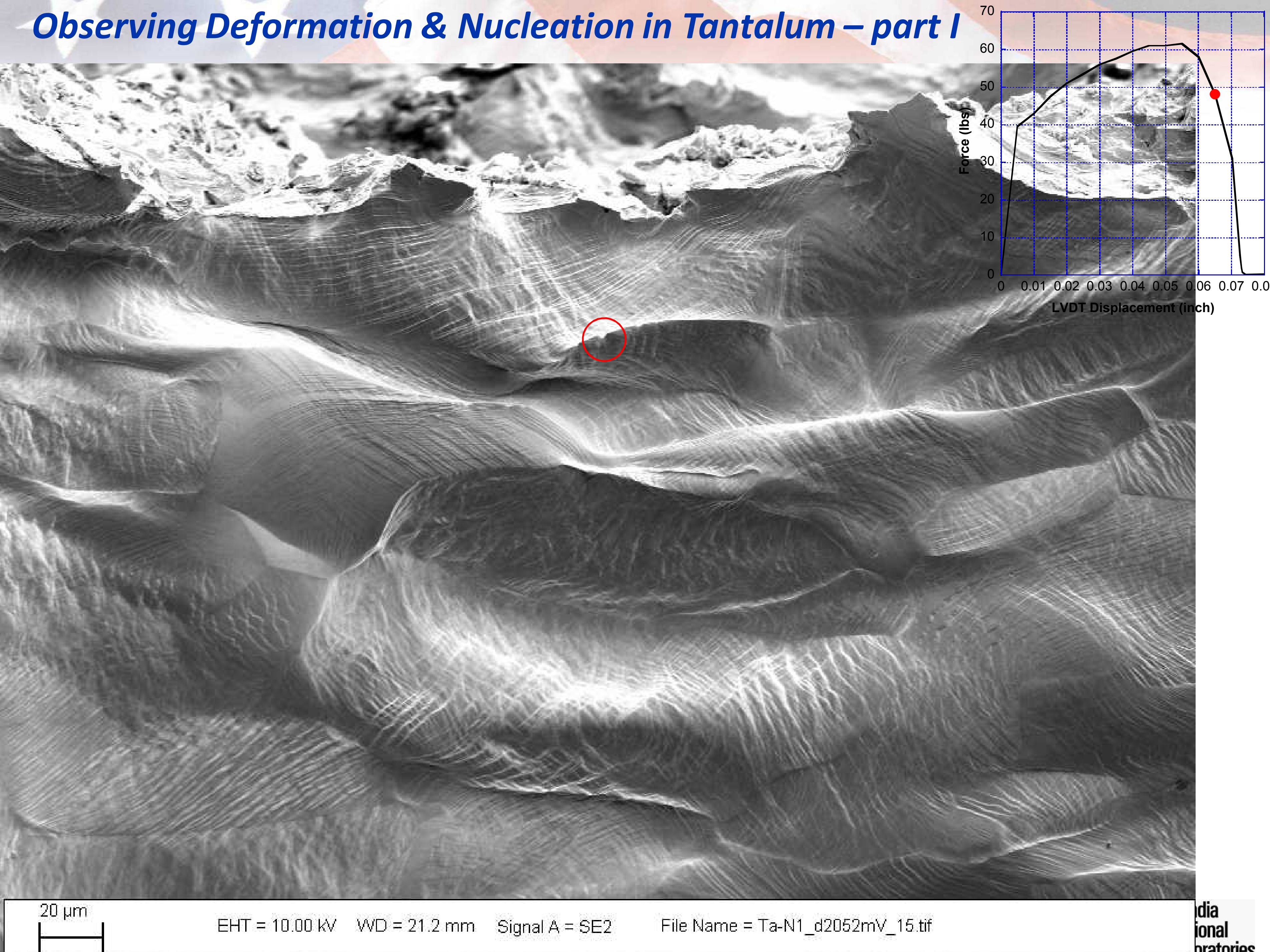

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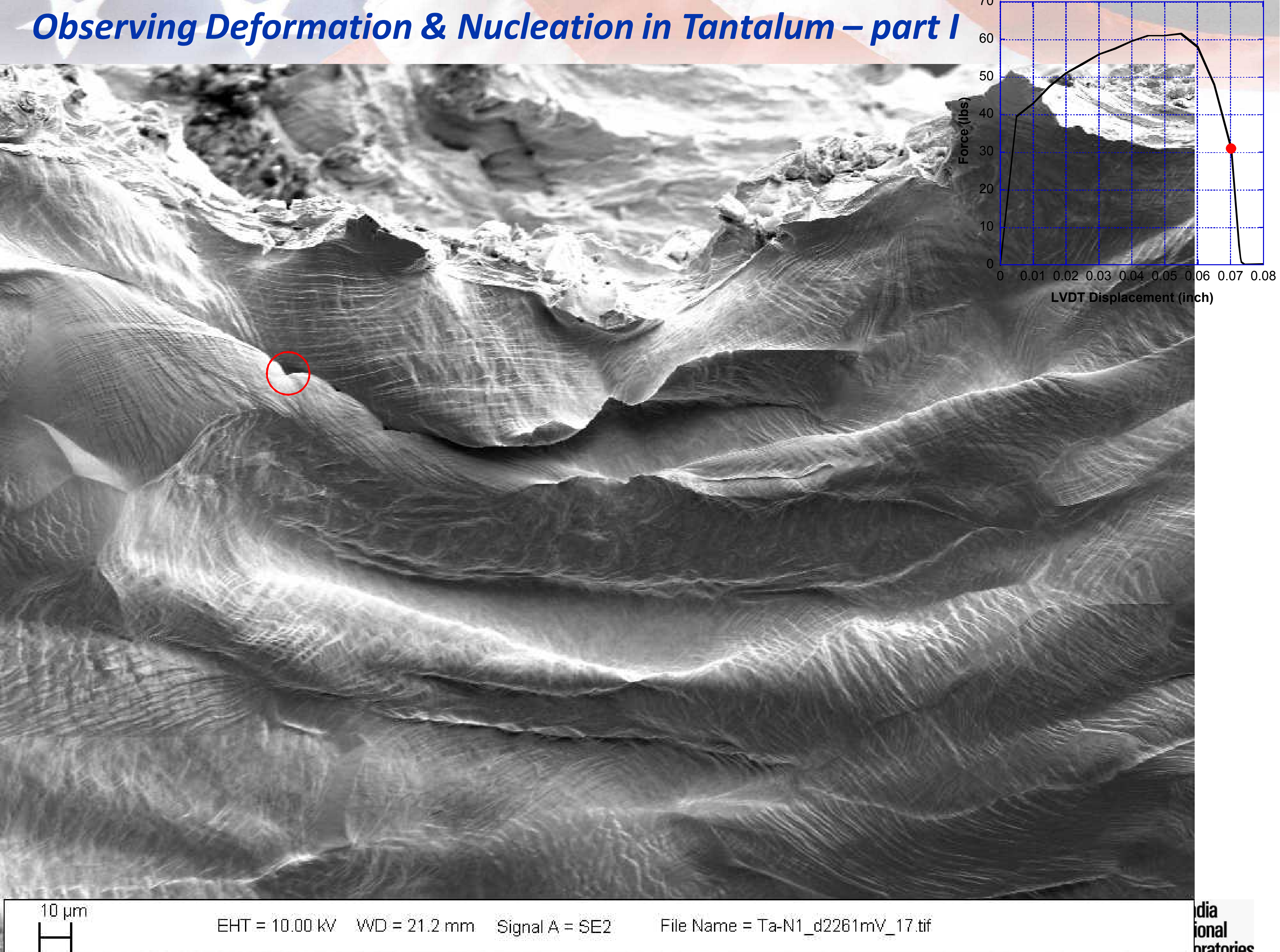

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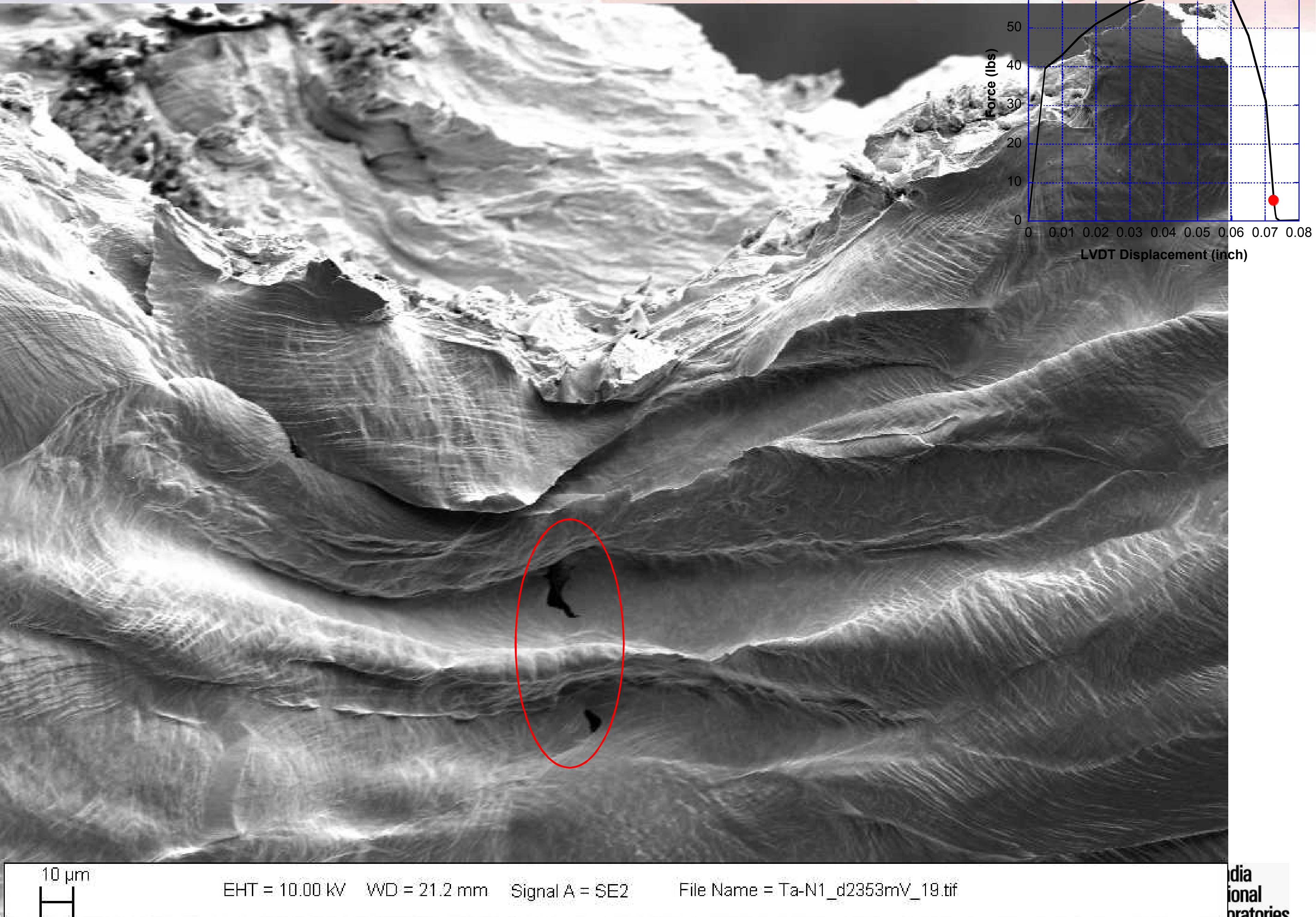

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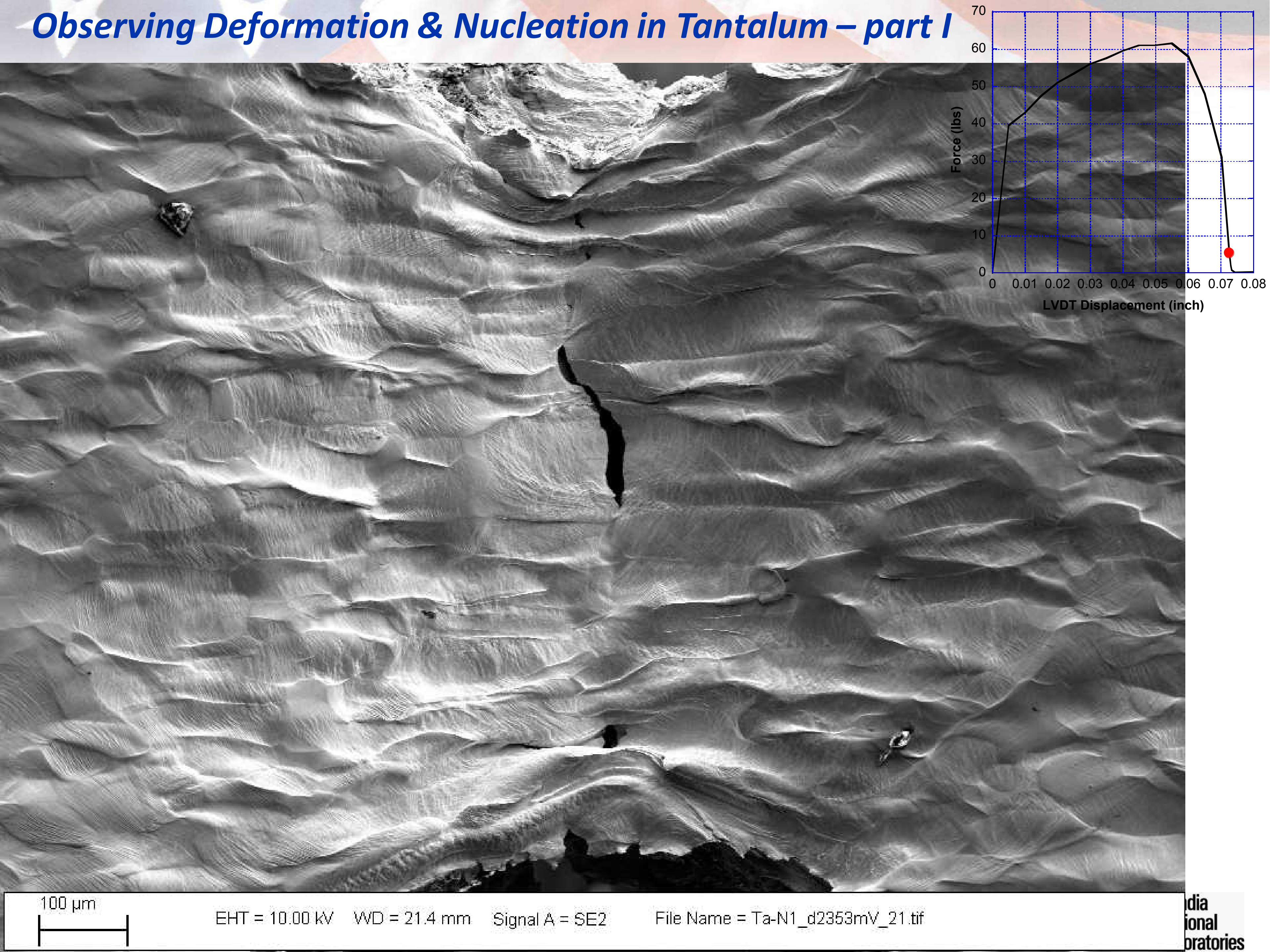

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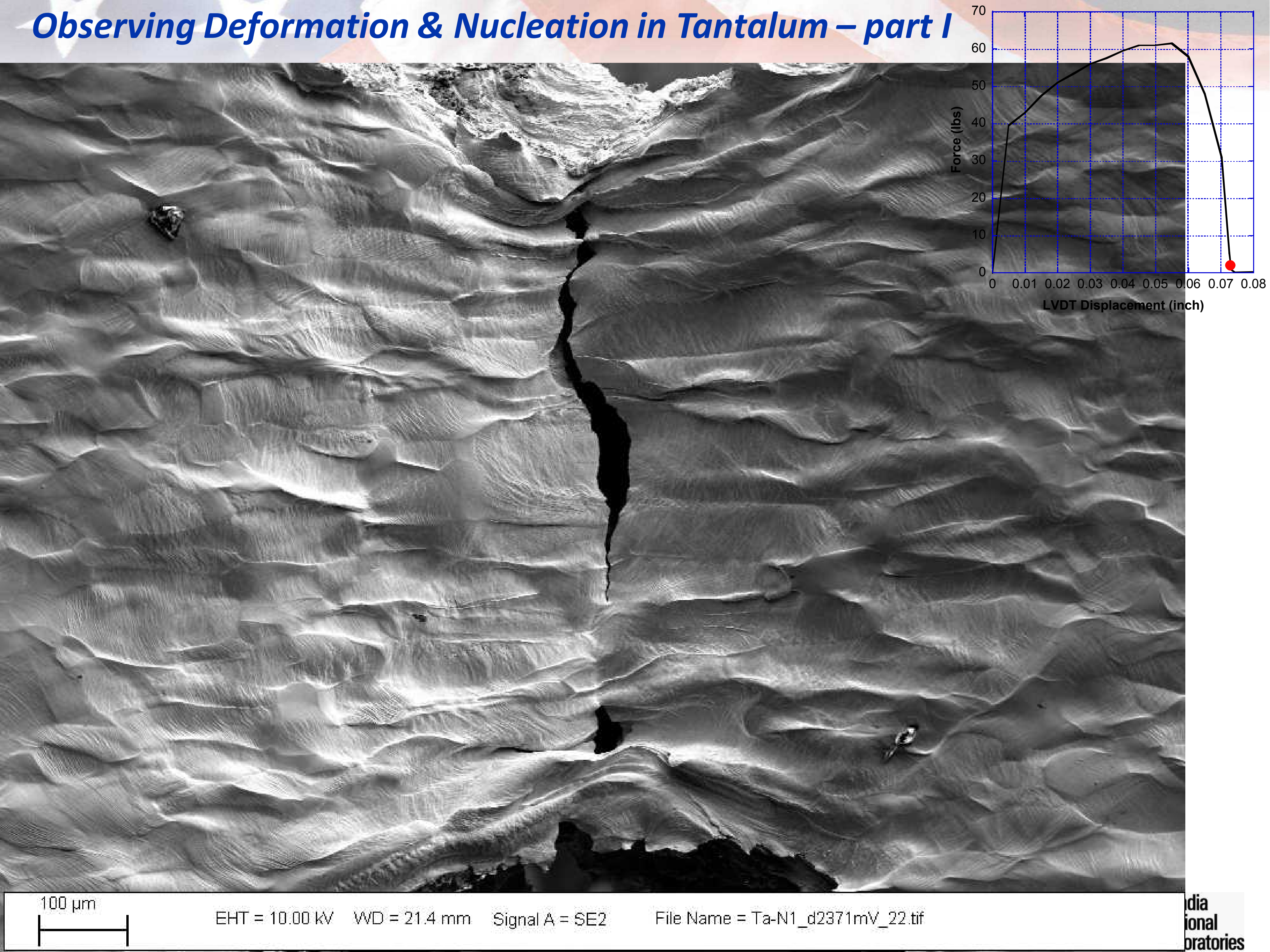
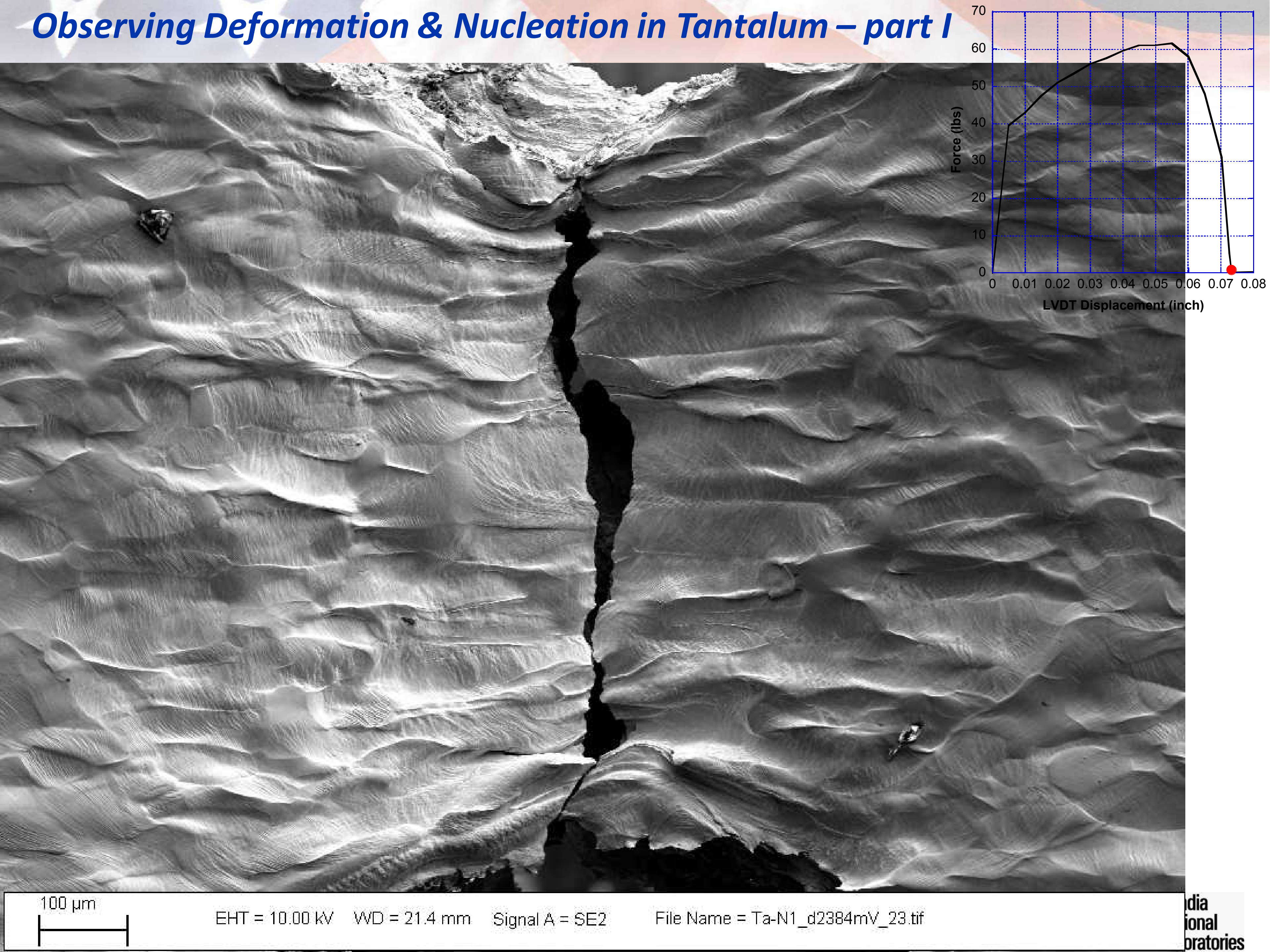
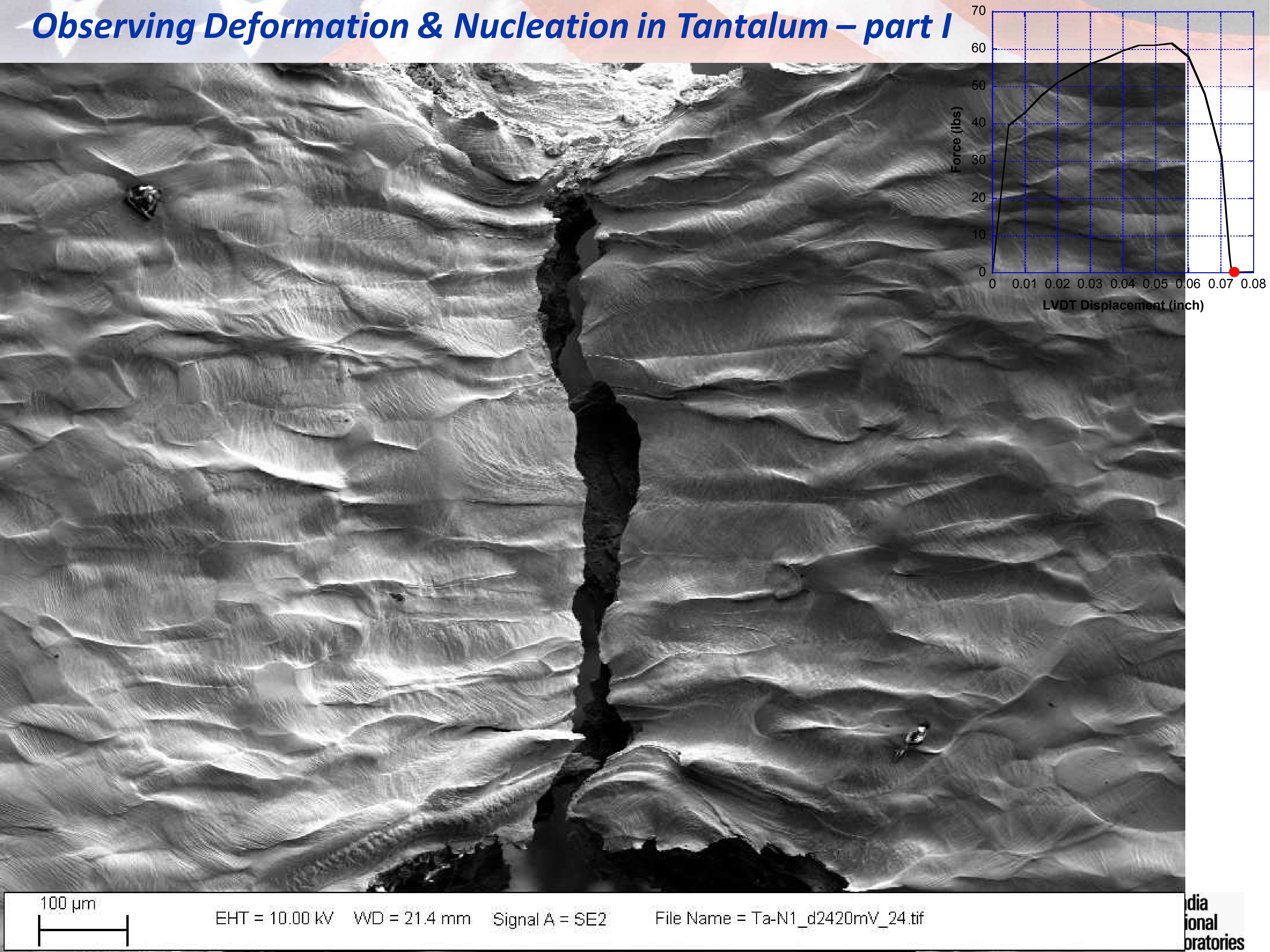


Observing Deformation & Nucleation in Tantalum – part I



Observing Deformation & Nucleation in Tantalum – part I



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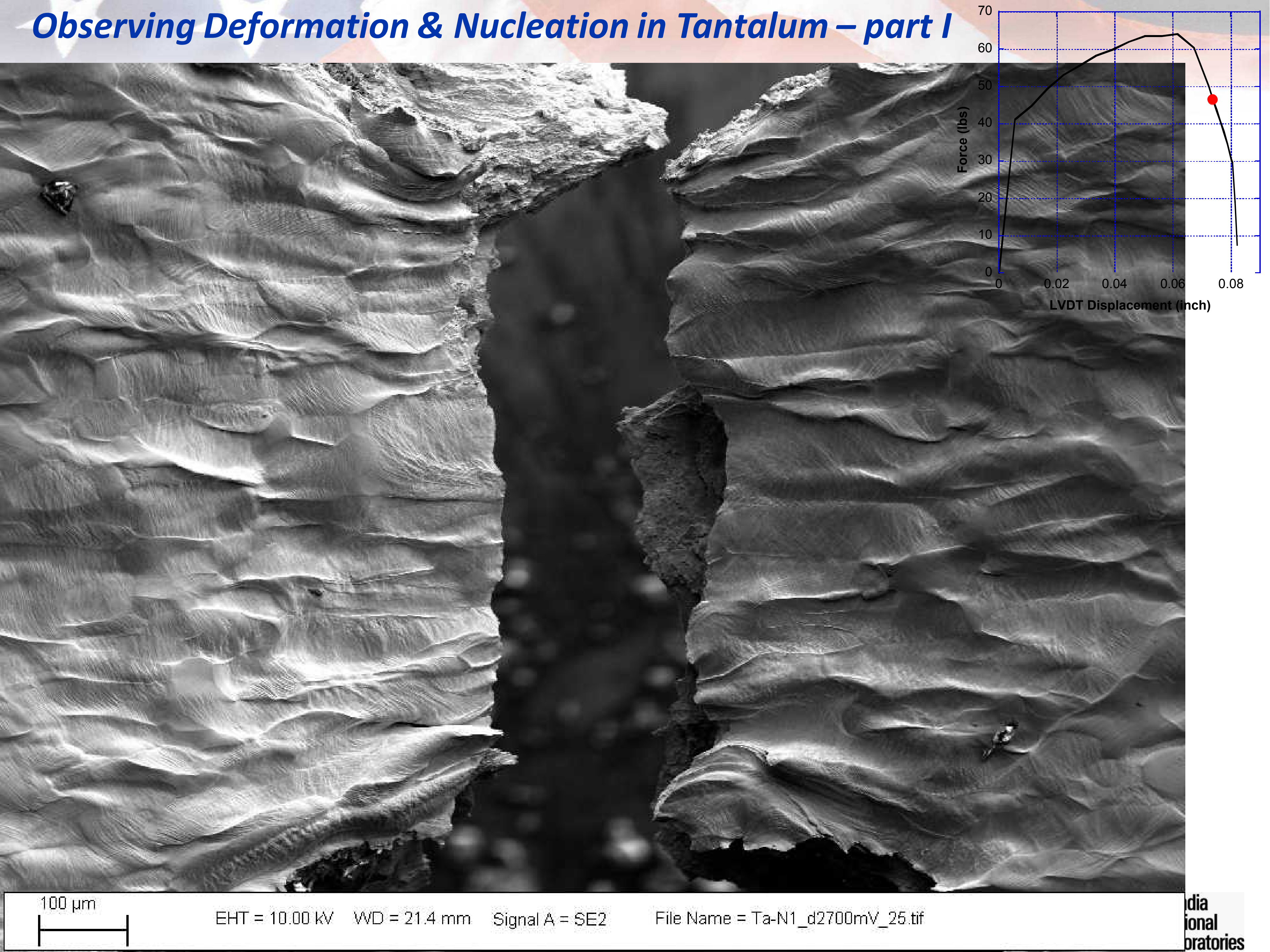

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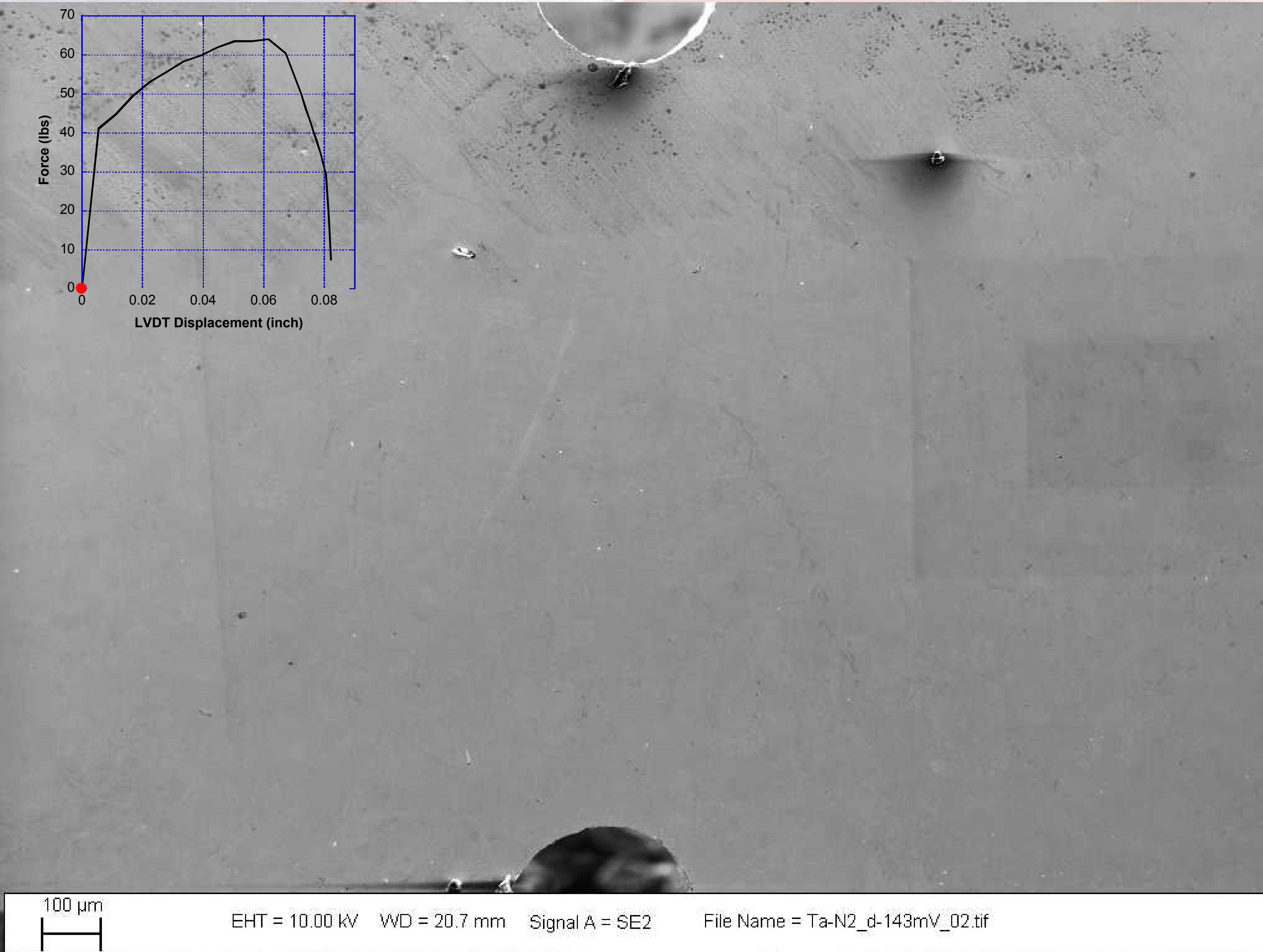
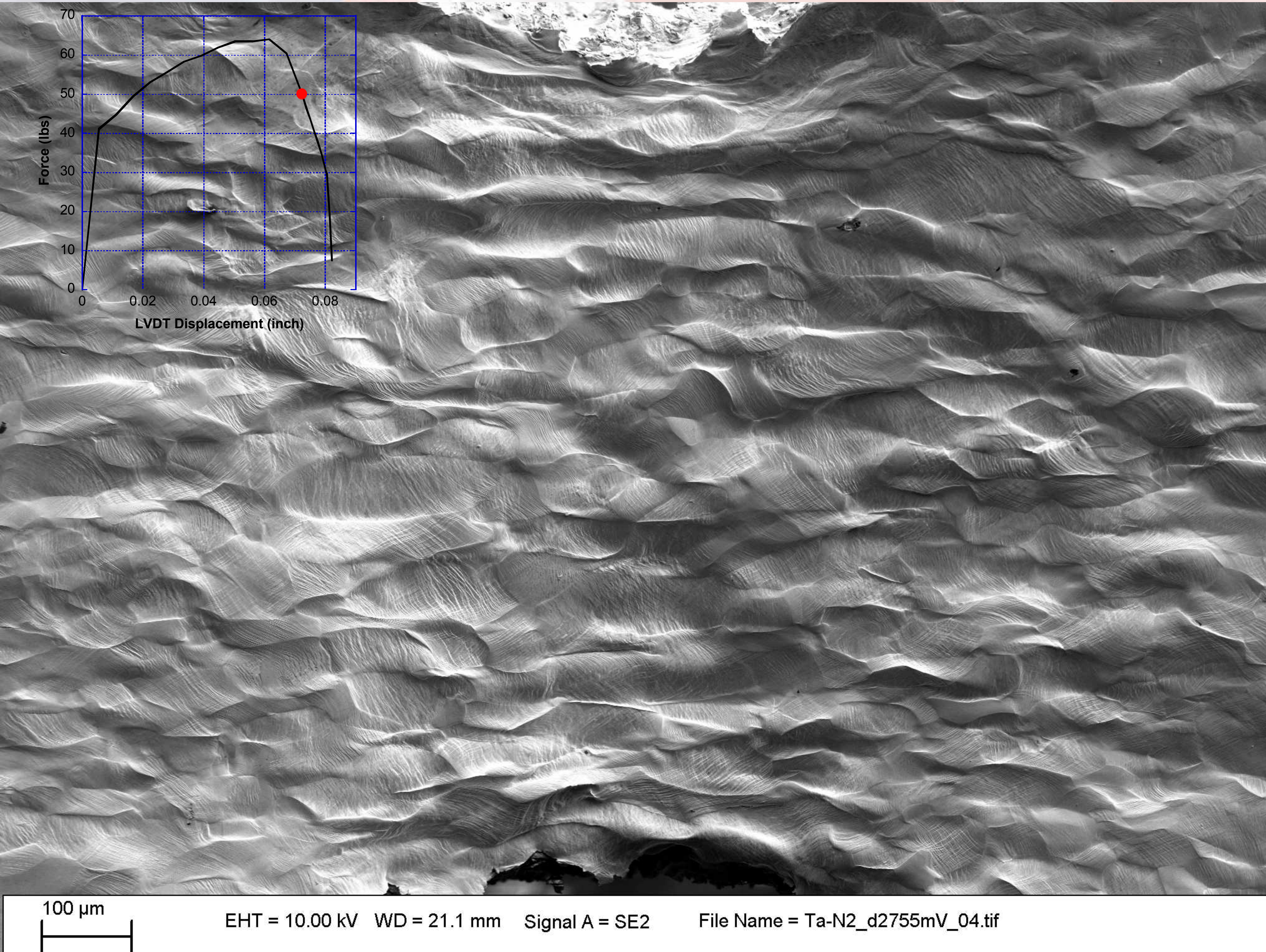
Observing Deformation & Nucleation in Tantalum – part II



Observing Deformation & Nucleation in Tantalum – part II



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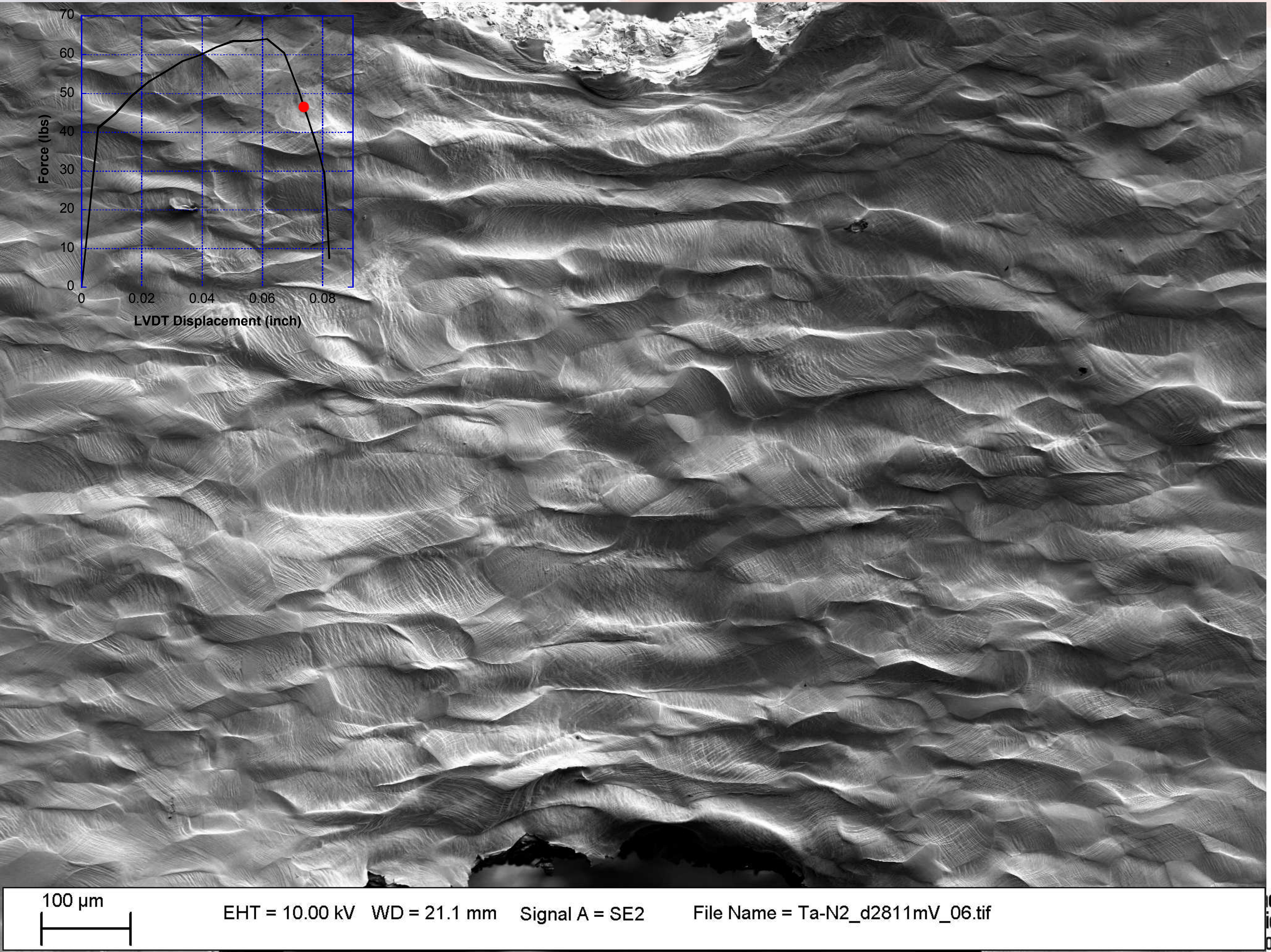

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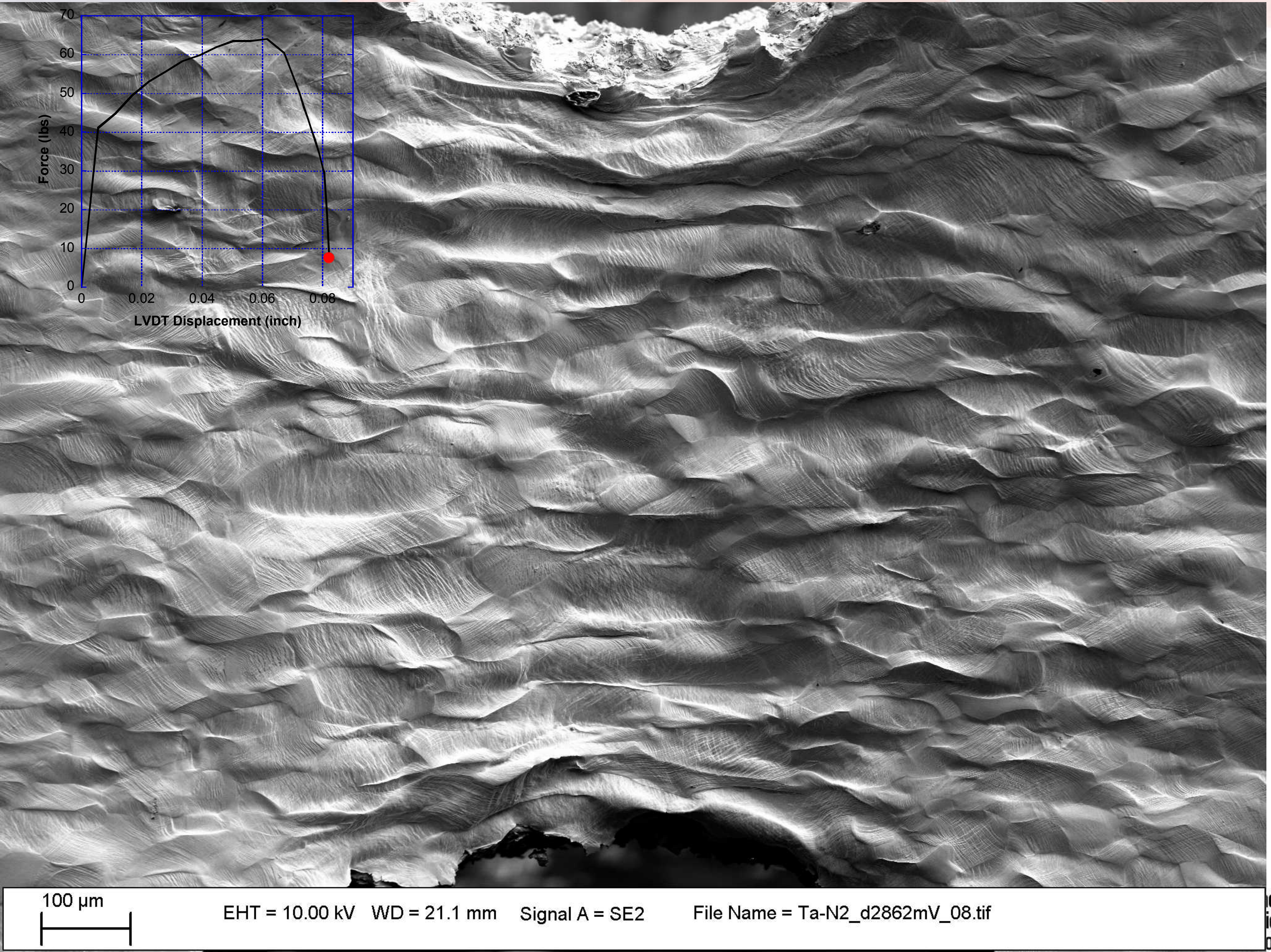

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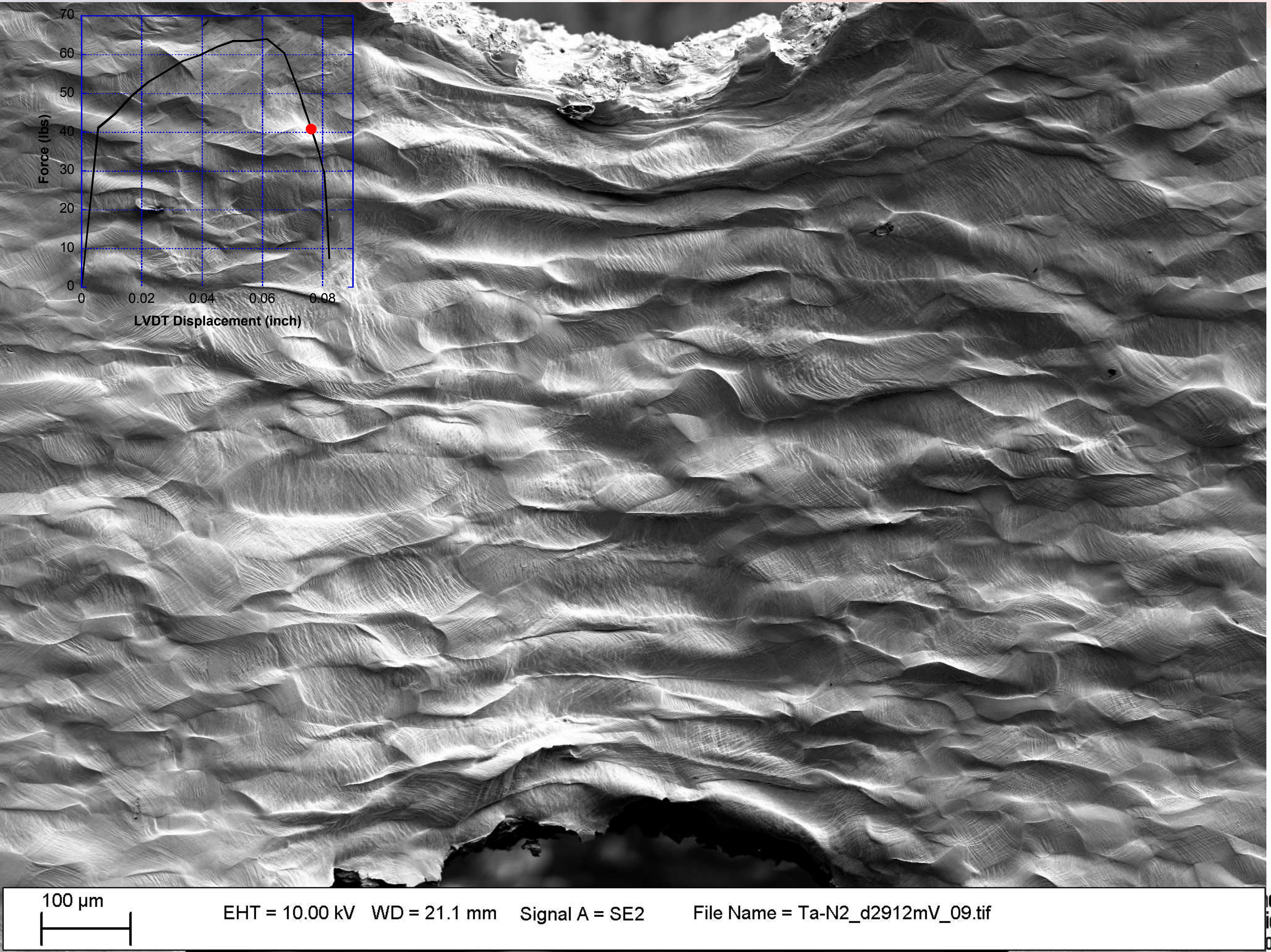
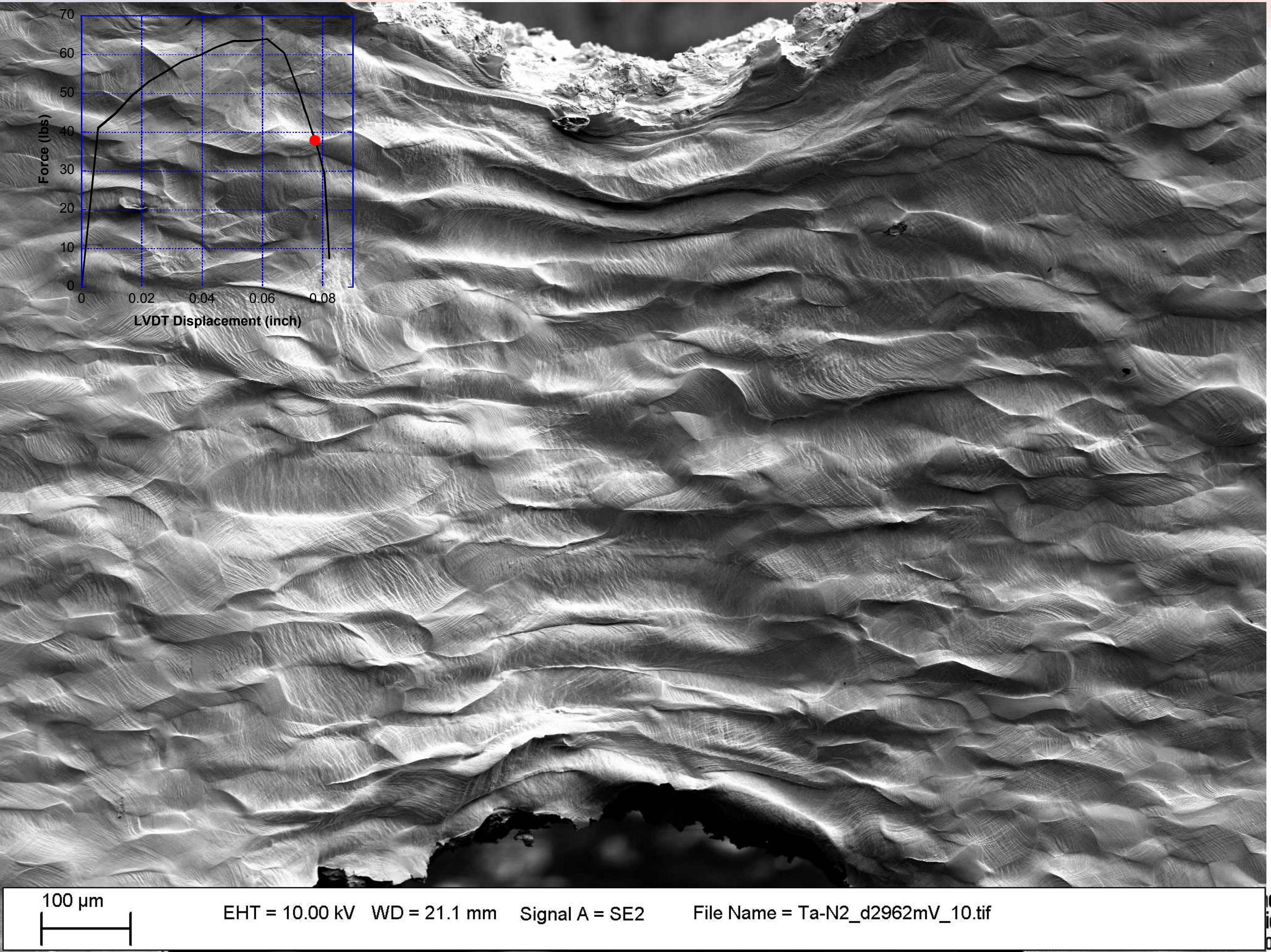
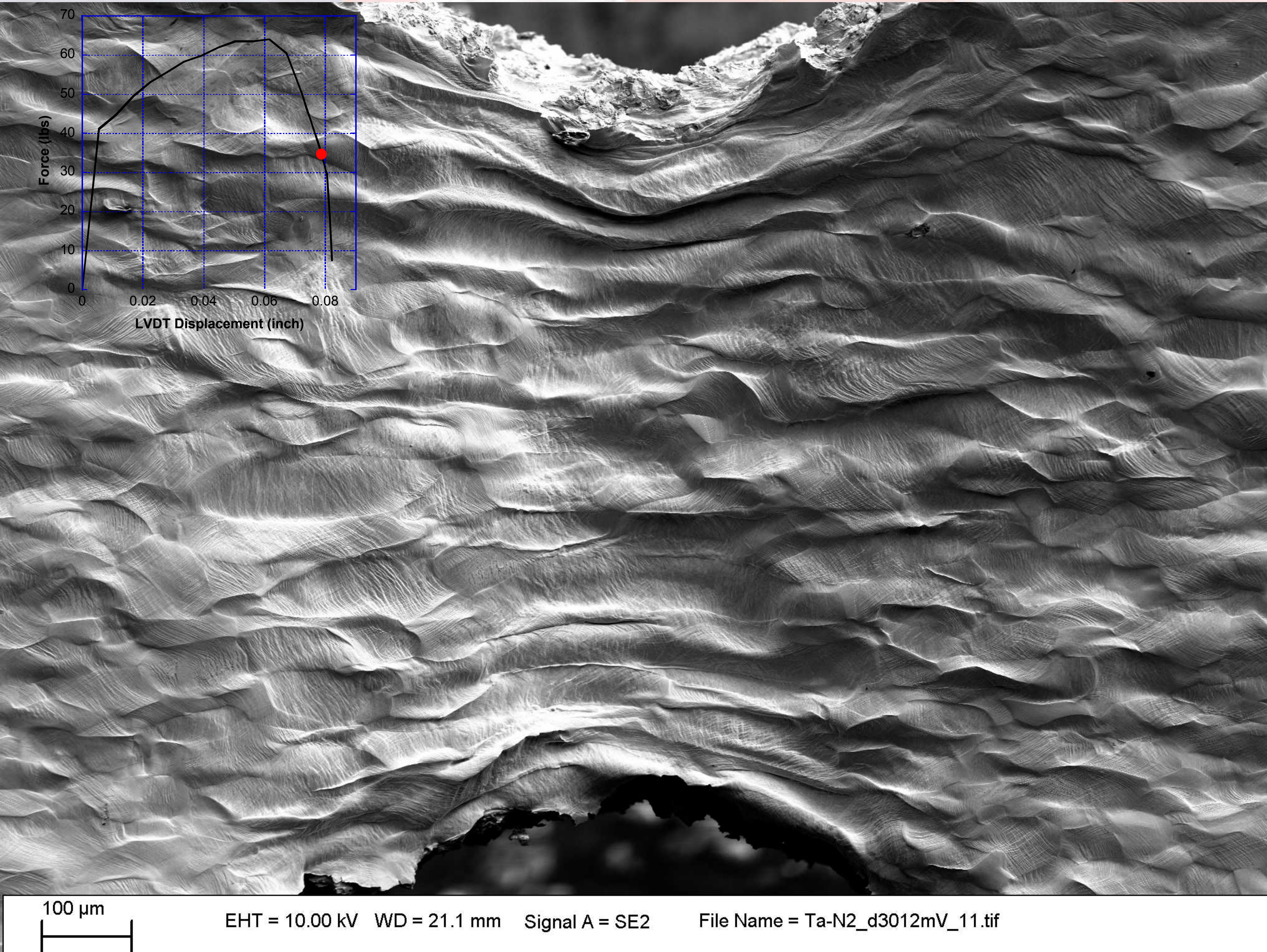


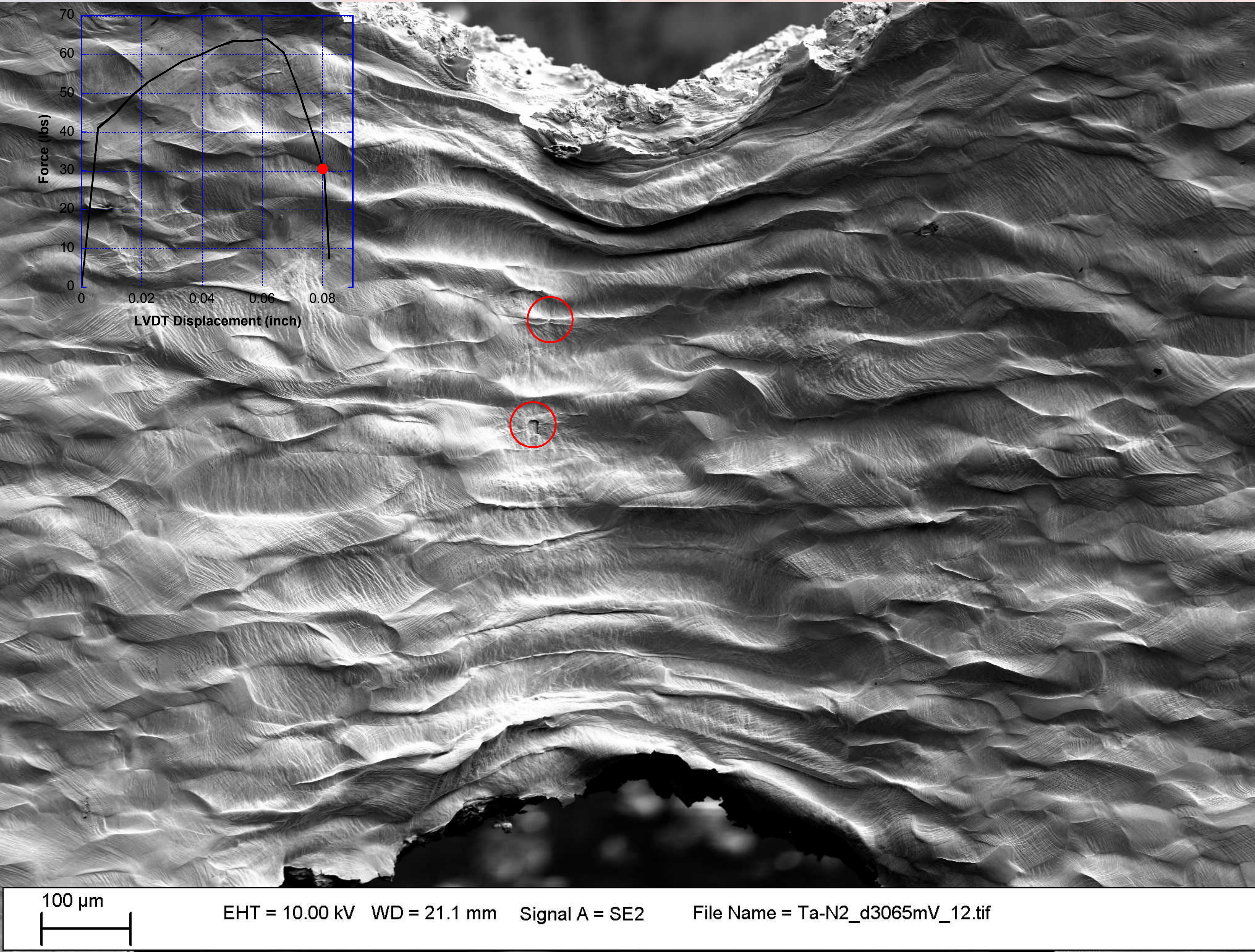
Observing Deformation & Nucleation in Tantalum – part II



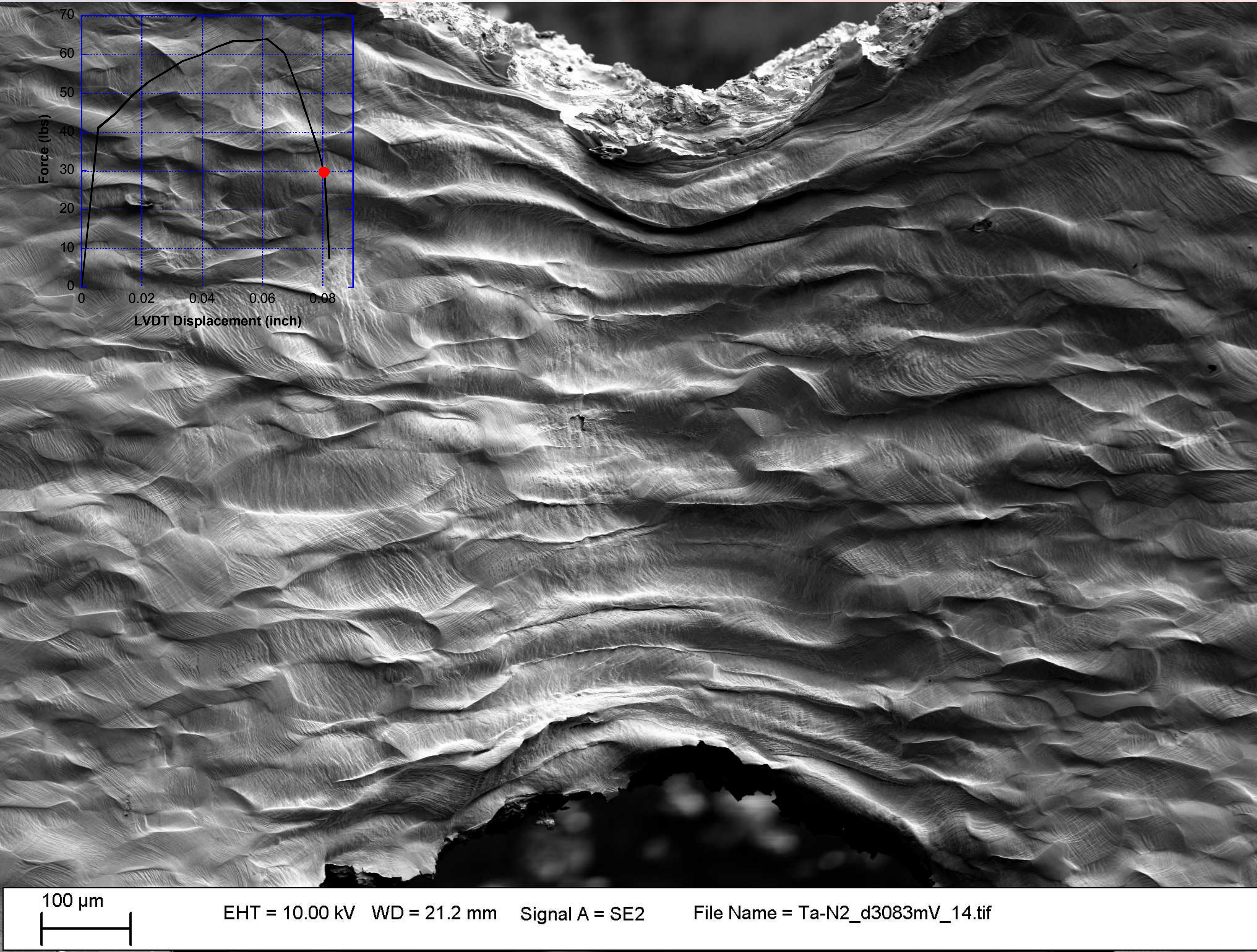
Observing Deformation & Nucleation in Tantalum – part II



Observing Deformation & Nucleation in Tantalum – part II



Observing Deformation & Nucleation in Tantalum – part II



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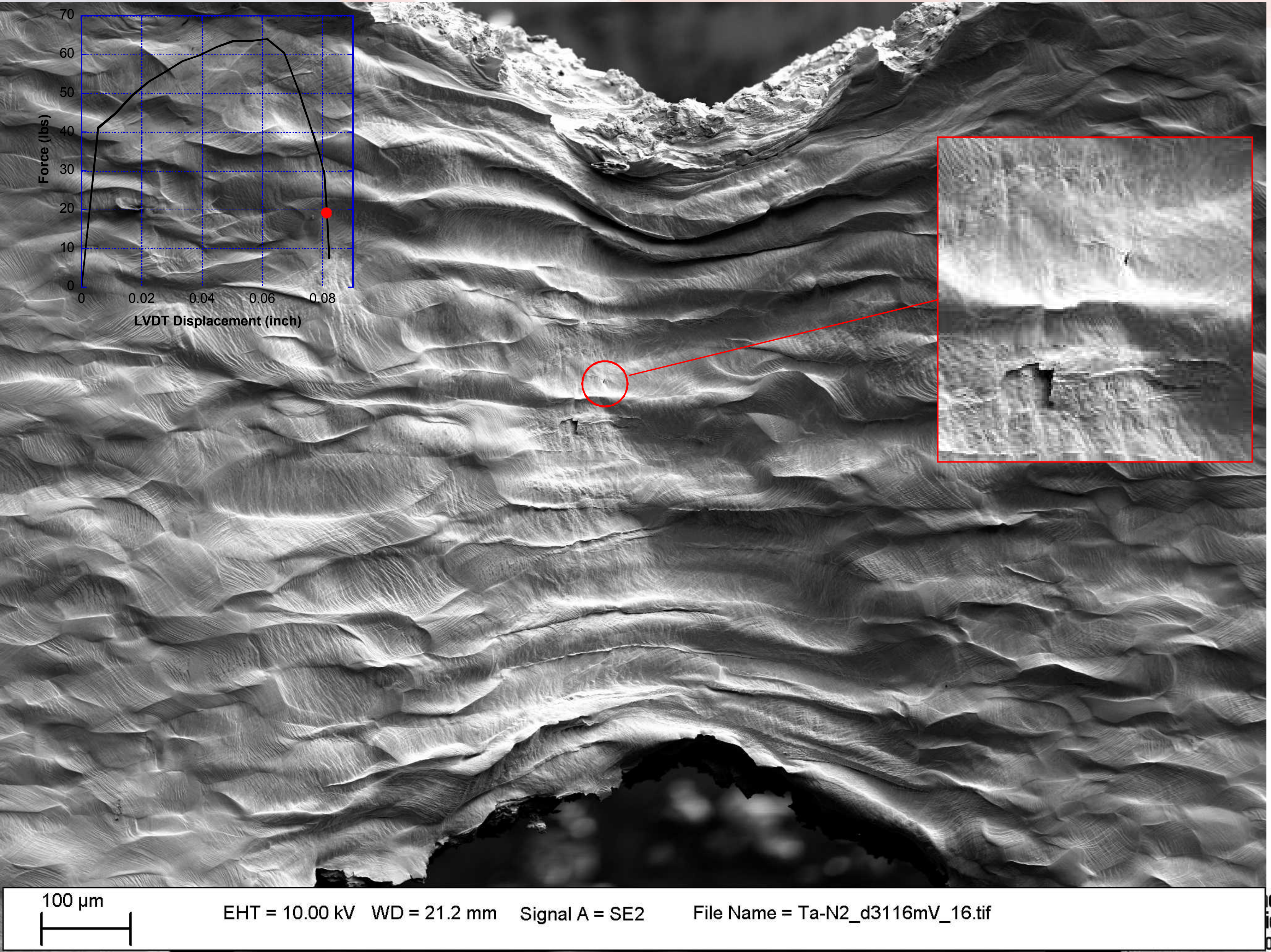
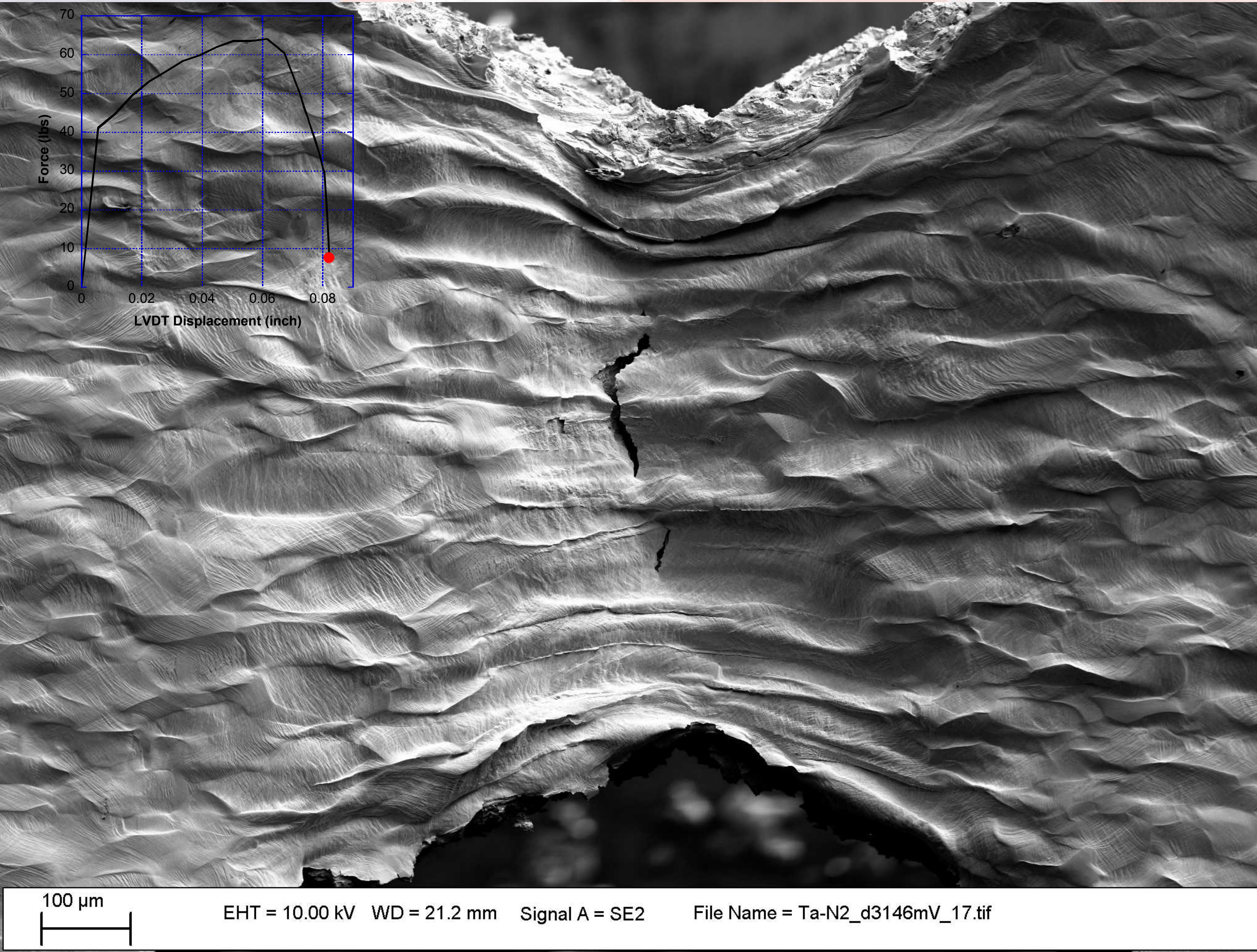
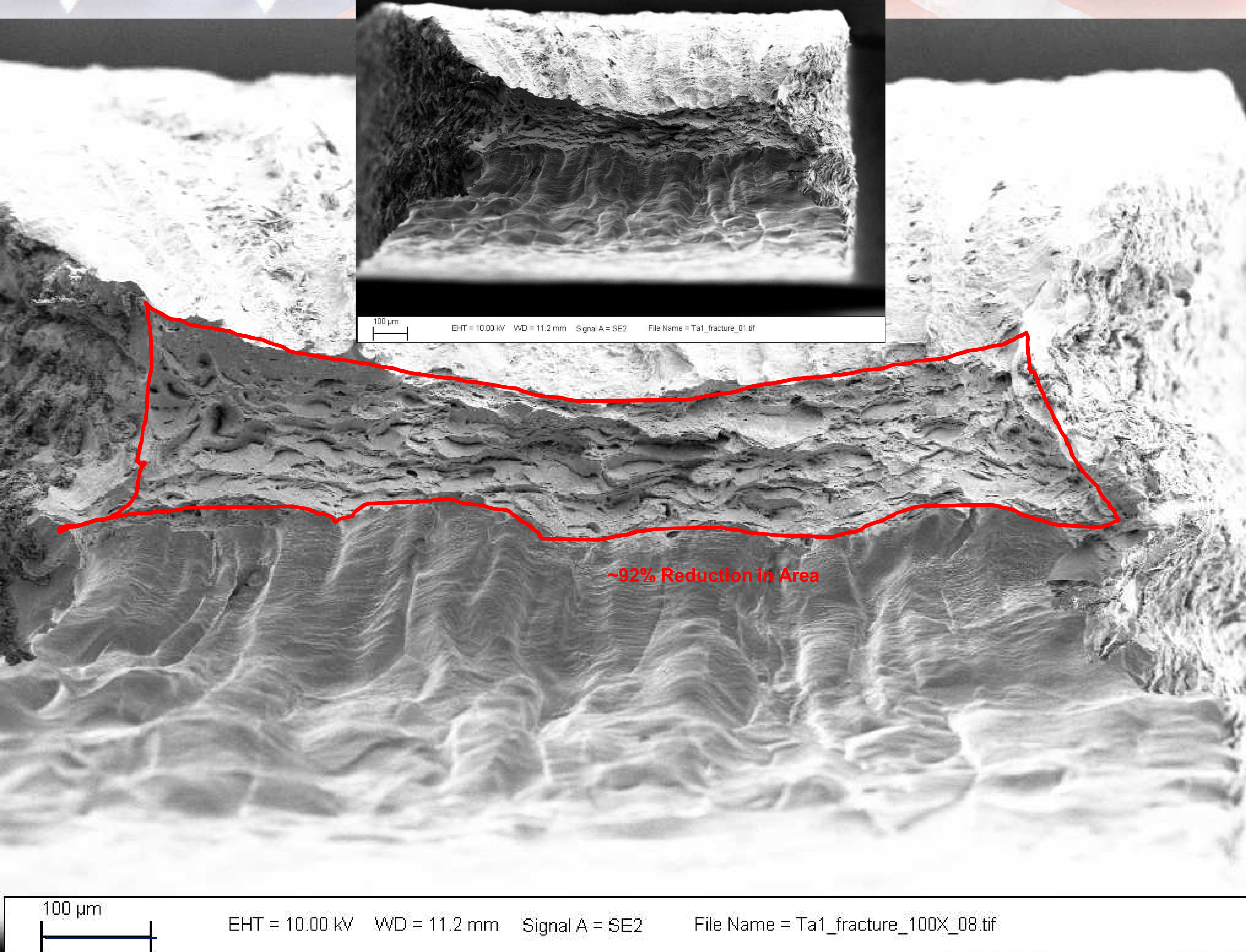
Observing Deformation & Nucleation in Tantalum – part II



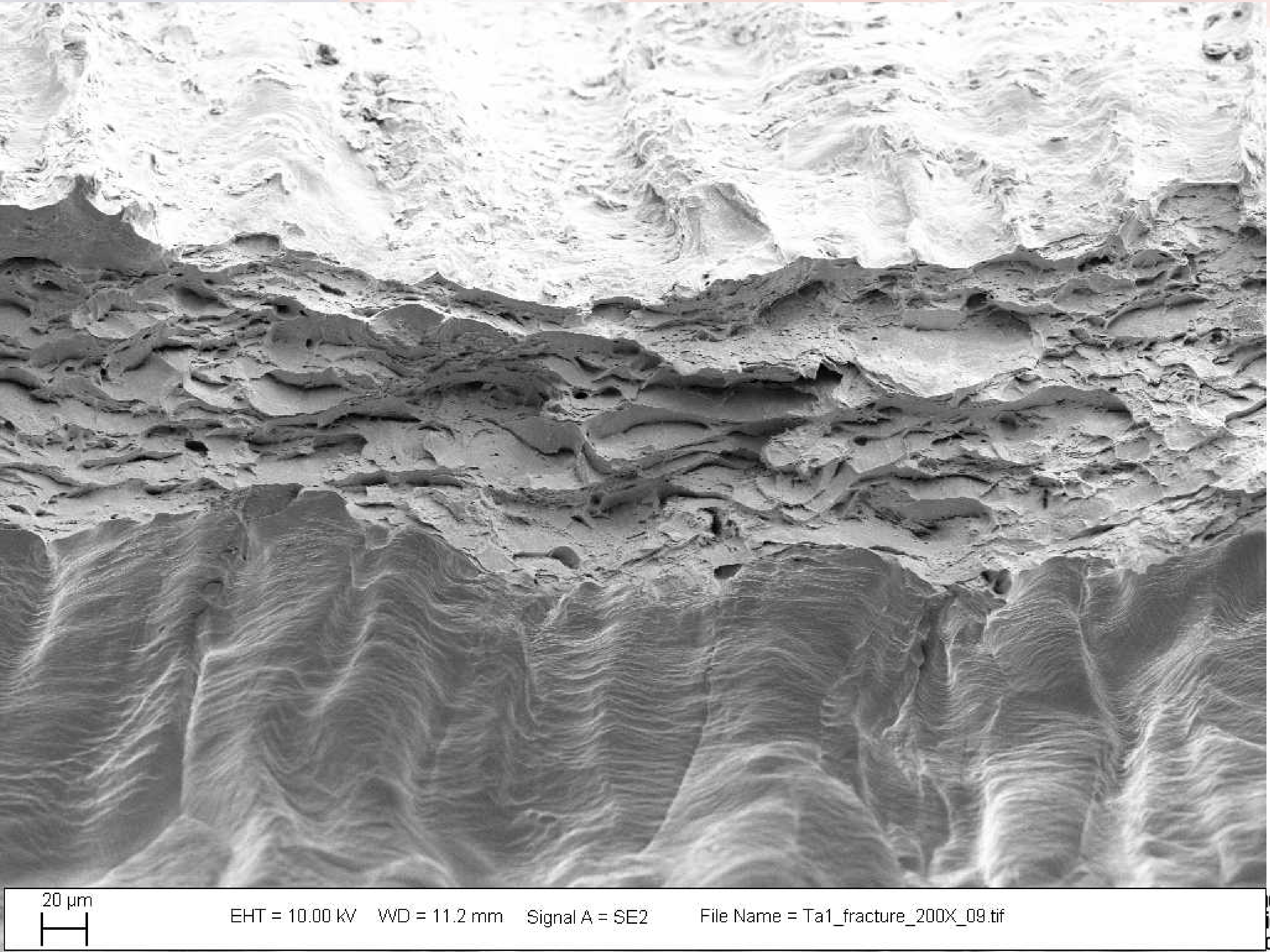
Observing Deformation & Nucleation in Tantalum – part II



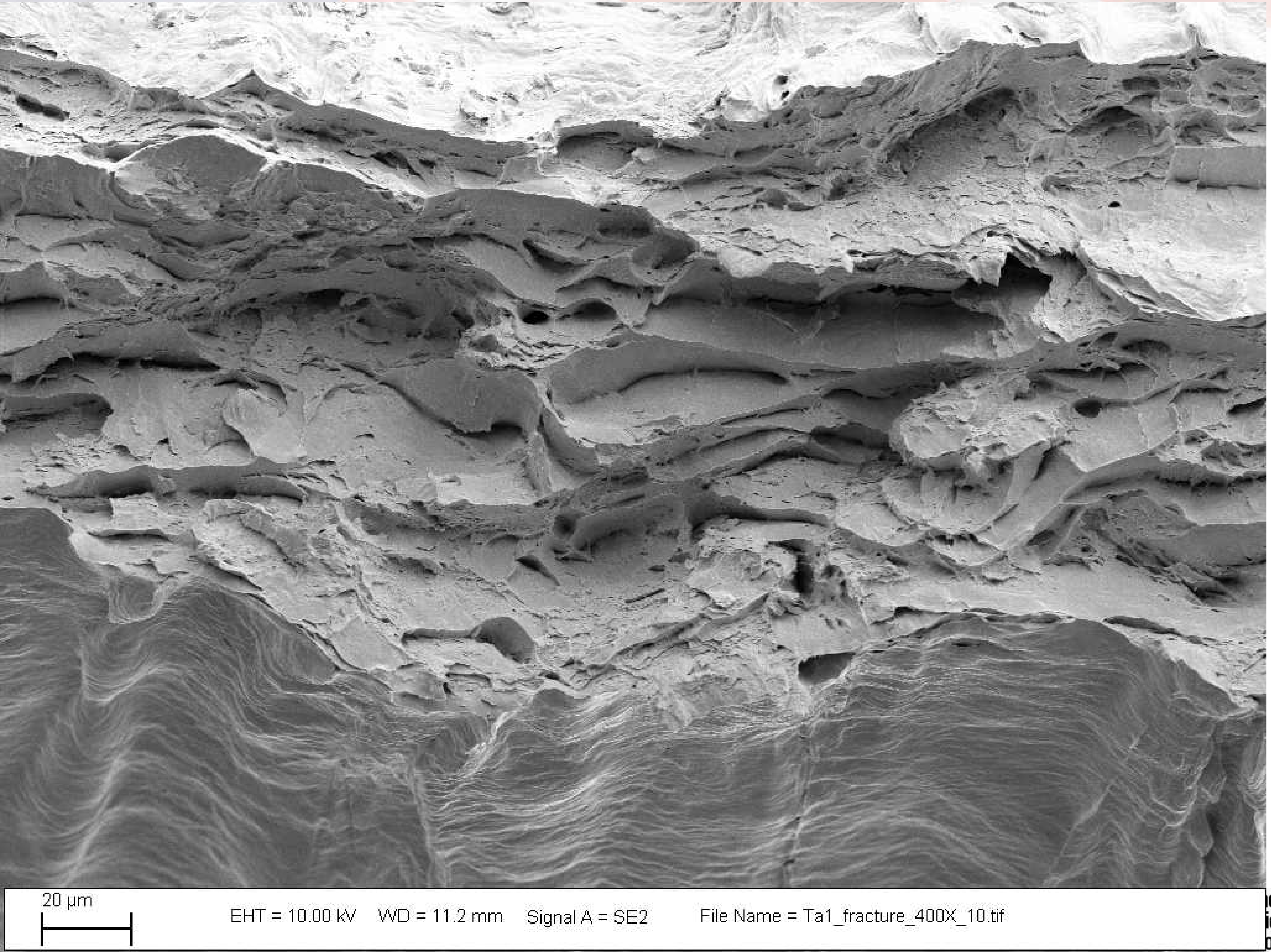
Tantalum Fractography



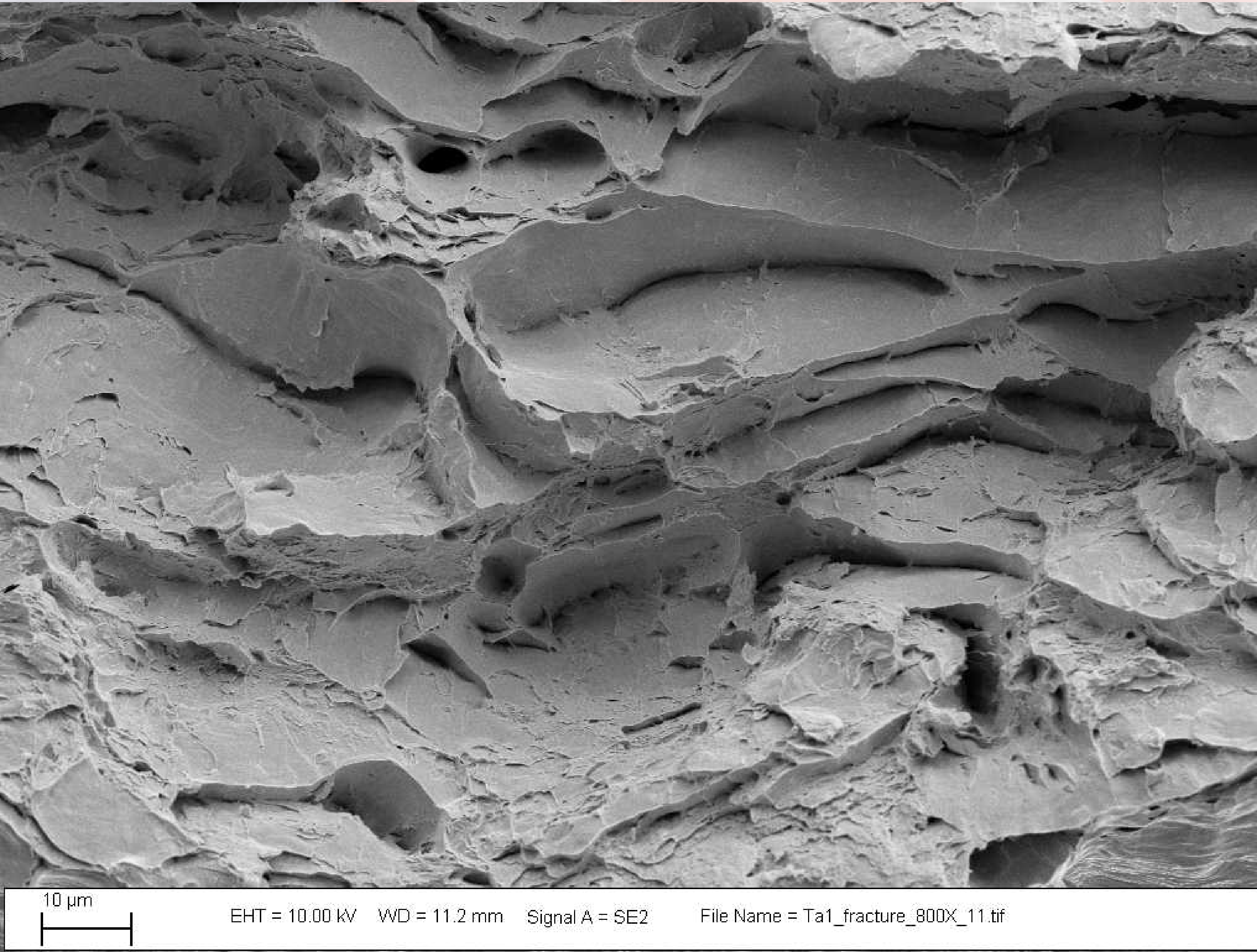
Tantalum Fractography



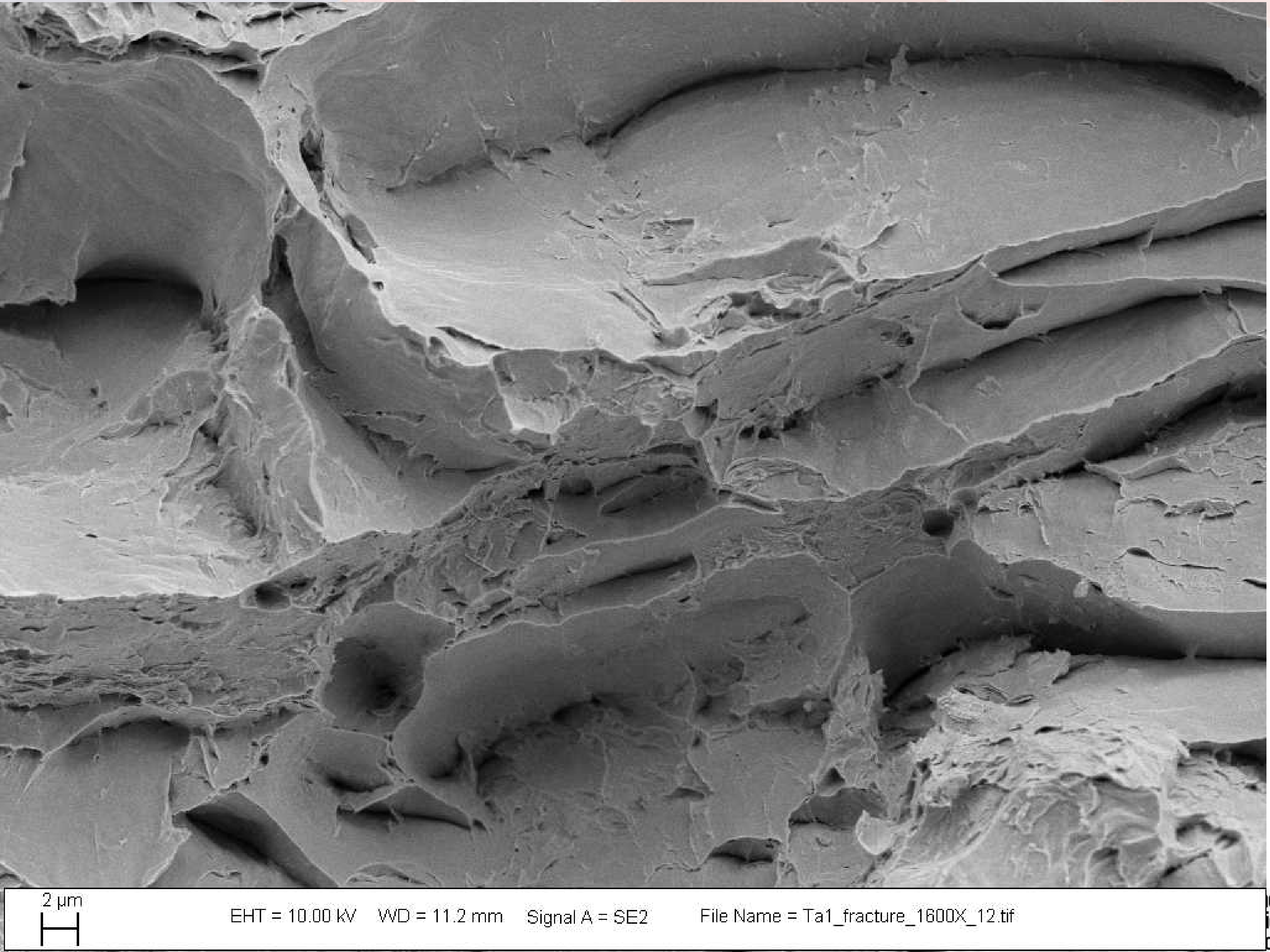
Tantalum Fractography



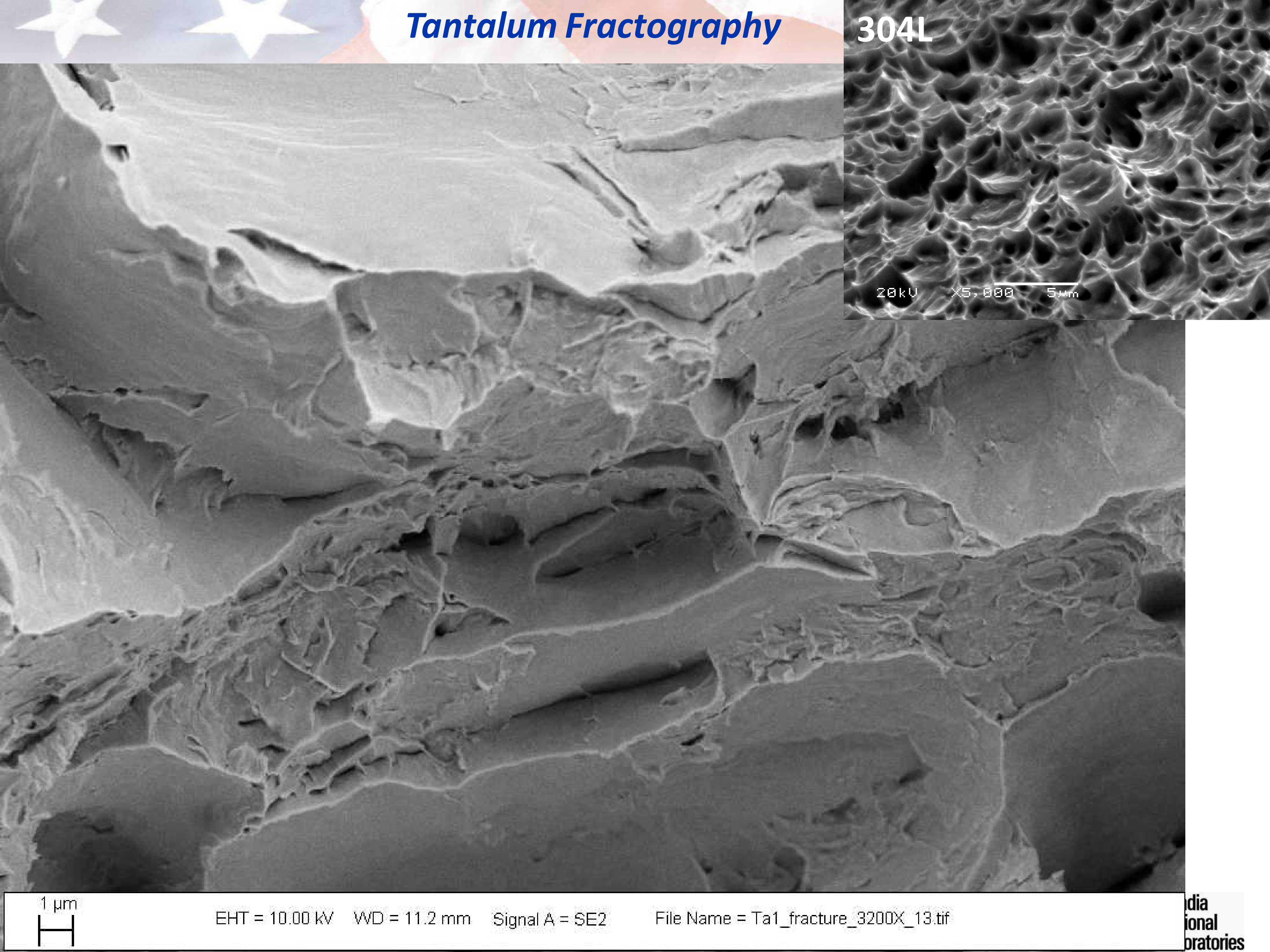
Tantalum Fractography



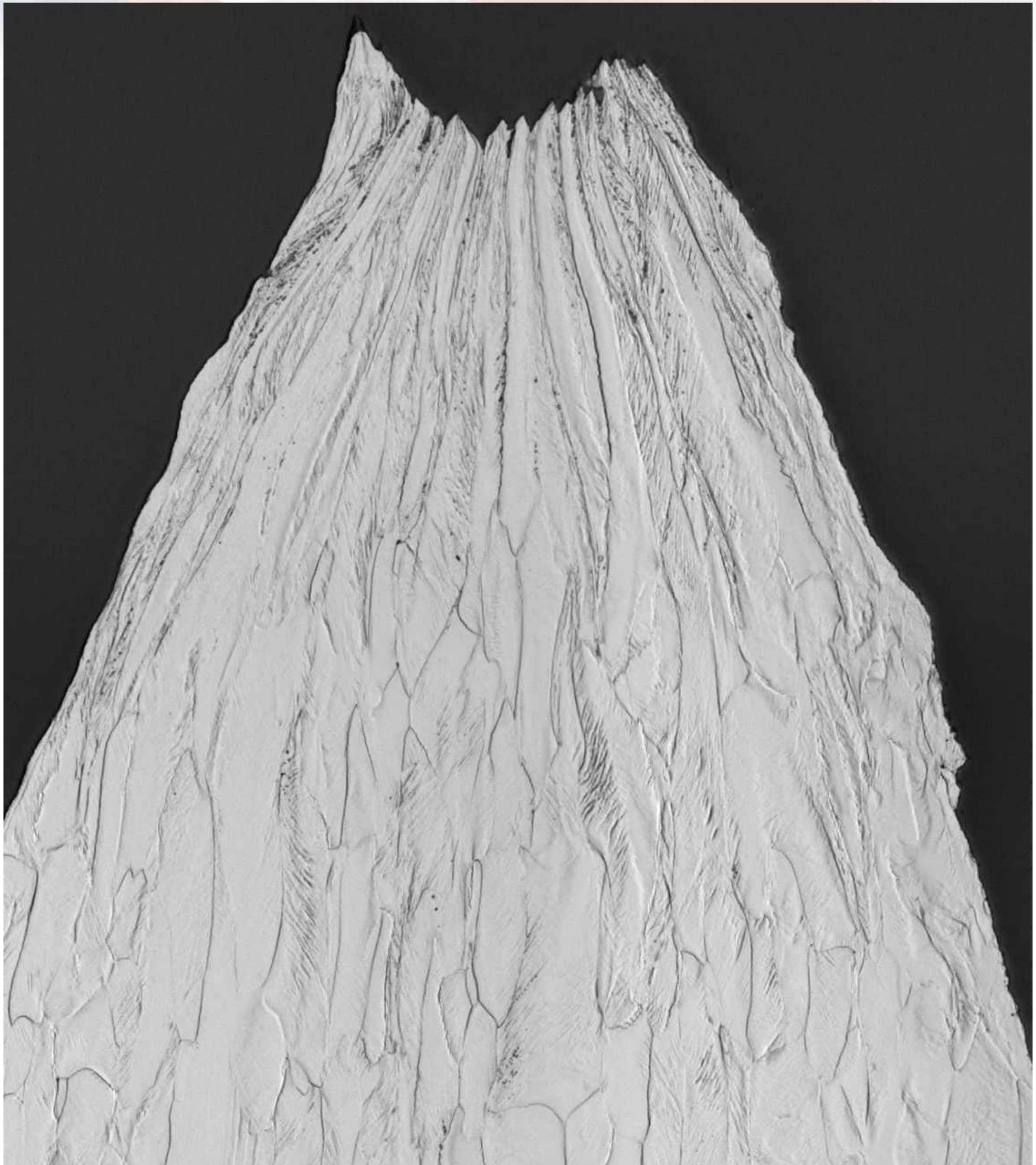
Tantalum Fractography



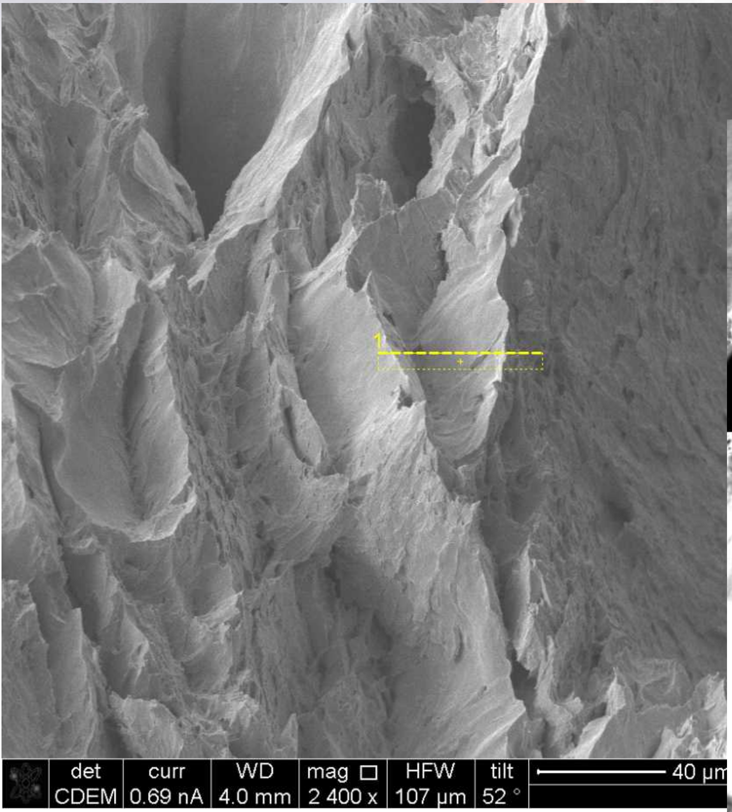
Tantalum Fractography

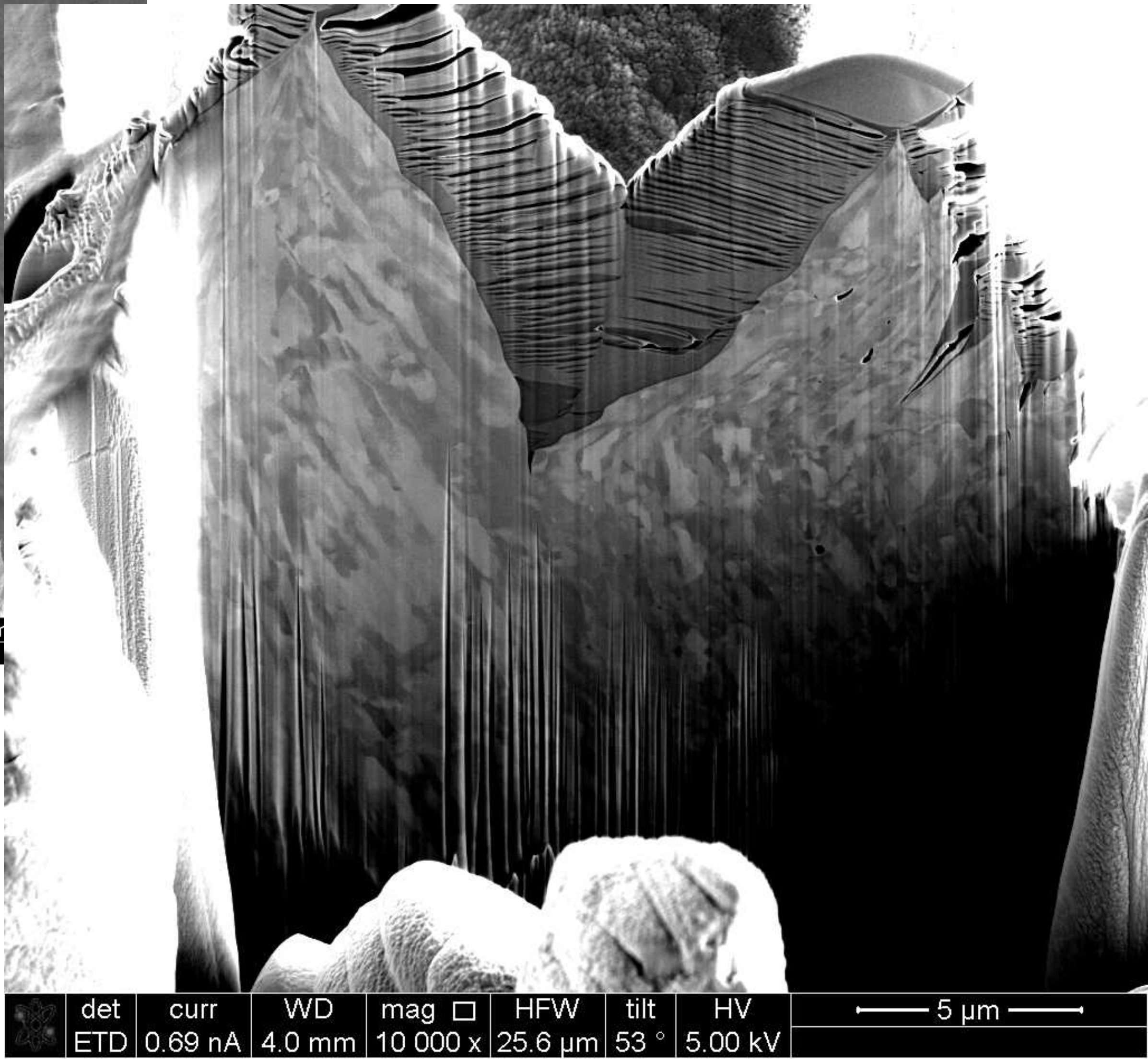


Cross-section of fractured neck in Tantalum

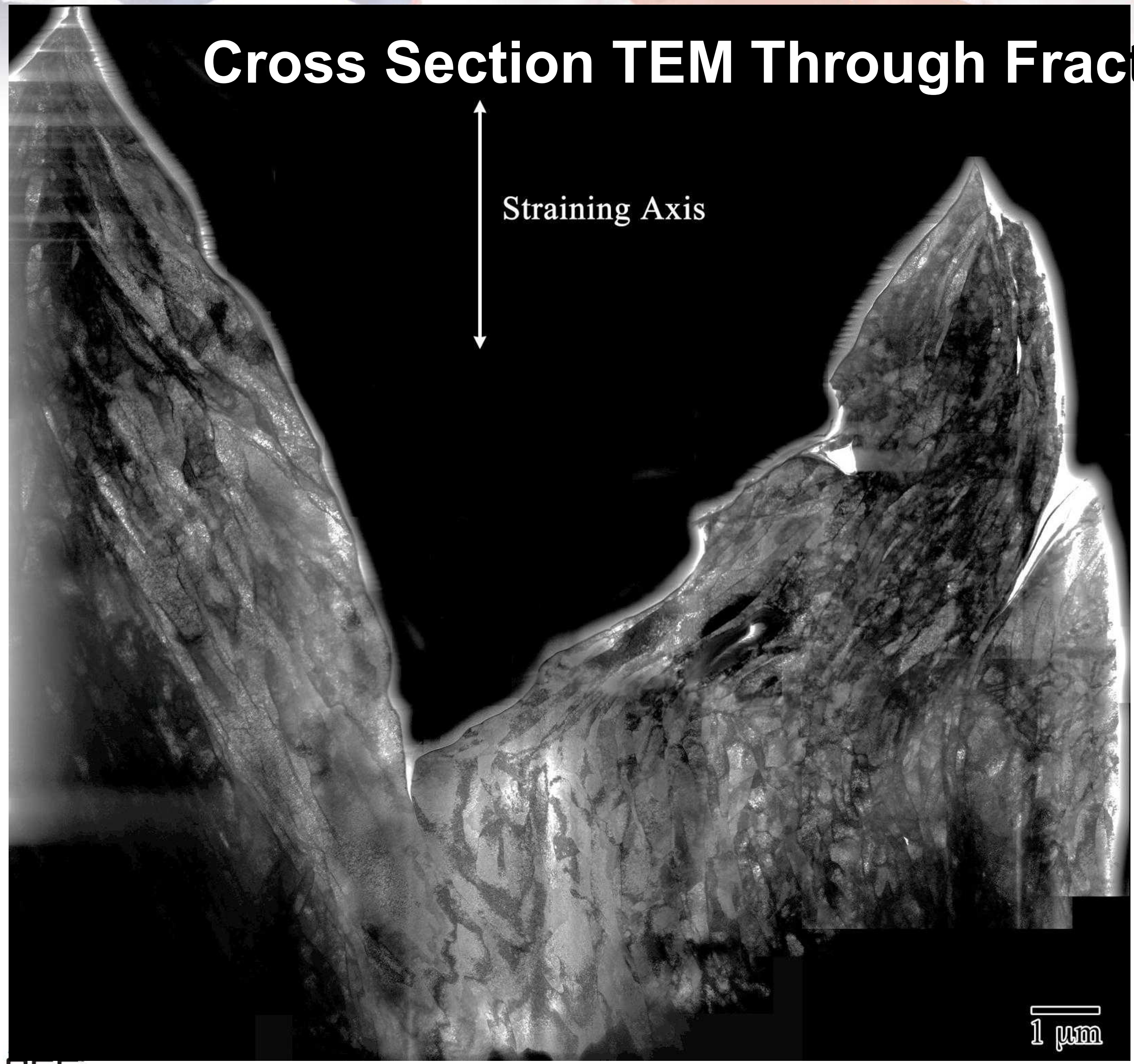


FIB lift-out of fracture-surface features



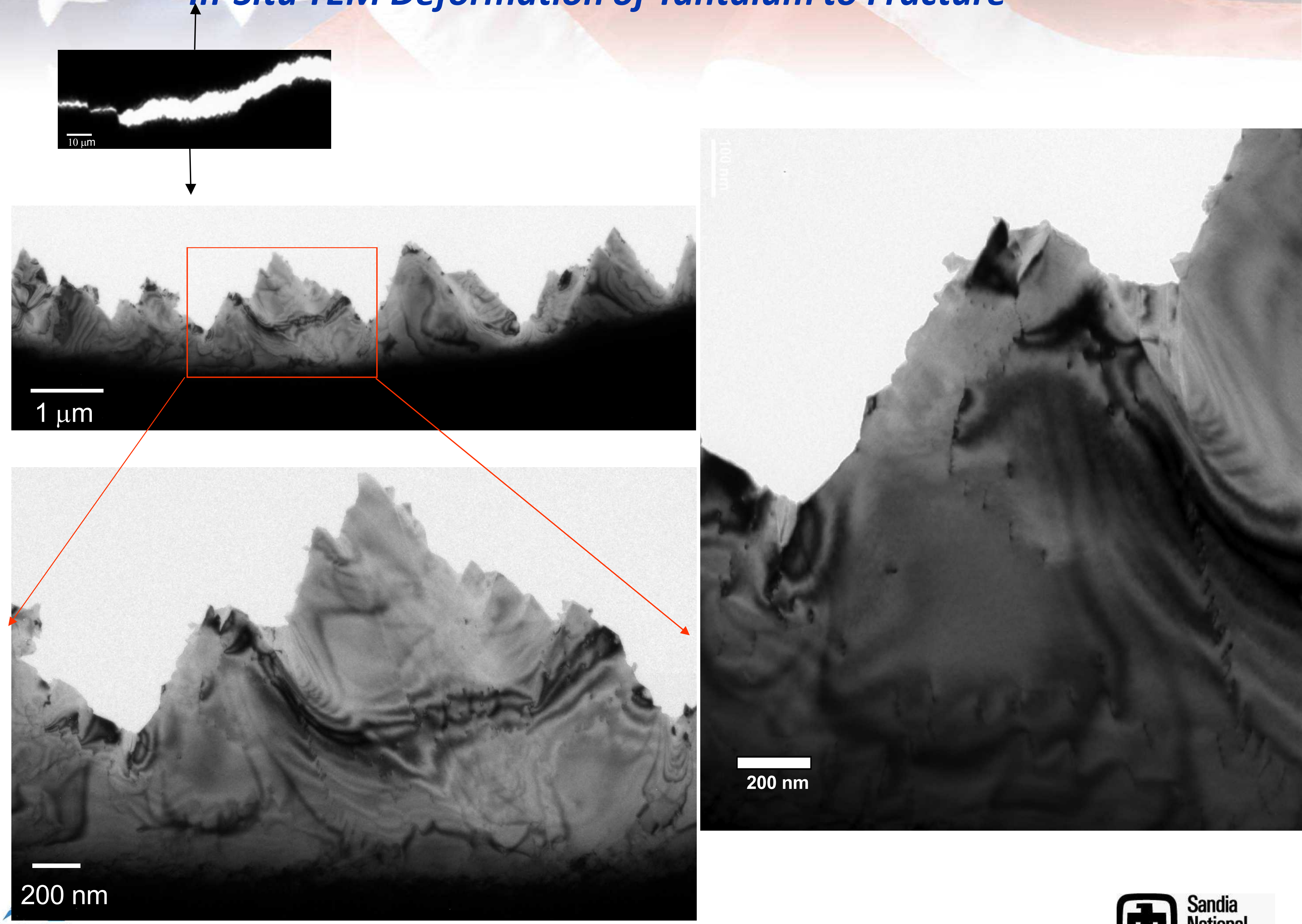


Cross Section TEM Through Fracture



- BF-STEM used to image sample to enable diffraction contrast in thick sample regions
- Widespread subgrain formation
- Original grain size ~10 to 100 um

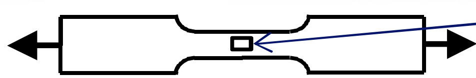
In-Situ TEM Deformation of Tantalum to Fracture

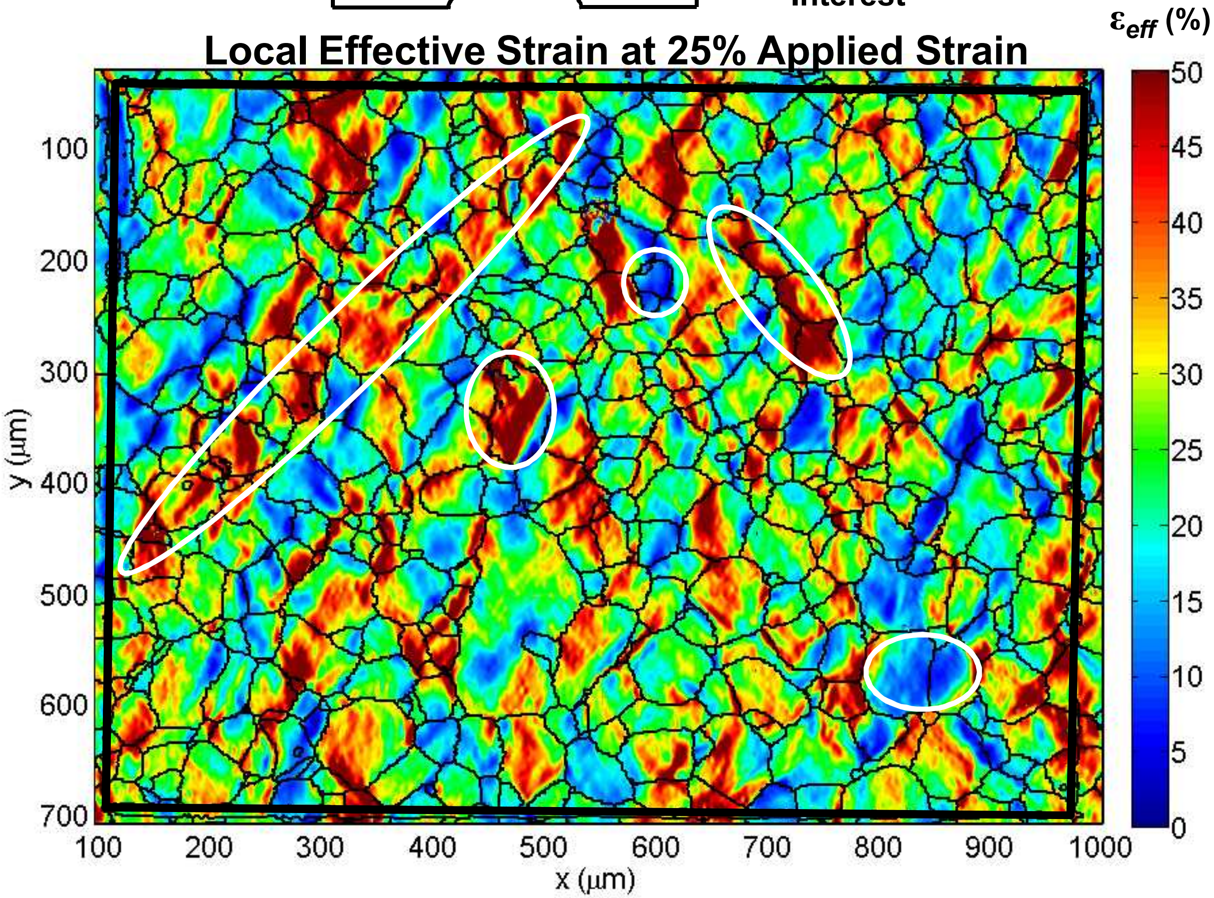


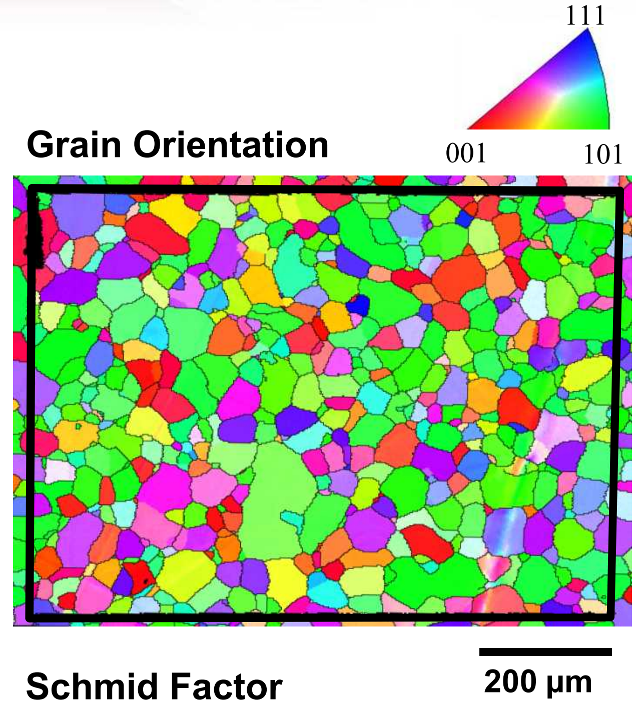
The preceding slides on tearing in Tantalum are largely qualitative in nature…

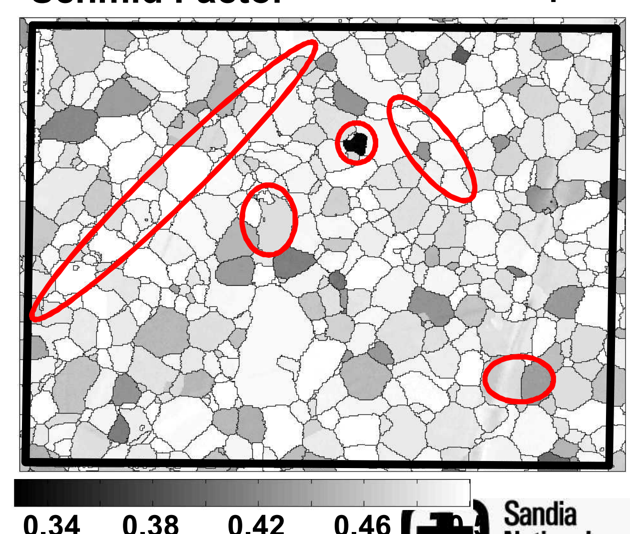
Can we be more quantitative regarding the local mechanical state leading to crack nucleation?

SEM-DIC allows intergranular strain quantification… to some extent









- Microstructural strain is highly inhomogeneous: when the macrostrain is 25%, local microstrains range from 0% to 50%.
- As a crude first-approximation, high Schmid factor grains are associated with high plastic strain, and vice versa.
- Grain neighborhoods and banding develop under plastic straining.
- The simple Schmid analysis suggests that (110) slip dominates over (112) or (123).

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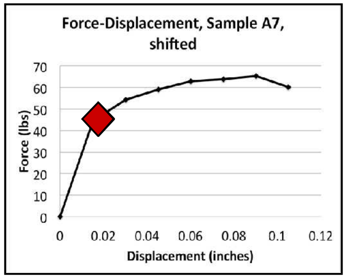
In-Situ SEM-EBSD allows intergranular rotation tracking… to some extent

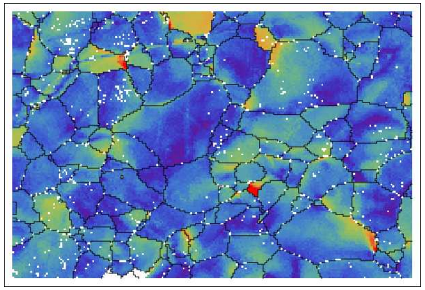
Tensile Strain

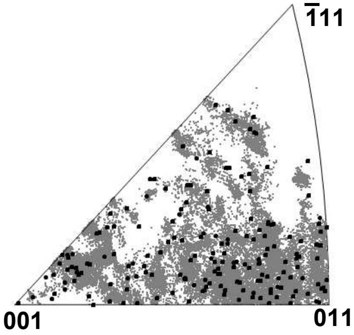
Misorientation maps
-relative to original averaged grain orientation

□IPF□ maps
- **original average grain orientation**
- **current measurement data**

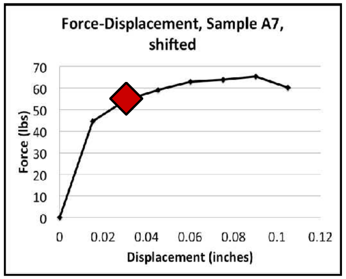
ε=3%

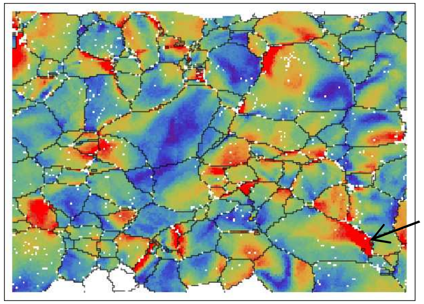


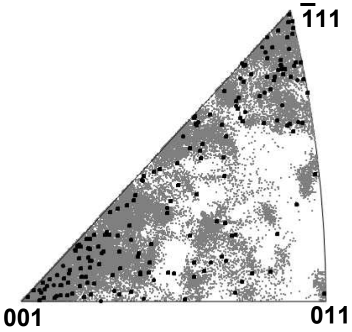




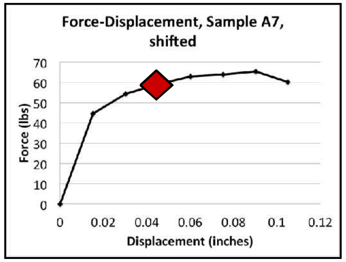
ε=6%

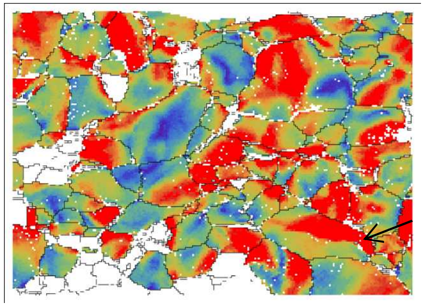


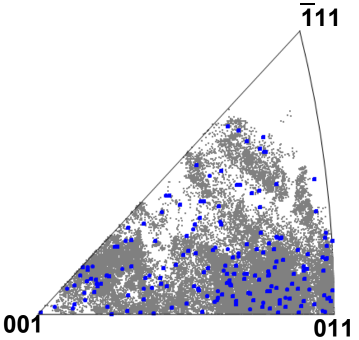




ε=9%







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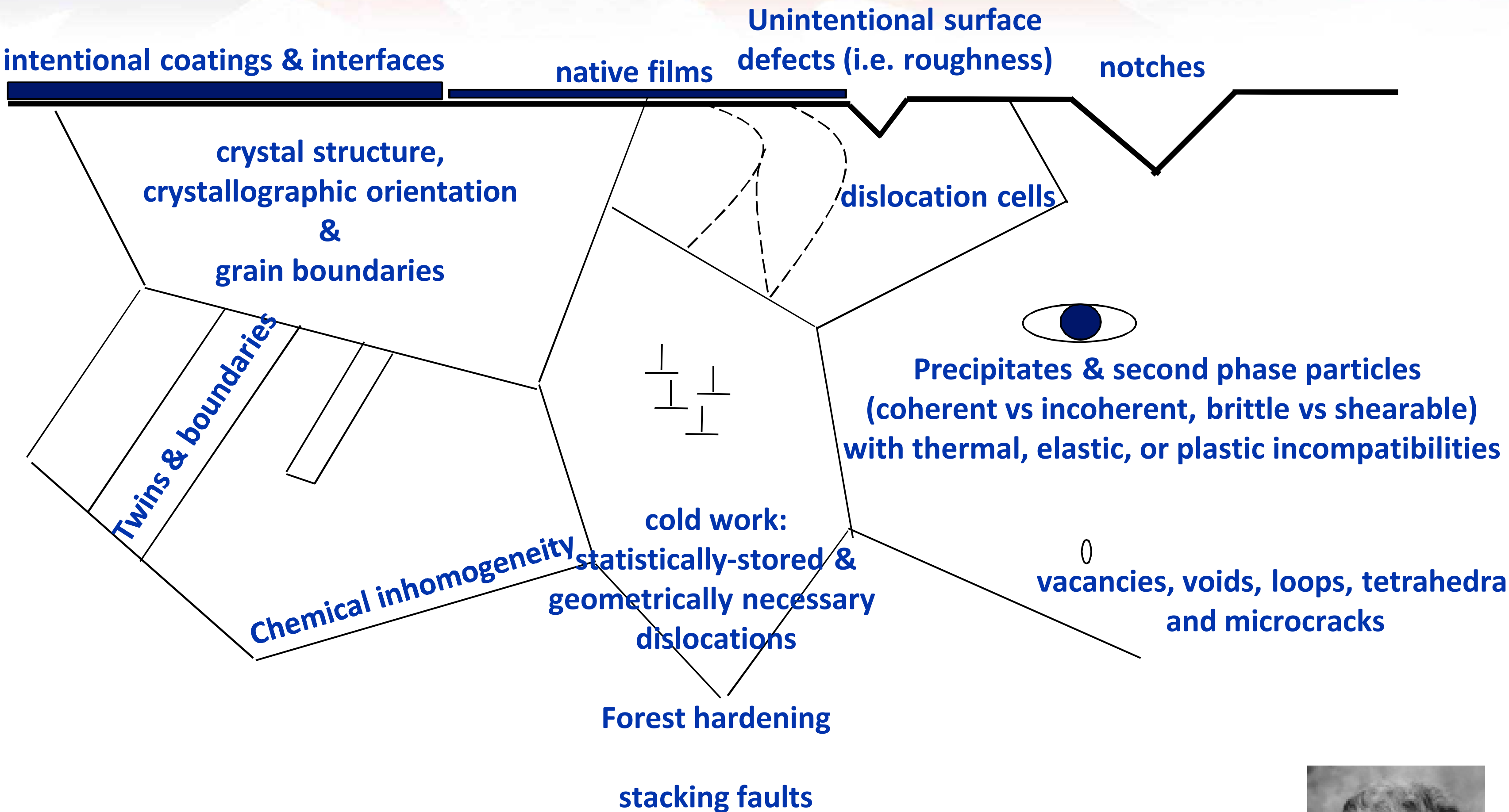
summary

- Ductile tearing is difficult to predict, even in 'simple' scenarios. Sandia's blind validation exercise is providing a quantitative benchmark to the limits of predictivity.

- Ductile tearing phenomena are difficult to experimentally observe, even with advanced techniques. Existing concepts such as microvoid coalesence may not provide the whole 'story'. The extreme deformation state leading to crack nucleation makes quantitative assessments (EBSD, DIC, etc) challenging. There is much more work to be done in this area – stay tuned!

backup slides

Real Materials Have Complex Features that Influence Failure



The relative importance of each of these factors varies from material to material

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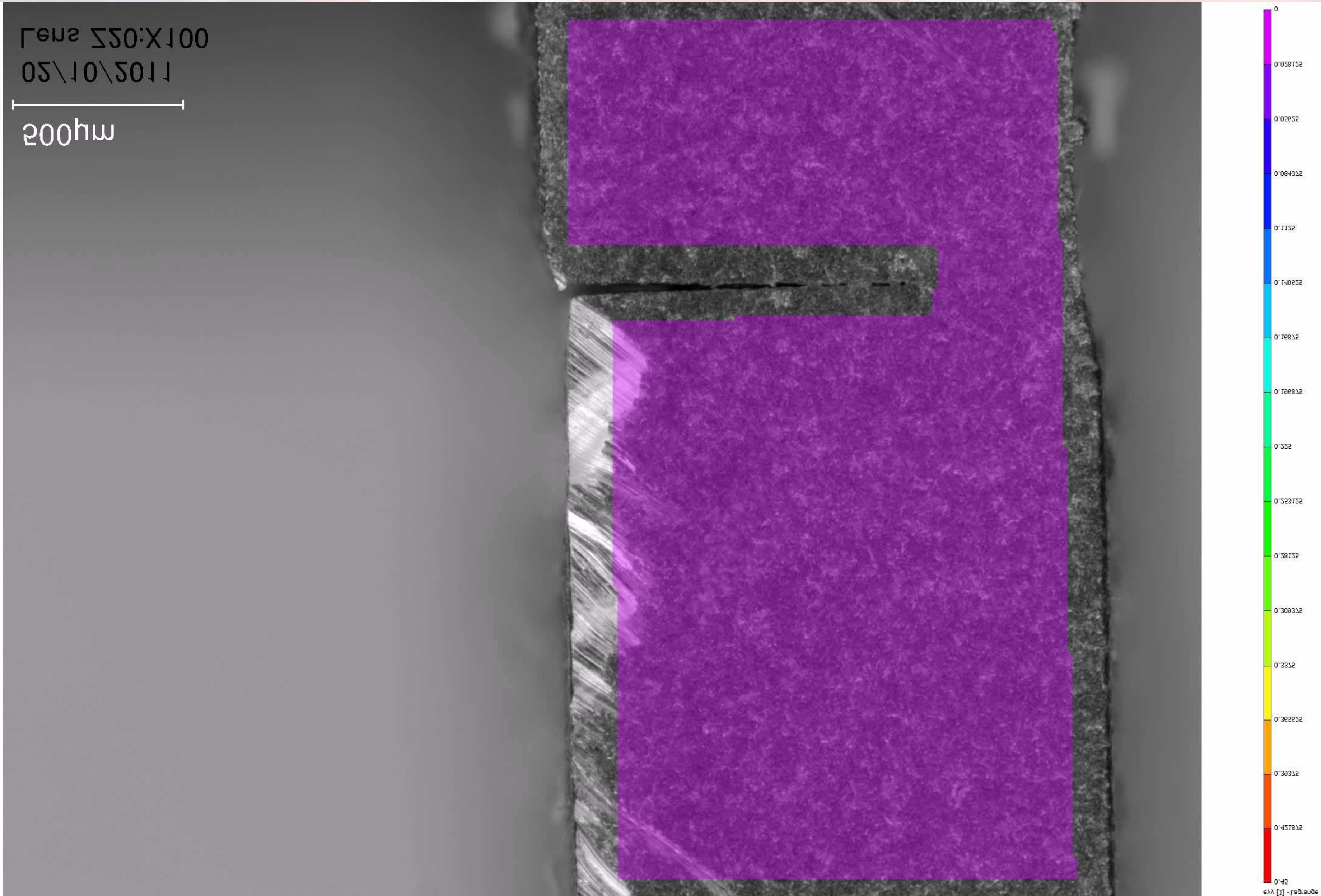
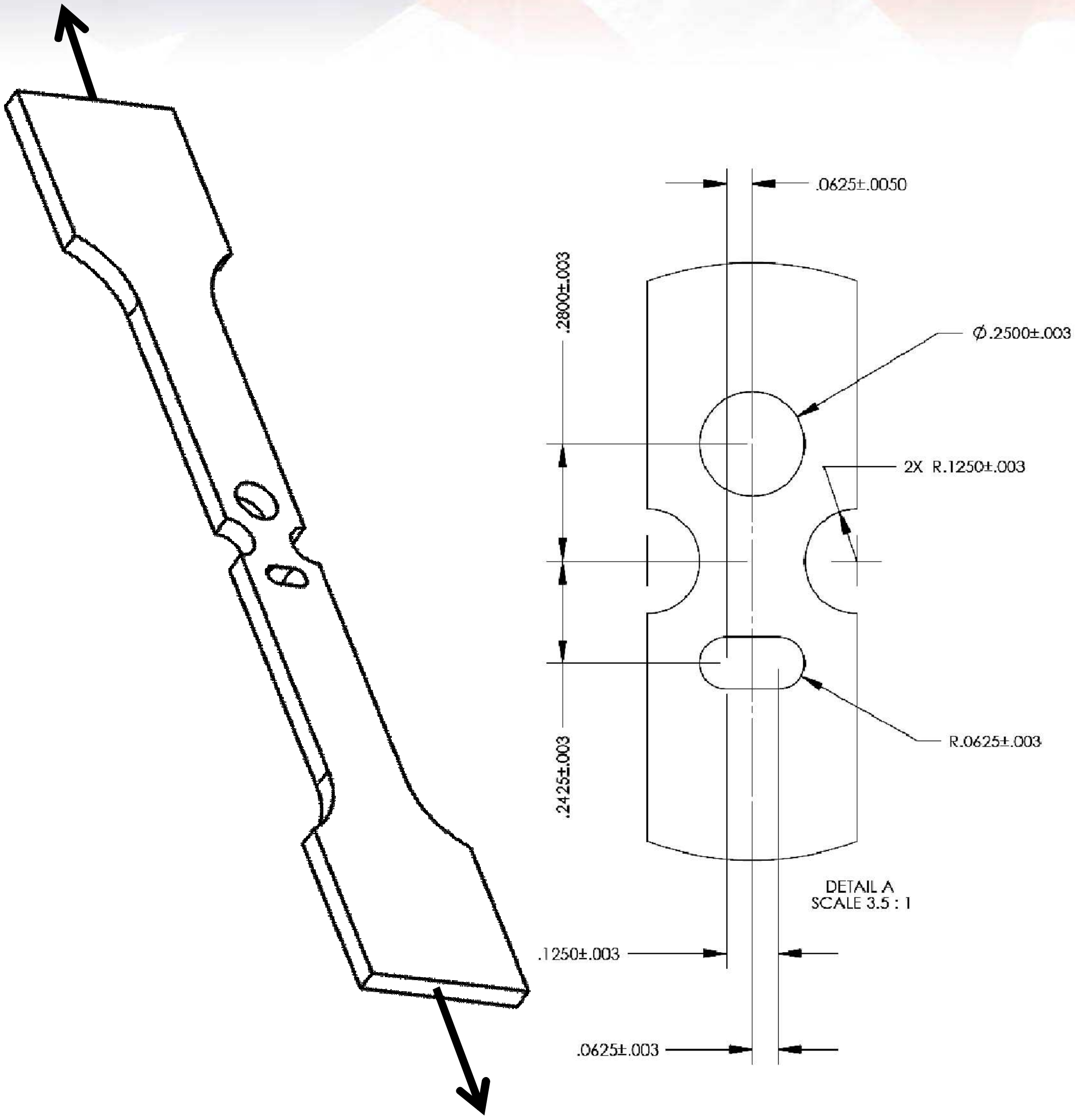

Lens Z20:X100
02/10/2011
500μm
0
0.028125
0.05625
0.084375
0.1125
0.140625
0.16875
0.196875
0.225
0.253125
0.28125
0.309375
0.3375
0.365625
0.39375
0.421875
0.45

Next Step: Can we predict large deformation necking instability?

Progression of Fracture ↓

- Elasticity (viscoelasticity, anisotropic elasticity, non-linear elasticity, etc.)
- Yielding (yield surfaces, rate sensitivity, microplasticity, etc.)
- Plastic Flow (work hardening, shear banding etc.)
- Necking (instability, localization)
- Damage Evolution (incubation, void nucleation, coalescence)
- Crack Initiation (definition of crack initiation, distributed microcracking)
- Crack Propagation (deflection, shielding, bifurcation, fragmentation, etc.)

4th Challenge: Predict 304L Behavior



In annealed 304L, predict the location of crack initiation, the peak force prior to crack initiation, the strain of a 1" extensometer at crack initiation, and the path of crack propagation.

AN OPEN INVITATION:
Sandia Fracture Challenge

•The challenge scenario will involve predicting deformation, crack nucleation, and propagation in a common engineering alloy.

•The challenge will be issued by e-mail and posted on imechanica.org on May 15th, with predictions due 5pm EST Sept 15th.

•Any research institution can participate.

•Participants will be offered an invited talk at ASME IMECE 2012 next November in Houston to present their methodology.

•Participants can request to have their predictions be anonymous.

To confirm participation, please e-mail Brad Boyce blboyce@sandia.gov

SUMMARY

1. Clearly, blind prediction of crack initiation and propagation is not trivial. None of the teams were consistently predictive. Each team had instances where the predictions were a factor of 2 or more away from the observed behavior.

Are LLNL or LANL any better at blind ductile failure prediction?

The current X-Prize effort provides 'benchmarking'.

1. Like other benchmarks, it merely provides a quantitative metric of performance.

2. Like other benchmarks, it will quantify the performance of a tool only under a very specific set of conditions.

3. Like other benchmarks, it only quantifies the current state-of-performance, not the potential for future improvement.

4. Like other benchmarks, the sources of poor performance may be difficult to diagnose from the benchmark alone.

FY 11 Level 2 Milestone Description:

This milestone shall complete an impartial quantitative assessment of tearing prediction methodologies for a range of NW relevant ductile metals under room temperature quasi-static conditions resulting in a FY12 redirection of failure modeling activities. Four modeling paradigms are being evaluated: peridynamics, localized elements, tearing parameter, and extended finite elements. This milestone represents both the groundwork performed in FY10 (focused on crack initiation) and the FY11 work which culminates both initiation and propagation predictivity.

Milestone Due Date: 09/2011

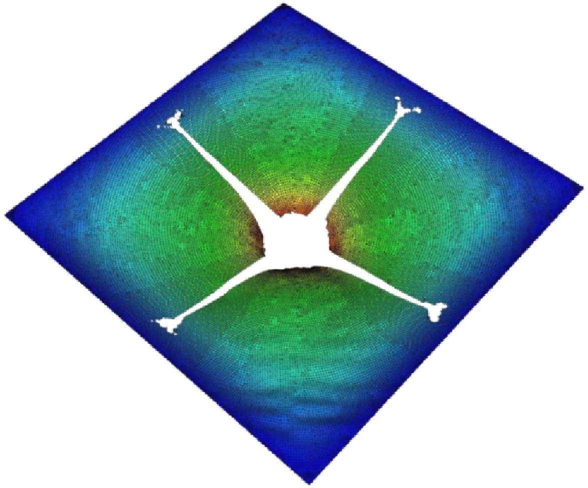
The X-Prize concept gets the competitive juices flowing

"Revolution through Competition"

- Award-based technology competitions inspire progress
  - -Ortiz Prize for nonstop flight US→Europe
  - -Anasari X-Prize for manned spaceflight
  - -Google Lunar X-Prize
  - -Progressive 100-mpg X-Prize

- The X-prize is not always about accomplishing a single far-reaching goal. Sometimes 'levels' are used to judge/award progress through increasingly complex challenges.

"Revelation through Co-opetition"



- This is Sandia's first X-Prize style 'co-opetition'. This format may lay the groundwork for future assessment activities.

- The Ductile Fracture X-Prize will step through a progressive series of increasingly complex prediction challenges.

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The 'Challenge' puzzle must be cleverly designed

-No intuitively obvious or closed-form solution exists.

-There exists a single, unambiguous, repeatable solution.

-Well-defined, simple uniaxial boundary conditions with simple reaction forces.

-Easily measured geometric features.

-Easily measured force and displacement ranges allow low-cost experimental testing in numerous labs.

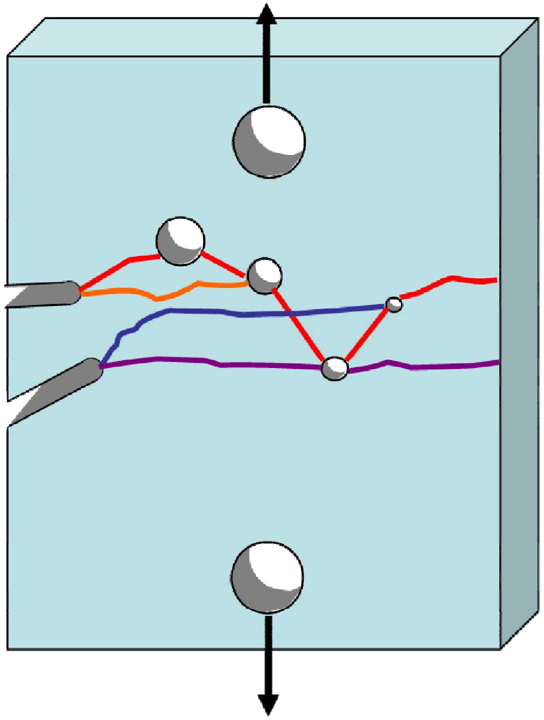
-No stress-gradients or unusual surface conditions (i.e. No EDM critical features).

-The geometry is quick, cheap and easy to manufacture in a wide range of materials with reasonable manufacturing tolerances that do not add significantly to variability in response.

-The geometry is two-dimensional (…eventually 3-dimensional)

-Once the problem is solved, it can be readily reinitialized by simple geometry changes.

-Must be designed to prevent buckling or other unwanted deformation modes.



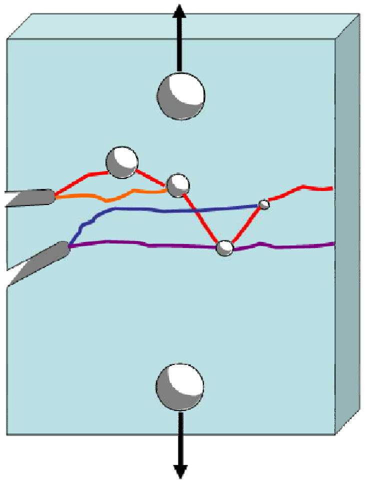
"Crack-in-a-maze" Concept

Ground Rules for the "X-Prize" Ductile Fracture "Co-opetition"

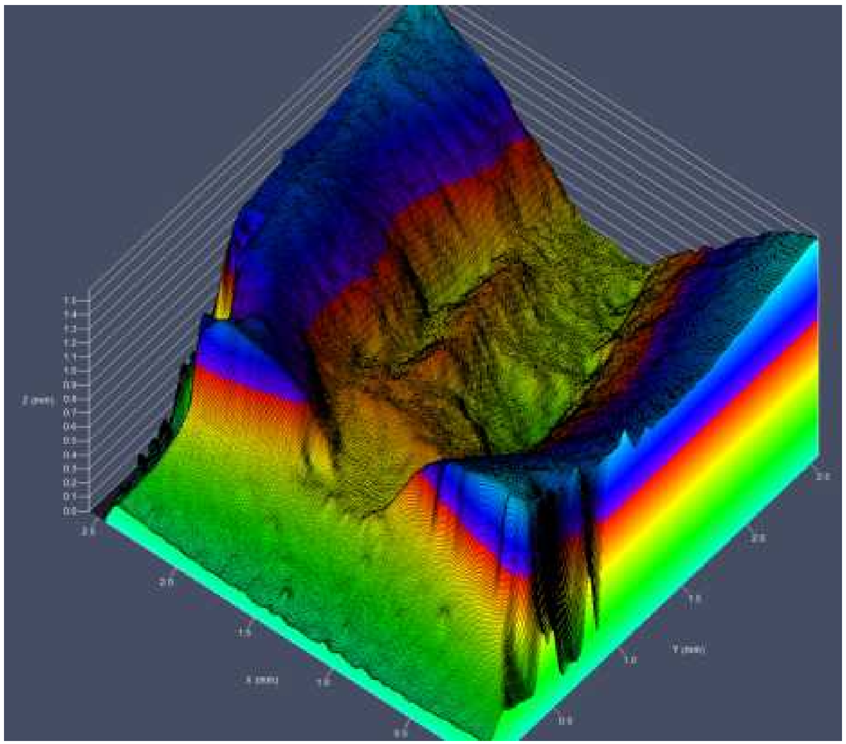
1. An independent moderator is responsible for establishing the challenges, collecting the blind predictions, coordinating the experiments, and distributing comparisons between the experimental data and all of the predictions.

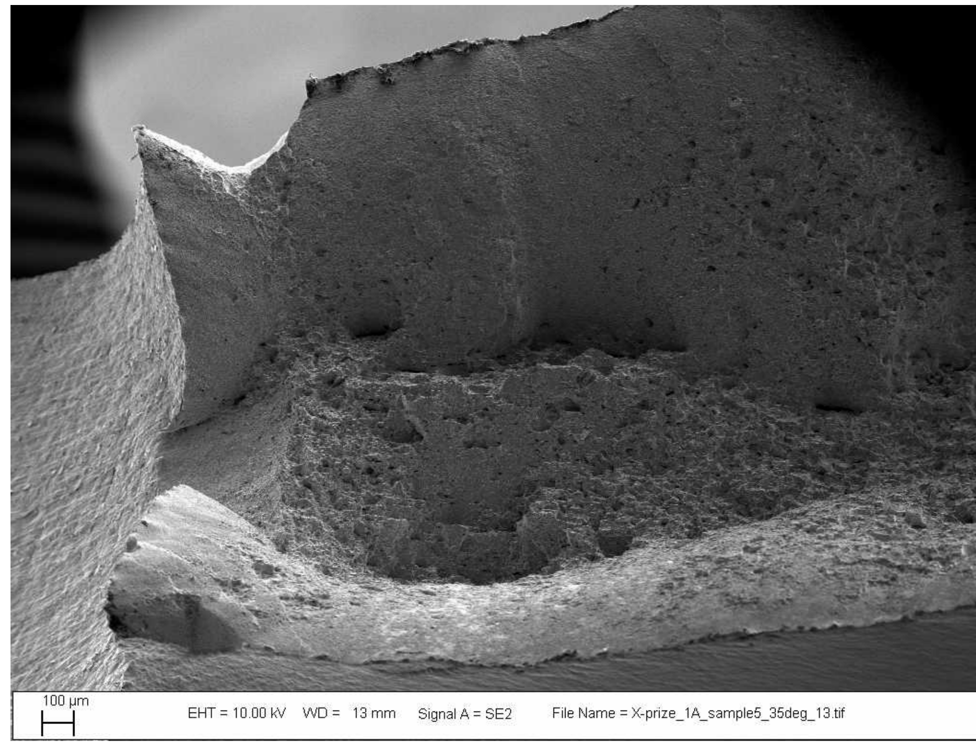
2. Teams can predict a bounded range of response rather than a determinstic value. Representation of uncertainty is up to the teams.

3. Teams are limited to existing material property data (no new experiments to calibrate their models). Material property data (literature, databases, etc) are shared among teams.



Shear lips form during fracture of PH13-8 H950





None of the modeling methods would capture the complexity of shear lips which dominate the fracture surface.

Sources for Poor Predictions…

1. Physics

What are the governing equations that describe fracture processes?

2. Numerics

Is the physics implemented in a computational code that handles geometric complexities, stresses and strains correctly?

3. Material Properties

What are the right constitutive models for material behavior?

4. Boundary Conditions

What are the boundary conditions that mimic the experimental conditions?

5. 'Operator' Errors

Pathological assumptions; misinterpretation of question; misreporting of results

SOME WRAP-UP COMMENTS AND DISCLAIMERS

1. **Clearly, blind prediction of crack initiation and propagation is not trivial. None of the teams were consistently predictive. Each team had instances where the predictions were a factor of 2 or more away from the observed behavior. These assessments represent only the current state of Sandia's capabilities in a few specific scenarios, and do not necessarily reflect the *potential* of a paradigm to eventually solve ductile fracture problems with high predictivity.**

2. **One paradigm may not be suitable for all fracture problems. There are many different types of problems (brittle/ductile, static/dynamic, distributed damage, fragmentation) which requires that Sandia develops a suite of fracture capabilities.**

3. **There are many sources of potential error – here are the 3 most common:**
   - Inadequate 'physics' in the intiation criteria.
   - Available material property data are insufficient for calibration
   - A surprisingly important error is 'operator' error: pathological assumptions, misinterpretation, and misreporting.

next step….