Refining Crystal Plasticity Finite Element Model for Deformation of Single Crystal Niobium

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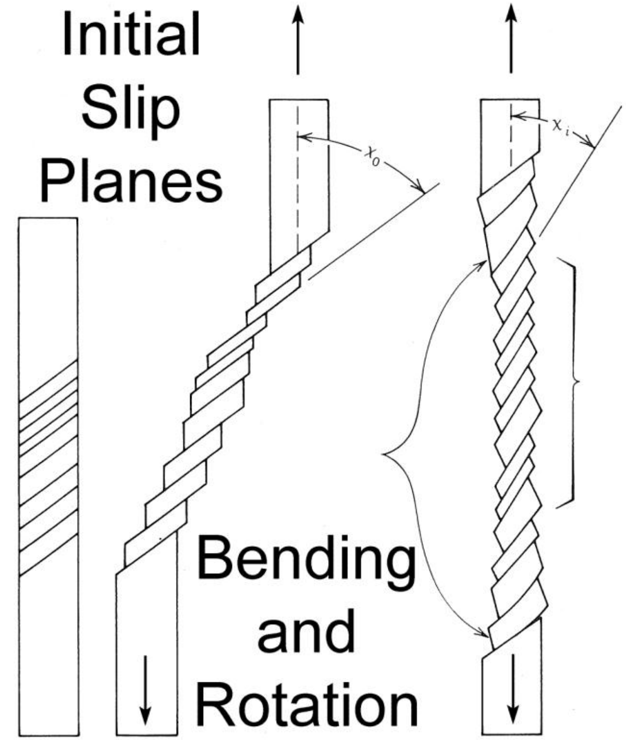
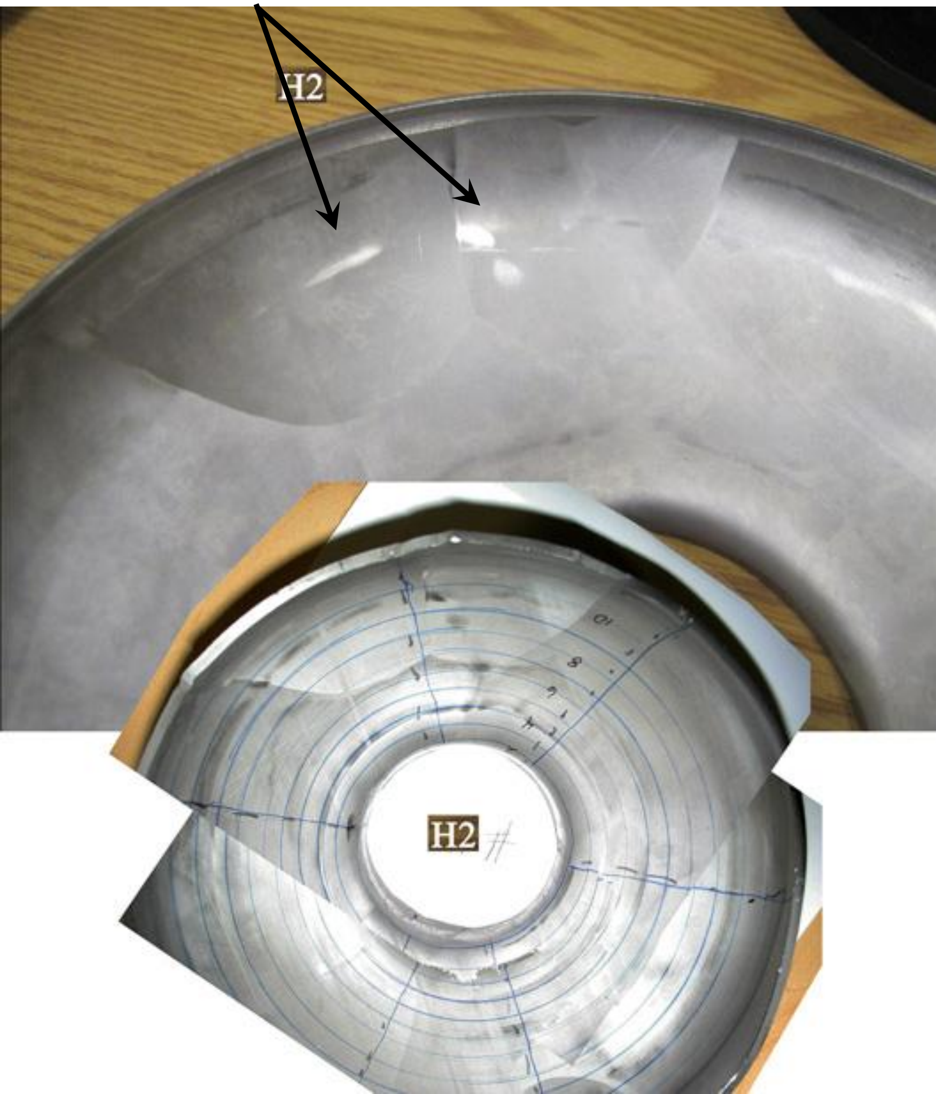
Motivation



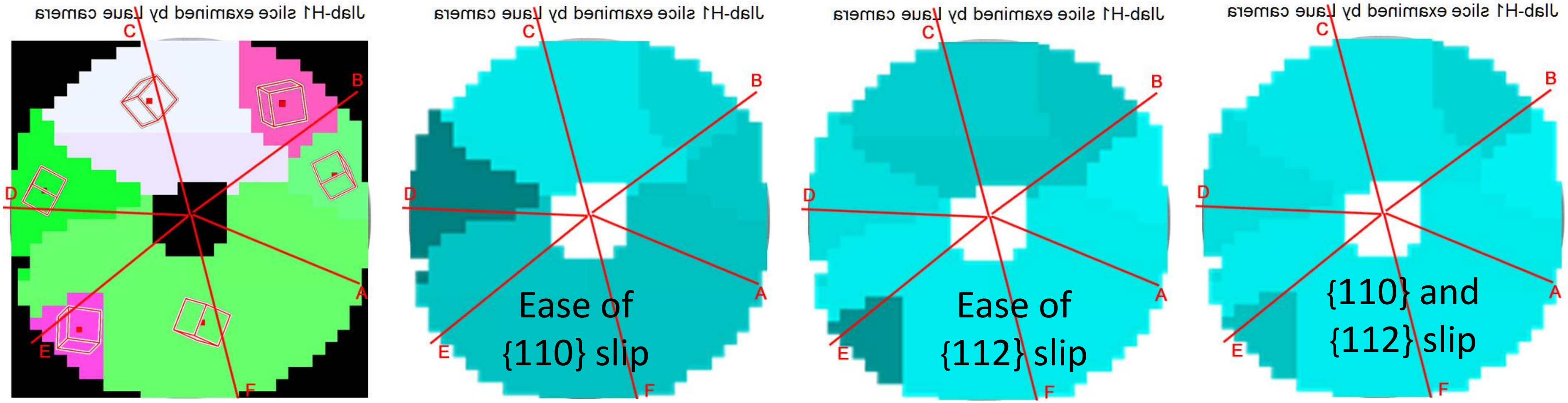
- Heterogeneous deformation caused by crystallographic slip makes forming of complex shapes challenging
  - Uniform thickness, uniform shape does not naturally occur due to effects of crystal slip systems; crystals rotate about an axis perpendicular to the slip direction, at rates that depend on the rate of shear strain, and dislocations present on other slip planes that cause hardening (stress increase).
  - With deformation, the resolved shear stress and resistance to shear evolves differently on each slip system, leading to varying amount of shear in different slip systems and crystal orientations, and hence, heterogeneous deformation (Orange Peel Effect)

Example of effects of heterogeneous slip in deep drawn cavity half – differential thinning led to dragging, forming an ear, and a strange etch pit condition

Burnish marks indicate lesser thinning rate, grabbing die, leading to bizzare etch pit pattern



Cavity half prepared by Gigi Ciovati



No obvious trends/correlation between crystal orientation, thickness, **biaxial** stress, thickness

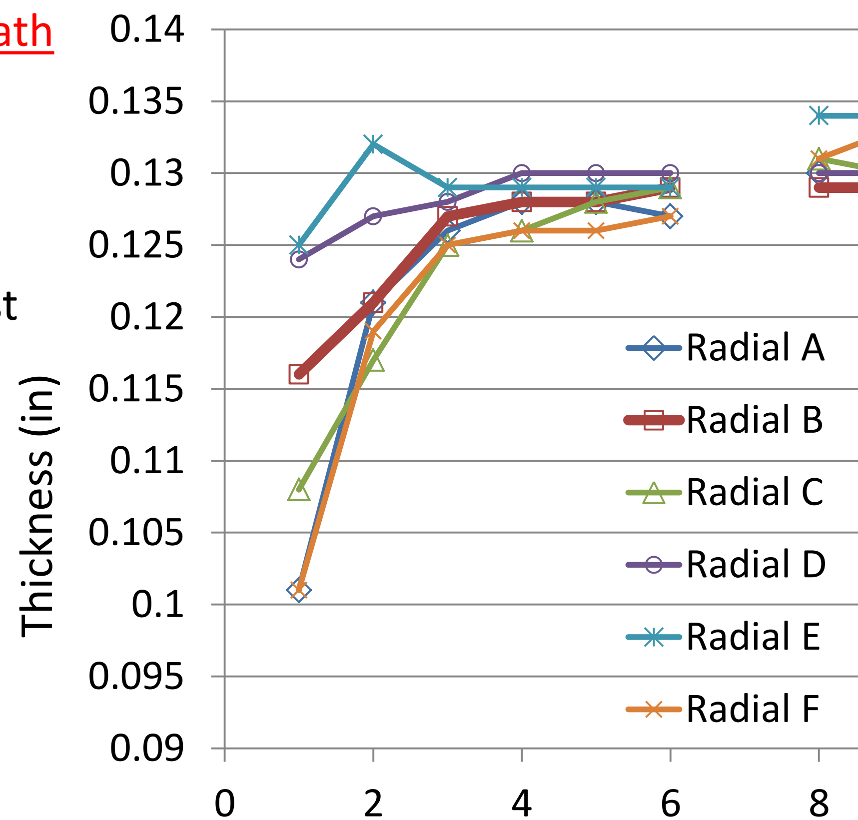
→ Simulate complex strain path

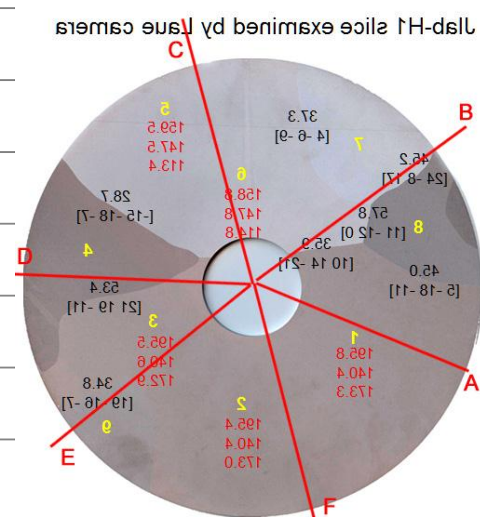
Sharp Ear

H1

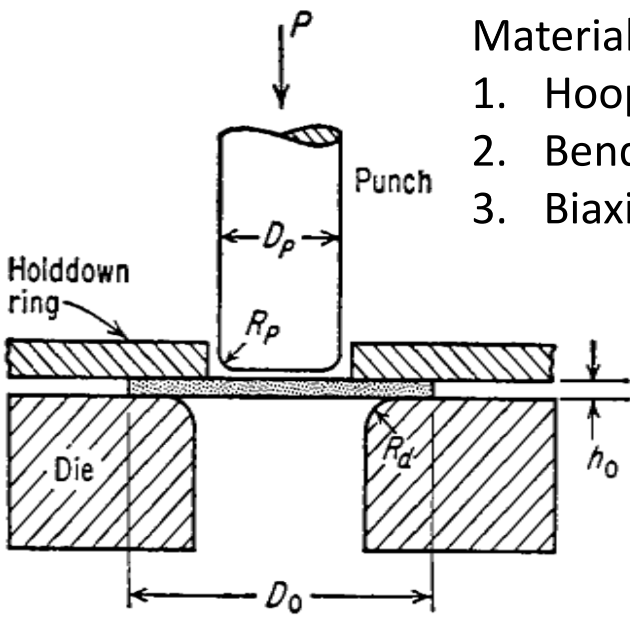
Sharpest Ear

Biggest Ear





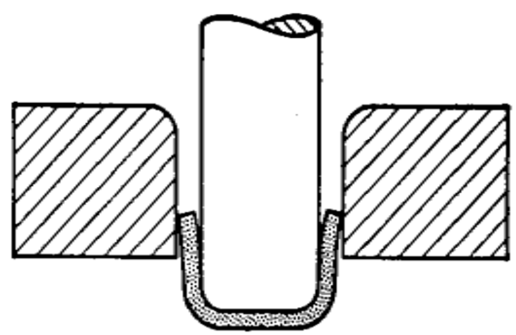
Strain path for drawing is complex, Kinematics of Crystal plasticity model OK



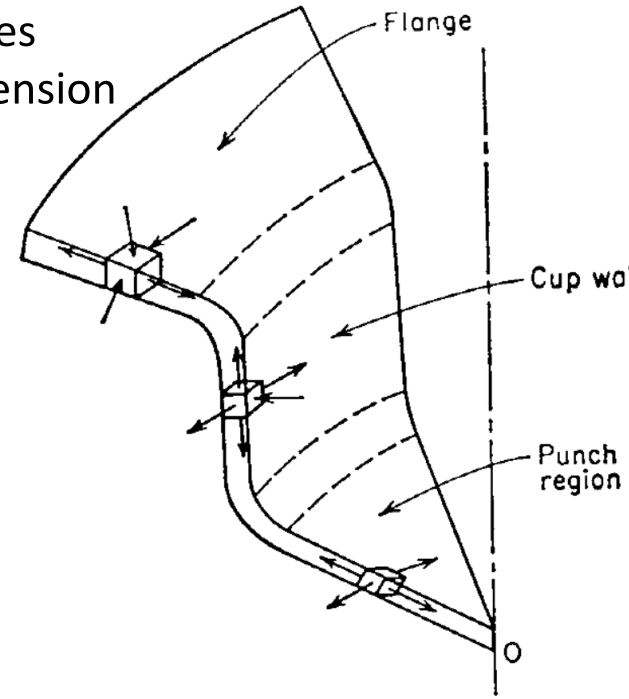
(a)

Material in Equator / Weld Experiences

1. Hoop Compression hoop, radial tension
2. Bending + unbending
3. Biaxial stretching (not balanced)



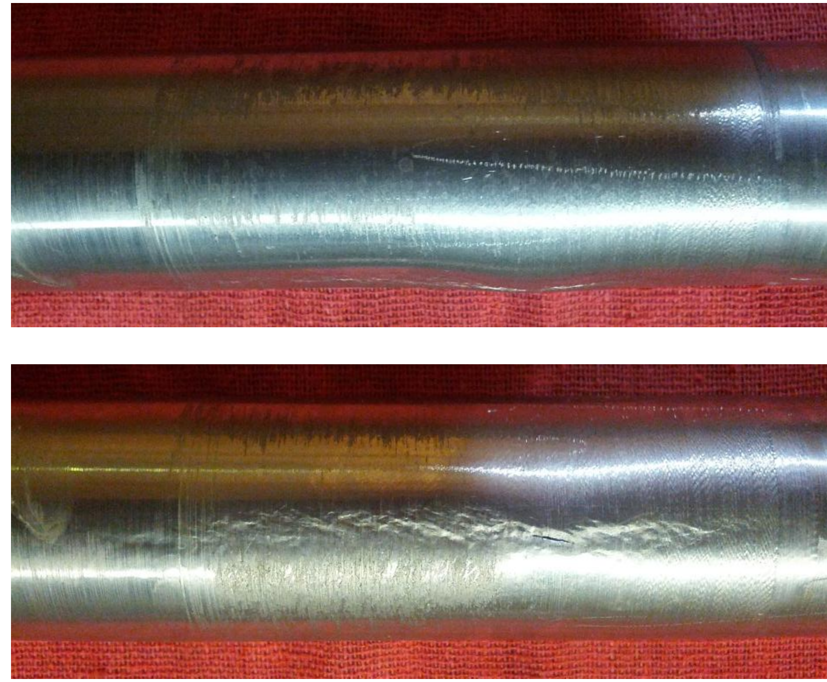
(b)



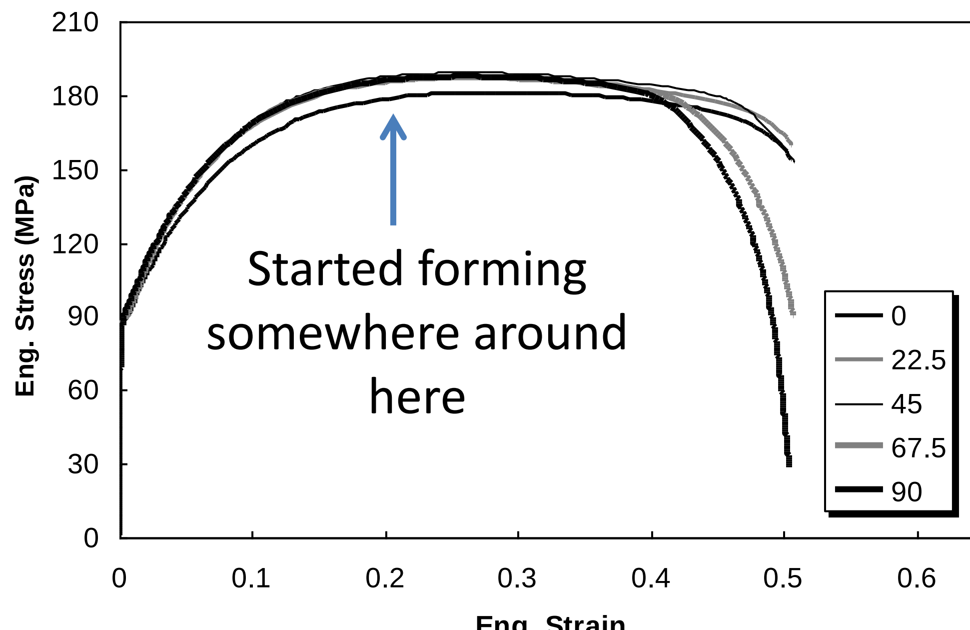
- Crystal plasticity models can simulate complex paths, and anisotropic slip, in general, the shape change is qualitatively modeled, but to be predictively quantitative, refining the stress-strain relationship is needed (as that affects how much strain can occur for a given increment of deformation)

1st attempt to bulge / inflate a non-optimal Nb tube

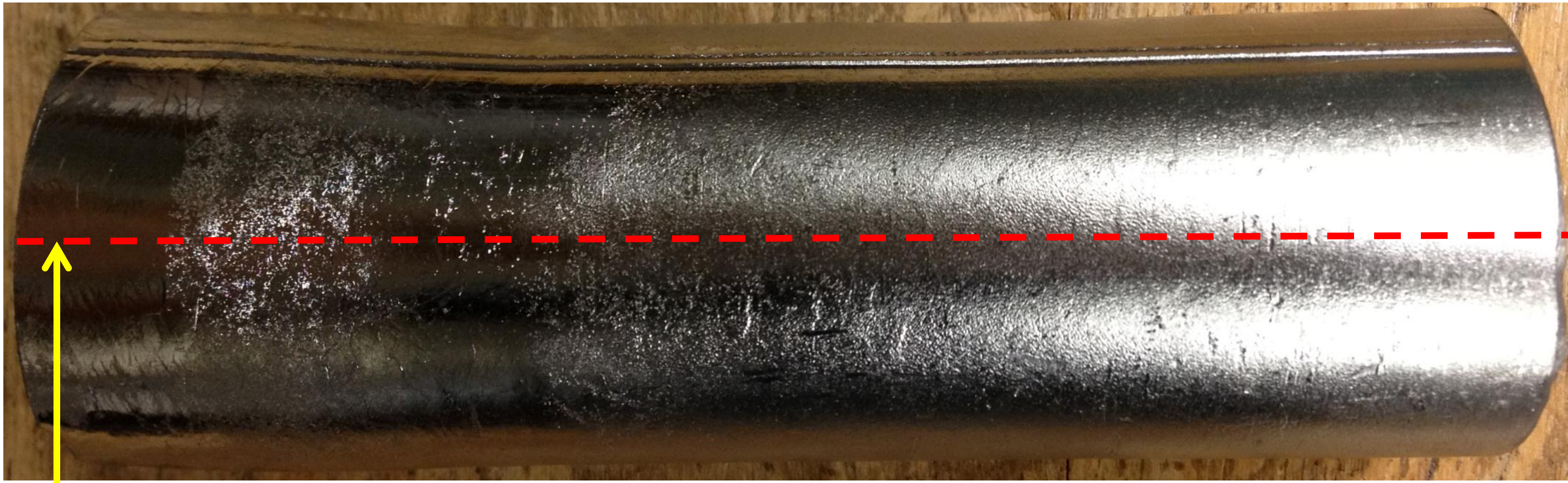
- Bent sheet metal to tube, welded along seam
  - Put in a lot of cold work by the bending process, then made large recrystallized grains
  - Tube was just over required dimension, so surface was machined (put even more cold work on surface)
- Such welded tubes sent to Jim Murphy at University Nevada Reno to convert into single crystal/large grain tubes

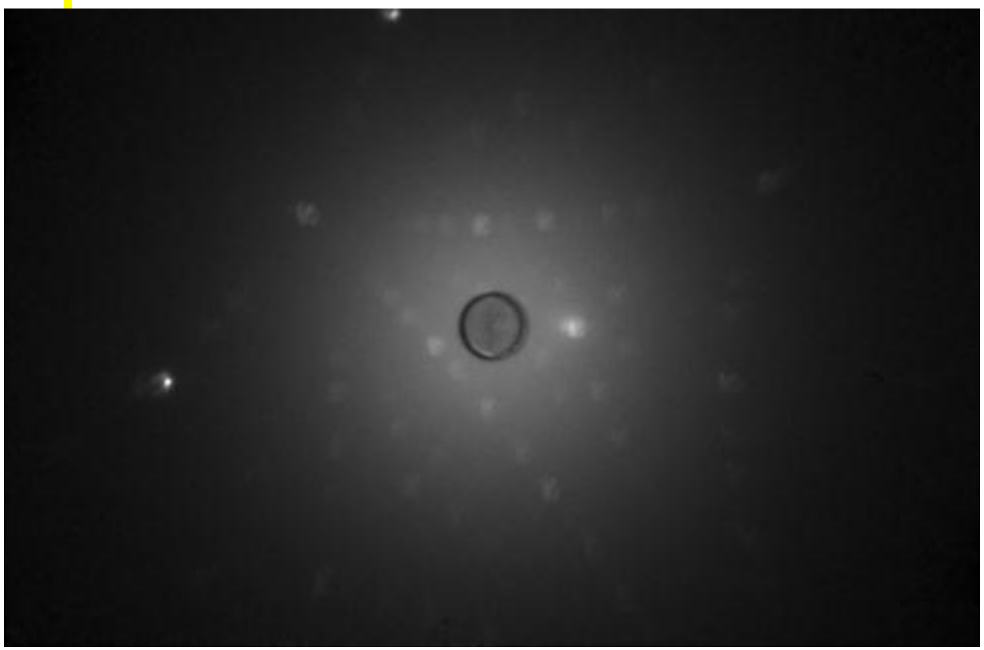


As expected, failed at weld



Tube processed by Jim Murphy, University of Nevada at Reno



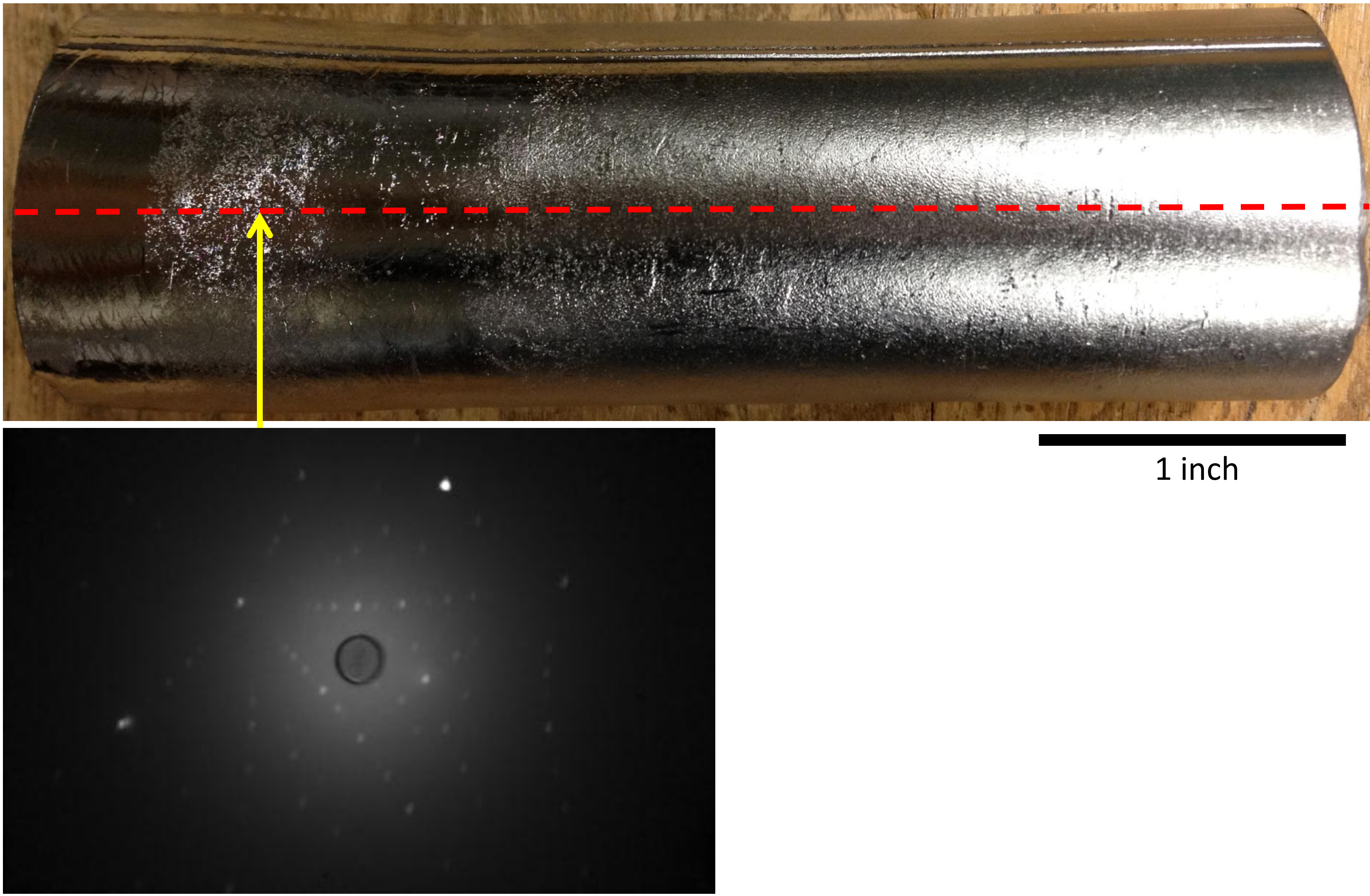


1 inch

Indicates the line all scans followed

Where roughly each scan was done

First tube (with an opening at left end)



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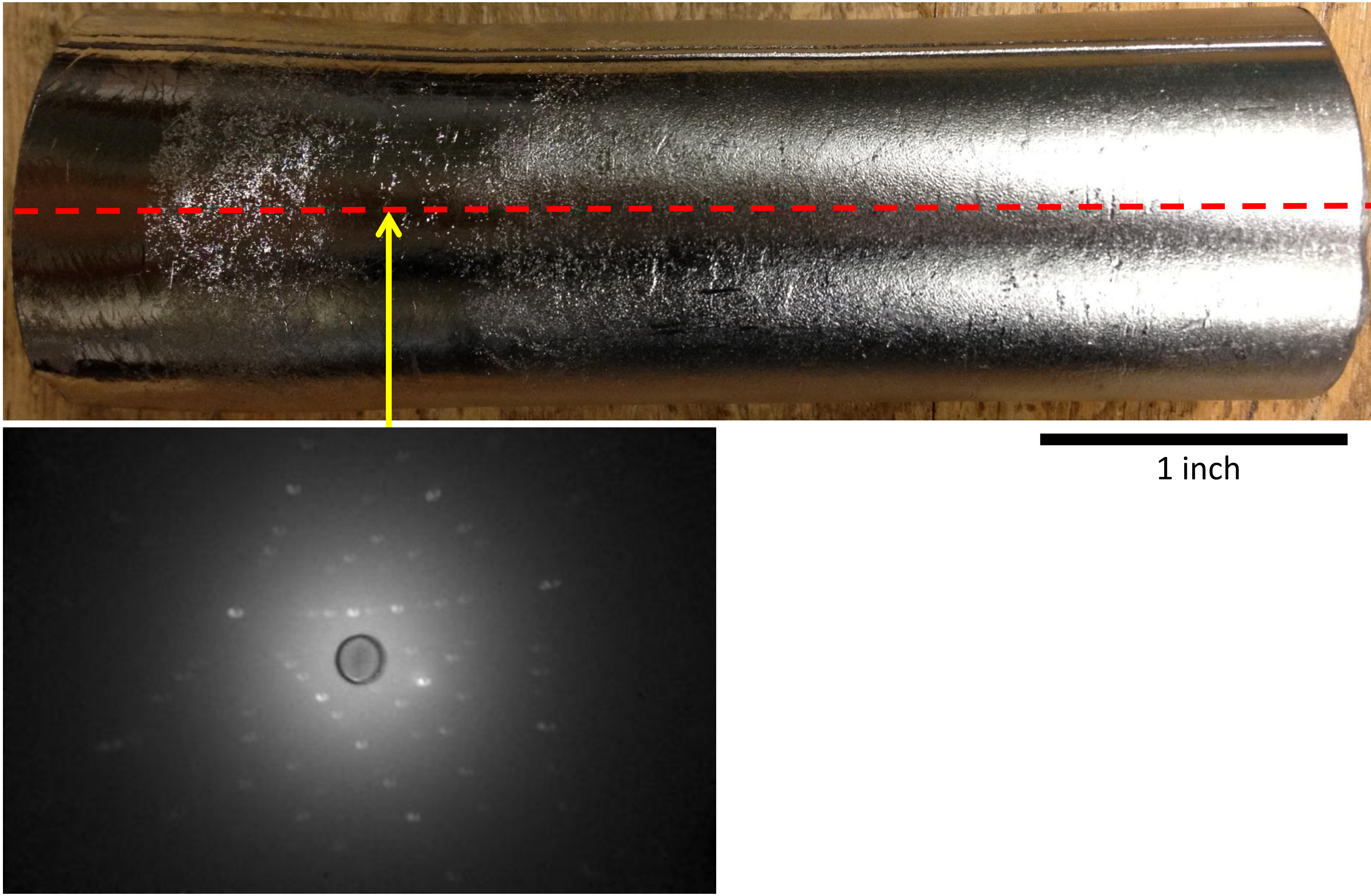

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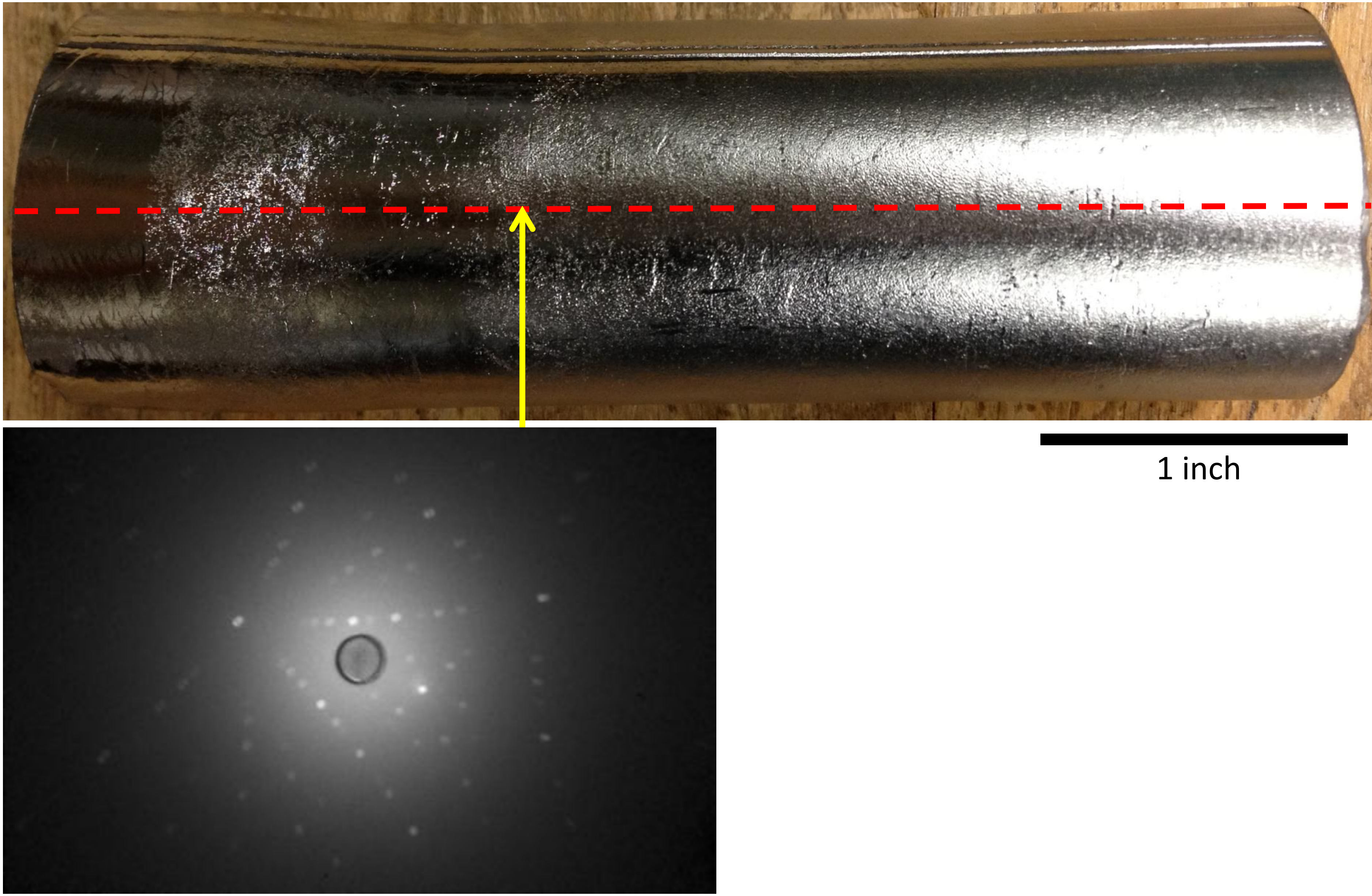

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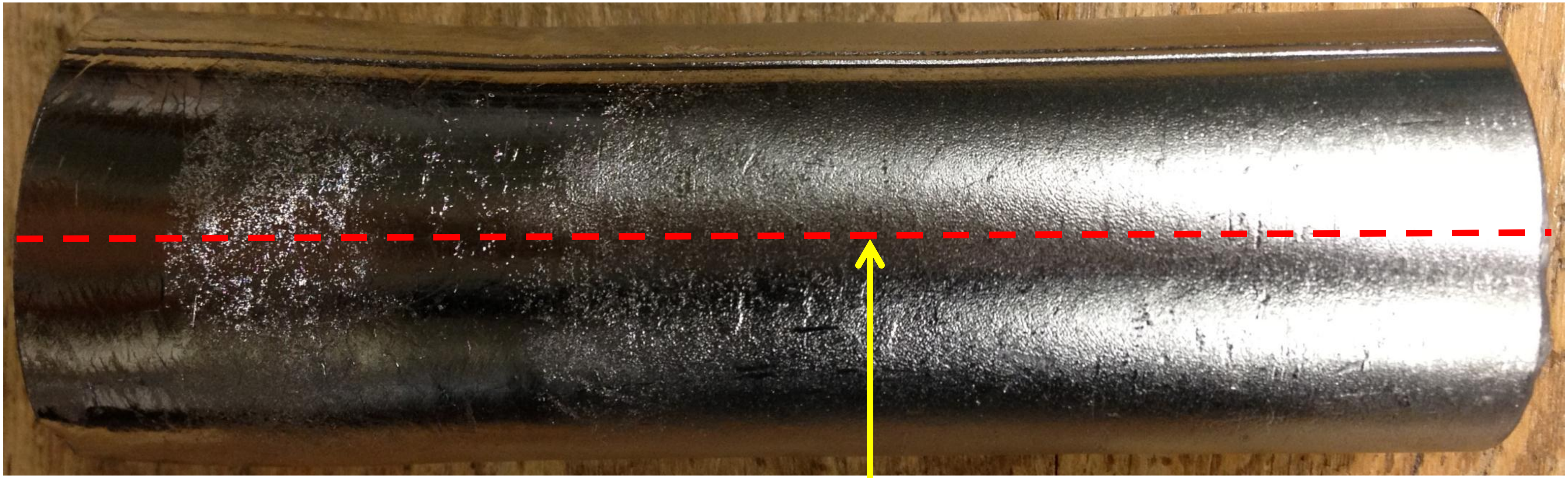
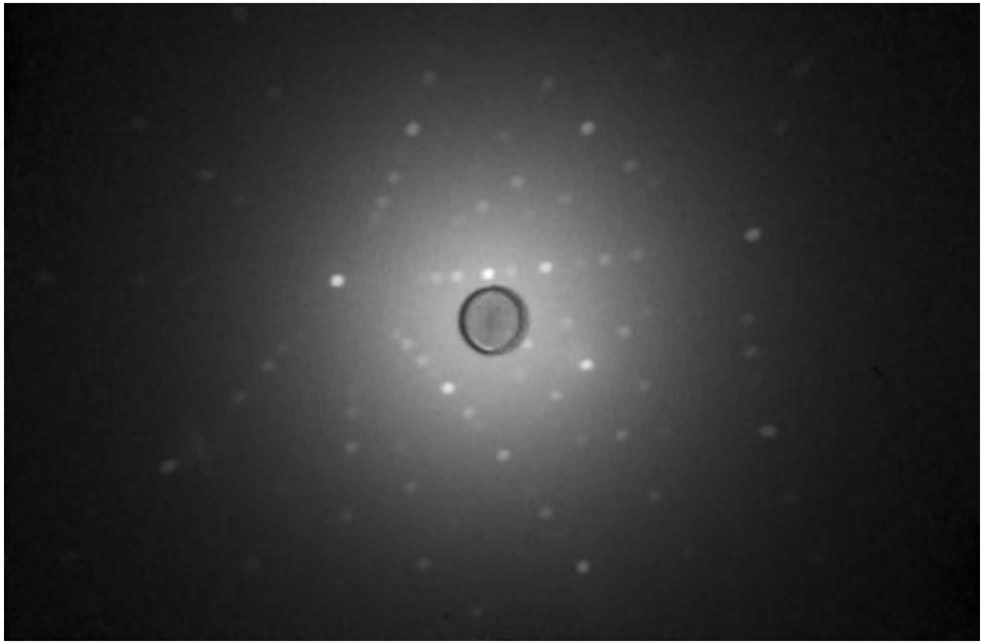


1 inch



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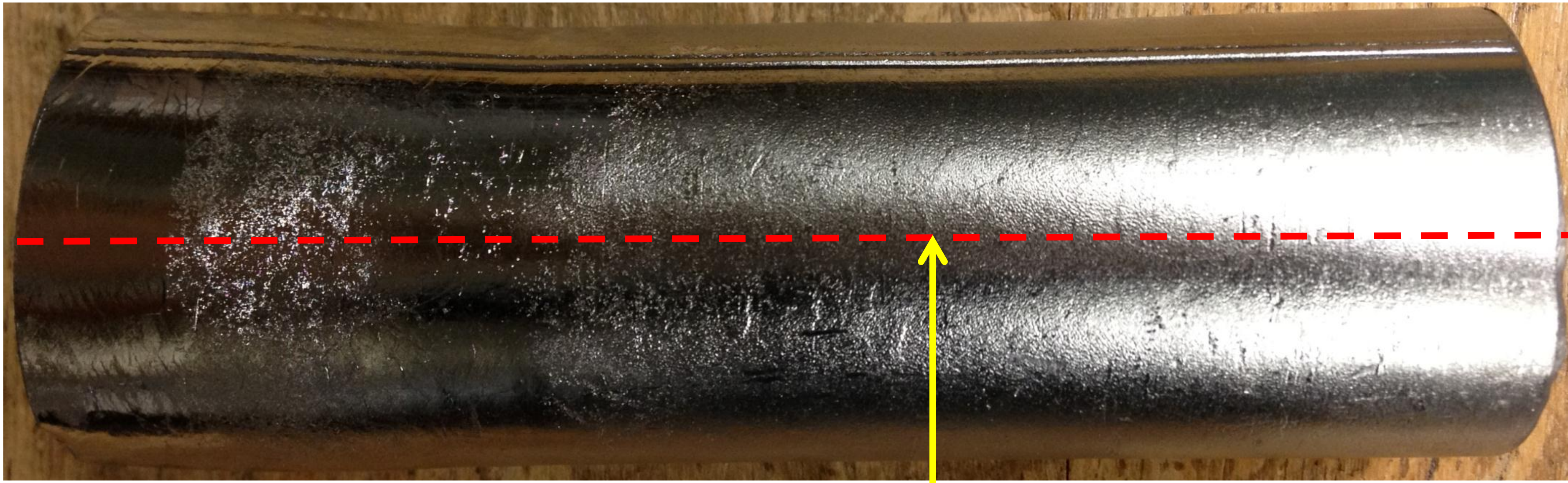
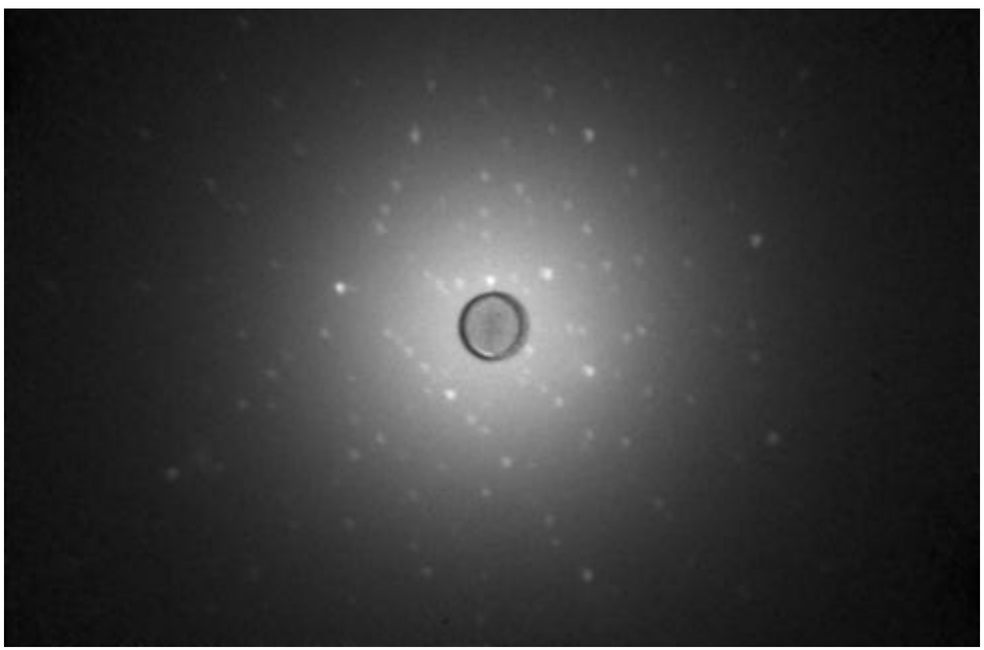


1 inch

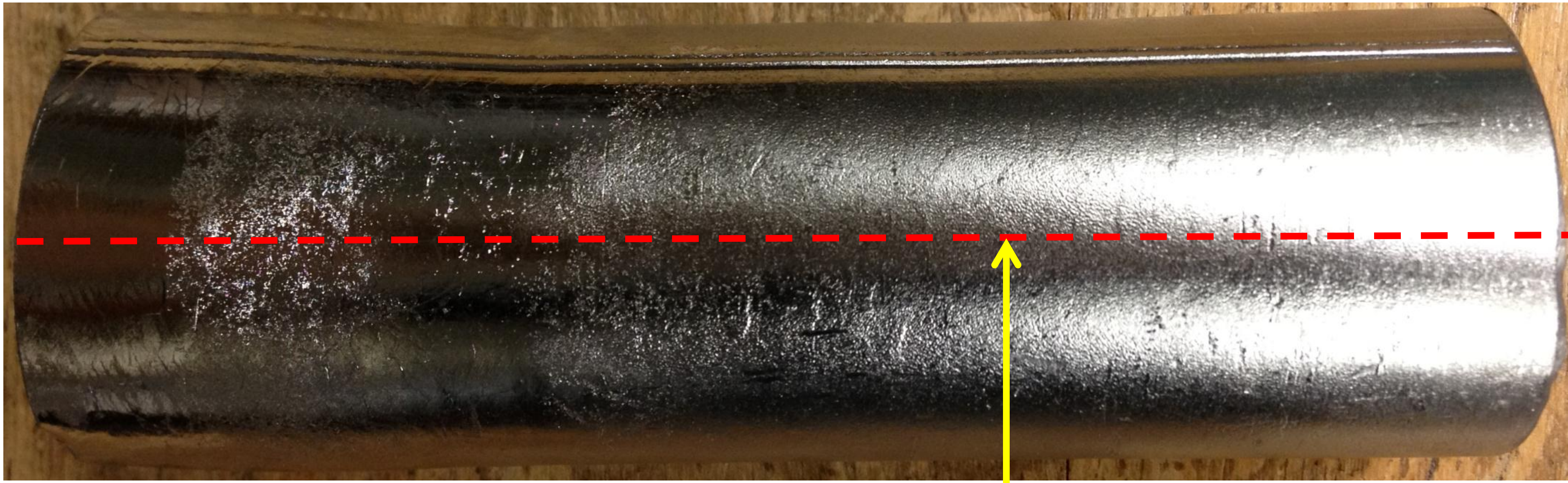


Here is the first grain boundary, ~2.6 inches from left end

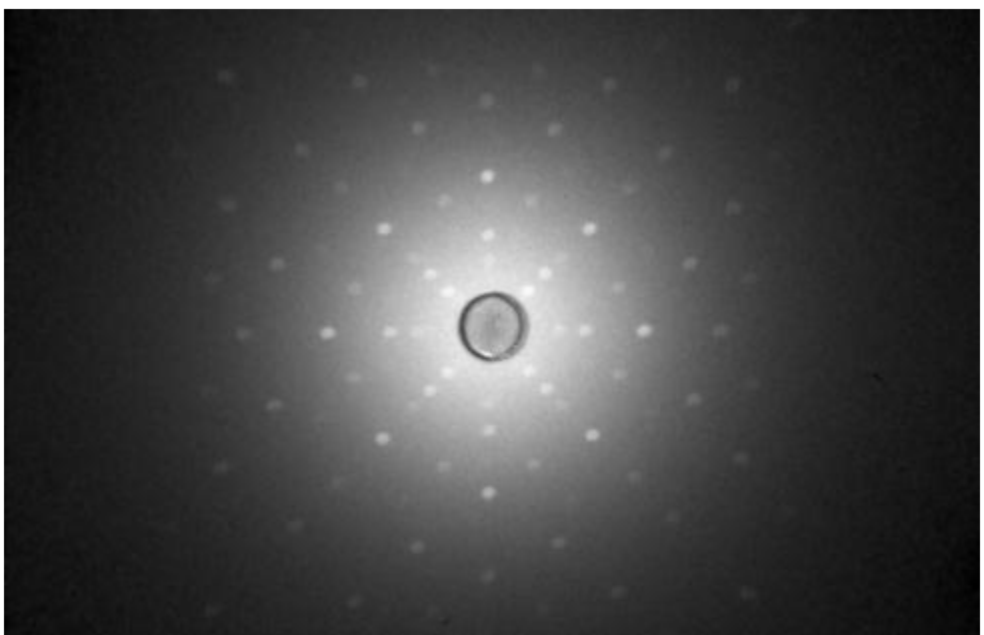
Orientation 1: 161.9049 152.6249 165.5003
Orientation 2: 307.4421 179.2676 172.9297

Misorientation @ rotation axis
50.1° @ <11 -1 -16>

First tube (with an opening at left end)

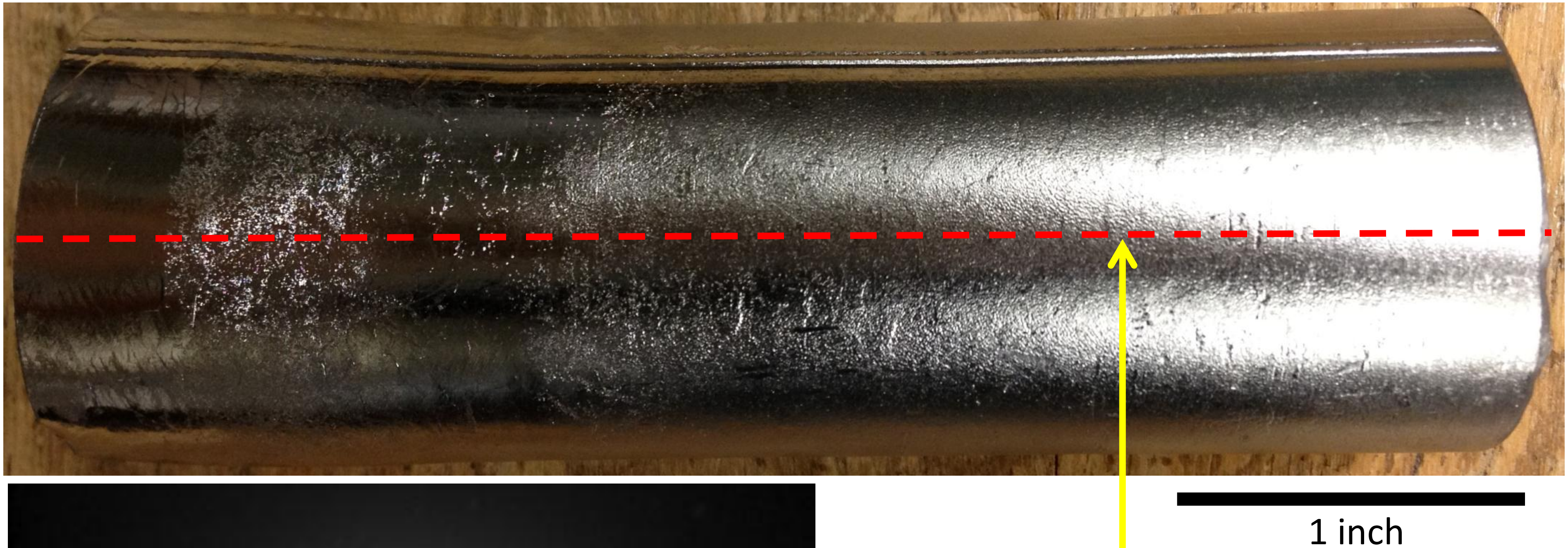


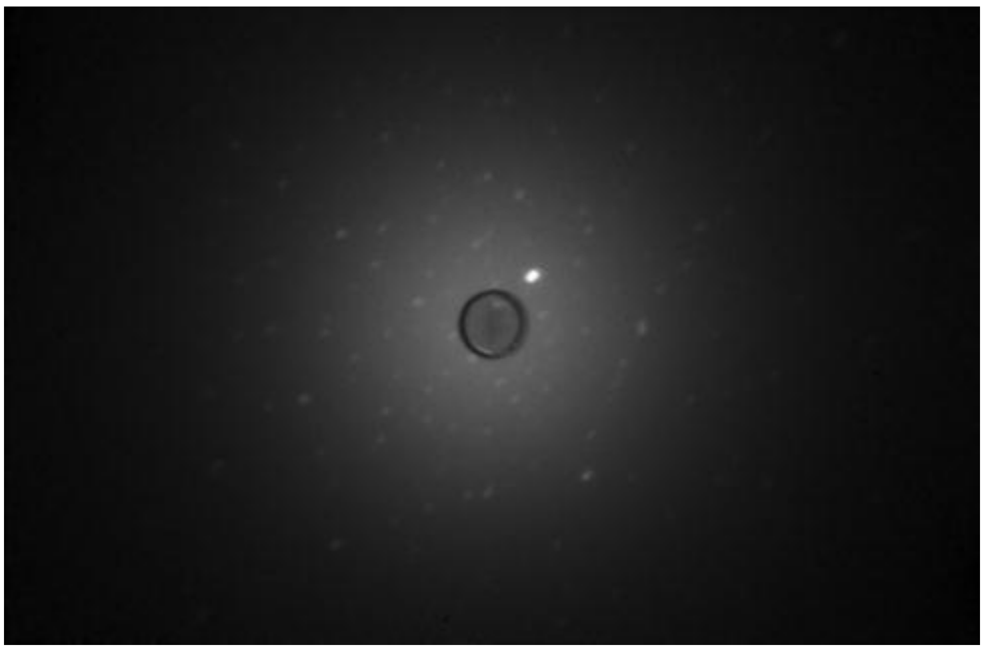
1 inch



The remaining grains are smaller compared to the first

First tube (with an opening at left end)





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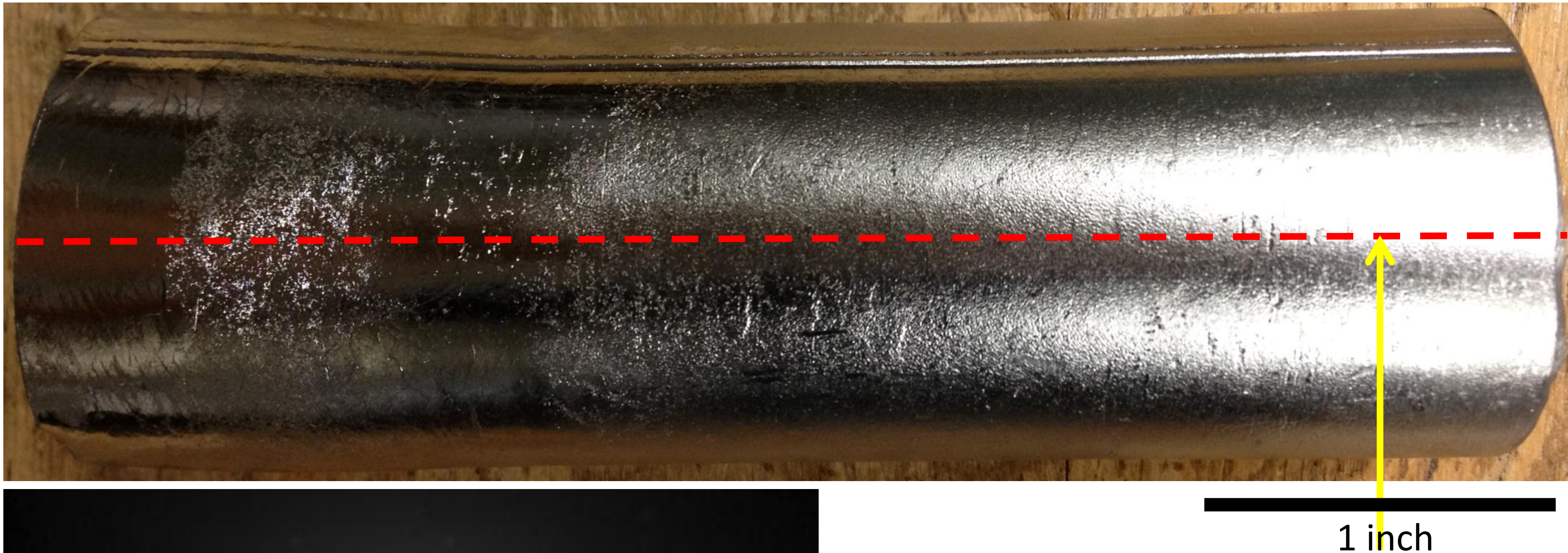

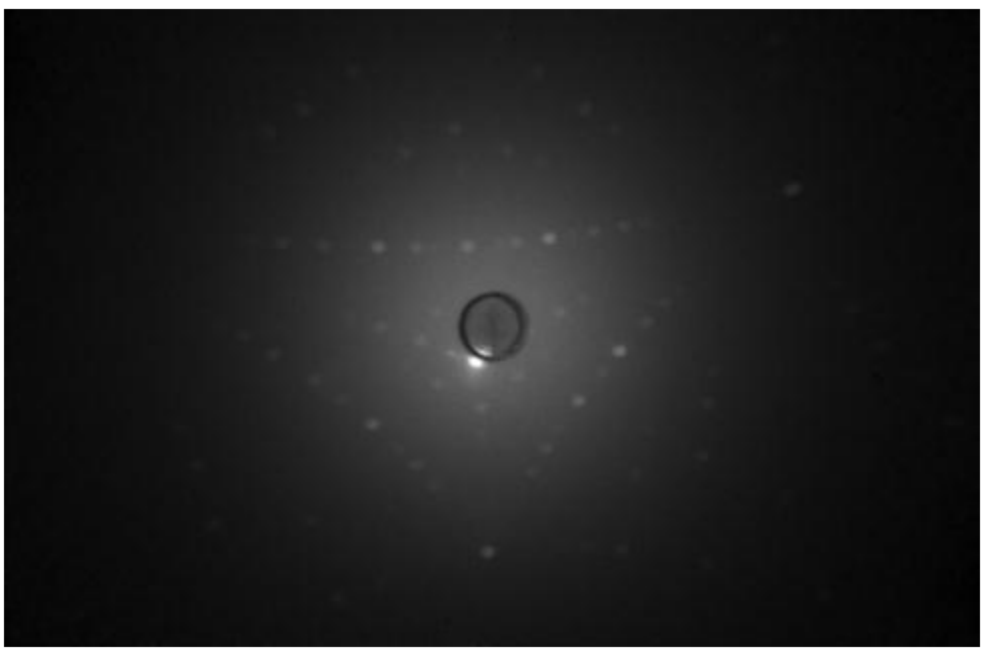

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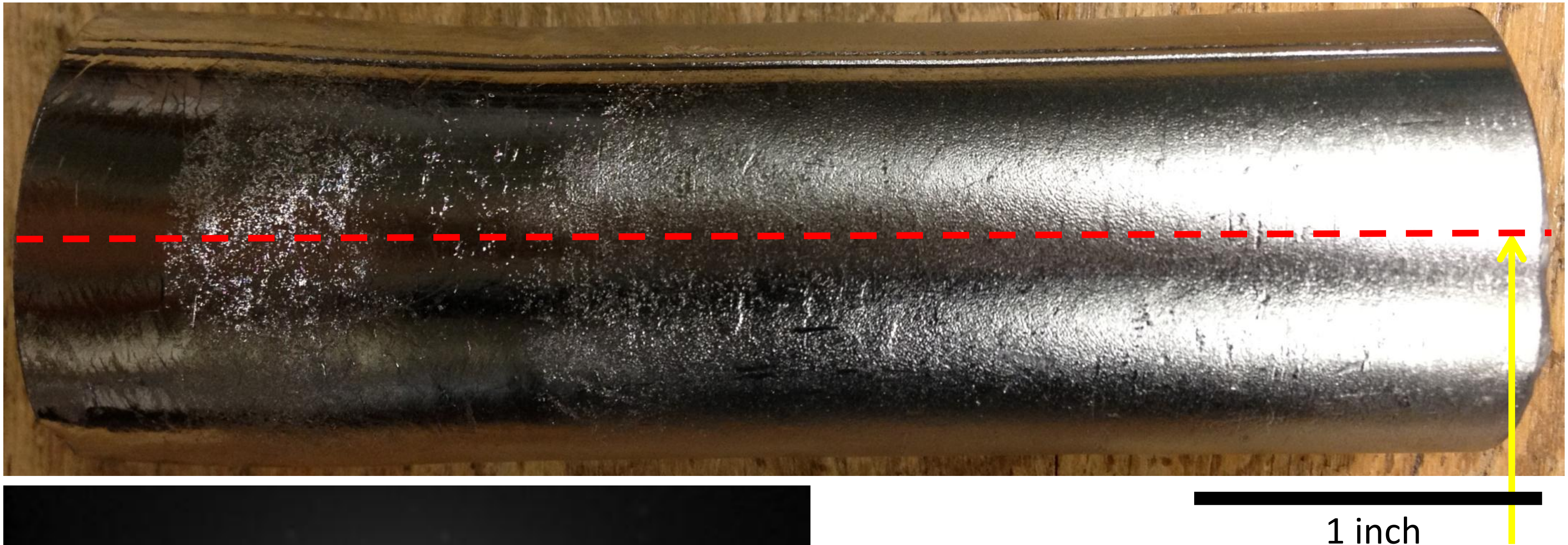
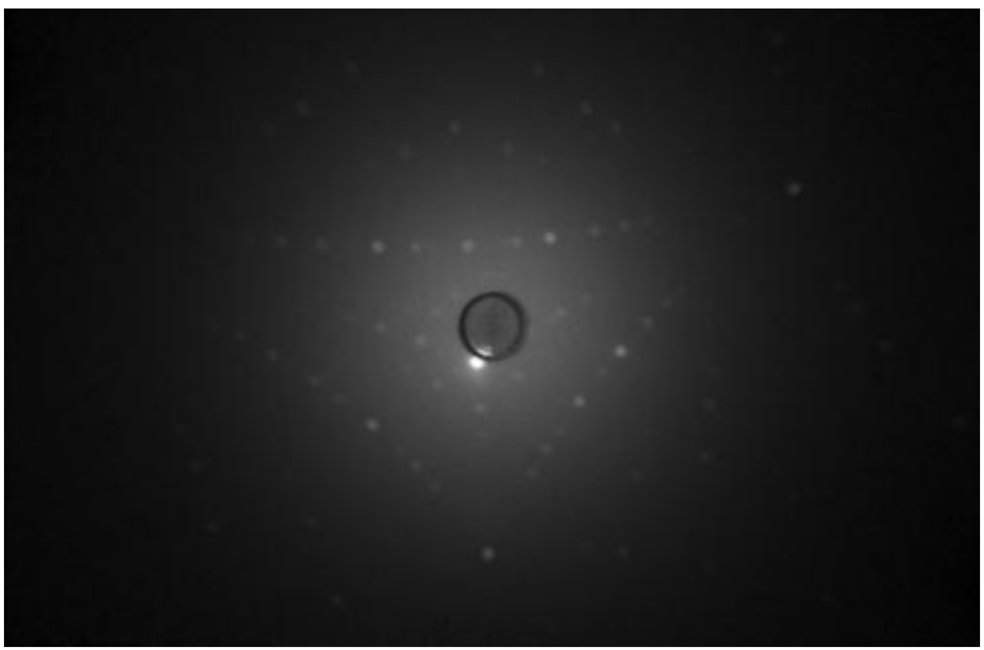
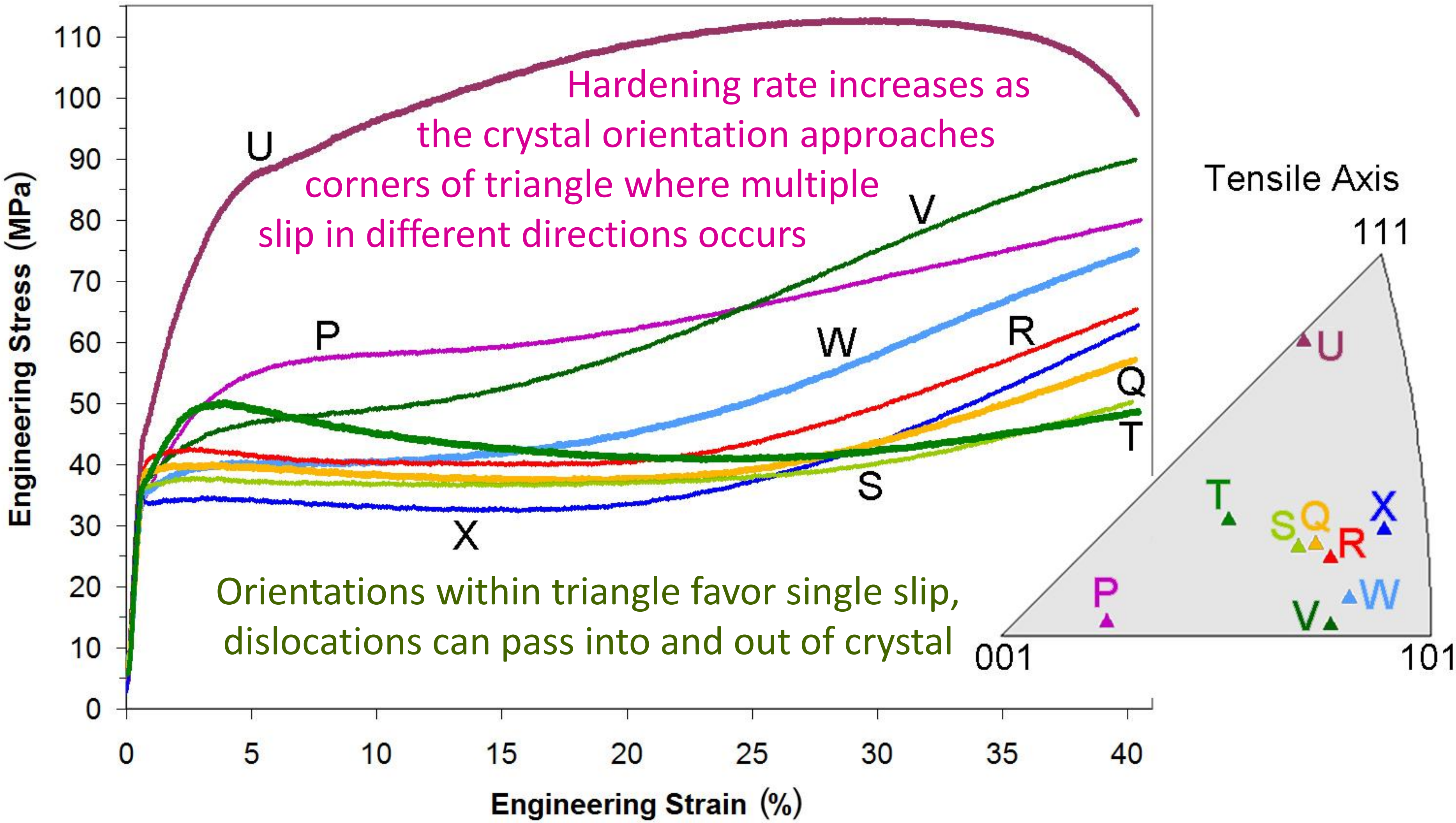


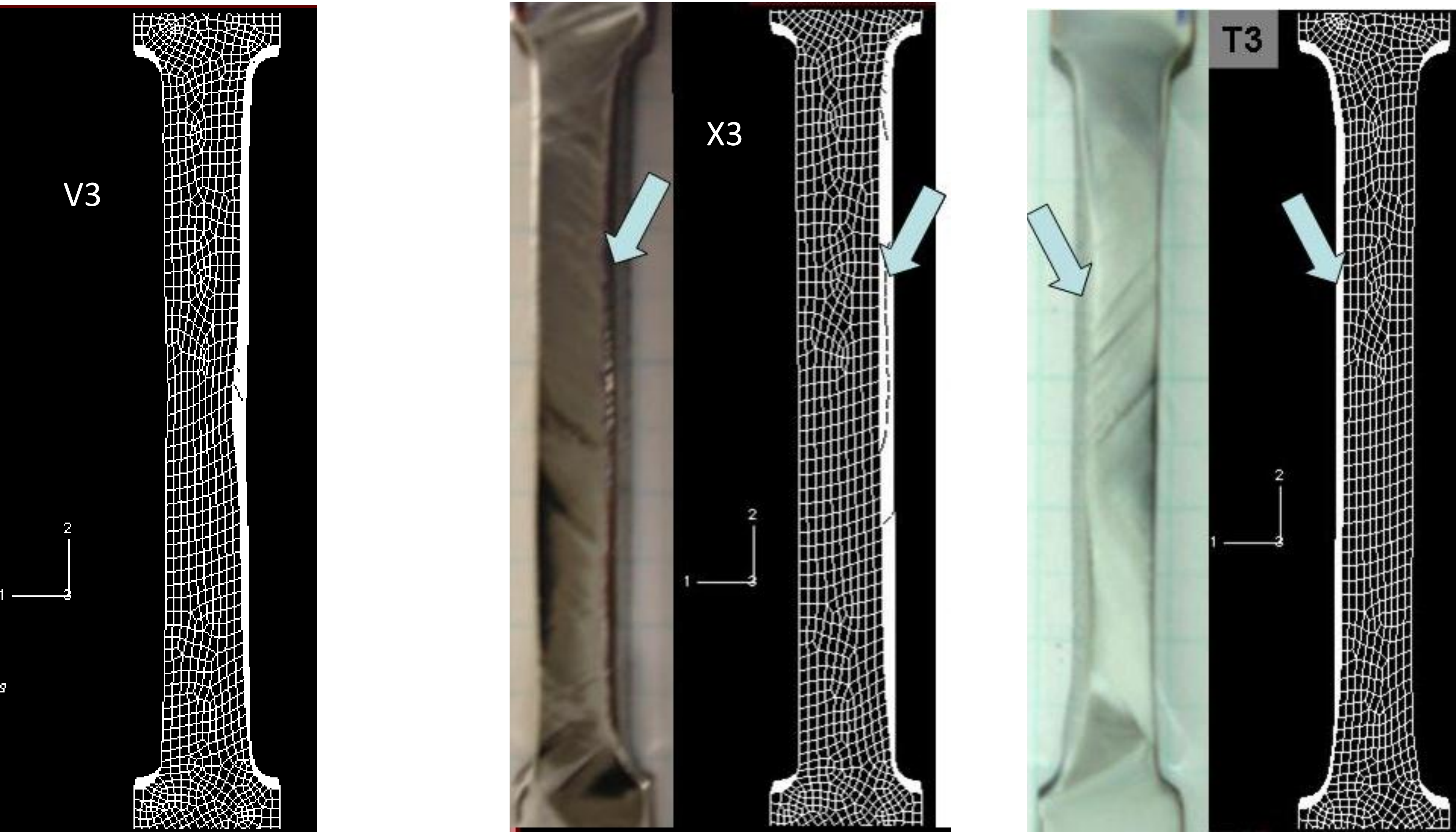


Single crystal stress-strain, lattice rotation from 3-D X-ray diffraction, related to crystal orientation



Some orientations can become unstable , R, X, Q, T orientations show softening!

In prior work, asymmetric shape changes come out right, but the stress history did not…



Hardening rule parametric study to simulate stress…

$$\dot{\tau}^{\alpha} = \sum_{\beta=1}^{N} h^{\alpha\beta}\left|\dot{\gamma}^{\beta}\right|$$

$$h^{\alpha\beta} = h^{\beta} Q$$

$$h_{\beta} = h_0 (1 - \frac{\tau_0^{\beta}}{\tau_s^{\beta}})^{a}$$

$$\dot{\gamma}^{\beta} = f(evolving\ yield\ surface)$$

$$\mathbf{q}=\begin{bmatrix} \mathbf{1} & \mathbf{1.4} & \cdots & \mathbf{1.4} & \mathbf{1.4} \\ \mathbf{1.4} & \mathbf{1} & & & \mathbf{1.4} \\ \vdots & & \ddots & & \vdots \\ \mathbf{1.4} & & & \mathbf{1} & \mathbf{1.4} \\ \mathbf{1.4} & \mathbf{1.4} & \cdots & \mathbf{1.4} & \mathbf{1} \end{bmatrix}$$

τ^{α}: is the current slip resistance on slip system α which evolves from the critical resolved shear stress τ_0^{α} with plastic slip on the active slip systems

$\dot{\gamma}^{\beta}$ is the plastic slip rate on the active slip system β

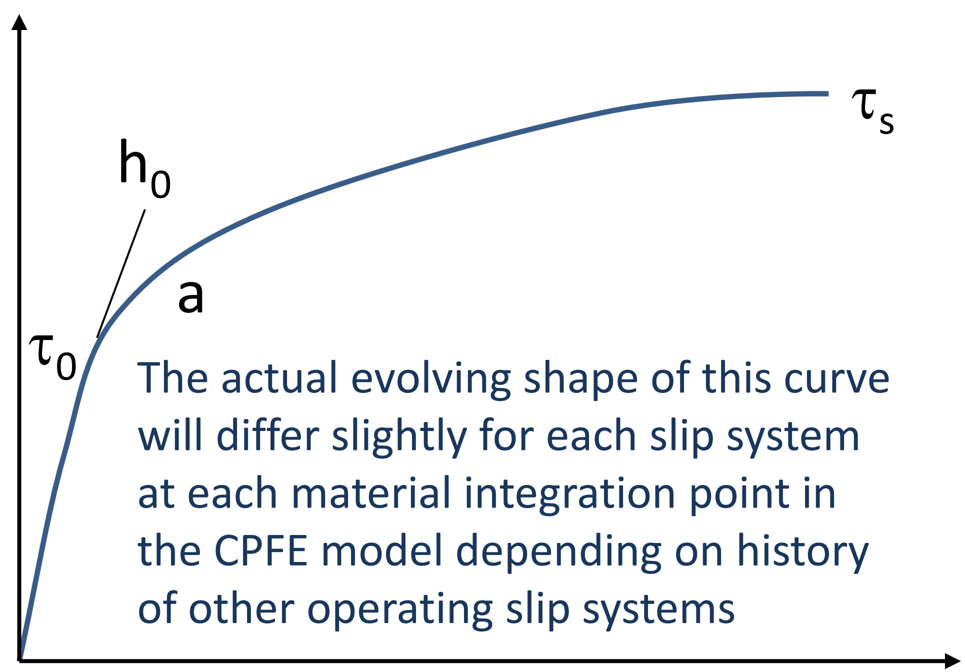
$h^{\alpha\beta}$ the components of the hardening matrix

q is the so-called latent-hardening ratio

h_0 denotes the initial hardening rate

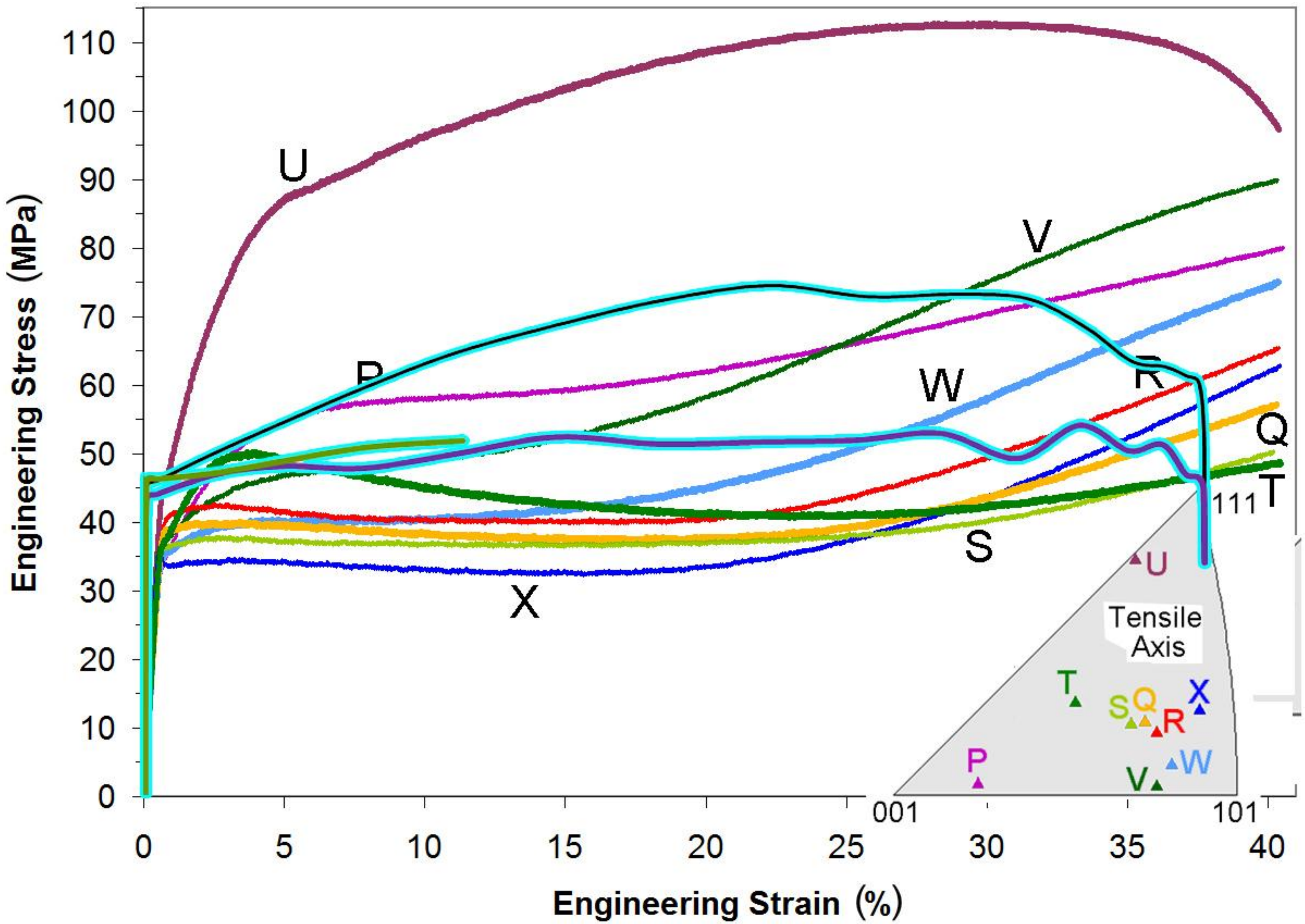
τ_s^{β} the saturation value of the slip resistance on slip system β

a is the exponent describing the shape of the function



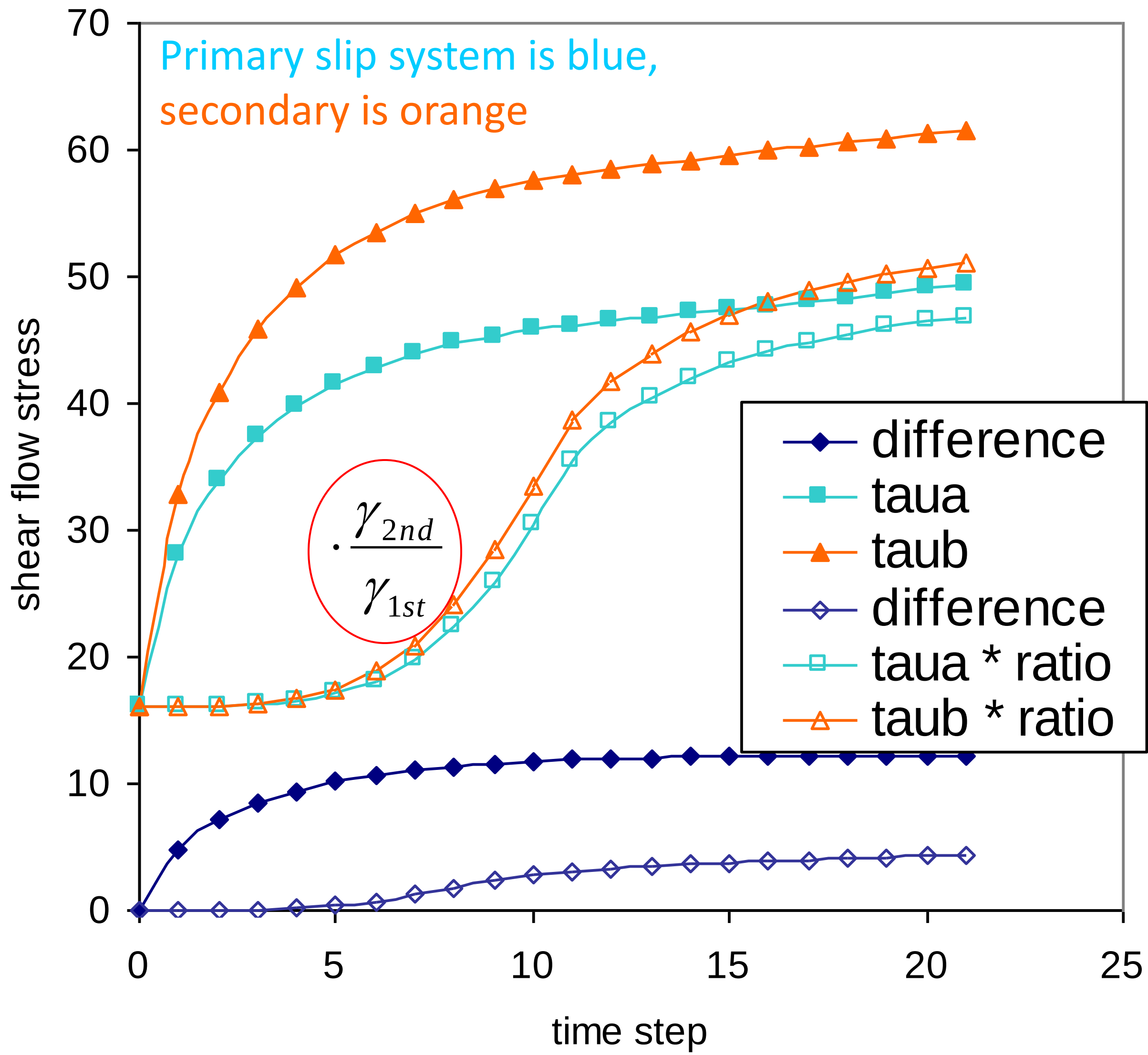
Recent simulations have the hardening rate a bit closer to reality, but not the later hardening process

Simulated S needs to be softer than P…



Thought experiment to examine effect of hardening law modification on sxl slip

- Two slip systems, one is highly favored at first, and dislocations pass **through** the specimen
  - No latent hardening
- When crystal rotates to favor other slip systems, normal hardening behavior develops, i.e. when shear on the secondary (unhardened) slip system becomes sizeable
- This coding is installed, and being adjusted



Crystal plasticity simulations needed for quantitative prediction of material flow

- Single crystal models needed for large-grain cavity deformation simulations since much of the crystal will slip without seeing a grain boundary
  - Different hardening strategy needed from polycrystal
  - A good single crystal model should work in a polycrystal too
- Role of favored {112} slip needs to be installed, too
- Grain boundary slip resistance (Hall-Petch Effect) is challenging to install in CPFE models – related research projects are pursuing this