THE OHIO STATE UNIVERSITY

C1OrG-05

Computational and experimental investigation of hydroformed niobium tubes for SRF cavities

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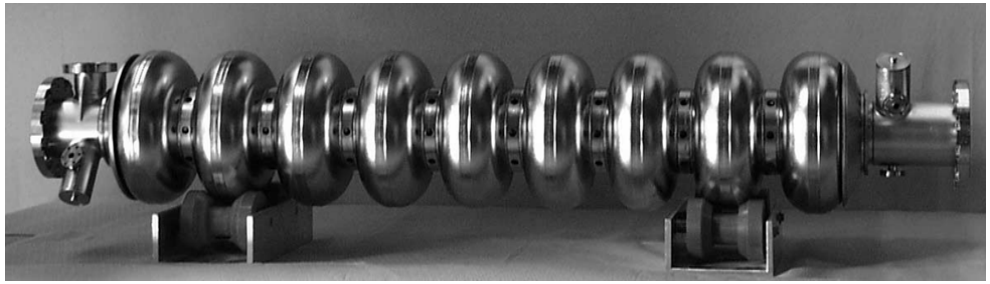
Contents

Objective

Testing the **hydroformability** using **hydraulic tube bulge test** in preparation for the hydroforming of multi-cell cavities



welded nine-cell cavity

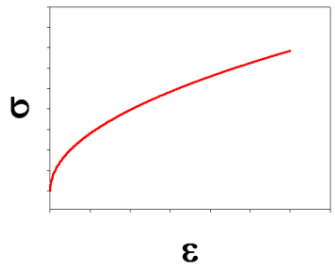
hydroformed nine-cell cavity

1. Obtain the accurate flow stress curve of tubular materials
2. Construct the simulation model

Simulation strategy

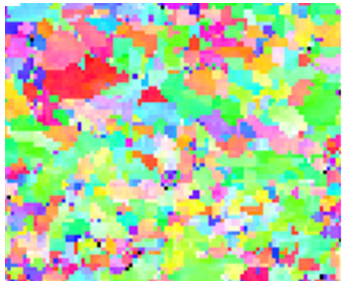
Macro scale

The flow stress curve



Micro scale

Microstructural analysis



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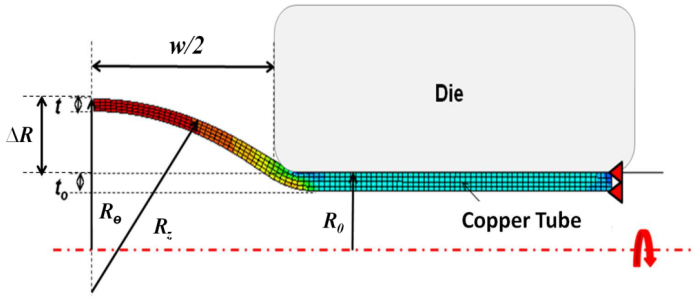


Finite Element Method

ABAQUS

Crystal plasticity (CP)– FEM

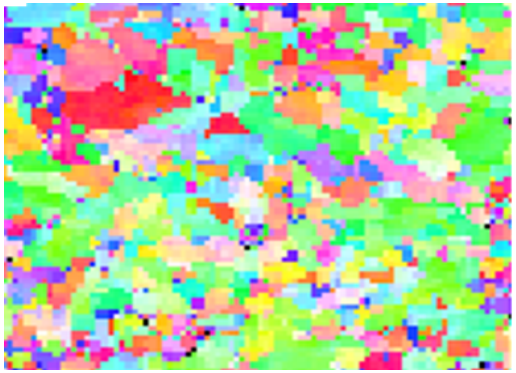
ABAQUS

User material subroutine (UMAT)

Multi scale

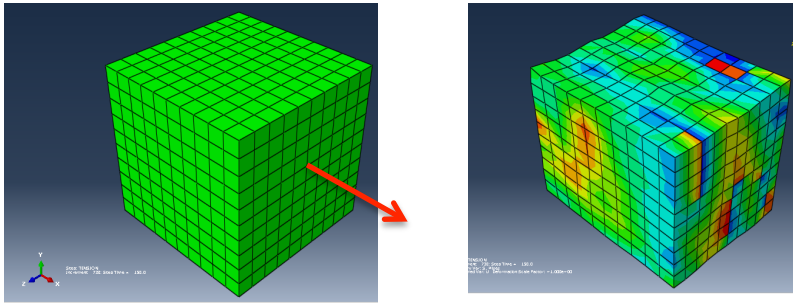
Micro scale

Microstructural analysis



Euler angles

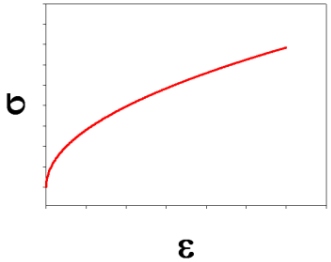
Input



Crystal plasticity (CP)– FEM
ABAQUS
User material subroutine (UMAT)

Result

The flow stress curve



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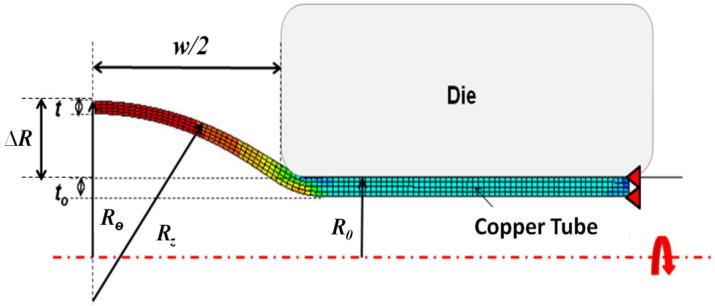


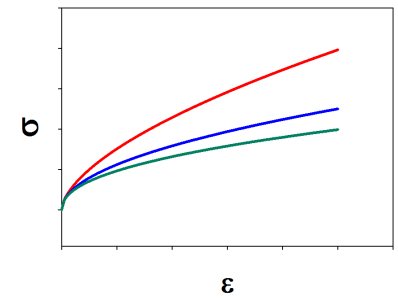
Research Outline

Macro scale

Tensile test
- Force
- Displacement

Bulge test
- Pressure
- Bulge height
- Thickness

Flow stress curves



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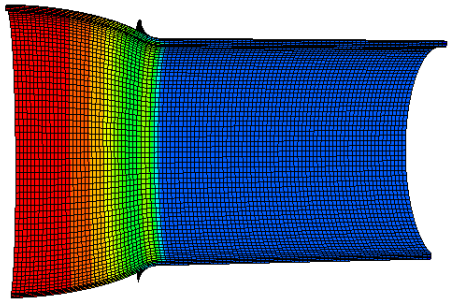
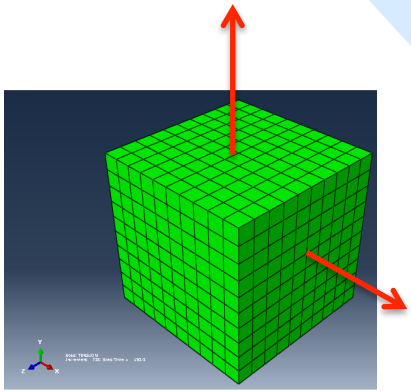


Multi scale

Microstructure
- Euler angle



Crystal plasticity
Bi-axial tension

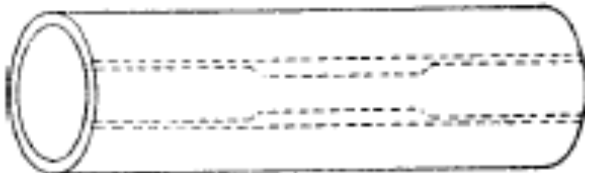
Experimental Materials

1. The Tube

- OD: 2.5” = 63.5 mm
- Thickness: 0.065” = 1.65 mm
- Heat treated at 600 °C for 1 hr

2. The tensile sample

- Tensile test specimens were cut from the tube with an ASTM standard dimension.
- Strain rate: 0.002 /s



Hydraulic Bulge Test

OSU's
Press for Hydraulic
Bulge Testing

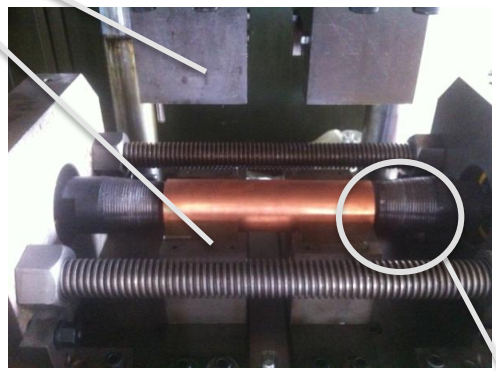
Press: Max. clamping force of 45 tons, provided by a small hydraulic press
Hydraulic Pump: Max. pressure of 68.9 MPa, provided by an air assisted hydraulic pump
Hydraulic cylinder: Max. sealing force of 20 tons

Hydraulic Bulge Test_(3)

Utrasonic Thickness Gauge

DAQ System

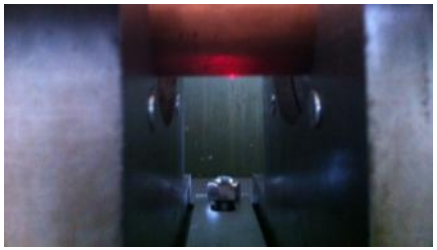
Upper and Bottom Dies



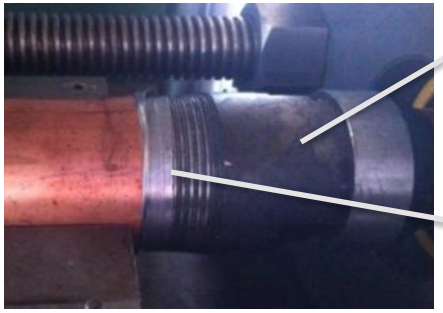
Cylinder for axial force

Pressure sensor

Hydraulic Pump



Laser sensor(Bulge height)



Punch

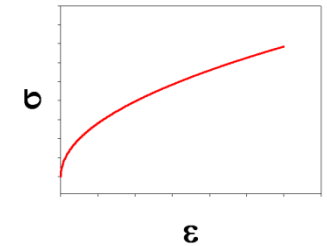
Sealing Material
(Lead Foil)

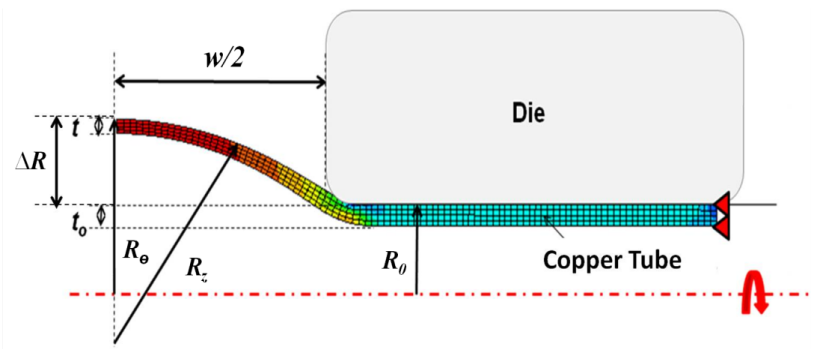
Analytical Model

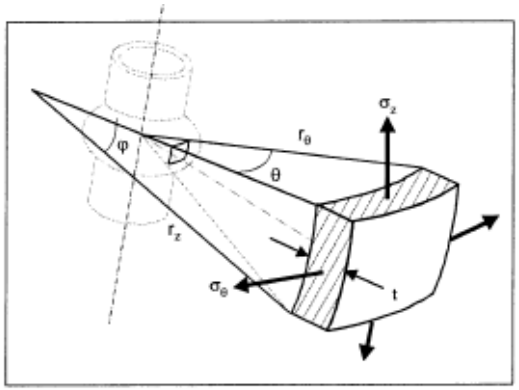
Bulge test
- Pressure
- Bulge height
- Thickness

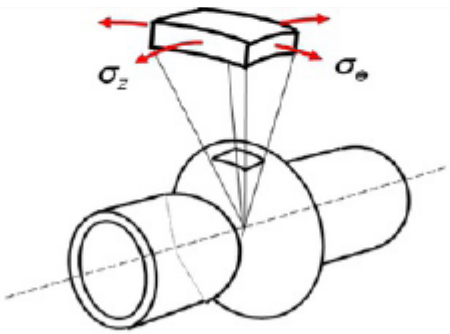
Analytical model

Flow stress curve









R_Θ R_Z σ_Θ σ_Z ε_Θ ε_Z

Analytical Model

$$R_\theta = R_0 + \Delta R \qquad R_z = \frac{[(w/2)^2 + \Delta R^2]}{2\Delta R} \qquad \varepsilon_\theta = \ln\left(\frac{R_\theta}{R_0}\right) \qquad \varepsilon_t = \ln\left(\frac{t}{t_0}\right)$$

$$R_\Theta \qquad R_Z \qquad \sigma_\Theta \qquad \sigma_Z \qquad \varepsilon_\Theta \qquad \varepsilon_t$$

Von Mises Yield Function (Isotropy)

$$\bar{\sigma} = \sqrt{\sigma_\theta^{\,2} - \sigma_\theta \sigma_z + \sigma_z^{\,2}}$$

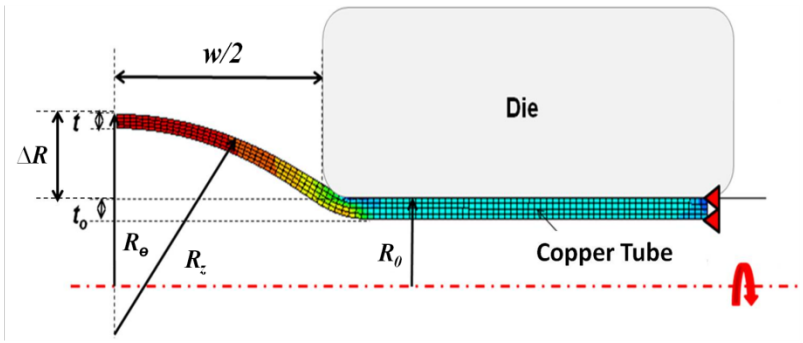
$$\bar{\varepsilon} = \frac{2}{\sqrt{3}} \sqrt{\varepsilon_\theta^{\,2} + \varepsilon_\theta \varepsilon_t + \varepsilon_t^{\,2}}$$

Finite Element Simulation

1) **Program**: ABAQUS/Explicit

2) **Geometry**

- Axisymmetry cross-section of the tube
- Only half tube was modeled
- The ends of the tube were constrained
- Four-noded solid elements (CAX4R)



$$w/2 = 35mm$$

$$R_0 = 31.75mm$$

$$t_o = 1.65mm$$

3) **Elastic properties**

- Elastic Modulus: 115 GPa

4) **Plastic Properties**

- Effective stress – Effective plastic strain obtained from tensile and bulge tests and Crystal Plasticity simulation (Bi-axial force applied)

Crystal plasticity_(1)

1) Program: ABAQUS + Fortran

2) Model: Taylor model (iso-strain with multiple slip in each grain

3) Geometry

- Cube shape (One element)
- X and Y axis Symmetry
- Force is applied by displacement

4) Parameters (Hardening formulation)

$$\dot{\gamma}^{\alpha} = \dot{\gamma}_0 \left(\frac{\tau^{\alpha}}{g^{\alpha}} \right)^{1/m} sign\left(\tau^{\alpha}\right)$$

[Hutchingson, 1976, Peirce et al., 1982]

$$\dot{g}^{\alpha} = \sum_{\beta} h_{\alpha\beta} \dot{\gamma}^{\alpha}$$

$$h^{\alpha\beta} = q^{\alpha\beta} h^{(\beta)} \quad \text{(Hardening matrix)}$$

$\dot{\gamma}^{\alpha}$: Plastic shearing rate

τ^{α} : Resolved shear stress

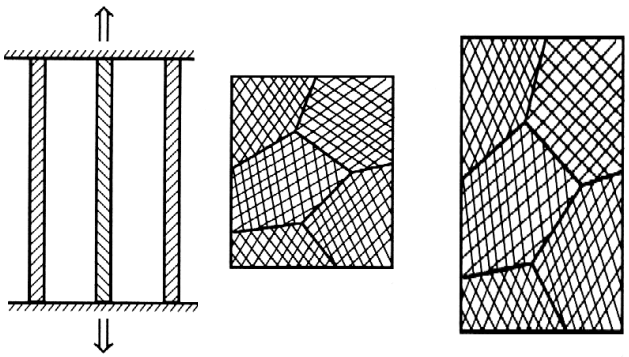
g^{α} : Slip resistance (or flow stress)

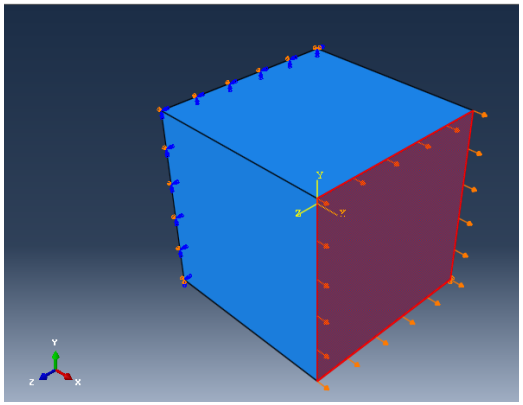
m : Rate sensitivity exponent

$q^{\alpha\beta}$: diagonal - self-hardening
Off-diagonal - hardening to other slip systems

$$h^{(\beta)} = h_0 \left(1 - \frac{g^{\beta}}{g^{s}} \right)^{a}$$

[Asaro, 1983]





Tensile test
<determine the parameters>
1. Initial val. of the def. resis.
2. Value of the initial hardening rate
3. Saturation value for the def. resis.
4. Exponent in hardening equation

Crystal plasticity_(2)

5) Slip system: 12

slipsys.in - Notepad

File Edit Format View Help

```
MAXIMUM NUMBER OF SLIP SYSTEMS
12
SLIP SYSTEMS
1       1       1       1       -1      0
1       1       1       -1      0       1
1       1       1       0       -1      1
1       -1      1       1       1       0
1       -1      1       -1      0       1
1       -1      1       0       1       1
-1      -1      1       1       -1      0
-1      -1      1       1       0       1
-1      -1      1       0       1       1
-1      1       1       1       1       0
-1      1       1       1       0       1
-1      1       1       0       -1      1
```

6) Euler angles φ_1, Φ, φ_2,

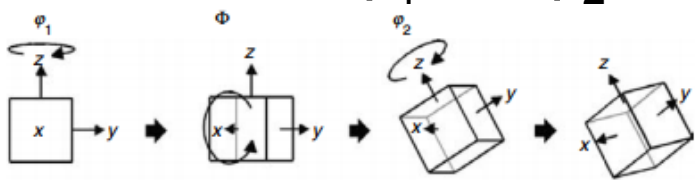


FIGURE 2.14. Euler angle rotations according to Bunge's convention. (Adapted from [13].)

aeuler.in - Notepad

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KFLAG : 1 --- SAME CRYSTAL OR SET OF CRYSTALS AT ALL INTEGRATION POINTS
        2 --- DIFFERENT   CRYSTALS AT INTEGRATION POINTS
1
NCRYS
1000
EULER ANGLES FOR EACH CRYSTAL AT AN INTEGRATION POINT
  THETA        PHI        OMEGA
349.2395485    54.36853814    43.8736702
147.5515291    53.20657973    2.864216018
239.1823775    86.76586371    141.2295128
238.1350106    85.75172841    321.1628977
278.6786501    134.1087934    196.4718116
123.863735     89.08290503    344.1751746
122.9229383    89.23301997    74.67874606
97.76149675    125.1975808    10.09150565
2.197866102    98.50175822    233.7054739
97.73342182    125.1878405    9.338639103
0.607335263    96.72329723    55.10020524
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134.7671219    91.24639366    344.5659318
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95.98360871    103.5924882    52.33110022
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68.72170386    94.47787563    43.47546454
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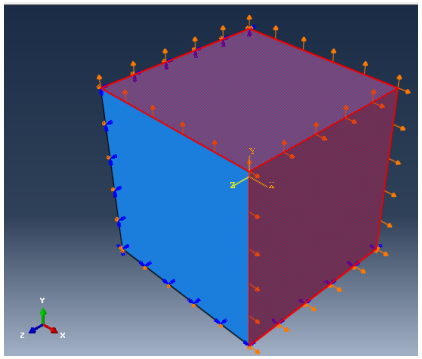
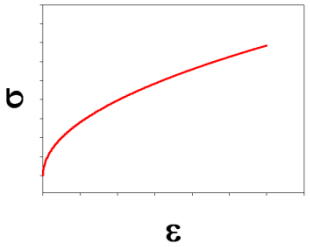


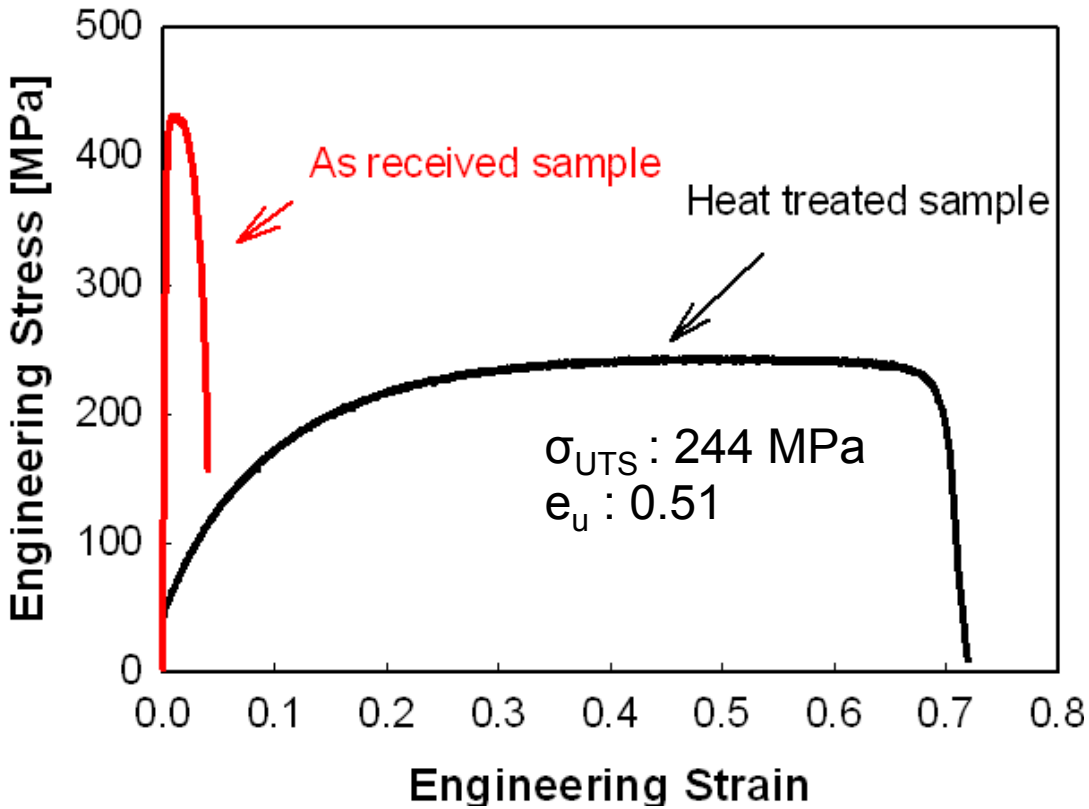
Biaxial tension test

Flow stress curve



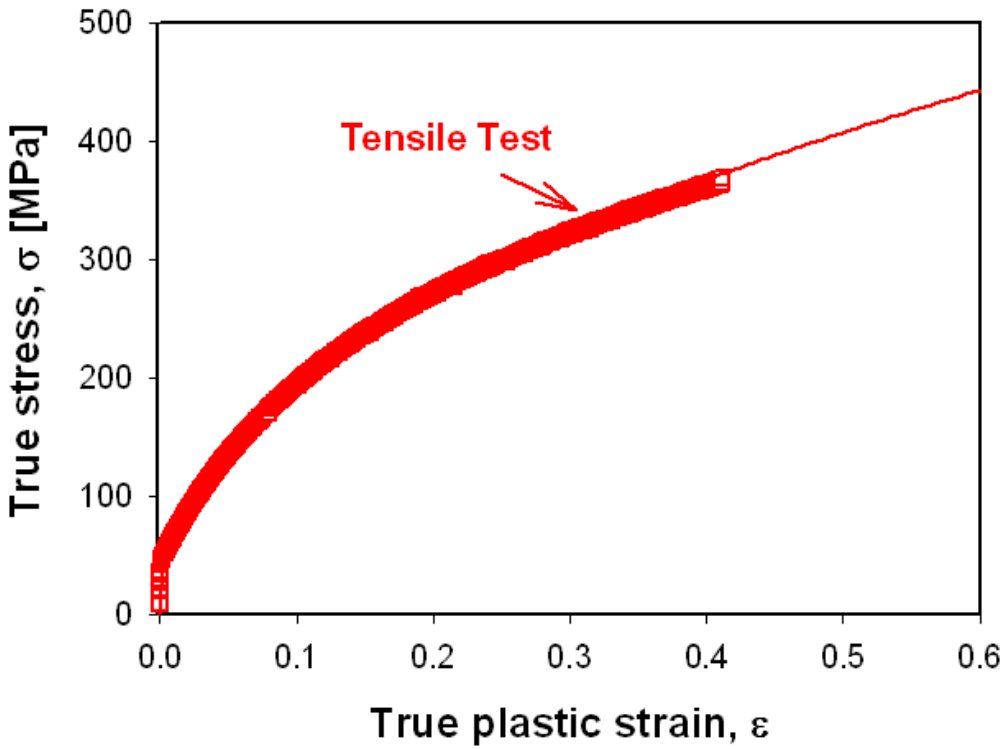
Tensile Test Results_(1)

Engineering stress – Engineering strain curve



Tensile Test Results_(2)

True stress – True plastic strain curve



Hollomon format $\bar{\sigma} = K \cdot \bar{\varepsilon}^{n}$

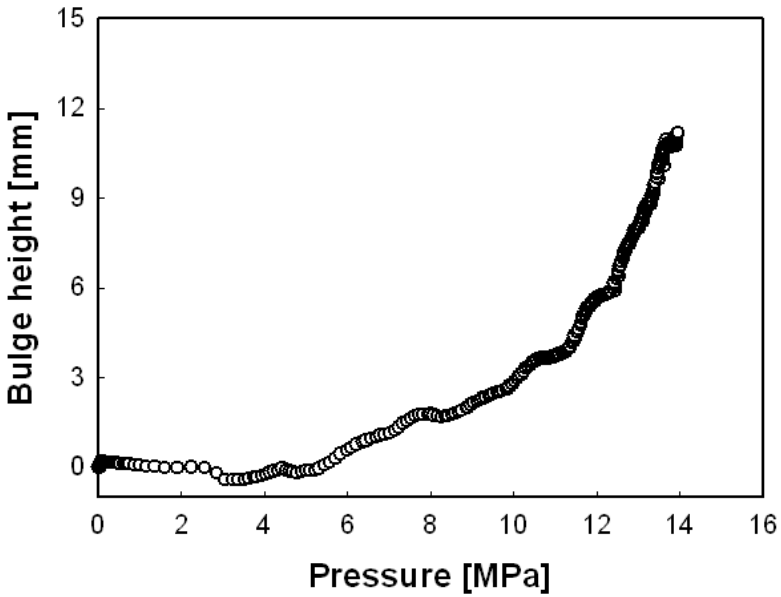
	K	***n***
Tensile	561.20	0.4596

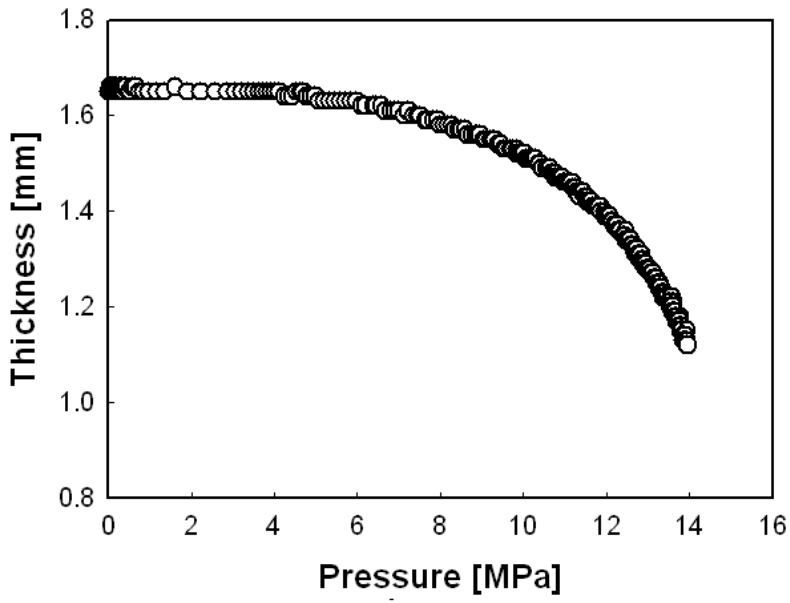
The strain range for fitting: 0.02 ~

- Fitting curve to the data using least square method

Bulge Test Results

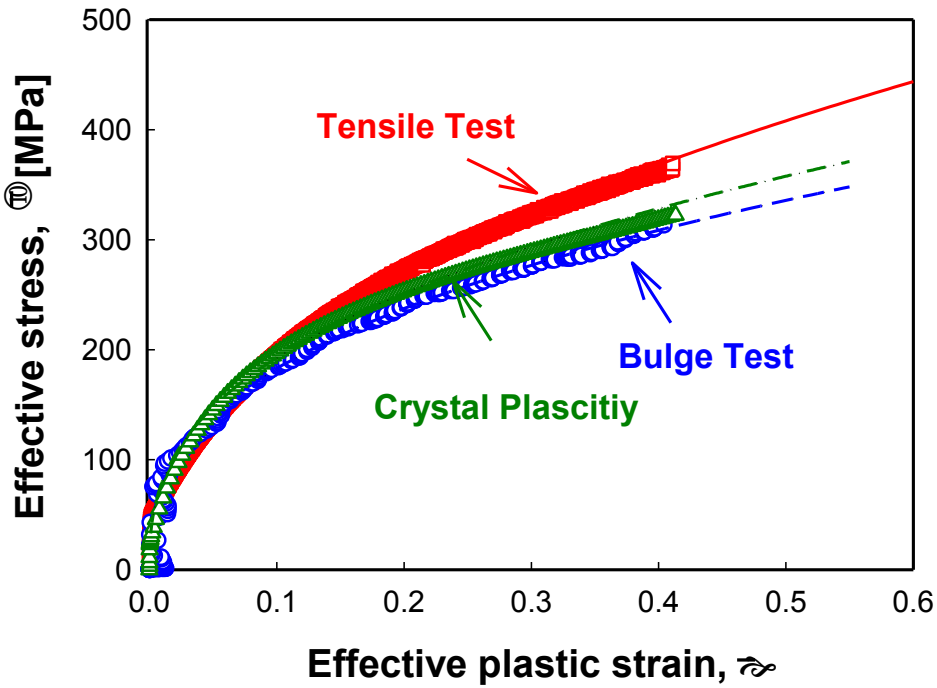
Tube: Heat treated at 600 °C for 1 hr





Flow stress curves

Effective Stress – plastic strain curve

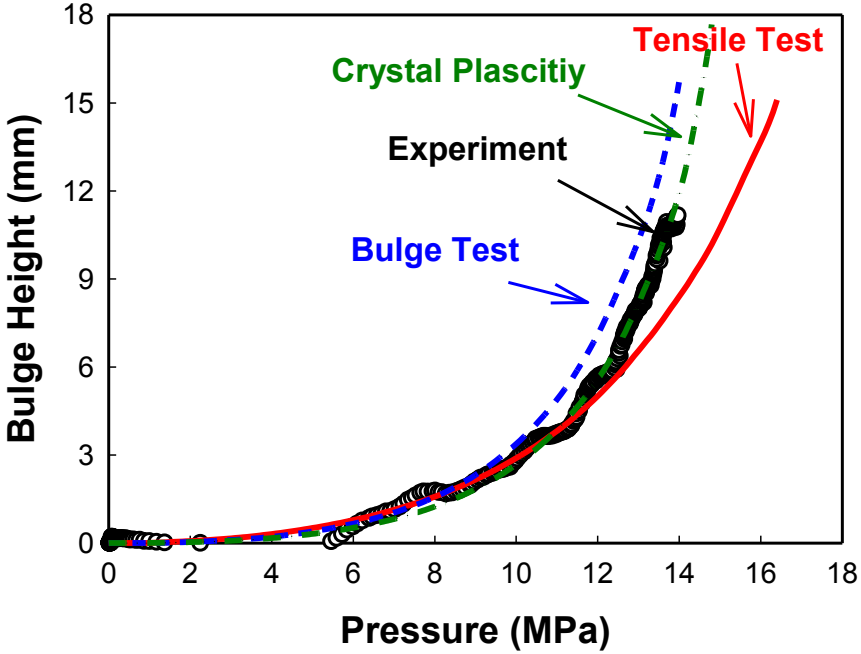


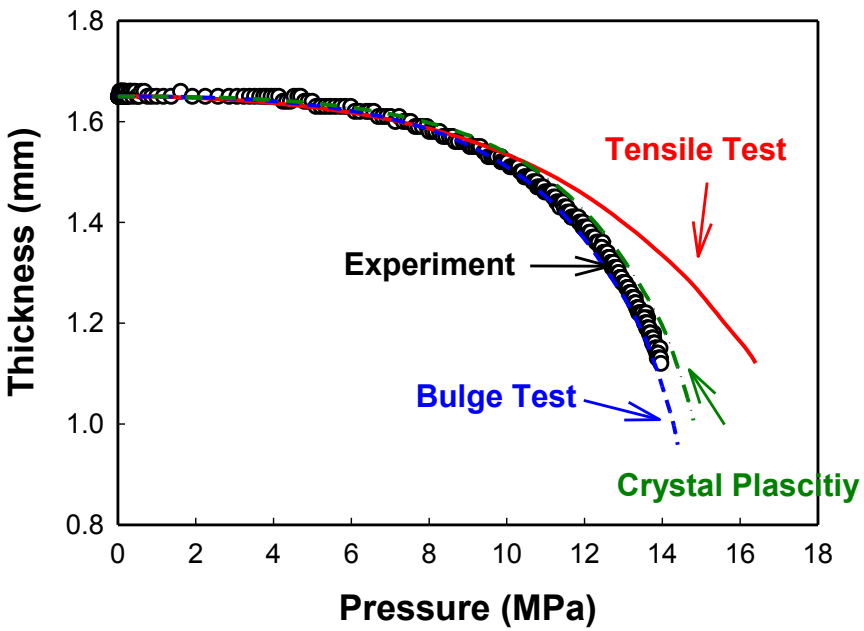
Hollomon format $\bar{\sigma} = K \cdot \bar{\varepsilon}^{n}$

	K	***n***
Macro_Tensile	561.20	0.4596
Macro_Bulge	436.40	0.3776
CP_Biaixal	448.76	0.3635

FEA Simulation results

Combined simulation results using flow stress curves from **tensile test**, **bulge test** **and** **microstructure (CP)**





-The simulation results using the flow stress curve from crystal plasticity is well matched to the experimental data.

Concluding Summary & Future Work

- Obtain the three different flow stress curves from tensile, bulge tests and crystal plasticity simulation using texture.
- The simulation results using the flow stress curves from the CP simulation is closer to the experimental data.
- Need to reduce the simulation time for CP

Next Step

- Crystal plasticity simulation of free bulge test
- Crystal plasticity simulation using 3D orientation Map
- Crystal plasticity simulation for niobium tube
- Investigate the texture evolution after deformation

Acknowledgements

-This work was funded by the Unites States Department of Energy through Grant No. DE-SC0004217
- The heat treatment for Nb tube was supported by the Fermilab