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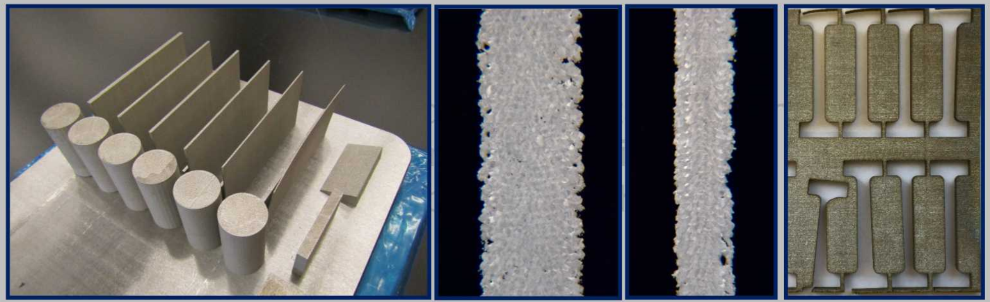
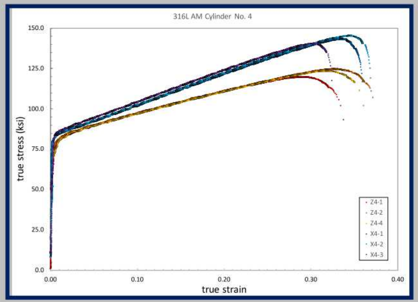
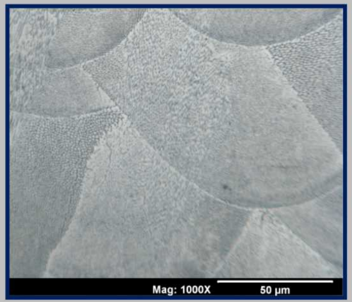
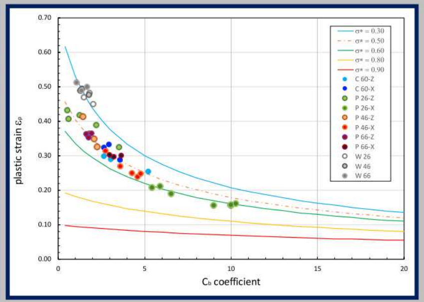
Session on Design, Modeling, Simulations, Defects, and Inspection









Constitutive structural parameter for the work hardening behavior of LPBF 316L

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Motivation

- To develop a model providing a *constitutive parameter* characterizing the underlying scale of microstructure for materials that have –
  - an apparent scatter in tensile behavior, perhaps due to dimensional effects
  - use in structural applications – as steels, aluminum, and titanium alloys
  - undergone rapid transients in their fabrication
  - anisotropic microstructures approaching the nanoscale
- Such materials are found processed through *additive manufacturing* (AM) methods such as *laser powder bed fusion* (LPBF)
- The tensile behavior of 316L is of interest for pressure vessels
  - test coupons are prepared from AM sheet printed to various thickness

Background

- A model was proposed by J.W. Morris, Jr. (2007) at the ISOPE meeting in Portugal to describe a *softening factor* c_b as modified in derivation from a Kocks-Mecking (K-M) model that provides insight to the scale of microstructure responsible for *nanosteel* mechanical behaviors
  - In particular, a model to predict the amount of plasticity that can be obtained in a two-phase structure maximizing the extent of work hardening by refining the microstructure towards the nanoscale
- Several measurable parameters from tensile experiments are used to determine a constitutive formulation for the softening factor c_b
  - plastic strain ε_p from the yield point to the instability
  - tensile strengths σ_y and σ_u as formulated through the Considère criterion, i.e. the subtangent method for determining the instability
  - work-hardening rate Θ that equals $d\sigma/d\varepsilon$

Softening factor c_b

- A linear form of the K-M relationship defines

$$\Theta = \Theta_o - c_b \cdot \sigma \qquad (1)$$

- The Considère criterion is

$$d\sigma/d\varepsilon = \sigma/(1+\varepsilon) \qquad (2)$$

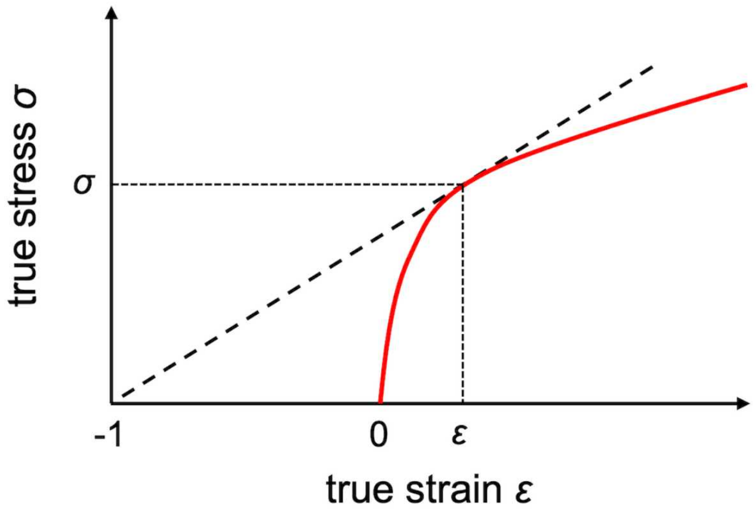
- The instability is determined when

$$\Theta_u = [d\sigma/d\varepsilon]_u = \sigma_u \qquad (3)$$

- The true strain ε to the instability point is determined by evaluating the integral from σ_y to σ_u (where $\sigma_y^* = \sigma_y/\sigma_u$) as

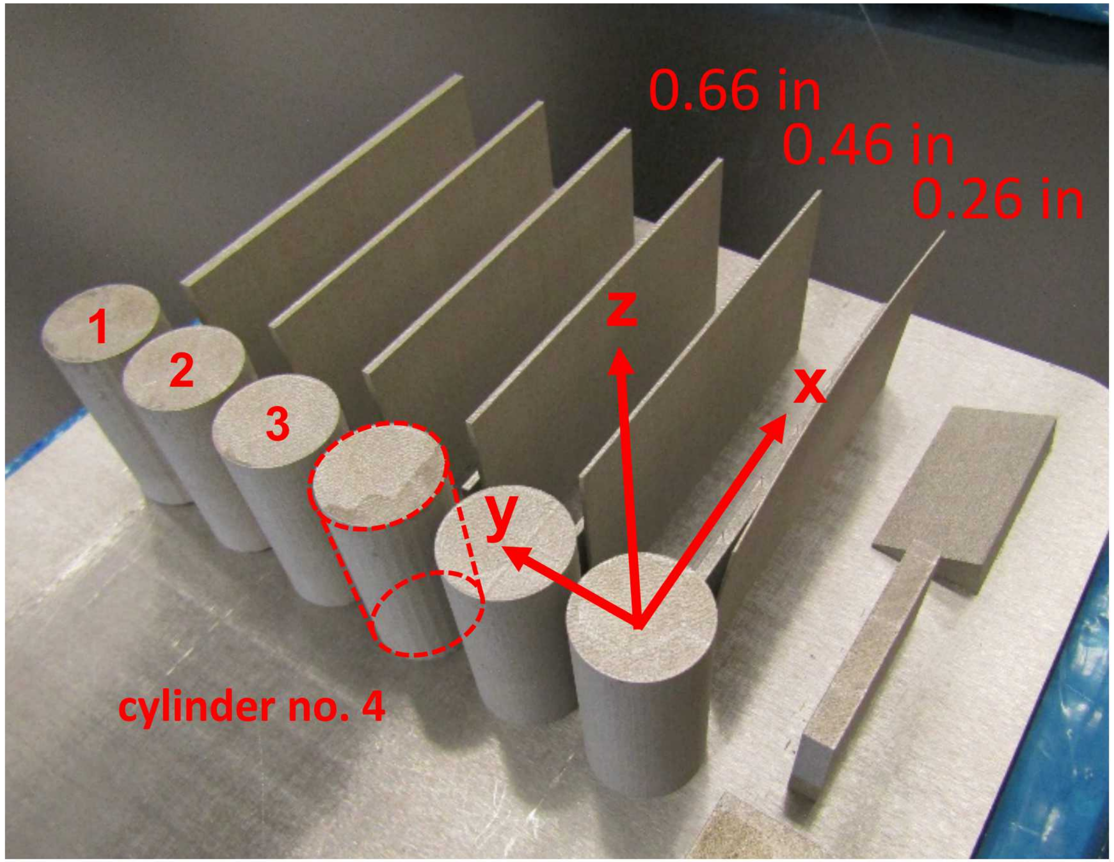
$$\varepsilon = \int (d\varepsilon/d\sigma) \cdot d\sigma = \int [\Theta(\sigma)]^{-1} \cdot d\sigma \qquad (4)$$

$$\varepsilon_p = (c_b)^{-1} \cdot \ln[1 + c_b \cdot (1 - \sigma_y^*)] \qquad (5)$$

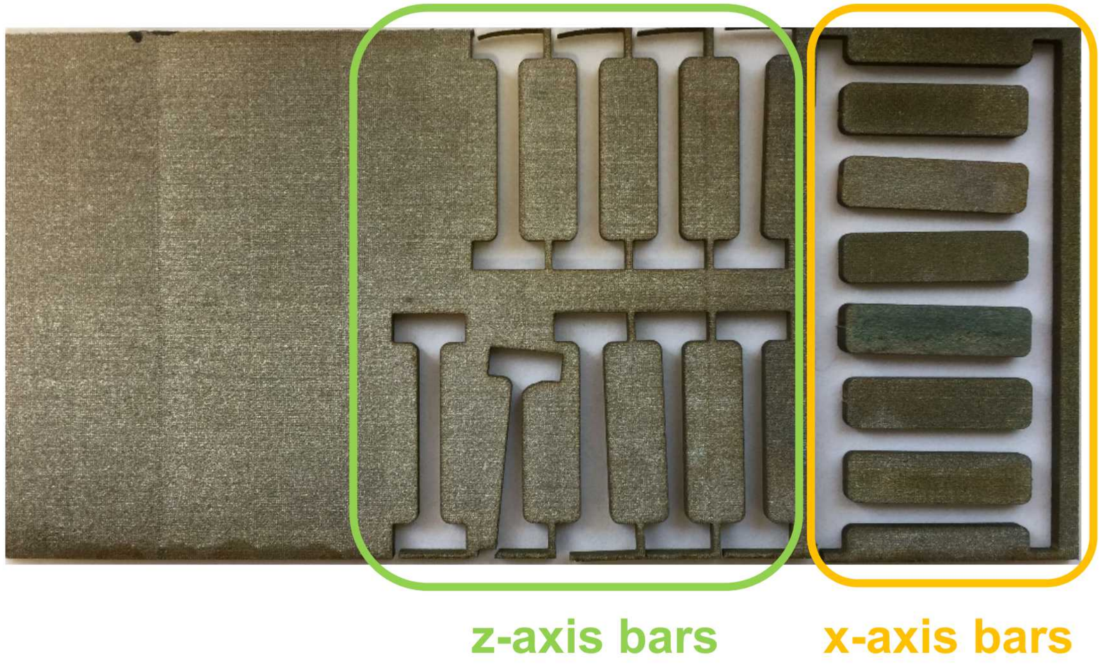


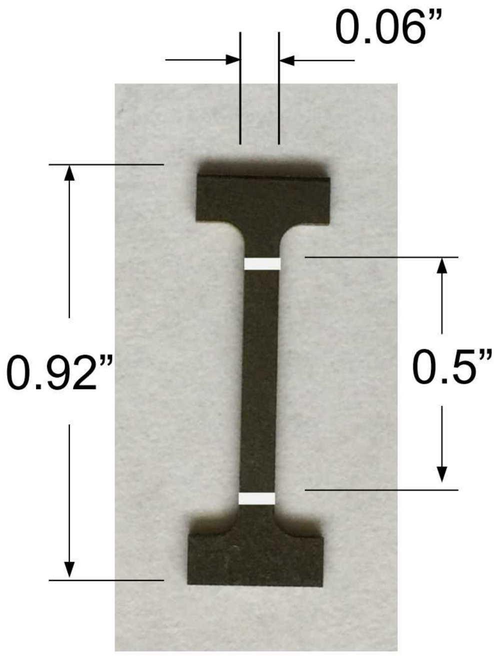
Materials

- The mechanical behavior of 316L is affected by the microstructure and surface irregularities that dominate thin cross-sections
  - 4”x2” sheets and 1.2”D cylinders are printed using LPBF
  - tensile specimens
    - bars are cut using electro-discharge machining (EDM) in the rolling (x-axis) and build (z-axis) directions
    - 0.060”D cylinders are machined



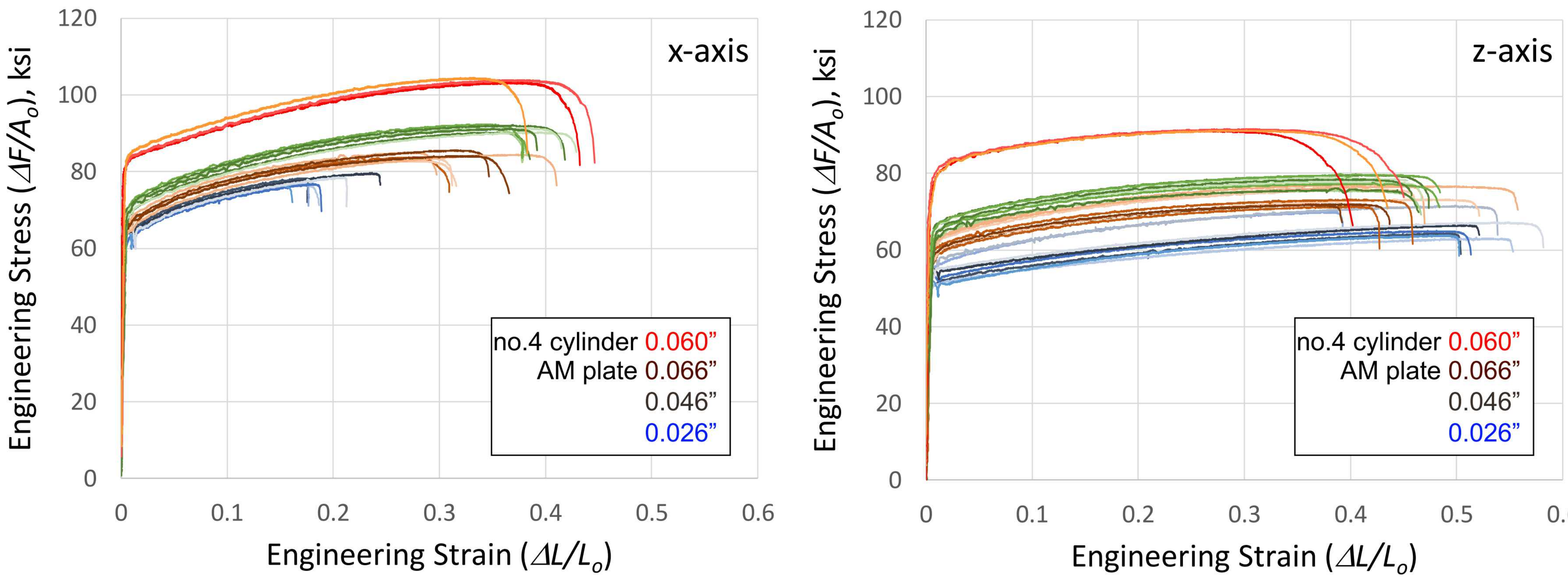
Tensile tests





- A quasi-static strain rate of 10^{-5} s^{-1} is used for all tests to failure.
  - tensile bars are tested with surfaces in the as-deposited condition

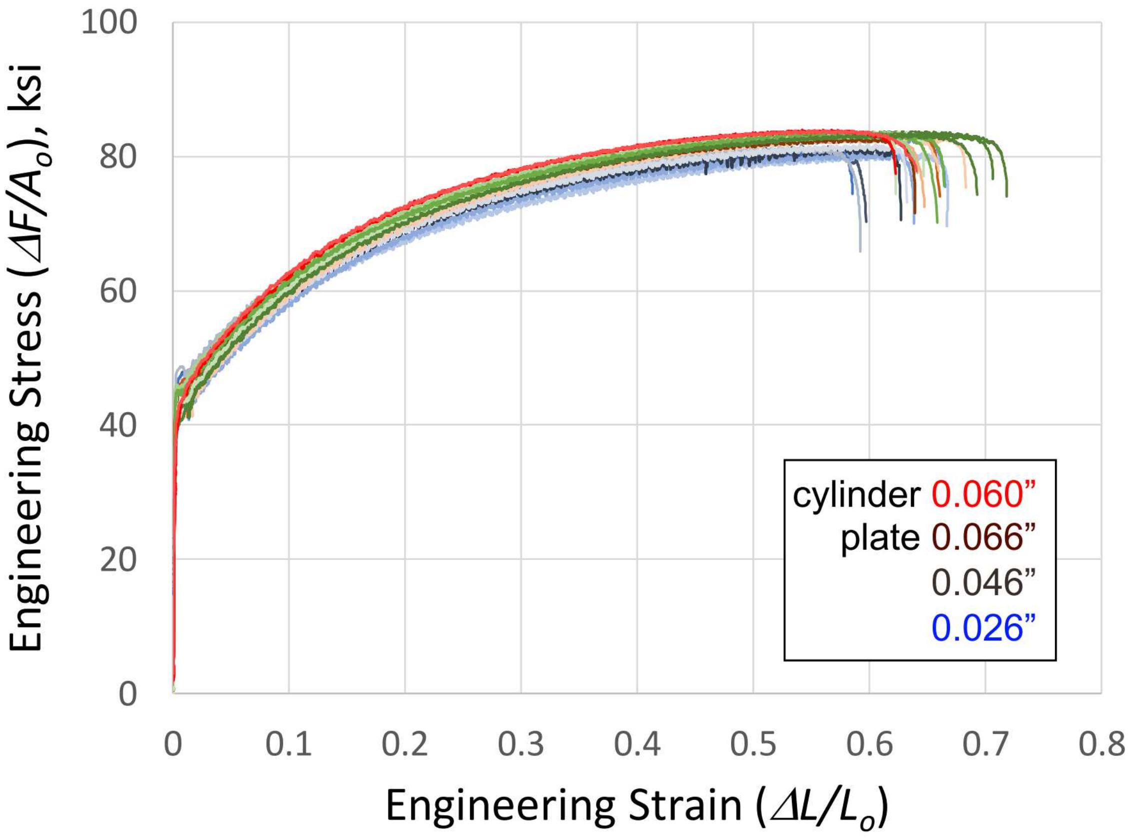
Test results for AM 316L



- Anisotropy and surface roughness affect the scatter in the AM data
  - σ_y:σ_u appears to scale with thickness, with greater ε_p along z-axis

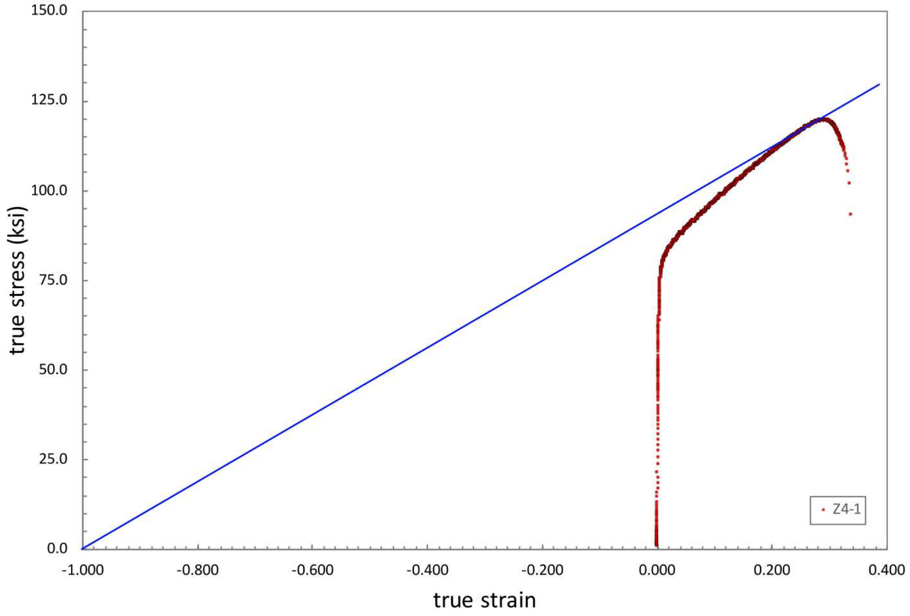
Test results for wrought 316L

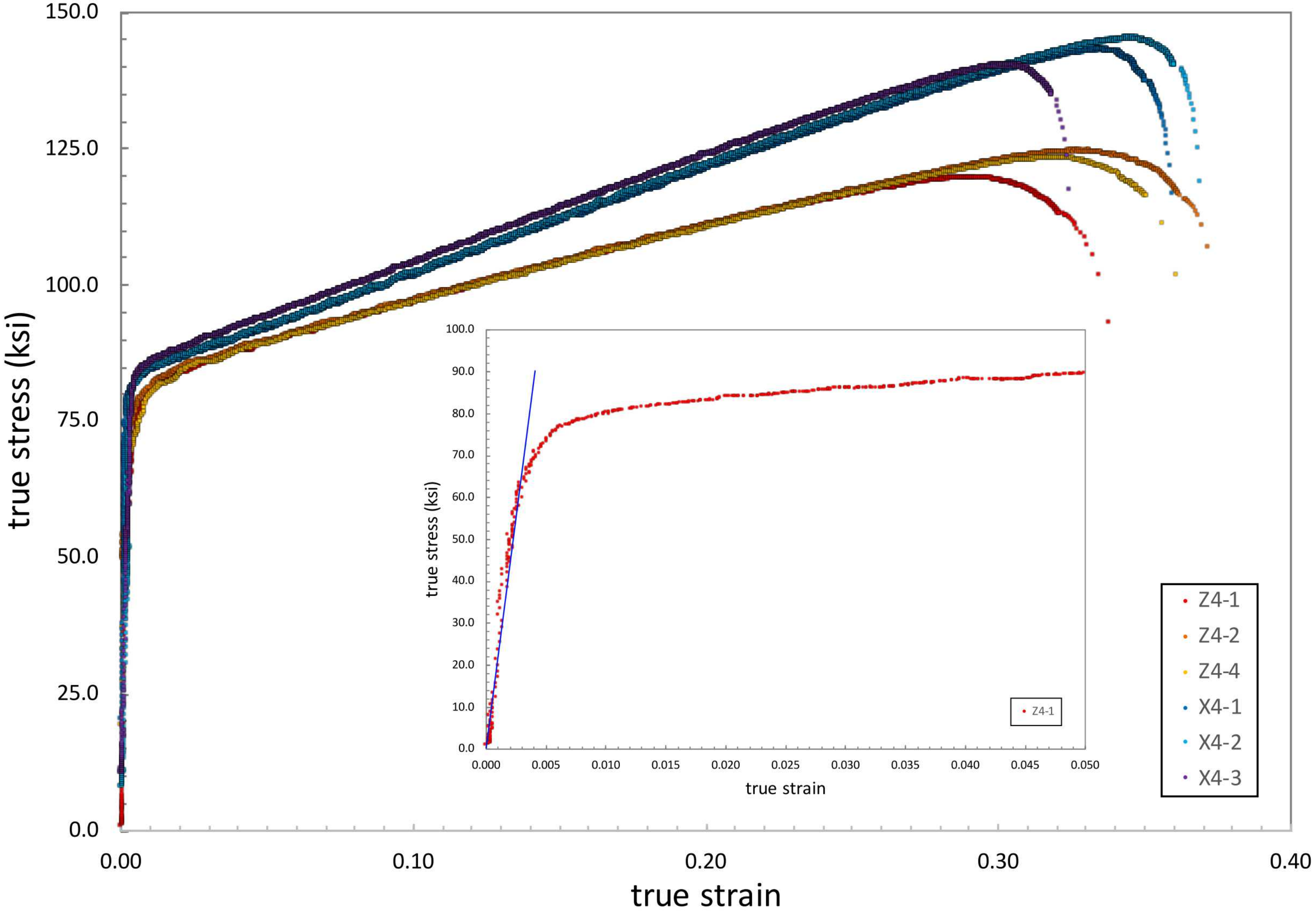
- Wrought 316L stock is machined into tensile bars as well as cylinders for comparison with the AM test results
  - samples cut from plates at random directions
  - σ_y:σ_u appears to scale with thickness as well
  - cylindrical samples results are similar to the thickest tensile bars



Data analysis

Cylinder no.4 test no.1 z-axis

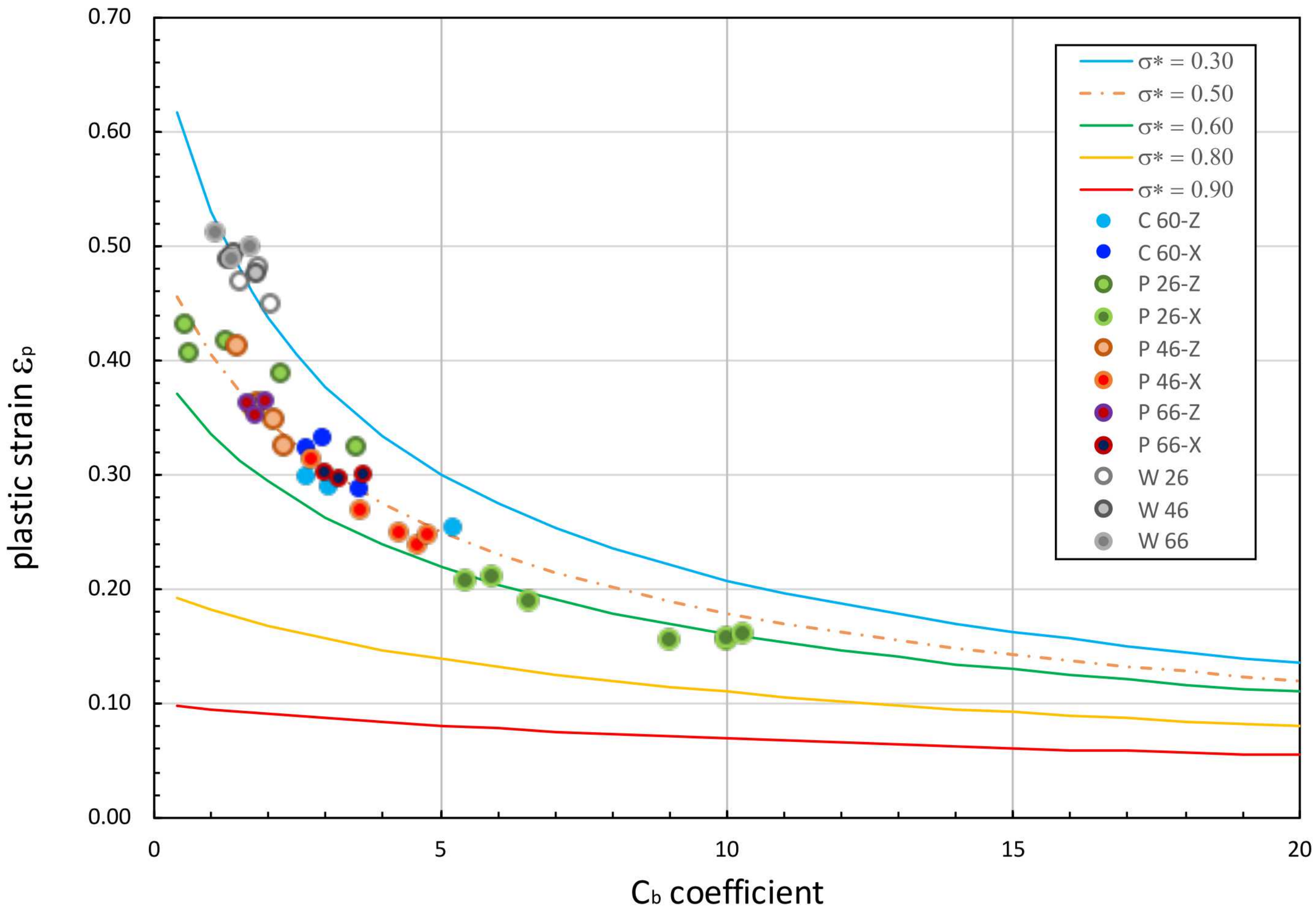




- True stress-strain behavior: the proportional limit for yield strength σ_y is determined with $R^2 = 0.98$; and the ultimate strength σ_u is located at the instability using the Considère subtangent construct.

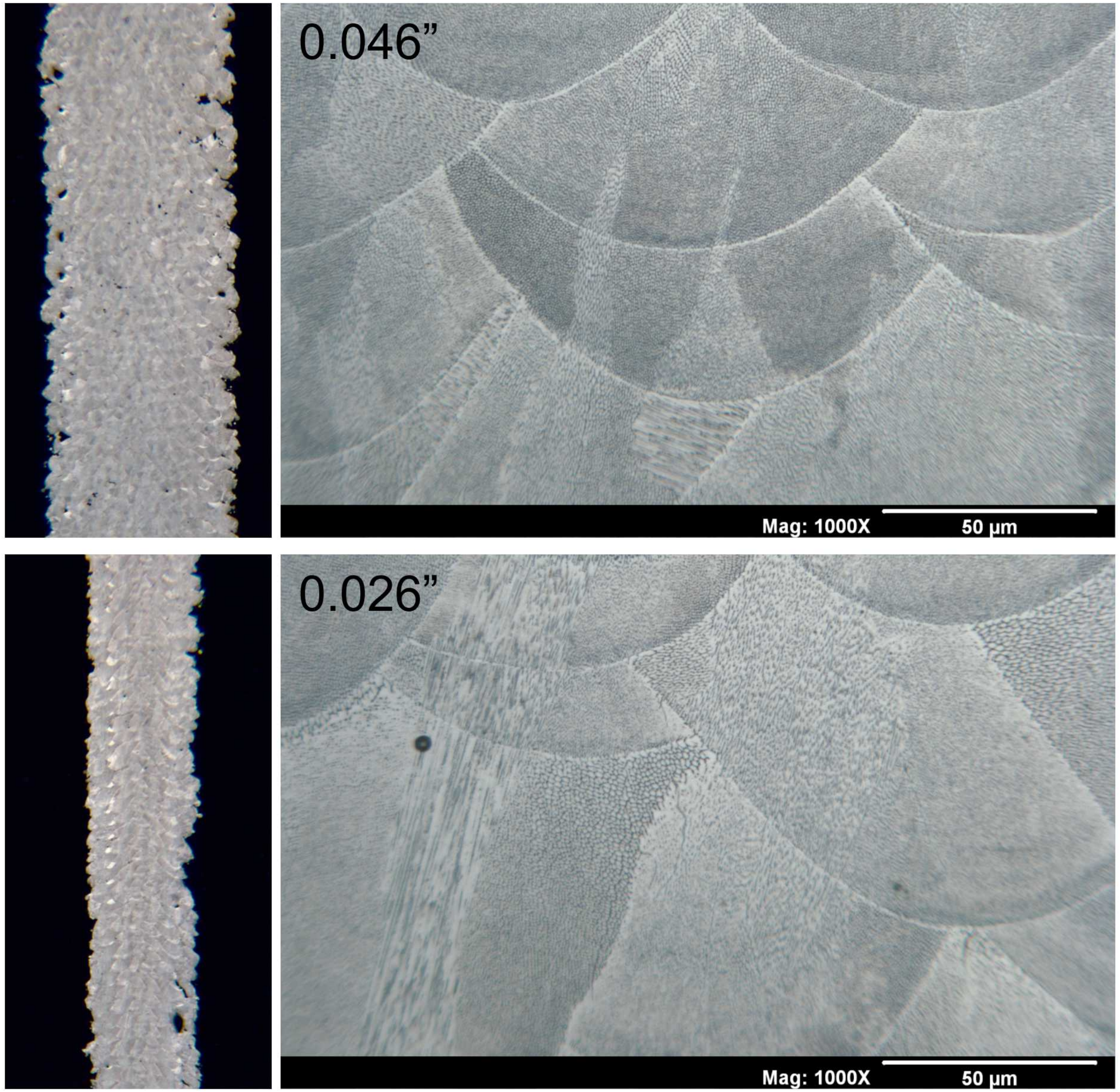
Trend analysis

- The c_b vs. ε_p plot shows that plasticity is enhanced for a constant σ^* as c_b decreases
  - the c_b-value is relative to the alloy system
- The c_b values for AM 316L converge to ~2.5 for a σ^* of ~0.5 as thickness increases
- The wrought material is different than AM as c_b ~2 for σ^* ~0.3



AM microstructures

- The 316L behavior varies with plate thickness – indicative of surface roughness effects on providing a continuous cross-section and reduced plasticity
- The microstructure within the overlapping melt zones is on the same scale, independent of plate thickness
  - views are in cross-section
  - interior features are submicron



Discussion

- The tensile bars and cylinders produce similar behaviors with similar cross-section thicknesses – i.e. the specimen geometry has little effect
- However, the effects plate thickness coupled with of surface defects leads to lower strength values and a distribution in c_b-values for the AM material
- Mechanical anisotropy is seen between the roller direction (lower strength, reduced plasticity, and higher c_b) and build direction (greater strength, higher plasticity, and smaller c_b)
- The intrinsic microstructure is consistent, apparently independent of AM plate thickness
- The wrought material is fundamentally different than the LPBF sheet material in its σ^* behavior

Summary

- A model is developed that includes ε_p, σ_y and σ_u to define a softening coefficient c_b that reveals a scale of microstructure attributed to work hardening behavior from the yield point to the instability
  - J W Morris, Jr (2007) – based a K-M approach and the Considère criterion
- The application to metal AM provides results consistent with observed mechanical behaviors, defect structure, and microstructure intrinsic to the LPBF process.
- A unique value of ~2.5 for c_b, independent of thickness, is converged upon for the AM sheet material with σ^* ~0.5

for further information – see, e.g., A.F. Jankowski, et al., *Inter. J. Mater. Res.* (2019) *in press*