Predicting Mechanical Behavior

Fall Meeting

October 13th – 15th 2020

- Student: Andrew Temple, Maria Quintana (ISU)
- Faculty: Dr. Peter Collins (ISU)
- Industrial Mentors:

Predicting Mechanical Behavior

- Student: Andrew Temple, Maria Quintana (ISU)
- Advisor(s): Peter Collins (ISU)

Project Duration

PhD: Spring 2020 to Spring 2021

- Problem: Traditional strain hardening equations (e.g., Ludwik, Hollomon, Swift, and Voce) are entirely empirical.
- Objective: Develop an in-depth understanding of process-agnostic microstructure-composition-property relationships as they relate to the underlying "material state".
- Benefit: Enables the potential applicability of the predictive stress-strain (elastic AND plastic) model to a wide variety of AM materials.

Recent Progress

- Determination of Kocks-Mecking (KM) storage and recovery coefficients for AM Ti-6Al-4V
- Generation of synthetic stress-strain curves using only three material properties
- Process-agnostic prediction of ultimate tensile strength within 5% for AM Ti-6Al-4V

Metrics

Description	% Complete	Status
1. Literature review	90%	●
2. Fitting of the KM model to stress-strain data for AM Ti-6Al-4V to determine coefficients	85%	●
3. Microstructural characterization and image analysis for feature quantification	75%	●
4. Determine microstructure and defect dependence of KM model coefficients	5%	●
5. Extension of the predictive model to AM alloys beyond Ti-6Al-4V	0%	●

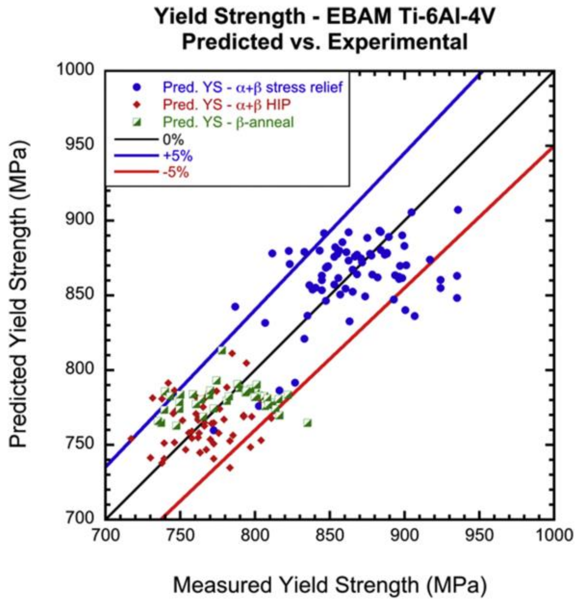
Predictive Yield Strength Equation

$$\sigma_{ys} = \begin{cases} F_V^{\alpha} \cdot \sigma_O^{\alpha} + F_V^{\beta} \cdot \sigma_O^{\beta} + & \text{Intrinsic Strength} \\ F_V^{\alpha} \cdot \sigma_{SS}^{\alpha} + F_V^{\beta} \cdot \sigma_{SS}^{\beta} + & \text{Solid Solution Strengthening} \\ F_V^{col} \cdot C_{\alpha-lath} \cdot (t_{\alpha-lath})^{n} \cdot (t_{\beta-rib})^{-n} + & \text{Hall} - \text{Petch Strengthening (alpha laths)} \\ F_V^{col} \cdot C_{col} \cdot (t_{colony})^{n} + & \text{Hall} - \text{Petch Strengthening (colonies)} \\ (-1) \cdot (AxisDebit) + & \text{Texture Debits (easier slip)} \\ F_V^{BW} \cdot \alpha M G b \sqrt{\rho} & \text{Taylor Hardening} \end{cases}$$

Contribution to YS:
Composition: 70-80%
Dislocation density: 0-18%
Texture: 0-10%
Microstructure: 10-20%

$$\sigma_{ys} = \begin{cases} F_V^{\alpha} \cdot 89 + F_V^{\beta} \cdot 45 + \\ F_V^{\alpha} \cdot \left(149 \cdot x_{Al}^{0.667} + 759 \cdot x_O^{0.667}\right) + F_V^{\beta} \cdot \left(\left(22 \cdot x_V^{0.7}\right)^{0.5} + \left(235 \cdot x_{Fe}^{0.7}\right)^{0.5}\right)^{2} + \\ F_V^{col} \cdot 150 \cdot (t_{\alpha-lath})^{-0.5} \cdot (t_{\beta-rib})^{0.5} + \\ F_V^{col} \cdot 125 \cdot (t_{colony})^{-0.5} + \\ (-1) \cdot (AxisDebit) + \\ F_V^{BW} \cdot \alpha M G b \sqrt{\rho} \end{cases}$$

Works without modification for:
3 different heat treatments,
2 different chemistries,
Wrought material



Hayes, Brian J., et al. "Predicting tensile properties of Ti-6Al-4V produced via directed energy deposition." Acta Materialia 133 (2017): 120-133.

Going Beyond Yield Strength

$\sigma = \sigma_0 + h\epsilon^m$ (Ludwik)[11]

$\sigma = K_1 \epsilon^{n_1}$ (Hollomon)[1]

$\sigma = K_2(\epsilon + \epsilon_0)^{n_2}$ (Swift)[12]

$\sigma = B - (B - A)\exp(-n_3\epsilon)$ (Voce)[13]

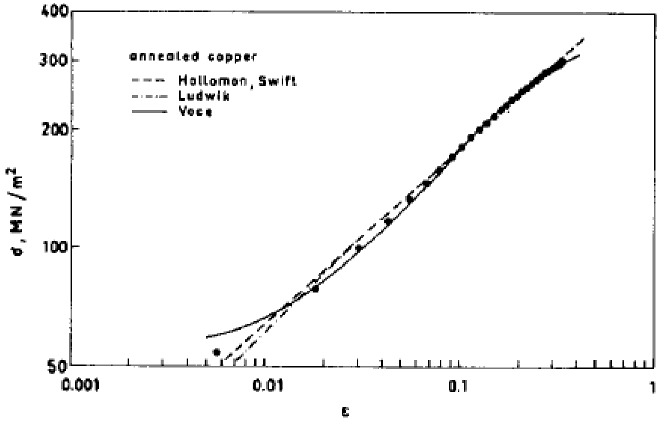


Fig. 2—Analysis of a stress-strain curve of annealed copper using Eqs. [1] through [4].

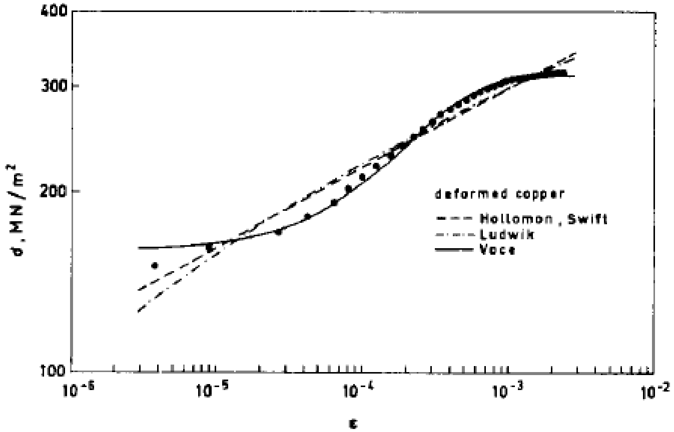


Fig. 3—Analysis of a stress-strain curve of deformed copper using Eqs. [1] through [4].

Kleemola, H. J., and M. A. Nieminen. "On the strain-hardening parameters of metals." Metallurgical transactions 5.8 (1974): 1863-1866.

Kocks-Mecking (KM) Model

- Kocks, Mecking, Estrin, Vinogradov, Yasnikov, et al.
- Dislocation density evolution with strain

$$\frac{d\rho}{d\varepsilon} = k_1\sqrt{\rho} - k_2\rho$$

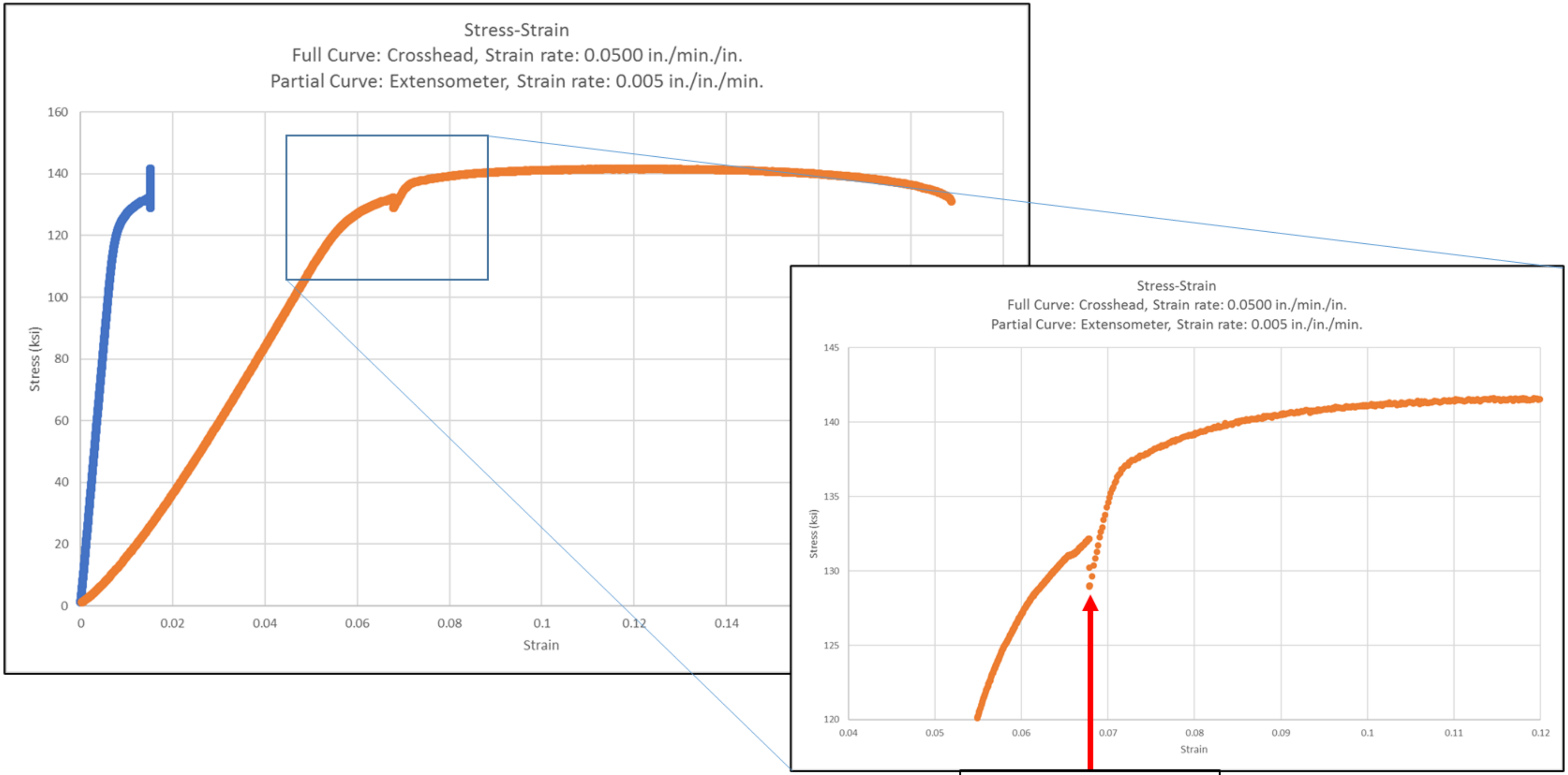
$$\sigma = \sigma_0 + \frac{\alpha GMbk_1}{k_2}\left(1 - \exp\left(-\frac{k_2 M\varepsilon}{2}\right)\right)$$

$$\varepsilon_n = \frac{2}{k_2 M}\ln\left(\frac{(2 + k_2 M)(\alpha GbMk_1)}{2(\alpha GbMk_1 + k_2\sigma_0)}\right)$$

- σ_0 is the flow stress (i.e., the yield stress)
- k_1 is the dislocation storage coefficient
- k_2 is the recovery coefficient – controls the annihilation rate

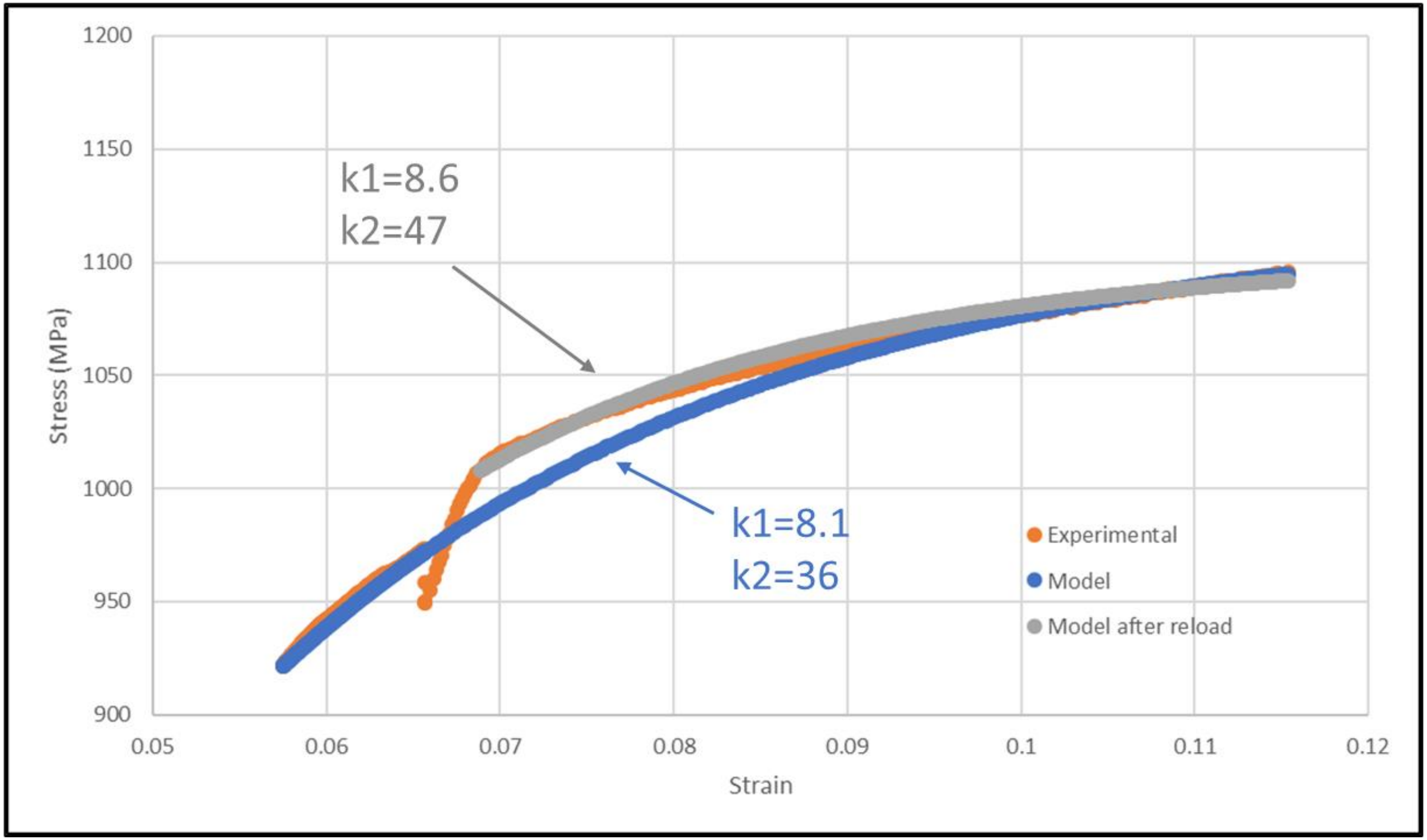
Vinogradov, A., I. S. Yasnikov, and Y. Estrin. "Irreversible thermodynamics approach to plasticity: dislocation density based constitutive modelling." Materials Science and Technology 31.13 (2015): 1664-1672.

Tensile Testing

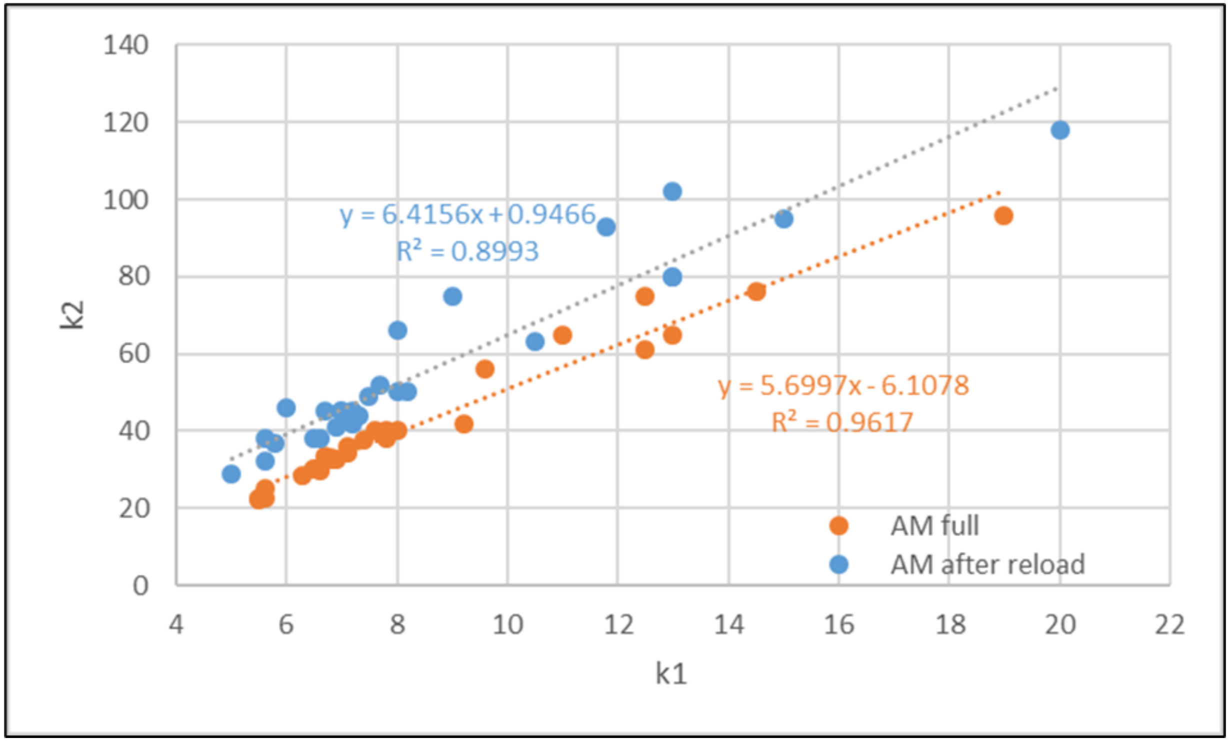


Strain rate jump

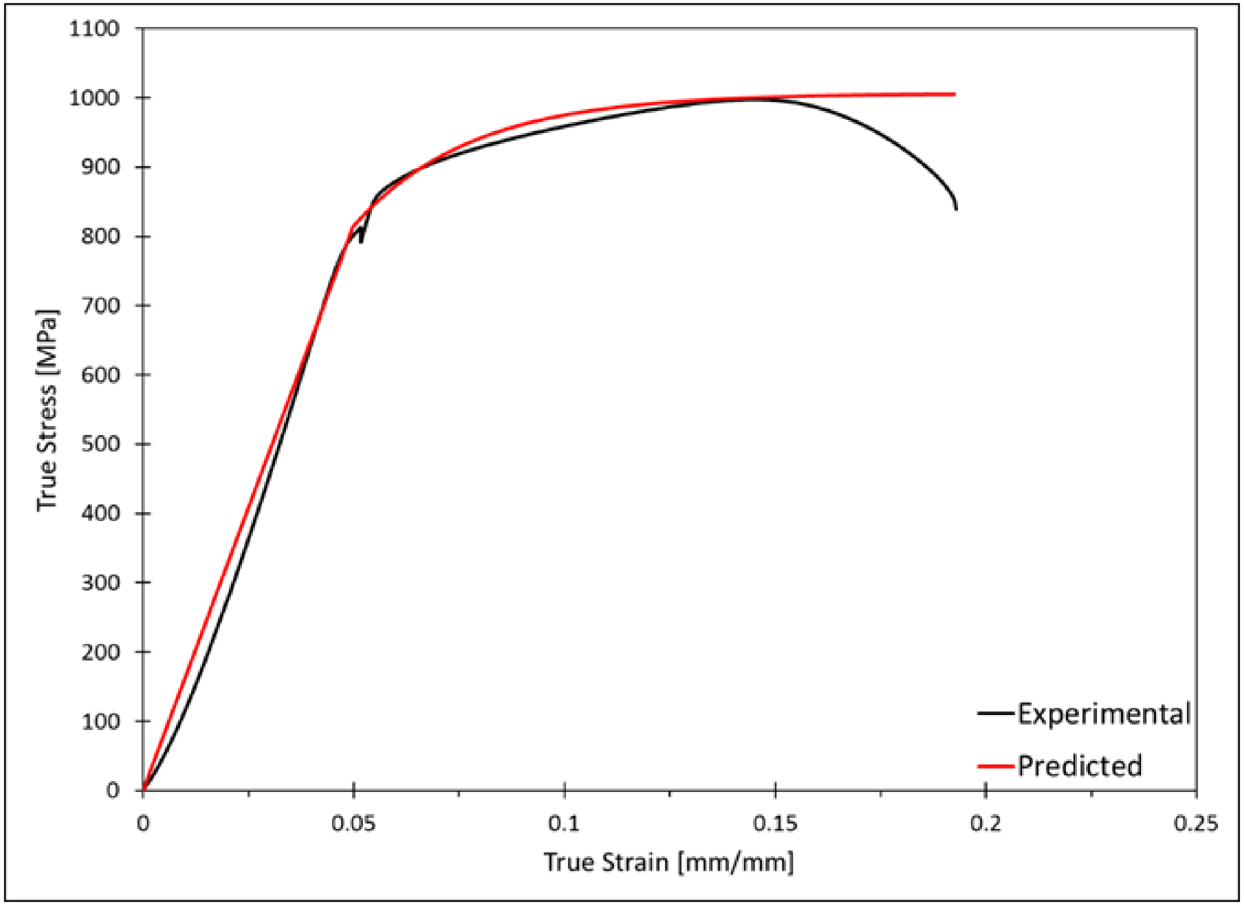
KM Model – Experimental Curve



Correlation of KM Model Coefficients

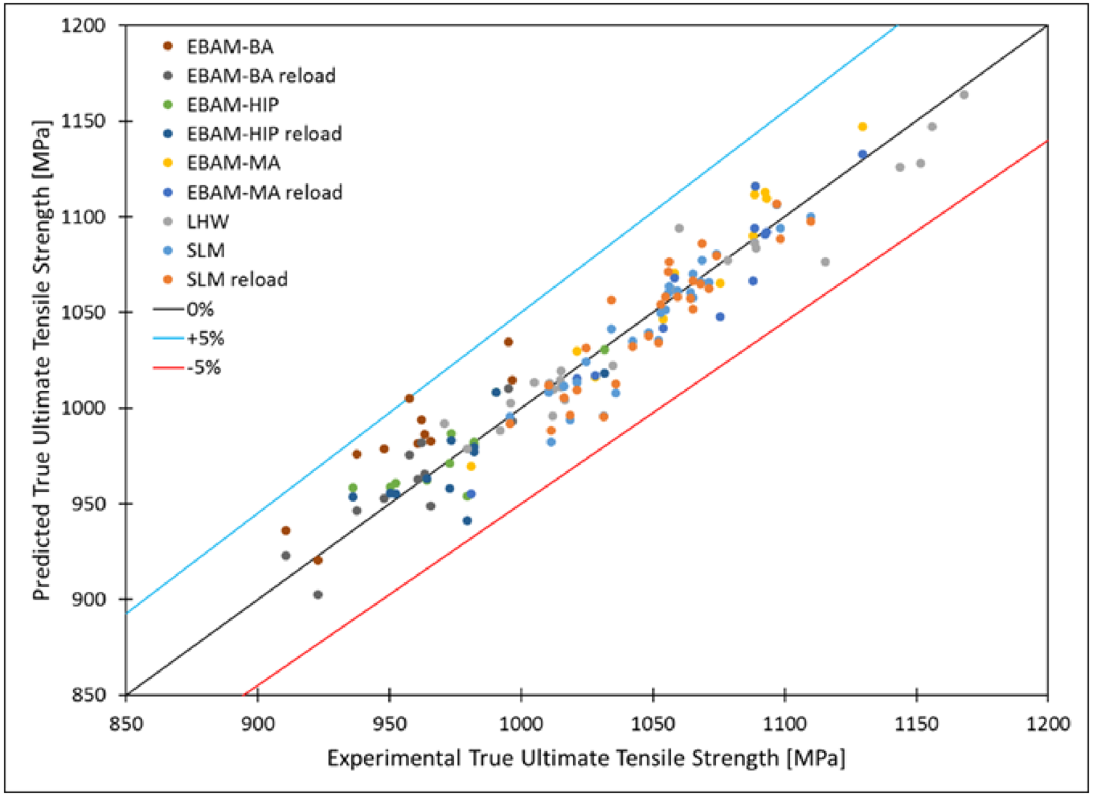


Synthetic Stress-Strain Curve (Elastic AND Plastic)



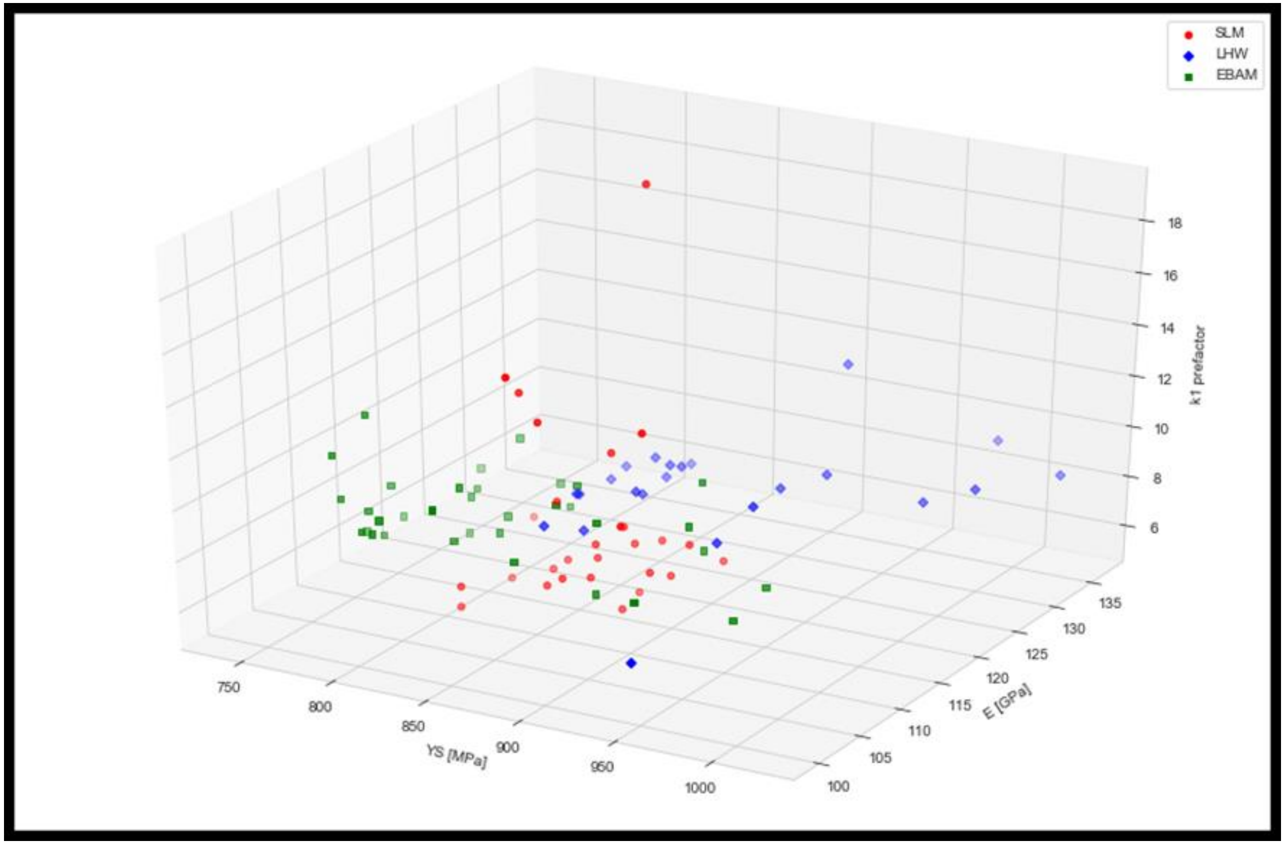
Three material properties: elastic modulus, yield strength, and dislocation storage coefficient

Ultimate Tensile Strength Predictions



Center Proprietary – Terms of CANFSA Membership Agreement Apply

Industrial Relevance



Implications:

- Multiple stress-strain curves are represented in a single plot

Applications:

- AM Ti-6Al-4V
- other AM alloys

Benefits:

- process-agnostic
- informed by “material state”
- elastic AND plastic behavior

Challenges & Opportunities

- Represent stress-strain behavior as a function of “material state”
  - Determine the microstructure and defect structure dependence of the KM model coefficients
  - Assessment of model uncertainty and identification of potential sources of variability
- Process-agnostic predictions of stress-strain behavior
  - Elastic AND plastic
- Applicability to a wide variety of AM materials and AM processes (with and without heat treatments)
  - Beta titanium alloys, aluminum alloys, steels

Thank you!
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References

[1] Hayes, Brian J., et al. "Predicting tensile properties of Ti-6Al-4V produced via directed energy deposition." Acta Materialia 133 (2017): 120-133.

[2] Kleemola, H. J., and M. A. Nieminen. "On the strain-hardening parameters of metals." Metallurgical transactions 5.8 (1974): 1863-1866.

[3] Vinogradov, A., I. S. Yasnikov, and Y. Estrin. "Irreversible thermodynamics approach to plasticity: dislocation density based constitutive modelling." Materials Science and Technology 31.13 (2015): 1664-1672.