Project 14: Measurement and Modeling of Anisotropy in Ti-6Al-4V Forgings

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Faculty: Terry Lowe (Mines), Kester Clarke (Mines)
Industrial Mentors: Tony Yao (Weber Metals), Adam Pilchak (AFRL)

Project 14: Measurement and Modeling of Anisotropy in Ti-6Al-4V Forgings Dashboard

- Student: Connor Campbell (Mines)
- Advisor(s): T. Lowe (Mines), K. Clarke (Mines)

Project Duration

PhD: January 2015 to December 2019

Problem: Preferred crystal orientation (texture) in forgings of Ti-6Al-4V limits the inspectability and predictability of mechanical properties in forgings.

Objectives: Assessing capability of current models to predict localized texture, extending them to address limitations, and applying the code to a complex forging

Benefit: Validated microstructural models to predict texture that can be integrated into an industrially-relevant software package (DEFORM®)

Recent Progress

- Literature review emphasizing microstructural evolution during Ti-6Al-4V processing
- Identified limitations of current transformation texture model
- Identified microstructural (variant selection) models to assess impact on texture prediction

Metrics

Description	% Complete	Status
1. Survey of current knowledge	75%	● (green)
2. Baseline deformation texture simulation (upset of cylindrical sample)	85%	● (green)
3. Assessment of transformation texture limitations	30%	● (green)
4. Extension of current models to more accurately predict texture	0%	● (yellow)
5. Application of extended models to industrial forging	0%	● (yellow)

Presentation Outline

- Background information and industrial relevance
- Previous work
  - Baseline deformation-induced crystallographic texture
- Recent progress
  - Identified limitations of transformation texture model
- Future plans
  - Focus on variant selection (VS)

Industrial Relevance

- Ti-6Al-4V is the most common titanium alloy
- Properties are dependent on processing
  - Largely determined by anisotropic α phase
    - Orientation, distribution, and morphology
- Localized texture can occur during processing
  - Microtextured regions (MTRs), or macrozones
  - Detrimental to first- and second-tier properties
  - Impede ultrasonic inspection

Industrial Relevance cont'd

- Uncertainty can cause costly false negatives
- If MTRs could be predicted
  - Fewer parts could be scrapped
  - Local material properties could be predicted
  - Process paths could be optimized
- Current models need further development
  - Industrial goal: "**Predictable** and controllable **location-specific** properties and microstructure"

Project Goal

- Understand which microstructural processes dominate texture evolution in Ti-6Al-4V
- Provide a method to predict texture resulting from thermomechanical processing of Ti-6Al-4V
  - DEFORM® software used to predict deformation
  - Emphasis on phase transformation, variant selection
    - Assess existing models from literature

Methodology

1) Assess capability of current DEFORM® models
   - Accomplished via a simple, baseline simulation
   - Where are the limitations?
2) Extend models to address current deficiencies
   - Phase transformation and variant selection
3) Apply improved models to an industrial forging
   - Determine what improvements were made
   - Assess new limitations

Previous work: Simulation Construction

Stage 1: ***Isotropic*** Forging (DEFORM®)

Material Behavior	Tool Geometry	Transformation

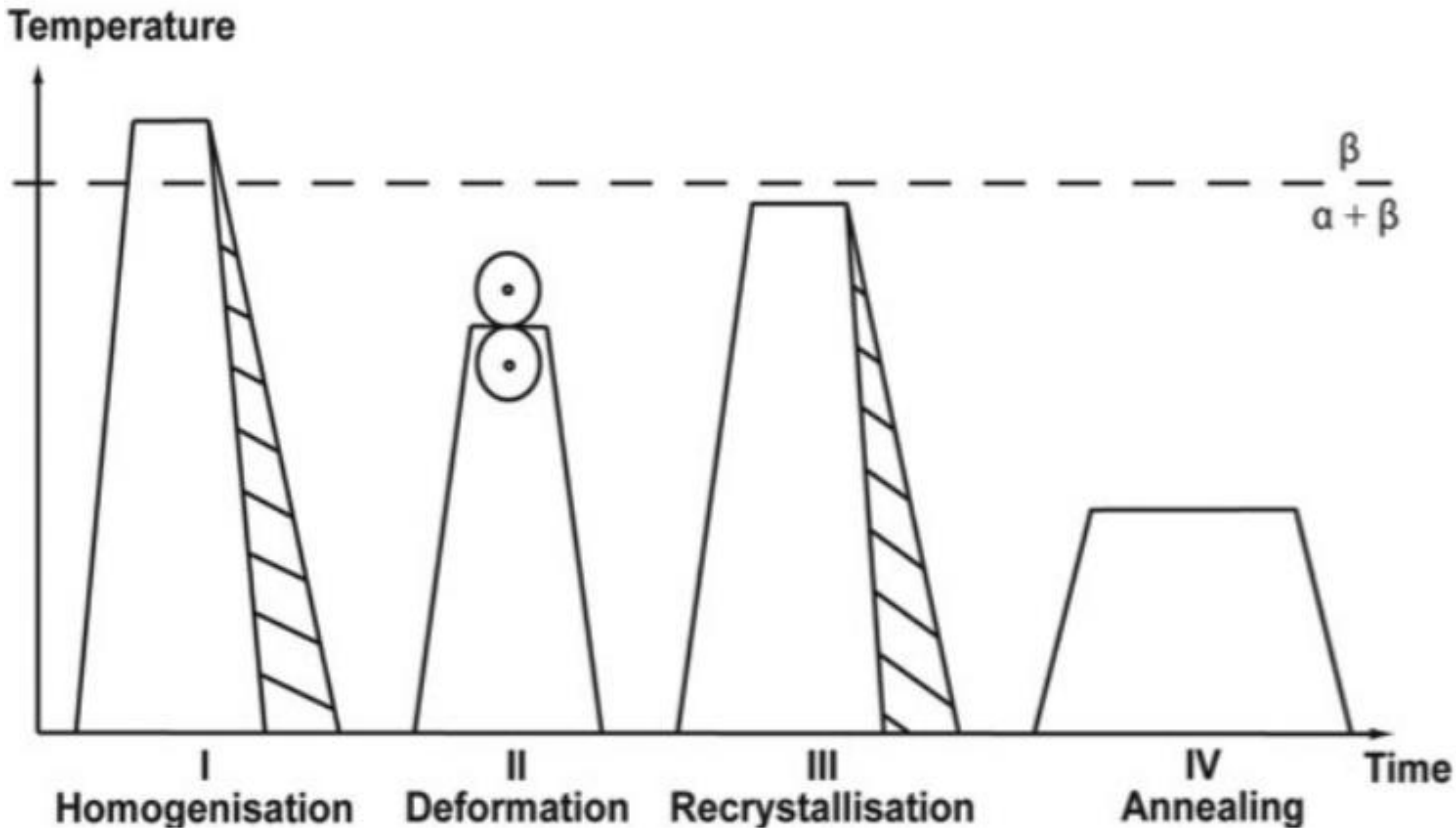
Strain increments ↓ Phase fractions

Stage 2: Texture Simulation (DEFORM® Material Suite)

Initial Texture	X-tal Plasticity	Variant Selection

Schematic TMP of Ti-6Al-4V

Lutjering, G., and J. C. Williams. *Titanium*. Springer, 2003.



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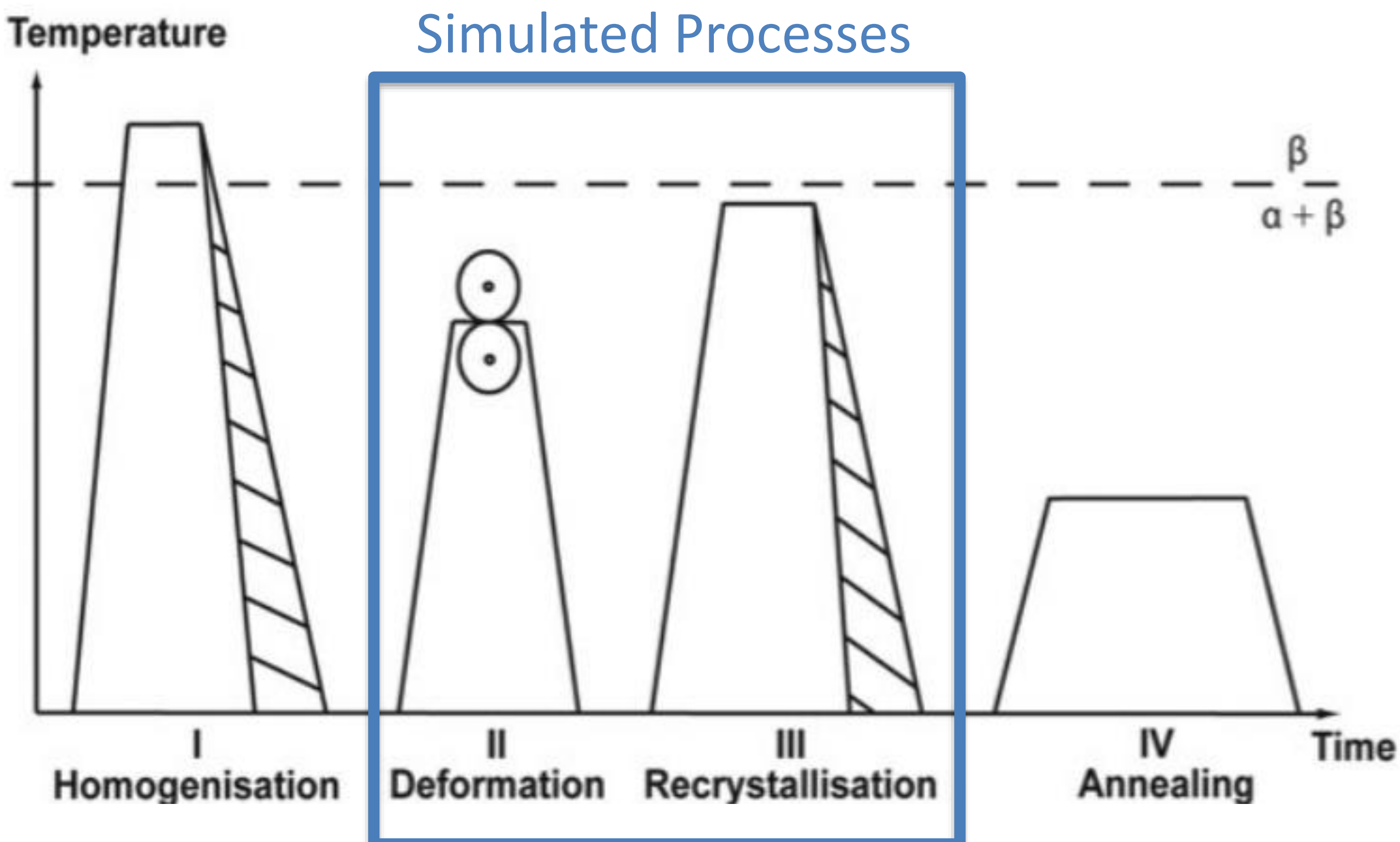
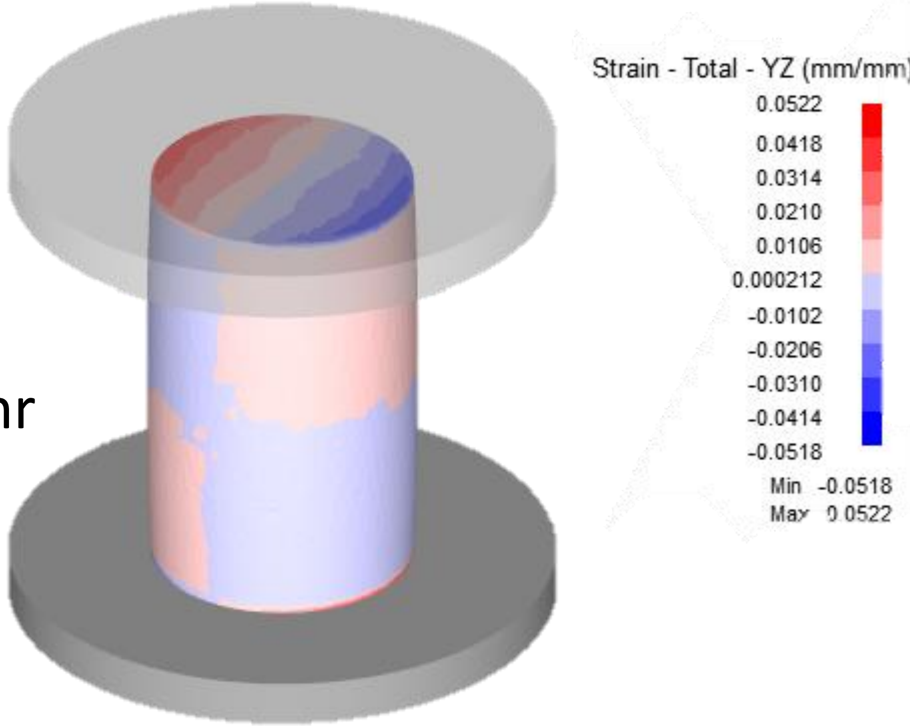


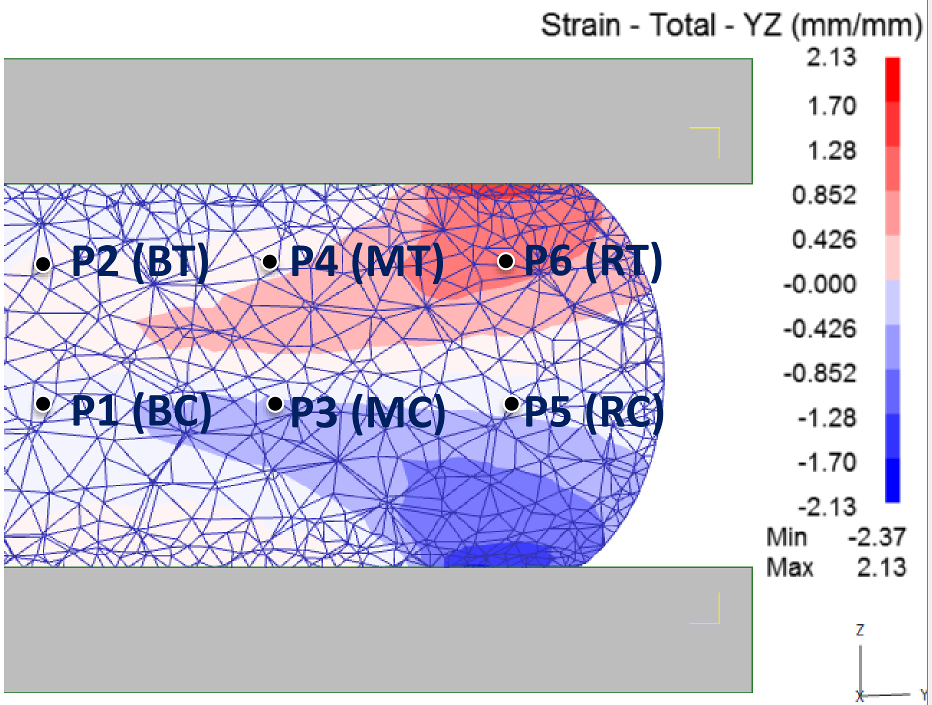
Stage 1: Simulation of Previous Forging

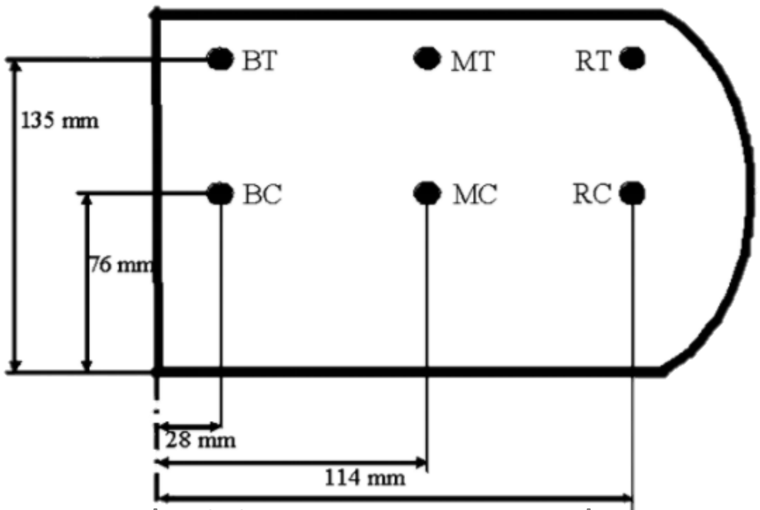
- Replicating experiment from literature
  - Simple cylindrical specimen was compressed to 30% height
  - 50°C subtransus
  - Quasi-isothermal
- After deformation:
  - Water quenched
  - Held 30°C subtransus for 1hr
  - Quenched again



Calculation of Strain Increments

- Strain increments, phase fractions fed into post-processor to predict crystallographic rotations





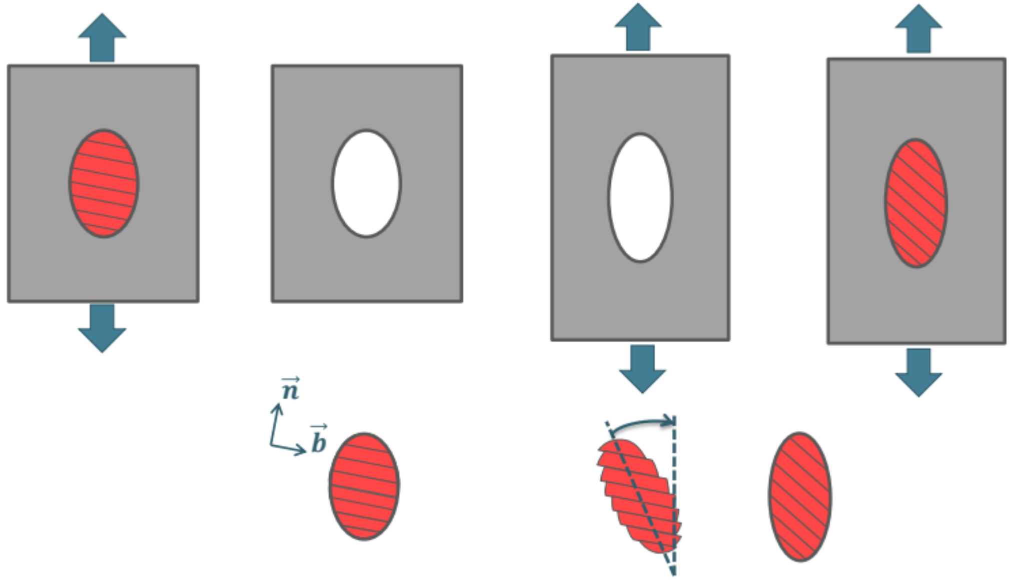
M.G. Glavicic, R.L. Goetz, et al., Met. Trans. A, vol. 39, issue 4, April 2008, pp 887-896.

Phase Transformation Model as Implemented in DEFORM®

- Outputs are only phase fractions
  - Used for strain partitioning (Viscoplastic Self-Consistent)
  - No grain size or morphology predictions
  - Further work needed to incorporate heterogeneity
- Phase fractions initiated using ß-approach curve
  - Only primary α grows according to MEDC model
  - Secondary α thickening **can be** predicted (SALT)
  - Grain-boundary α growth **can be** predicted
    - Detrimental to properties and therefore usually avoided

Stage 2: Material Suite Texture Prediction

- Pole figures taken from six points specified by Glavicic et al.
- Figures taken along axis of compression (sample Z-axis)
- Viscoplastic self-consistent (VPSC) scheme used to partition strain b/t phases

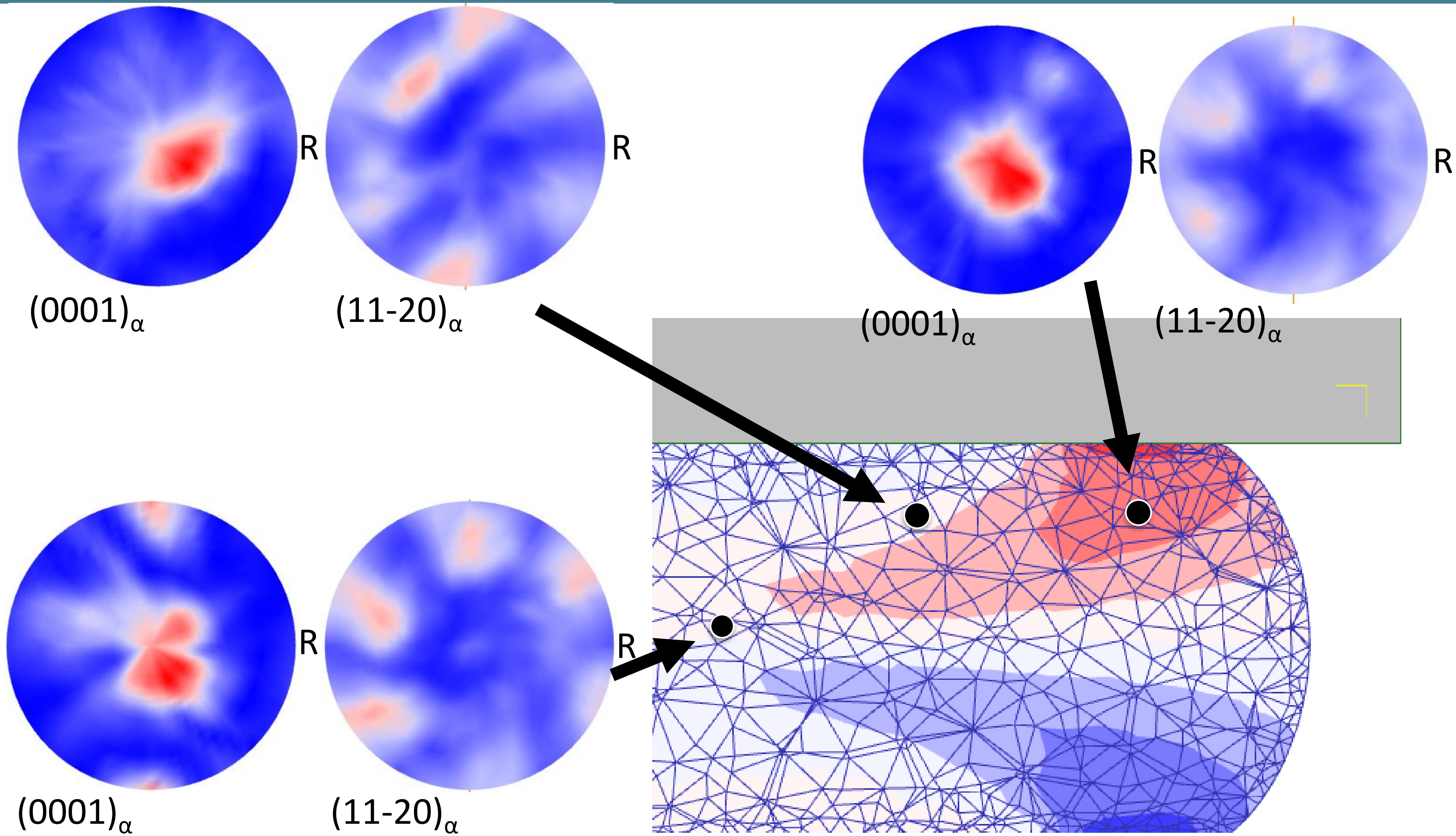


R. A. Lebensohn and C. N. Tomé, Acta Metallurgica et Materialia **41**, 2611 (1993).

Texture Simulation Key Assumptions

- **<u>Initial texture was completely random</u>**
- Random variant selection
  - Though no evolution during heat treatment
- ß strength/hardening = 1/3 that of α
- Penalty imposed to pyramidal slip in α
- Basal CRSS = Prismatic CRSS

DEFORM® Predicts Spatial Variations of Texture



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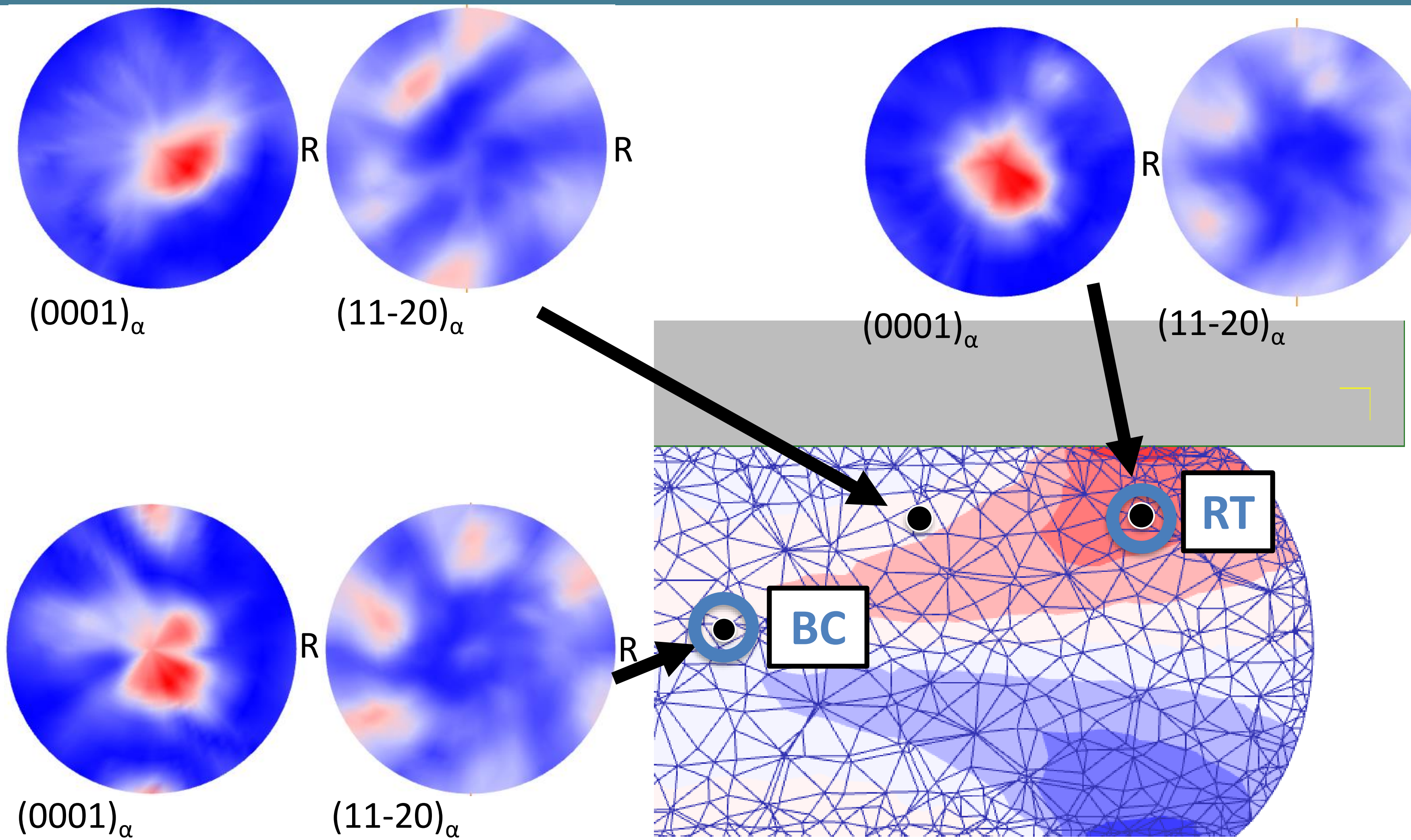
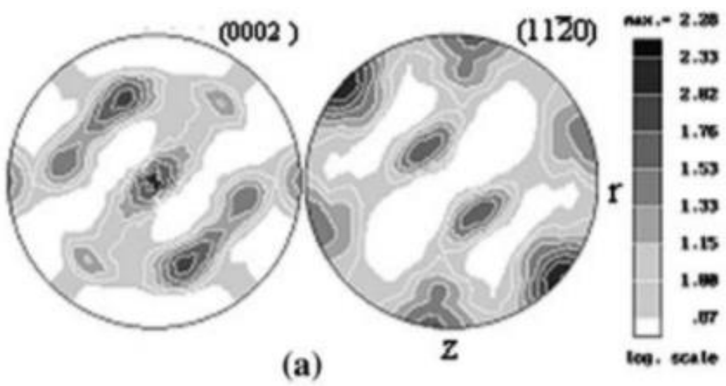
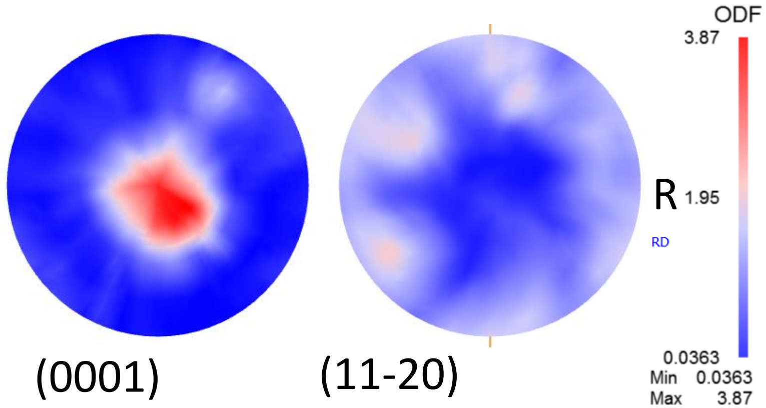


Current Predictions Differ from Measured Results





M.G. Glavicic, R.L. Goetz, et al., Met. Trans. A, vol. 39, issue 4, April 2008, pp 887-896.

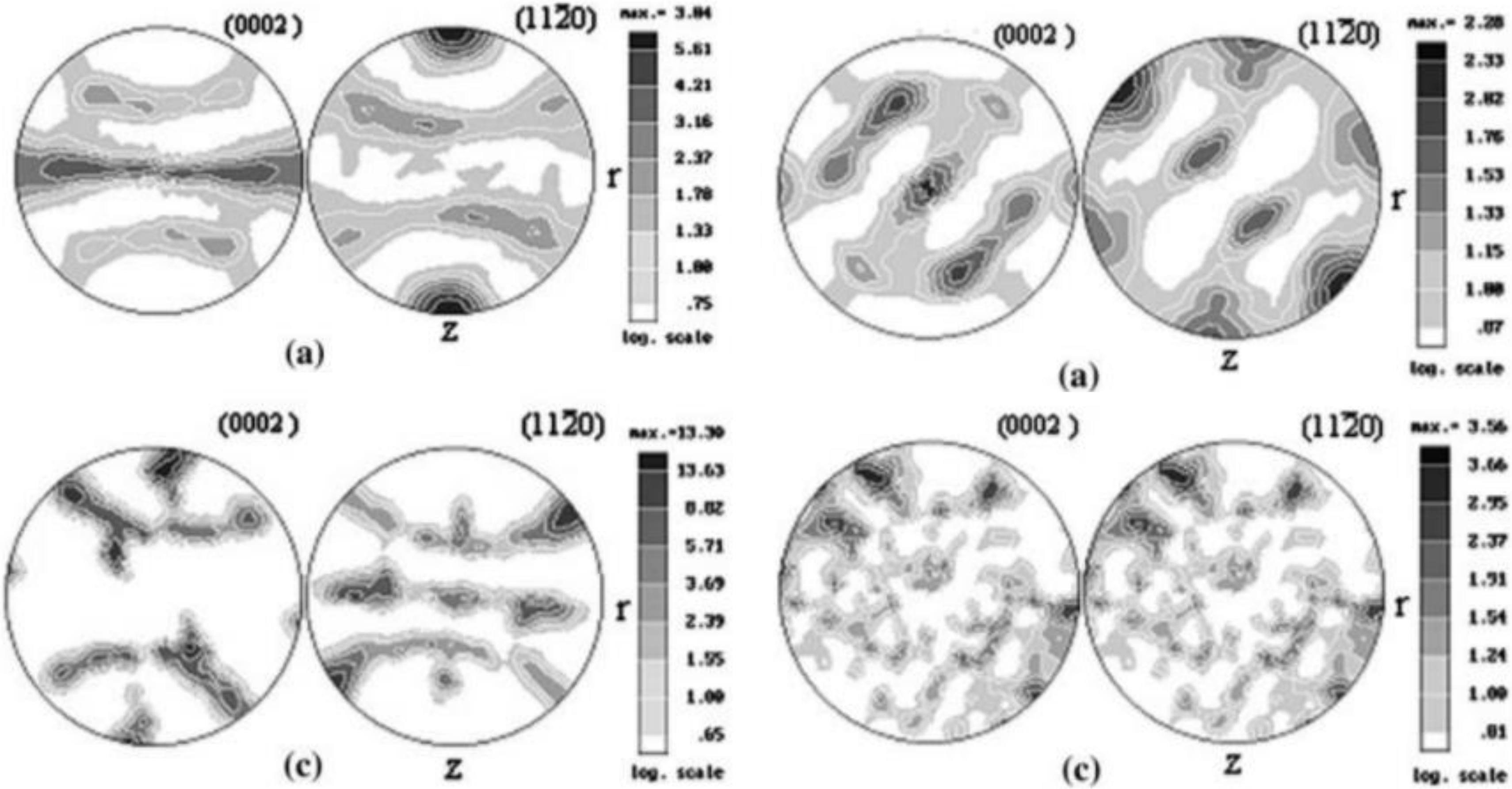
- Little, if any similarities to measured results
- Current models:
  - Don't crash
  - Predict spatial variations
  - Are works in progress
- Where to go from here?

Variant Selection Affects Texture Prediction

Location: BC | Location: RT

Measured

Simulated



Current Progress: Focusing on VS

$$\{110\}_{ß} \; // \; (0001)_{\alpha}$$
$$\langle 111\rangle_{ß} \; // \; [2\bar{1}\bar{1}0]_{\alpha}$$

- What is variant selection?
  - ß → α following a Burgers orientation relationship (BOR)
  - 12 possible variants of α from ß decomposition
  - If all variants equally likely → weak transformation texture
  - However, this is usually not what is observed!
- Many different theories as to how variants are selected!

Reported VS Mechanisms and Variables

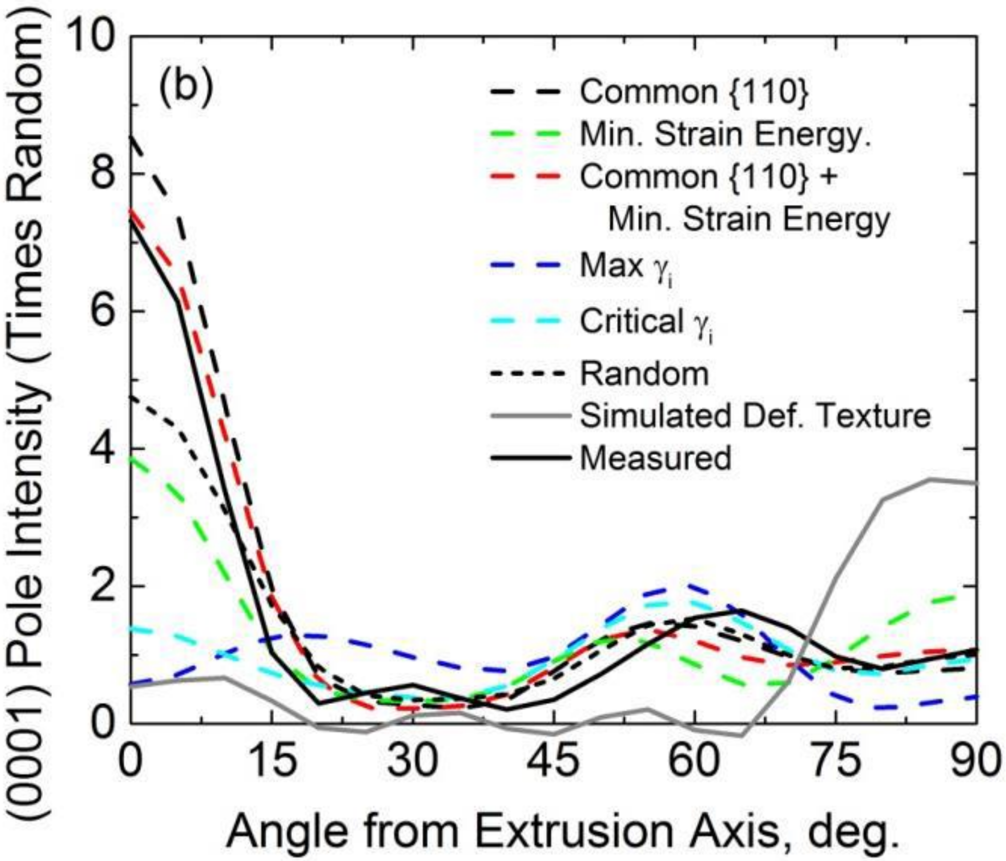
- Random
  - # variants per ß grain
- Common $\{110\}_{ß}$ plane
  - ß phase misorientation distribution, # neighboring grains
- Slip on $\{110\}_{ß}$
  - ß texture, slip system strengths
- Minimize local elastic strain energy density (E_{int})
  - Local σ_{ij} from FEM, transformation strain ε_{ij}^{*}
- Combination of Common $\{110\}_{ß}$ + min(E_{int})

Codes for these models have been provided by Adam Pilchak (Thanks, Adam!)

Previous Work: Extrusion VS @ 899°C

- Common {110} + min(E_{int}) are best **for this case**

- There is a *vast* unexplored space of process parameters!



Ma, Pilchak, Allison, unpublished, 2013

Leveraging Past Experiments

- There is a significant body of work on Ti-64 processing
    - Samples available at AFRL (as-rolled/extruded/forged)
- DEFORM® has **some** capability
    - More predictive models + validation necessary
- Most work conducted on as-deformed samples
    - Less work on solution HT in α/ß field

Characterizing samples and predicting transformation texture with available VS schemes will provide insight into where each of these schemes dominates texture evolution

Plans for Next Reporting Period

- Continue literature search, DEFORM model development
  - Investigate S.L. Semiatin's work to find experiments of interest
- Compile VS schemes into one single file
  - Currently, 5 separate codes → challenging to test
- Investigate influence of α_p orientation on VS
  - Can use ultrafine grained Ti as a "baseline"
    - UFG has random α_p distribution
  - Compare to other product forms/strain paths

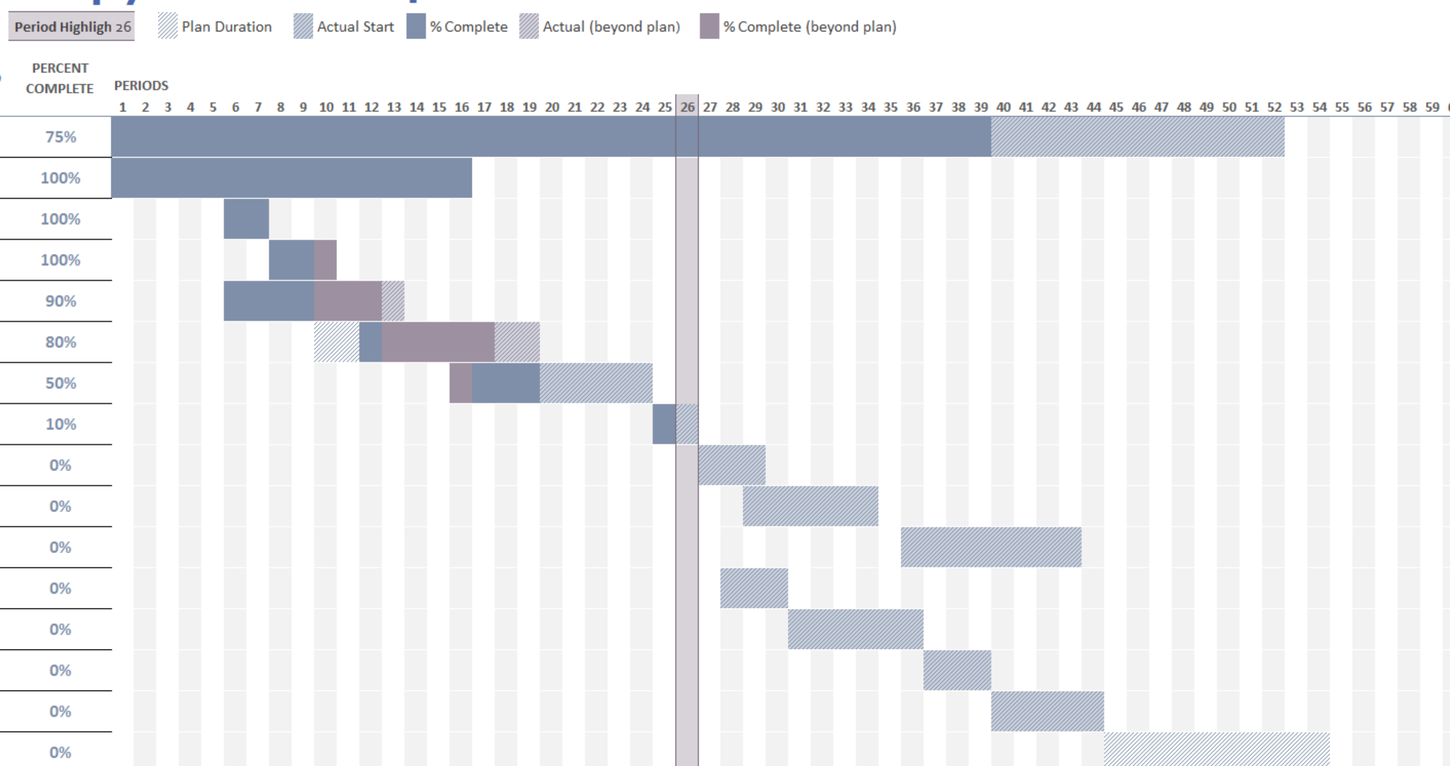
Summary

- We are evaluating and evolving texture models using DEFORM®
- We are focused on variant selection schemes
- We will leverage past experiments to further explore effects of VS during α/ß heat treatment
- This will determine the conditions under which different VS schemes drive transformation texture
    - Developers are waiting to get hands on validated models so that forging industry can benefit!

Progress

Project 14: Anisotropy in Ti-6Al-4V

ACTIVITY	PLAN START	PLAN DURATION	ACTUAL START	ACTUAL DURATION	PERCENT COMPLETE
Literature Review	1	52	1	52	75%
Construction of Baseline Sim.	1	16	1	16	100%
Initial Texture Calculations	6	2	6	2	100%
Assessment of Initial Results	8	2	8	3	100%
Texture Sim. Parameter Test	6	4	6	8	90%
Current VS Assessment	10	3	12	8	80%
Add'l Deformation Sims.	17	8	16	9	50%
Combining VS Codes	25	2	25	2	10%
Assessing VS Codes	27	3	27	3	0%
Extending VS Codes	29	6	29	6	0%
Applying VS Codes	36	8	36	8	0%
ID'ing Samples of Interest	28	3	28	3	0%
Characterizing Samples	31	6	31	6	0%
Heat Treat. Of Samples	37	3	37	3	0%
Texture Measurements	40	5	40	5	0%
Analysis of Results	45	10	0	3	0%



Center Proprietary – Terms of CANFSA Membership Agreement Apply

Thank you very much!

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Project 14 - Measurement and Modeling of Textural Anisotropy in Ti-6Al-4V

Graduate Student – Connor Campbell (CSM)
Faculty/Advisors – T. Lowe, Z. Yu, K. Clarke (CSM)
Industrial Mentor – T. Yao (Weber Metals)

Program Goal

Microstructural texture in forgings of Ti-6Al-4V can interfere with their inspection via ultrasonic techniques. Predicting texture will identify regions where texture can impair nondestructive inspection

Approach

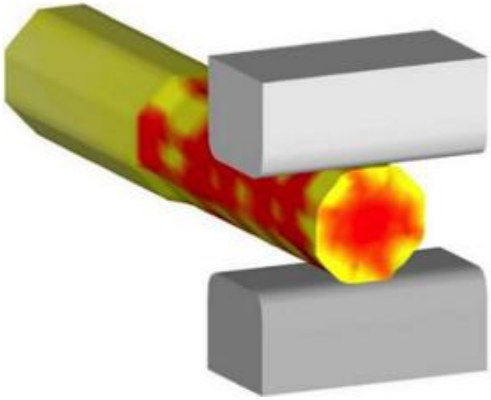
Utilize DEFORM software to model microstructure and texture development in Ti-6Al-4V alloys during forging

Verify modeling results with experimental data

Benefits

Generate constitutive law implementing microstructural effects on mechanical properties and design optimizations

Address/mitigate issues of ultrasonic inspection associated with texture in forged components



DEFORM-3D simulation of cogging

http://wildeanalysis.co.uk/fea/software/deform/deform-3d-suite/deform-cogging

Project Duration

Jan. 2015 to Dec. 2019