The Effects of Microstructure and Material Length Scales on the Fatigue Crack Growth Rates for Thin Wall Additive Manufactured Components

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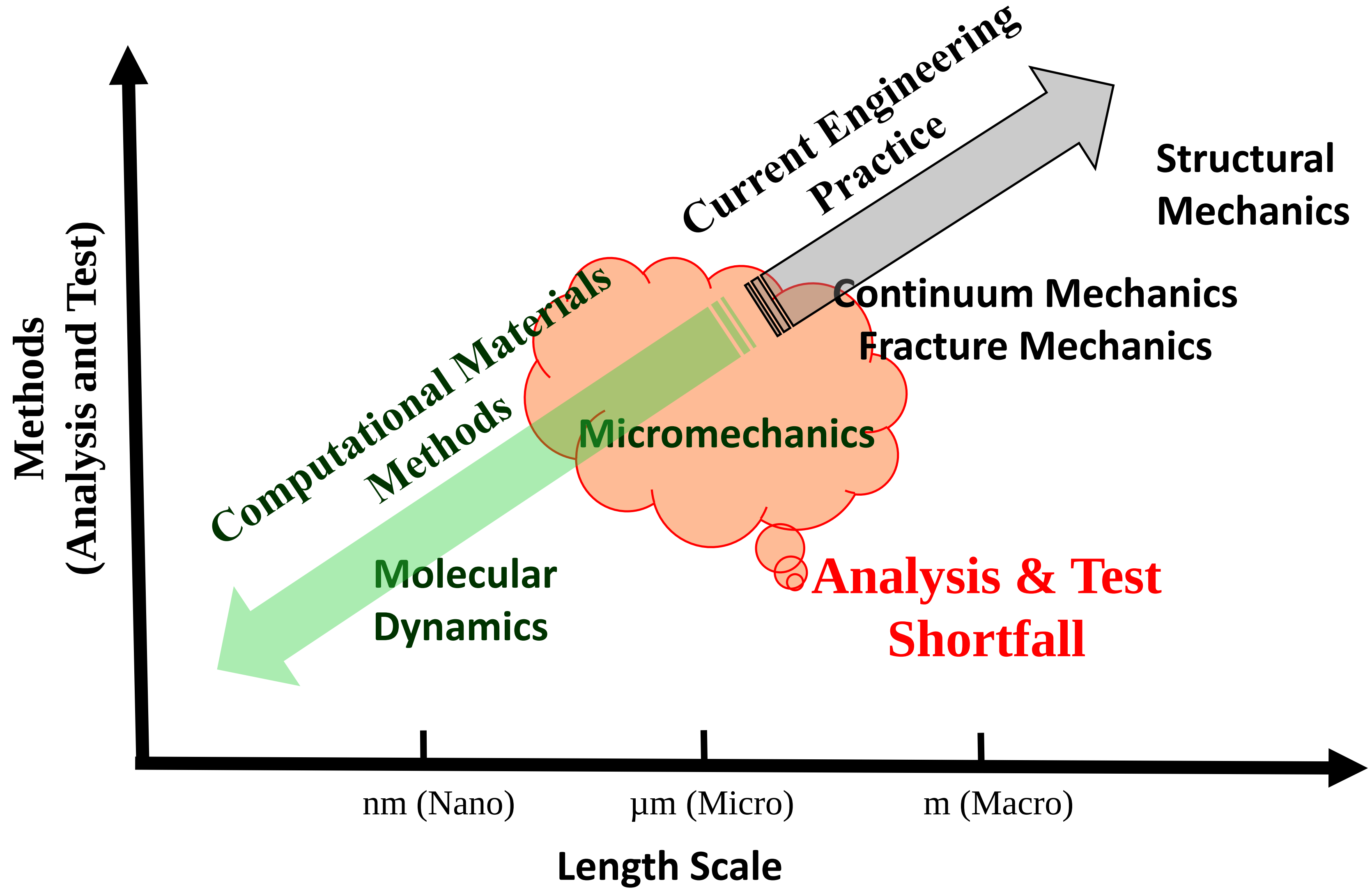
Motivation – Durability and Damage Tolerance Shortfall

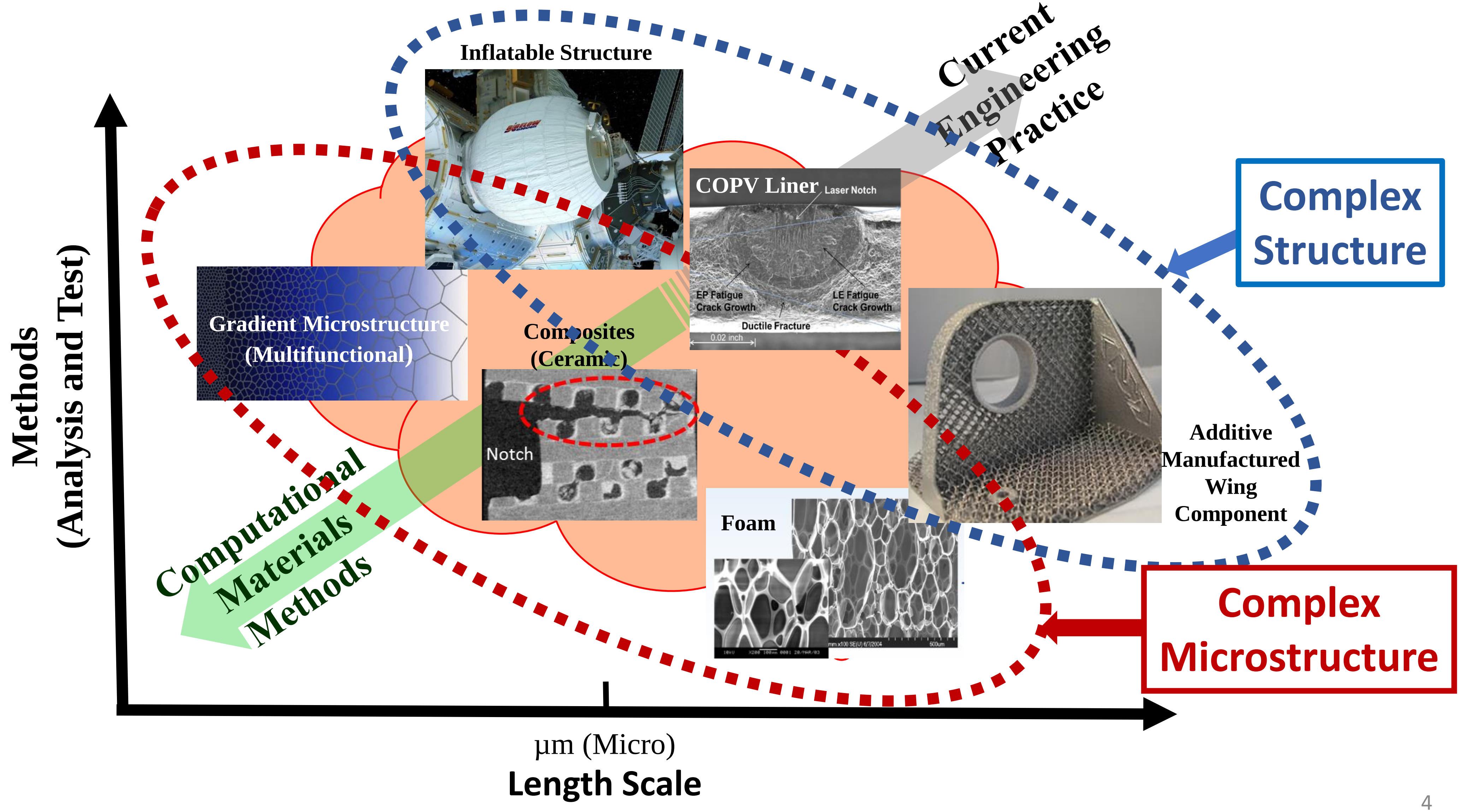
- There is growing concern within NASA that technology gaps are leading to the use of D&DT tools beyond their capabilities (Analysis and Test)
- Many are still using continuum based LEFM in a noncontinuum regime
  - Global properties may not apply
  - Damage growth processes are dependent on local environments
  - Need to understand
    - Local Properties
    - Local Environments
    - Develop new noncontinuum methods

D&DT

- Analysis and Test Methods -



D&DT Analysis and Test Shortfall (Micromechanics Regime)

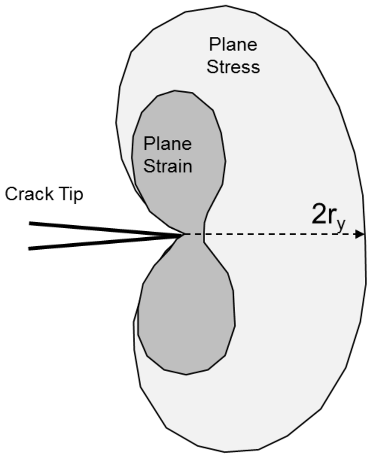


COPV Fracture Control Safe-Life Requirements

- COPVs with elastically responding liners
  - The initial crack is based on the largest crack that can be missed by the NDE inspection
  - The undetected crack (part-though surface crack) is assumed to exist at the "most unfavorable location" with respect to the applied stress and material properties
  - The "most unfavorable" crack must be shown analytically to be able to survive 4 lifetimes
  - Safe-life testing can be performed in lieu of analysis (4 lifetimes are still required)
- COPVs with plastically responding liners
  - "No generally accepted elastic/plastic analytical method is available"
  - Testing is the only acceptable method of demonstrating safe-life (4 lifetimes are still required)

Thin Walled COPVs - Fracture Control Concern

1. Linear elastic fracture mechanics (LEFM) assumptions at some point will become violated as the liner thickness is reduced
   a) Are the current theories that define the LEFM limitations relative to thickness (e.g., crack depth + plastic zone < remaining ligament, 5 to 10 grains in the remaining ligament) valid?
   b) Can better guidelines be developed to quantify when the use of LEFM is invalidated by decreasing thickness (influenced by applied stress, yield stress, and microstructure)?
2. Safe-life testing procedures or recommendations are not specified



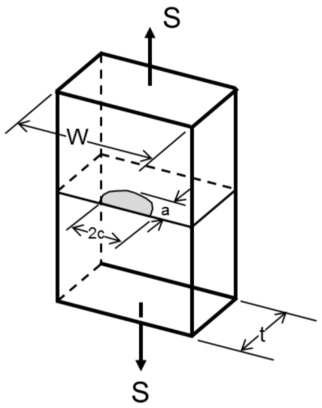
Plane Stress

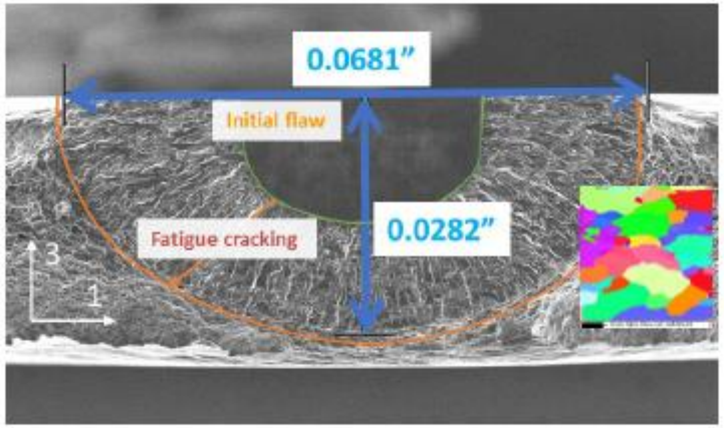
$$2r_y = \frac{1}{\pi}\left(\frac{K}{S_y}\right)^2$$

Plane Strain

$$2r_y = \frac{1}{3\pi}\left(\frac{K}{S_y}\right)^2$$

LEFM is valid if $t > a + 2r_y$





$2r_y = plastic\ zone\ size$

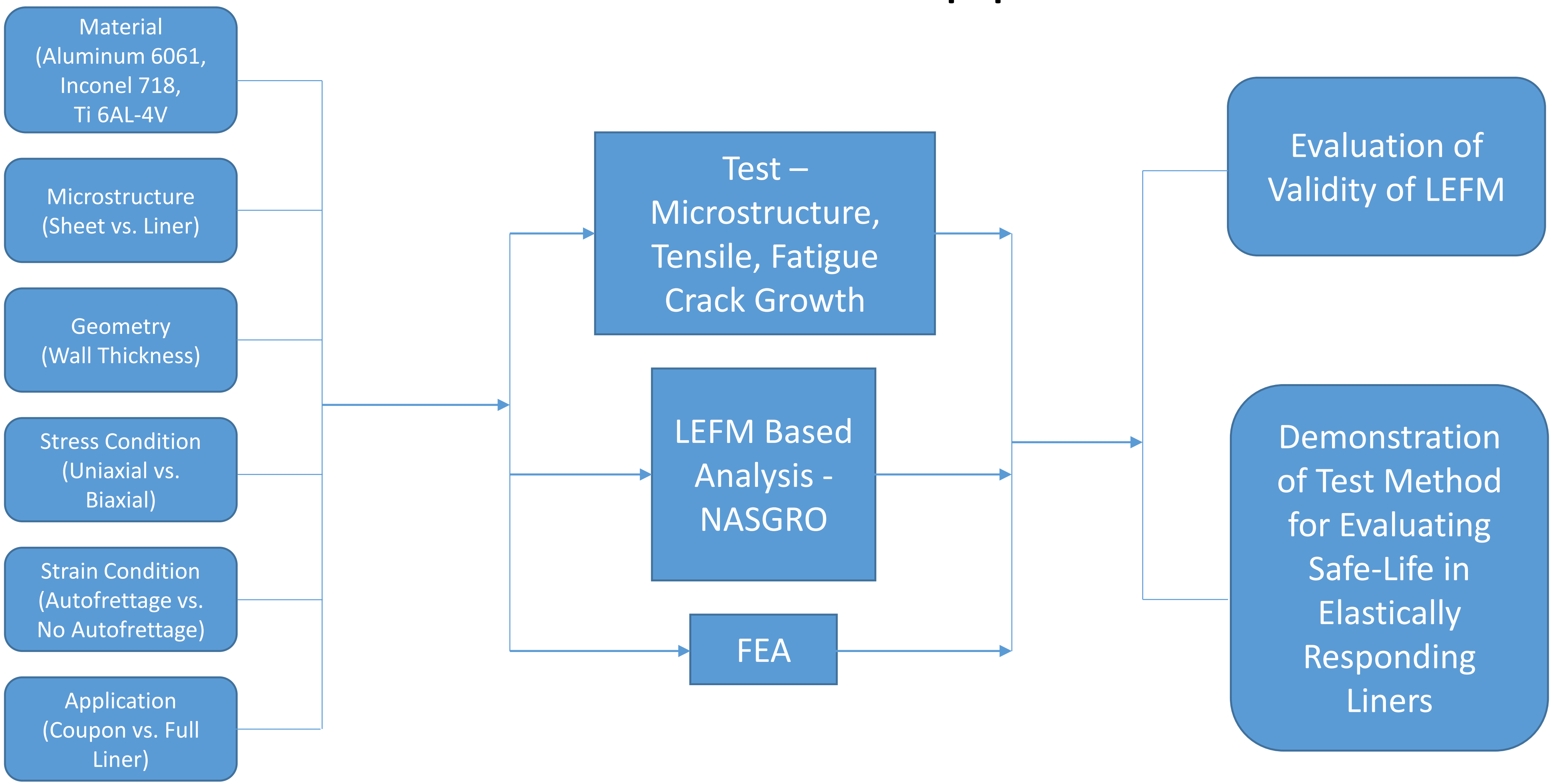
$\frac{K}{S_y} = ratio\ of\ stress\ intensity\ factor\ to\ yield\ stress$

COPV Life Test Assessment

Objectives

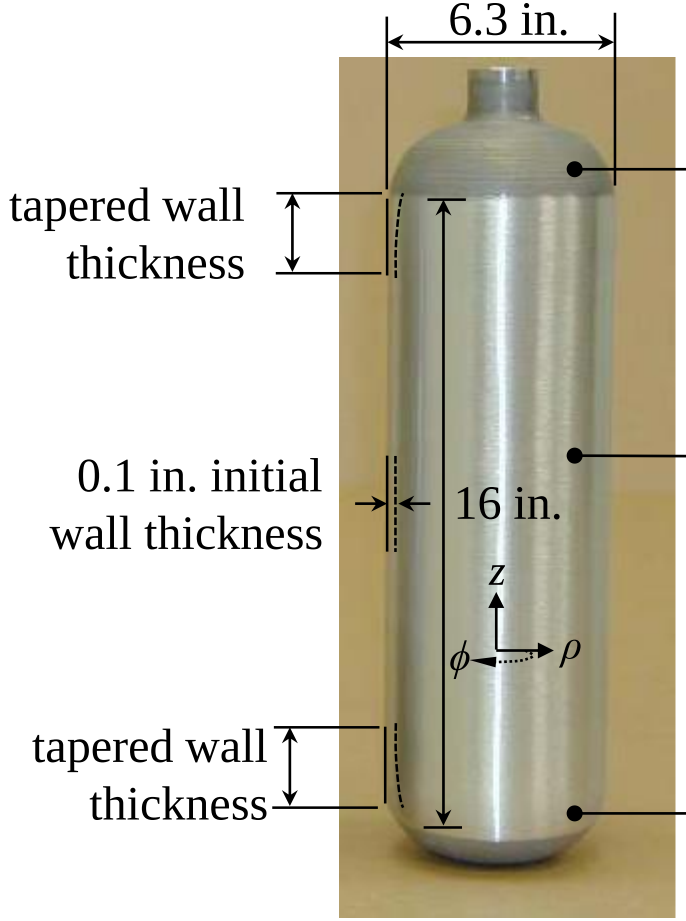
1. Evaluate the applicability of linear elastic fracture mechanics (LEFM) based life predictions for metal liners of composite overwrapped pressure vessels (COPVs)
2. Develop a test procedure for experimentally evaluating COPVs when LEFM is not applicable

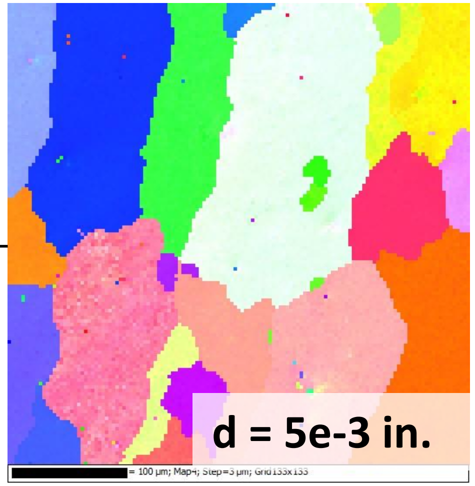
Technical Test Approach

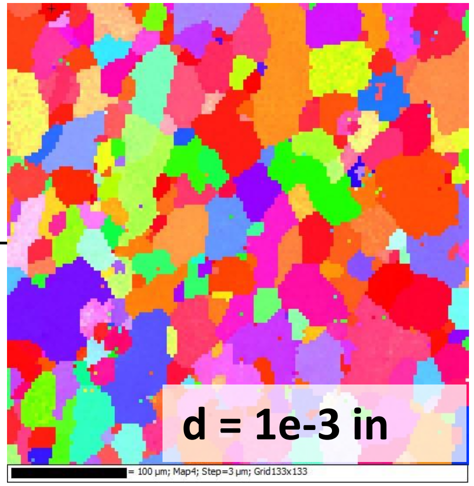


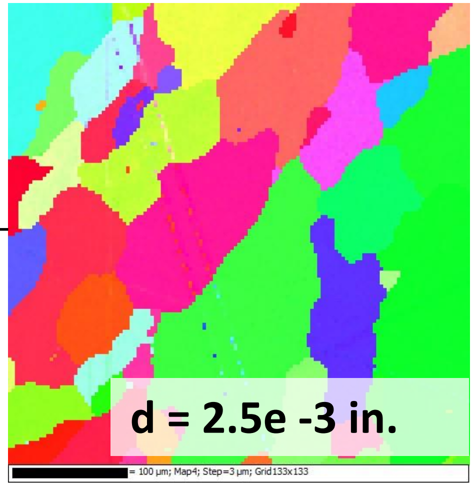
Liner Microstructure Variation

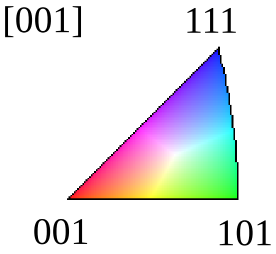
Spin-formed liner









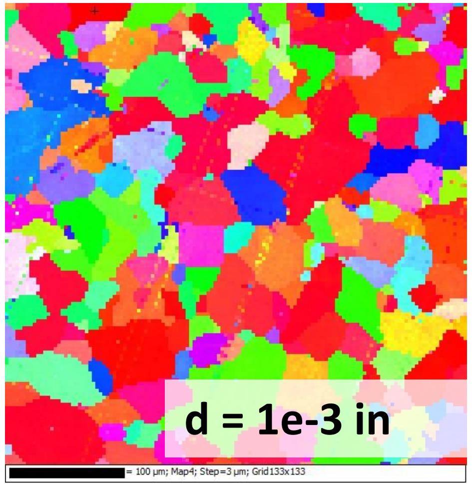


Microstructure inconsistency

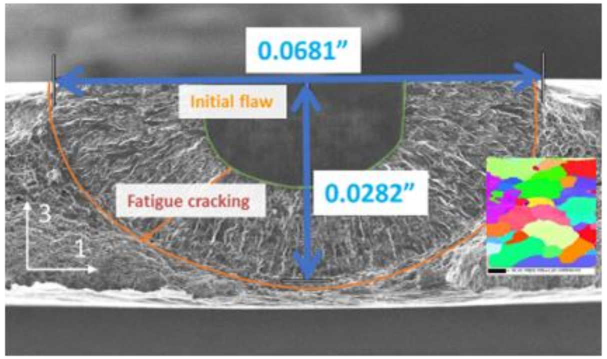
Spin-formed liner:
- follows flow lines
- random texture
- varies along length

Rolled sheet:
- elongated grains
- rolled texture
- consistent across sheet

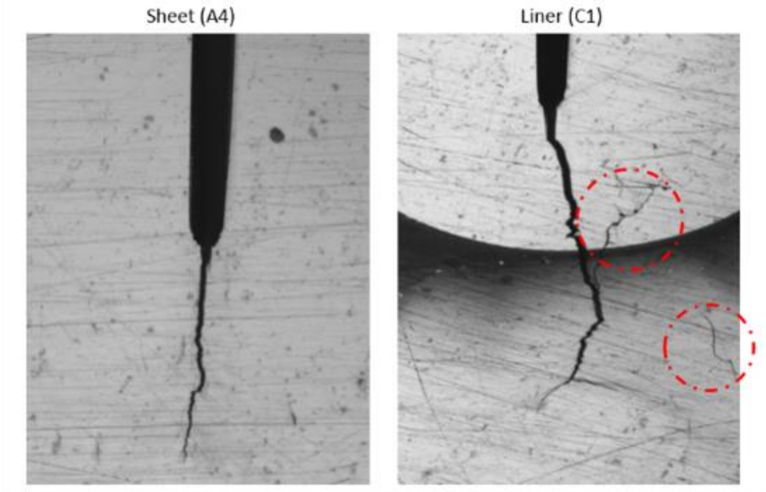
Rolled sheet



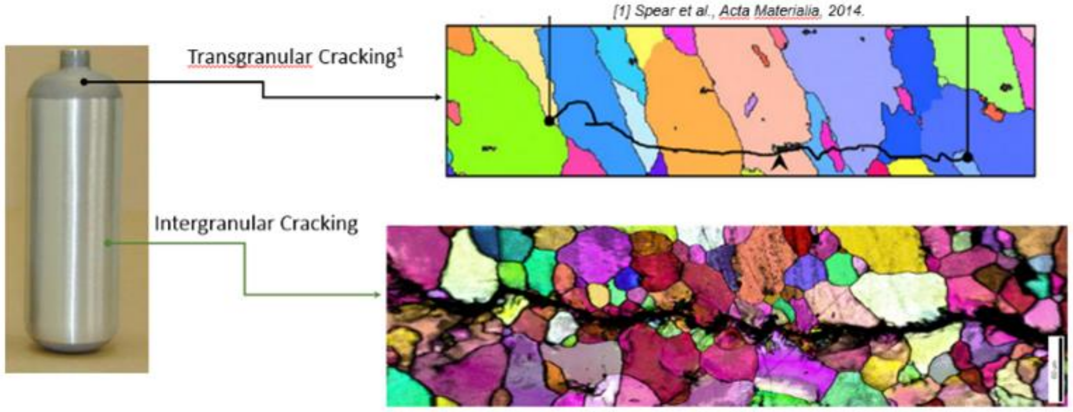
Small-Scale Testing: Fatigue Crack Growth Rates Comparison

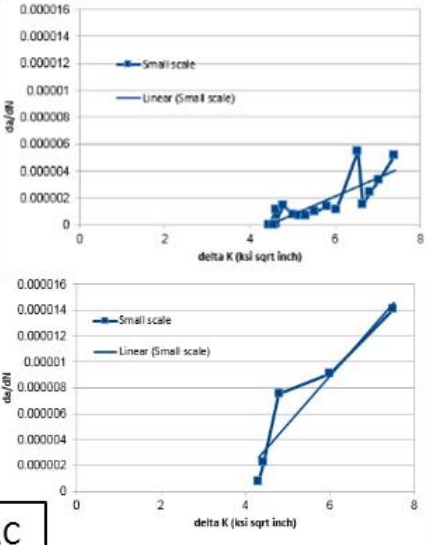


Flaws introduced using PFIB, able to characterize grains with EBSD.



Secondary cracking occurred in spun-formed material that does not form in sheet

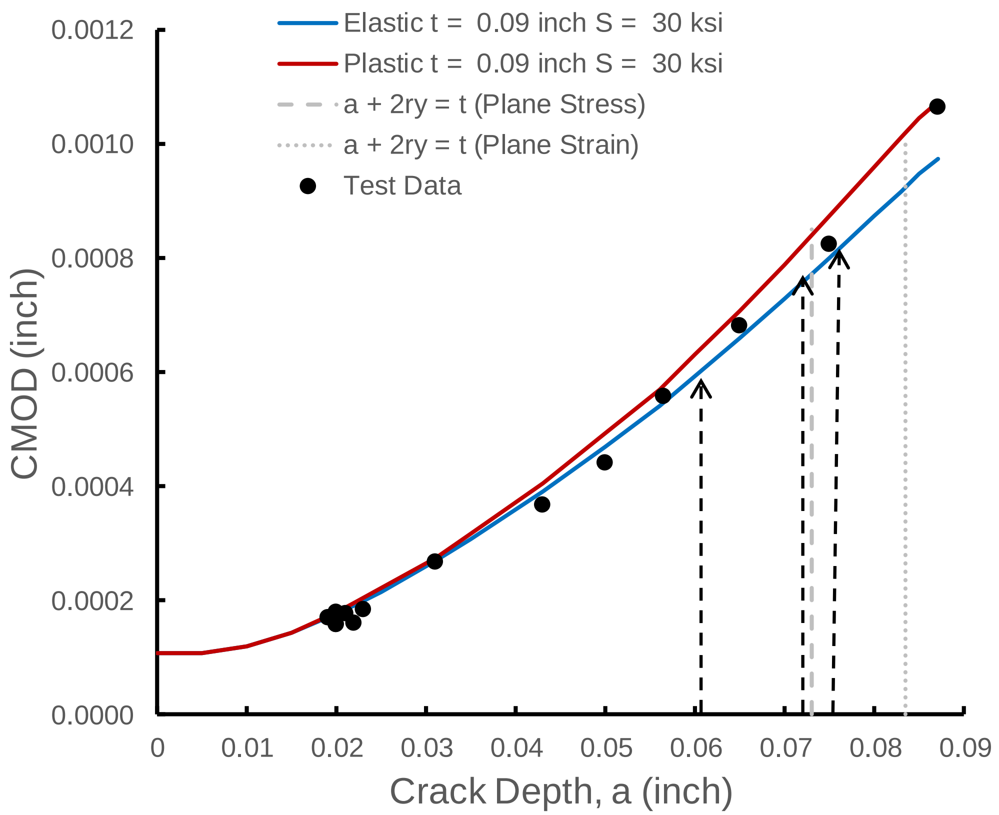


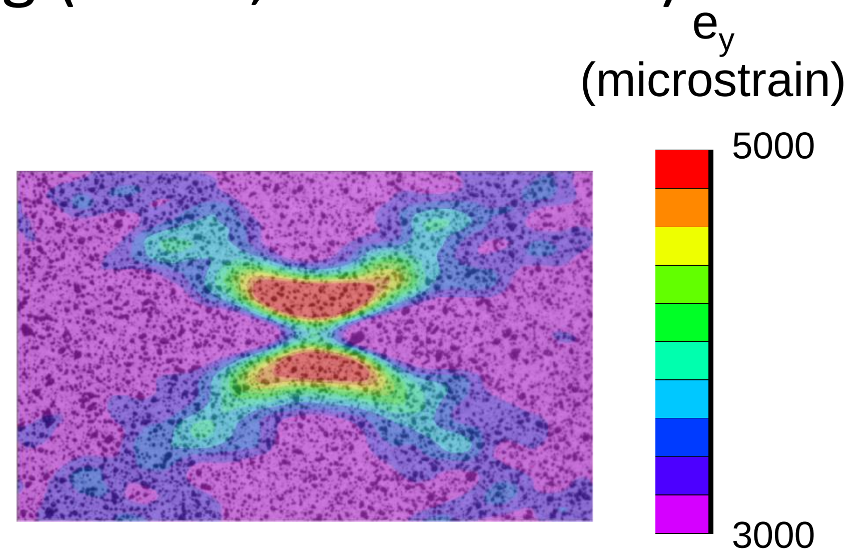


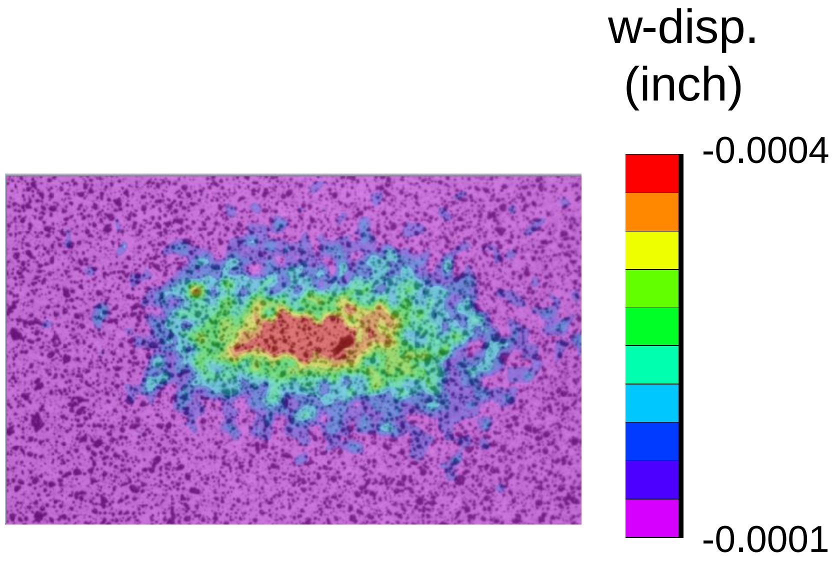
FCGR was higher in small grain material due to intergranular nature of crack growth. This grain size/FCGR relationship is not expected and could potentially be effect of spun-formed product.

All data from J. Hochhalter, et al, LaRC

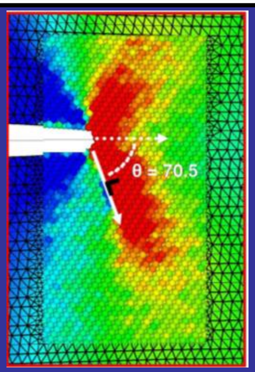
Back Face Strain and Dimpling (30 ksi, t = 0.09 inch)



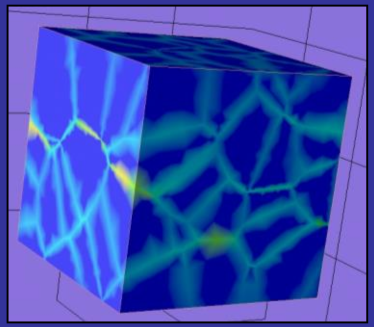




Computational Materials for Material Performance



Modeling Plasticity at a Crack Tip



Simulation of Crack Growth in a Material Microstructure

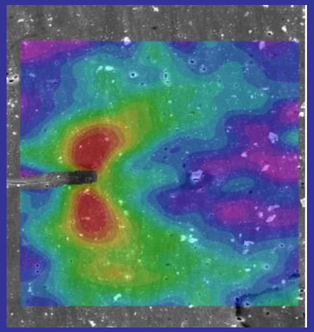
Simulate Operative Physical Processes at Relevant Length Scales

- Simulate critical damage processes
- Develop micro-/nano-structure-based simulations that interrogate damage processes at local length scales and local environments
- Propagate uncertainties across length scale to predict component reliability
- Design materials to extend structural life

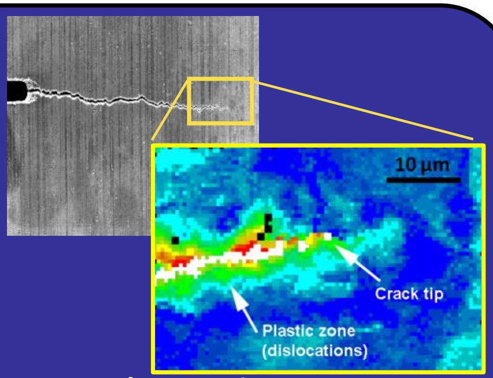
Physics-Based Material Design & Certification Requires Close Integration of Analysis and Experimentation

Characterize the Physics of Damage via Experimental Evaluation

- Develop micro-/nano-structure-based testing & characterization that interrogates damage processes at local length scales and local environments
- Validate damage models and understand operative processes
- Fabricate and evaluate model materials

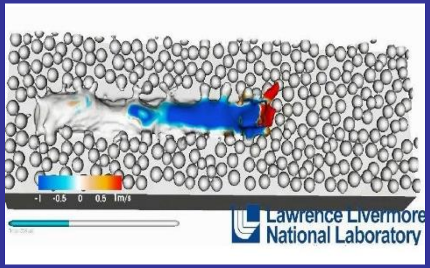


Measure Deformation at Crack Tip

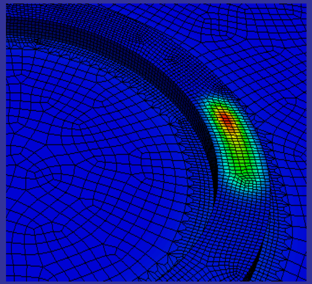


Characterize Damage Evolution

Computational Materials for Material Processing



Simulation of Laser-Powder Bed Interactions


Prediction of Local Heat Distribution

Simulate Fundamental Physics Governing Processing

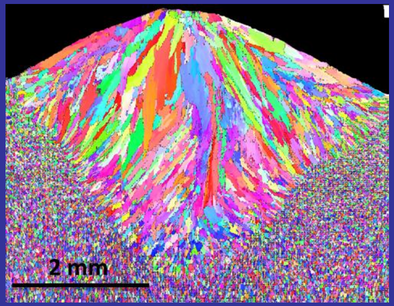
- Determine role of processing parameters and composition on microstructure
- Simulate physical processes including laser beam absorption in powder bed, heat transfer via conduction and radiation, and fluid flow at the melt pool, particle flow
- Simulate residual stress, distortion, microstructural evolution and precipitate growth

Develop Physically Correct Models Needed to Support Certification of AM Feed Stock and Manufacturing Process

Characterize Material Evolution using Experimental Methods

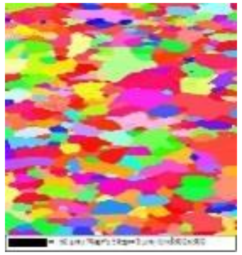
- Employ heavily-instrumented SLM machine and synchrotron beam lines (APS, CHESS)
- Produce coupon-size specimens using well-controlled parameters
- Understand details of the relationship between processing parameters and resulting microstructure


Selective Laser Melting

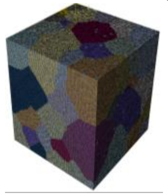


Grain Structure from Additive Process

Development of Microstructurally-Informed D&DT – Big Picture



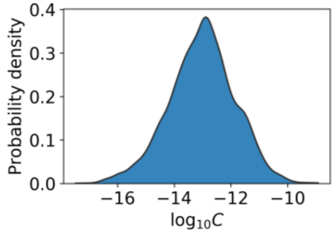
Characterize Microstructure using Quantitative Measurements



Localized FEA Models and Analyses Exploiting Fitted Measured Data

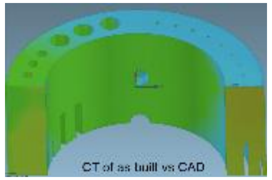
Microstructurally Small Crack Growth Model and Analysis to Understand Local Parameters

Fatigue Crack Growth Parameter Distributions



D&DT Analysis Tools (NASGRO, LEFM, EPFM, etc)

Global FEA Models and Analyses Subject to Service Environments



Today's D&DT Engineering Standard Practice

- Today's standard D&DT standard engineering practice relies on continuum assumptions
- Microstructurally-informed D&DT will consider local length scales, environments and material properties
  - Expanded effort on small-scale testing and physics-based material model calibration
  - Produce distributions of behavior by relying more heavily on modeling and simulation

What’s Next

Materials
NDE
Fracture Control

Quantitative Defect (In-Situ) Monitoring

LEFM Breakdown (Length scale effects)

Microstructural Influences (Test & Modeling)

Damage Tolerance Testing

Certification Protocol