Fatigue Analysis of
Laser Power Bed Fusion (LPBF) Ti 6Al-4V

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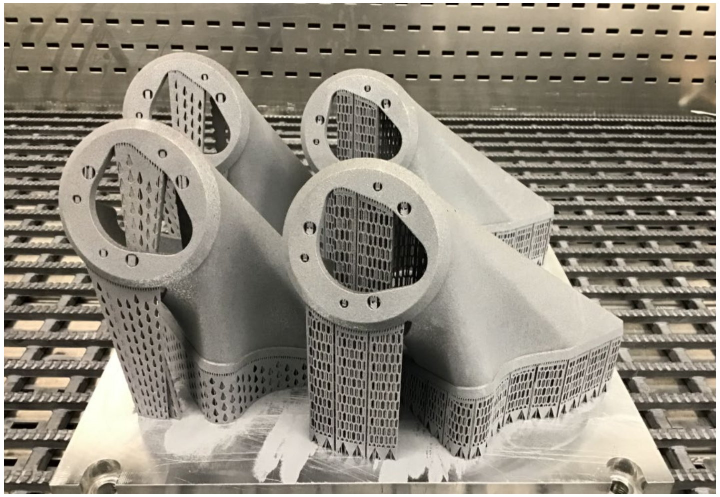
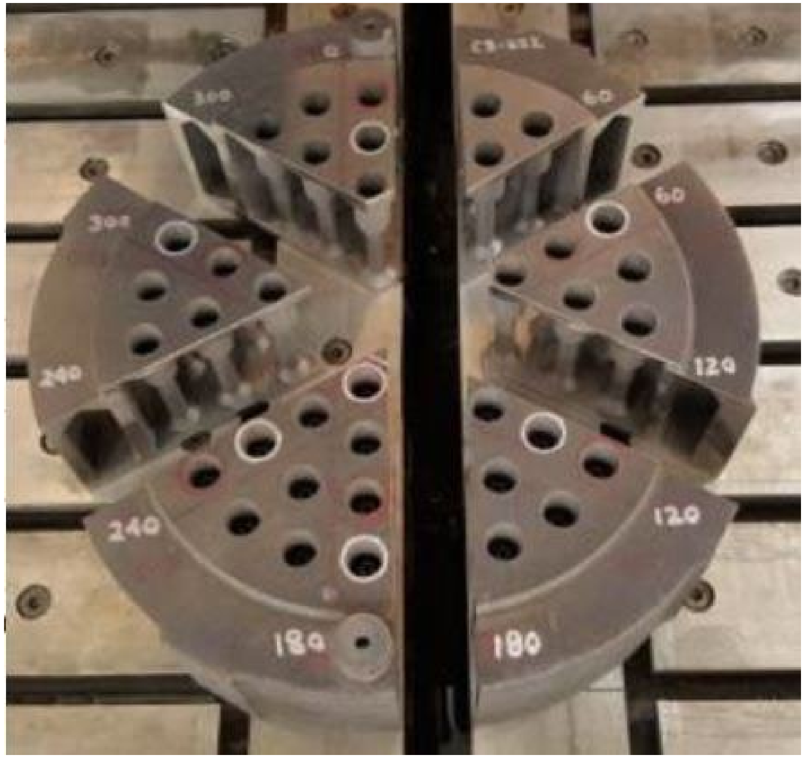
Outline

- Overview of Additive Manufacturing
- Methodology of Fatigue Life Analysis with Microstructural Properties
- Fatigue Tests of PBF Ti 64 Specimens
- Microstructural Material Property Development
- Comparisons of Test Data and Analysis Results
- Conclusions
- Future Work



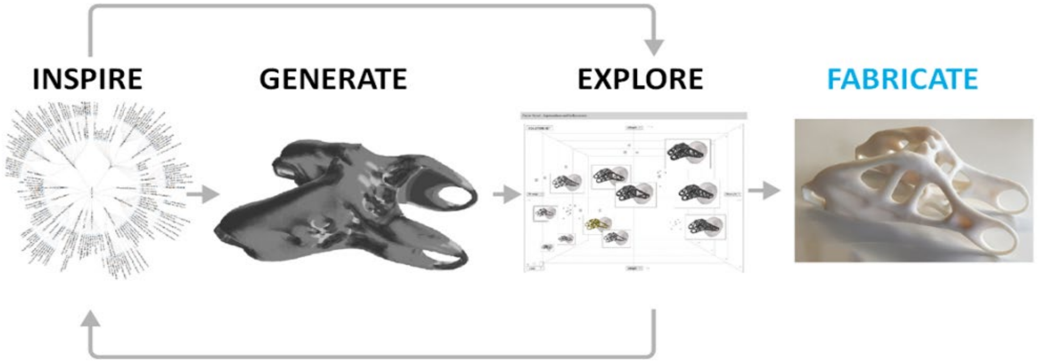
Overview of Additive Manufacturing



What is Additive Manufacturing (AM)?

- Additive Manufacturing, also known as 3D printing technology, is “process of joining materials to make objects from three-dimensional (3D) model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies” defined by ASTM (American Society for Testing and Materials).

- Benefits of AM
  - Form almost any shape or geometry
  - Minimize material waste
  - Repeated easily with CAD (Computer Aided Drawing)
  - Reduce significant amount of joining materials, i.e. fasteners, bolts and nuts



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Challenges of AM

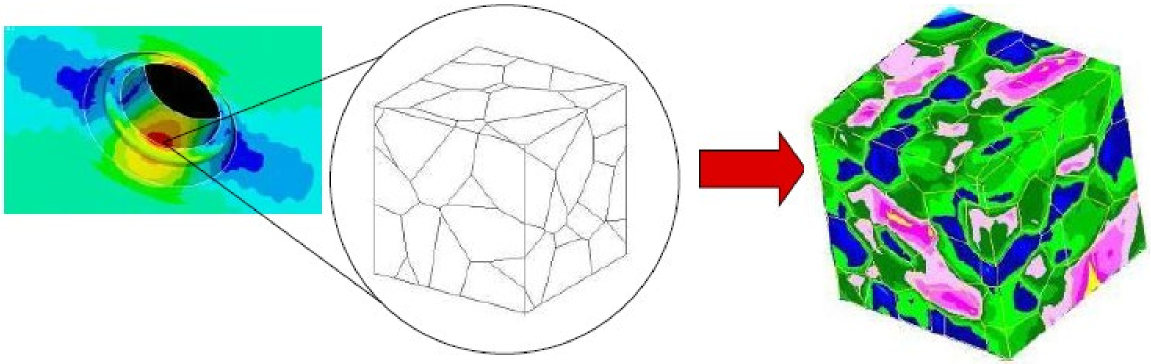
- Variability of microstructure of AM processed materials such as grain orientation and size, and defect/void distributions
- Solution for “As-Built” surface condition
- Determination of fatigue material properties of AM materials
    - material state variation: homogeneous vs heterogeneous
- Development of fatigue analysis methodology
    - Impact on fatigue life prediction due to microstructural material input
- Non-destructive Inspection (NDI) Technology

Typical AM Types for Metals

- Power Bed Fusion (PBF): use either laser or electron beams to fuse powder particles layer-by-layer
  - Selective Laser Sintering (SLS): used for polyamide, Alumide and rubber-like materials
  - Selective Laser Melting (SLM) / Direct Metal Laser Sintering (DMLS): similar process to SLS, but exclusively used for metal parts such as aluminum and titanium alloys
  - Electron Beam Melting (EBM): uses high energy electron beam, produces less residual stress resulting in less distortion. Requires less energy and produces layers faster than SLS. -> most useful in aerospace and defense

- Directed Energy Deposition (DED): creates parts by directly melting materials and deposing them on the workpiece, layer by layer. Mostly used with metal powders or wire materials
  - Electron Beam Additive Manufacturing (EBAM): produces large scale metal structures
  - Other DED processes – LENS and Aerosol Jet Technology by Optomec, Laser Deposition Welding (LDW)

Methodology of Fatigue Life Analysis with Microstructural Properties



Limitations of Current Fatigue and Crack Growth Analysis

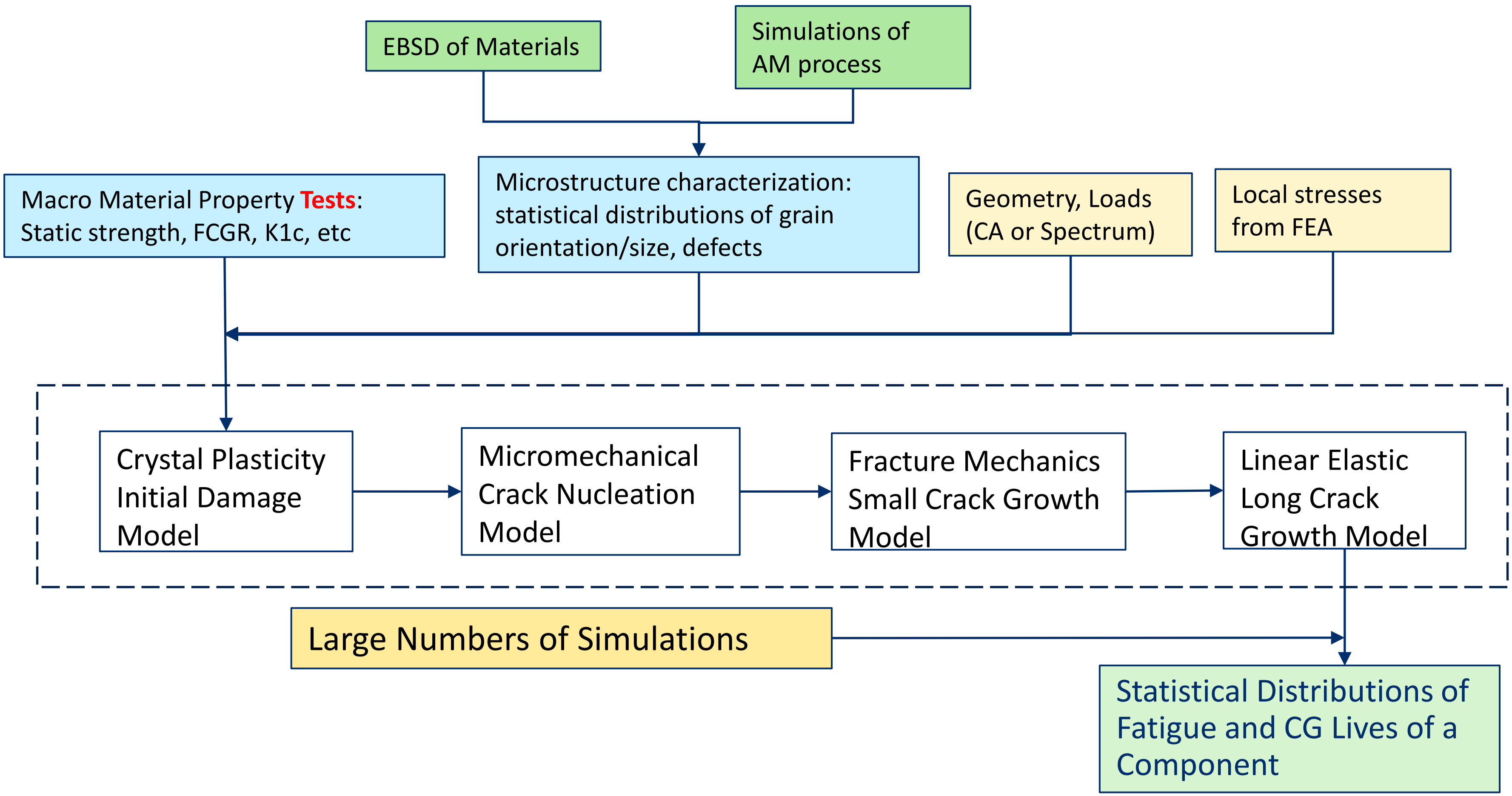
- Follows Linear Elastic Fracture Mechanics (LEFM)
  - Material is homogeneous & isotropic
  - Globally
- Microstructural properties have no impact.
  - No microstructure property variability
  - Additive Manufacturing Processes and Materials have wide range of variability per material processes
- Utilize deterministic material properties -> doesn't capture uncertainties from lab environment, numerical error, lack of data, etc..

Fatigue & Crack Growth Analysis of AM Materials:
Integrated Computational Materials Engineering (ICME) Application

- Since microstructural properties are different per base power, machine specification, and material process, microstructural analysis is required for AM material fatigue analysis
- Cost and schedule constraints to test each case by materials and processes
- Need to quantify effects of AM process variations on mechanical performance of AM-built parts
- Simulate different microstructures and develop statistical distributions of microstructural properties
- To capture variability of AM material properties, probabilistic approach is needed with statistical distributions
- Certification and developments including inspection techniques are required to expand AM to durability and fracture control parts

AM is an Ideal Case of ICME Application

AM Fatigue Life Process to meet ASIP Requirement



Fatigue Analysis of AM, VPS-MICRO - 1

- VEXTEC developed a fatigue analysis tool that predicts fatigue life with statistical distributions of microstructure, VPS-MICRO
- VPS-MICRO utilizes Monte Carlo analysis method combining the models of dislocation theory with random variable statistics
- VPS-MICRO has three stages of fatigue life: crack initiation, small crack growth and long crack growth

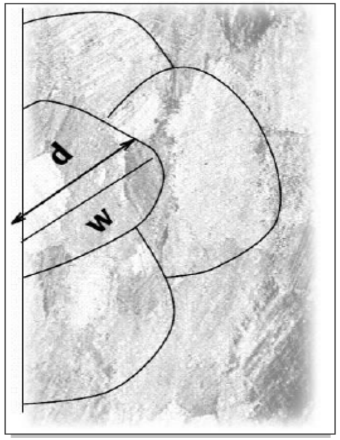
Fatigue Analysis of AM, VPS-MICRO - 2

- Crack initiation: smooth fracture surfaces at angle inclined to the loading direction -> shear stress fracture
  - The equilibrium condition of the grain on the first loading:

$$\tau_1^D + (\tau_1 - k) = 0$$

where K is the frictional stress, , τ_1 is the applied shear stress and τ_1^D is the back stress caused by the dislocations

  - The incremental stored dislocation strain energy is cumulated with each cycle and a crack nucleates when the total stored energy is equal to the fracture energy of grain



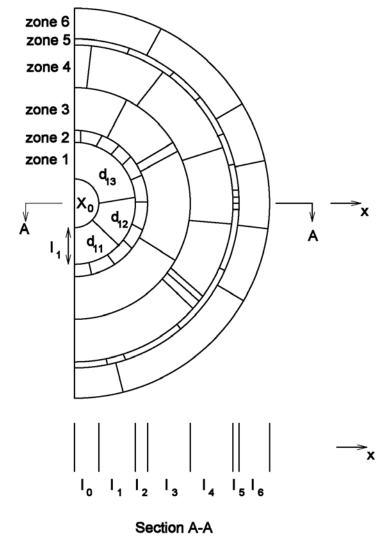
$$N_n = \frac{4GW_s}{\left(\frac{1}{m}\Delta\sigma - 2k\right)^2 \pi(1-\upsilon)d}$$

where N_n is number of cycles needed to nucleate a transgranular crack in a grain, W_s is specific fracture energy, m is Schmid factor and $\Delta\sigma$ is applied stress

Fatigue Analysis of AM, VPS-MICRO - 3

- Small Crack Growth: a function of the crack tip opening displacement (CTOD)
- Used the theory of continuously distributed dislocation to model the CTOD

$$\frac{da}{dN} = C'(\Delta COD)^{n'}$$



where a is the crack length, N is the number of cycles, C' and n' are empirical constants

- For the crack to overcome a grain boundary obstacle and propagate into the subsequent layers of grains, the local stress intensity factor must exceed the critical local stress intensity factor of the grain boundary
- CTOD depends on the relative location of the crack tip and the plastic zone tip
- Small crack growth phase: until the plastic zone spans many grains and the effective properties of the material between the crack tip and the slip band tip approach the bulk properties

- Long Crack Growth: Linear Elastic Fracture Mechanics (LEFM) and not affected by microstructure. Current long CG capability is limited.

Material Properties Required for Fatigue Analysis

Parameter	Nature	Explanation
Shear Modulus (G)	Deterministic	Ratio of the materials shear stress to shear strain
Poisson's Ratio (ν)	Deterministic	Ratio of the material's transverse strain to axial strain
COV on Micro Stress	Probabilistic	COV that describes the level of anisotropy in the material crystal system
Orientation	Probabilistic	The orientation of the crystallographic slip systems in the material
Grain Boundary Strength	Deterministic	Minimum Strength a nucleated crack must have to propagate beyond initiation
Small Crack Coefficient	Deterministic	Multiplicative coefficient to the small crack regime's growth rate
Specific Fracture Energy	Deterministic	Energy barrier for crack nucleation
Grain Size	Probabilistic	Size of the microstructural features participating in the damage mechanism
Frictional Strength	Probabilistic	Micro-yield strength of a grain that resists dislocation pile-up
Long Crack Parameter	Probabilistic (C) Deterministic (n)	Exponent and coefficient of the long crack regime's growth rate as described by the Paris relation
Defect Size & Population	Probabilistic	Size and population density of the defects participating in the damage mechanism

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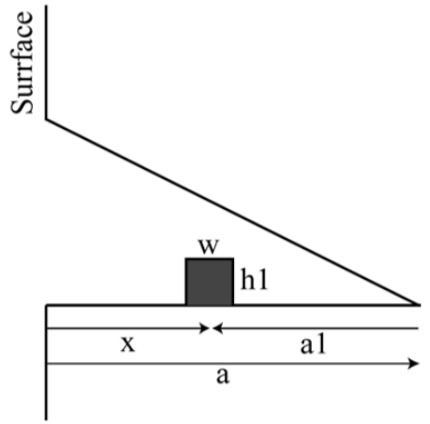
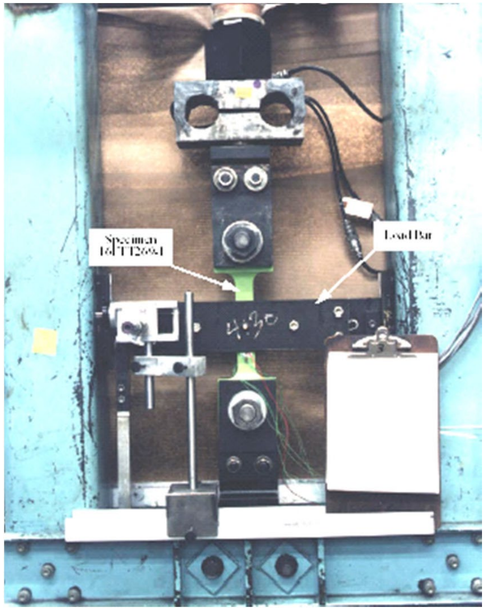
Defect Property Inputs

- Statistical Distribution of Defect Density and Defect Size
  - Defect Density: population of defects per unit surface area
  - Defect Size: length of the defect in the direction of crack growth
  - Defect parameters are determined from microscopic images of polished surfaces of the material microstructure
  - Reference: ASTM E3, ASTM E45, ASTM E1245
- Asperity Factors: Asperity Height Factor, Distance Factor, Width Factor and Modulus Factor
  - Contributes to crack closure and models fracture surface roughness
  - Asperity Height Factor: fracture surface roughness as a percentage of the average grain size
  - Asperity Distance Factor: distance behind the crack front that the fracture surface touch as a percentage of the average grain size
  - Asperity Width Factor: width of the asperity as a percentage of the average grain size
  - Asperity Modulus Factor: elastic modulus of the asperity as a percent of the matrix material



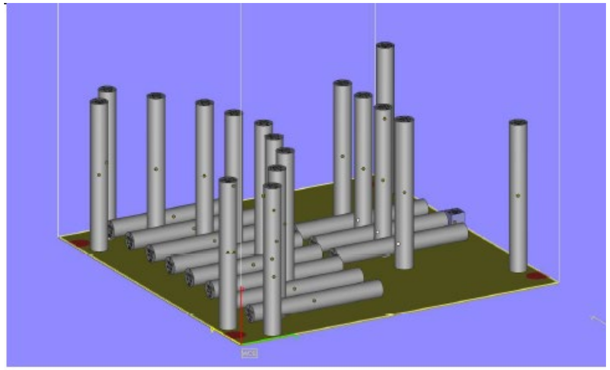
Crack with asperity of height h1 and width w.

Fatigue Test of L-PBF Ti 64 Specimens

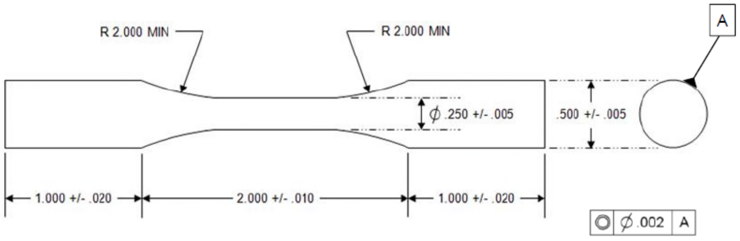


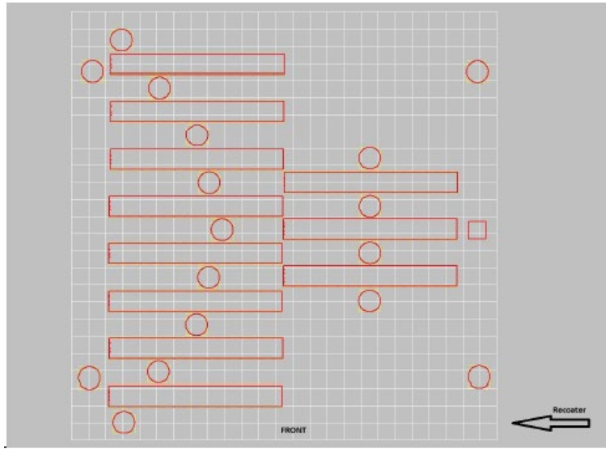
AM Ti 6Al-4V Specimens

- L-PBF Ti 6Al-4V specimens were built per LM AM material and process specifications.
  - Ambient temperature
  - xy and z build directions
  - All specimens were hot isostatic pressed (HIP) and annealed



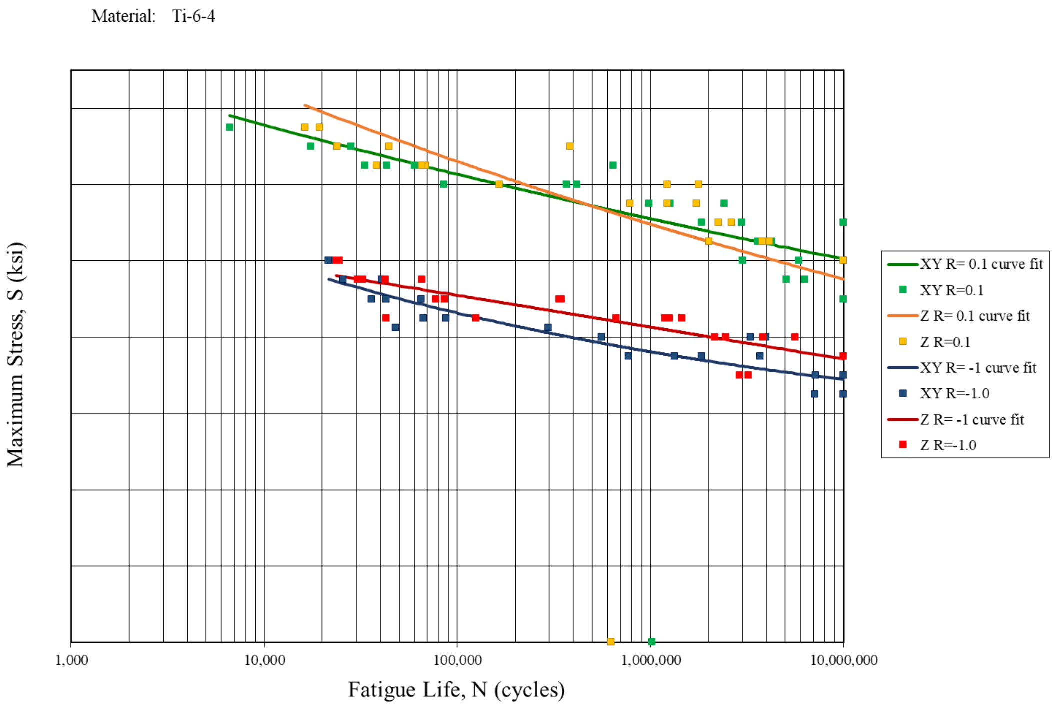
- Specimens were machined per ASTM E8

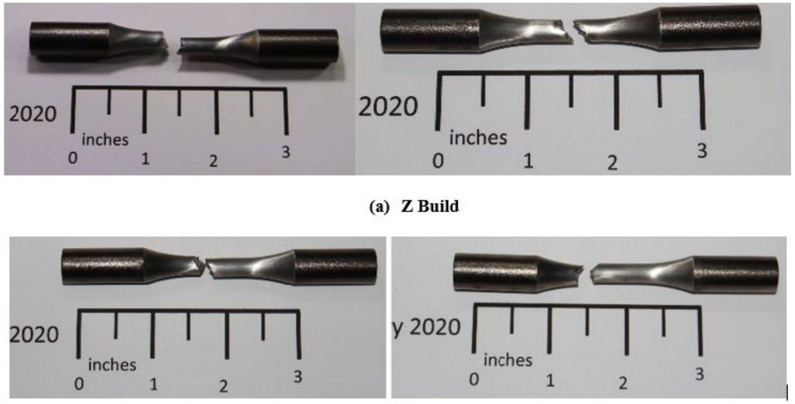




High Cycle Fatigue (HCF) Test Results

- HCF tests were run at two stress ratios, R=0.1 and -1
- The results indicate that there's no significant difference between XY and Z build directions

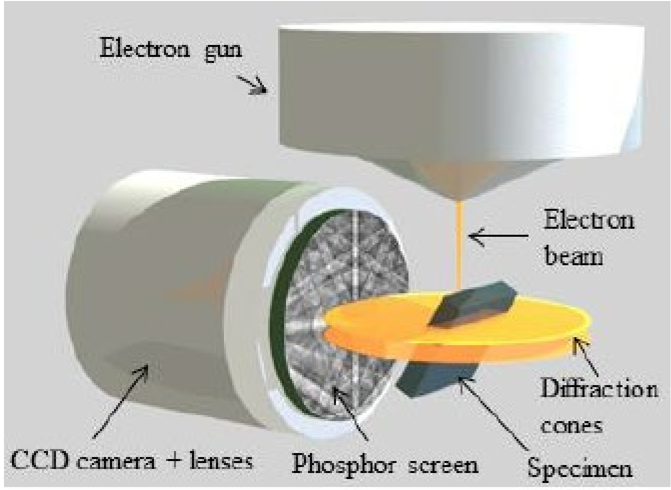




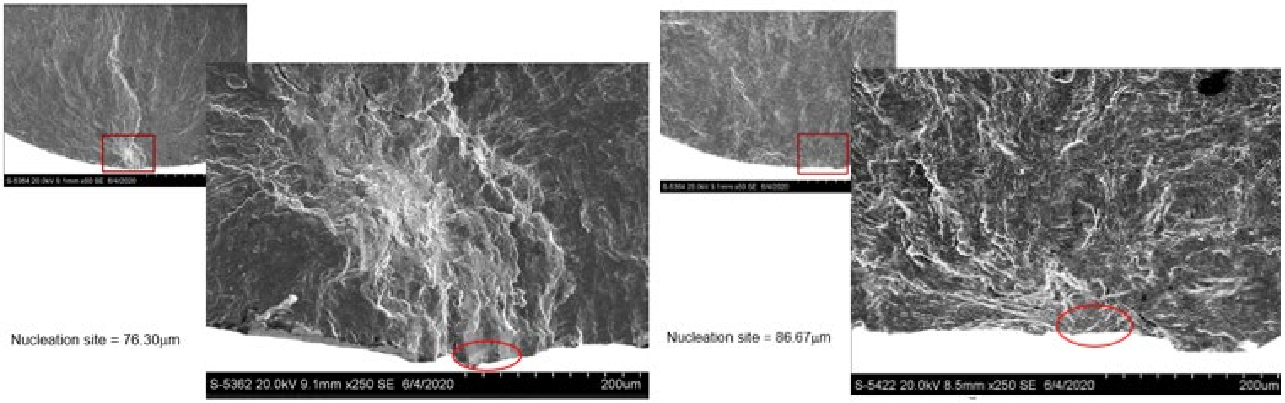
(a) Z Build

(b) XY Build

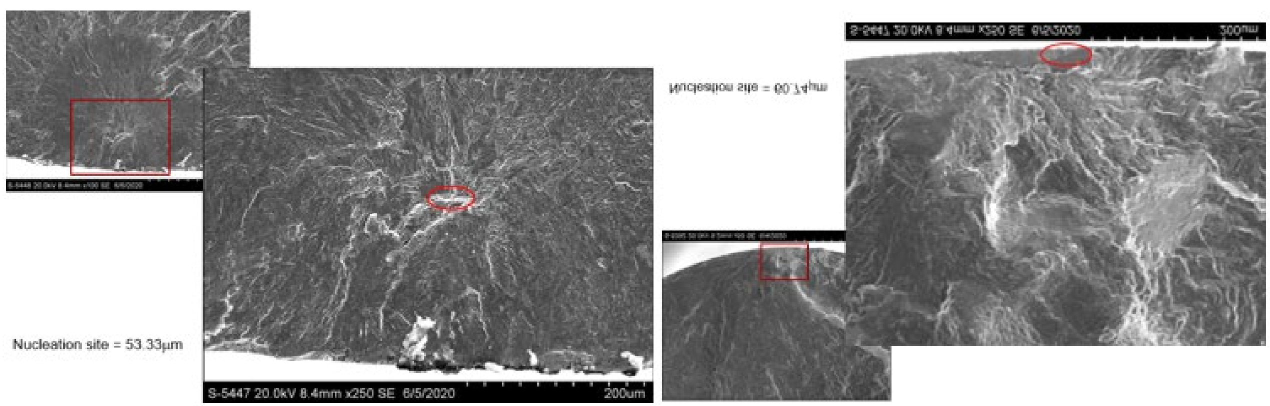
Microstructural Material Property Development



Fractography of PBF Ti 64 Specimens



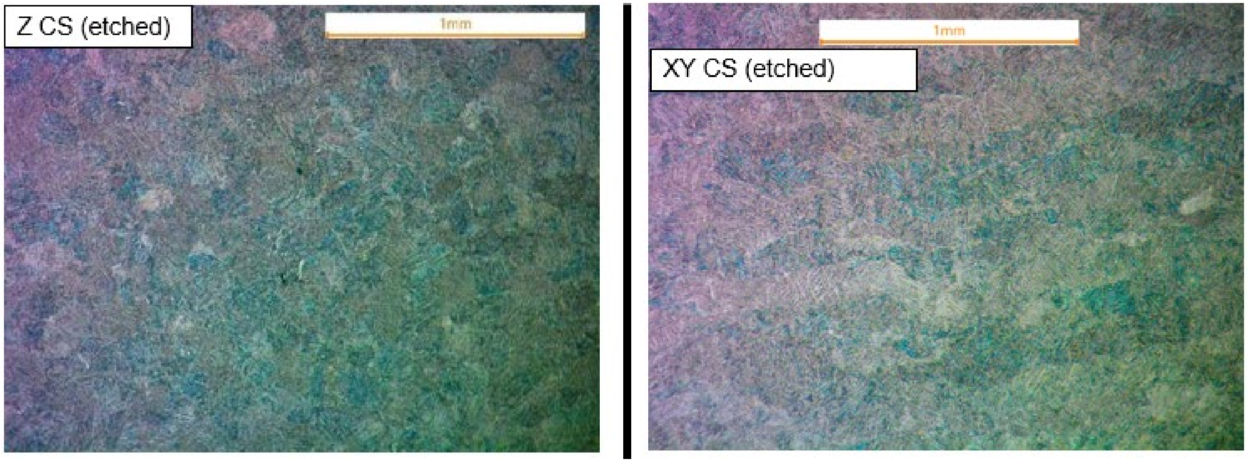
(a) XY Build Specimens



(b) Z Build Specimens

Microstructure of PBF Ti 64 Specimens

- After HCF test completion, two specimens in each direction were cut and etched to obtain grain size distribution

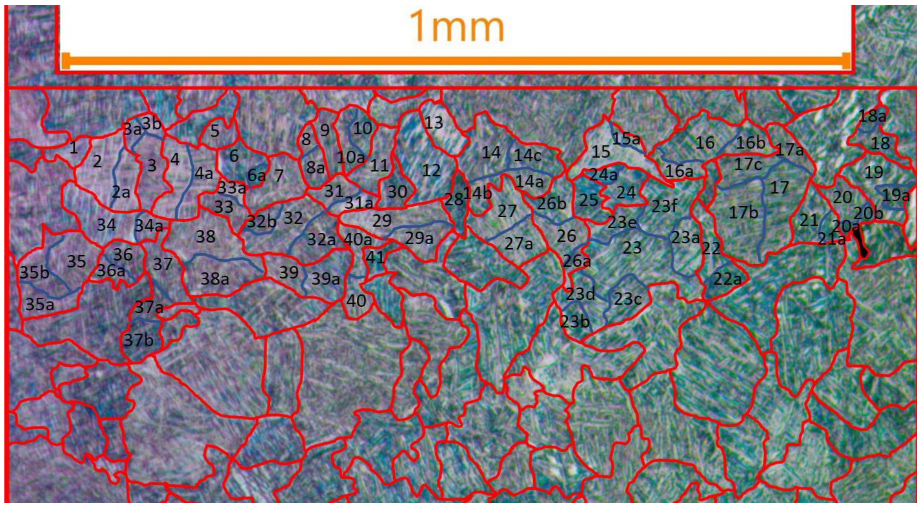


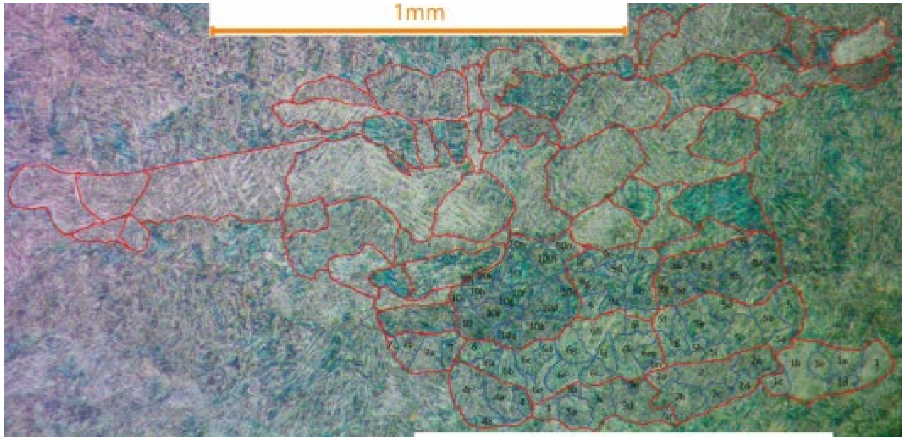
PBF Ti 64 Metallography

- No visual defects were identified due to HIP process

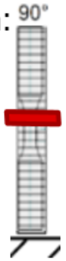
Grain Size Distribution of PBF Ti 64 Specimens

- Grain size is the microstructural feature that determines the length of a slip distance.
- This parameter is probabilistic, and is determined by conventional metallographic techniques





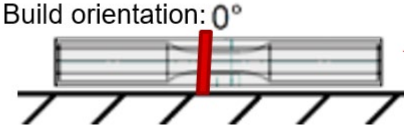
Build orientation:



Z direction

N_{grains} measured = 69

	image vertical	image horizontal
mean:	**3.418E-3 in** (86.82 μm)	2.957E-3 in (75.11 μm)
standard deviation:	1.345E-3 in (34.16 μm)	1.448E-3 in (36.78 μm)
COV:	**0.39**	0.49

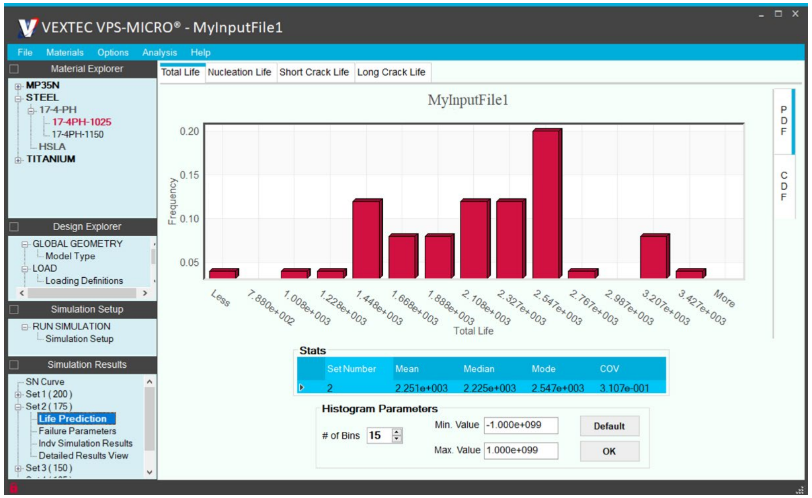


XY direction

N_{grains} measured = 59

	image vertical	image horizontal
mean:	**4.161E-3 in** (105.69 μm)	7.071E-3 in (179.60 μm)
standard deviation:	1.699E-3 in (43.152 μm)	3.794E-3 in (96.375 μm)
COV:	**0.41**	0.54

Fatigue Analysis of PBF Ti 6Al-4V



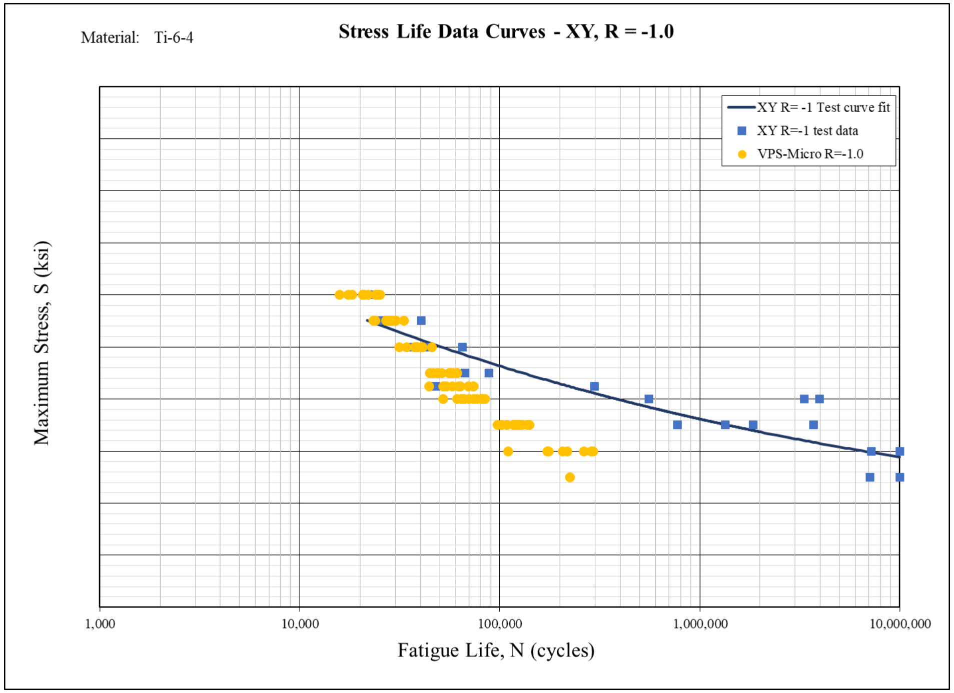
Material Properties from LM Test Specimens

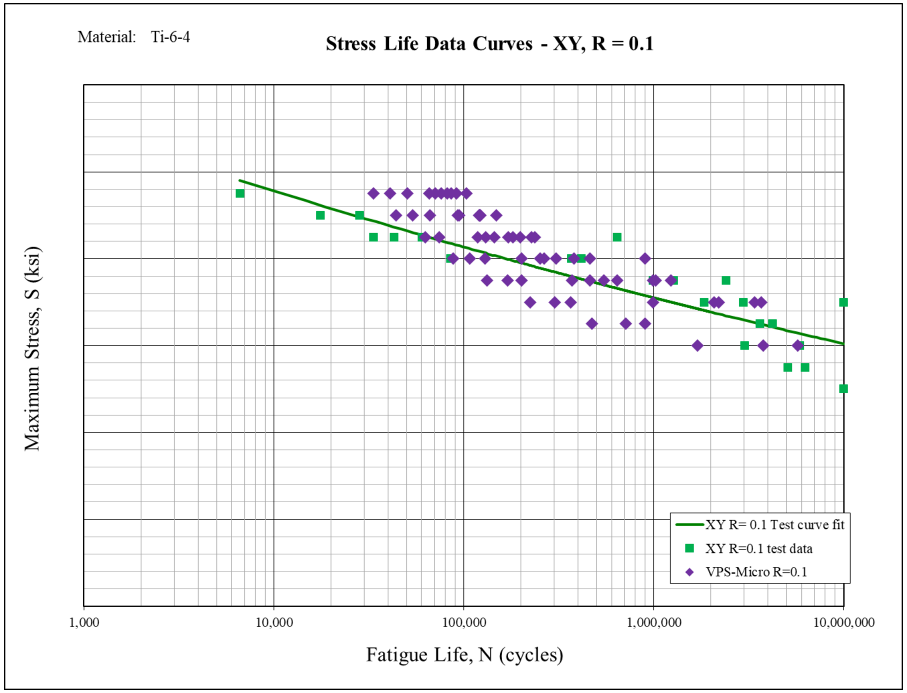
Material Properties		XY Specimen	Z Specimen	Source of Data
Shear Modulus		16,660 ksi	16,590 ksi	Tensile Testing and Material data sheets for alloy system and heat treatment
Frictional Stength	Distribution	Lognormal	Lognormal	80% of monotonic yield strength (Tensile Testing)
	Mean	101.68 ksi	99.46 ksi	
	COV	0.3	0.3	
Specific Fracture Energy		3.996 kip/in	4.435 kip/in	Proportional to the area under the sress/strain curve per ASTM E8
Grain Size	Distribution	Normal	Normal	Metallography (preparation per ASTM E3 and ASTM E1382 for measurements
	Mean	4.16E-03	3.42E-03	
	COV	0.41	0.39	
Asperity Height		2.0%	2.7%	Empirical value

Becker, T.H., Beck, M. and Scheffer, C., "Microstructure and mechanical properties of direct metal laser sintered TI-6AL-4V", *South Africa J. of Industrial Engineering*, Vol. 26, pp. 1-10, 2015.

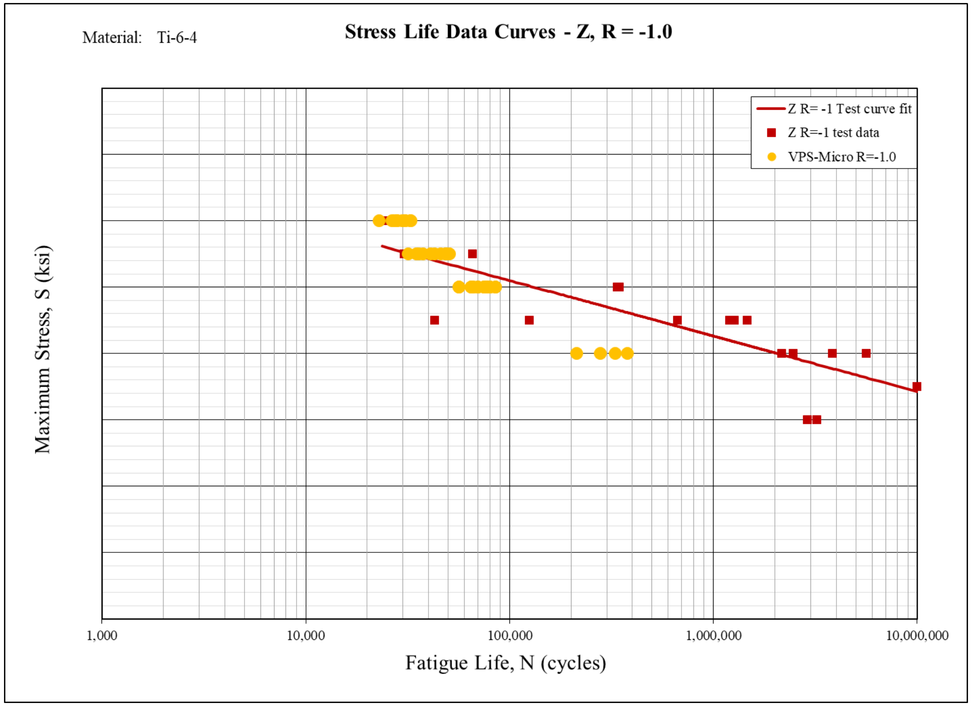
Gong, H., "Generation and Detection of Defects in Metallic Parts Fabricated by Selective Laser Melting and Electron Beam Melting and their Effects on Mechanical Properties", *Dissertation for the Doctor of Philosophy*, Department of Industrial Engineering of the University of Louisville, 2013.

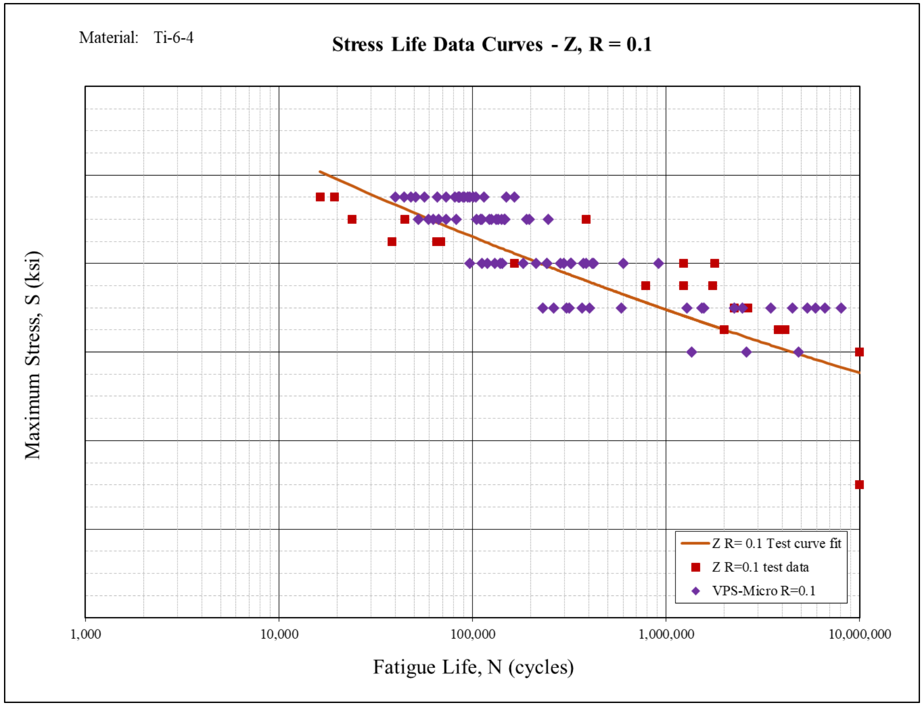
Stress-Life Comparison, XY Build Direction





Stress-Life Comparison, Z Build Direction





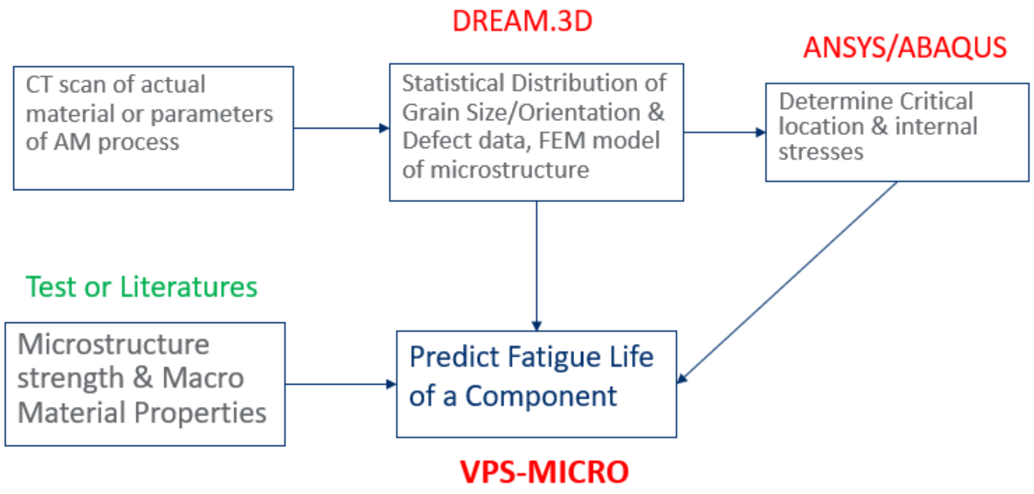
Conclusion and Future Works

Conclusion

- Fatigue properties of AM materials depend on microstructure such as defects/inclusions and grain size/orientation
- Microstructure variation is not able to be generalized by deterministic values -> must be represented probabilistically
- VPS-MICRO utilizes the statistics of the microstructure of AM processed materials
  - Statistical distributions of Ti 6Al-4V microstructure are observed and added to VPS-MICRO
  - Monte Carlo simulation generated microstructural variability
- The comparison of HCF test data and VPS-MICRO indicates the fatigue life predictions are generally in good agreement except xy build direction at R=-1.0
- Note that full material property development is required for more accurate fatigue life prediction

Future Works

- Determine Probability of Detection (PoD) of AM parts.
- Establish NDI processes
- Determine IFS for durability and damage tolerance analyses
- Set up the procedure for risk analysis
- Material property determination
  - Generate synthetic structures from experimental statistics. Generate equivalent microstructures/models and represent the statistical nature of materials process and properties.
  - Predict microstructure using in-situ data (laser intensity) or thermal history with DREAM.3D




Any Questions?

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