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Fatigue Analysis of Additive Manufacturing Materials with Microstructural Properties

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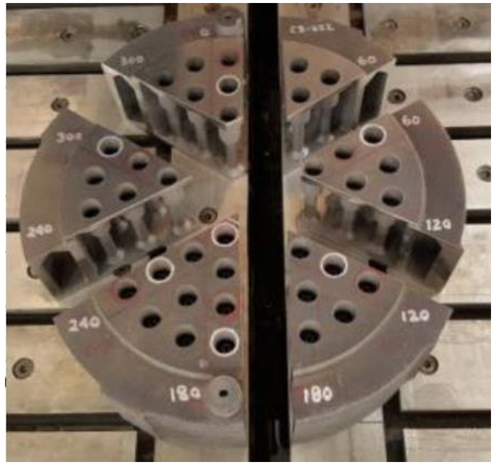
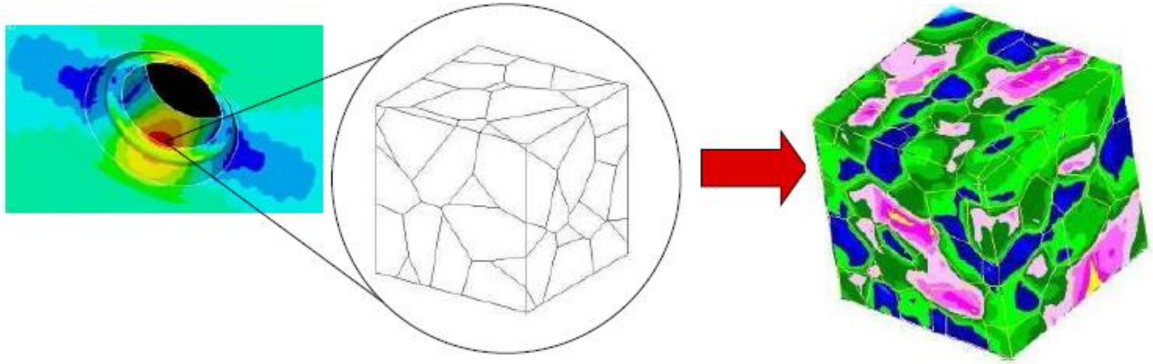
Outline

- Methodology of Fatigue Life Analysis with Microstructural Properties
- High Cycle Fatigue Tests
  - L-PBF AlSi10Mg
  - L-PBF Ti 6Al-4V
- Microstructural Material Property Development of L-PBF AlSi10Mg and TI 64 Specimens
- Comparison of Test Data and Analysis Results
- Conclusion
- Future Works



Methodology of Fatigue Life Analysis with Microstructural Properties

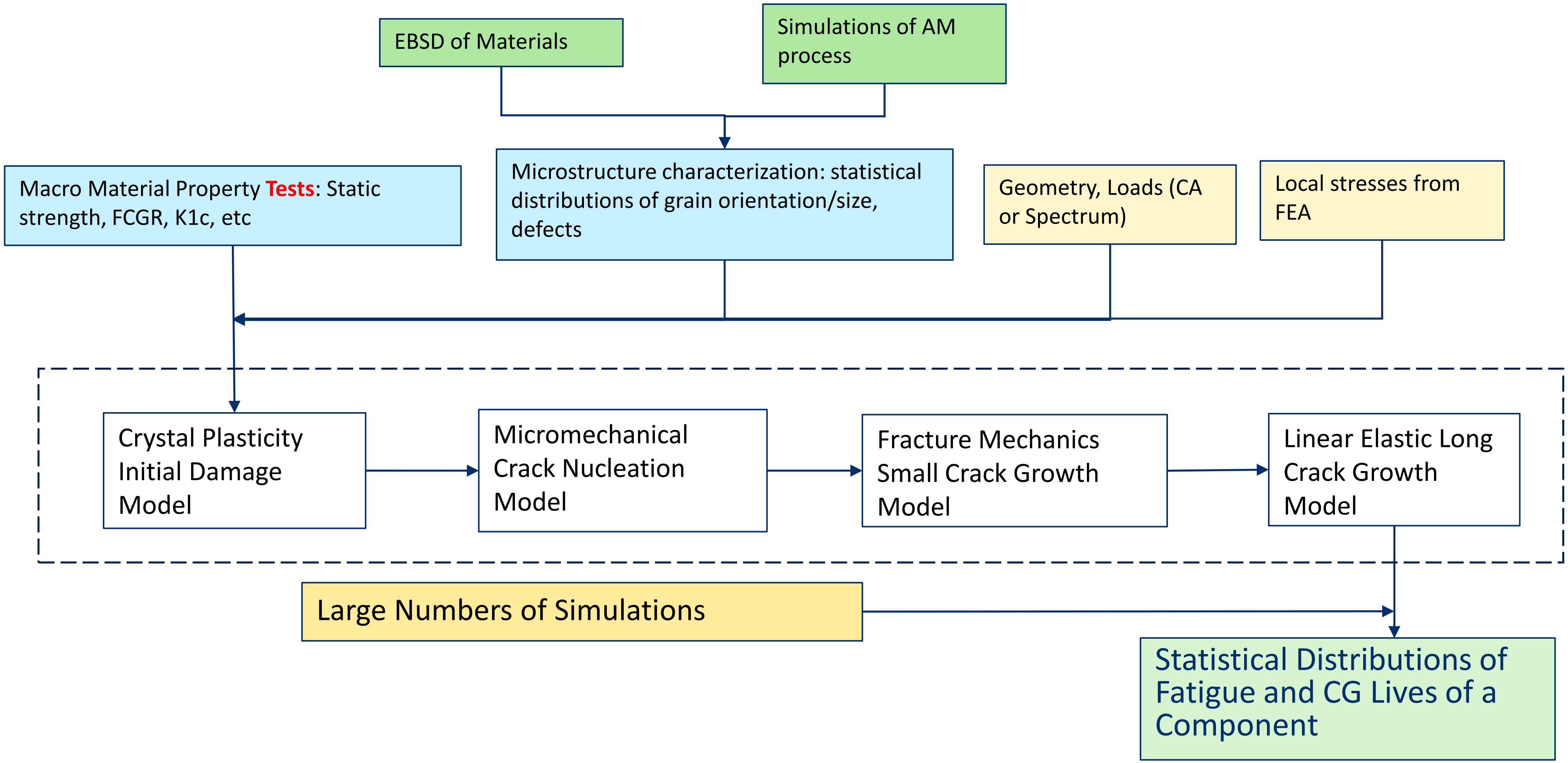


Fatigue and Crack Growth Analysis of AM Materials: ICME Application

- 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.

AM is an Ideal Case of ICME Application

AM Fatigue Life Process



Fatigue Analysis of AM, VPS-MICRO

- 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

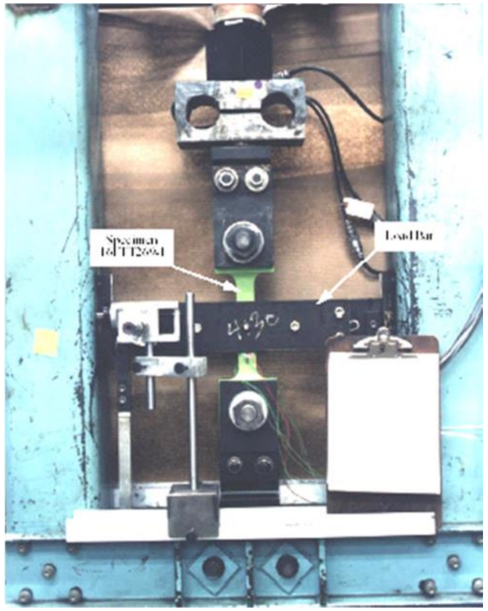
- VPS-MICRO has three stages of fatigue life: crack initiation, small crack growth and long crack growth
  - Crack initiation: smooth fracture surfaces at angle inclined to the loading direction -> shear stress fracture
    - The equilibrium condition of the grain on the first loading: $\tau_1^D + (\tau_1 - k) = 0$

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

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

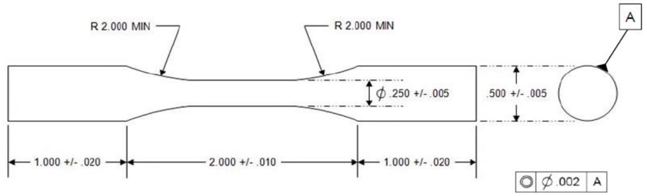
  - Long Crack Growth: Linear Elastic Fracture Mechanics (LEFM) and not affected by microstructure

High Cycle Fatigue Test of L-PBF AlSi10Mg and Ti 6Al-4V

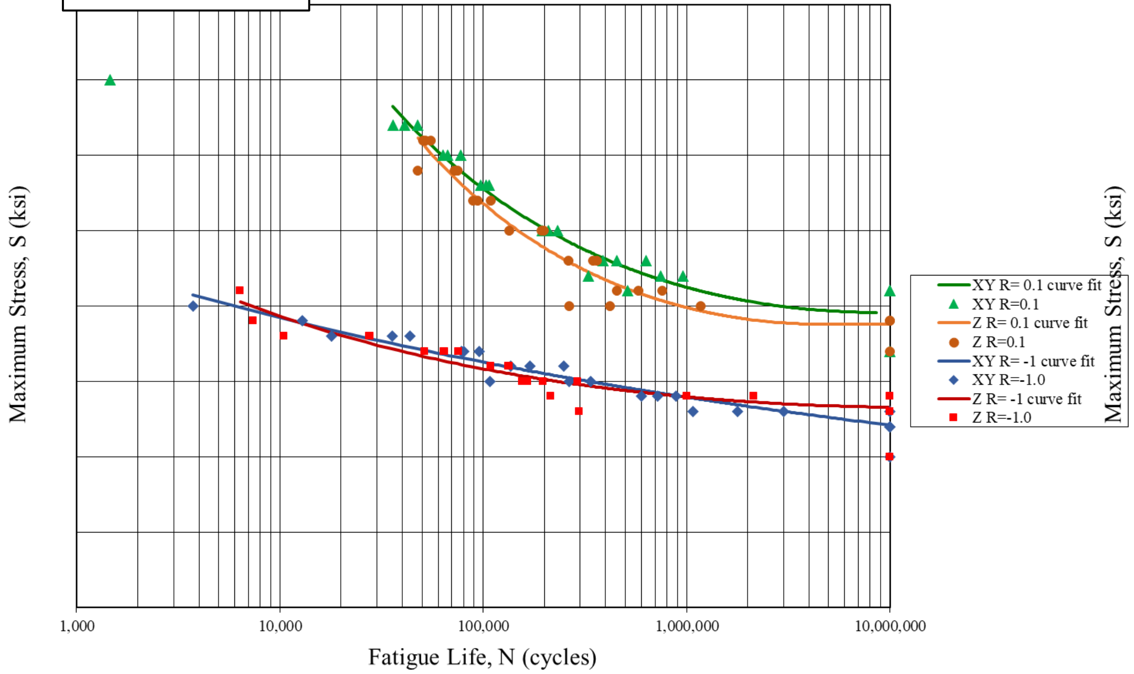


High Cycle Fatigue Tests

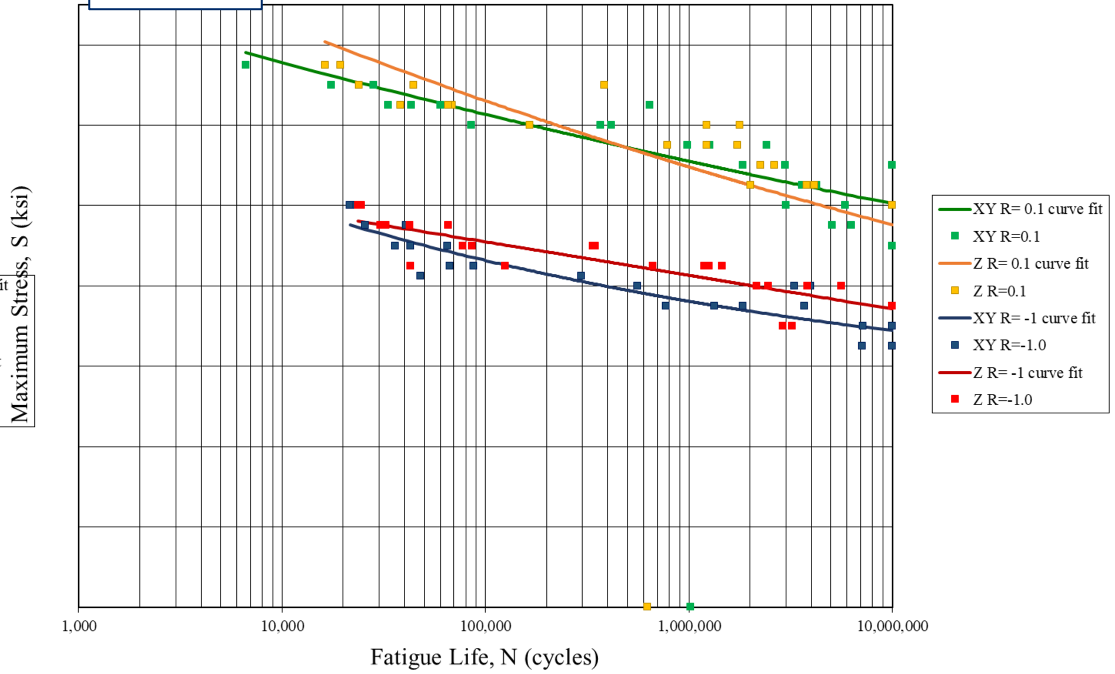
- L-PBF AlSi10Mg and Ti 6Al-4V specimens were built per LM AM material and process specifications.
  - Ambient temperature
  - xy and z build directions
  - Ti 64 specimens were hot isostatic pressed (HIP) and annealed
- HCF tests were run at two stress ratios, R=0.1 and -1



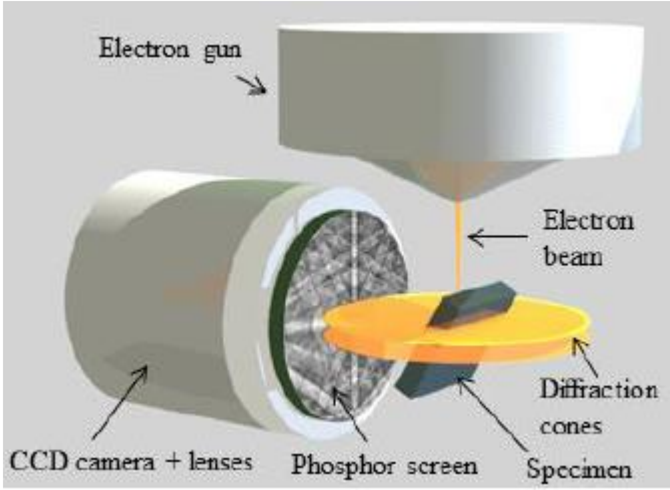
AlSi10Mg



Ti 64

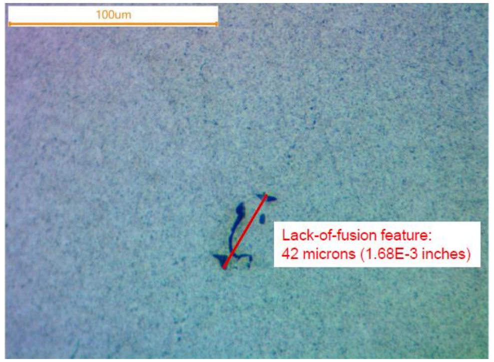


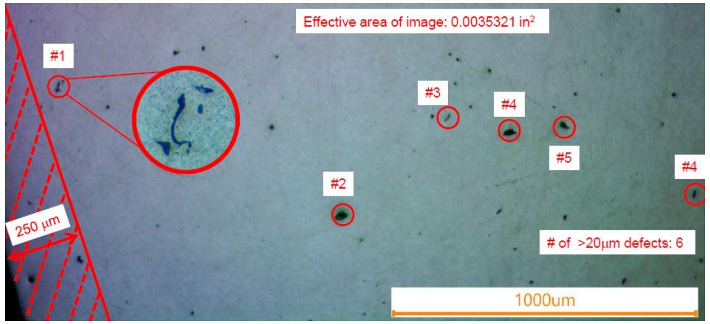
Microstructural Material Property Development



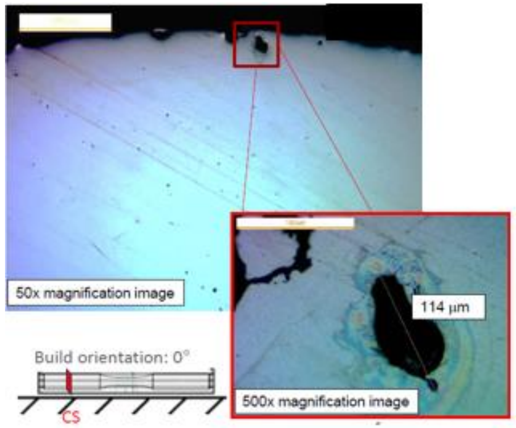
Defects of PBF AlSi10Mg Specimens

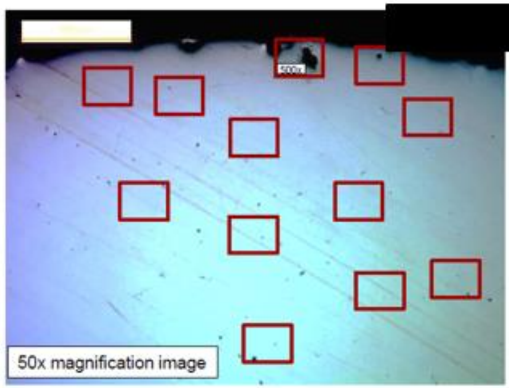
- In the magnified images, some lack-of-fusion features were identified.
- The largest dimension of each defect over 20μm in size was measured, and defect size and defect population density distributions are calculated.





Z-Build





XY-Build

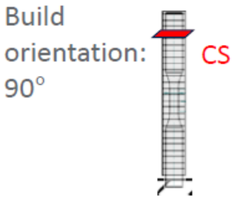
Mean: $\bar{x}_{defect\ size} = \frac{\sum defect\ sizes\ in\ a\ given\ sample}{N_{defects>20\mu m}}$

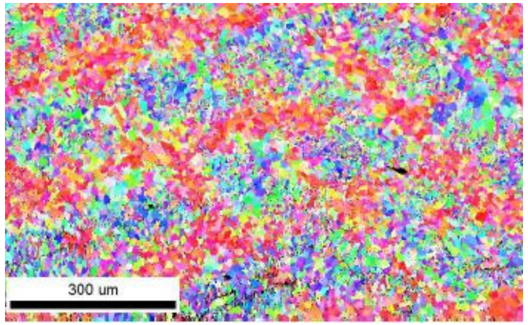
Standard Deviation: $s = \sqrt{\frac{1}{N_{defects}-1} \sum_{i}^{N} (x_i - \bar{x})^2}$

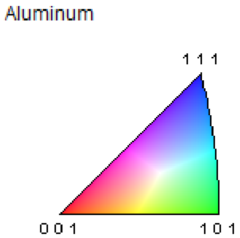
Coefficient of Variation: $COV = \frac{s}{\bar{x}}$

Grain Size and Orientation of PBF AlSi10Mg

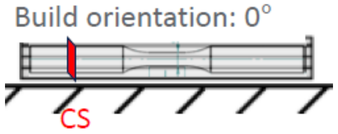
- Electron Backscatter Diffraction (EBSD) analysis for microstructural characterization.
- Grain size was determined from the minor axis length of the elliptical fit to grains.

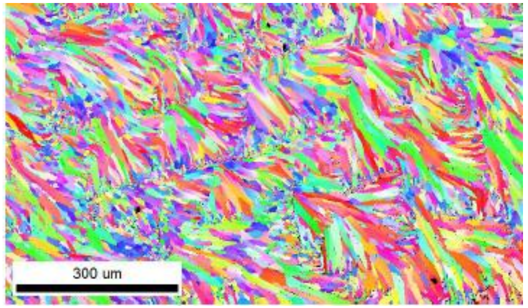






Z-Build





XY-Build

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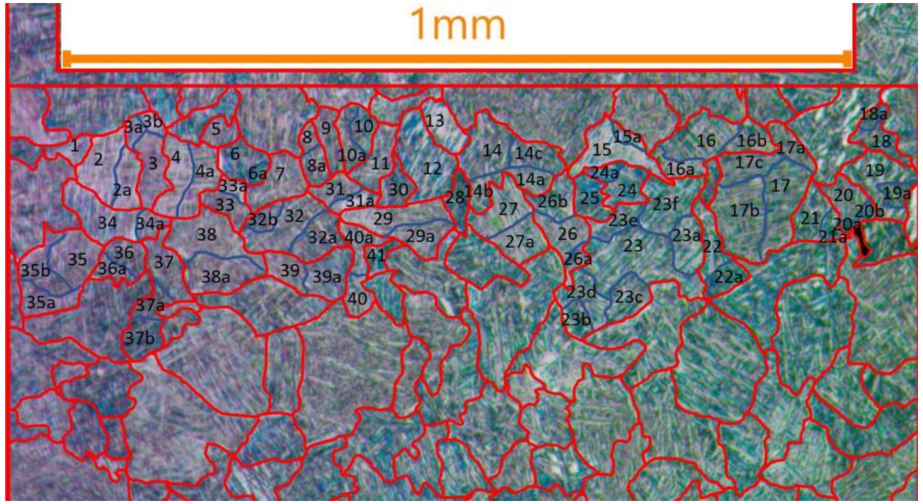
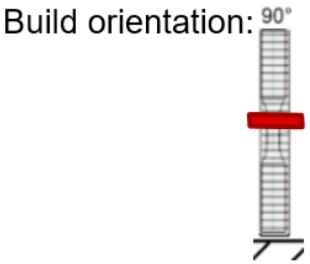
Grain Size Distribution of PBF Ti 64 Specimens

- 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

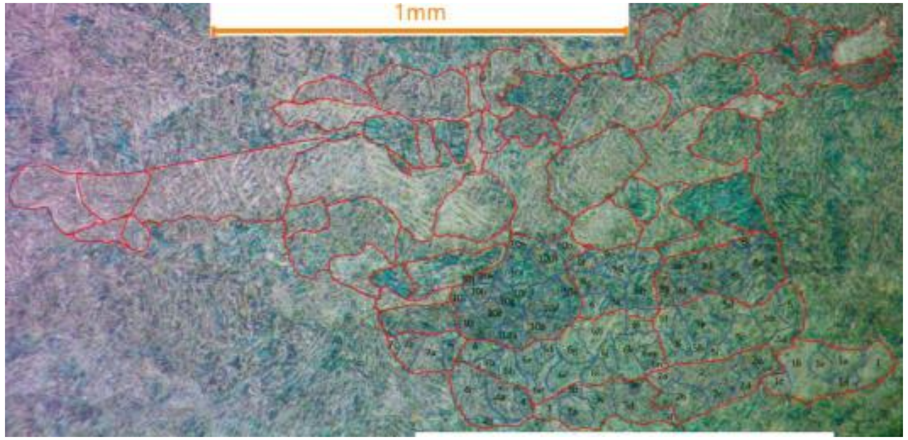


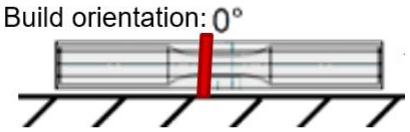


Z direction

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

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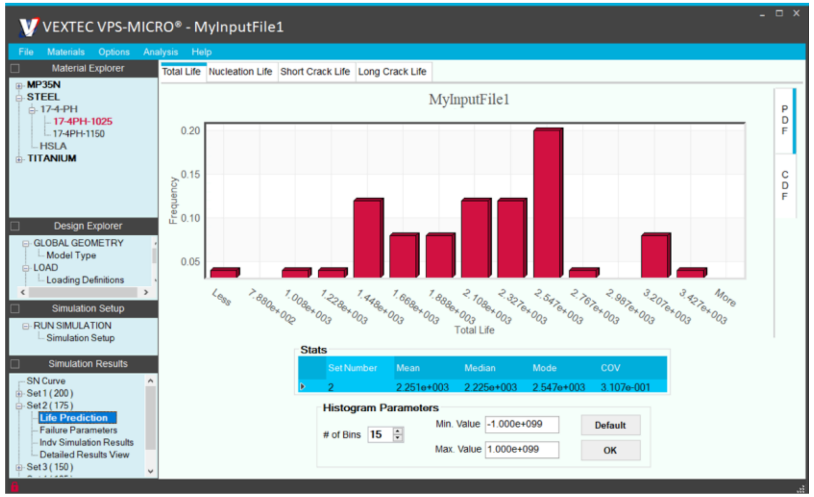
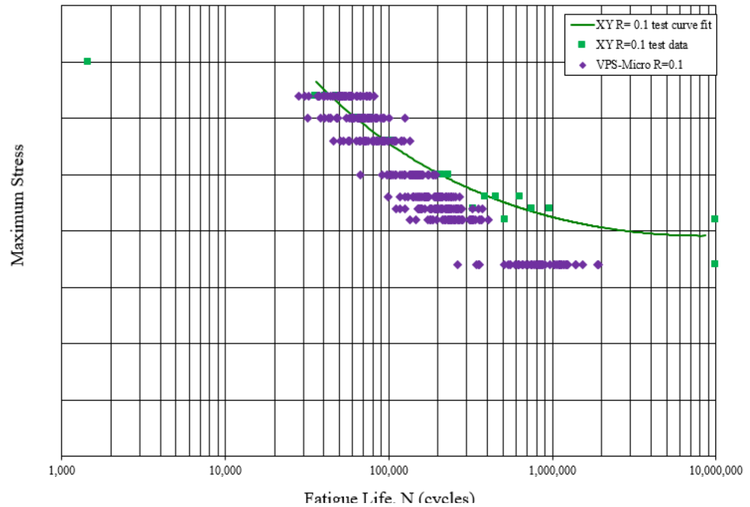
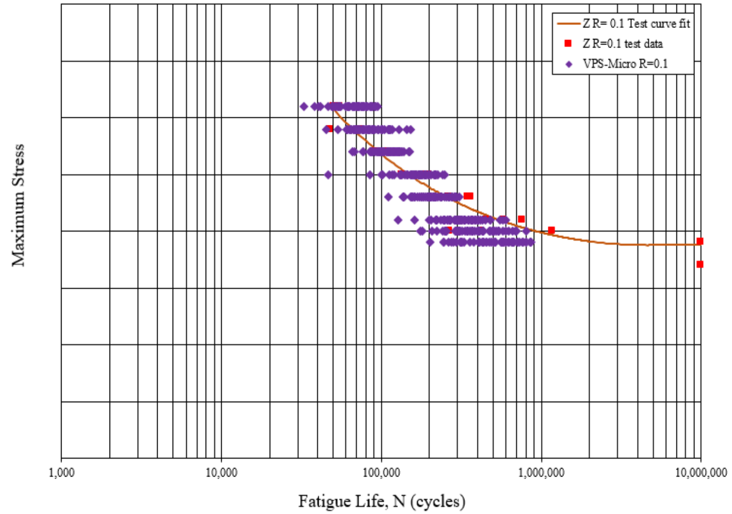
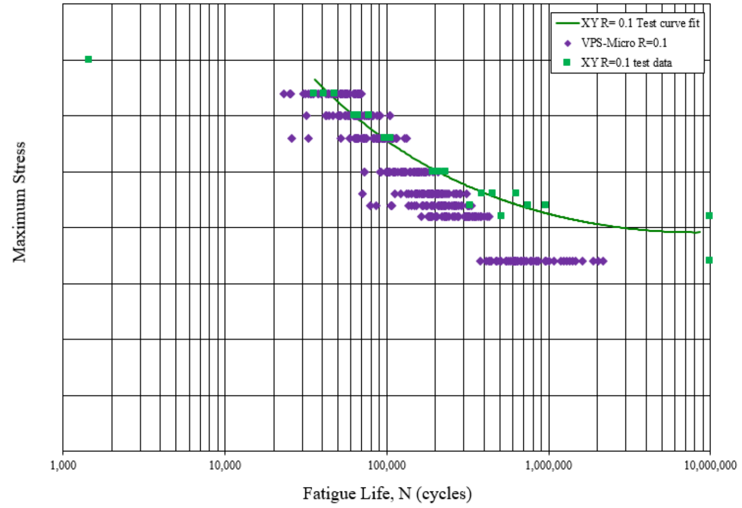
Fatigue Analysis of PBF AlSi10Mg and Ti 6Al-4V

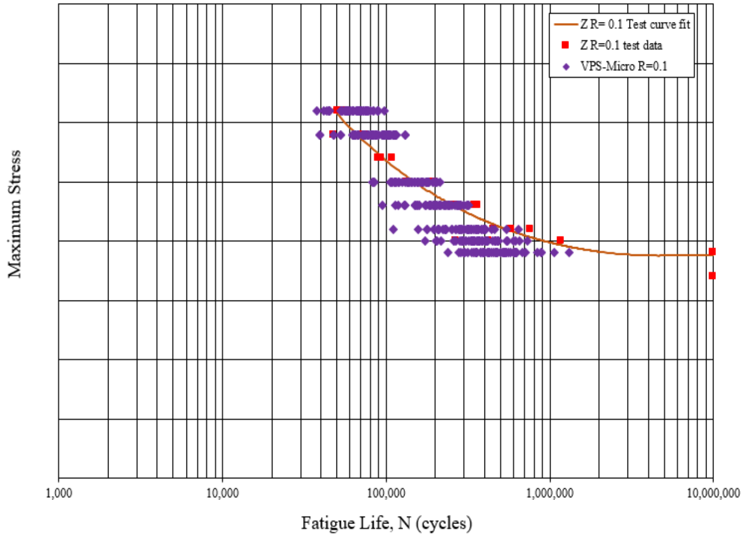


Stress-Life Comparison of AlSi10Mg, R=0.1

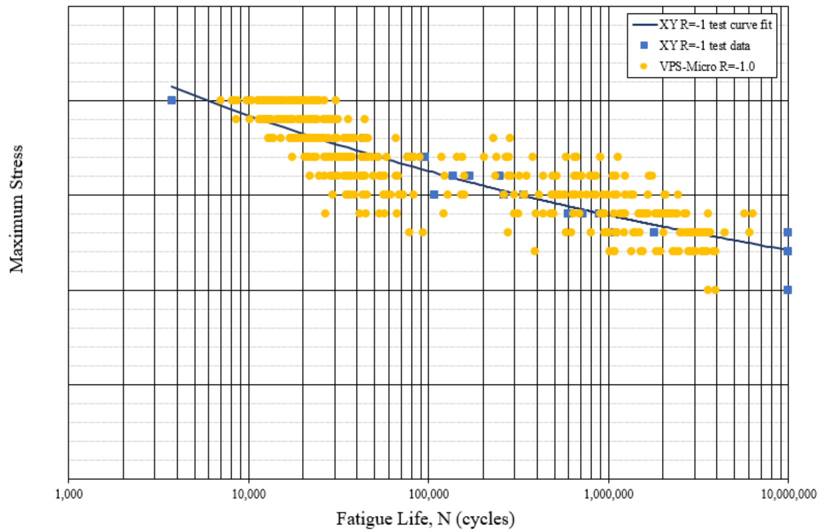


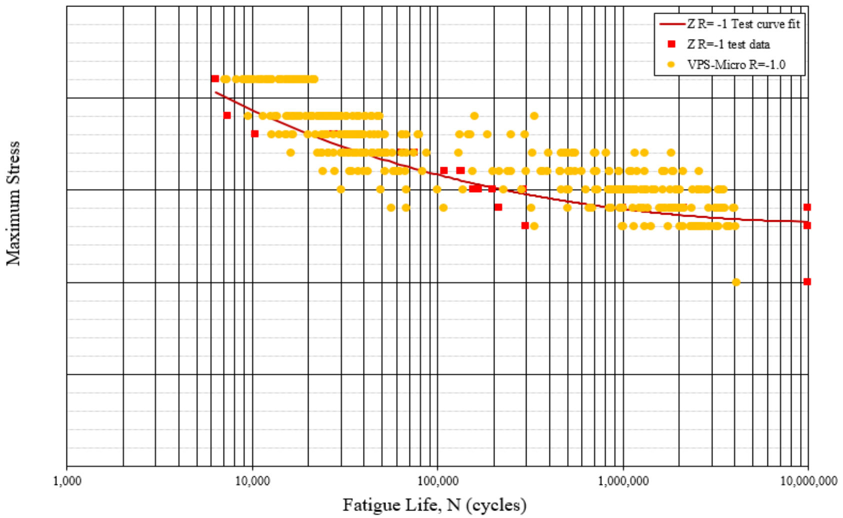


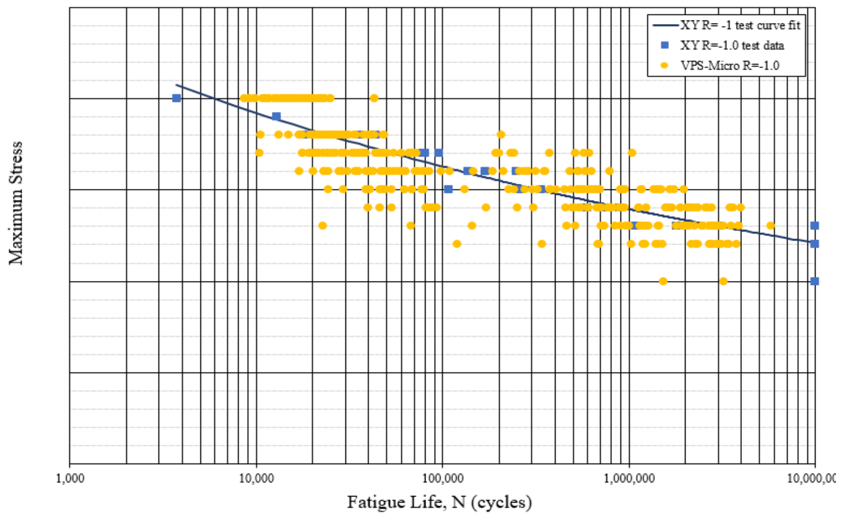


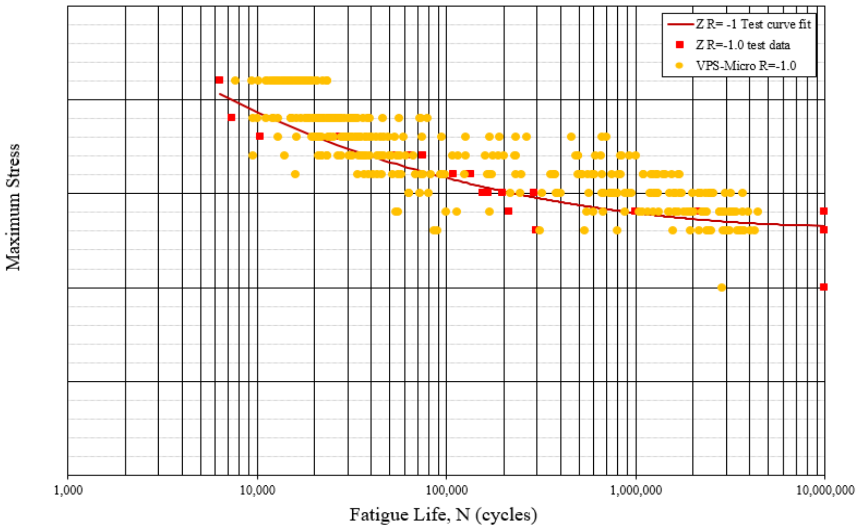


Stress-Life Comparison of AlSi10Mg, R=-1.0

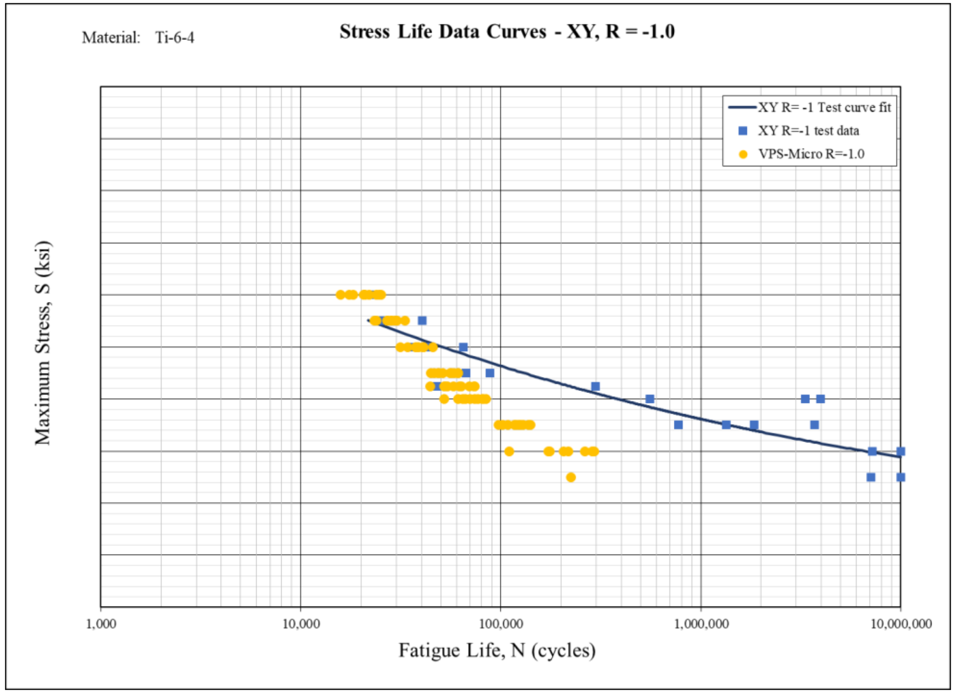


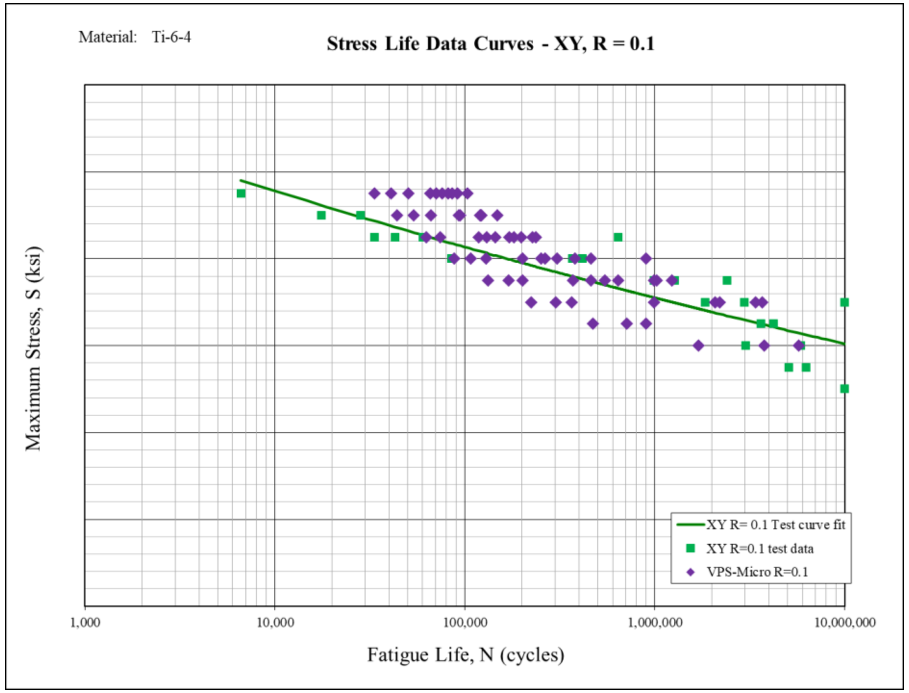




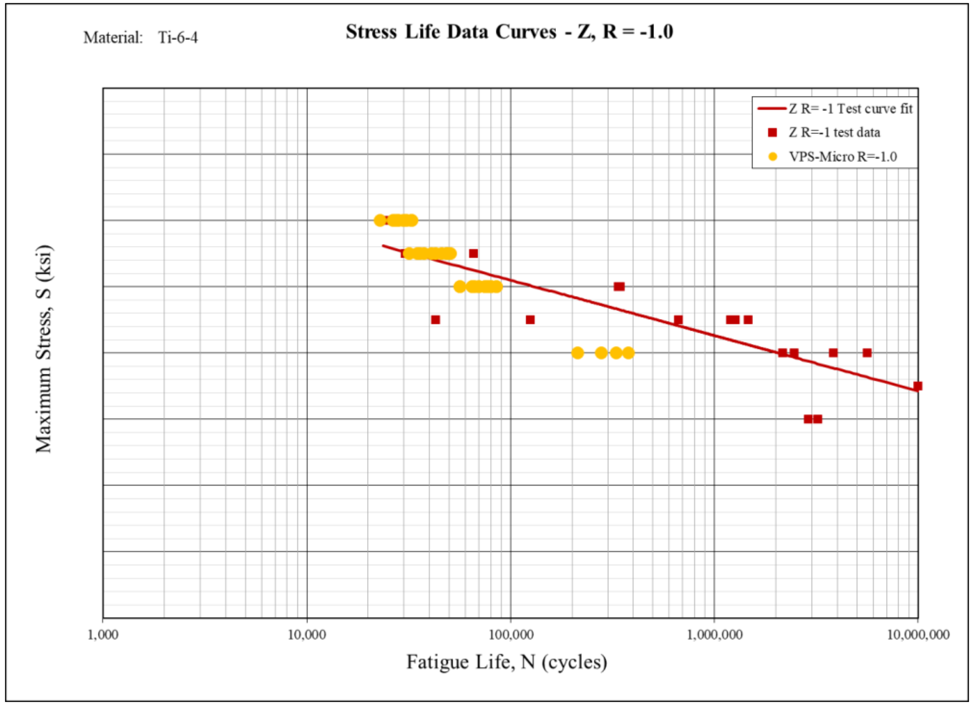


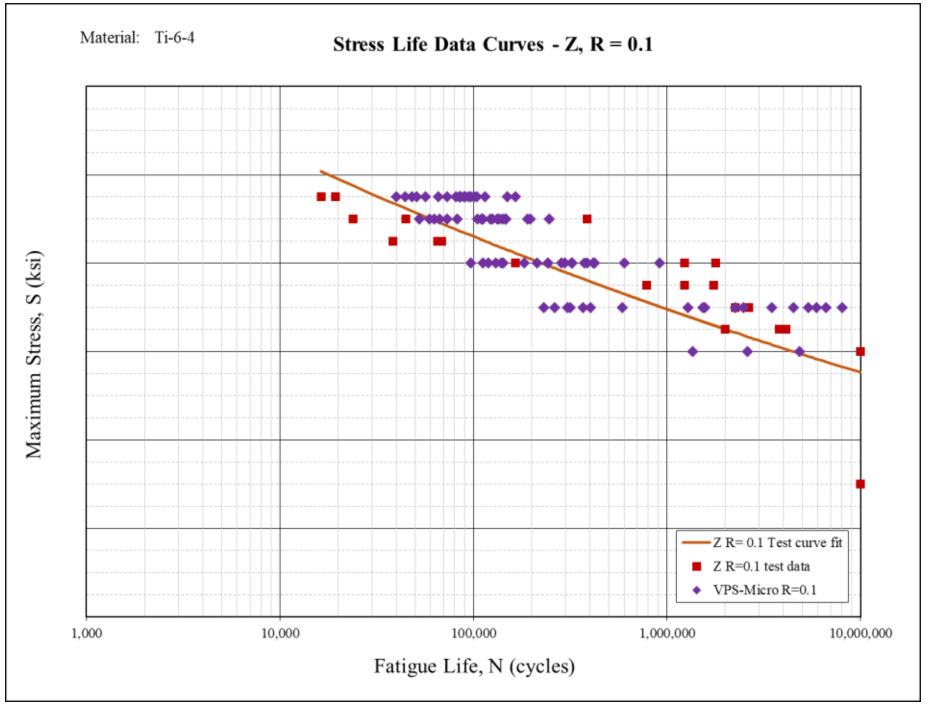
Stress-Life Comparison of Ti 6Al-4V, XY Build Direction





Stress-Life Comparison of Ti 6Al-4V, Z Build Direction





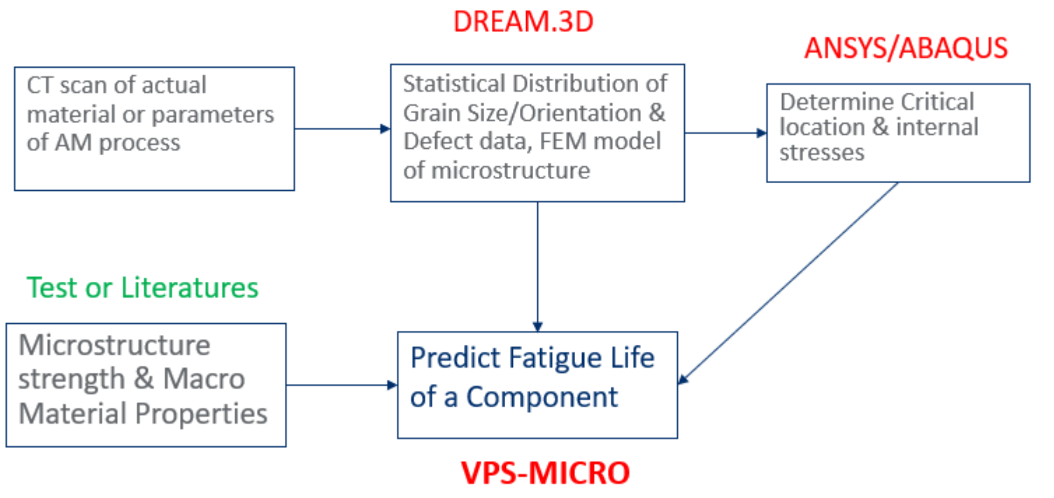
Conclusion and Future Works

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, AlSi10Mg and Ti 6Al-4V.
    - Statistical distributions of microstructure are obtained 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 for Ti 6Al-4V.
- 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?