UNIVERSITÀ DEGLI STUDI DI PADOVA

Numerical methods to study damage propagation in materials for aerospace structures

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Supervisor: Prof. Ugo Galvanetto

Co-supervisors: Prof. Mirco Zaccariotto

Dr. Francesco Scabbia

Meeting - 14 Oct

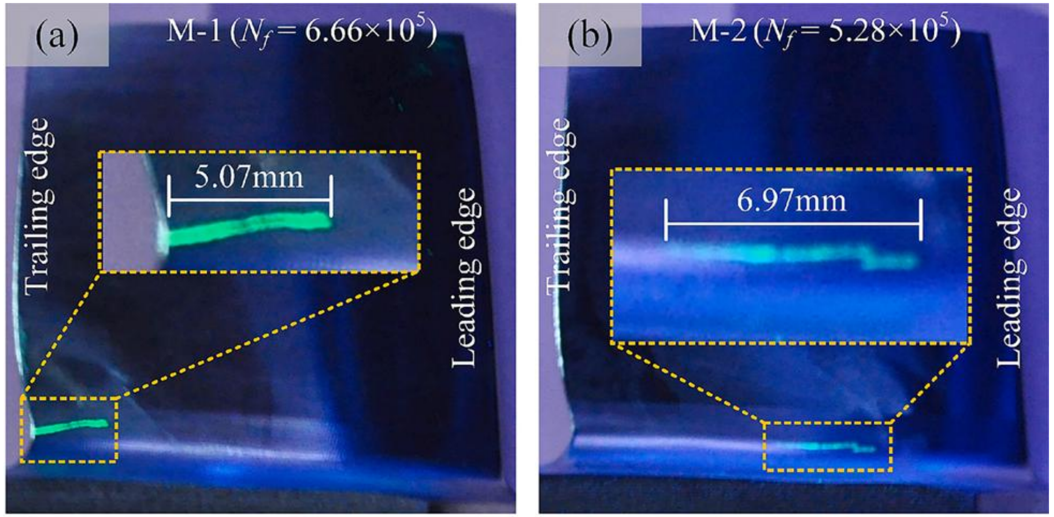
Introduction

Fatigue is the main source of failure in aircraft

Source of HCF damage in aircraft components:

1. Aerodynamic Excitation
2. Mechanical Vibration
3. Airfoil Flutter
4. Acoustic Fatigue

	Percentage of failures	
	Engineering components	Aircraft components
Corrosion	29	16
Fatigue	25	55
Brittle fracture	16	—
Overload	11	14
High temperature corrosion	7	2
SCC/corrosion fatigue/HE	6	7
Creep	3	—
Wear/abrasion/erosion	3	6



P. M. S. T. D. E. Castro, "An overview of fatigue in aircraft structures," pp. 1510–1529, 2017, doi: 10.1111/ffe.12631.

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Introduction

Article	Authors	Fatigue
Influence of ultrasonic surface rolling on fatigue performance of high carbon low alloy quenching-partitioning-tempering steel," International Journal of Fatigue, November 2024	Shengwei Qin, Guangrui Wang	Cracks typically initiate at the surface of samples
Crack initiation , small crack growth , and stress intensity factor in the very high cycle fatigue (VHCF) of wire arc additive manufactured (WAAM) nickel aluminum bronze (NAB)," Engineering Fracture Mechanics, September 2024.	Mohammad Bagher Mahtabi, Wiktor Bednarczyk	In HCF, failure initiates at the surface, mainly from large defects due to high surface roughness
Additive manufacturing of fatigue resistant materials : Challenges and opportunities," International Journal of Fatigue, 2025.	Aref Yadollahi , Nima Shamsaei	In HCF regimes, crack initiation dominates the fatigue process, surface roughness can be much more influential
Surface roughness parameter and modeling for fatigue behavior of additive manufactured parts : A non-destructive data-driven approach, Additive Manufacturing, 2024.	S. Lee, B. Rasoolian, D. F. Silva, J. W. Pegues, and N. Shamsaei,	Maximum valley depth parameters (S_v/R_v) can use as an appropriate parameter for the fatigue life prediction of AM materials with a very small error and a coefficient of determination as high as R^2 = 0.99

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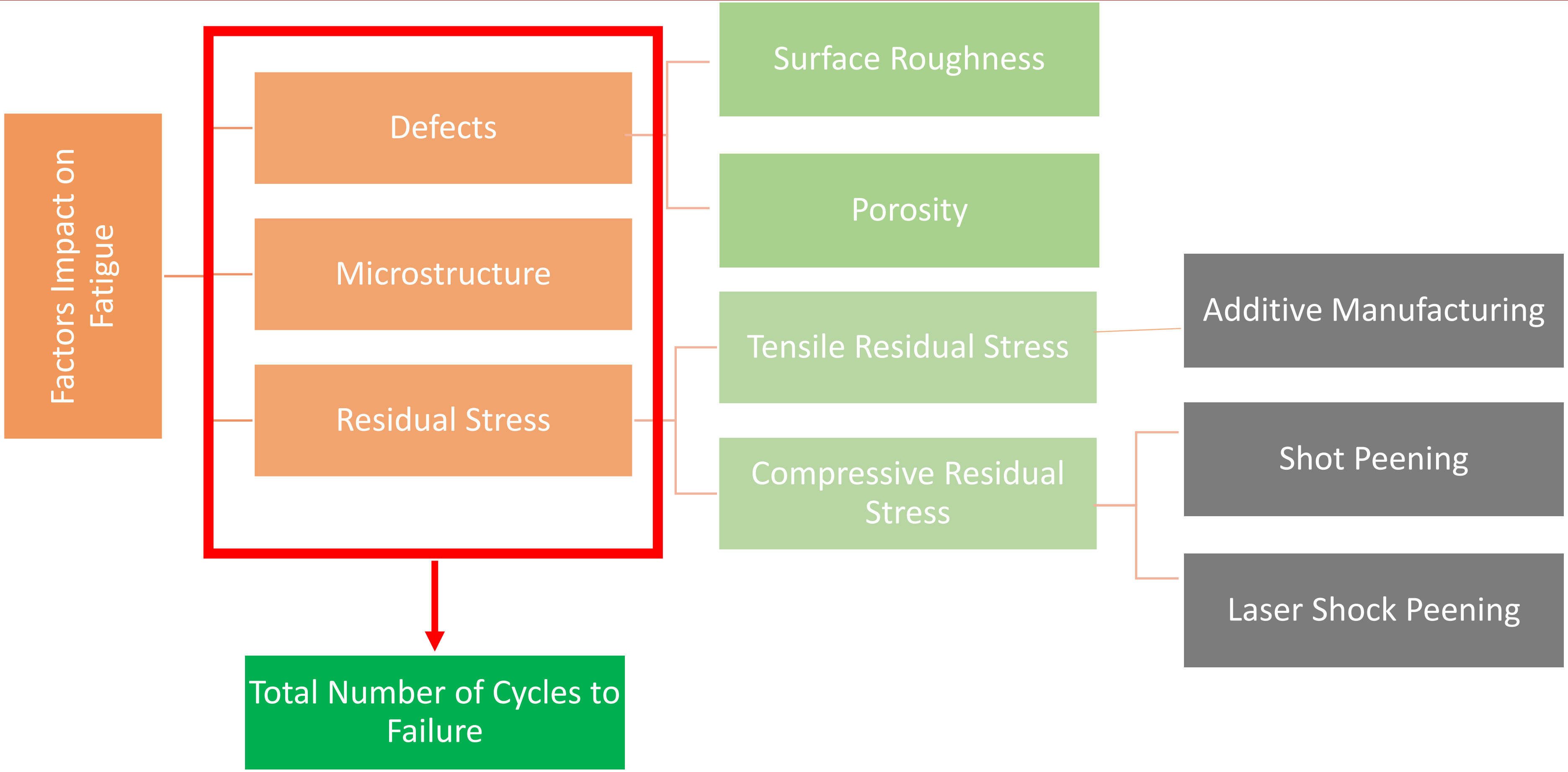
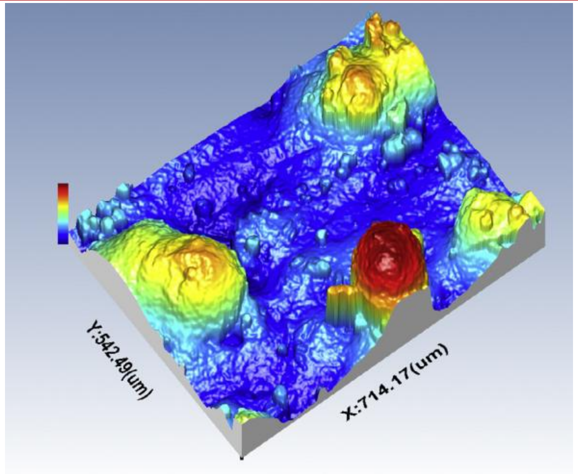
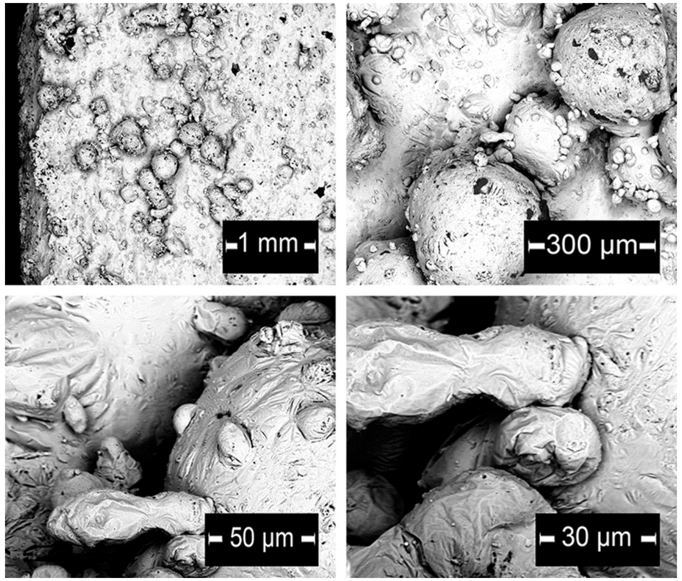
Factors Impact on Fatigue







Peridynamic

Peridynamic is a nonlocal continuum mechanics formulation

- Introduced to overcome limitations of classical continuum mechanics, especially for discontinuities
- Uses integral equations, enabling natural fracture initiation and propagation
- Simulate crack initiation and propagation

$$\rho(\boldsymbol{x})\ddot{\boldsymbol{u}}(\boldsymbol{x},t) = \int_{H_x} \boldsymbol{f}(\boldsymbol{u}(\boldsymbol{x}',t) - \boldsymbol{u}(\boldsymbol{x},t), \boldsymbol{x}'-\boldsymbol{x})\, \mathrm{d}V_{x'} + \boldsymbol{b}(\boldsymbol{x},t)$$

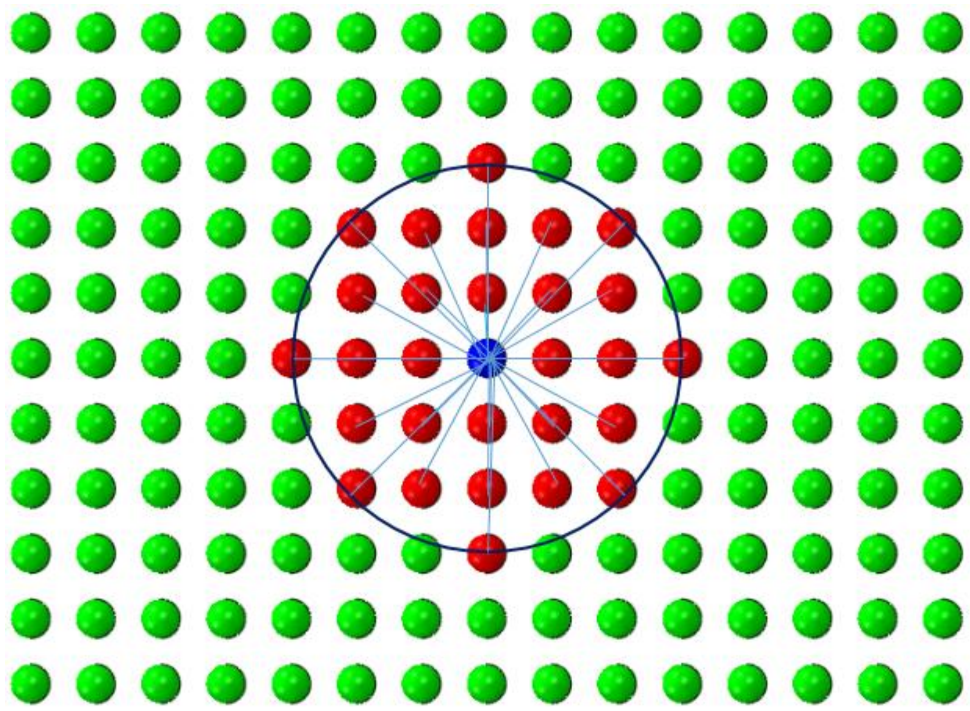
ρ : Mass density

u : Displacement vector

b : Body force

f : Pairwise force function

H_x : Neighborhood



Remaining life Approach

$$\lambda(0)=1$$

Initial value for each bond

$$\lambda(N)\leq 0$$

The bond breaks irreversibly

$$\frac{d\lambda}{dN}(N)=-A\varepsilon^{m}$$

Remaining Life Equation

$$A, m$$

Positive Constant

$$\varepsilon=\left|S^{+}-S^{-}\right|$$

Cyclic Bond Strain

$$S^{+}=\frac{\left|\boldsymbol{\eta}-\boldsymbol{\xi}\right|^{+}-\left|\boldsymbol{\xi}\right|}{\left|\boldsymbol{\xi}\right|}$$

$$S^{-}=\frac{\left|\boldsymbol{\eta}-\boldsymbol{\xi}\right|^{-}-\left|\boldsymbol{\xi}\right|}{\left|\boldsymbol{\xi}\right|}$$

$$R=\frac{S^{-}}{S^{+}}$$

Stress Ratio

$$\varphi(\mathbf{x})=1-\frac{\int_{H_{\mathbf{x}}}\mu(\boldsymbol{\xi},\boldsymbol{\eta})dV_{\mathbf{x}'}}{\int_{H_{\mathbf{x}}}dV_{\mathbf{x}'}}$$

Local damage

$$\varphi(\mathrm{x})<0.4$$

Transition from nucleation to propagation

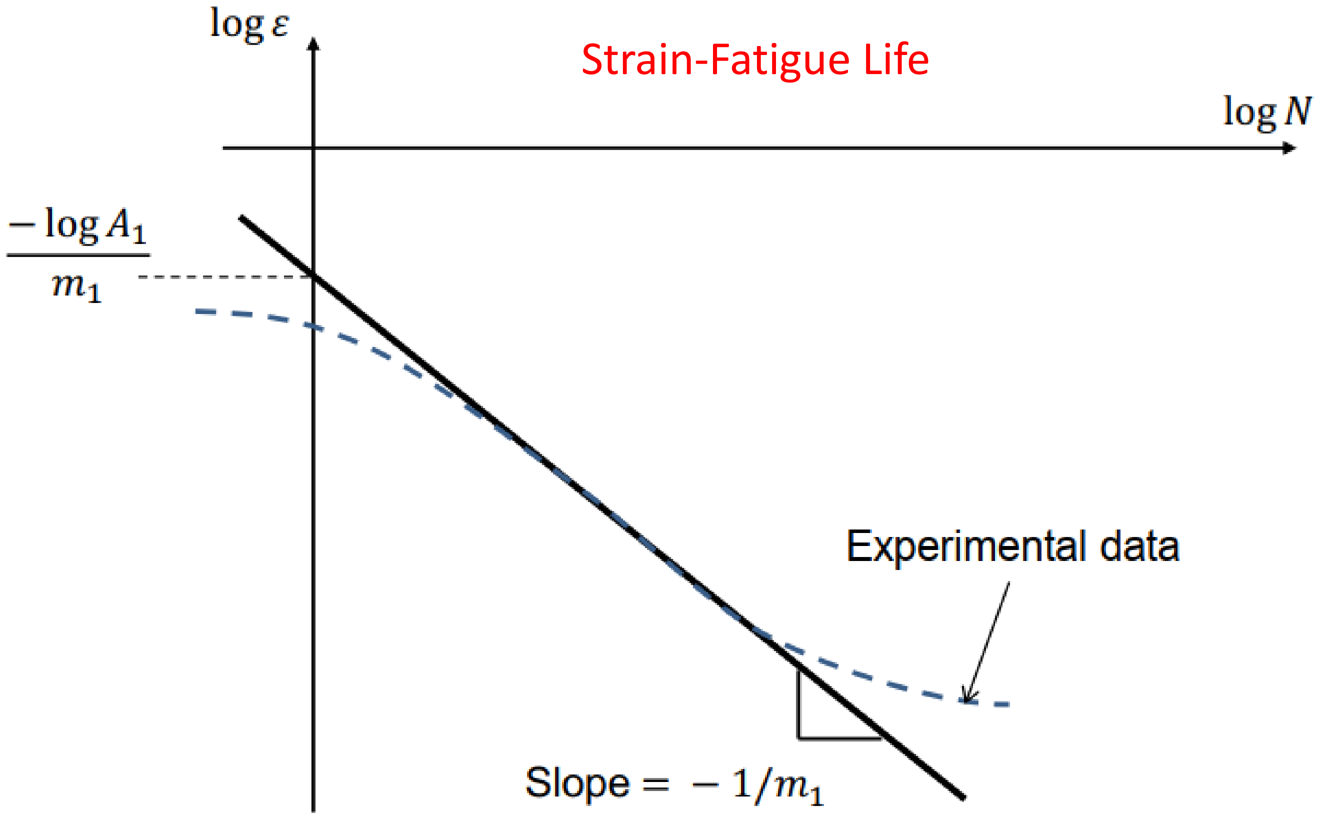
S. Silling, A. Askari, Peridynamic model for fatigue cracks, http://docs.lib. purdue.edu/ses2014/mss/cfm/22/%0Ahttps://www.osti.gov/scitech/biblio/ 1160289-peridynamic-model-fatigue-cracking , 2014.

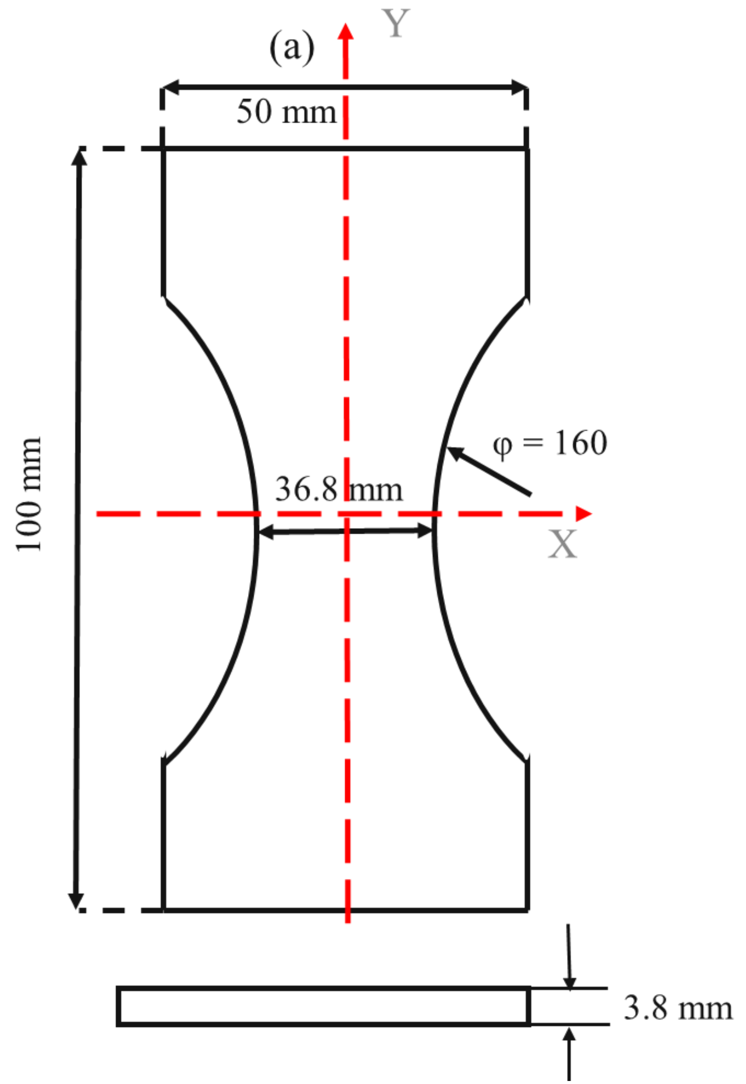
Nucleation Phase

$$\frac{d\lambda}{dN}(N) = -A\varepsilon^{m}$$

$A = A_1$

$m = m_1$





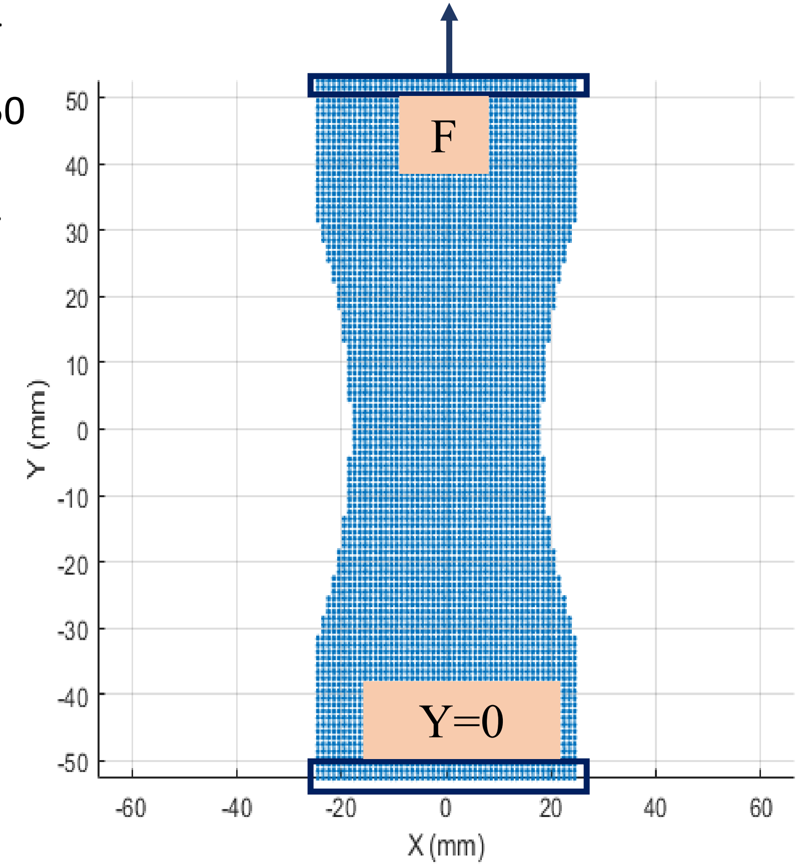
Validation

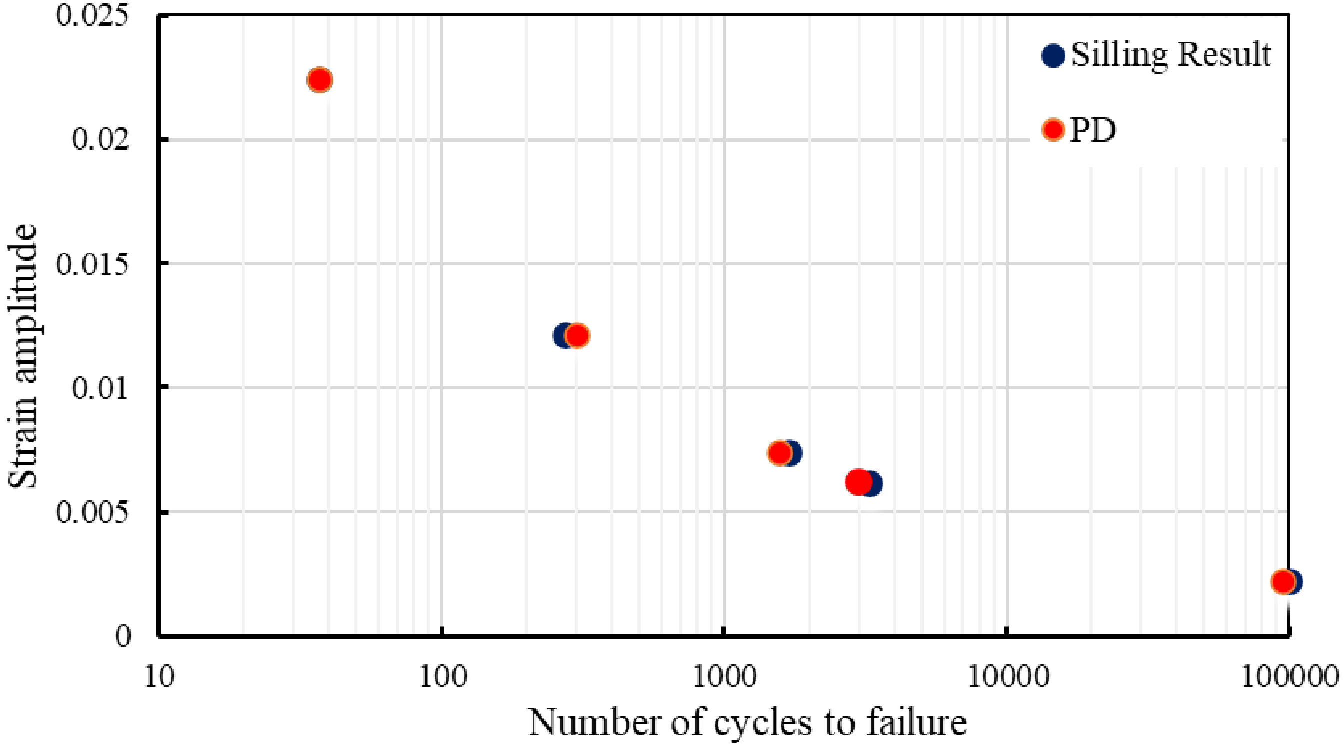
Aluminium7075-T651

A_1= 1050

m_1= 3.4

R = 0





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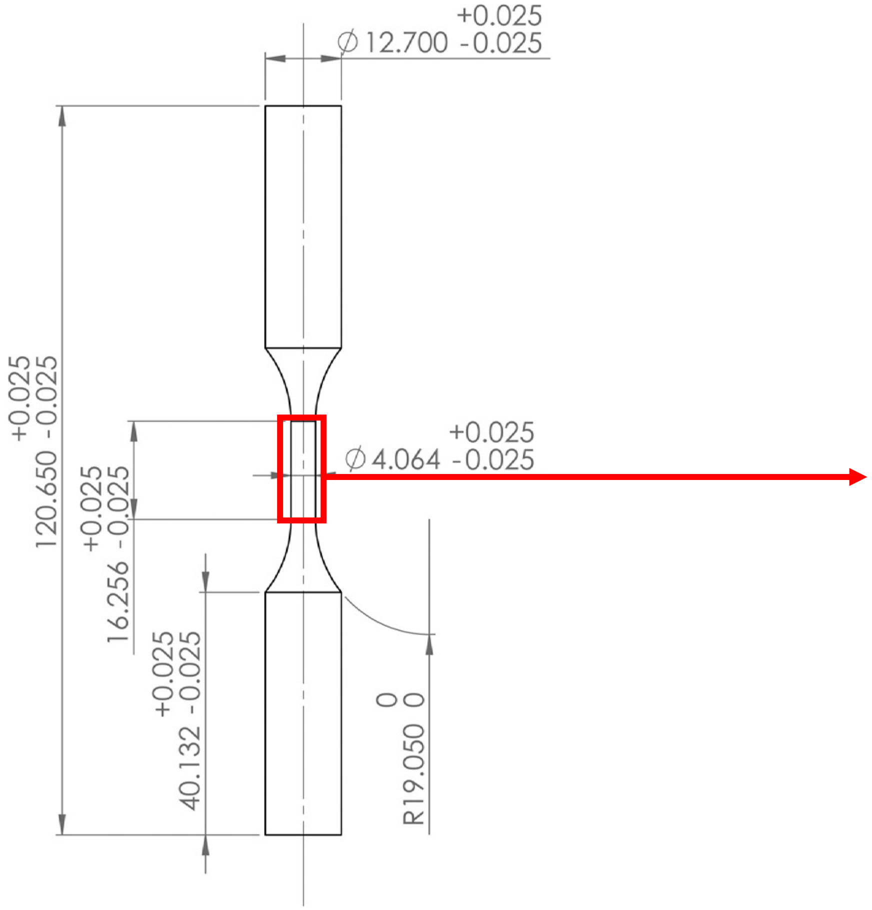
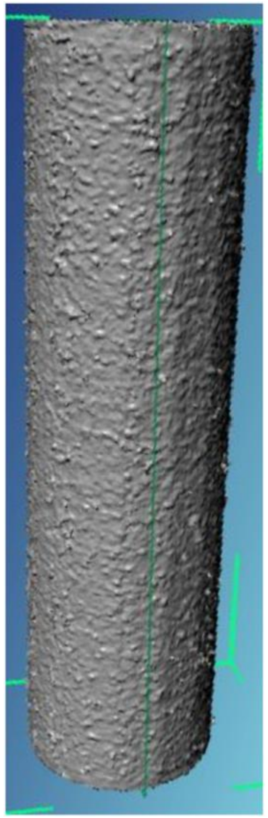
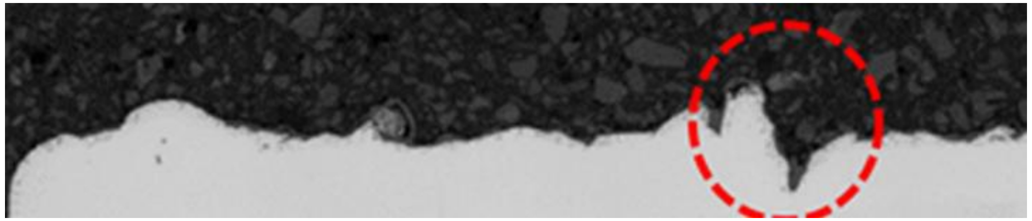
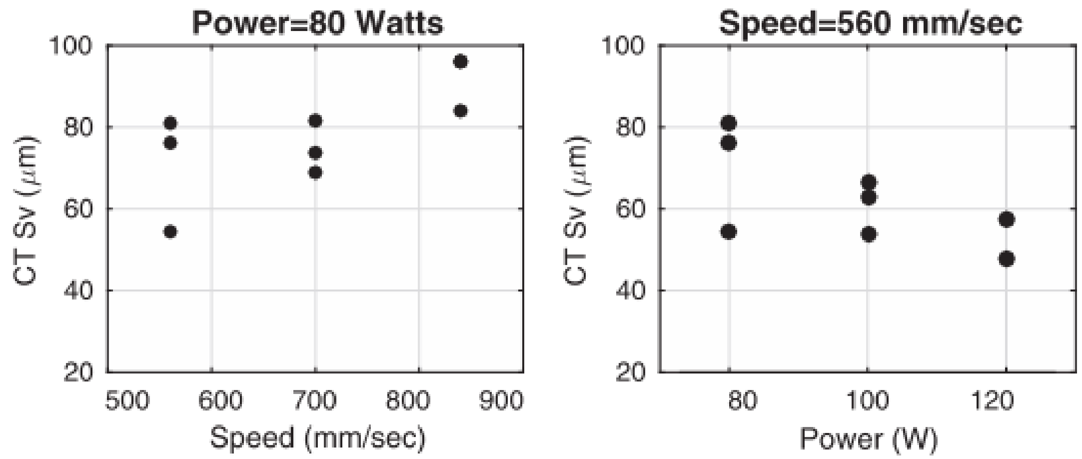
Surface Roughness







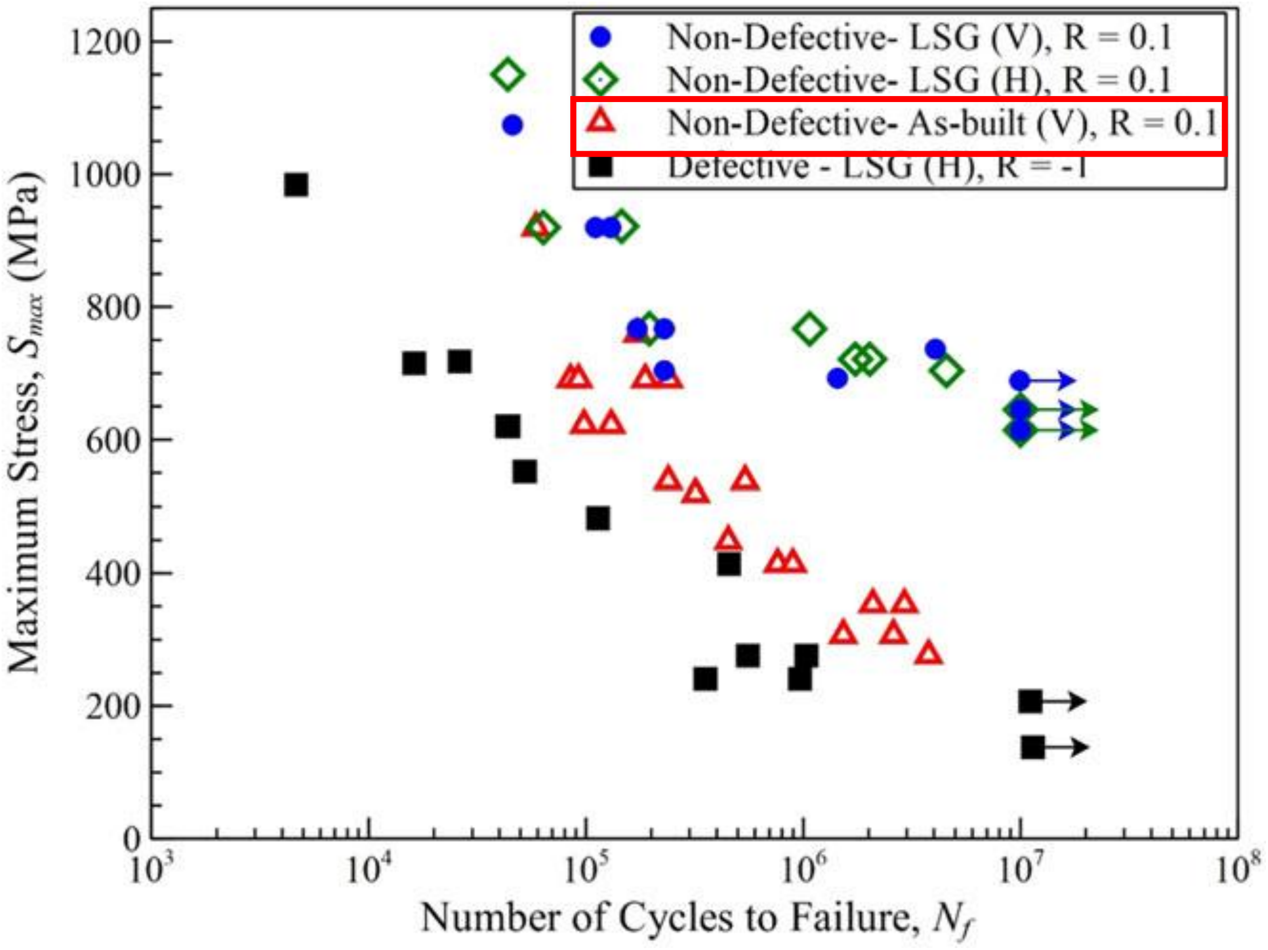


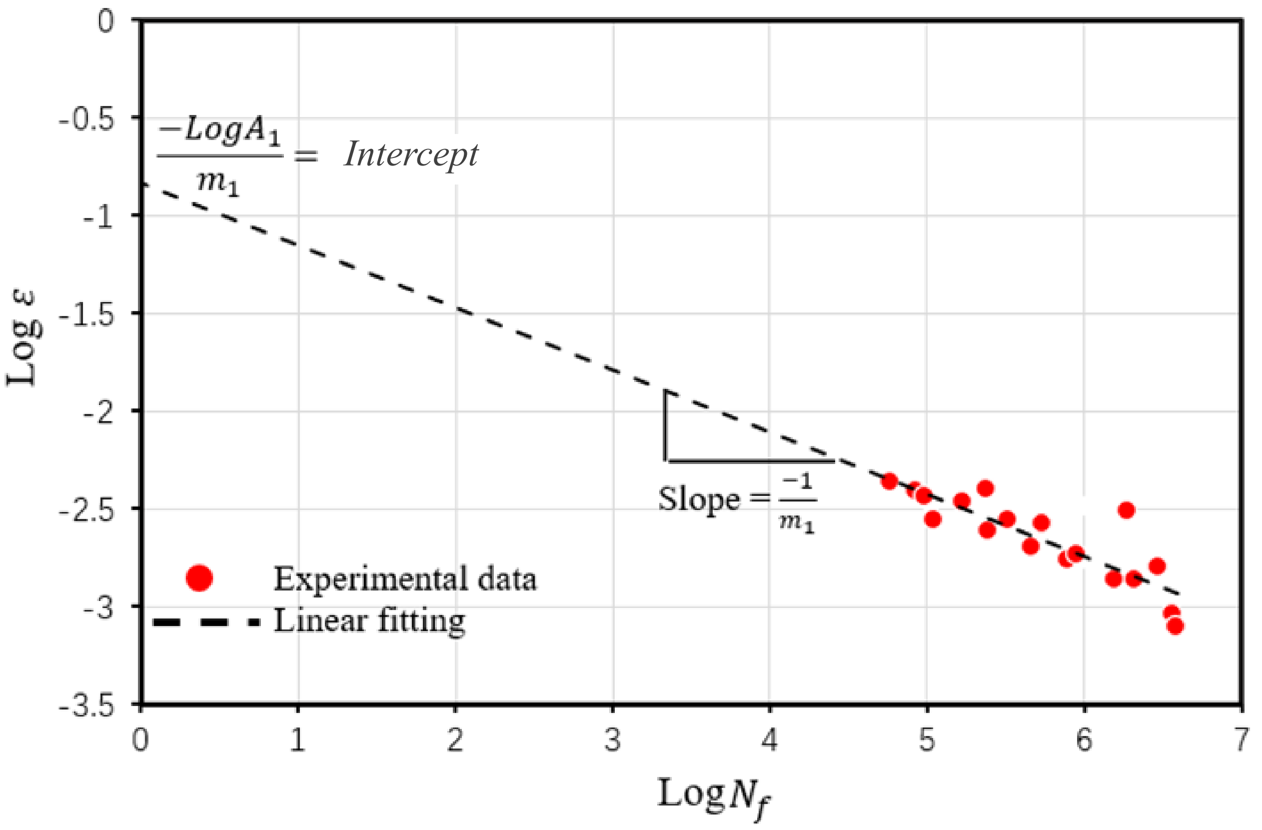
The largest defect is the site of fatigue crack initiation

For each fatigue specimen, the full surface is scanned, and the deepest Sv is reported

J. Gockel, L. Sheridan, B. Koerper, and B. Whip, “The influence of additive manufacturing processing parameters on surface roughness and fatigue life,” International Journal of Fatigue October 2018, pp. 380–388, 2019, doi: 10.1016/j.ijfatigue.2019.03.025..

Surface Roughness





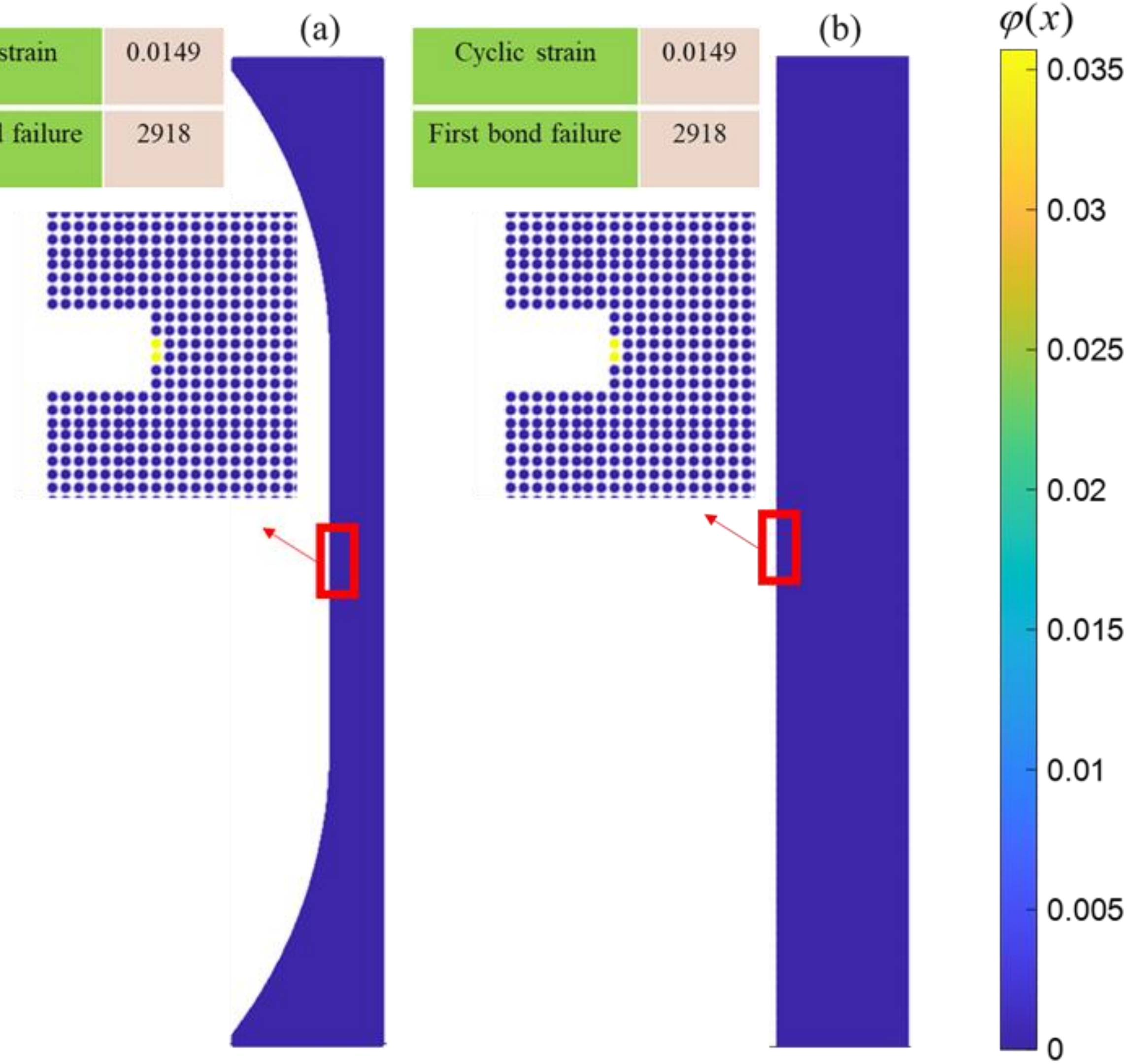
A_1= 450

m_1= 3.4

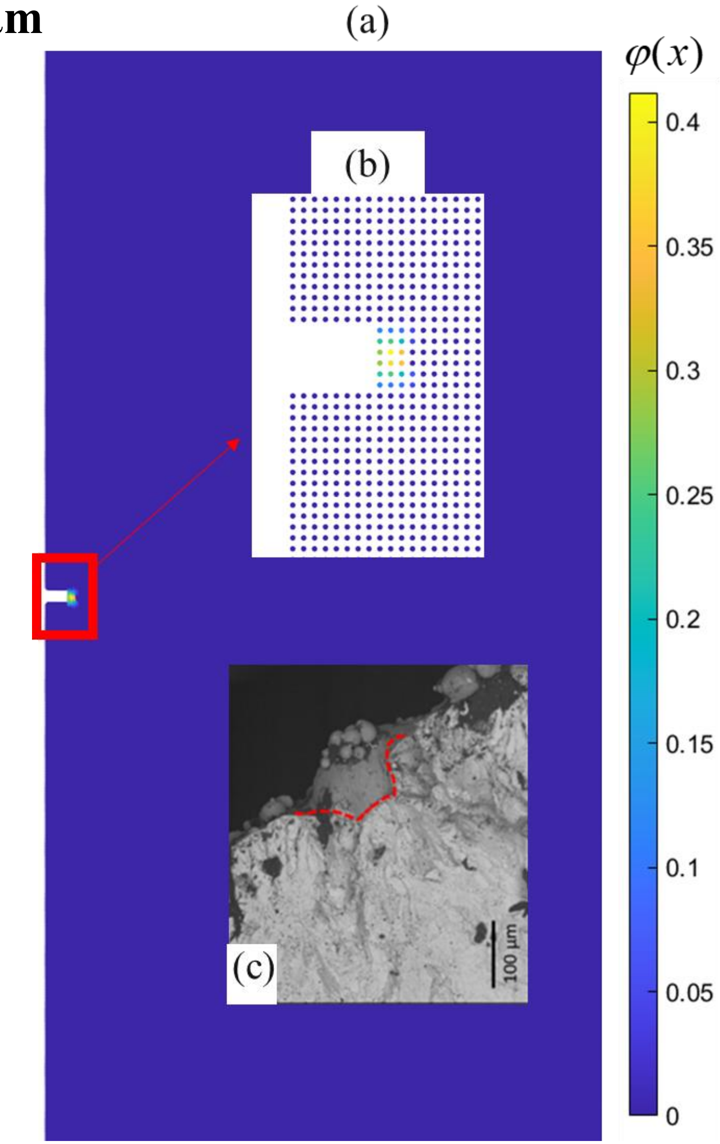
Surface Roughness Results

Cyclic strain	0.0149
First bond failure	2918

Cyclic strain	0.0149
First bond failure	2918



$S_v = 85\mu m$



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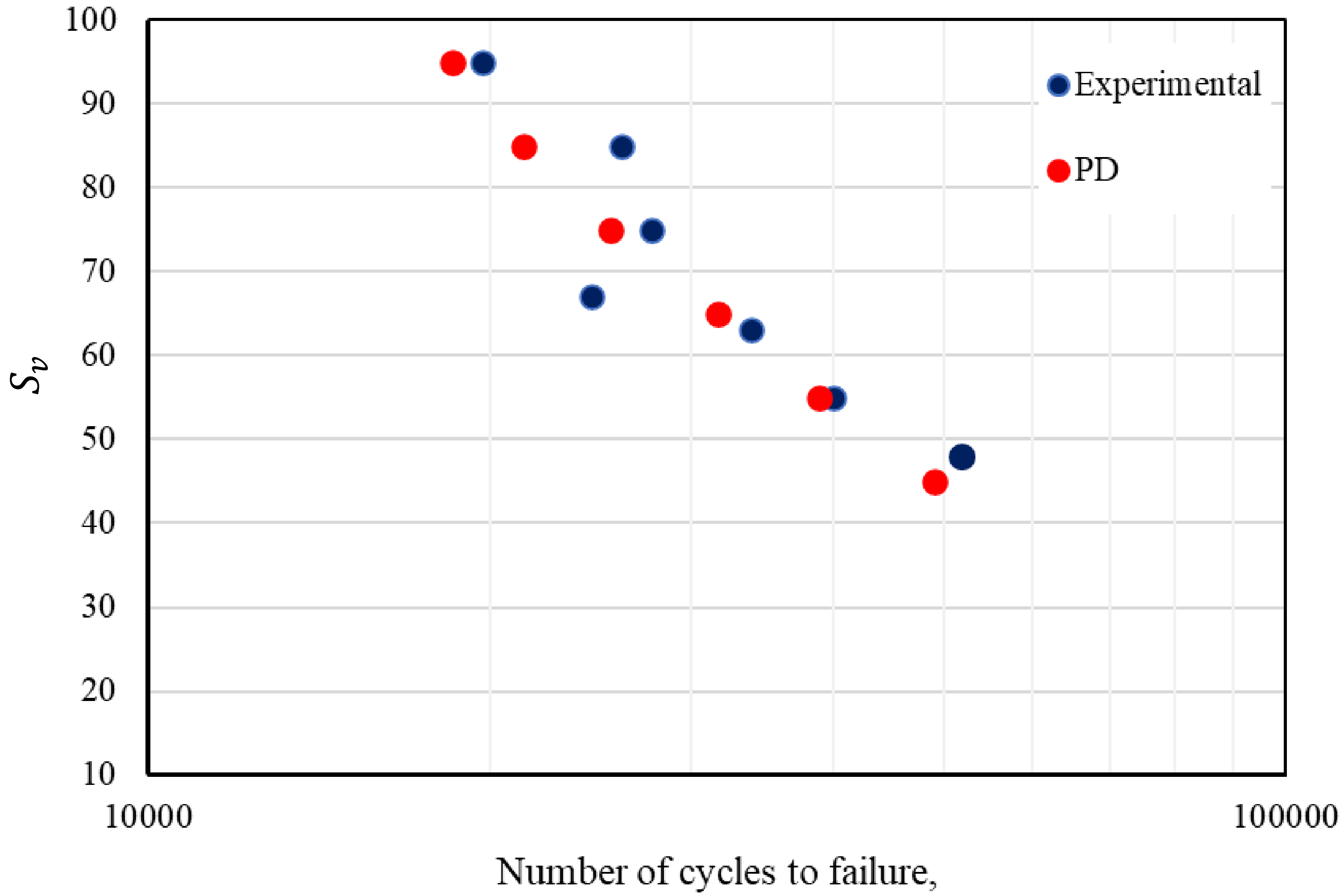

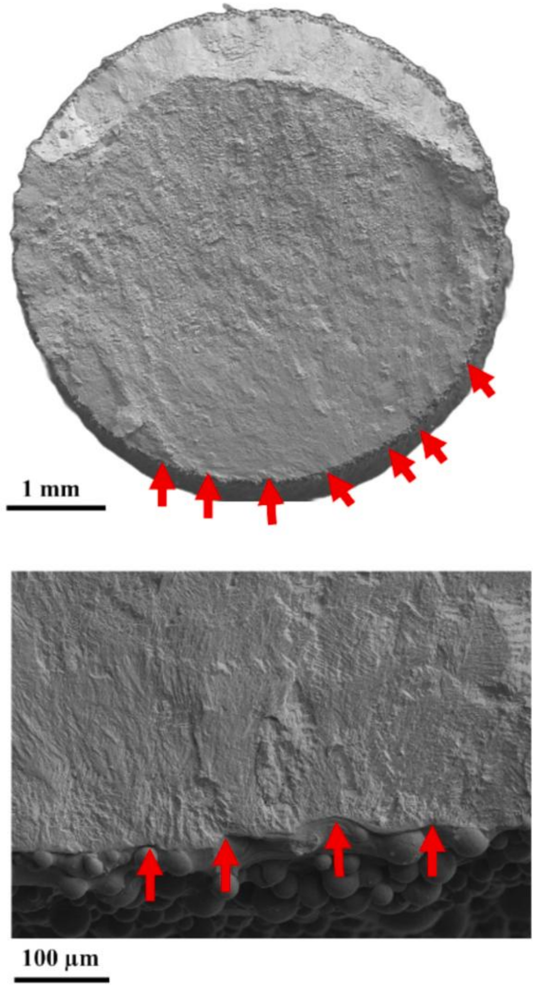

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Seminars and Publication

Seminars

28th International Conference on Fracture and Structural Integrity
(Catania, Italy, 15-18 September 2025)

Publications

- Peridynamic-Based Modeling of Fatigue Damage and Remaining Life Estimation in Metallic Components (28th International Conference on Fracture and Structural Integrity, September 2025, Catania, Italy)
- Capturing Defect-Sensitive Fatigue Behavior in Inconel 718: Peridynamic Modeling of Surface Roughness and Porosity Effects (In preparation)

Research Plan

Year II

- Investigating effect of porosity on fatigue life
- Apply residual stress and investigate its effect on fatigue behavior
- Analyze crack propagation stage

Year III

- Use machine learning to identify process parameters that minimize harmful defects and reduce post-processing in additive manufacturing
- Validate proposed evaluation approaches with experimental results
- PhD thesis

Expected Outcomes

- Develop more reliable and efficient models for fatigue failure prediction
- Apply machine learning to optimize process parameters for minimizing defect severity and post-processing requirements in additive manufacturing components
- Prepare scientific publications

Thank you for your attention !

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