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Peridynamics Modeling of Damage Nucleation From Forging Flaws in Rotor Components

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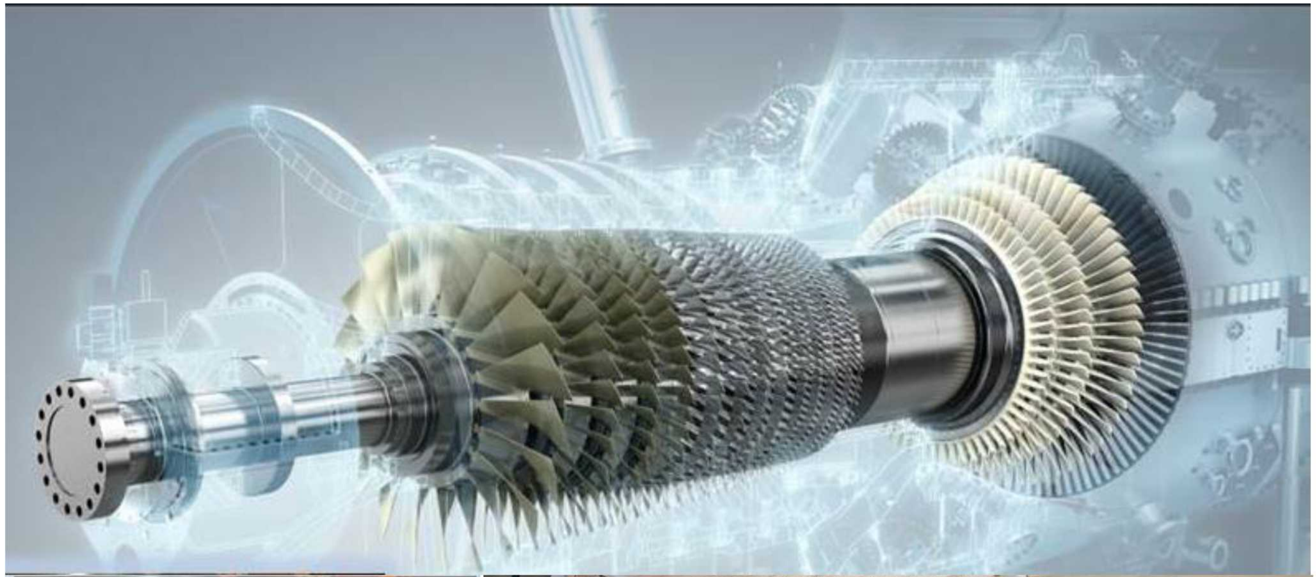
Outline

- Motivation and background
- Peridynamics basics and fatigue model
  - Crack nucleation
  - Crack growth
- Computational model setup
- Current capabilities: result and discussion
  - Effect of oxide inclusions on fatigue loading
- Future capabilities and application

Background information

- Turbine blades and rotor disks are exposed to extreme operating conditions.
- Weight is 5 tons with diameters and thickness up to 2 m and 0.4 m, respectively.
- Contain forging flaws during manufacturing process.
- Their presence needs to be accounted for as part of engineering life prediction methods, for both new apparatus and service applications.

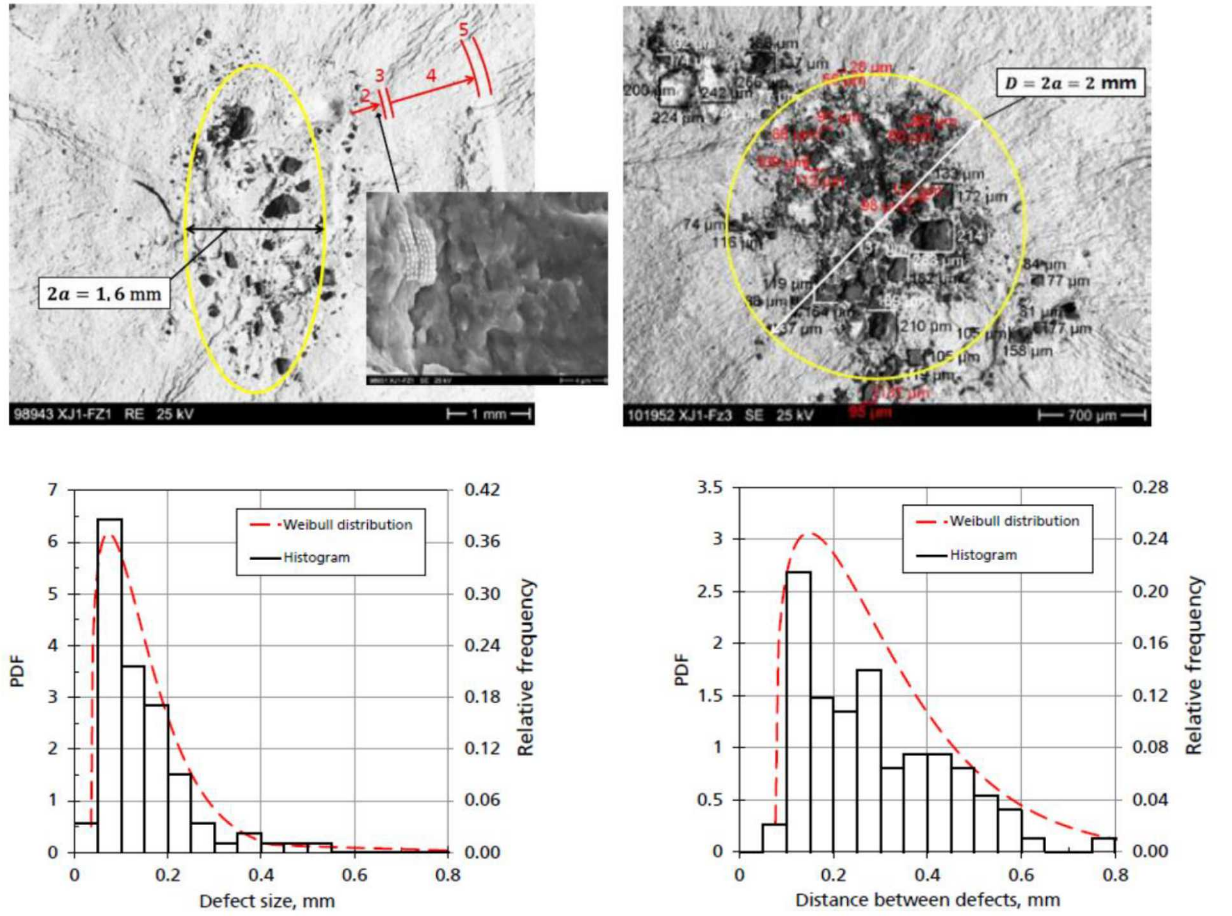


Heavy duty GT rotor disk forging at different manufacturing stage

Provided by Siemens Energy Inc.

Background information

- A typical forging flaw consists of a region of few millimeters in diameter.
- In order to predict the life of heavy duty rotor components, an assessment of these forging flaws is needed.
- The process of failure originating from forging flaws can be described by a crack nucleation phase and a subsequent fatigue crack growth phase.
- Fatigue crack growth can be described by engineering fracture mechanics and is well established. However, for the nucleation process no established engineering method is available.



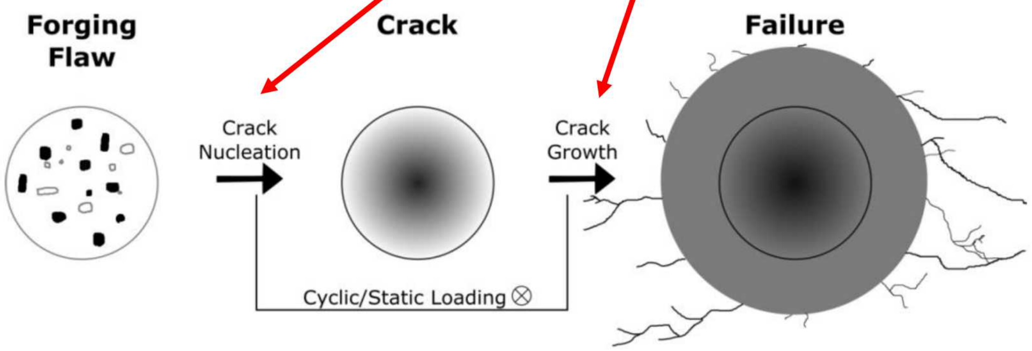
Top: Fractographic examinations of forgings flaws in high service temperature rotor steels. The dark spots are non-metallic inclusions in the bright steel matrix. Bottom: Size and distance distribution of the non-metallic inclusions in flawed areas as shown on top.

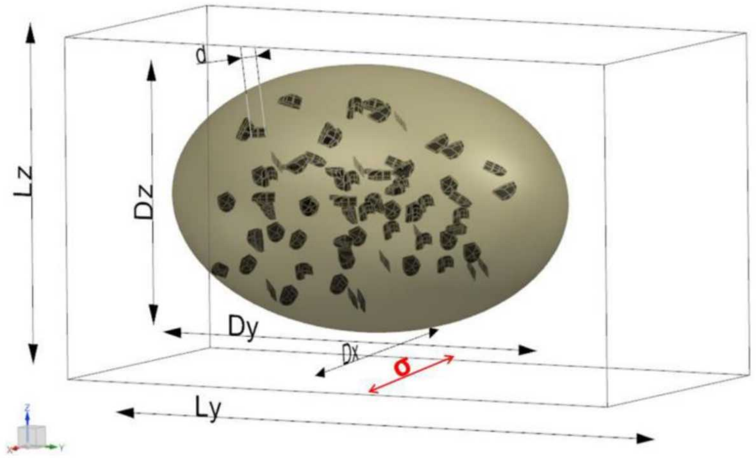
Varfolomeev, Igor, et al., 2017

Background information

- The number of cycles it takes to nucleate the flaw into a crack is often assumed to be zero in order to be conservative. This leads to an underutilization of component life time and reduced component operating flexibility.
- The fraction of lifetime due to the nucleation phase can be up to 50% of the experimentally observed lifetime including fatigue crack growth.
- This complex nucleation process is the subject of our study.
- We applied Peridynamics methods in order to understand crack nucleation from forging flaws.
  - Accurate life predictions
  - Improve efficiency of gas turbines (>65%)
  - Increased operational flexibility

$$N_{flaw} = N_{nuc} + N_{FM}$$





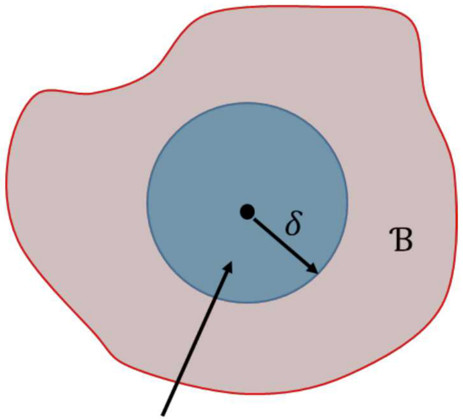
Peridynamics simulation cell illustration

Peridynamics basics

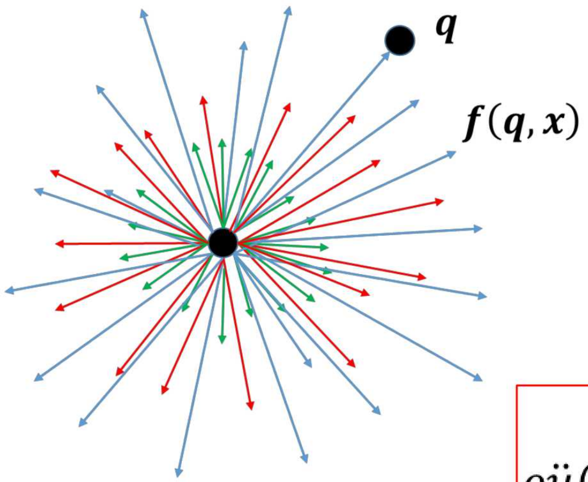
- Any point x interacts directly with other points within a distance δ called the “horizon”.
- The material within a distance δ of x is called the “family” of x, $\mathcal{H}_X$.
- Bond forces depend on the deformation of the families of both x and q, together with the material models at these points.
- The force state maps bonds to bond forces:

$$f(q,x) = T[x]\langle q-x\rangle - T[q]\langle x-q\rangle$$

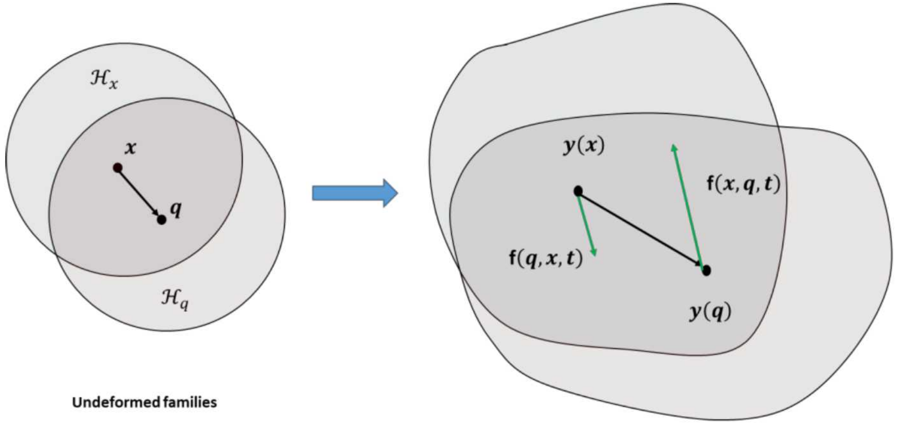
- Net damage is calculated by
- $$\emptyset(x) = \frac{\int_{\mathcal{H}_X} \underline{\emptyset}\langle\xi\rangle dV_\xi}{\int_{\mathcal{H}_X} dV_\xi}$$



Family of x



Bond forces between neighboring points



Undeformed families

Deformed families and bond forces

Equation of motion

$$\rho\ddot{u}(x,t) = \int_{\mathcal{H}_X} f(q,x)dV_q + b(x,t)$$

Fatigue model

- Assume a peridynamic solid undergoes loading that cycles between two extremes, denoted by S+ and S-. For a given bond ξ, bond strains at two extremes be defined by

$$S^{+} = \frac{|Y^{+}\langle\xi\rangle| - |\xi|}{|\xi|} \ ; \qquad S^{-} = \frac{|Y^{-}\langle\xi\rangle| - |\xi|}{|\xi|}$$

- The cyclic bond strain is defined by

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

- Each bond in the body has a remaining life $\lambda(N)$ where N is the cycle number. The remaining life is monotonically decreasing over time

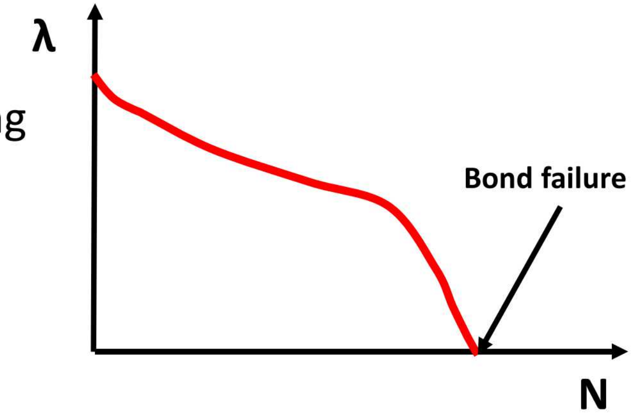
$$\lambda(0) = 1 \ ; \qquad \dot{\lambda} \leq 0$$

- Bond breaks at the earliest loading cycle N such that

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

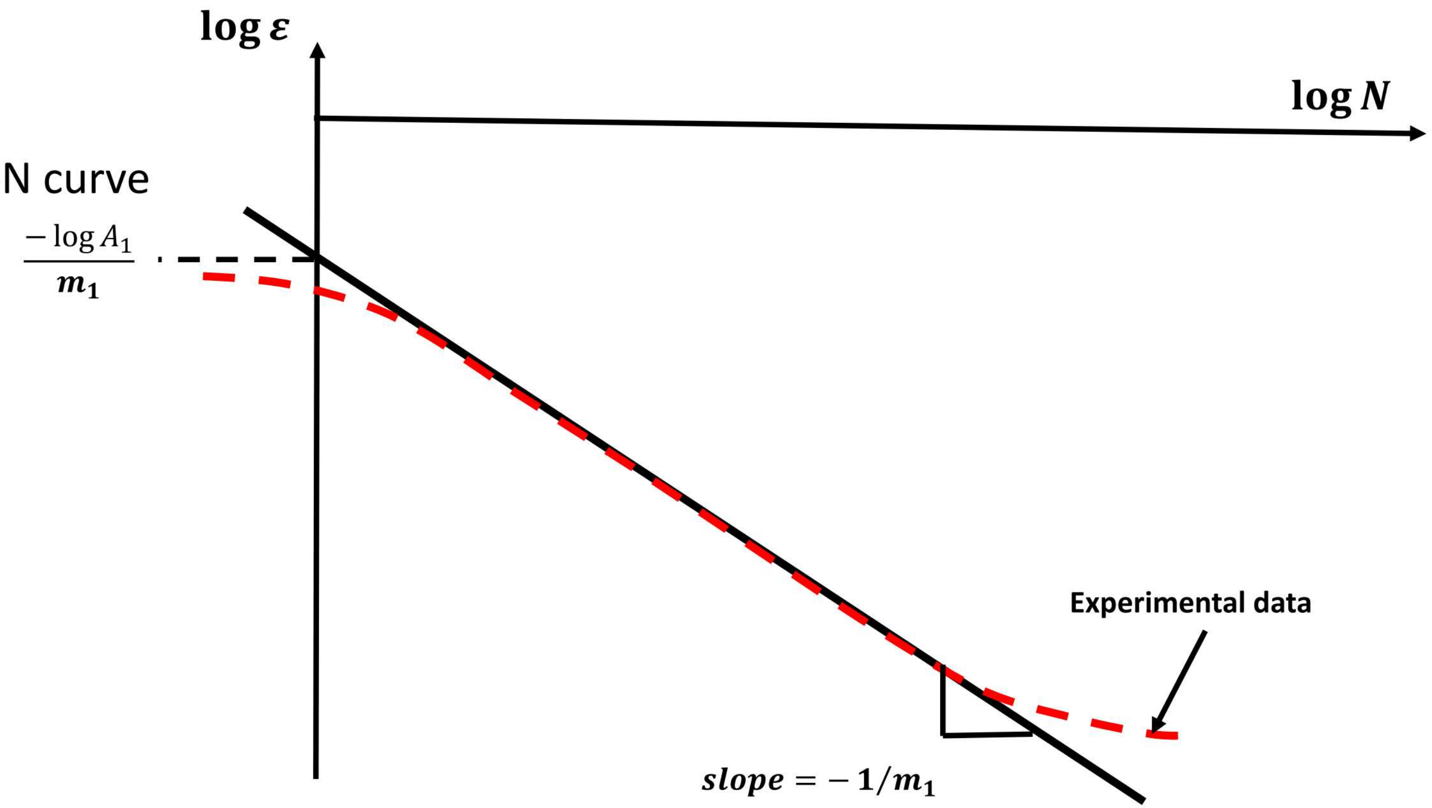
- Fatigue model specifies how the remaining life depends on loading cycle

$\frac{d\lambda}{dN}(N) = -A\varepsilon^{m}$; where A and m are constant and are calibrated separately for phases I and II (nucleation and growth).



Calibration of phase I: Nucleation

- To calibrate A_1 and m_1 with experimental data, run many cyclic loading test at different values of ε (from S-N data)
- $\frac{d\lambda}{dN}(N) = -A_1 {\varepsilon_1}^{m_1}$
- Bond breaks and nucleation occurs when
- $N_1 = \frac{1}{A_1 {\varepsilon_1}^{m_1}}$
- This parameters are fitted with experimental S-N curve



Loading cycle as a function of bond strain for nucleation of damage

Calibration of phase II: Crack growth

- A Paris law plot is required to find the parameters for phase II:

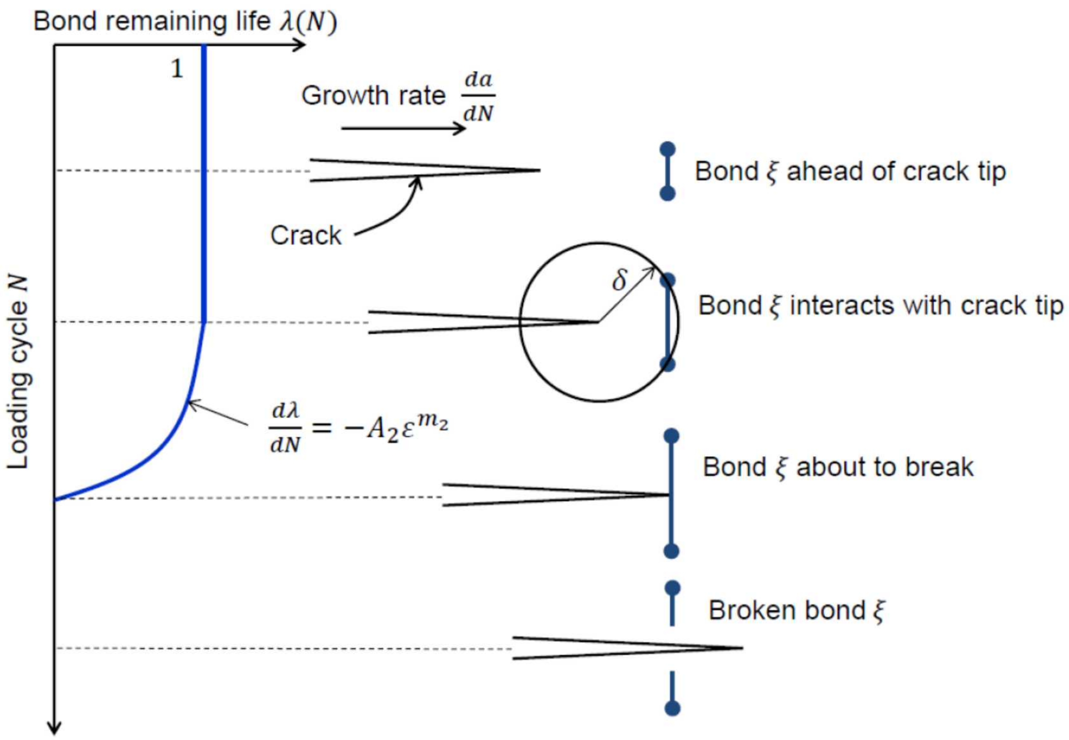
$$\frac{da}{dN} = c\Delta K^M$$; ΔK is the cyclic stress intensity factor,
which is proportional to the bond strain at the crack tip.

- Therefore, $m_2 = M$ can be obtained directly from Paris law plot.
- A simulation with some trial value A_2' has to be run to obtain the trial crack growth speed $\left(\frac{da}{dN}\right)'$. Then the real A_2 value can be found from

$$A_2 = A_2' \frac{\frac{da}{dN}}{\left(\frac{da}{dN}\right)'}$$

- Scaling of A_2 is required by the following method:

$$A_2(\delta) = \hat{A}_2 \delta^{(m_2-2)/2}$$



A bond ξ near an approaching fatigue crack undergoes cyclic strain, which changes over time, eventually causing the bond to break (Silling, 2014)

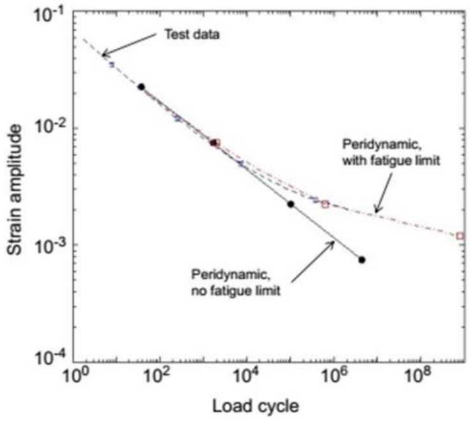
Computational model set up

- Fatigue model parameters are adopted from silling, 2004, for this study.
- Aluminum alloy of 7075-T651 is used and inclusions are stiffer than aluminum.
- Linear, isotropic and ordinary state material model is used in this study.
- Uses exponential time mapping:

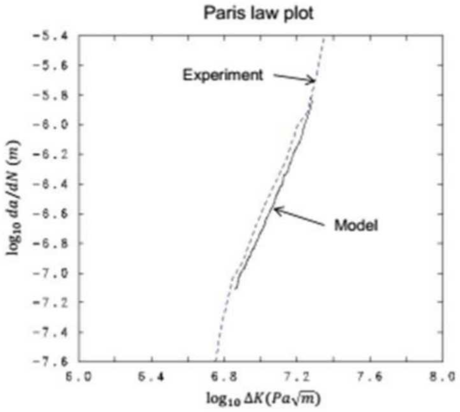
$$N = e^{t/\tau}$$

- Transition from phase 1 and phase 2 is carried out if there is a net damage of

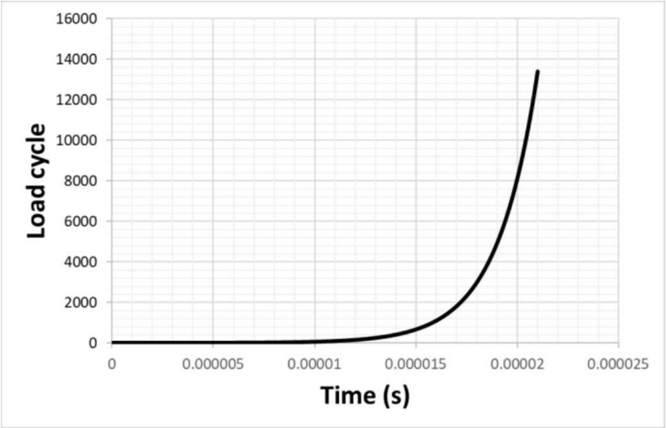
$$\emptyset(X') \geq 0.5$$

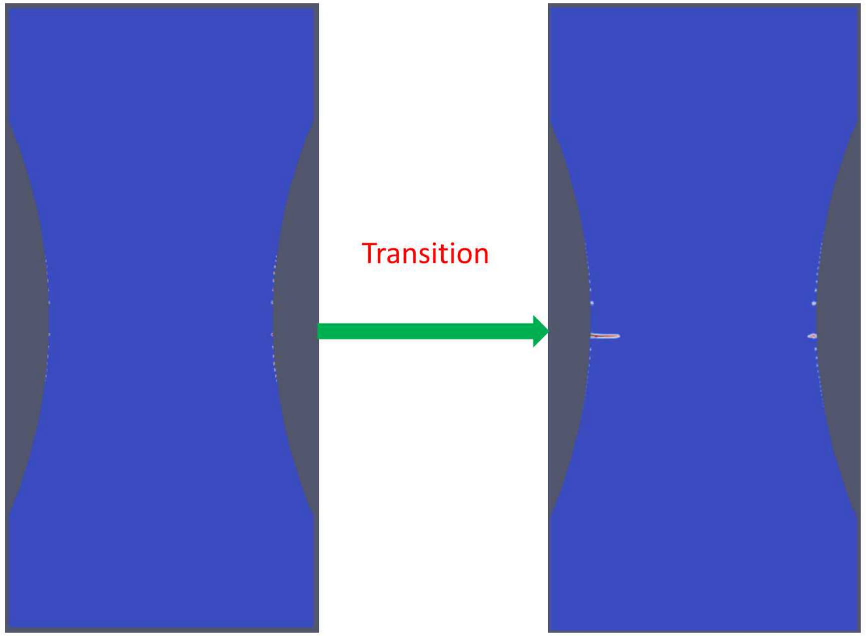


Calibration for phase I (Silling, 2014)



Calibration for phase II (Silling 2014)



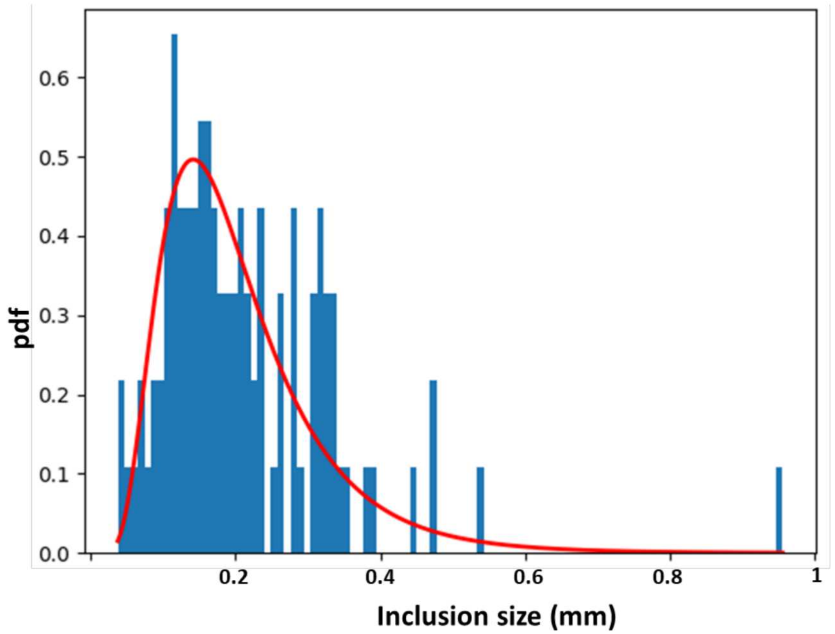


Nucleation: 1877 cycles

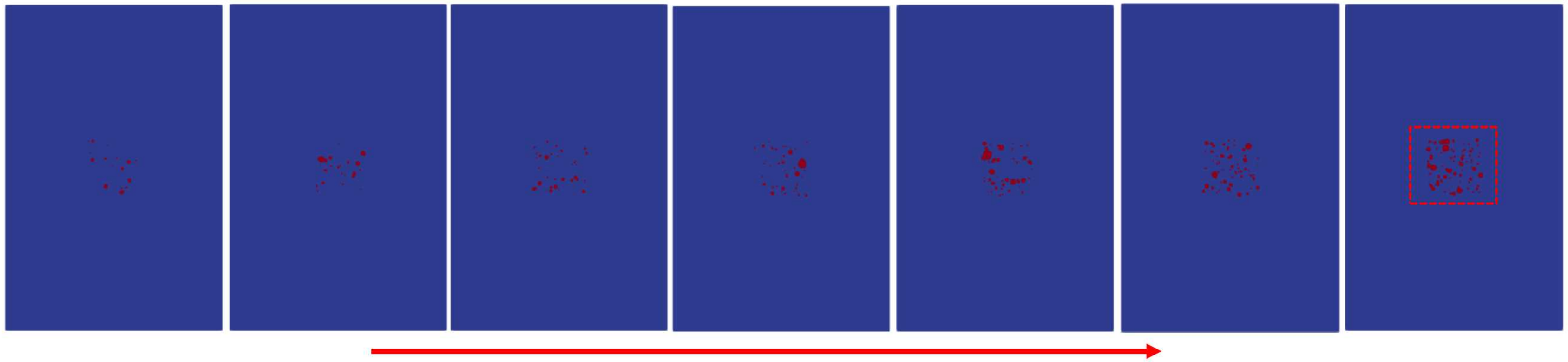
Growth: 3990 cycles

Computational setup of the oxide inclusion inside bulk material

- Prepare samples from log normal distribution
- Probability density function for log normal distribution is
- $P(x) = \frac{1}{\sigma x\sqrt{2\pi}} e^{\left(-\frac{(ln(x)-\mu)^2}{2\sigma^2}\right)}$
- μ is mean value (=0.6) and σ is the standard deviation (0.5)
- Inclusions are randomly distributed in 2mm × 2mm surface area
- Density of inclusions are 4, 7.5, 10, 12.5, 15, 17.5, 25 mm^{-3}
- Inclusion size ranges from 35-350 µm



Probability density function histogram plot for 25 mm^{-3} case (100 inclusions)

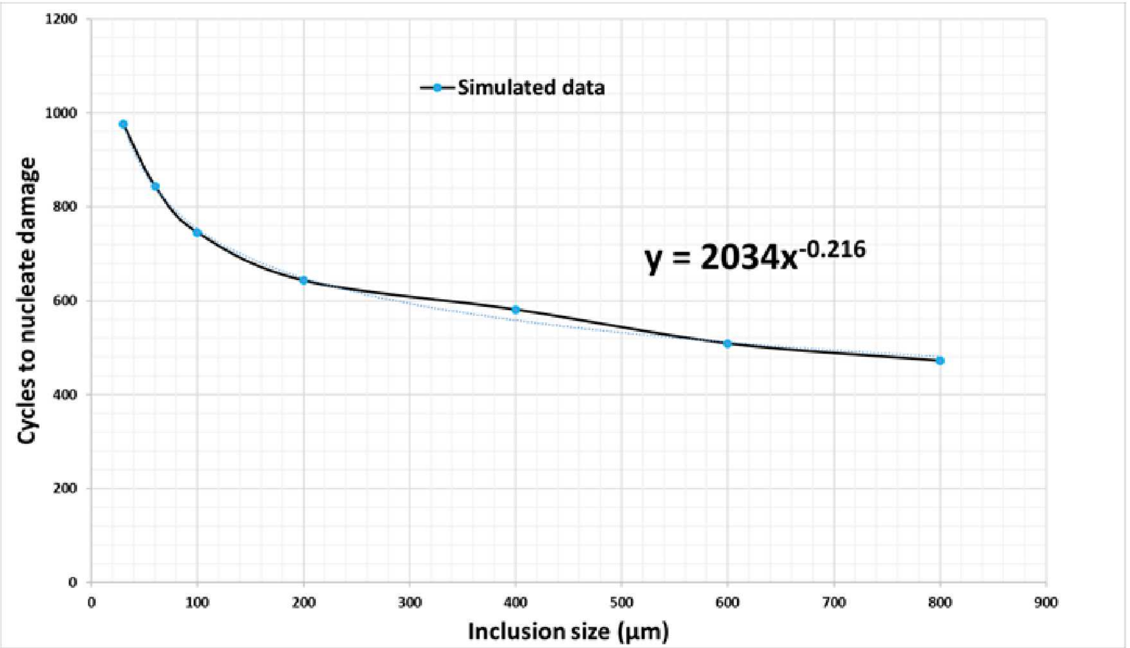


Samples with increasing inclusion density (rad colors are inclusions

Red dotted box is 2mm × 2mm surface area)

Result and discussion: Particle size effect

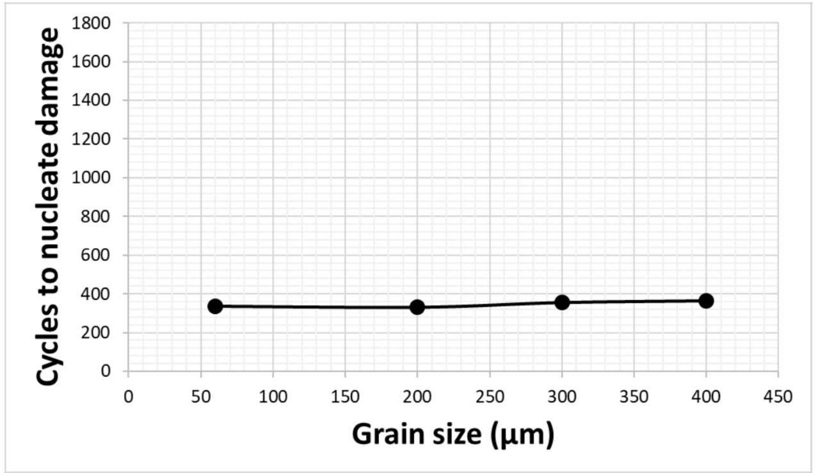
Inclusion size (mm)	Cycles to nucleate damage
0.03	976
0.06	844
0.1	745
0.2	643
0.4	581
0.6	509
0.8	472

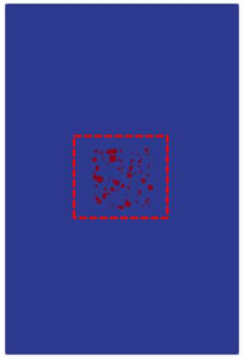


Y=cycles to nucleate damage and X=inclusion size

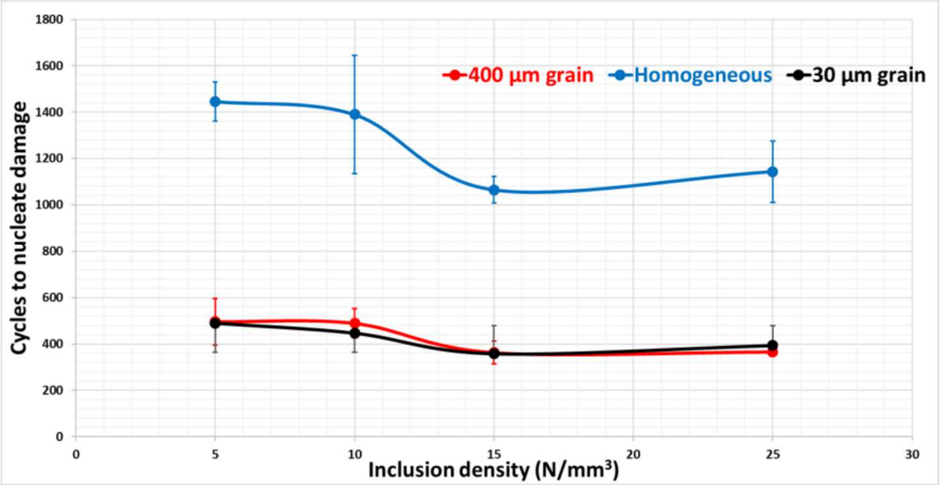
- Inclusion size vs cycle to nucleate damage fits very well with a power law relationship and we can represent them with a power law equation.
- 10 µm inclusion went up to 2100 cycles but could not produce any nucleation sites.

Result and discussion: Grain size effect

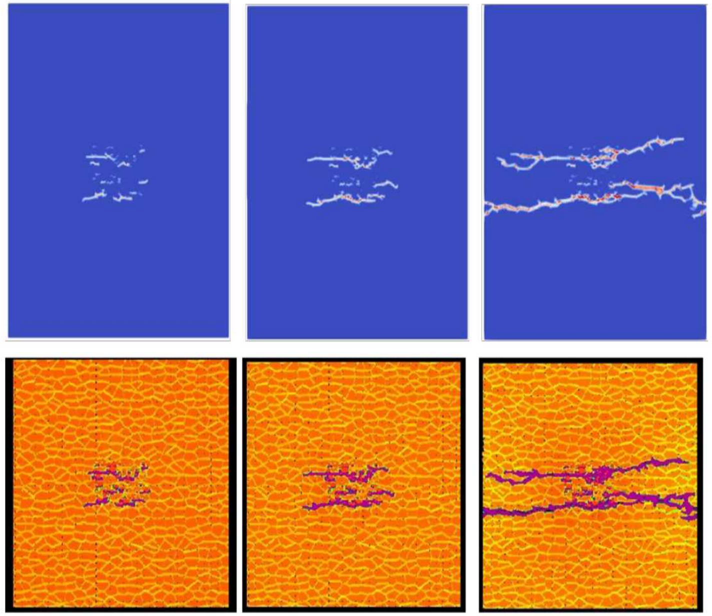




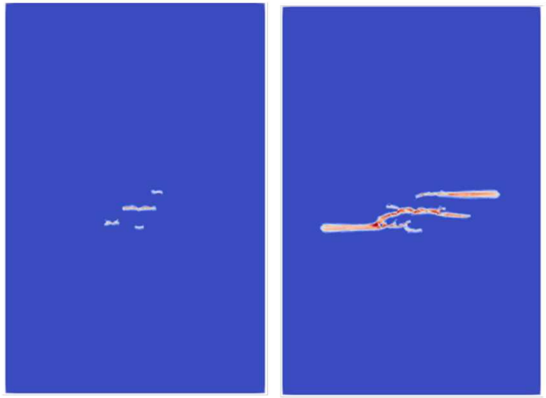
Sample: 2mm×2mm



- Grain size effect is carried out for inclusion density of 25 N/mm^3 and 400, 300, 200 and 60 µm grain size and interface strength is 20%.
- Effect of 400 and 30 µm grains are compared with homogeneous materials.
- In polycrystalline, leading cracks propagate in a zigzag manner because leading crack tip is obstructed by grain boundary.
- Branching of crack from leading crack is also observed along grain boundary, because bonding cohesion between grains are weaker.
- In homogeneous material, leading crack just merge with the secondary crack and propagated without any branching.

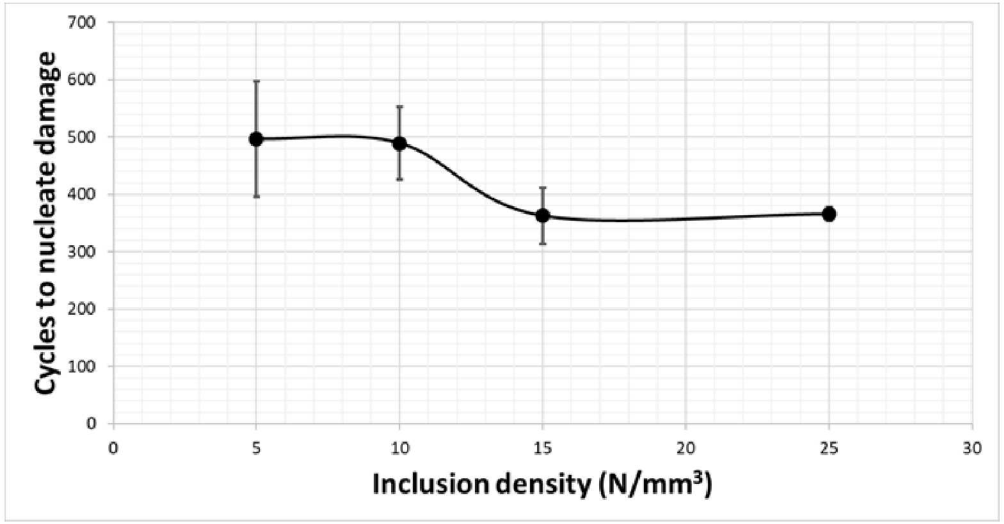


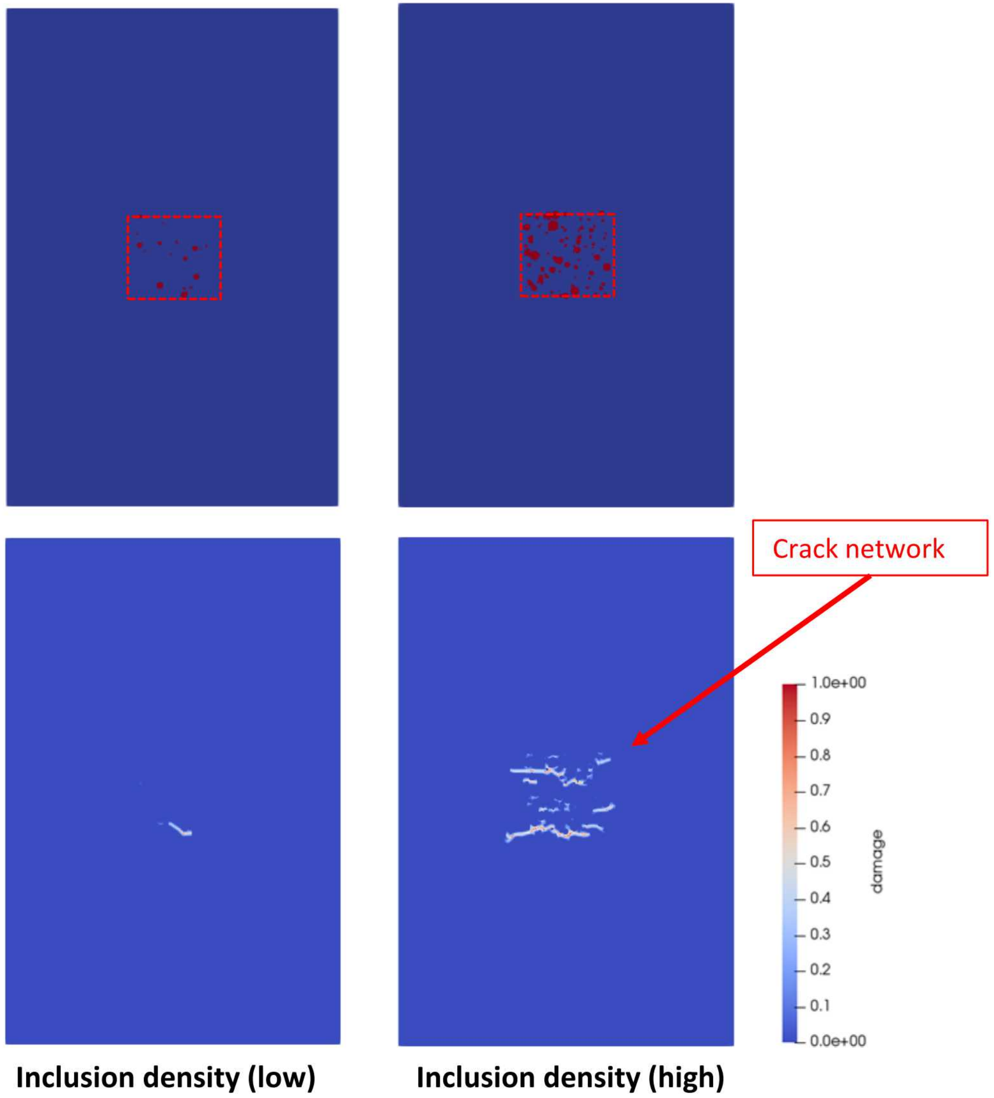
Polycrystalline



Homogeneous

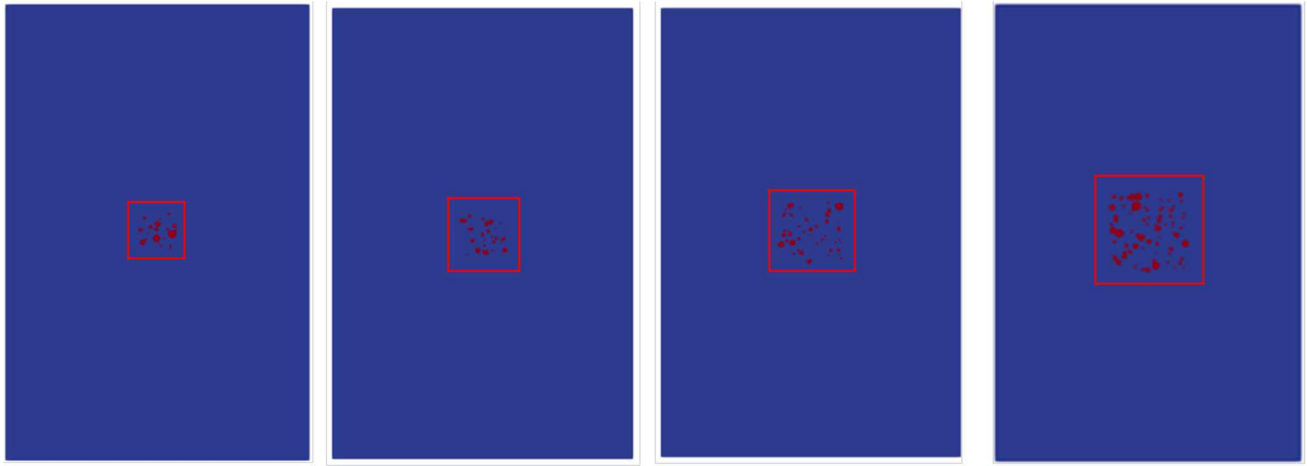
Result and discussion: Inclusion density effect



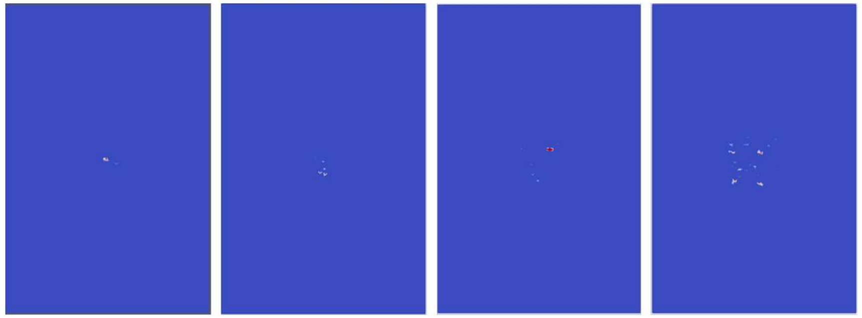


- 10 samples are considered for each density within 2 mm× 2mm region.
- Multiple damages are nucleated with the increase of inclusion density.
- A crack networks are observed at high inclusion density (for 12.5, 15, 17.5 and 25 mm^{-3}).

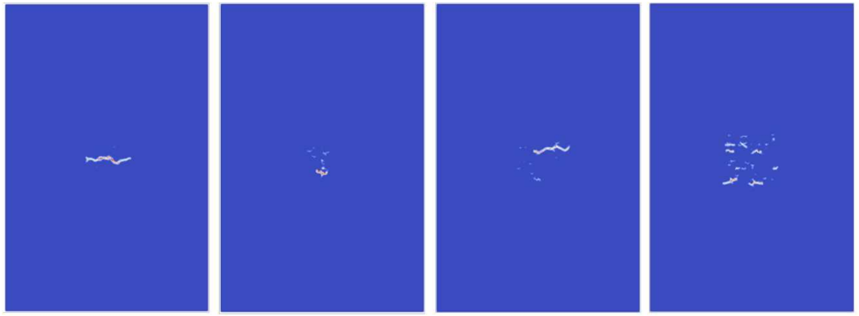
Result and discussion: Effect of inclusion region



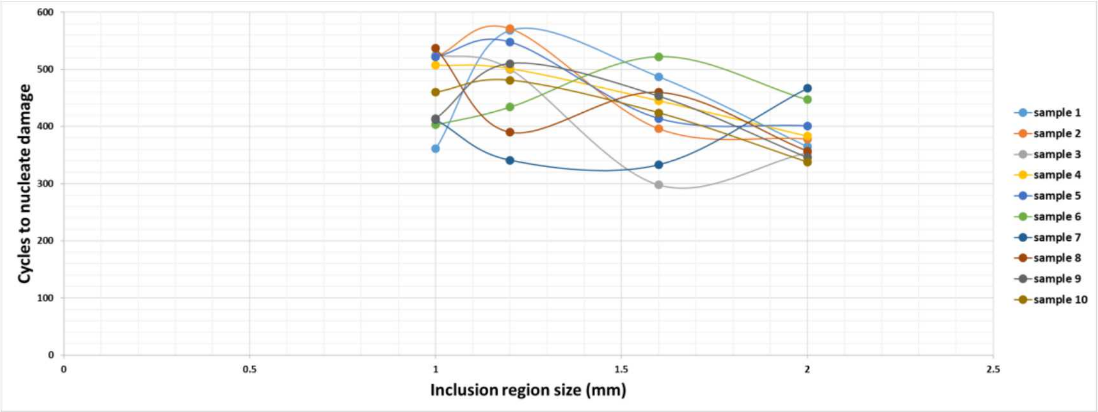
1 mm × 1 mm   1.2 mm × 1.2 mm   1.6 mm × 1.6 mm   2 mm × 2 mm



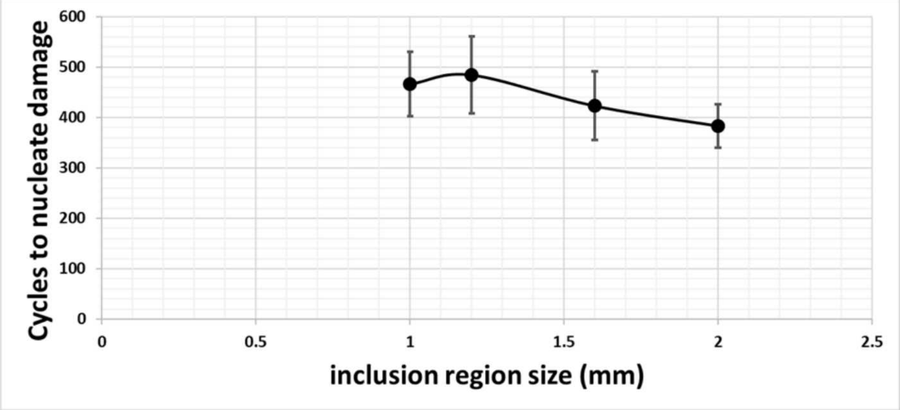
Nucleation



Growth



- 10 samples are considered for each case.
- high inclusion region can nucleate damage at earlier cycles



Consider average value

Summary

- Current capabilities
  - Minimum oxide inclusions (<10 μm) are required to initiate crack nucleation.
  - In polycrystalline, cracks propagate in a zigzag manner due to barrier by grain boundary.
  - There is a threshold inclusion density (< 10 N/mm^3) above which cycles to nucleate damage become stable.
  - High inclusion regions are more favorable to nucleate crack at earlier stage.
  - High temperature can dense crack network.

- Future development
  - Develop a relationship between load drop rate with crack growth distance.
  - Set up PD fatigue model with rotor steel and calibrate modeling result with experimental data.