Very-high-cycle fatigue

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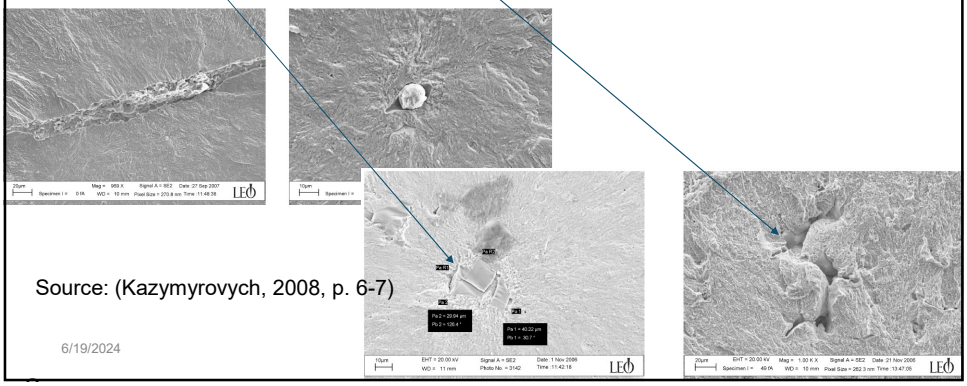
Background

- Study fatigue life above 10^9 cycles
  - Experiments contradicts presence of fatigue limit at 10×10^6 cycles
- Tested using ultrasonic fatigue testing equipment
- Causes & Mechanisms investigated by high-resolution electron microscope
  - Mostly originates at slag inclusions
    - Stringer type
    - Single particle
- “Fish-eye” characteristic of very high cycle fatigue

Principle

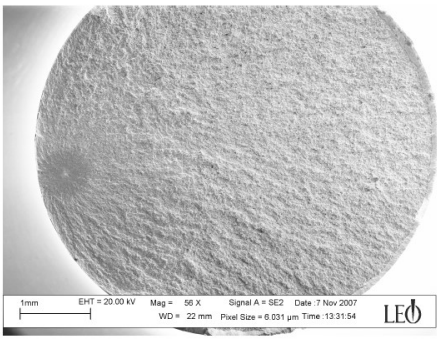
- Mostly: Crack initiate internally
  - Slag inclusion
    - ❑ Of stringer type
    - ❑ Single particle inclusion
  - Void created by trapped gasses
  - Carbide

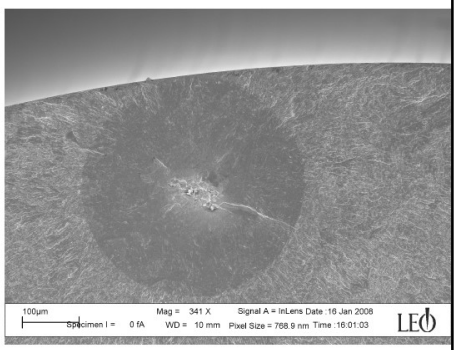


Source: (Kazymyrovych, 2008, p. 6-7)

Fracture morphology

- “Fish-eye” forms around fatigue initiating defect
  - Has flat morphology
- Changes shape when crack reaches surface





“Fish-eye” as evaluating parameter

- Only “fish-eyes” away from surface should be used
- “Fish-eyes” reaching surface:
  - Size largely defined by distance from initiating defect t surface
  - Crack grows beyond the “fish-eye” boundary until it reaches a critical size and rapid failure occurs

Crack initiation and growth according to Kazymyvorych (2008, p. 8)

- Crack growth within “fish-eye”: 10 to 20 nm/cycle
- Crack growth outside “fish-eye”: 30 to 140 nm/cycle
- Portions of fatigue life for crack to grow within and outside “fish-eye” insignificant comparison to total fatigue life
  - < 1% of total life
- Concept of VHCF initiation zone:
  - Area around fatigue origin where striations not distinguishable in SEM (Scanning Electron Microscope)
  - Estimated diameter 50 µm
  - Conclusion
    - ❑ In VHCF regime ~100% of fatigue life is consumed during crack initiation

If assumed that the fatigue crack growths with each cycle by smallest possible step of 0.1 nm – the interatomic distance

- Then it would take < 10^6 cycles for crack to grow through initiating zone! (Kazymyvorych, 2008, p. 10)
  - Then there must be mostly non-propagating cycles during initiation stage!
  - Non-propagating cycles constitute 99% of VHCF life
    - Life should be related to stress state at the crack tip during initiation stage
- Two mechanisms?:
  - Hydrogen-assisted growth
    - During non-propagating cycles, H-atoms diffuse to most stressed regions – the crack tip
    - When H-concentration is high: crack propagates short distance
    - New period of crack stagnation & H-atom diffusion begins
  - Dislocation rearrangement
    - During non-propagating cycles: continuous dislocation rearrangement takes place
    - When favourable positioning achieved: crack advances by small step

Marukami

- In the VHCF range crack growth during initiation stage enabled by synergistic effect of cycle stresses & hydrogen that is trapped by the inclusion
  - Without hydrogen
    - Crack size equal to the VHCF initiating inclusion would be non-propagating
  - Effect of hydrogen
    - Results in crack growing to a certain size where after it is big enough to propagate due to stress only
- ODA: Optically Dark Area
  - Represents H-assisted crack growth
    - Appears dark on optical microscope
    - Appears light when viewed with SEM (Scanning Electron Microscope)

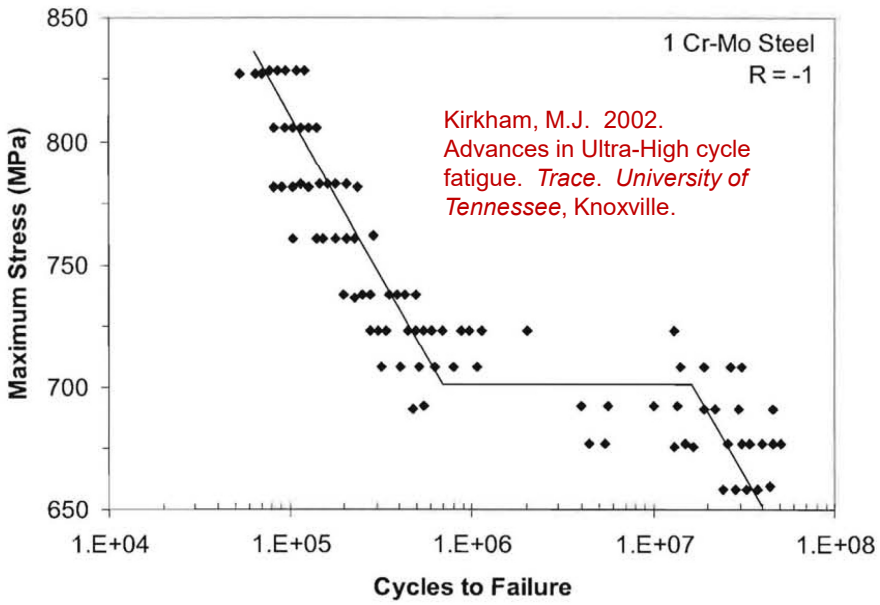


Figure 1: S-N curve of 1Cr-Mo steel with R = -1 in air at room temperature [5].

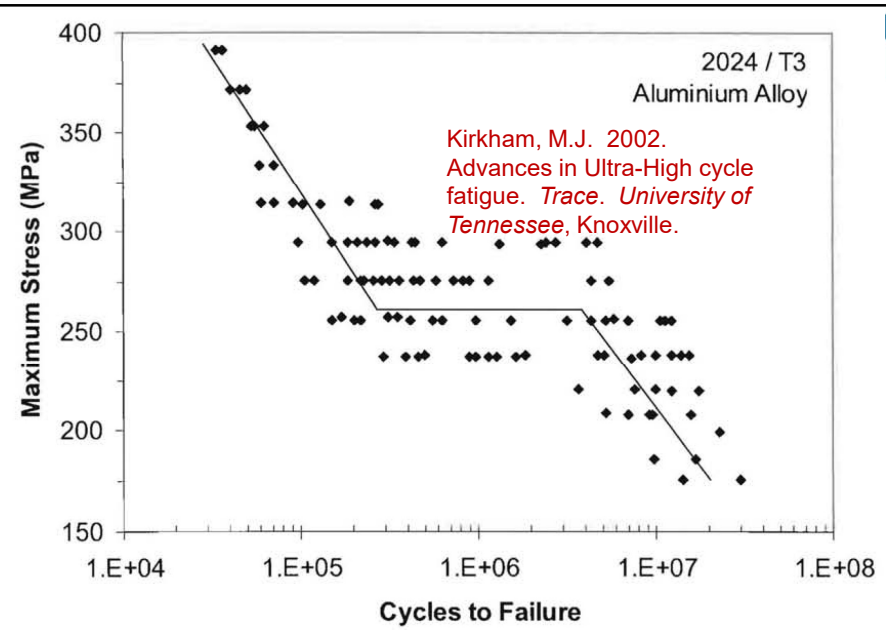


Figure 2: S-N curve of 2024/T3 aluminum alloy in air at room temperature [1].

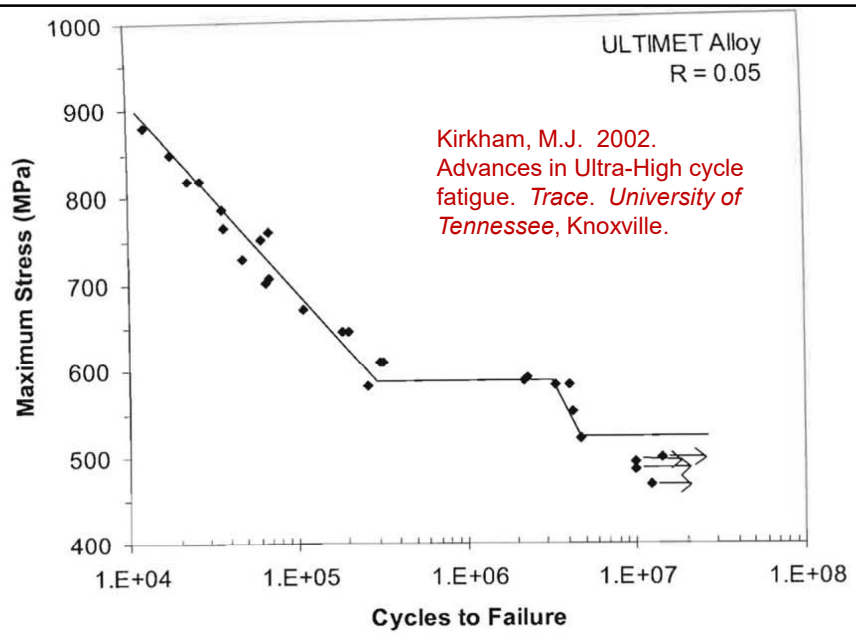


Figure 3: S-N curve of ULTIMET superalloy with R = 0.05 in air at room temperature [6, 8].

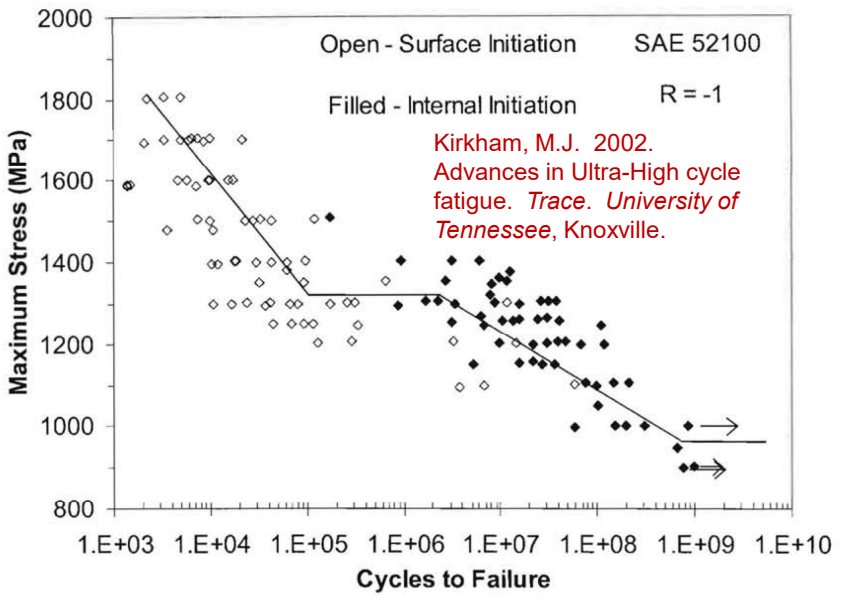


Figure 4: S-N curves of SAE 52100 bearing steel showing initiation location with R = -1 in air at room temperature [9].

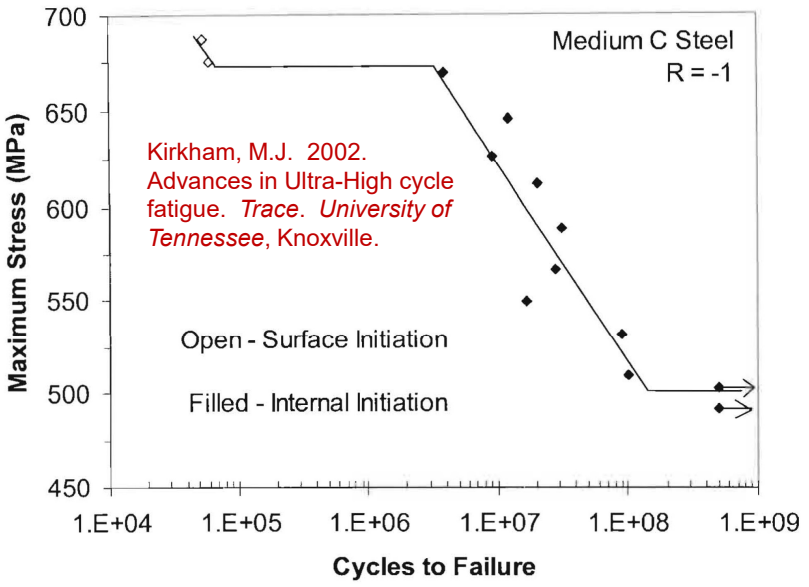


Figure 5: S-N curve of medium carbon steel showing initiation location with R = -1 in air at room temperature [10].

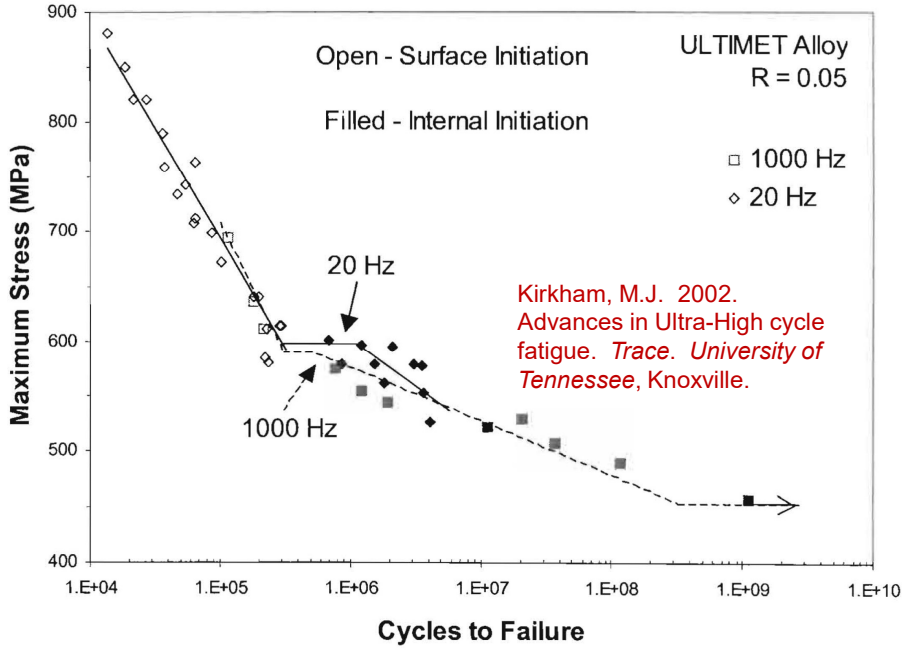
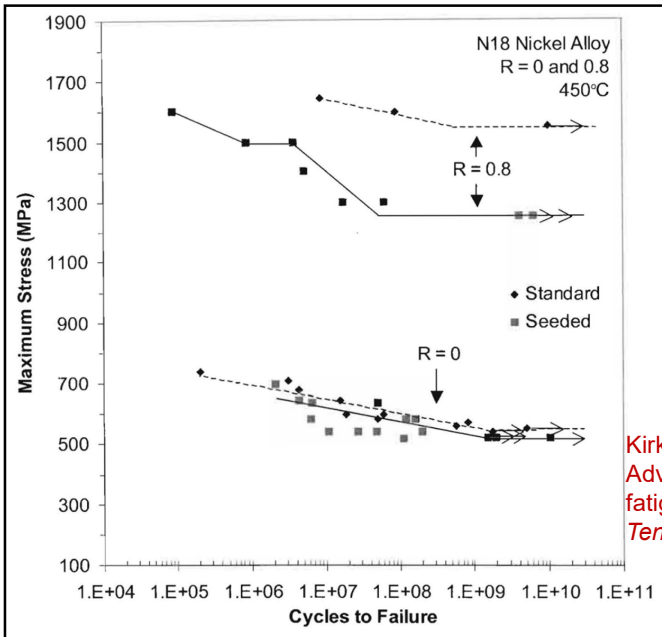
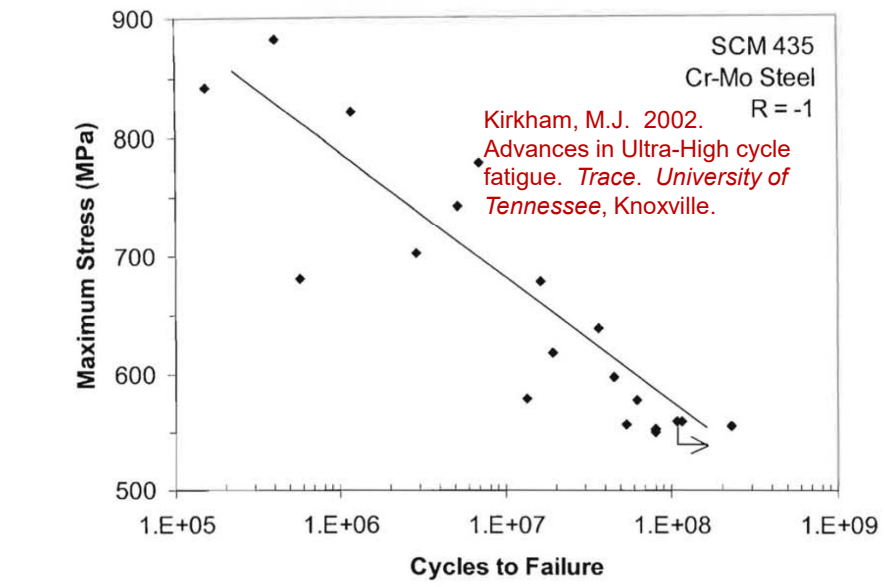


Figure 6: S-N curve of ULTIMET alloy with R = 0.05 in air at room temperature [6, 8].



Kirkham, M.J. 2002. Advances in Ultra-High cycle fatigue. *Trace*. *University of Tennessee*, Knoxville.

Figure 7: S-N curves of seeded and standard N18 nickel alloy with R = 0 and 0.8 in air at 450°C [7].



Kirkham, M.J. 2002. Advances in Ultra-High cycle fatigue. *Trace*. *University of Tennessee*, Knoxville.

Figure 8: S-N curve of carburized/nitrided SCM 435 Cr-Mo steel with R = -1 in air at room temperature [10].

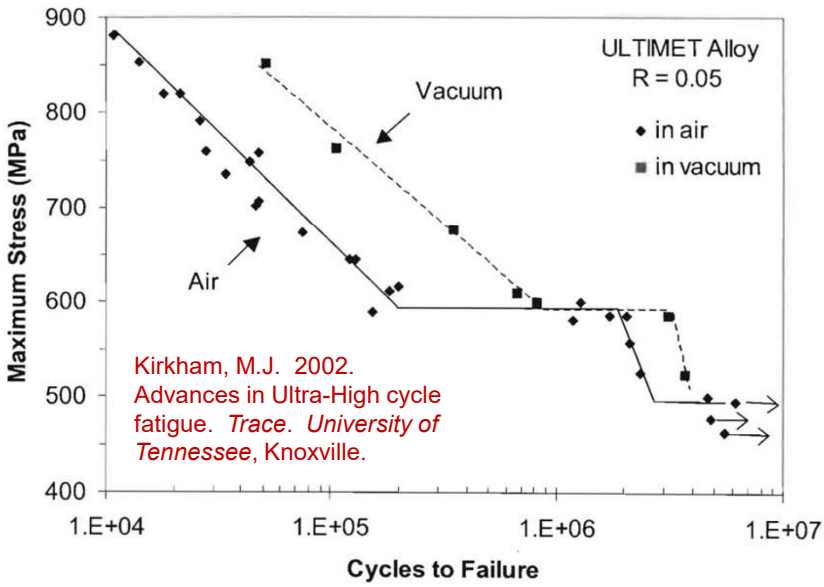


Figure 9: Effect of environment on S-N curve of ULTIMET alloy with R = 0.05 in air at room temperature [6, 8].

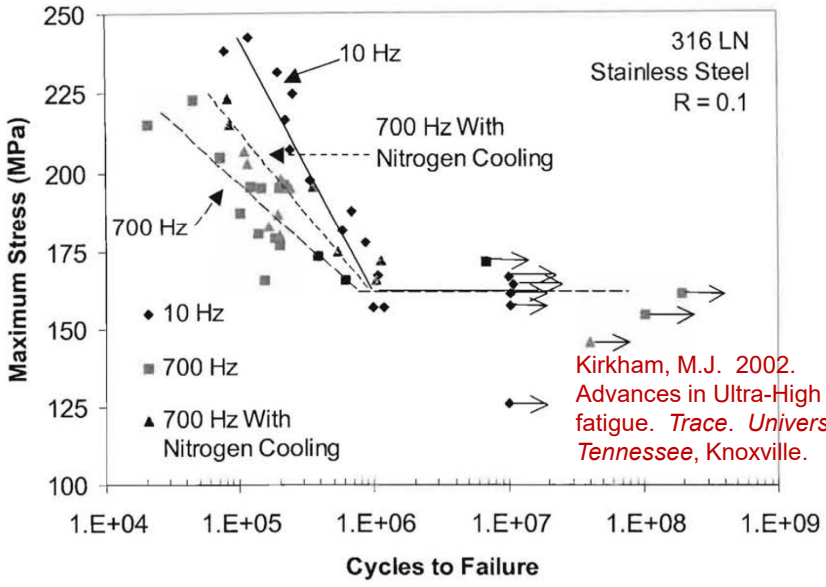


Figure 10: Effect of frequency on S-N curve of 316LN stainless steel with R = 0.1 in air at room temperature [16].

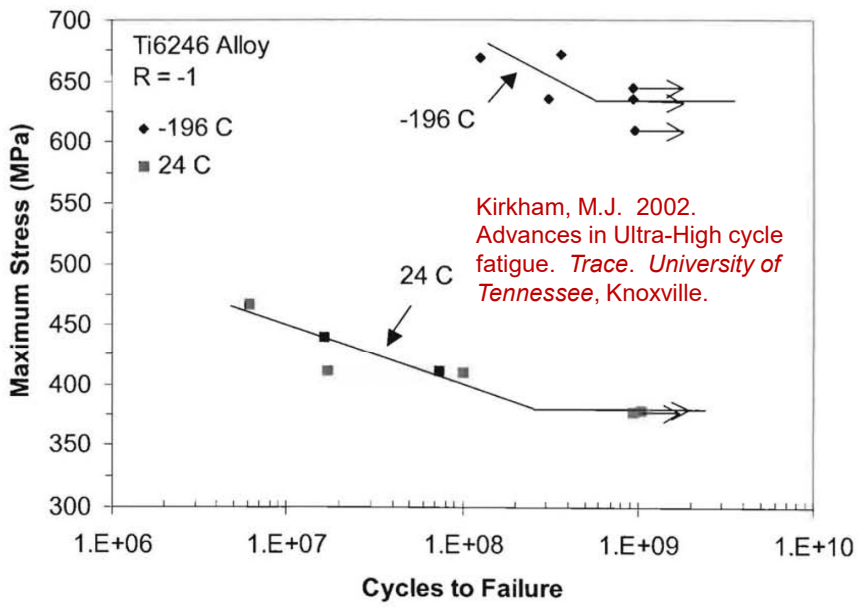


Figure 11: Effect of temperature on S-N curve of Ti6246 titanium-based alloy with R = -1 in air at -196°C and 24°C [7].

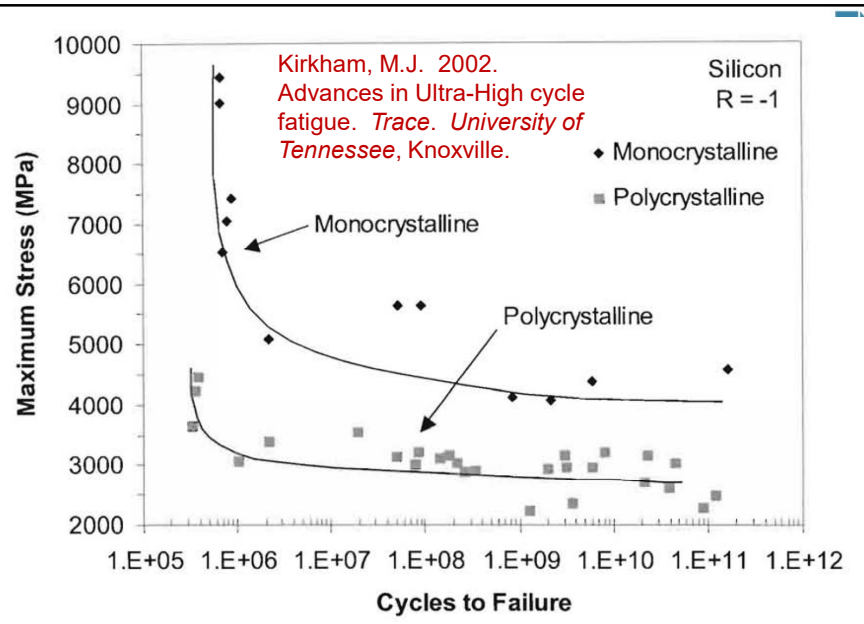
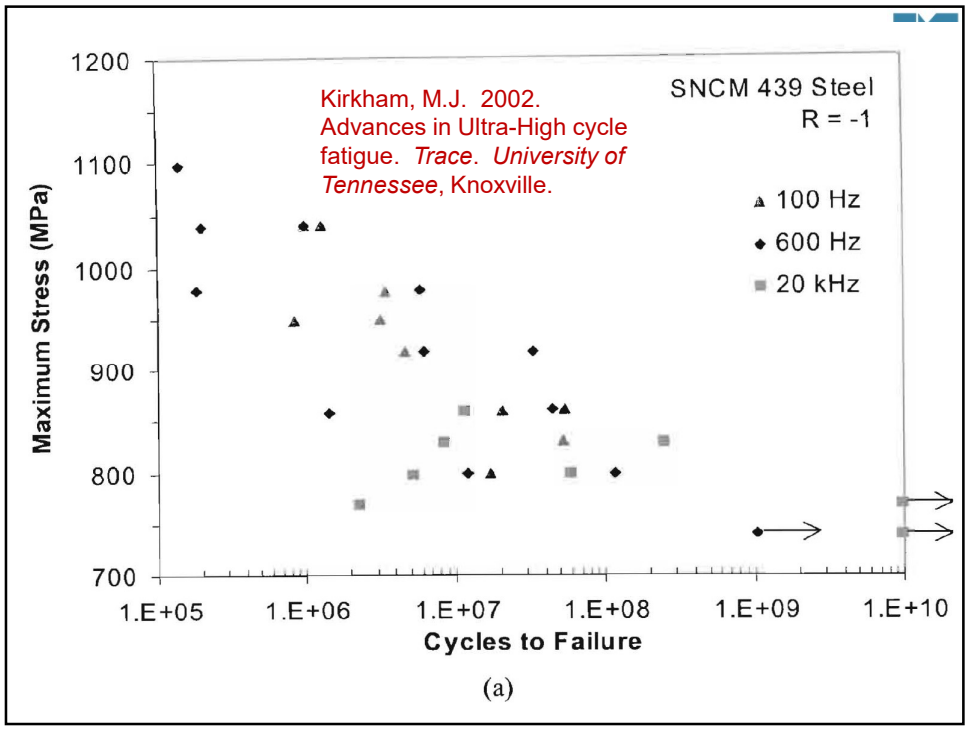
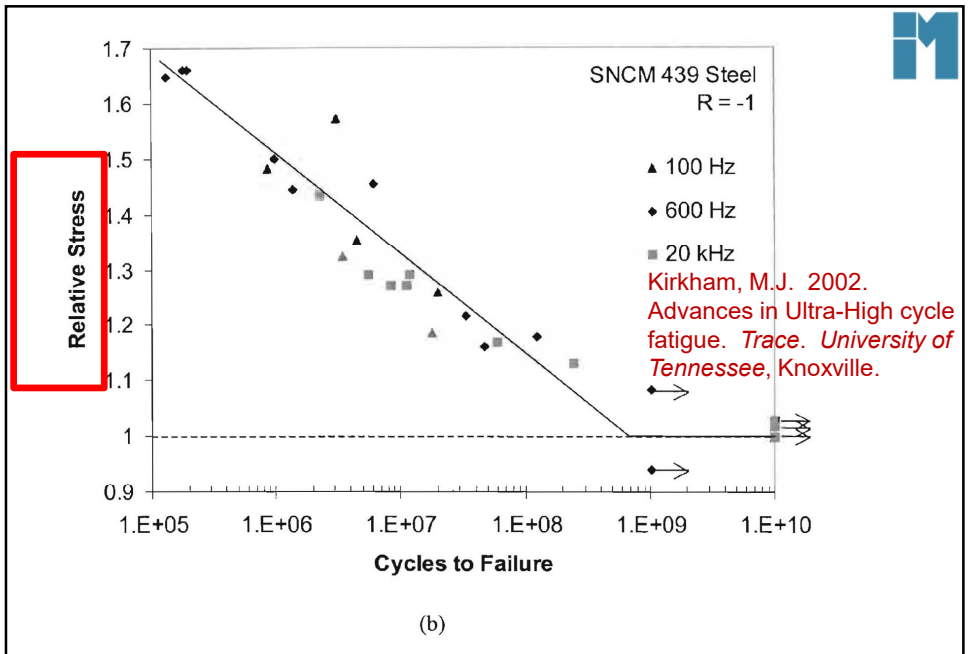


Figure 12: S-N curves of mono- and poly-crystalline thin-film silicon with R = -1 in air at room temperature [3, 4].



(a)



(b)

Figure 13: Effect of frequency on S-N curve of SNCM439 steel with R = -1 in air at room temperature, showing (a) normal and (b) modified plots [19].

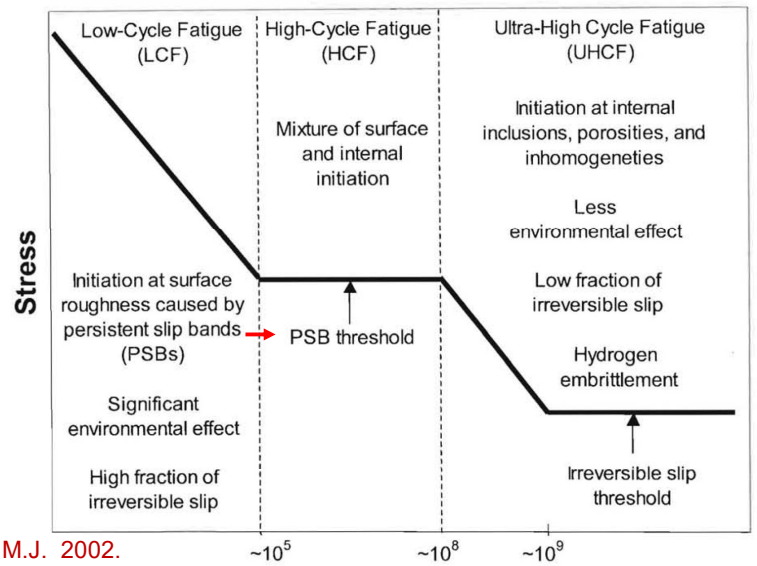


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Figure 14: Schematic of a typical S-N curve with a HCF plateau around 10^6 to 10^8 cycles and a UHCF plateau above about 10^9 cycles.

Bearing steels

- Main factors involved in fish-eye initiation:
  - Microstructure
  - Residual austenite
  - Oxide inclusion
  - Sulphur
  - Phase transformation[1]

References:

[1] Bathias, C. 2012. Gigacycle fatigue of bearing steels. *Institute of Materials, Minerals and Mining, vol. 28, no. 1, pp. 27 – 33.*