An Evaluation of the Staircase and Over-Stress Probe Methods for Fatigue Life Characterization in Aluminum Sand Castings

Dr. Robert Mackay (Nemak), Dr. Glenn Byczynski (Nemak), Dr. James Boileau (Element Materials Technology)

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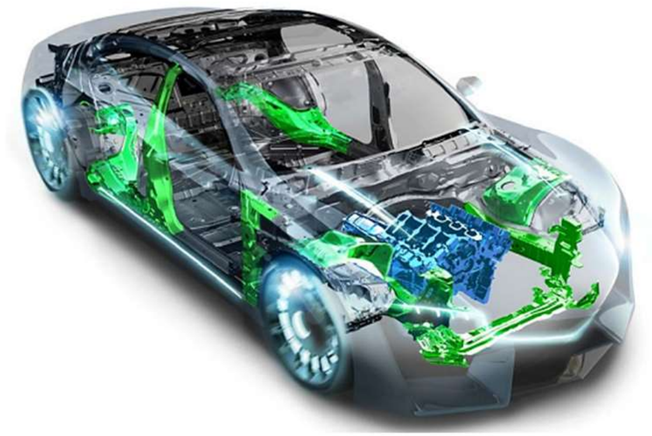

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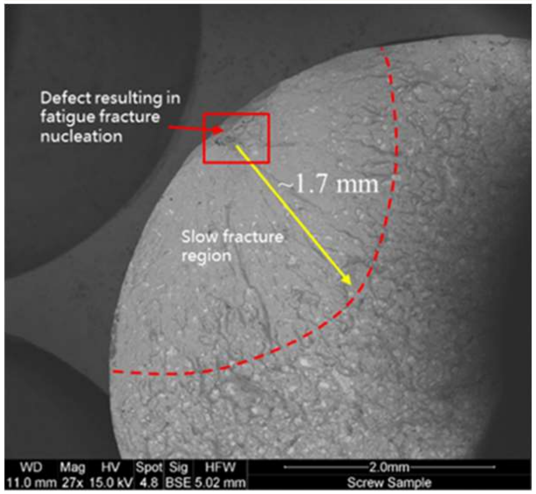
Introduction

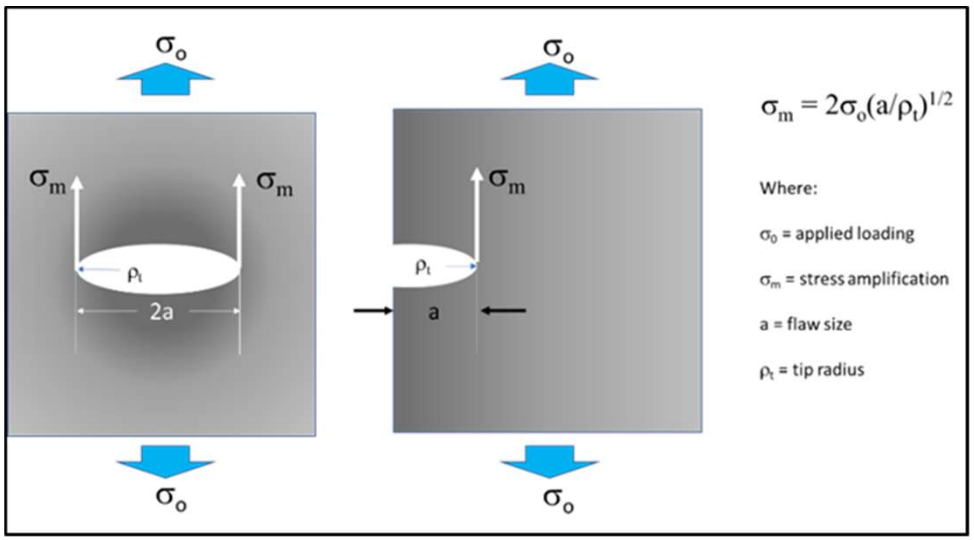
- The most common root cause of failure in mechanical structures is material fatigue. Fatigue is the process by which cracks develop and propagate to failure under cyclic loading
- Due to the need for simplified & rapid testing, laboratory Life-to-Failure methods have been developed and allow for estimation of lifetime under representative service conditions
- Two common laboratory-based methods used for fatigue durability are the Staircase and the Over-Stress Probe (OSP) method
- ***Compliant*** samples are defined as those that survive the target lifetime (10^7 cycles)
- It will be shown for the OSP method fractography can be conducted on ***compliant*** and ***non-compliant*** test samples which in turn will assess the level of porosity/oxide damage
- One drawback of the Staircase method is that it allows only fractographic examination of ***non-compliant*** test samples

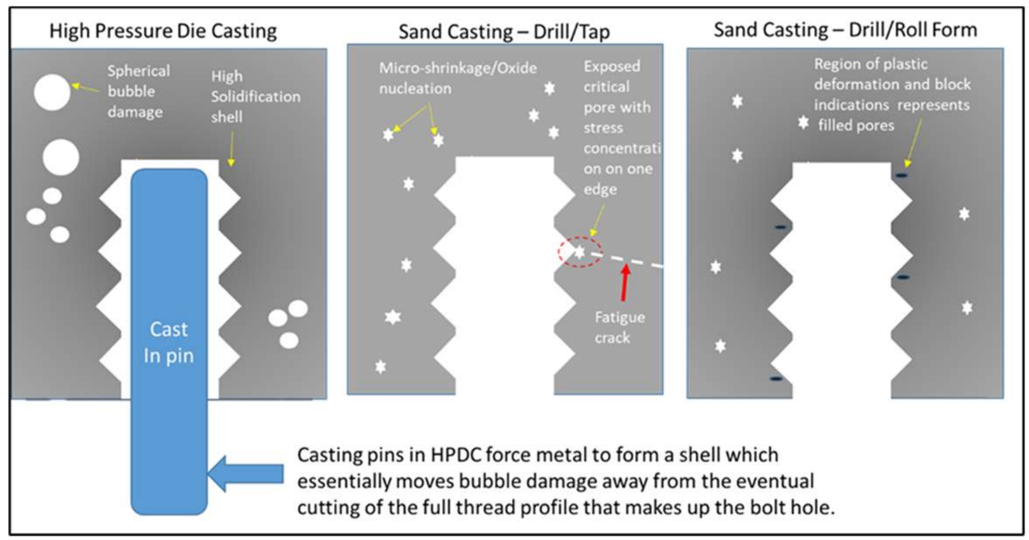


Effect of Critical Flaw Size and Location & Casting Process

- Stress amplification is dependent on the flaw size and location with respect to an exposed surface
- Flaws exposed to a free surface will result in stress amplification to be concentrated on one tip edge

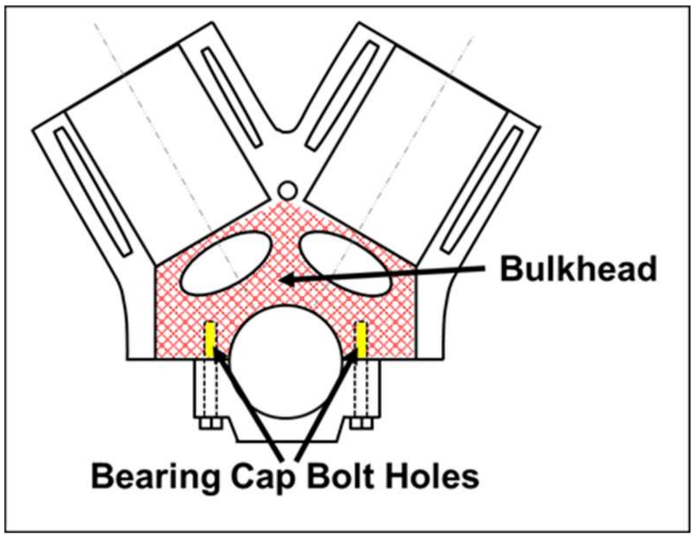
- Casting process has an effect on the probability of a pore exposed to the surface
- HPDC uses a core pin promoting a rapidly solidified shell and pushing pores inward
- Thread roll-forming can also nullify the stress amplification effect of exposed pores

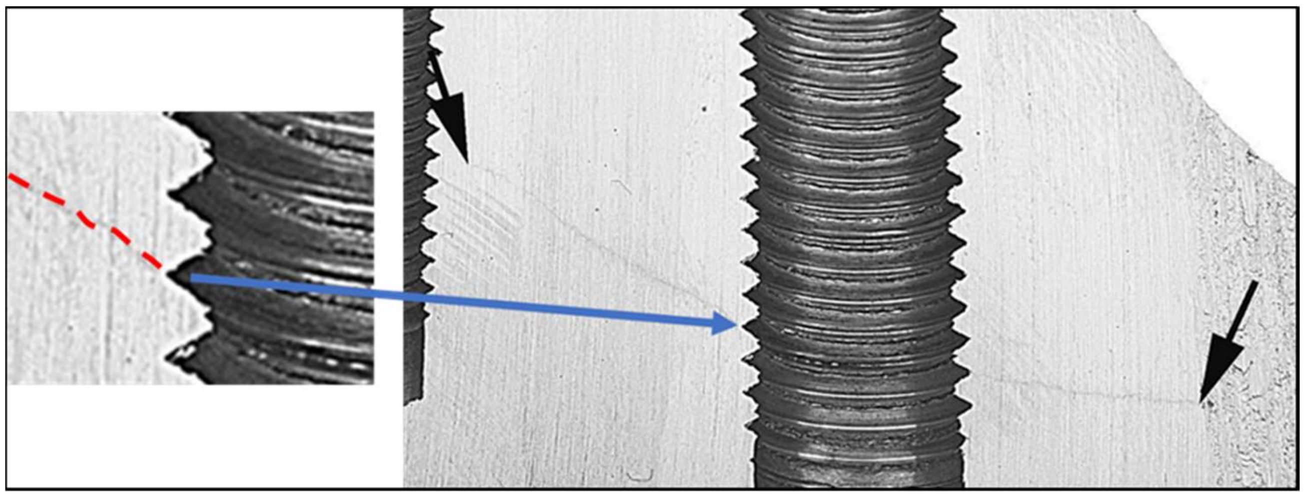




Engine Blocks – Bulkhead Section

- Bolt holes in the engine block bulkhead region are typically 8 or 10 mmΦ and help secure bearing caps and crankshaft.
- Energy associated with combustion results in crankshaft rotation which in turn produces cyclical tensile and compressive stress (fatigue). Typically as part of a fatigue monitoring process fatigue test samples are extracted from the bulkhead region.
- The most deleterious location for fatigue crack to nucleate is from an exposed pores from the root of the thread profile.

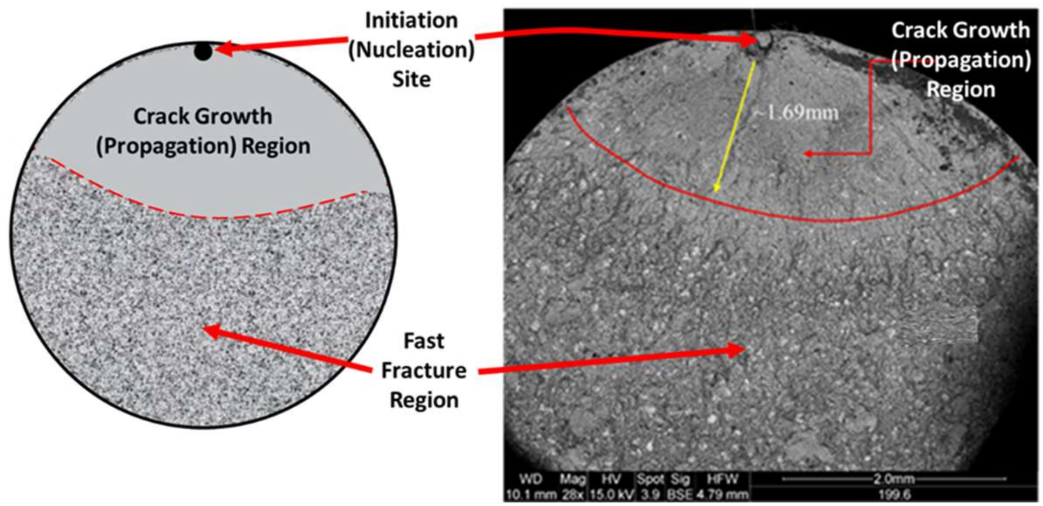




Three Stages of Fatigue Growth

- $N_{tctf} = N_i + N_p + N_{ff}$

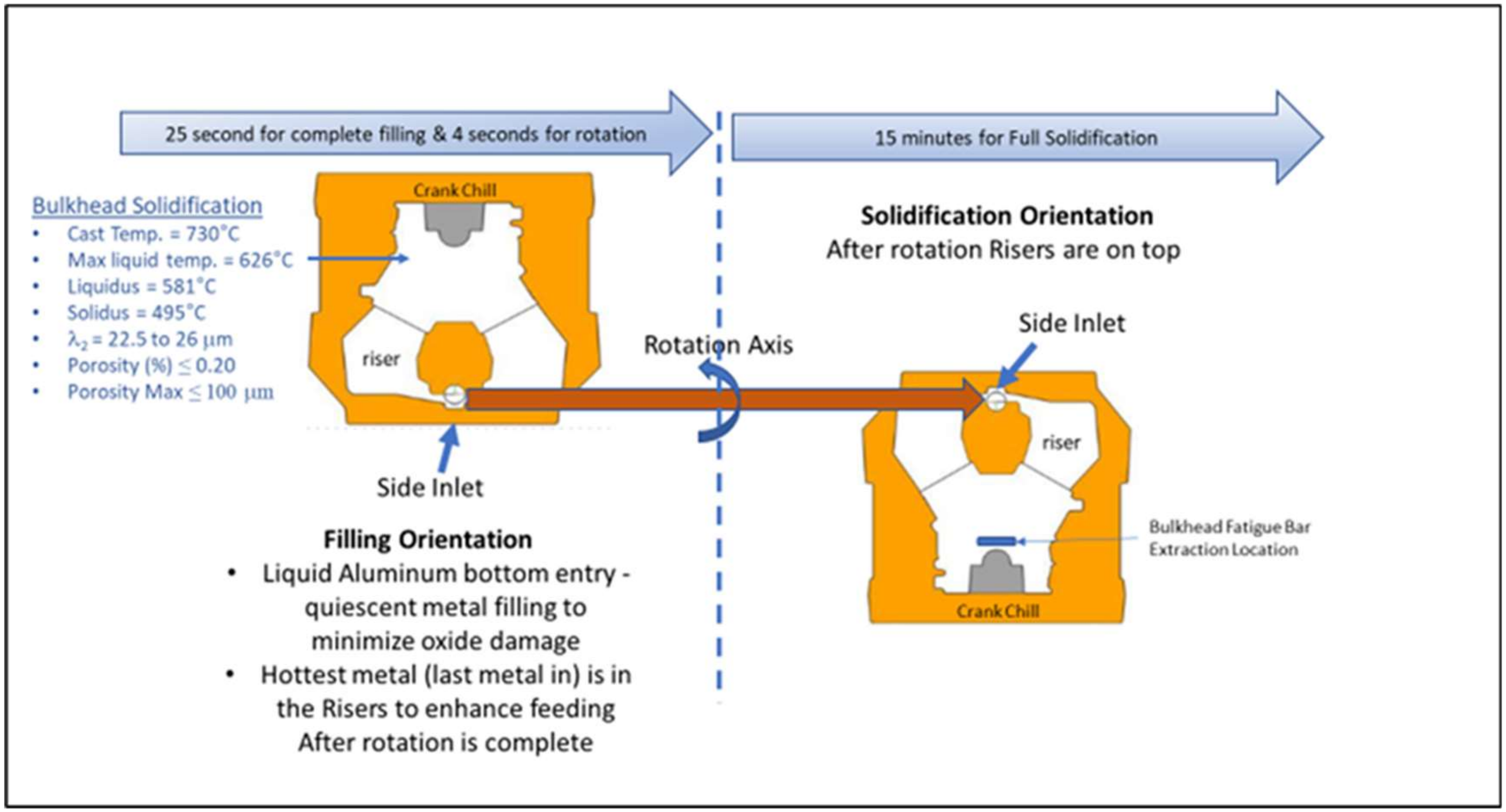
- N_{tctf} = total cycles until failure in a component;
- N_i = the number of cycles required to initiate a crack; (*associated with stress concentrator*)
- N_p = the number of cycles required to propagate (grow) the crack to a critical size where the structural integrity of the component is fully compromised; and
- N_{ff} = the number of cycles required to cause a critical-sized crack to rapidly propagate (or rupture) through the remaining cross-sectional area of the component, causing separation into two or more pieces.



Nemak-Cosworth Sand Casting Process

Thermal Sand Removal = 485 ± 5°C

- 18 - 25 second inverted fill followed by 15 minute solidification → TSR → T7 heat treatment.



Solidification Details – Nemak Cosworth

Casting Parameter	Value	Notes
Casting Temperature	730 ± 5º C	Control Pannel Monitored
Melt Tempearture in Bulkhead	626 °C	Established from In-situ Thermal Analysis of Precsion Sand Engine Blocks
$T_{Liquidus}$	581° C	Establish by Test Cup Method with Sampled metal from Pouring Furance.
$T_{Al\text{-}Si\ Eutectic}$	561° C	
$T_{solidus}$	495° C	
Reduced Pressure Test	2.70 - 2. 72 grams/cc	RPT maintained at - 27 ± 2 in Hg and had sample mass of 230 ± 15 grams (λ_2 = 25 to 26 mm). This density Corresponds to 0.011 H_2 cc/100 grams Al (Determined by In-situ Alspek Probe)

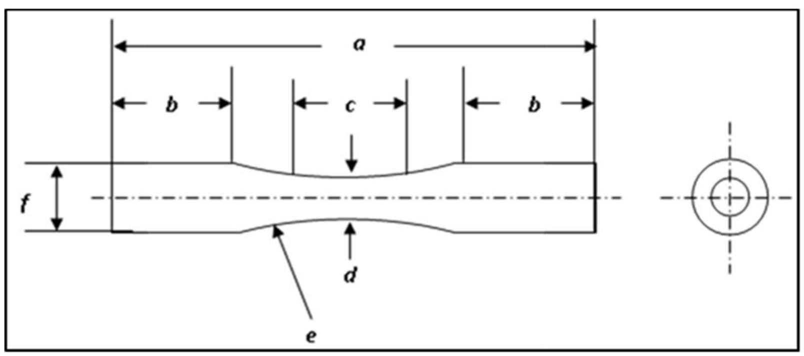
Chemistry Process Limits

Element	Si	Cu	Fe	Mg	Mn	Zn	Ti	Sr	Ni	Sn	Pb	Na
Minimum wt%	8.10	2.60	0.00	0.31	0.00	0.40	0.12	0.010	<0.014	<0.04	<0.05	<0.002
Maximum wt%	8.90	2.95	0.60	0.40	0.45	0.80	0.16	0.016				

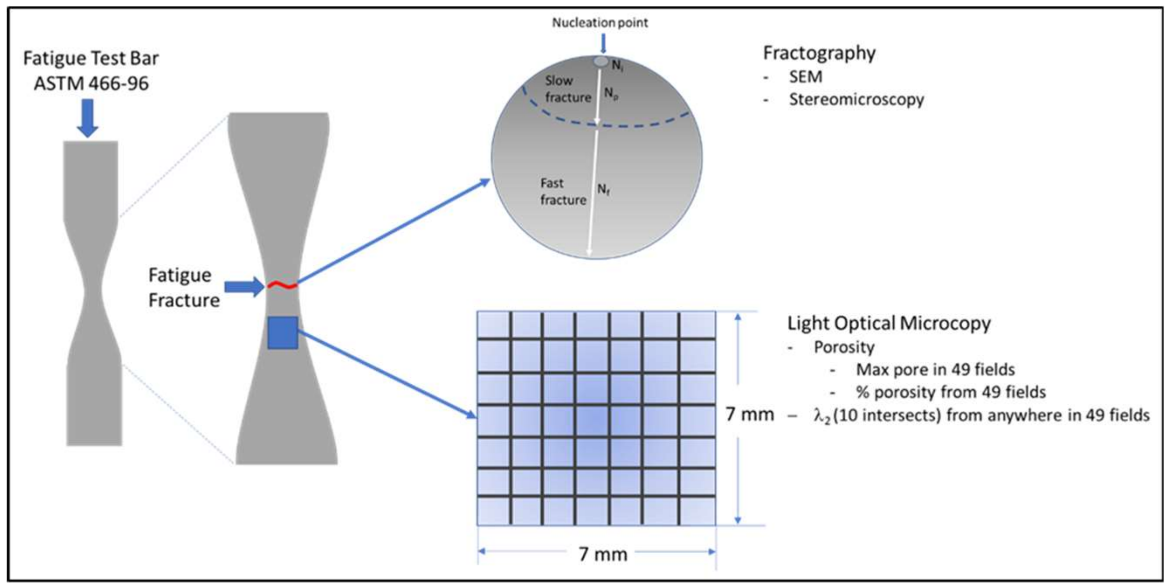
Fatigue Test Sample – ASTM E466

- Fatigue Test Sample Final dimensions
- Identical for OSP and Staircase samples
- Frequency was 98 Hz

Fatigue test sample feature	*a*	*b*	*c*	*d*	*e*	*f*
Dimension (mm)	127.0	28.5	16.0	8.0	63.75	15.0



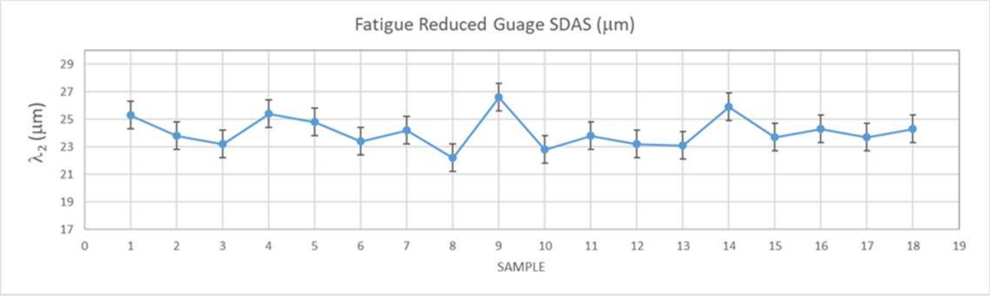
- Post test the following analysis:
  - Fractography – flaw size and location
  - 7mm X 7mm polished section below fracture for porosity and SDAS
  - N = 9 for OSP samples
  - N = 9 for Staircase samples



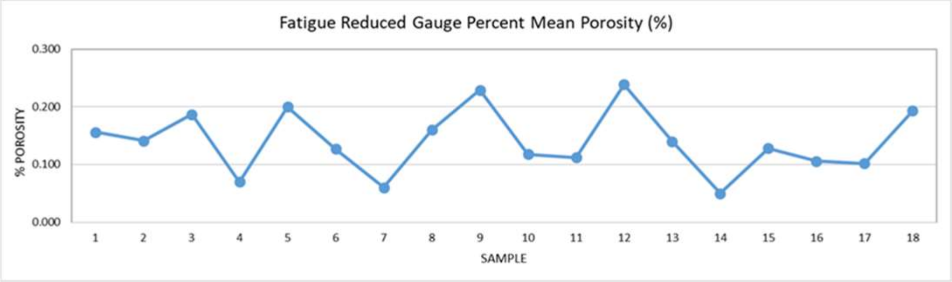
Results

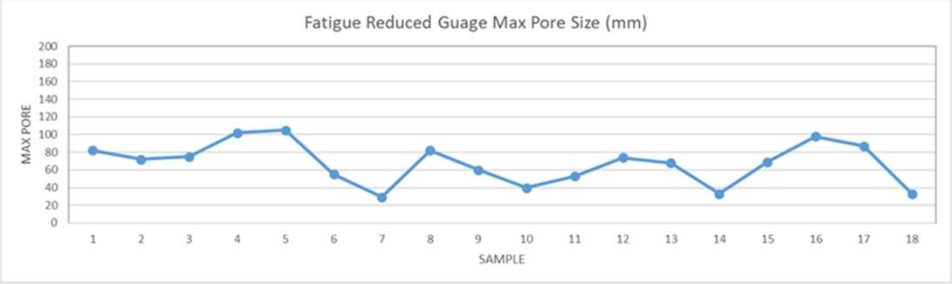
Microstructure Results from Fatigue Test Samples (n =18)

- Solidification Rate:
  - Secondary Dendrite Arm Spacing (λ_2) as measured from 7mm x 7mm grid below fracture line.
  - Line intercept method used with 6 dendrite cells min intercepted. Repeated 10 times.
  - Values consistently between 23 to 27 μm. Standard deviation for each measurement was less than 2 μm (most at $\sim 1\pm$).



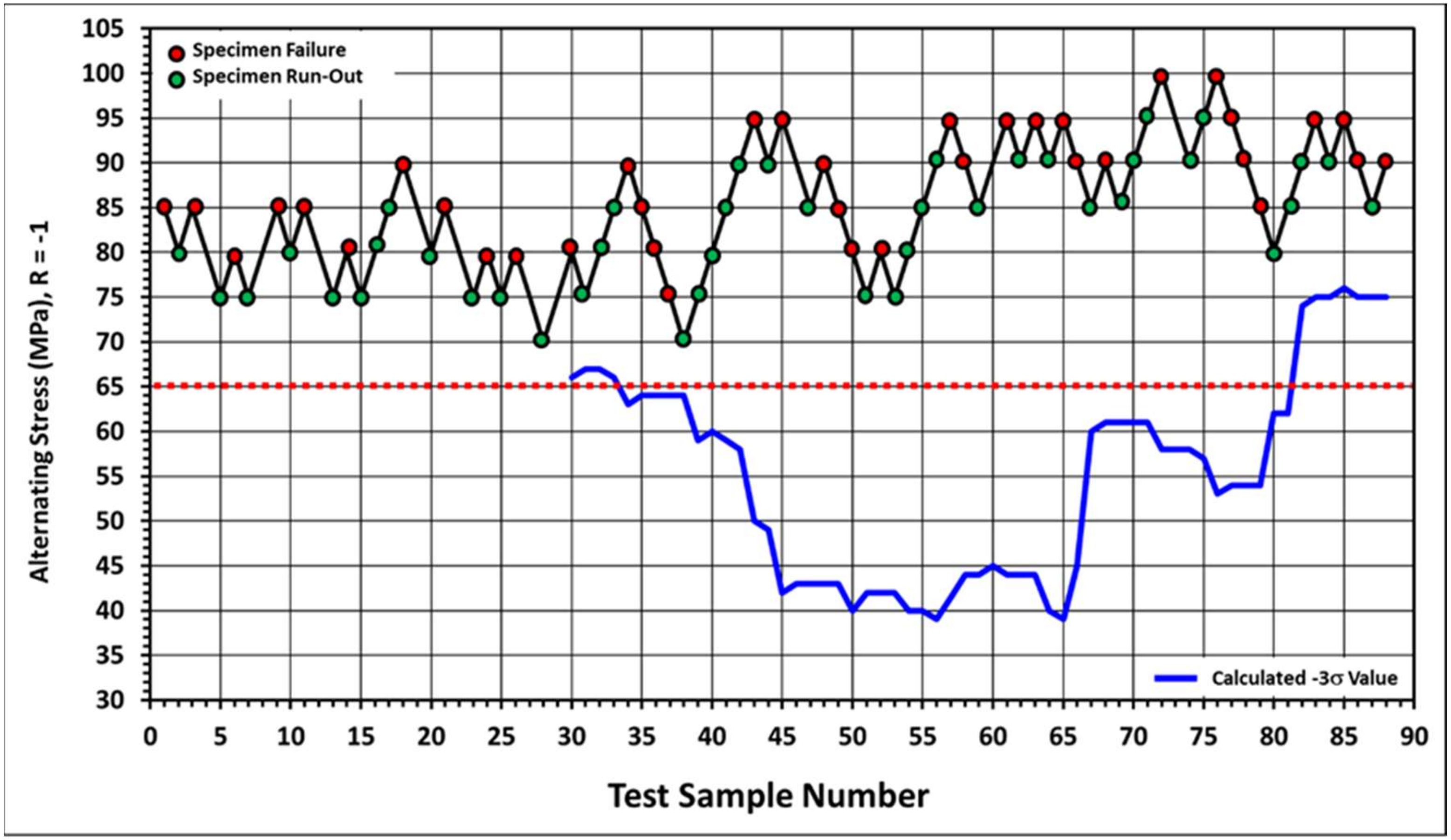
- Porosity:
  - Percentage and Maximum size pore found in 7 mm x 7 mm grid.
  - Percentage porosity ranged from 0.05 to 0.22%
  - The maximum pore size ranged from 31 - 100 mm in diameter





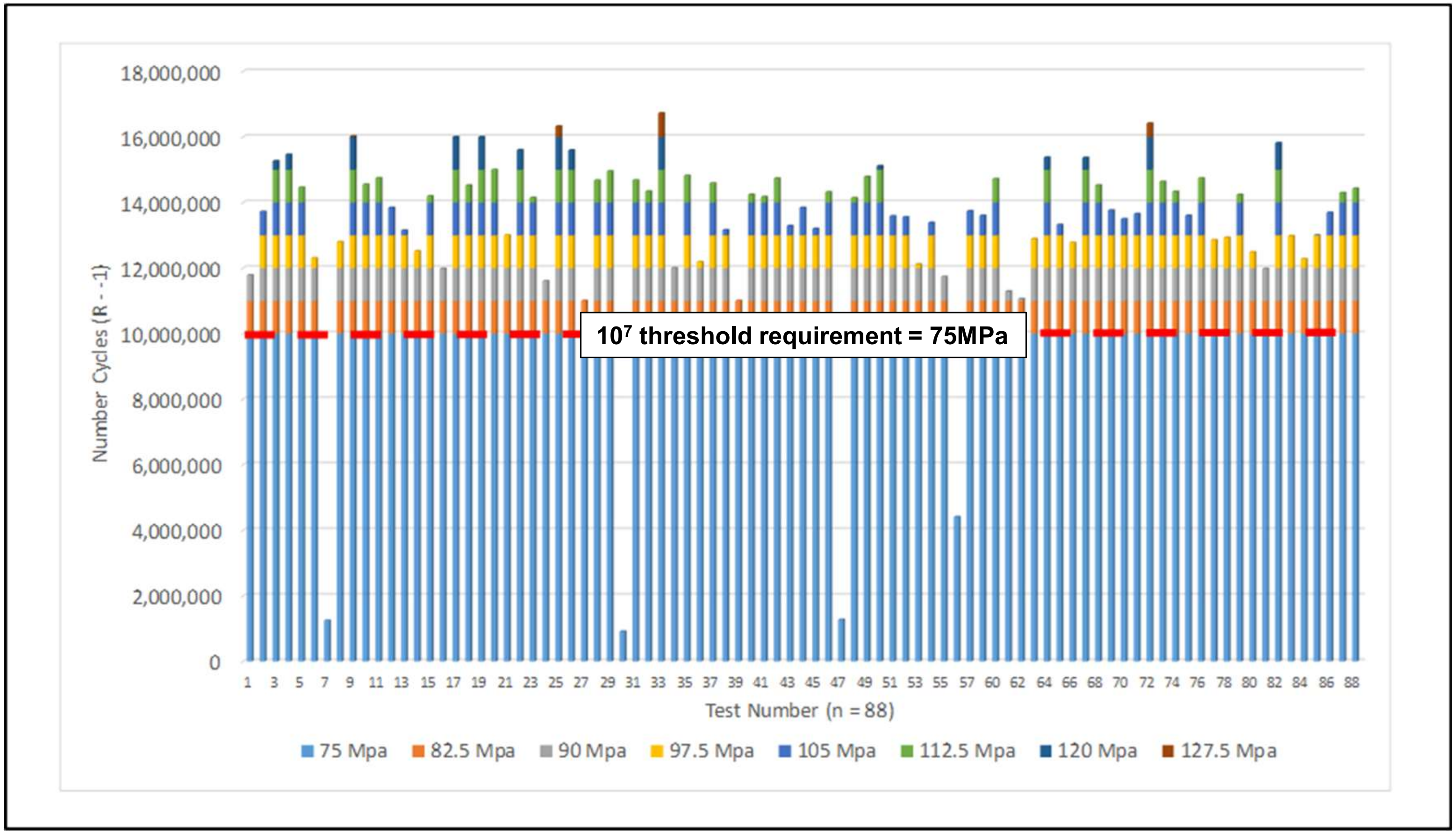
Fatigue Test Results – HCF

- **Results from the Staircase Testing of the AlSiCuMg fatigue test specimens.**
- *Please note: (1) Of the 88 specimens tested, 44 specimens were run-outs with no failure; (2) The red dotted line represents the specified minimum endurance limit of 65 MPa; and (3) The -3σ curve (blue solid line) is calculated only after the 30th consecutive sample because of statistical sampling relevance criteria*



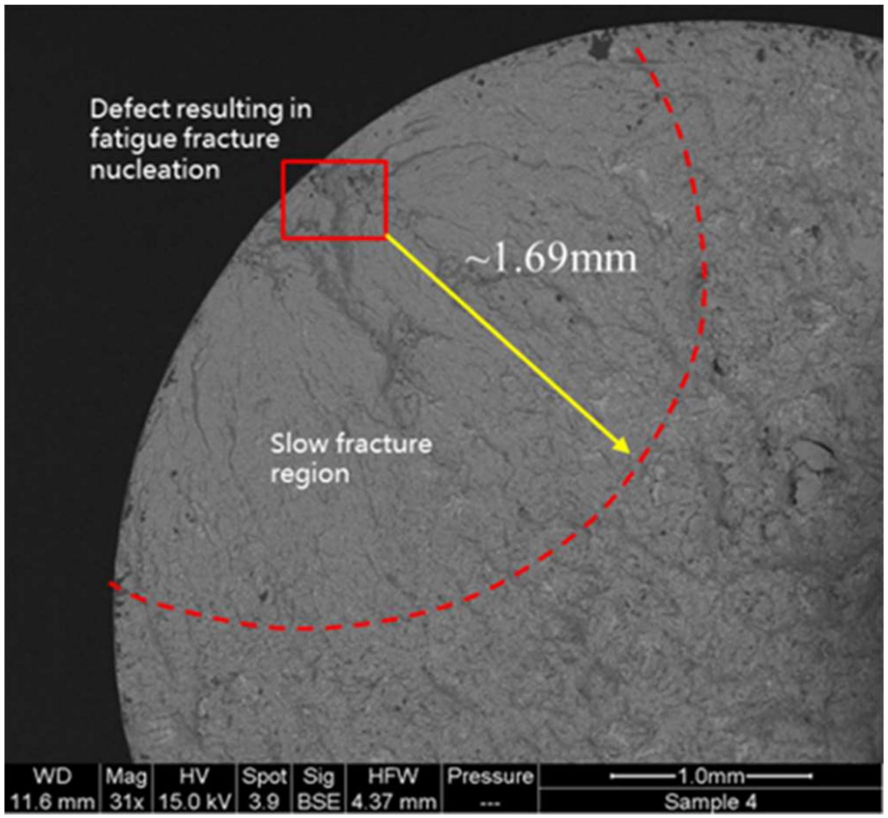
Fatigue Test Results - OSP

- **Results from the Over-Stress Probe Testing of the AlSiCuMg Fatigue Test Specimens.**
- *Please note: (1) Of the 88 specimens tested, 84 specimens met the specified minimum endurance limit of 75 MPa at 10^7 cycles; and (2) the colors of the bars represent the number of test cycles completed at the given stress level(s) prior to sample failure.*

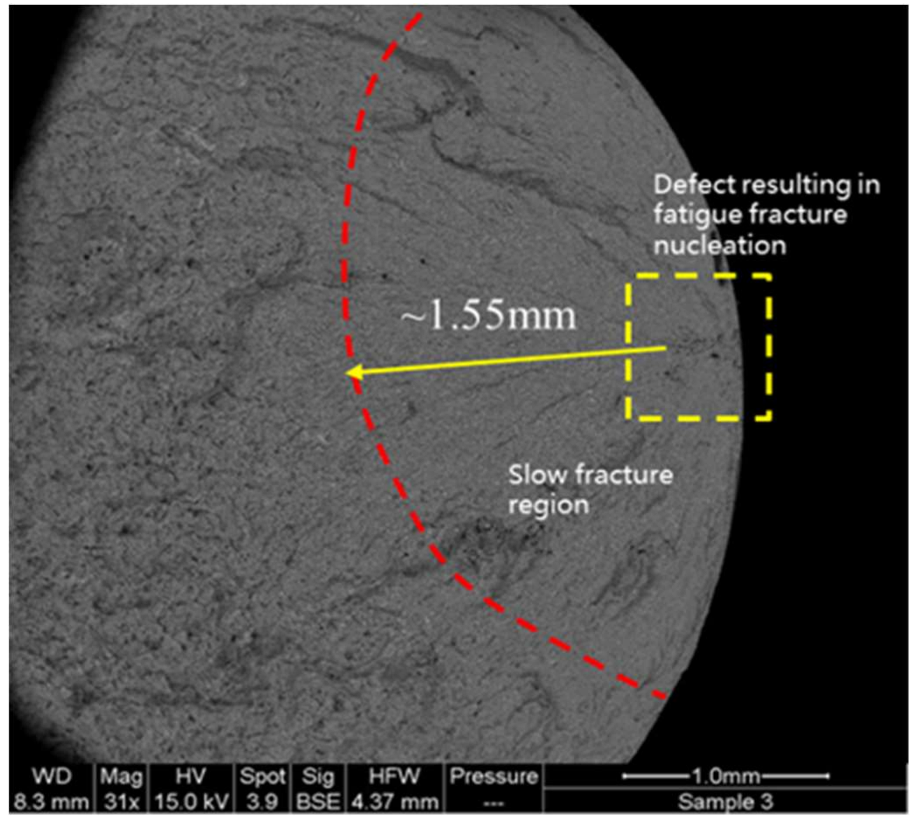


Fractography (HCF) – SEM/BSE Mode Imaging

- σ_a = 75 Mpa, N_f = 1,235,880 (Fail)

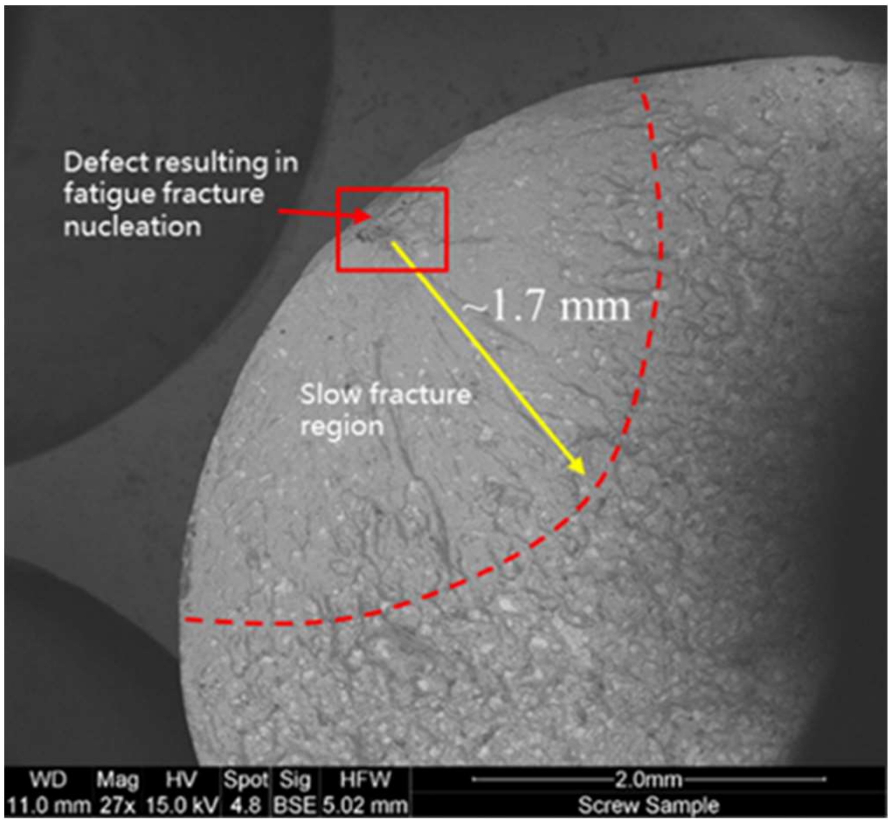


- σ_a = 80 Mpa, N_f =3,445,000 (Fail)

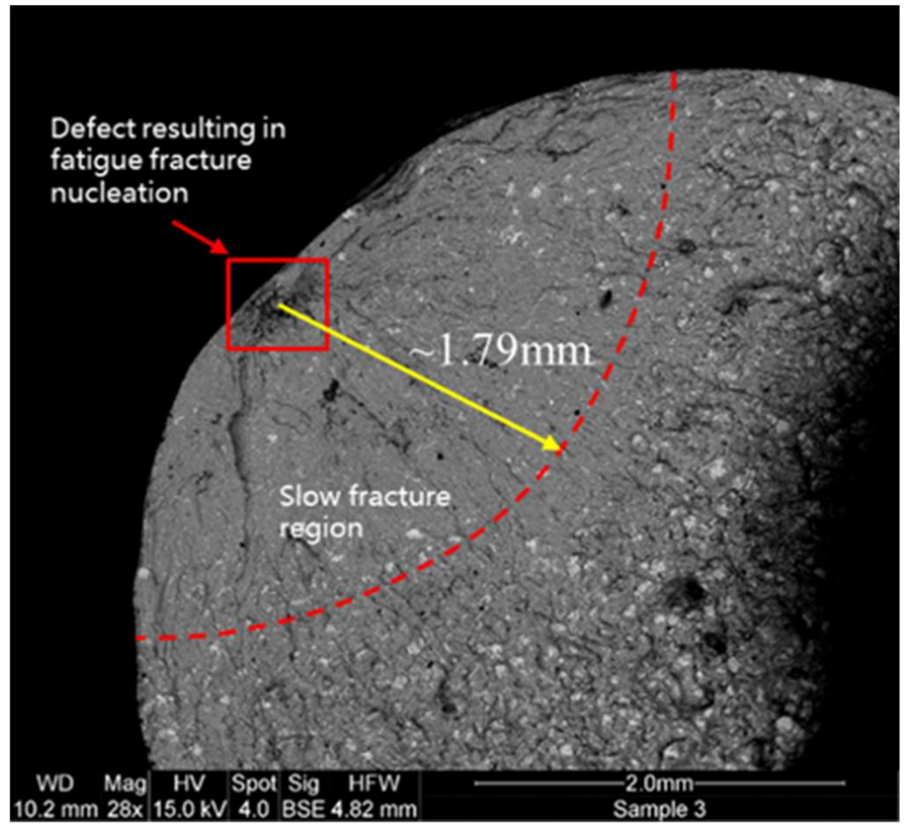


Fractography – SEM/BSE Mode Imaging

- σ_a = 90 Mpa, N_f = 986,574 (Fail)

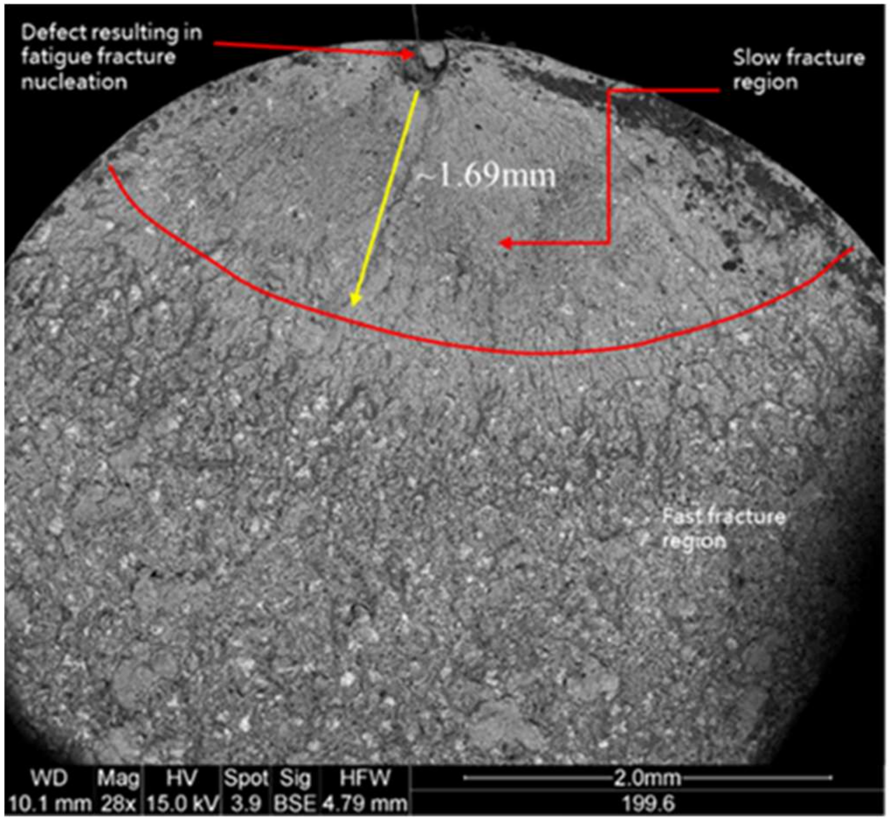


- σ_a = 90 Mpa, N_f = 5,717,400 (Fail)

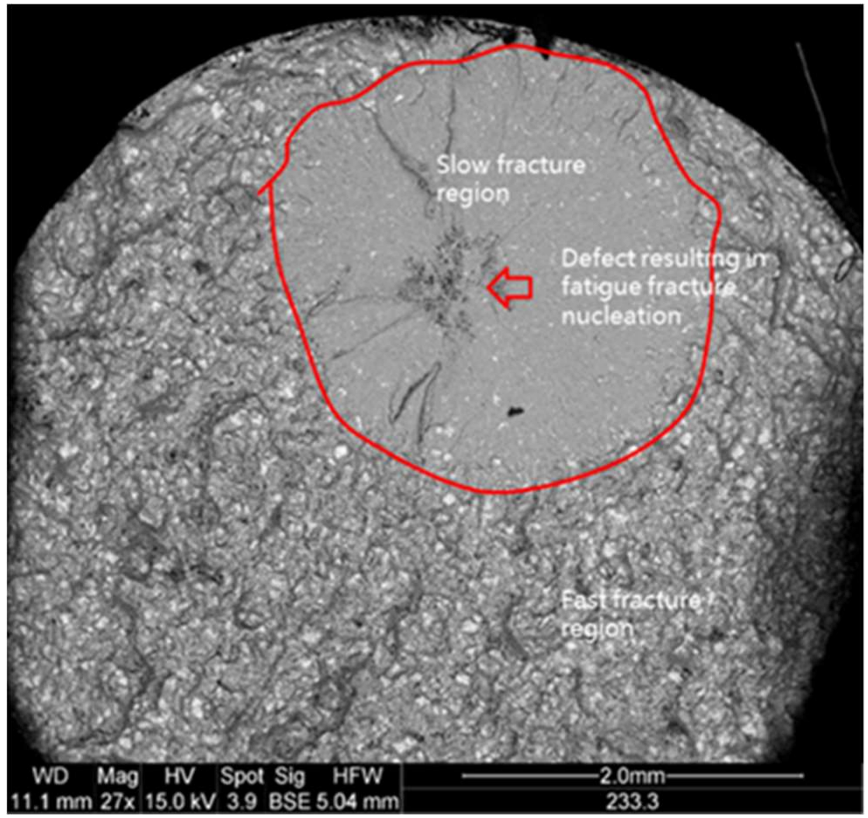


Fractography (OSP) – SEM/BSE Mode Imaging

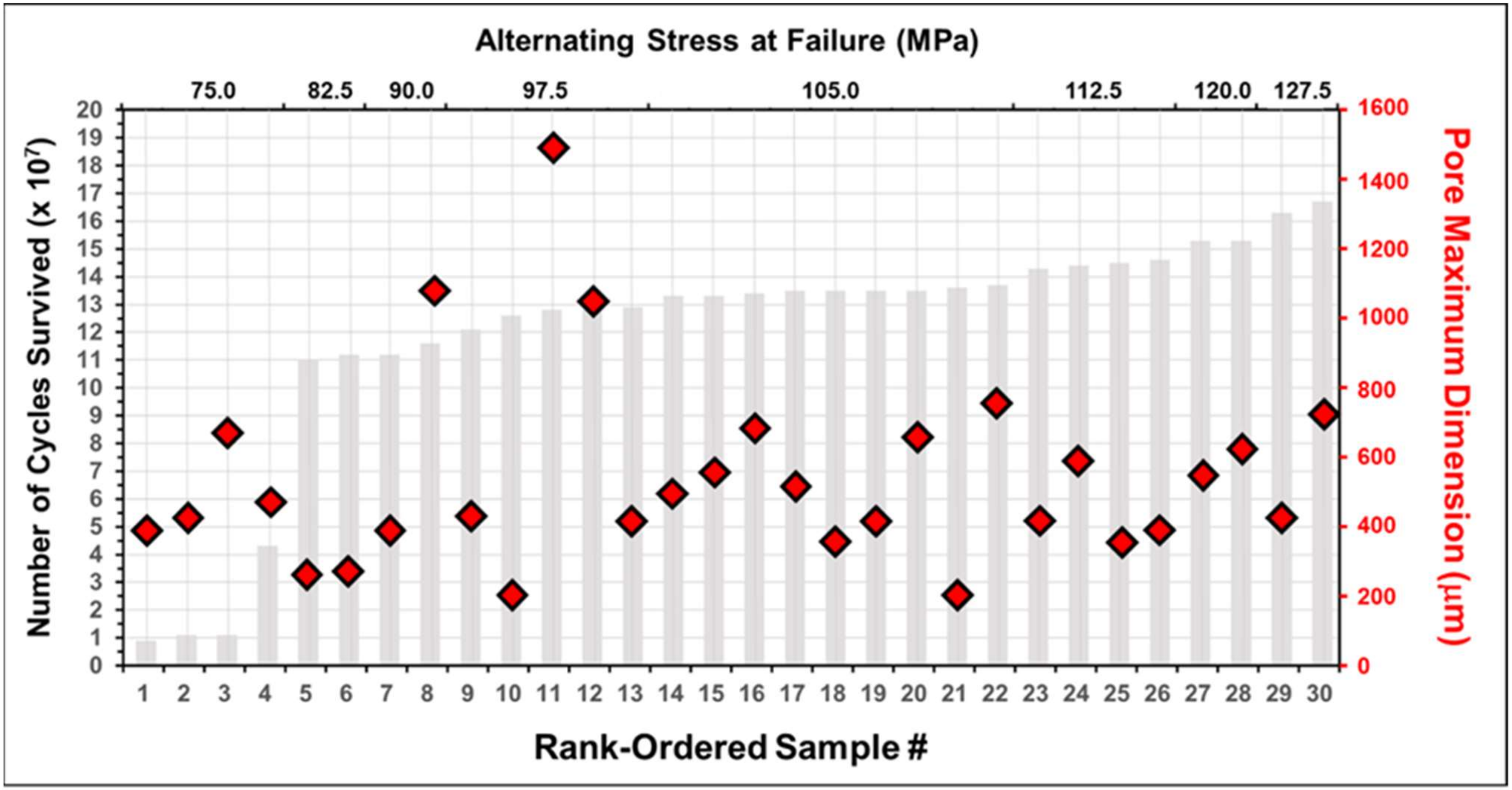
- σ_a = 75 Mpa, N_f = 911,699 (Fail)



- σ_a= 127.5 Mpa, N_f = 16,722,237 (Pass)



OSP Ranked from Shortest to Longest Lifespan



Discussion / Conclusions

Discussion

- A study was conducted on assessing the applicability of the Staircase and Over-Stress Probe fatigue test methodologies
- This study employed 176 specimens taken from the same engine block geometry cast over multiple years using nominally the same AlSiCuMg alloy and the same process parameters
- Test specimens were machined from the same location to a single sample geometry
- It's believed that the majority of variation is due to the inherent variation associated with industrial manufacturing processes used over a long period of time
- The two different fatigue test protocols are both currently widely used in industry; however, each yields different benefits in terms of understanding the effects of defects on fatigue life results.

Conclusions

- The nucleation of the fatigue crack is the result of a complex interaction between the applied stress, the pore size, and the pore location.
- Because the Over-Stress Probe method tests all samples to failure, it inherently yields more information (approximately double) about the nature of the fatigue fracture and initiation sites.
- Therefore, it can be concluded that the Over-Stress Probe method has an advantage over the Staircase method in terms of enabling improved process monitoring.
- The Over-Stress Probe method then is a superior tool to better drive decisions regarding process changes to ensure/increase a desired specific outcome in terms of product performance and durability.

Contact: robert.mackay@nemak.com