Impact of Columnar Grain Structure on Over-Stress Probe (OSP) Method for Fatigue Life Characterization in Aluminum Sand Castings

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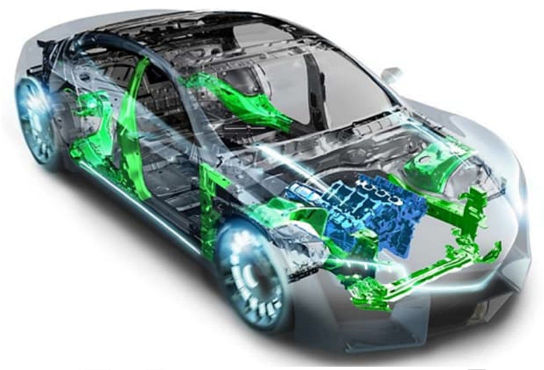
2022 Society of Automotive Engineers - Fatigue, Design, and Evaluation (SAE FD&E)

October 25th & 26th, 2022



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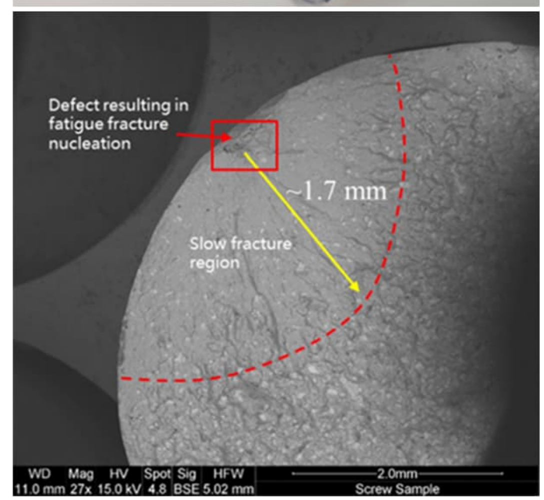
Introduction

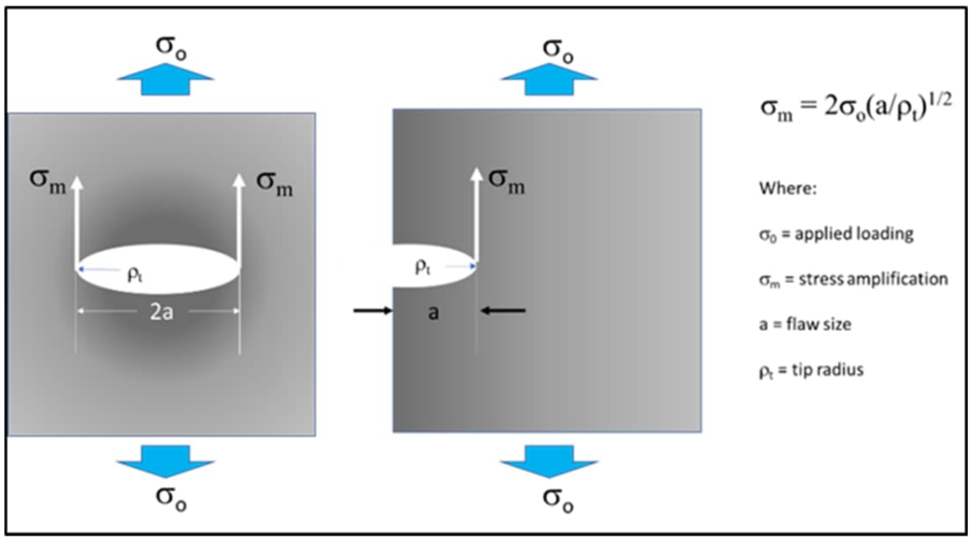
- The most common root cause of failure in mechanical structures is material fatigue. Fatigue is the process by which cracks develop and propagate to failure under cyclic loading.
- Due to the need for simplified & rapid testing, laboratory Life-to-Failure methods have been developed and allow for estimation of lifetime under representative service conditions.
- The Over-Stress Probe (OSP) method has been growing as an effective method to gauge fatigue durability of components.
- ***Compliant*** samples are defined as those that survive the target lifetime (10^7 cycles) at a defined alternating stress (R = -1).
- 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 (example shown to the right) damage and columnar zones.

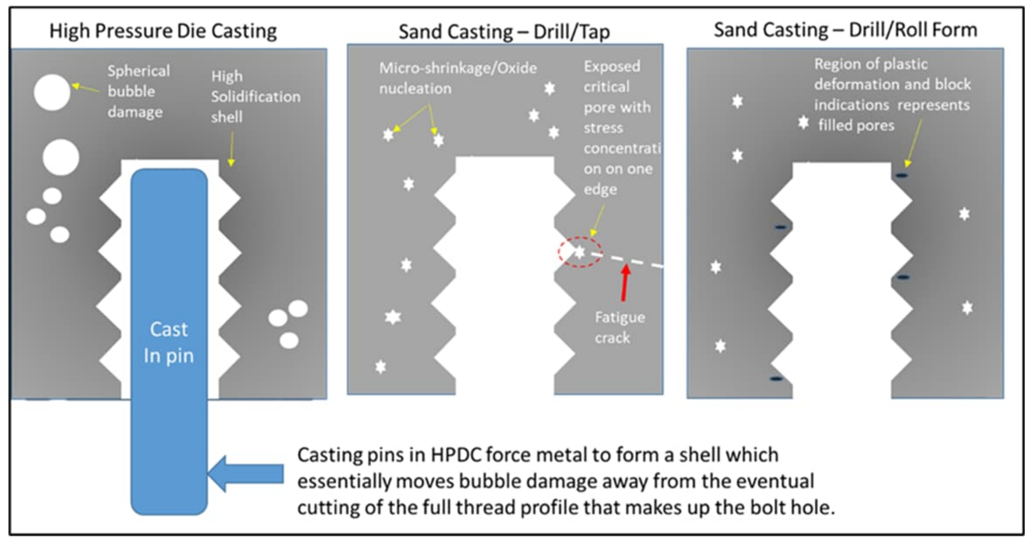


Effect of Critical Flaw Size and Location & Casting Process

- 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.

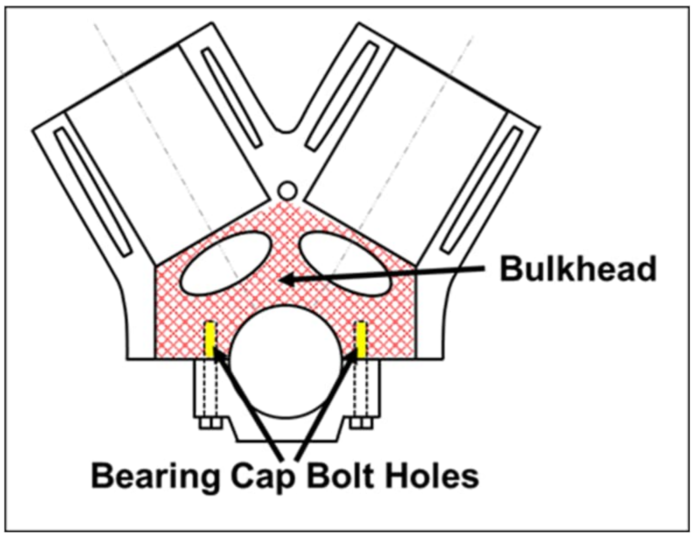
- Casting process has an effect on the probability of a pore exposed to the surface.
- HPDC uses a core pin promoting a rapidly solidified shell and pushing pores inward.
- Thread roll-forming can also nullify the stress amplification effect of exposed pores.

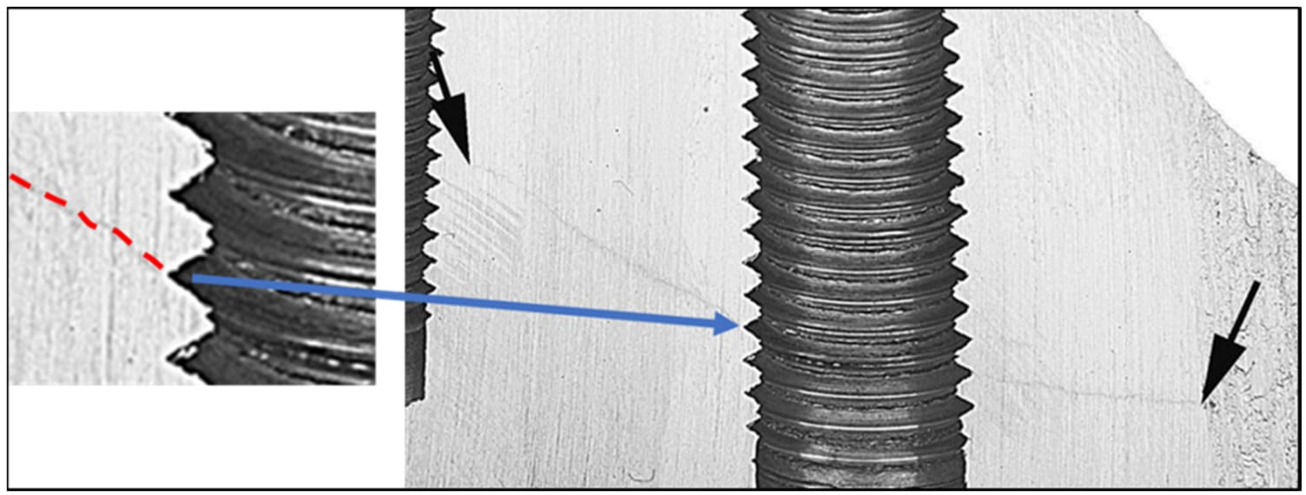




Engine Blocks – Bulkhead Section

- 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.

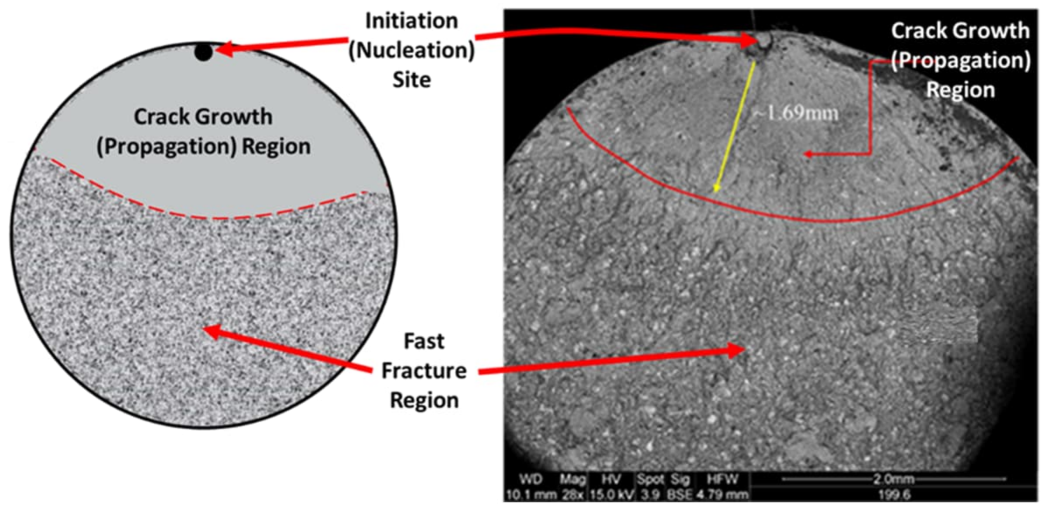




Three Stages of Fatigue Growth

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

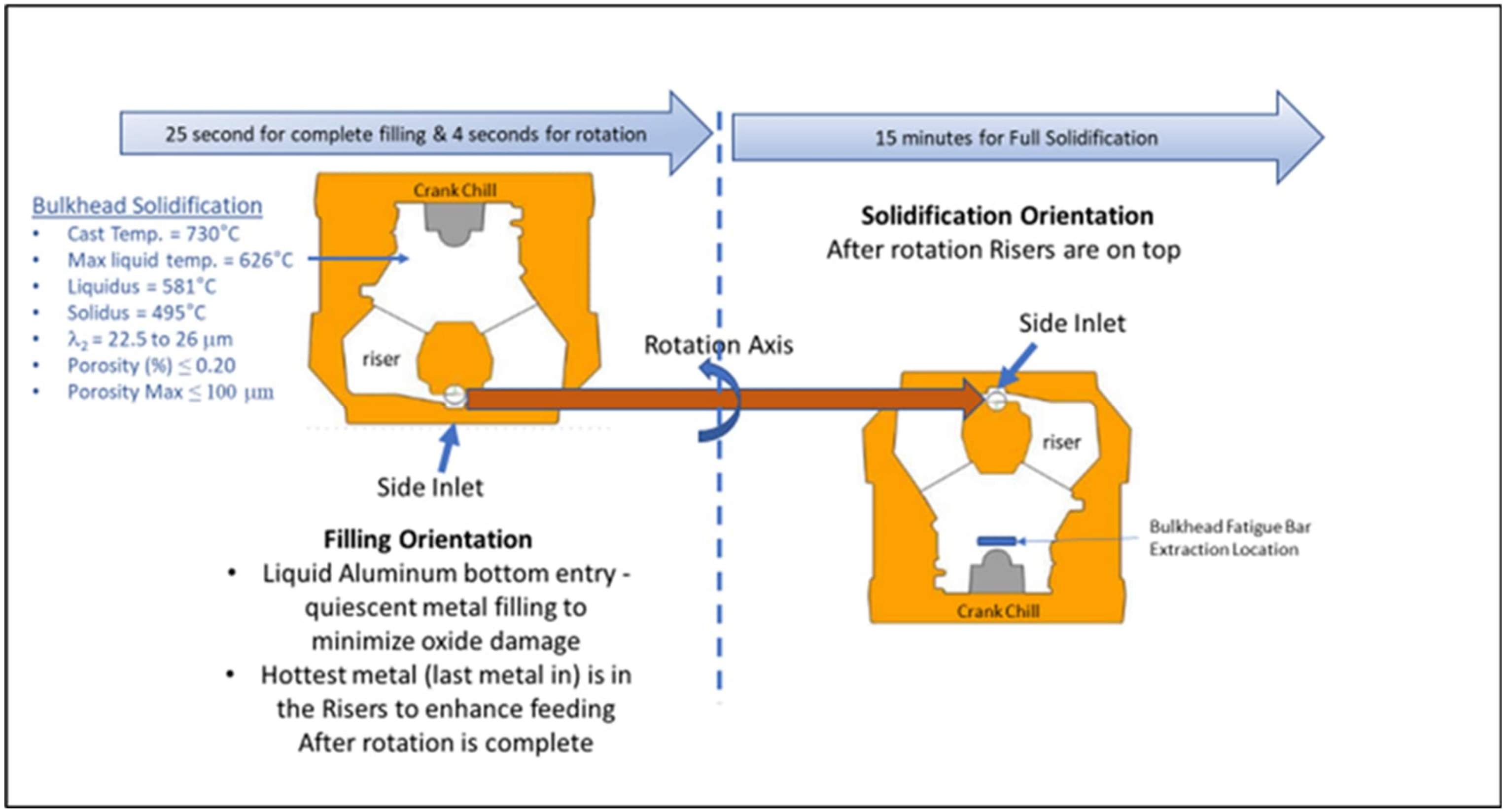
- N_{tctf} = total cycles until failure in a component;
- N_i = the number of cycles required to initiate a crack; (*associated with stress concentrator*)
- N_p = the number of cycles required to propagate (grow) the crack to a critical size where the structural integrity of the component is fully compromised; 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)

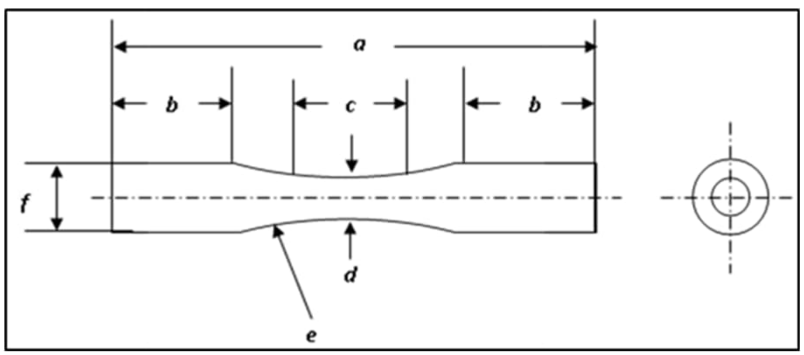
Chemistry Process Limits

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				

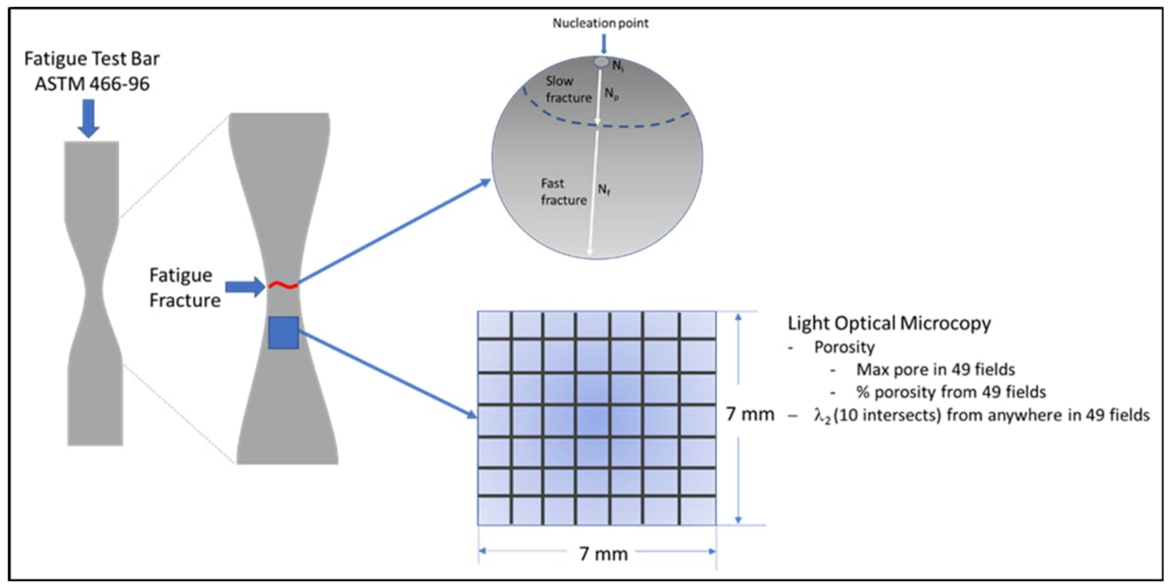
Fatigue Test Sample (ASTM E466) & Metallography

- Fatigue Test Sample Final dimensions (below).
- Alternating Frequency (R = -1) was 98 Hz.
- Total number of OSB samples in the study was n = 67.

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 = 20 for OSP samples (selected from total number of OSB samples, n = 67).



Over Stress Probe Protocol:

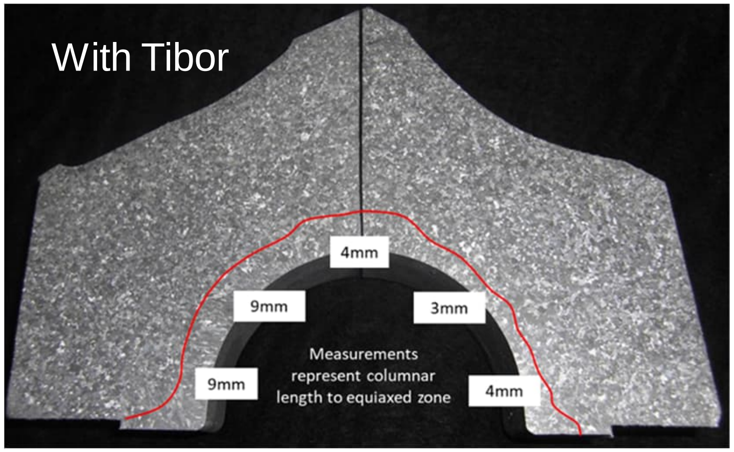
- The successive test protocol is conducted as follows. Should the fatigue test sample survive the initial 10^7 cycles without a failure the test is considered a pass and the same fatigue test sample in the same test frame will then have the alternating stress increased by 10% (increment of 7.5 MPa, or 82.5 MPa) and then run at 10^6 cycles. Should the fatigue test sample survive that stage then the alternating stress is increased a further increment of 7.5 MPa, or 90 MPa, for another 10^6 cycles. Subsequent testing with a 10% increase in alternating stress at 10^6 is repeated until failure (complete fracture) has occurred in the reduced gauge section.
- The purpose for using a step increment in stress and a smaller number of alternating cycles (10^6) after achieving the compliance threshold (10^7 cycles at 75 MPa), instead of just running at 75 MPa till failure is time and cost, and not on a technical aspect of the test. Using a 7.5 MPa increment in alternating stress for each surviving 10^6 regime is meant to quicken the test time and allow one axial fatigue test frame conduct more tests. For example, using round figures a single fatigue staircase sample could cost $300 USD, while a single OSP fatigue sample will cost $400 USD (or 33% more) to account for the added time post the initial 10^7 cycles that must be run till completion. As will be shown in the OSP results the samples having the longest life is nearly 40% longer and 60% higher in alternating stress than the compliance threshold.

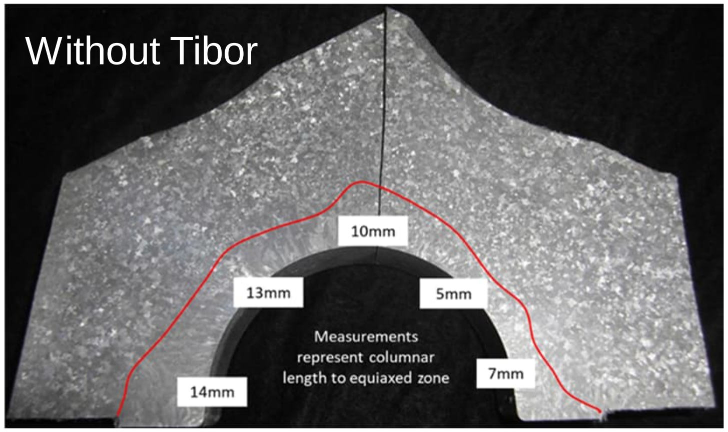
Results

Fatigue test bar sectioning from the bulkhead

- Etched bulkhead with fatigue test bar overlay:
  - The half-round is in direct contact with the cast iron chill which promotes rapid solidification which in turns drives up fatigue durability.
  - Fatigue test bar is at an angle with respect to the half-round. This can restrict the microstructure ranges that can be incapsulated by the test sample geometry.
  - The reduced gauge section can come into contact with the columnar region which extends from the half-round.

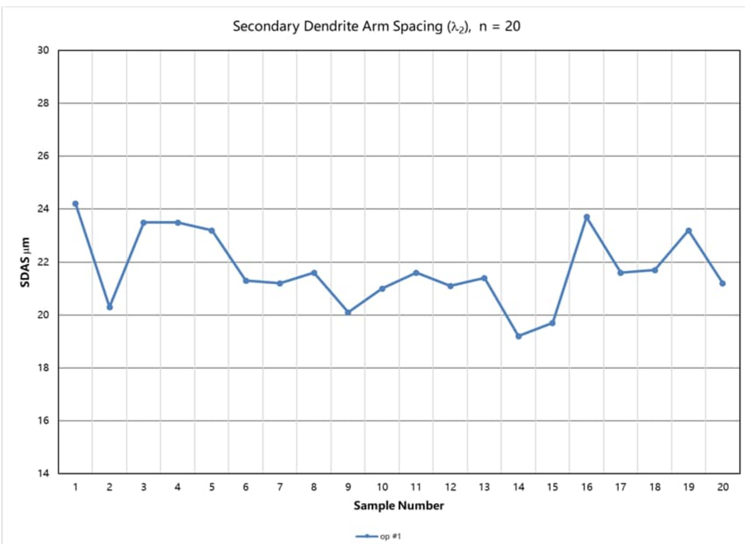
- Etched Bulkheads



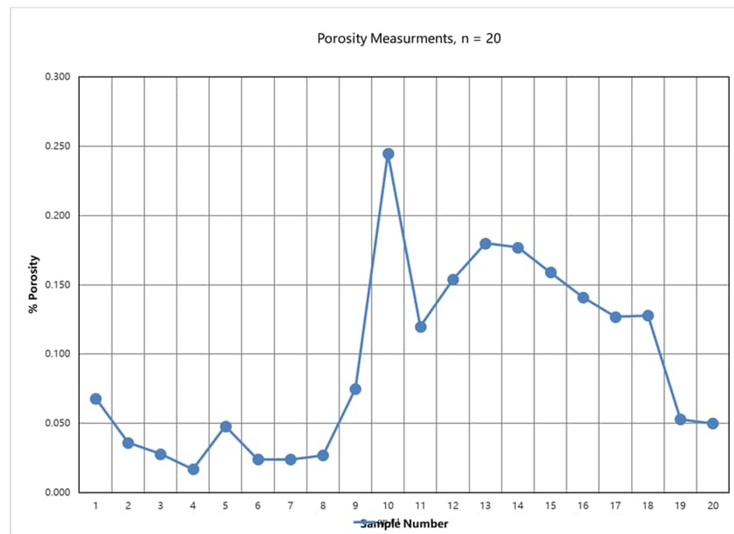


Microstructure Results from Fatigue Test Samples (n =20)

- 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 19.5 to 26 μm. Standard deviation for each measurement was less than 2 μm (most at ~ 1±).

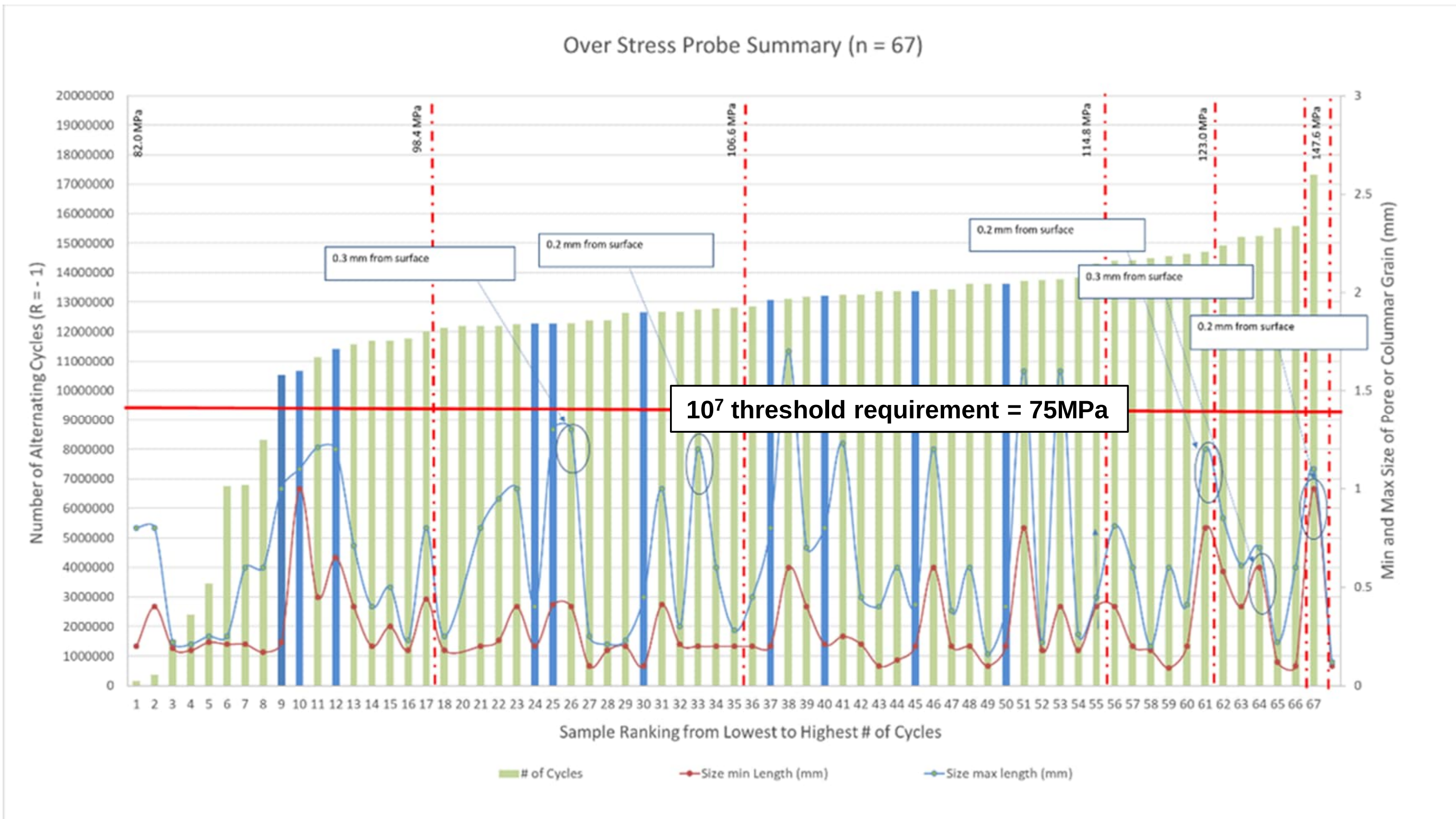


- Porosity:
  - Percentage and Maximum size pore found in 7 mm x 7 mm grid.
  - Percentage porosity ranged from 0.05 to 0.22%



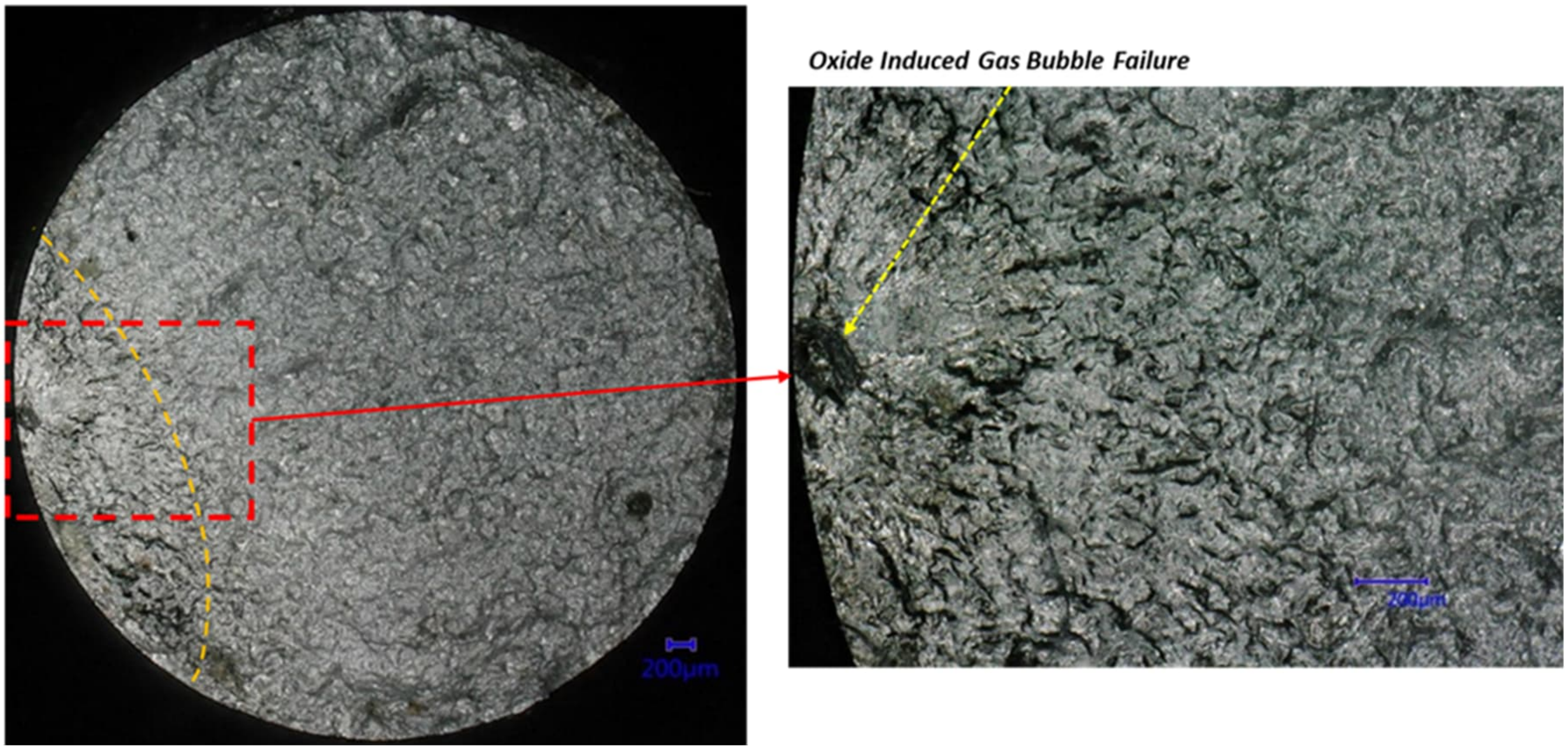
Fatigue Test Results - OSP

- **Results from the Over-Stress Probe Testing of the AlSiCuMg Fatigue Test Specimens**.
- Bar graph data in blue where identified to have a columnar zone as the nucleation of the fatigue crack.
- Bar graph data in green were identified to have a micro-shrinkage pore as the nucleation of the fatigue crack.
- *Please note: Of the 67 specimens tested, 59 specimens met the specified minimum endurance limit of 75 MPa at 10^7 cycles.*



Fractography of Fatigue Test Results

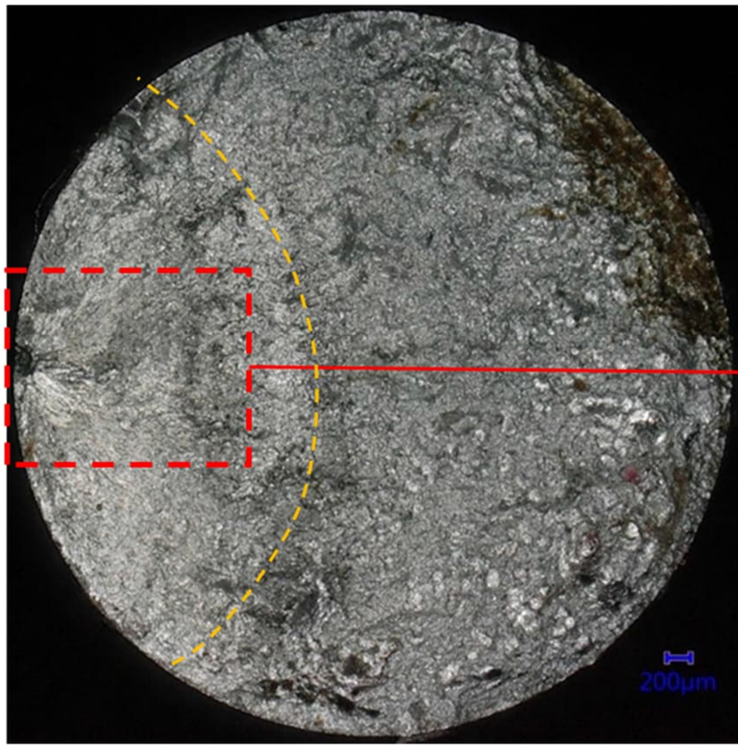
Result: ***FAIL*** – 24% of Specification



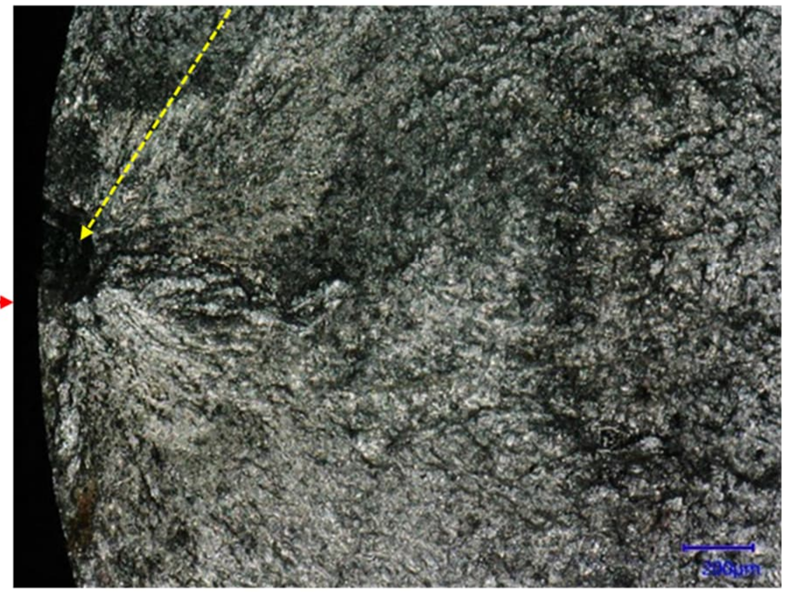
Oxide Induced Gas Bubble Failure

Fractography of Fatigue Test Results

Result: ***FAIL*** – 16% of Specification

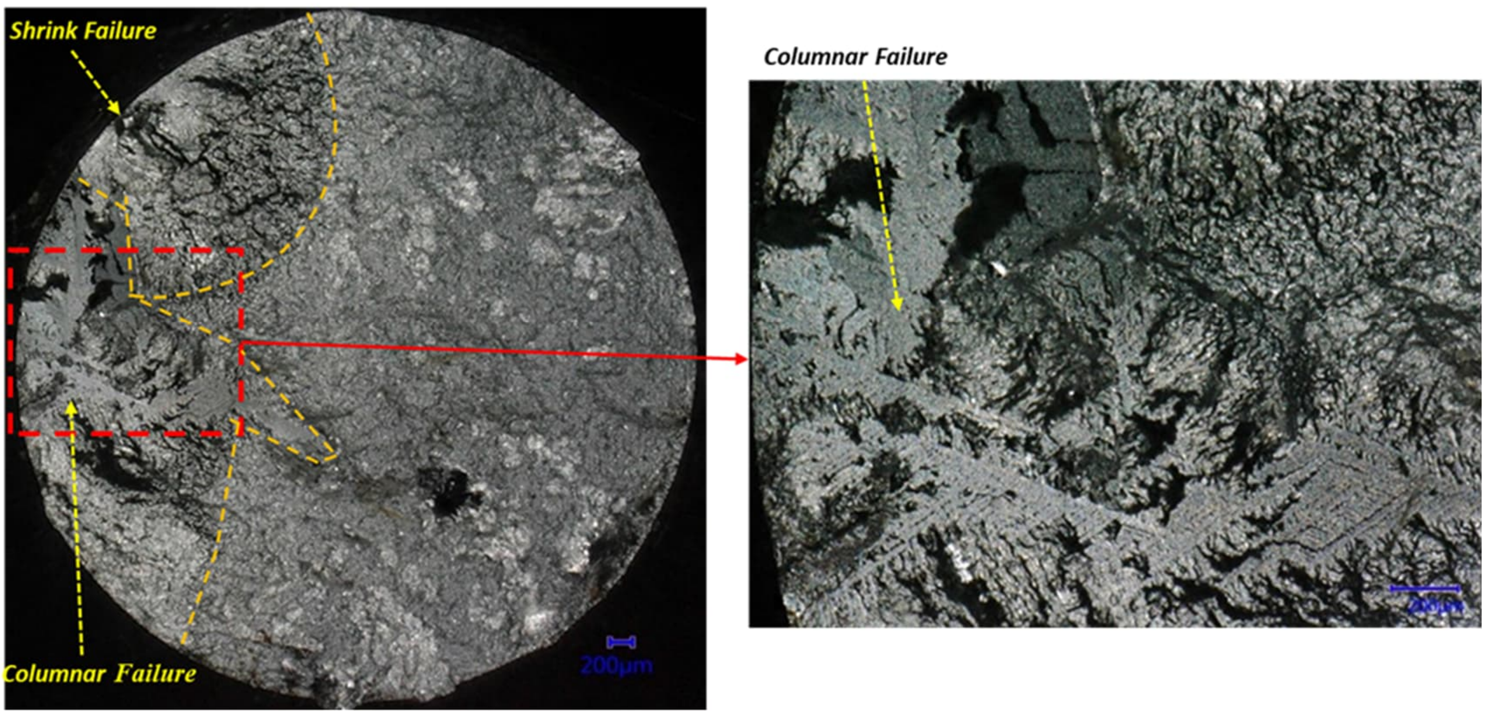


Oxide Induced Gas Bubble Failure



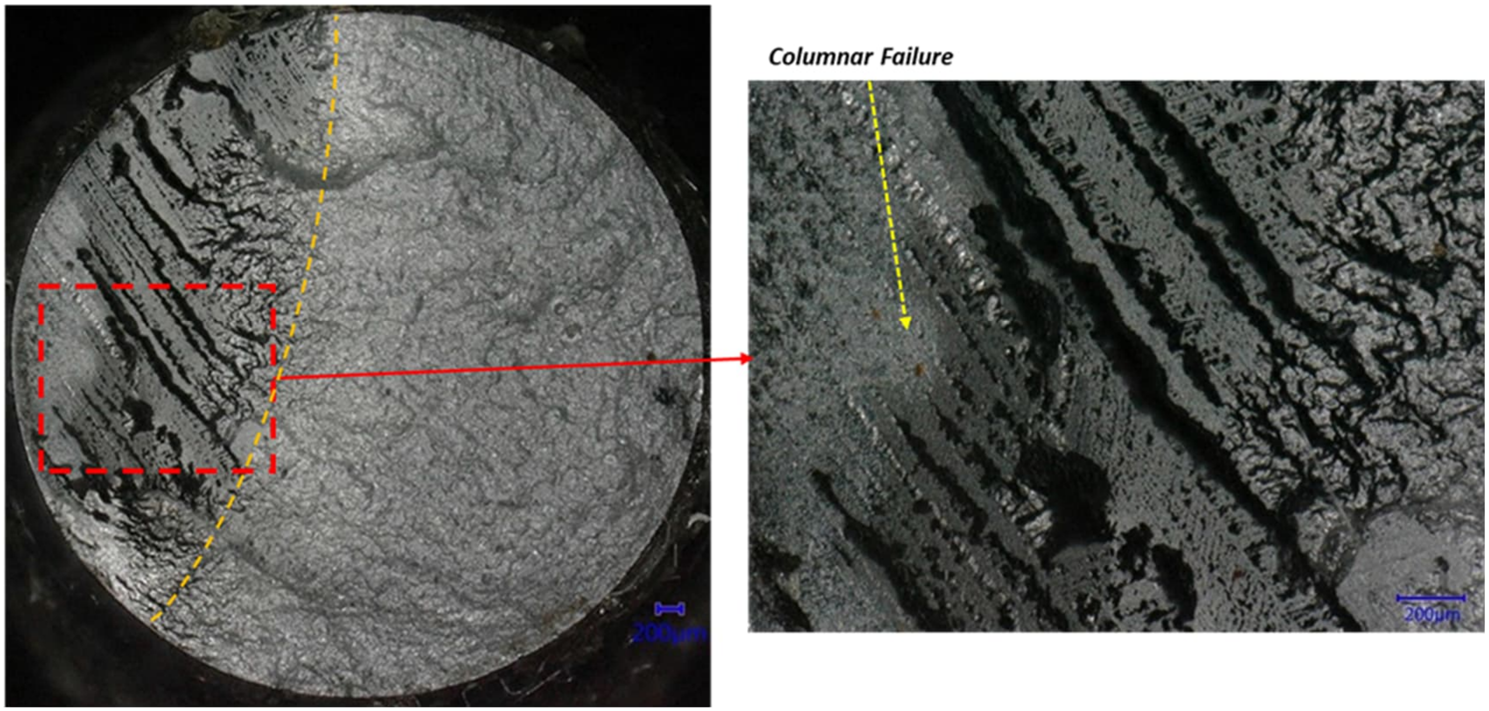
Fractography of Fatigue Test Results

Result: ***PASS*** – 107% of Specification

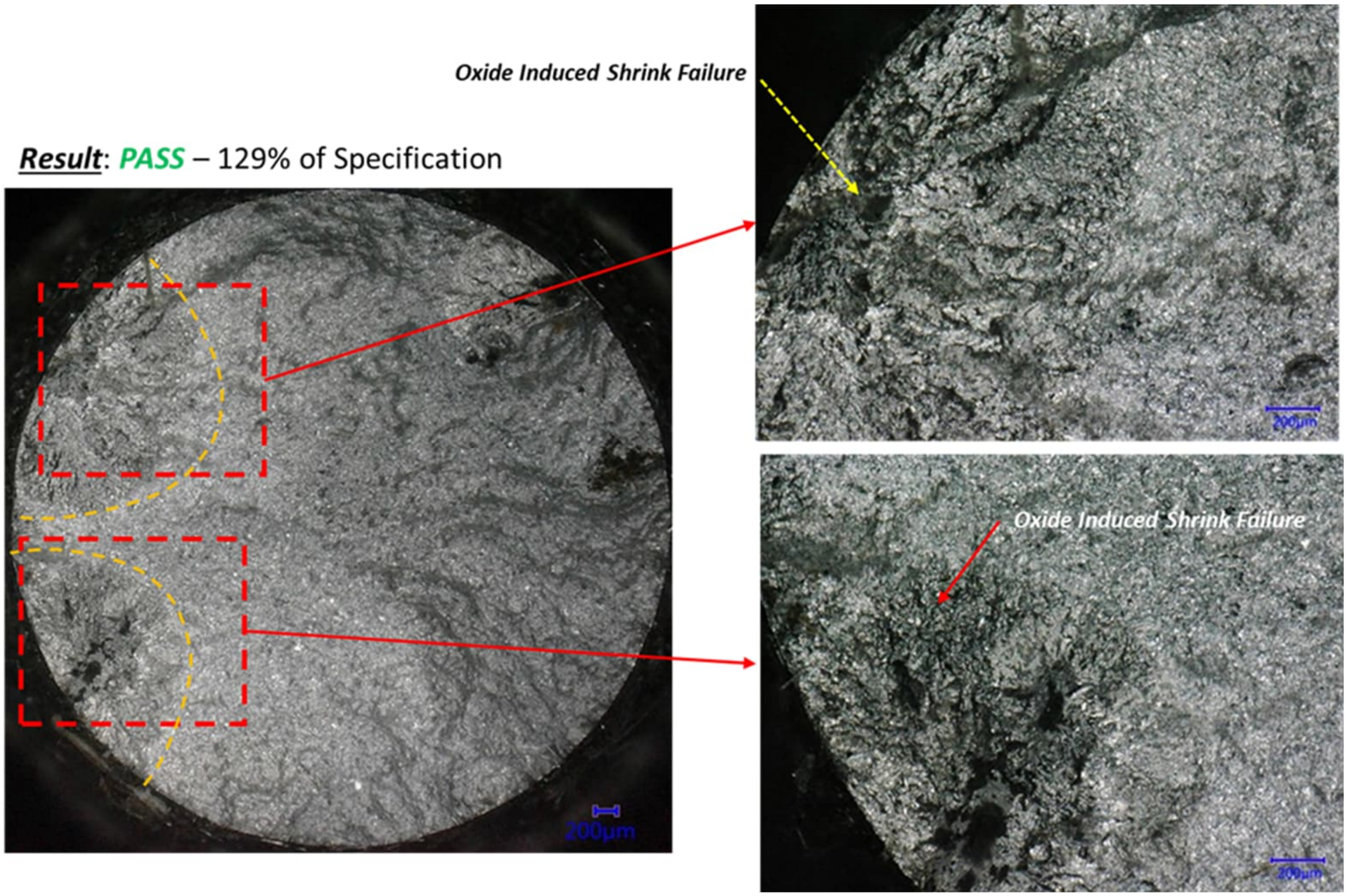


Fractography of Fatigue Test Results

<u>Result</u>*: *PASS – 136% of Specification

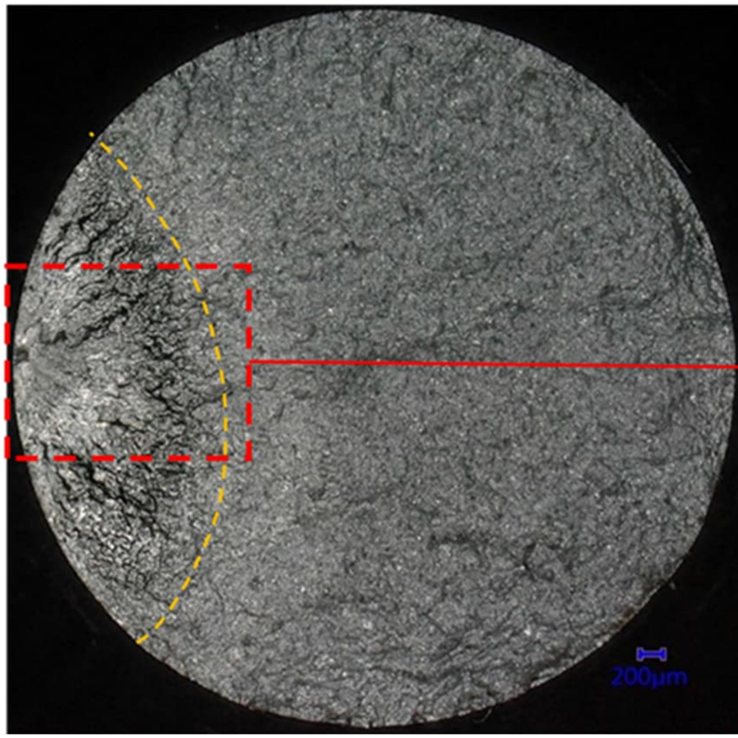


Fractography of Fatigue Test Results

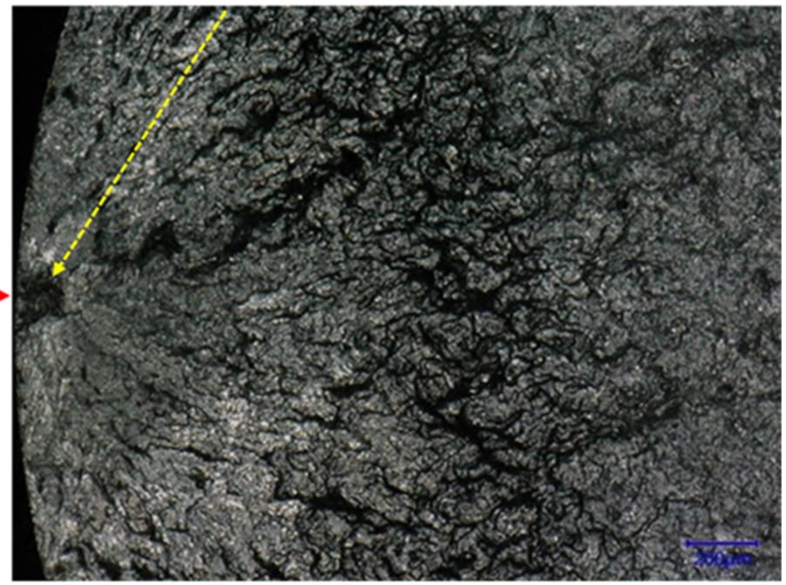


Fractography of Fatigue Test Results

Result: ***PASS*** – 173% of Specification



Oxide Induced Gas Bubble Failure



Impact of Columnar Grains

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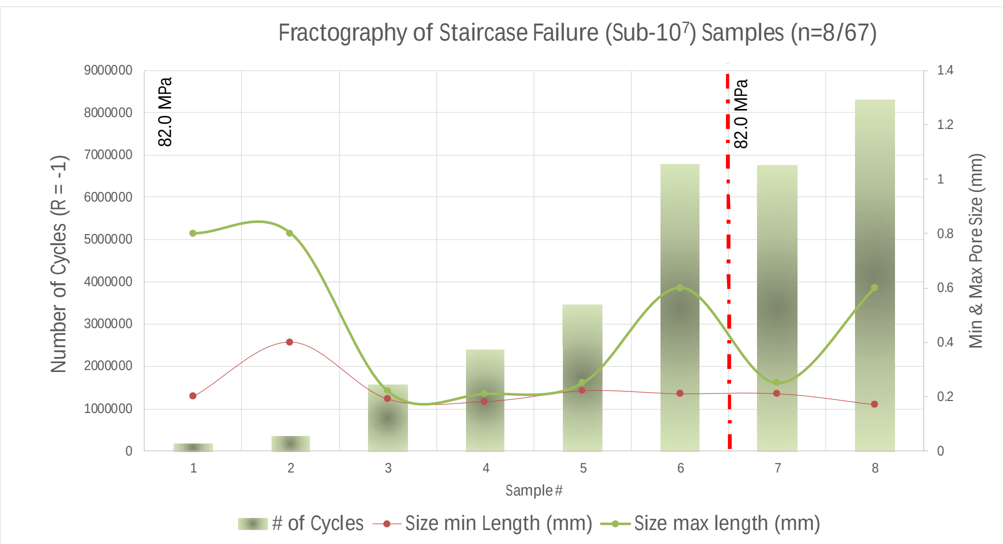
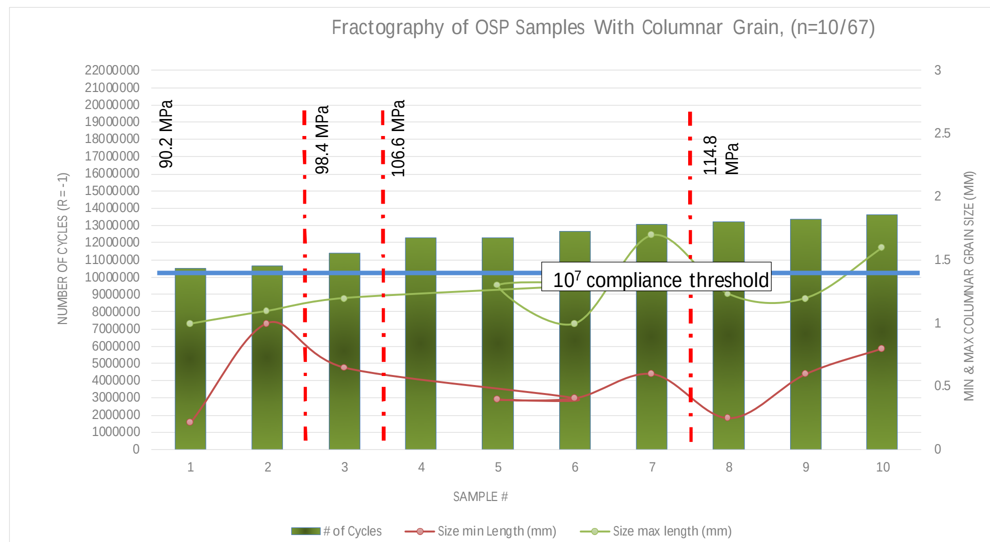
- None of the sub-10^7 OSB samples had columnar zones as their respective fatigue crack nucleation sites. All were with micro-shrinkage presumably nucleated by an oxide skin and located at the surface of the reduced gauge section.

- OSB samples which had columnar grains as their respective fatigue nucleation sites were compliant however the size of the defect is roughly 1 - 2 mm, larger than the sub-1mm size typically seen for the compliant samples which failed die to a mico-shrinkage pore.





Discussion / Conclusions

Discussion

- A fractography study was conducted on 67 OSB test samples to catalog the fatigue nucleation site. All fatigue samples were sectioned from 67 castings and the data was used to assess the fatigue durability of the cast component.
- Of the 67 samples:
  - 8 samples failed (<10^7 cycles) for micro-shrinkage defects at the near surface of the reduced gauge section.
  - 10 samples passed (<10^7 cycles) for columnar zones at the surface of the reduced gauge section.
  - 49 samples passed (<10^7 cycles) for micro-shrinkage pores located at the near surface of the reduced gauge section, or is a micro-shrinkage located in the interior of the fracture surface.
- Most likely increasing the quantity of Tibor may have reduced the size of the columnar grain region further reducing the number of OSP samples which may fail due to columnar grains.
- It is difficult to provide a group-quantification for the above categories due to the fact that for every alternating stress used there will also be a range of cycles sustained before complete failure.

Conclusions

- The impact of columnar grains on the OSP data set does not appear to be significantly deleterious.
- Increasing the amount of Tibor used may reduce the size of the columnar zone (from the half-round) and then reduce the possibility of a columnar zone being part of the reduced gauge section.
- Its only presumed at this point that if columnar grains were reduced then those OCP samples which failed due to columnar zone would improve in terms of both the number of alternating cycles and the alternating stress sustained, especially of the critical flaw which will nucleate a fatigue crack is located away from the surface of the reduced gauge section.

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