IOWA STATE UNIVERSITY
Industrial and Manufacturing
Systems Engineering

Characterization of the casting surface and the impact of surface on fatigue life of steel castings

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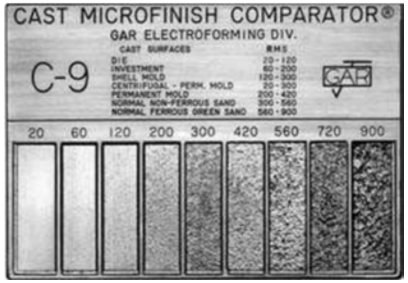
Surface Roughness: Standards

- Common today: visual and tactile comparison with standards (SCRATA plates, GAR C-9)
  - Subjective results cause issues
- Demand for reliable objective results



Objective Methods


https://scientificservices.eu/item/1524/image/intra_50.jpg

- Today's objective methods include:
  - Profilometer: often 2D or small test area
  - Laser scan + 3D roughness standard Sq: needs underlying geometry detection and are not based on spatial information
- ➢ Mostly useful for machined surfaces

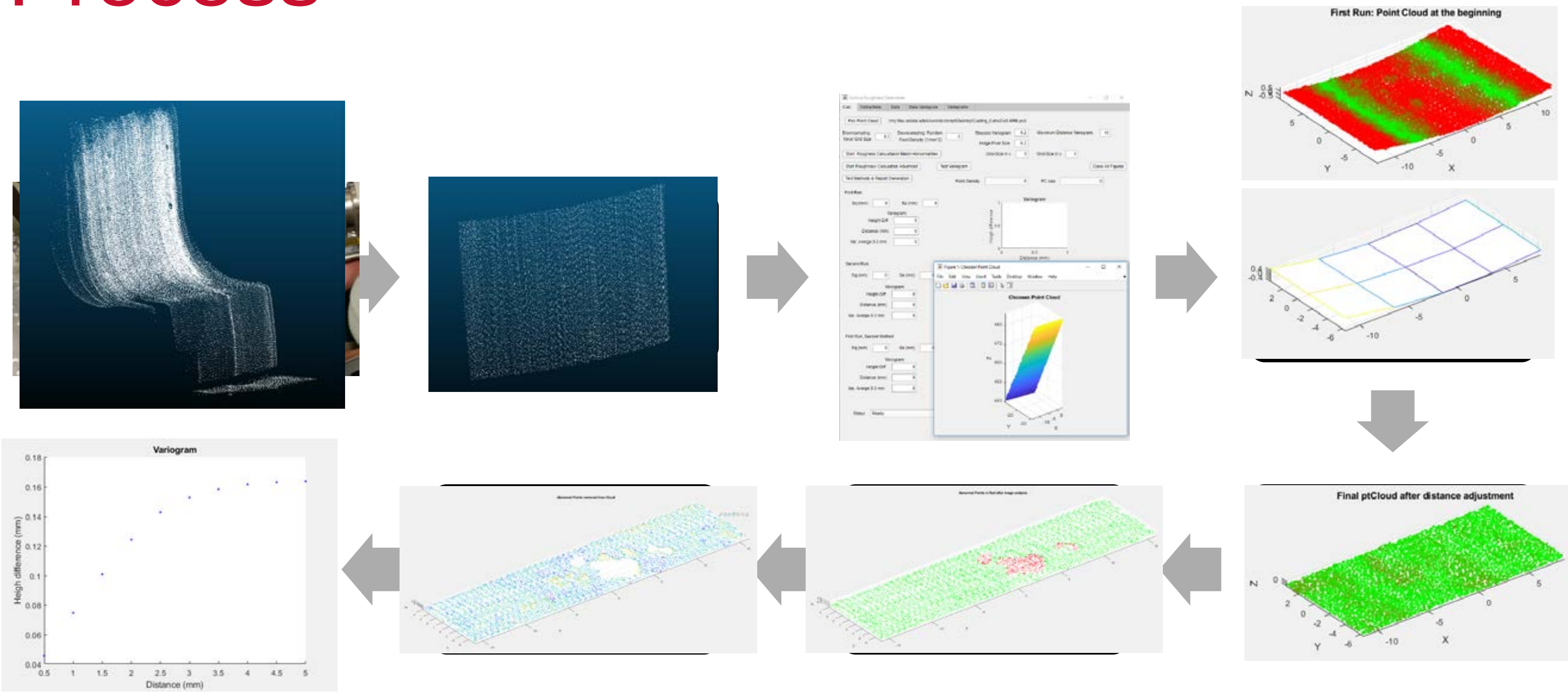
Goal

- Digital standard for roughness determination
- An app or widget that works with laser scanner

Surface Quality Inspection

- New standard to reliably specify and detect the required surface conditions
- Quantitative method considers:
  - Spatial information
  - Underlying geometry
  - Abnormalities
- Variogram roughness values are comparable to Sq & Sa values
  - Usually variogram roughness will be lower than Sq & Sa values
  - For random point clouds Sq equals variogram roughness

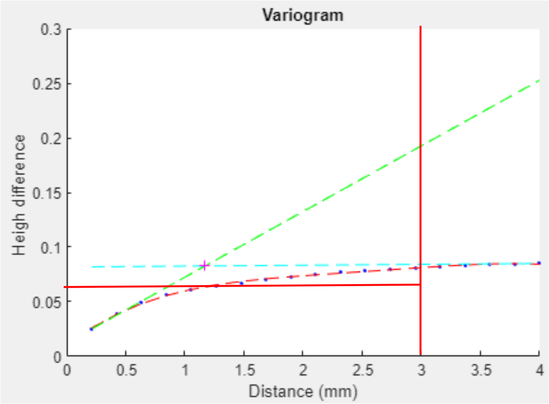
Process


First Run: Point Cloud at the beginning
Final ptCloud after distance adjustment
Variogram
Heigh difference (mm)
Distance (mm)

6

2. Spatial Information: Variogram

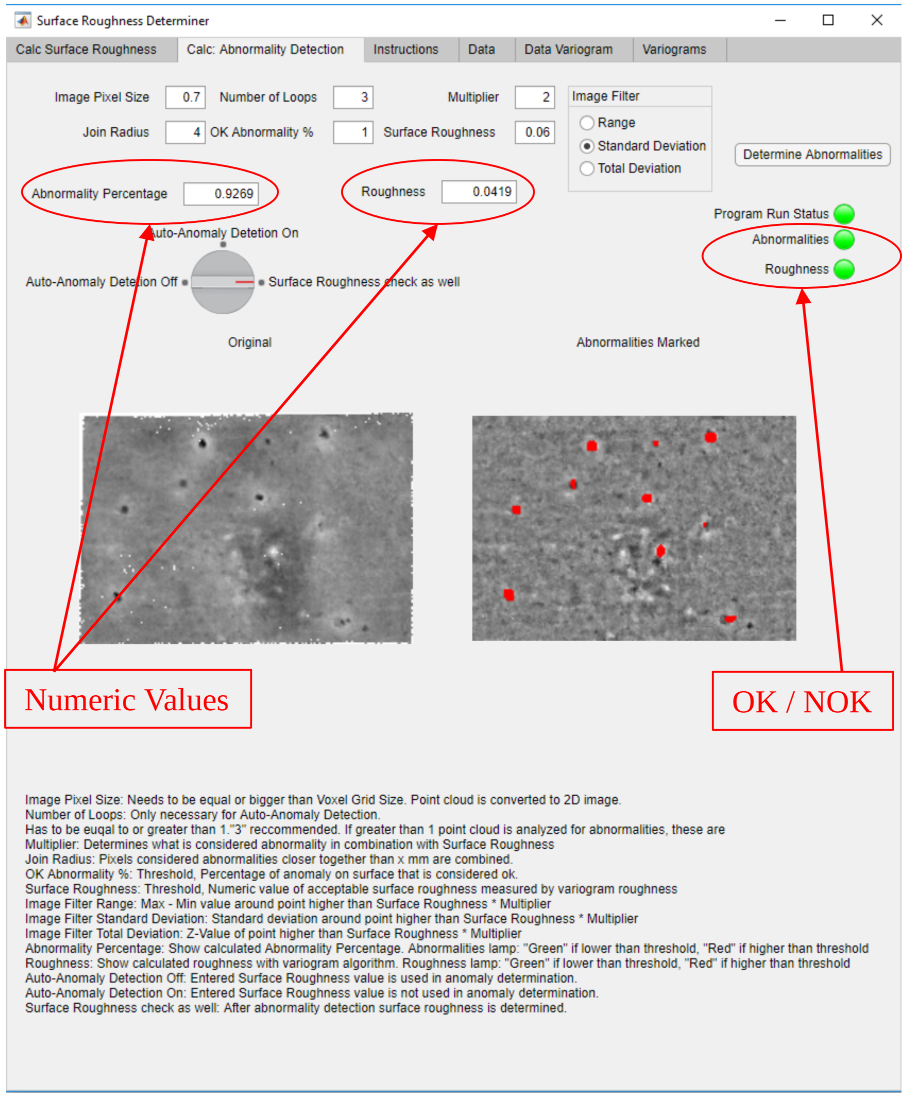
- Variogram plots the squared height difference for two points over the distance that they are apart
- For bigger distances between points one expects a higher height difference than for points that are close together
- Method used in geology: ground analysis



$$\hat{\gamma}(h \pm \delta) := \frac{1}{2|N(h \pm \delta)|} \sum_{(i,j) \in N(h \pm \delta)} |z_i - z_j|^2$$

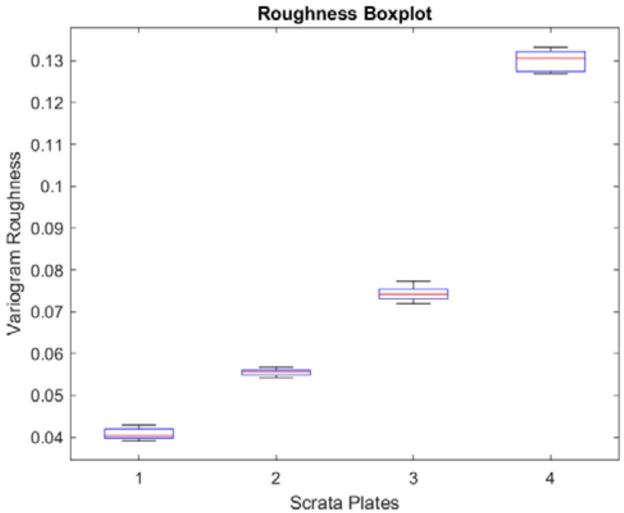
Application

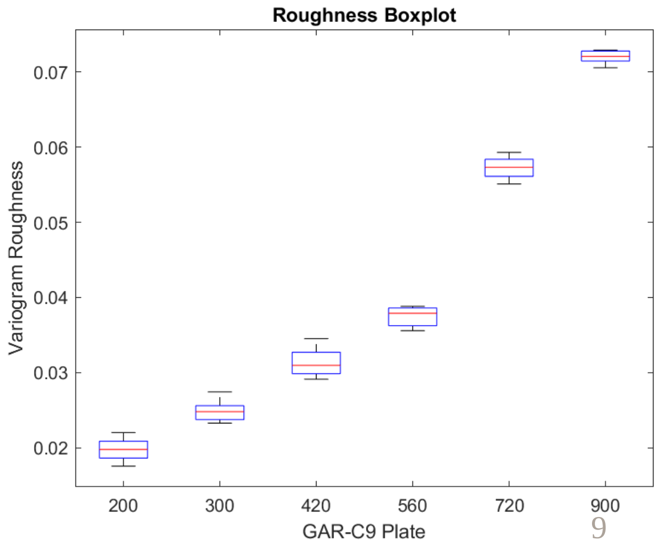
- Input
  - Point cloud
  - Acceptable surface roughness and abnormality area percentage
  - Optional extra parameters
- Output: surface roughness and abnormality percentage
  - OK / NOK
  - Numeric values



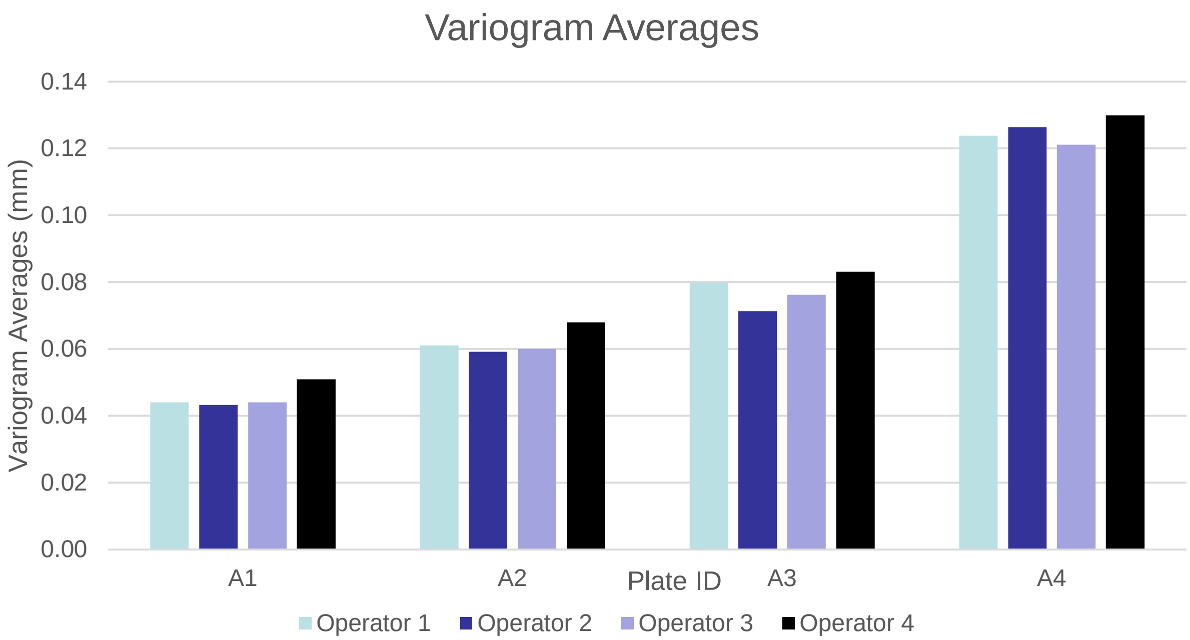
Results: Comparator Plates

- Clear differences between roughness levels for GAR-C9 and SCRATA A Plates.
- 8 scans of each surface (single Operator)
- ➢ Usable to differentiate between common casting comparator plate surface roughness levels





Results: Gage R&R

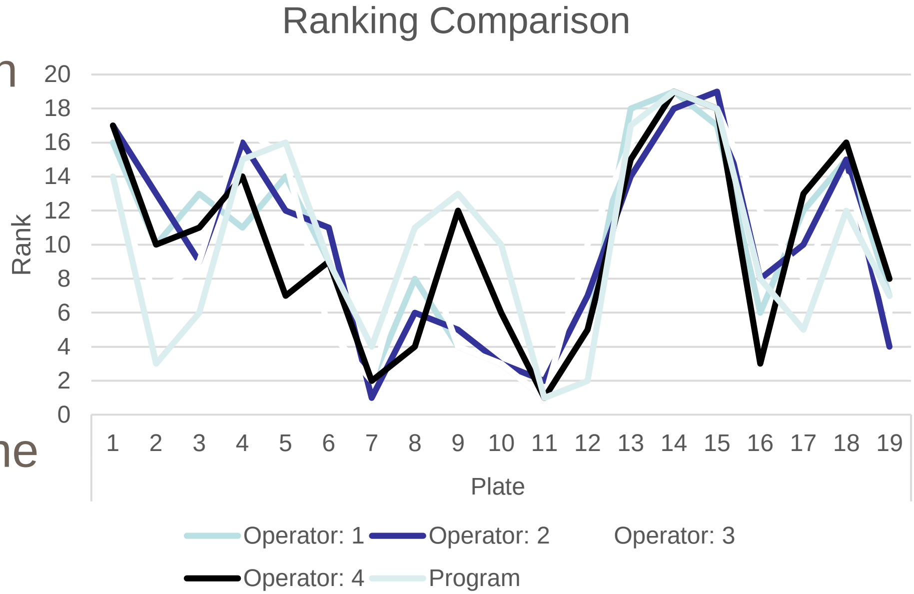


Gage R&R Category	Error
Repeatability (Equipment)	9.22 %
Reproducibility (Operator)	9.46 %
Repeatability & Reproducibility	13.21 %

- Each bar is the mean of four scans
- ➢ Good repeatability and reproducibility

Results: Rank Comparison

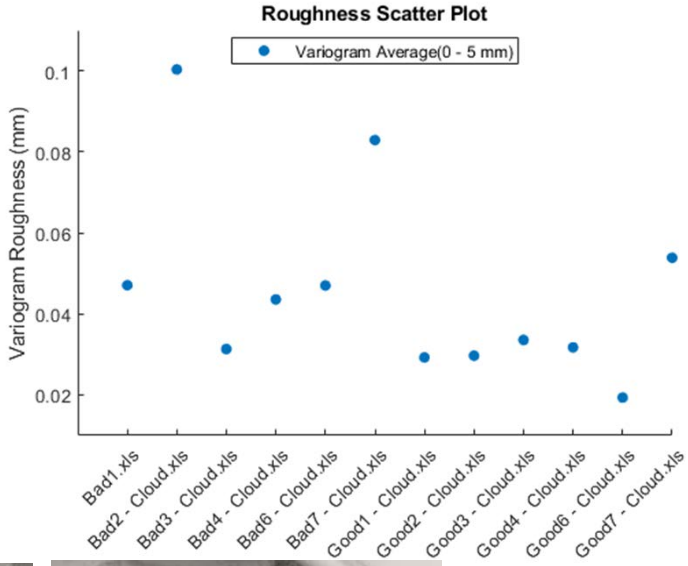
- Operators are current "roughness standard"
  - Thus checking for correlation program vs operator
- Rank 19 molds of real castings based on surface roughness
- 4 Operators + Program
- Mean operator ranking correlates with ranking based on calculated surface roughness
- Operator ranking has big spread for some plates
  - Plate 9: Op1 – Rank 13, Op3 – Rank 4



Results: Industry

- Scans of casings at 3 different foundries
- Compared surface roughness of “good” and “bad” surface patches on castings with similar geometry
- Pairwise comparison was able to show higher surface roughness on most “bad” castings
    - Exceptions seem to be caused by anomalies on surface

Results at one foundry



Surface rougher

Surface smoother

Anomaly

Measurement error in wet MPI

1) Measurement error due to surface roughness
   - Rough surfaces tend to cause particles tend to catch in the valleys of the surface [1]
   - What is the effect of surface roughness?
   - Can we quantify it?
2) Measurement error due to human and process
   - Gauge R&R

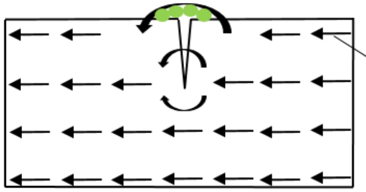
[1] "Magnetic Particles," NDT Resource Center. [Online]. Available:https://www.nde-ed.org/EducationResources/CommunityCollege/MagParticle/Equipment/Particles.htm.

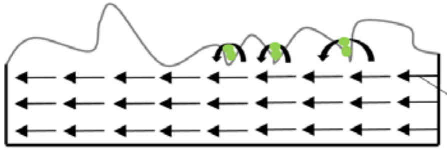
1) Measurement error due to surface roughness

Why does surface roughness matter?

1) Particles gets caught in the valleys of the surface
   - Wet particles (10µm) smaller than dry particles (50-150µm) [1]
   - Hence, tend to catch especially on rougher surfaces [2]
   - Makes it harder to see indication / false positives

2) Some extreme surface textures may create magnetic flux leakage areas
   - Makes it harder to see indication / false positives





[1] "Wet Suspension Inspection," NDT Resource Center. [Online]. Available: https://www.nde-ed.org/EducationResources/CommunityCollege/MagParticle/TestingPractices/Wet Suspension.htm.
[2] "Magnetic Particles," NDT Resource Center. [Online]. Available: https://www.nde-ed.org/EducationResources/CommunityCollege/MagParticle/Equipment/Particles.htm.

1) Measurement error due to surface roughness

Research Question 1: Do particles collect more on rougher surfaces?

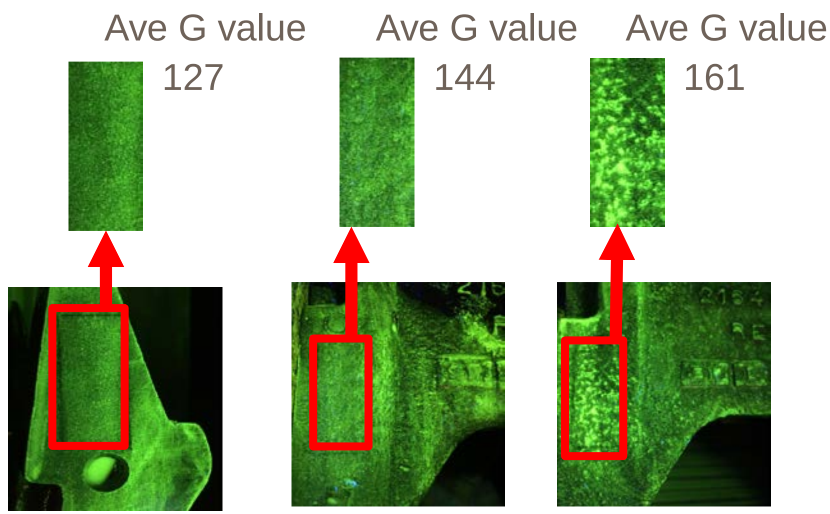


Figure 1. A1 sample Figure 2. A2 sample Figure 3. A3 sample

To answer Question 1:

- Utilized Green (G) value from RGB scale to determine average green intensity of an area
- The higher the average G intensity, the higher the particle collection in the surface texture
- We found a significant increase in particle collection as surface roughness increases

1) Measurement error due to surface roughness

Research Question 2: How much do the particles on the surface deter a person from seeing the indications?

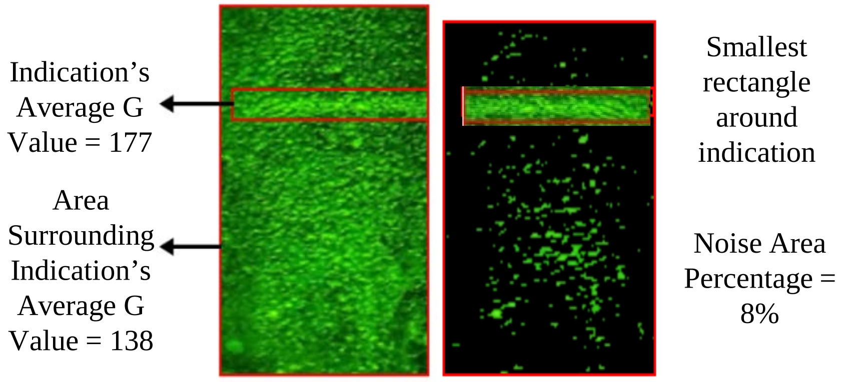


Figure 1.Image containing indication

Figure 2. Noise Area Percentage

To answer Question 2:

- To quantify how hard it is to see an indication due to surrounding particles on the surface
  - Compare indication intensity to surrounding area not including indication
- Hence, we can find the percentage of pixel surrounding the indication that is brighter than the average of the indication
- This percentage represent our noise %
- We found an increasing trend in noise as surface roughness increases

Developed Experiment to Couple Ketos Ring with Surface Roughness

- Three parts with four levels of surface roughness were tested
- Depth of hole – 0.01’’, ⌀ of hole – 0.07’’

Figure 1. Ketos Ring

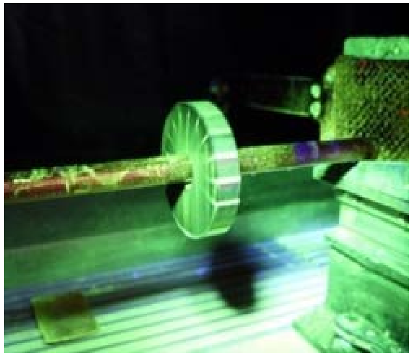


Figure 2. Wet MPI on Ketos Ring

Figure 3. Diameter of 0.07 in a Depth of 0.01 in

Experimental Setup

2 Levels, 3 Factors, 2 Replicates

Surface Roughness

Figure 1. A1

Figure 2. A4

Depth

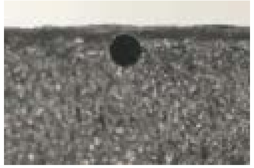


Figure 3. 0.01’’

Figure 4. 0.07’’

Diameter

Figure 5. 0.07’’

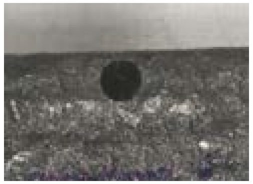


Figure 6. 0.14’’

Experiment Output

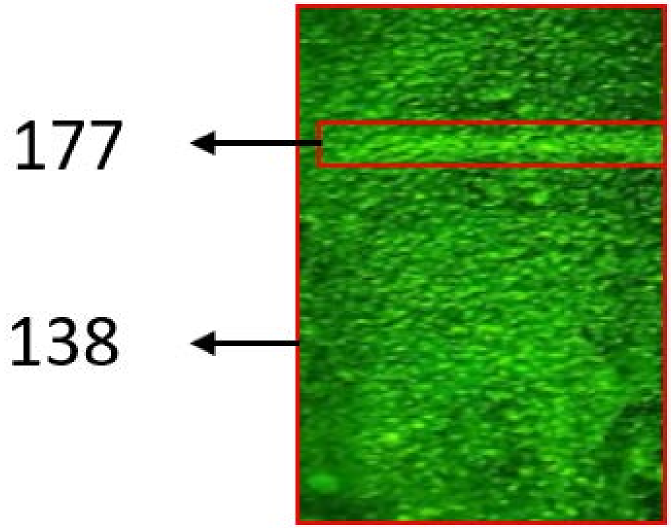


Figure 1.Average G Value for the Indication and Surrounding Area

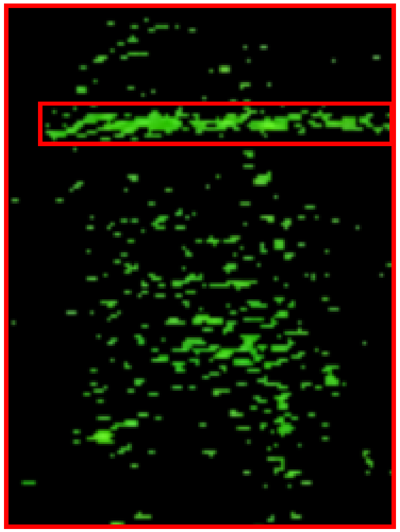


Figure 2. Noise Area Percentage

Noise Area Percentage = 8%

Experimental 3 (3 Factors) - Results

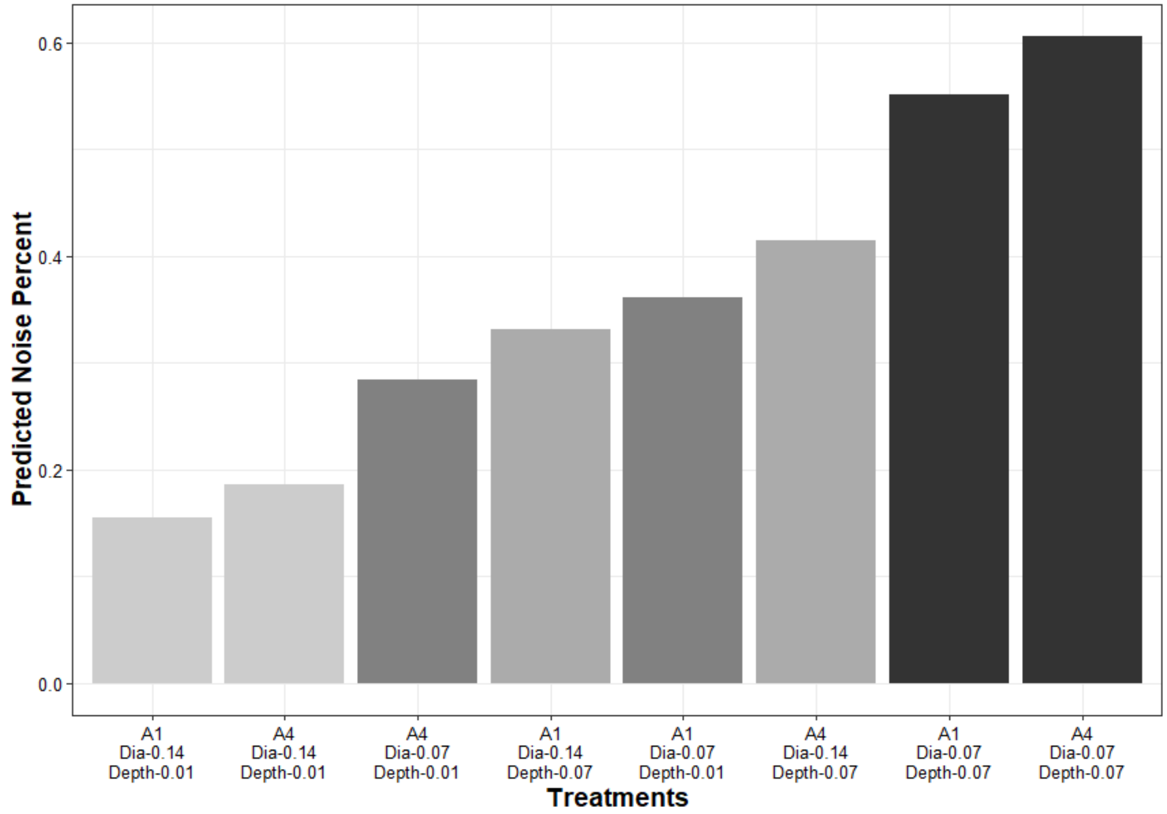
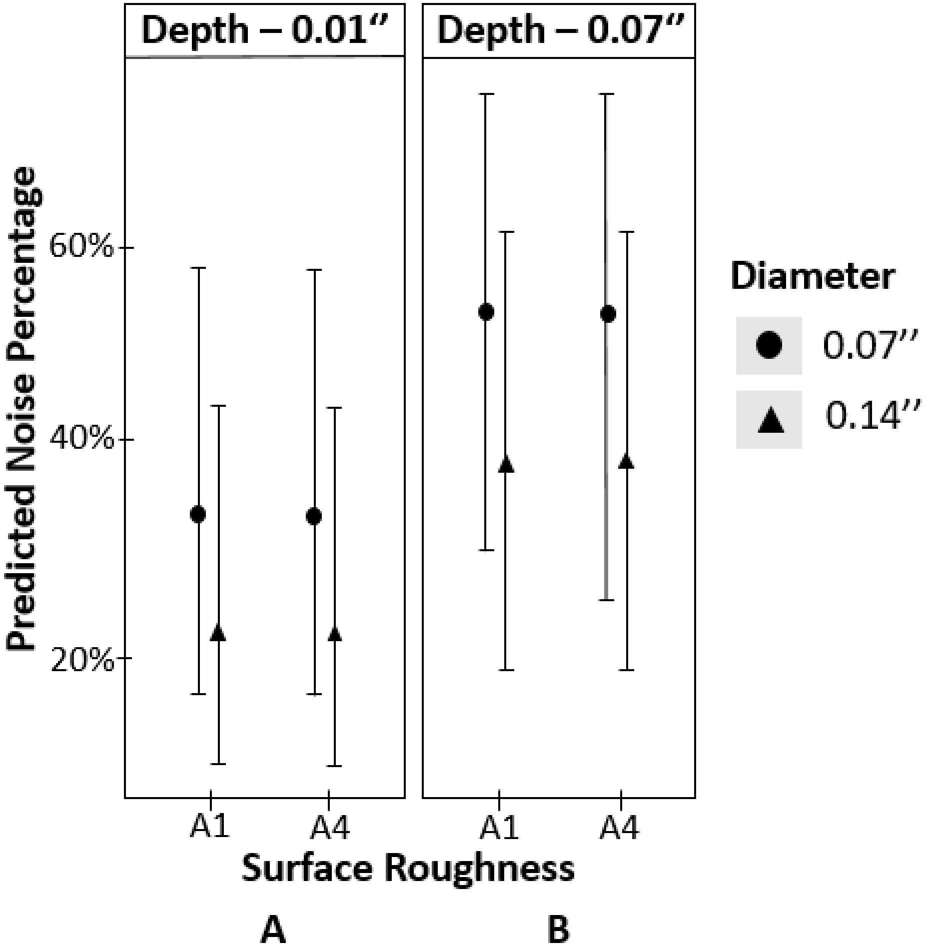


Figure 1. Predicted Noise Area Percentage Versus All the Treatment Levels

Experimental 3 (3 Factors) - Results



- Depth was found to affect the noise area percentage the most ($p = 0.09$).
- Diameter and surface roughness had less significant effects ($p = 0.22, 0.72$)
- The model accounts only for 31% of variability

Figure 1.
A) Predicted Values for Noise Area Percentage with All the Combinations of Roughness and Diameter at Depth of 0.254 mm (0.01 in)
B) Predicted Values for Noise Area Percentage with All the Combinations of Roughness and Diameter at Depth of 1.78 mm (0.07 in)

2) Measurement error due to human & process

- Gauge R&R (3 foundries)
  - Method – Used magnets to identify where operators find indications

    –Calculations (see images below)

Repeatability = 40% because 2 out of 5 match

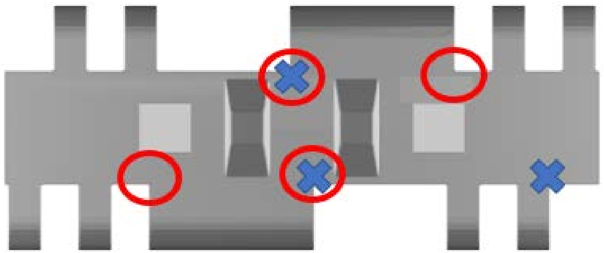


Figure 1. Blue “x” represents Operator 1 Part 1 Trial 1
Red circles represent Operator 1 Part 1 Trial 2

Reproducibility ≈ 67% because 4 out of 6 match

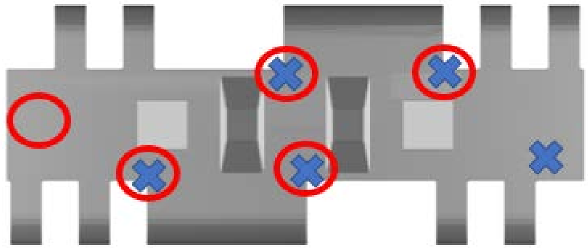


Figure 2. Blue “x” represents the union of Operator 1 Part 1 all Trials
Red circles represent the union Operator 2 Part 1 all Trials

2) Measurement error due to human & process

Results (% indication matched) :-

- Foundry 1 (3 op, 6 parts, 2 times) - 73% for repeatability 48% for reproducibility
- Foundry 2 (2 op, 6 parts, 2 times) - 39% for repeatability 22% for reproducibility
- Foundry 3 (1 op, 4 parts, 2 times) - 29% for repeatability

What caused low % match?

Could be the orientation or magnetic field strength.

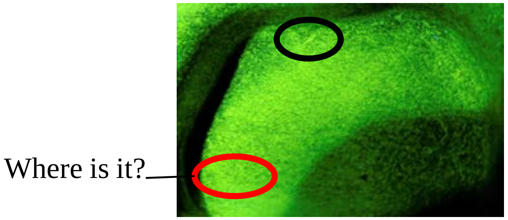


Figure 3.Trial 1 Area A

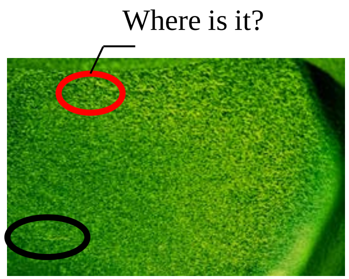
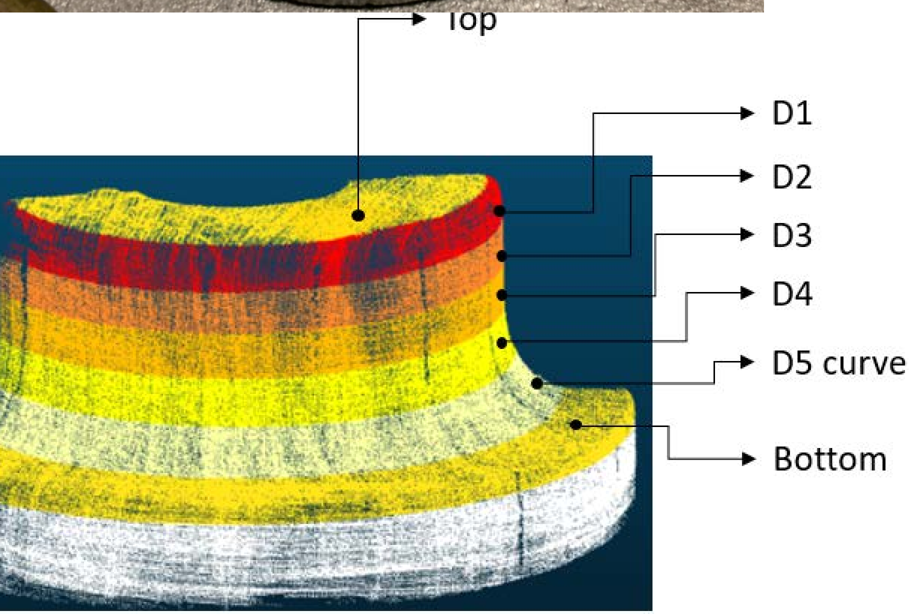
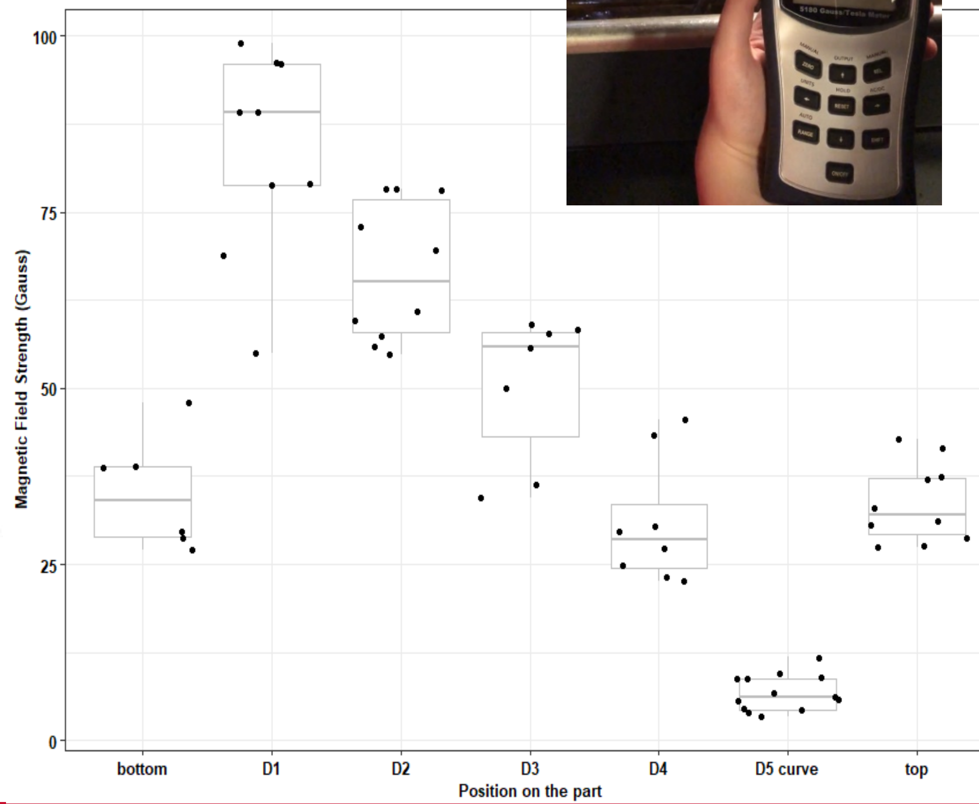


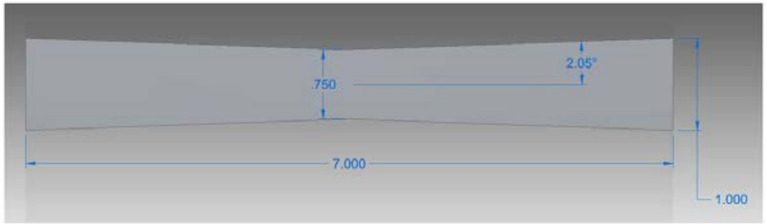
Figure 4. Trial 2 Area A

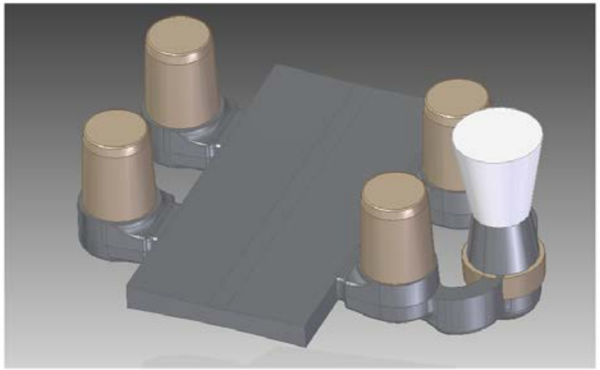

Top
D1
D2
D3
D4
D5 curve
Bottom


Magnetic Field Strength (Gauss)
100
75
50
25
0
bottom
D1
D2
D3
D4
D5 curve
top
Position on the part

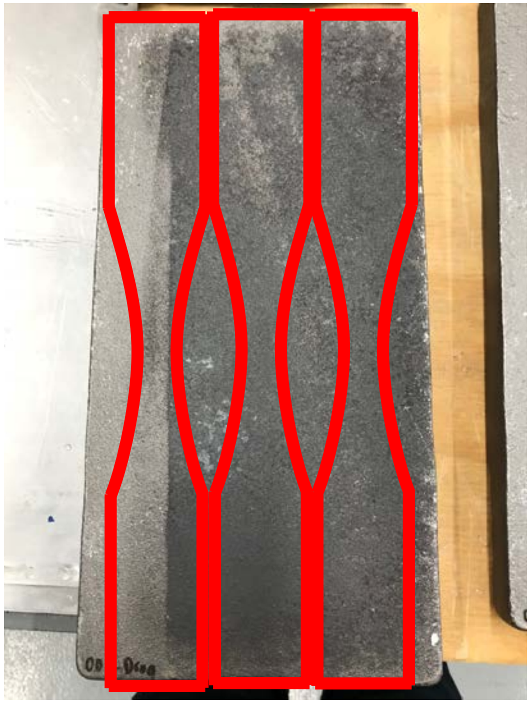
ISU Test Casting to Study Impact of Surface Roughness on Fatigue

- Casting designed with little centerline shrink
- 7 x 14” – can get up to 3 specimens from plate
- Produced with varying surface roughness and intentional and unintentional porosity and inclusions



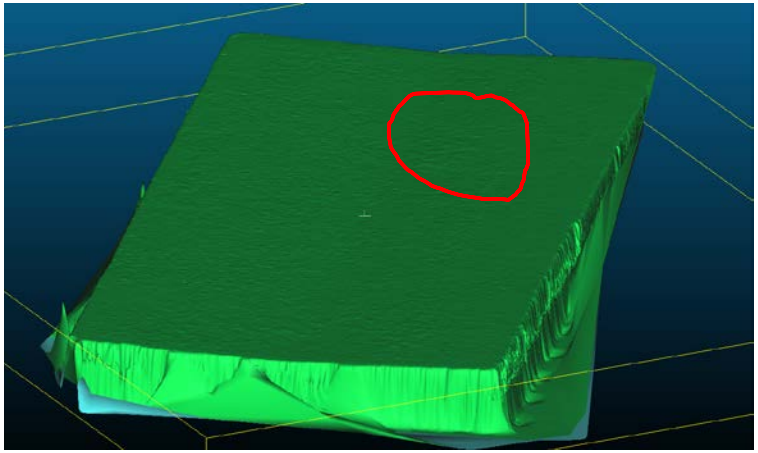


ISU Test Casting to Study Impact of Surface Roughness on Fatigue



- Up to 3 bars per casting
- Position based on surface conditions
- Water jet cut from plate


005-0X00

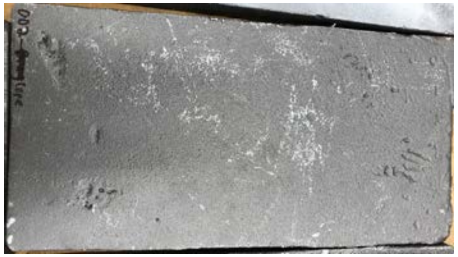


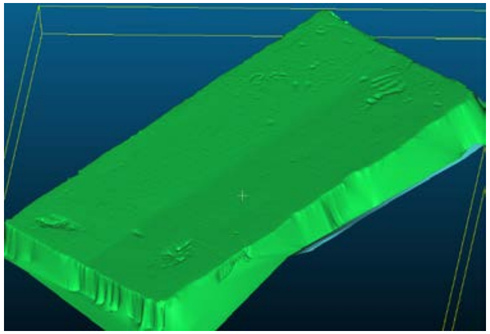
Goals

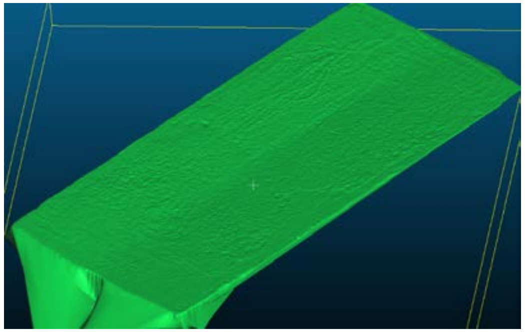
- Analysis of castings via NDE and surface classification methods
- Determine the effect casting surface and near surface condition on fatigue life
- Develop relationship between NDE results and casting life

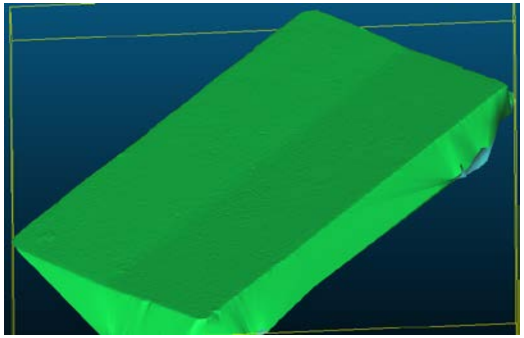
Test Plan

- Visually inspect per ASTM A802 (SCRATA)
- Laser scan
- Create rubber impressions of the surface
- Radiography
- Magnetic Particle Inspection
- Decide locations of test bars
- Water jet test bars from plates
- Uniaxial fatigue testing on test bars including areas of interest (surface and internal discontinuities)
- Material characterization by UAB







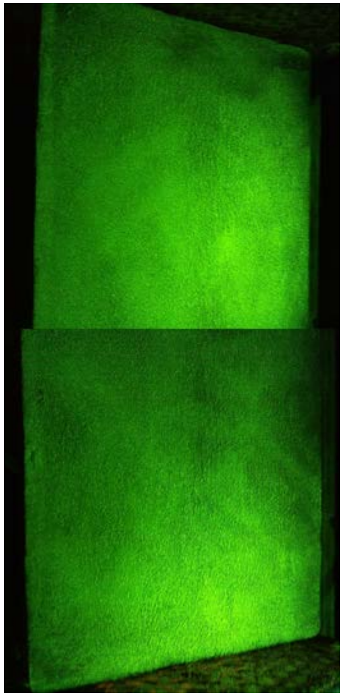
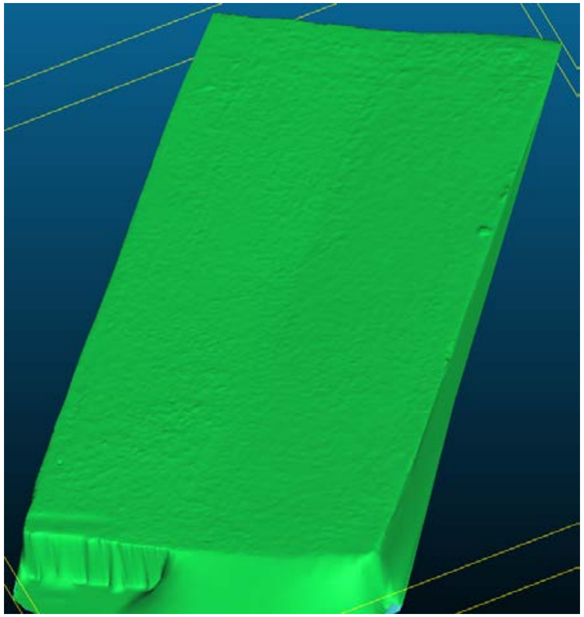


Machining Steps

- Datum edges are machined to allow for easier identification of test bar locations in NDE images
- Water jet cut specimens
- Test bars are machined to provide appropriate gripping surface

NDE

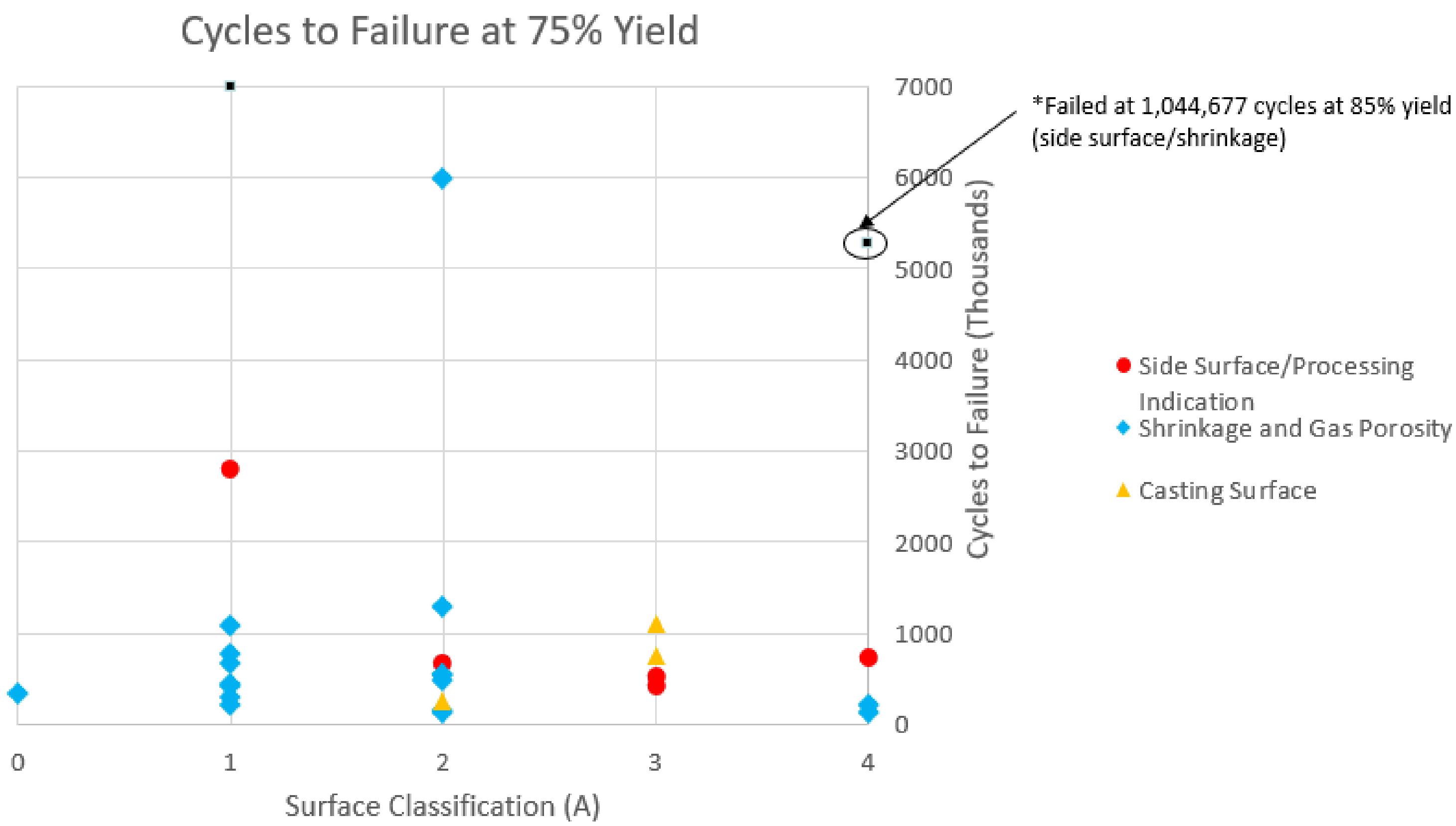
- Radiograph
- Magnetic Particle Inspection (MPI)
- Laser scanning

Fatigue Testing

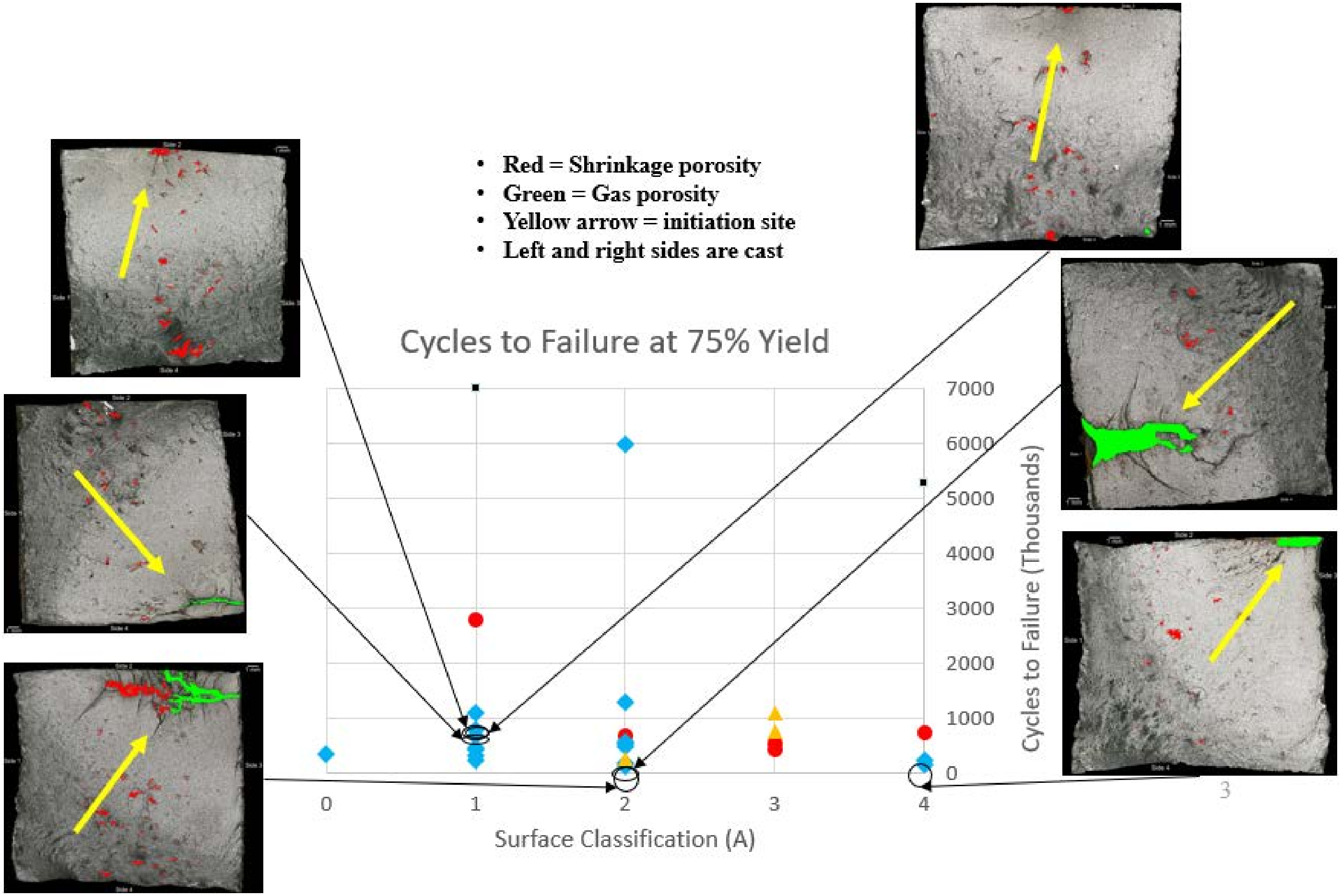
- Uniaxial full tension (at 75% yield for now)
- 10 Hz
- Initial test with strain gauges showed that cyclic ratcheting and shear were not factors

Results so far….



Results so far….

- Red = Shrinkage porosity
- Green = Gas porosity
- Yellow arrow = initiation site
- Left and right sides are cast



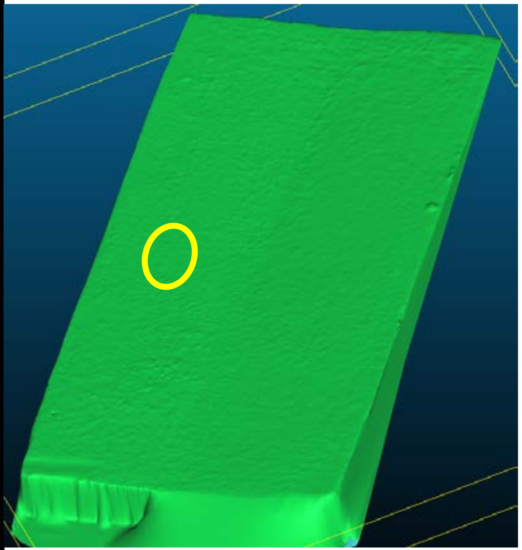
Gas Porosity

Side Surface

Shrinkage and Gas Porosity

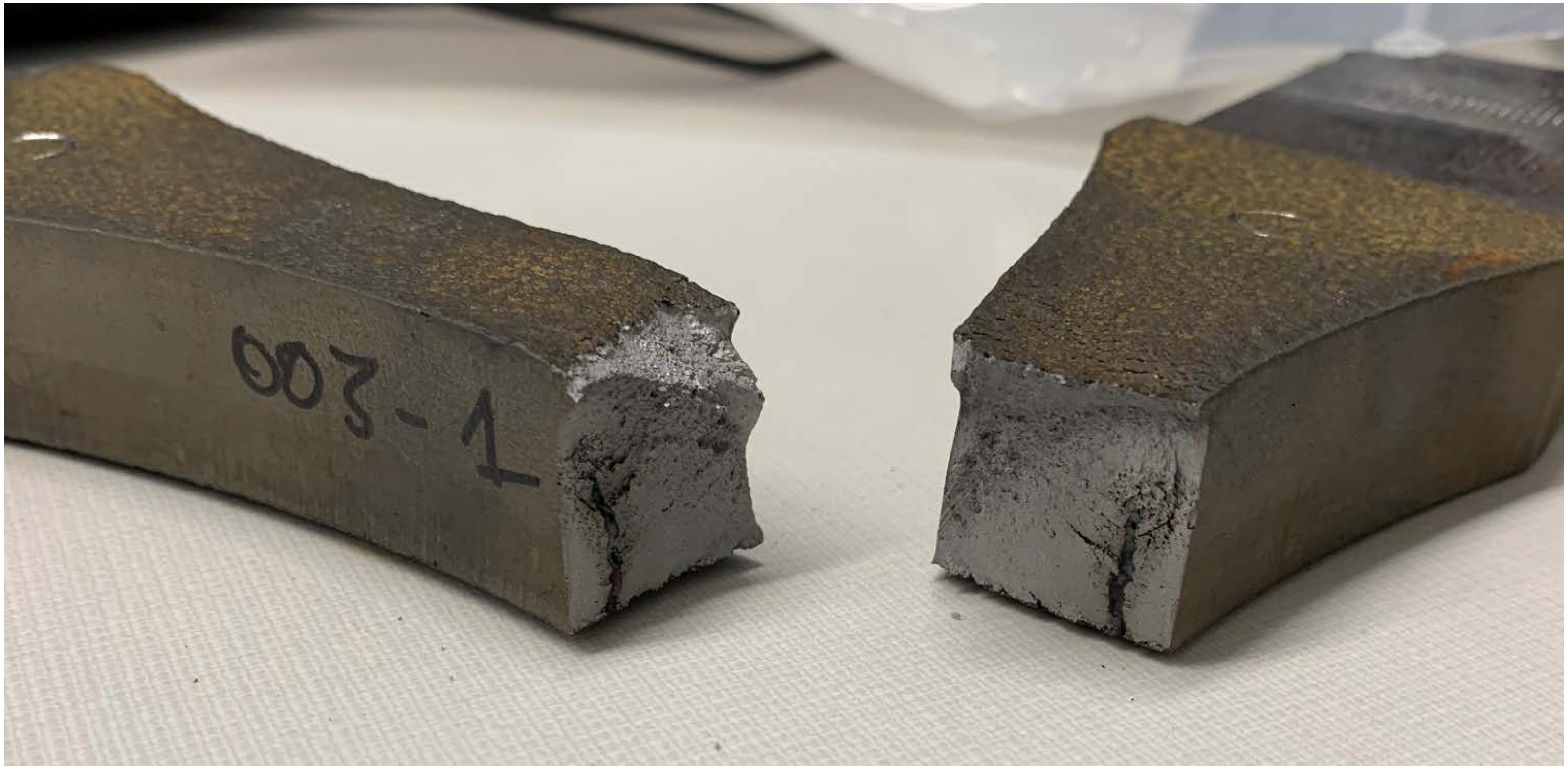
Casting Surface

Results – 003-1

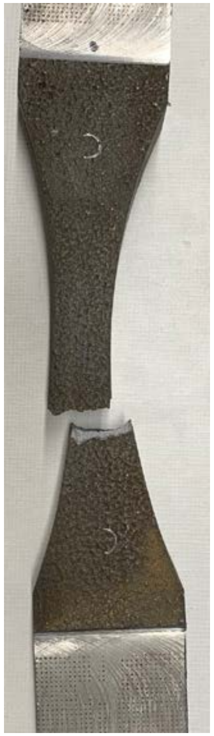


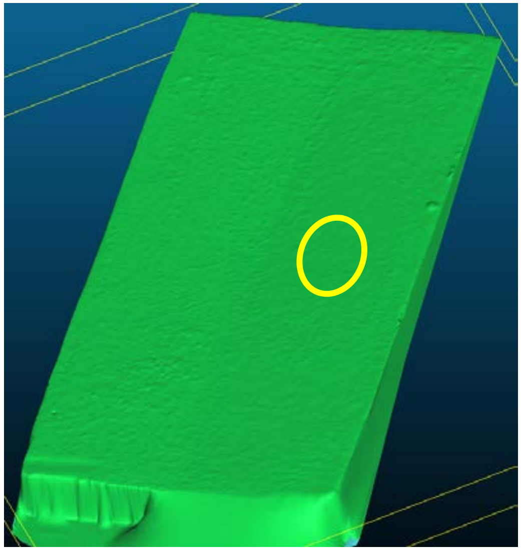
Results – 003-1

- Cycles to failure = 216,810
- A1 surface



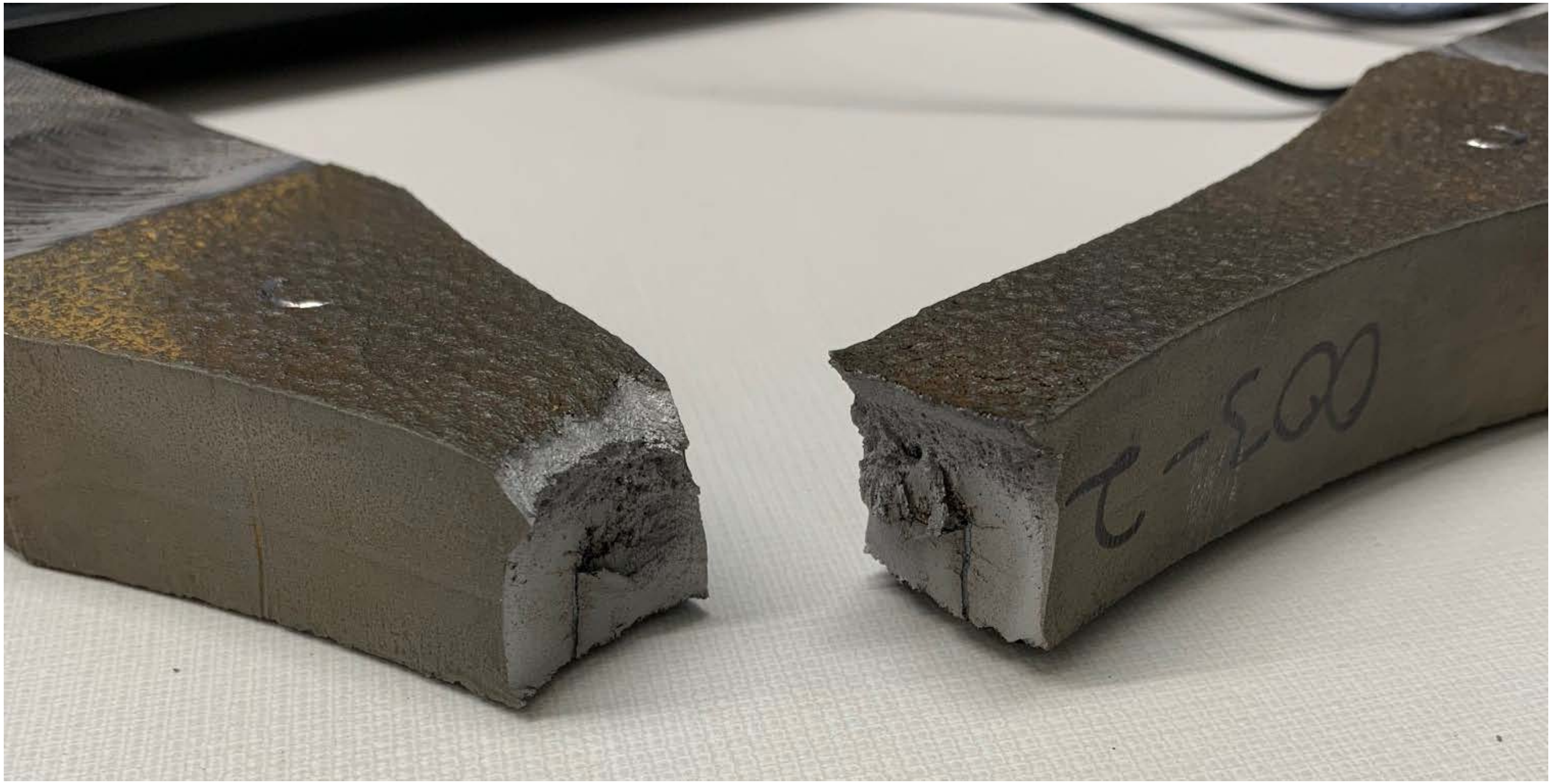
Results – 003-2



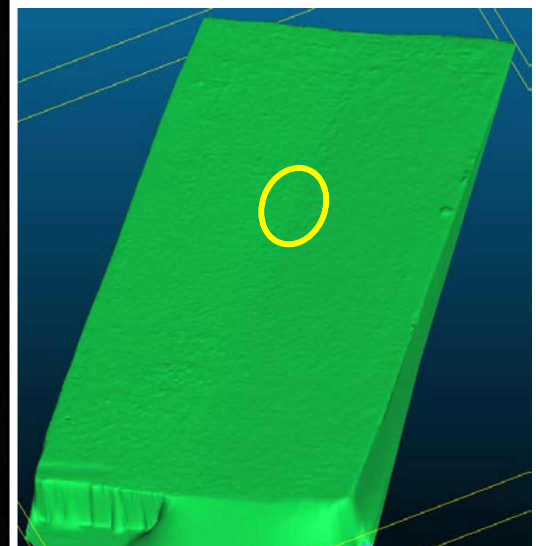


Results – 003-2

- Cycles to failure = 421,342
- A1 surface



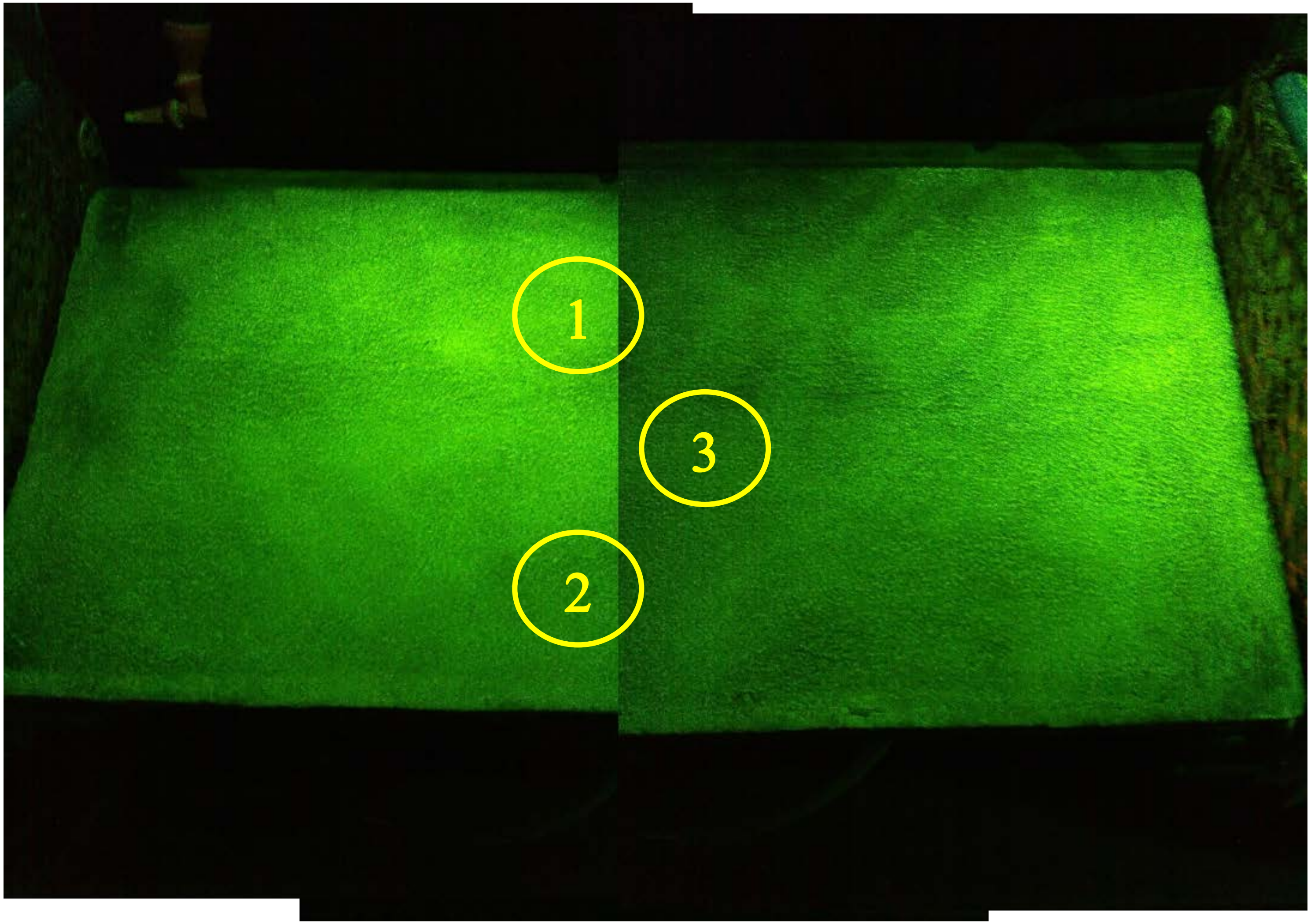
Results – 003-3



Results – 003-3

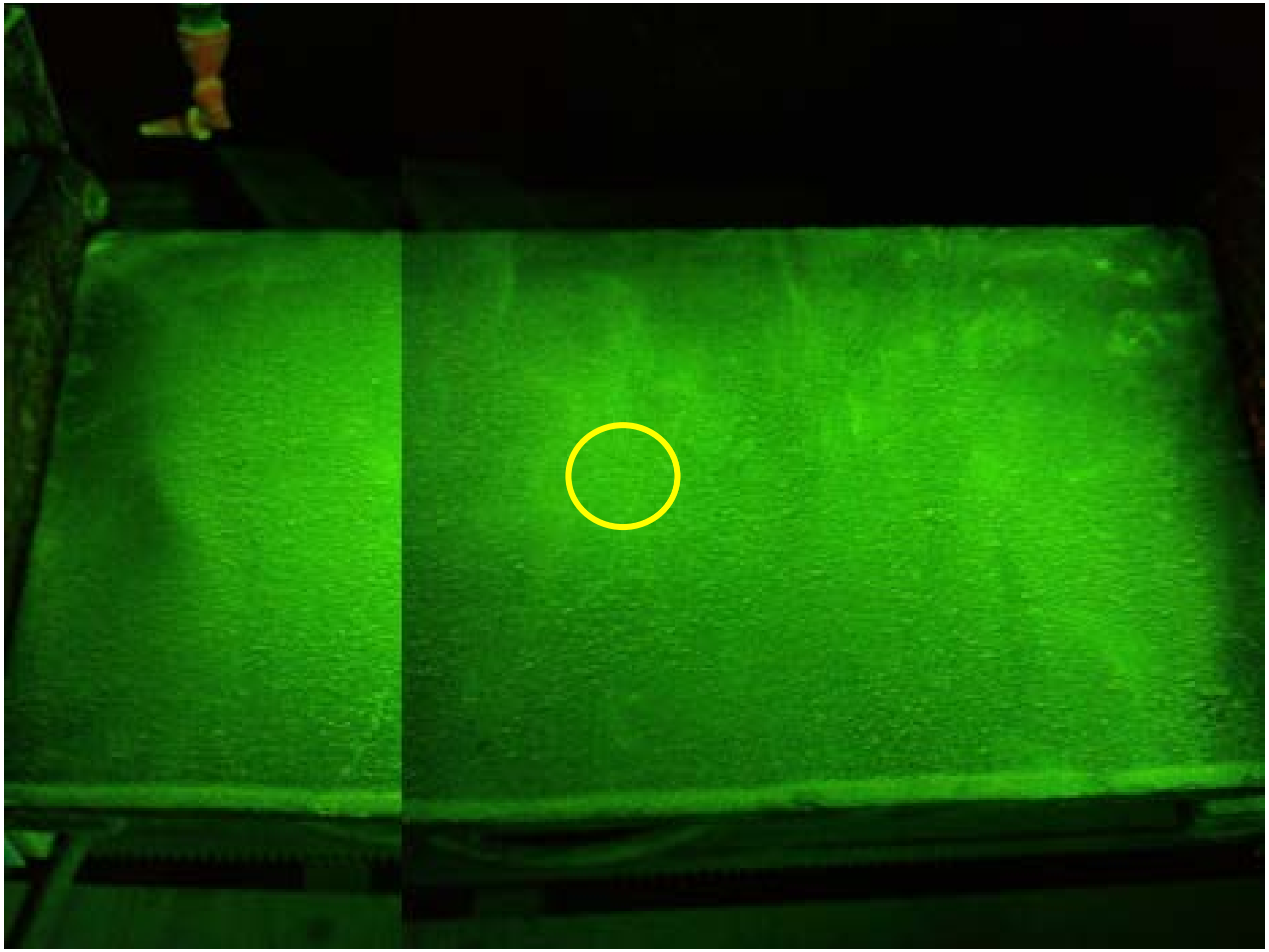
- Cycles to failure = 333,369
- **Machined surface**

Results – 003



Results – 001-2

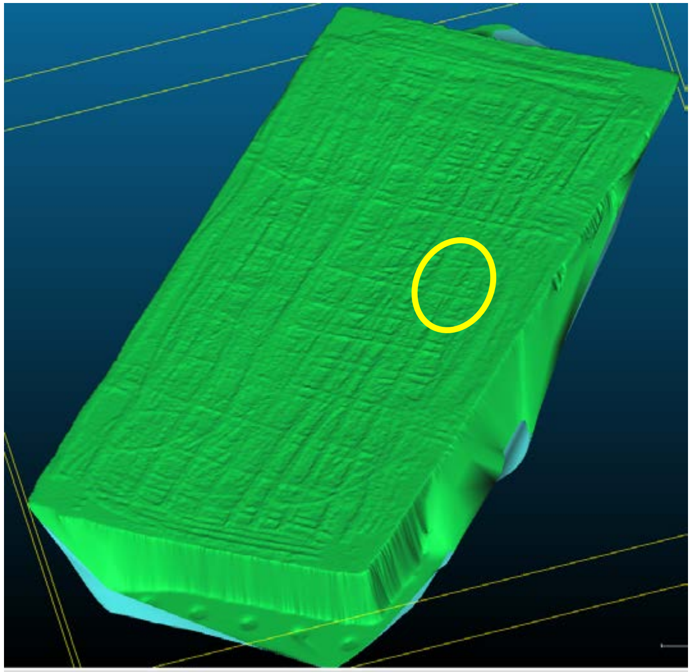
Results – 001-2



Results – 001-2

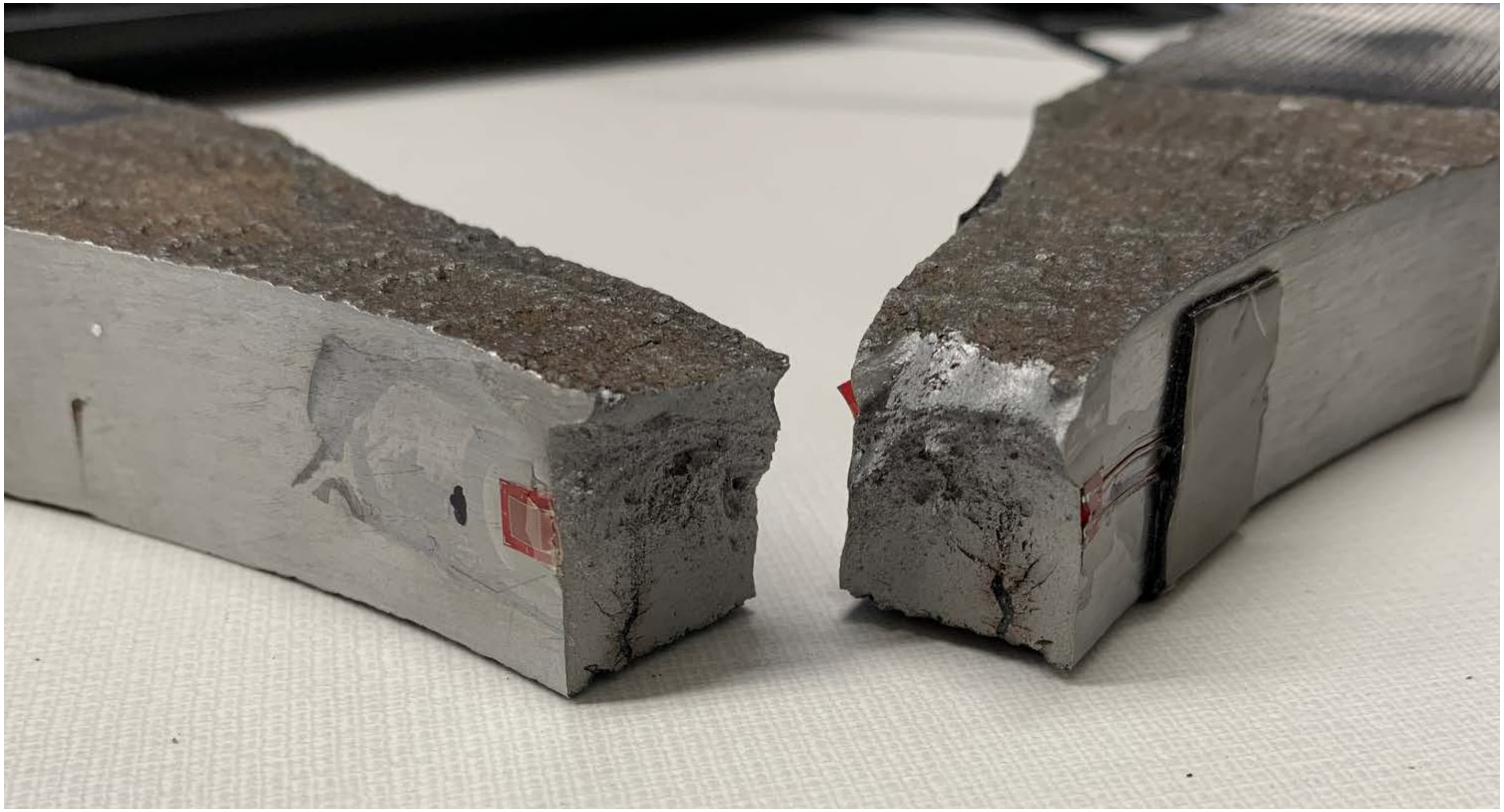
- Cycles to failure = 440,223
- A1 surface

Results – 004-1

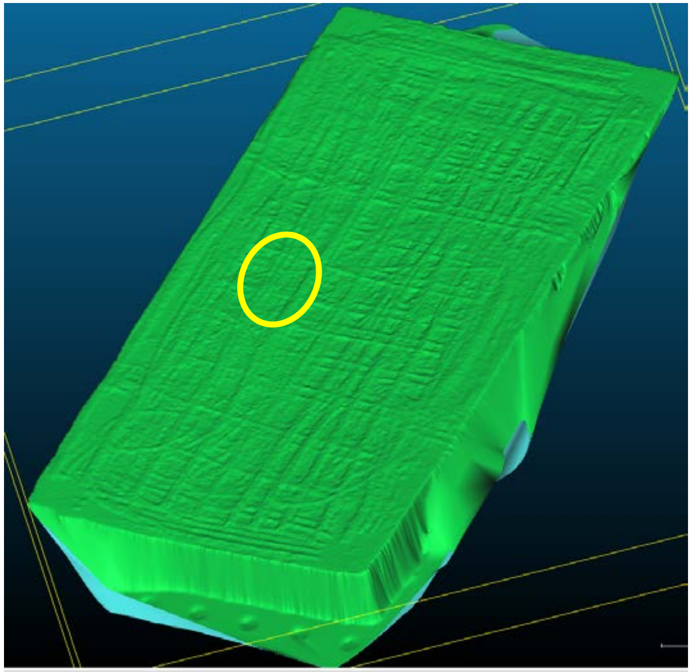


Results – 004-1

- Cycles to failure = 228,000
- A4 surface



Results – 004-2



Results – 004-2

- Cycles to failure = 736,158
- A4 surface

Observations so far

- Dr. Socie was right. Inclusions/porosity appear to influence fatigue life more than casting surface finish
- Casting surface does not seem to be significant?

Next Steps

- More alloys to be tested
- Surface decarburization
- Machined indications
- Use results from UAB to guide future direction and conclusions
- Bridge the gap between NDE and fatigue lives

Thank You!

- Disclaimer: The publication of this material does not constitute approval by the government of the findings or conclusion herein. Wide distribution or announcement of this material shall not be made without specific approval by the sponsoring government activity.
- Acknowledgement: This research is sponsored by the DLA-Troop Support, Philadelphia, PA and the Defense Logistics Agency Information Operations, J62LB, Research & Development , Ft. Belvoir, VA