IOWA STATE UNIVERSITY

Fatigue Properties of Steel Castings and their Relation to NDE Results

Dr. Frank Peters

Dr. David Eisenmann

Digital Innovative Design

for Reliable Casting Performance

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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

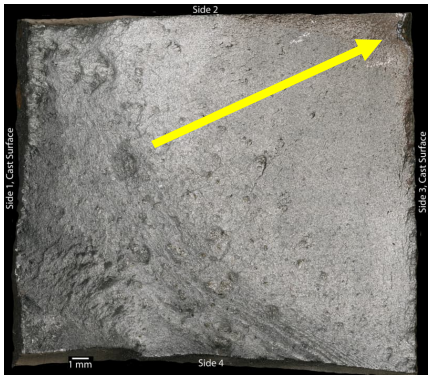
Initiation Site Examples from UAB Images

Casting/Side - Gas

Cycles: 1,099,616

Initiation site length: 0.97mm

Variogram avg: 0.061mm

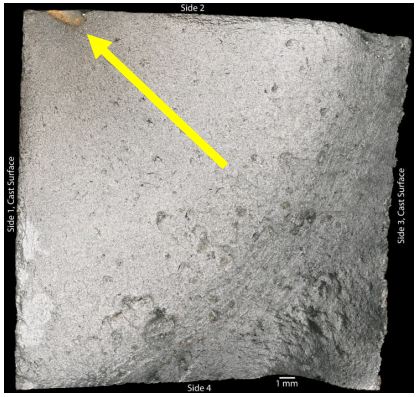


Cutting Gouges

Cycles: 2,794,392

Initiation site length: 1.33mm

Variogram avg: 0.061mm

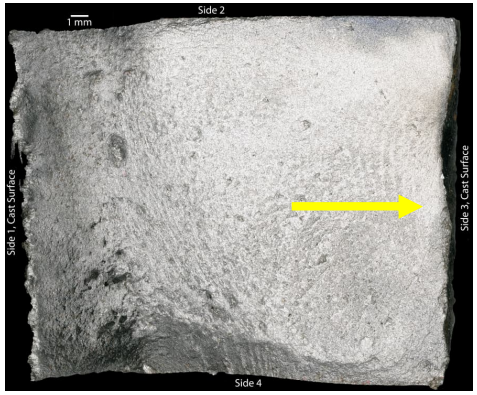


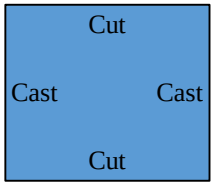
CS=Cast Surface

Cycles: 751,221

Initiation site length: N/A

Variogram avg: 0.087mm



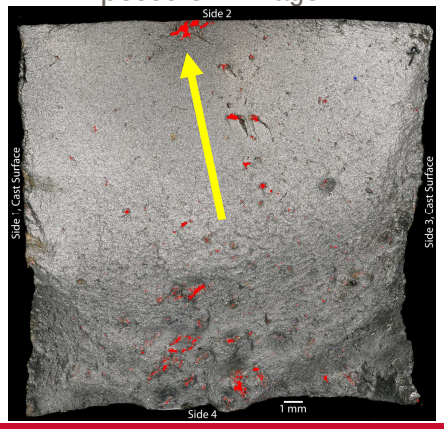


Exposed Shrinkage

Cycles: 425,687

Initiation site length: 0.75mm

Variogram avg: 0.075mm

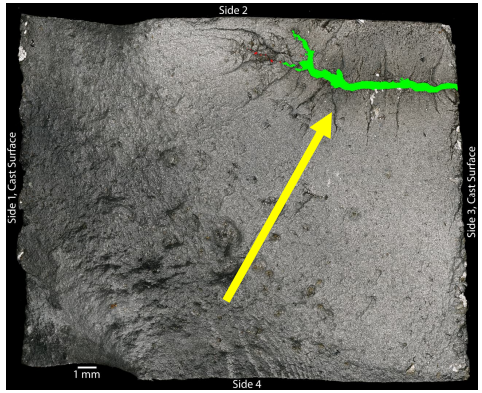


Gas

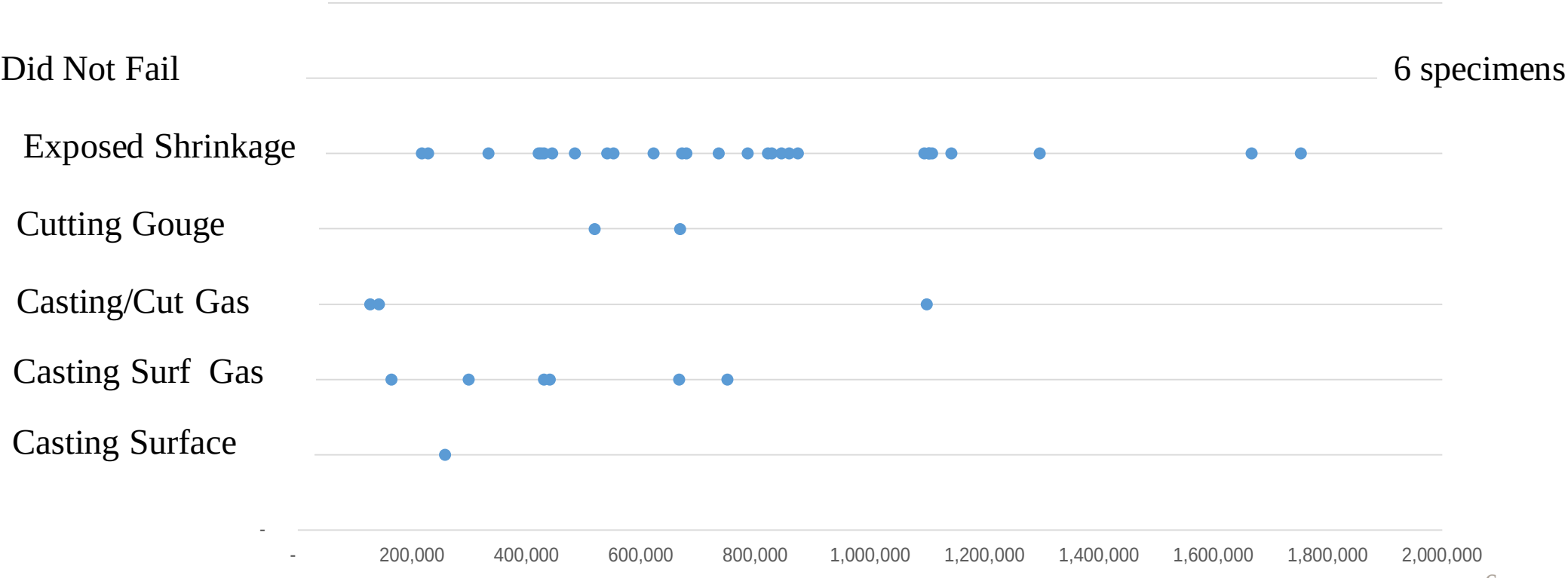
Cycles: 298,751

Initiation site length: 2.05mm

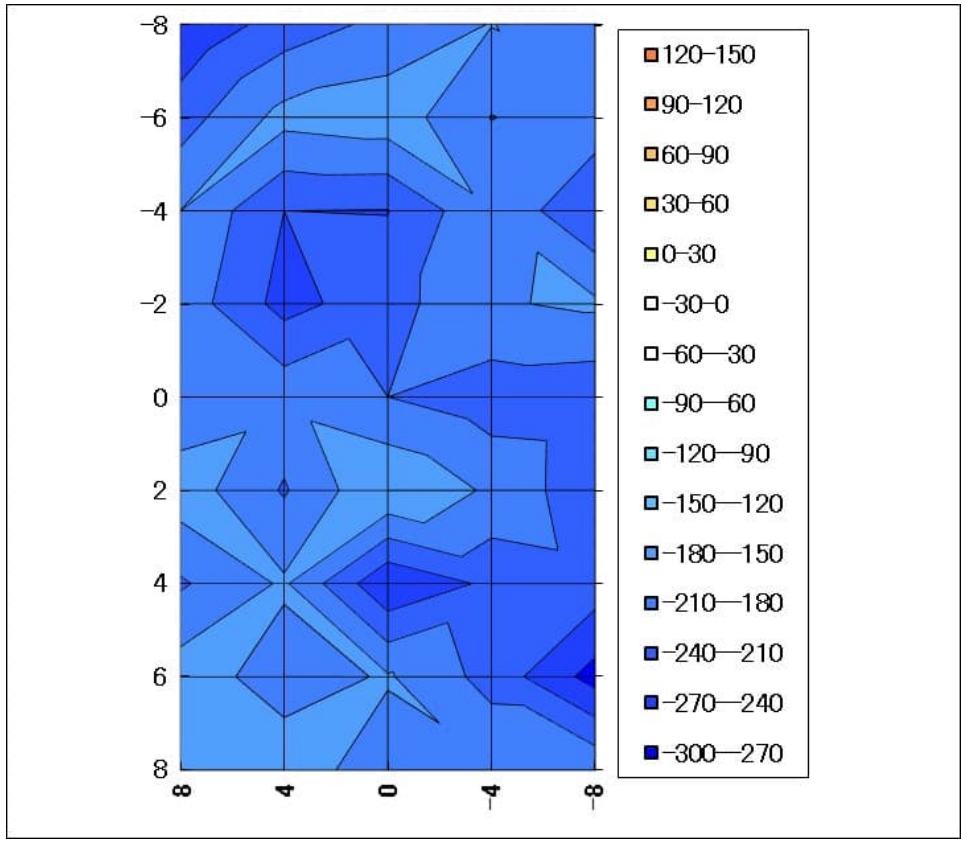
Variogram avg: 0.08mm



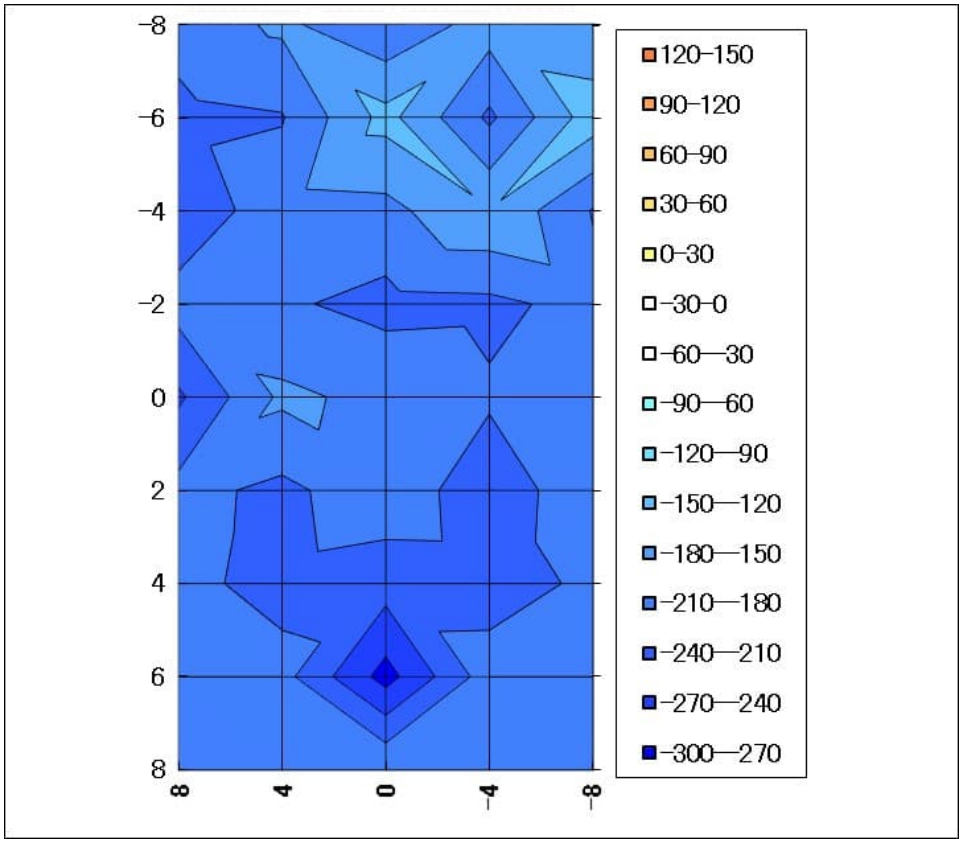
WCB Testing Results – By Cause

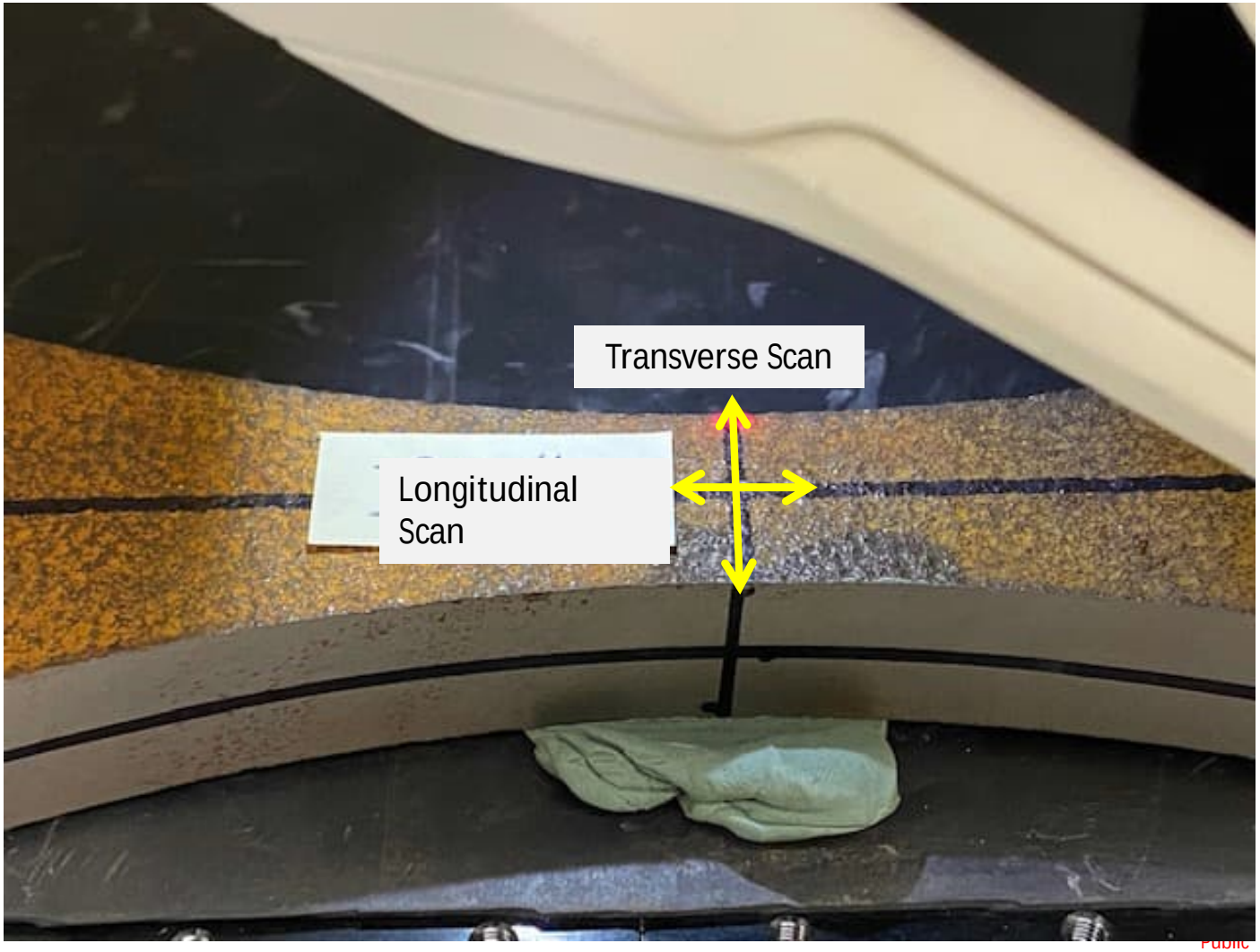


Sample “G1” Front
Min: -282 MPa
Max: -151 MPa



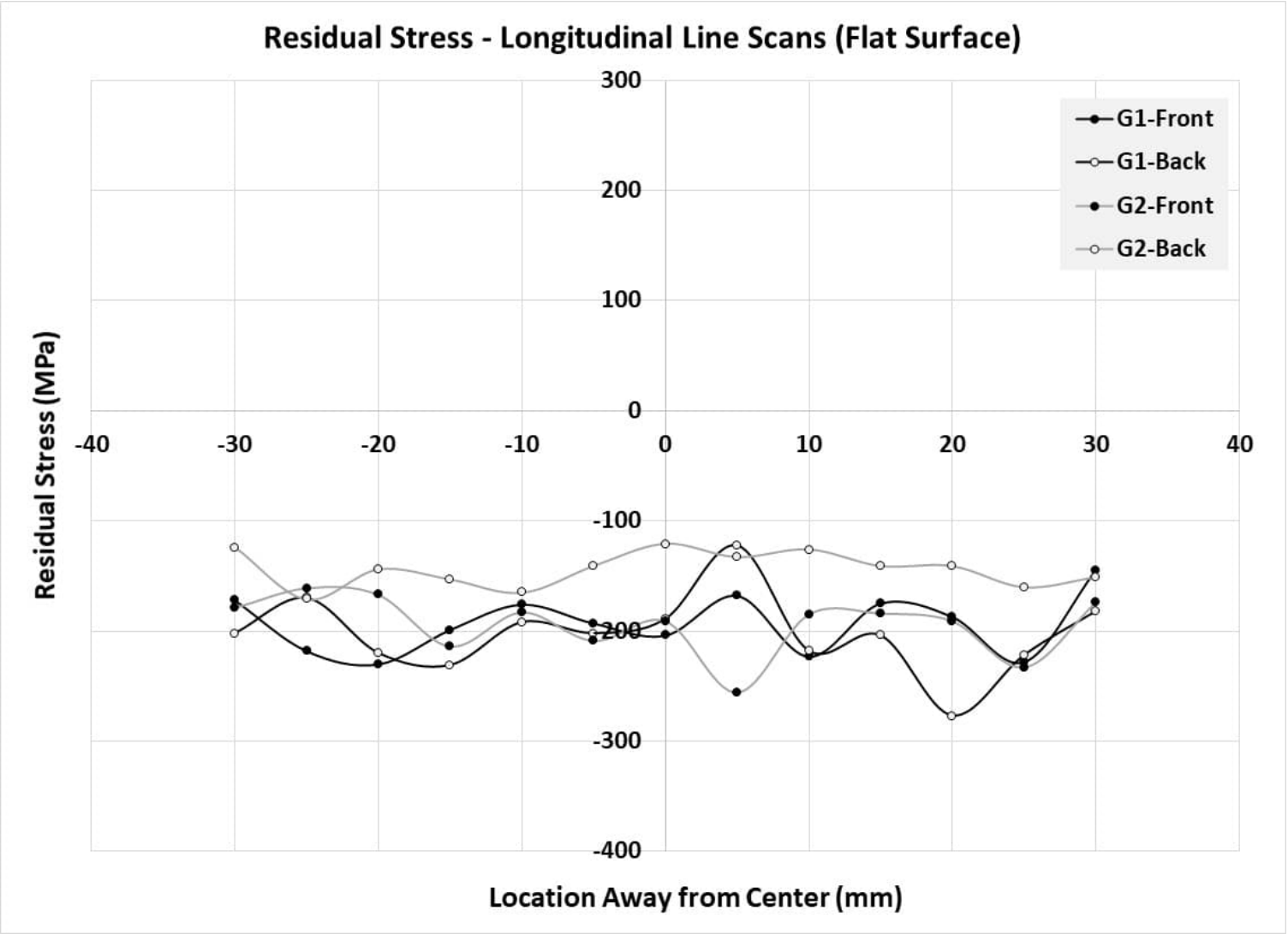
Sample “G1” Back
Min: -282 MPa
Max: -134 MPa





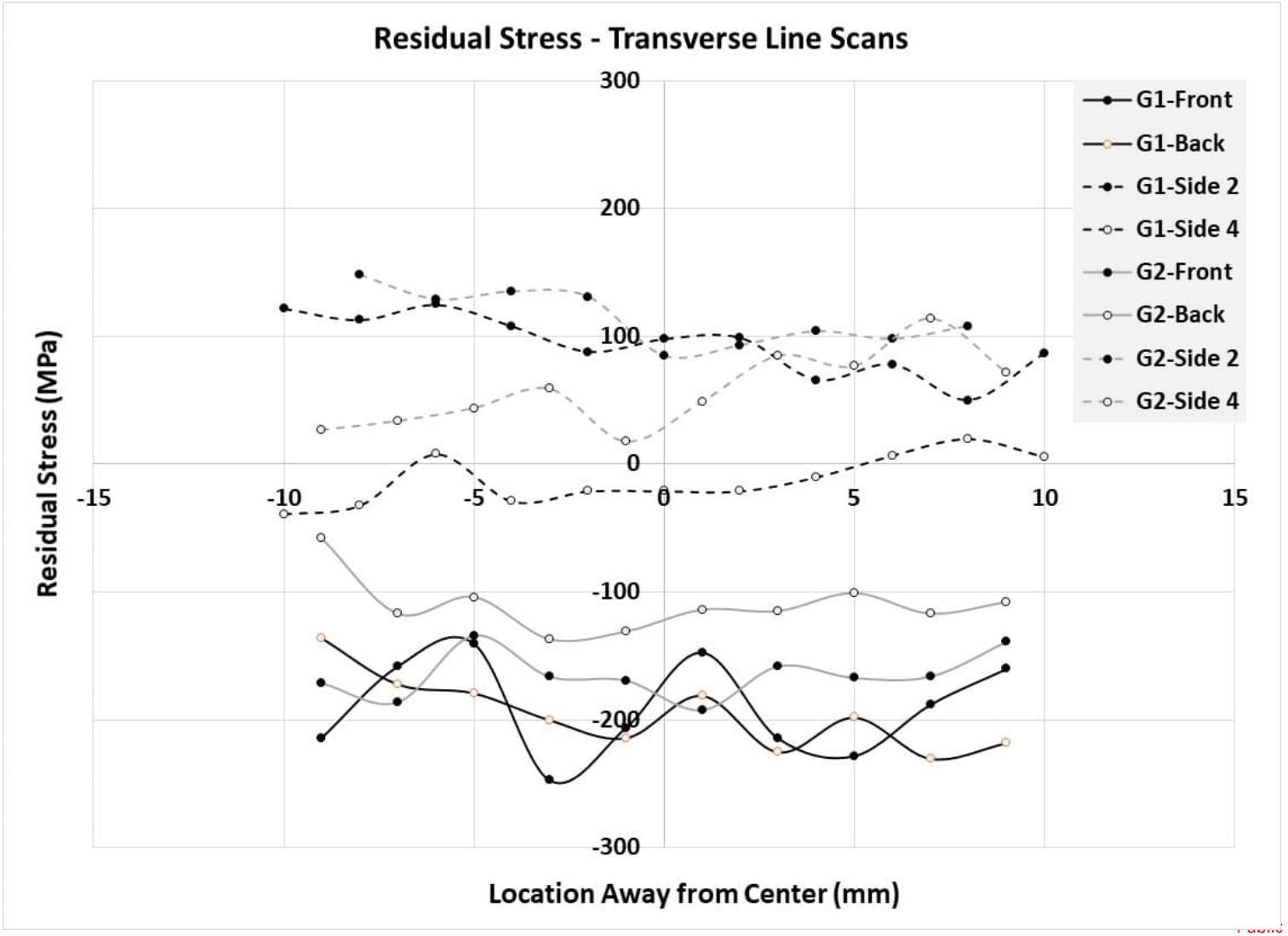
Longitudinal lines scans, which were only possible on the flat as-cast surfaces

As-cast surfaces exhibited a lower (more compressive) residual stress. This is likely due to abrasive blast cleaning.



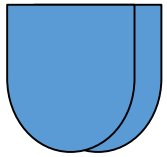
Transverse lines scans, which were possible on <u>all</u> sides

Machined surfaces exhibited a higher (more tensile) residual stress



Moving Forward

- "Now exposed" center line shrinkage is dominating results
- Conduct testing of WCB specimens with EDM notches in gage length.



- Plate for 8630 plate with improved riser design

8630 Plates –

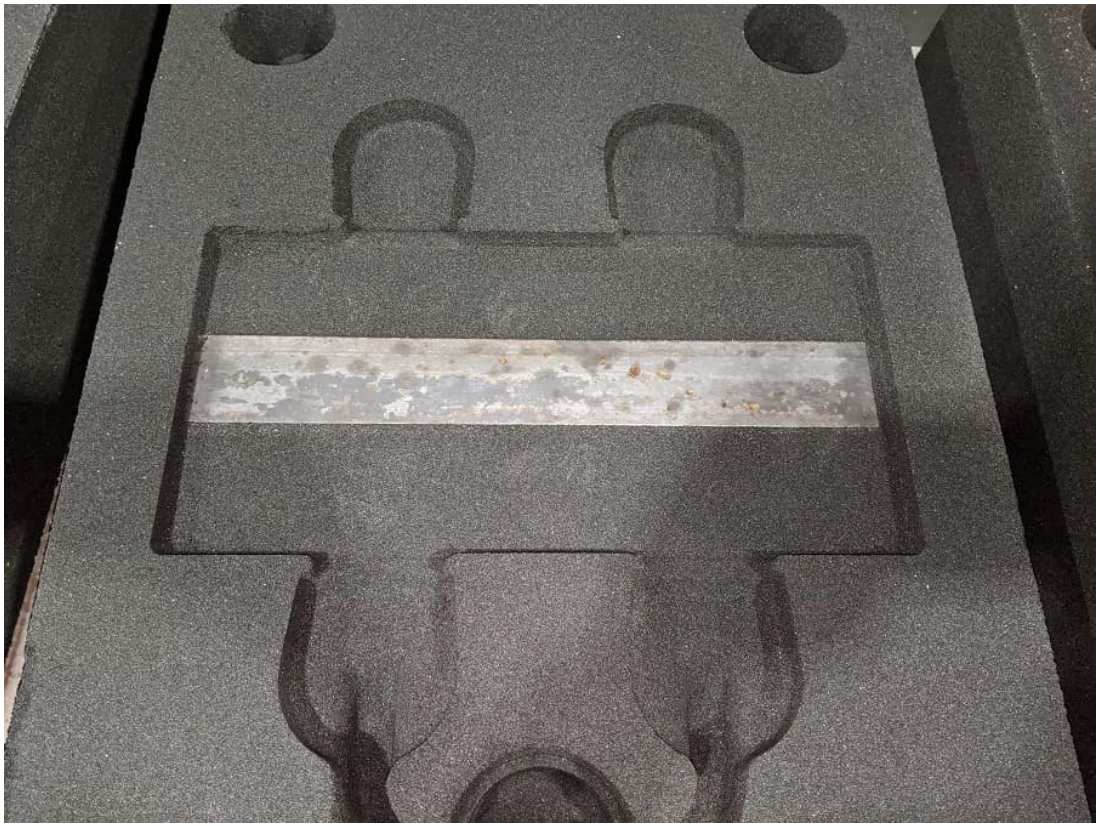


Plate #
114

Plate #
114
A B

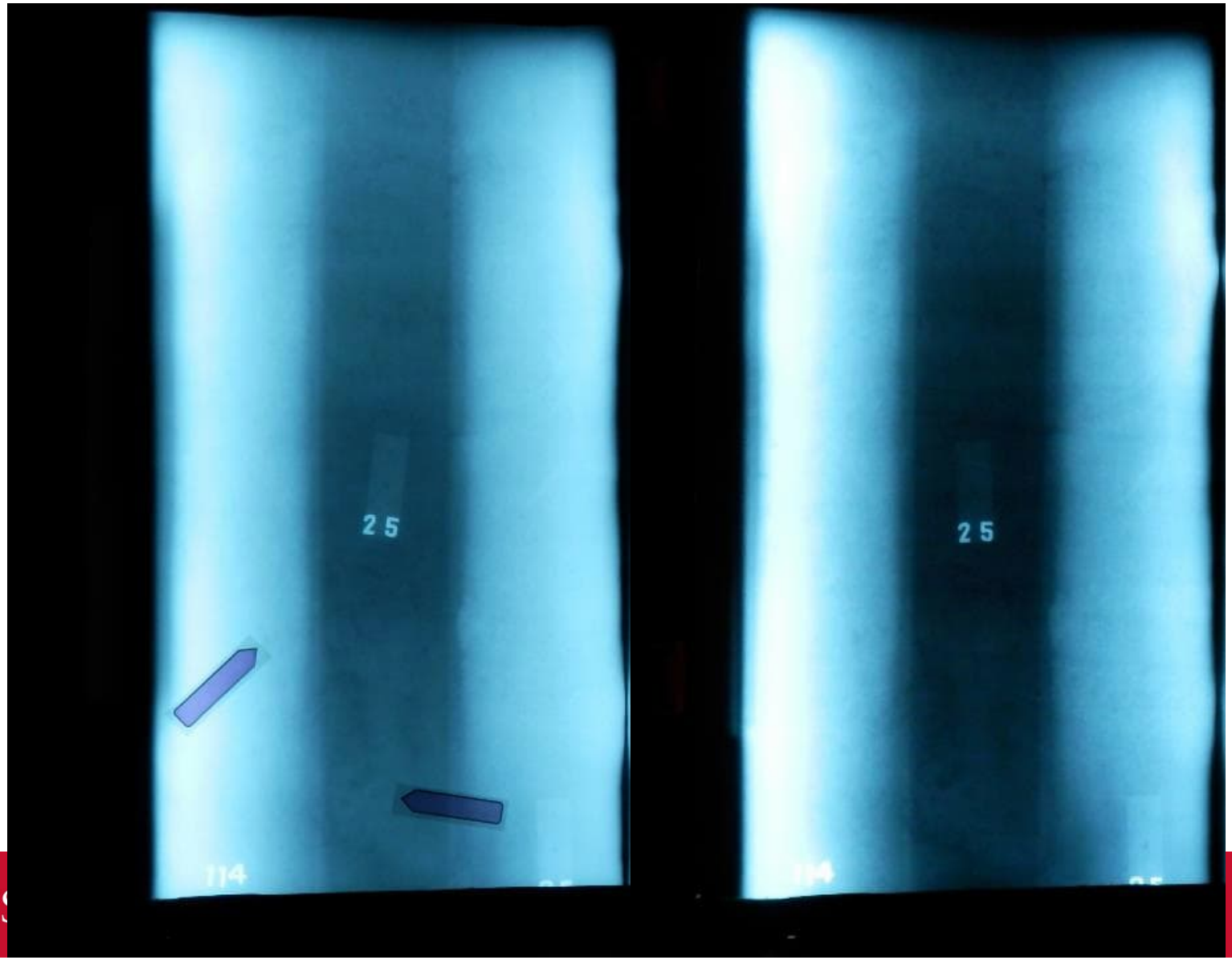
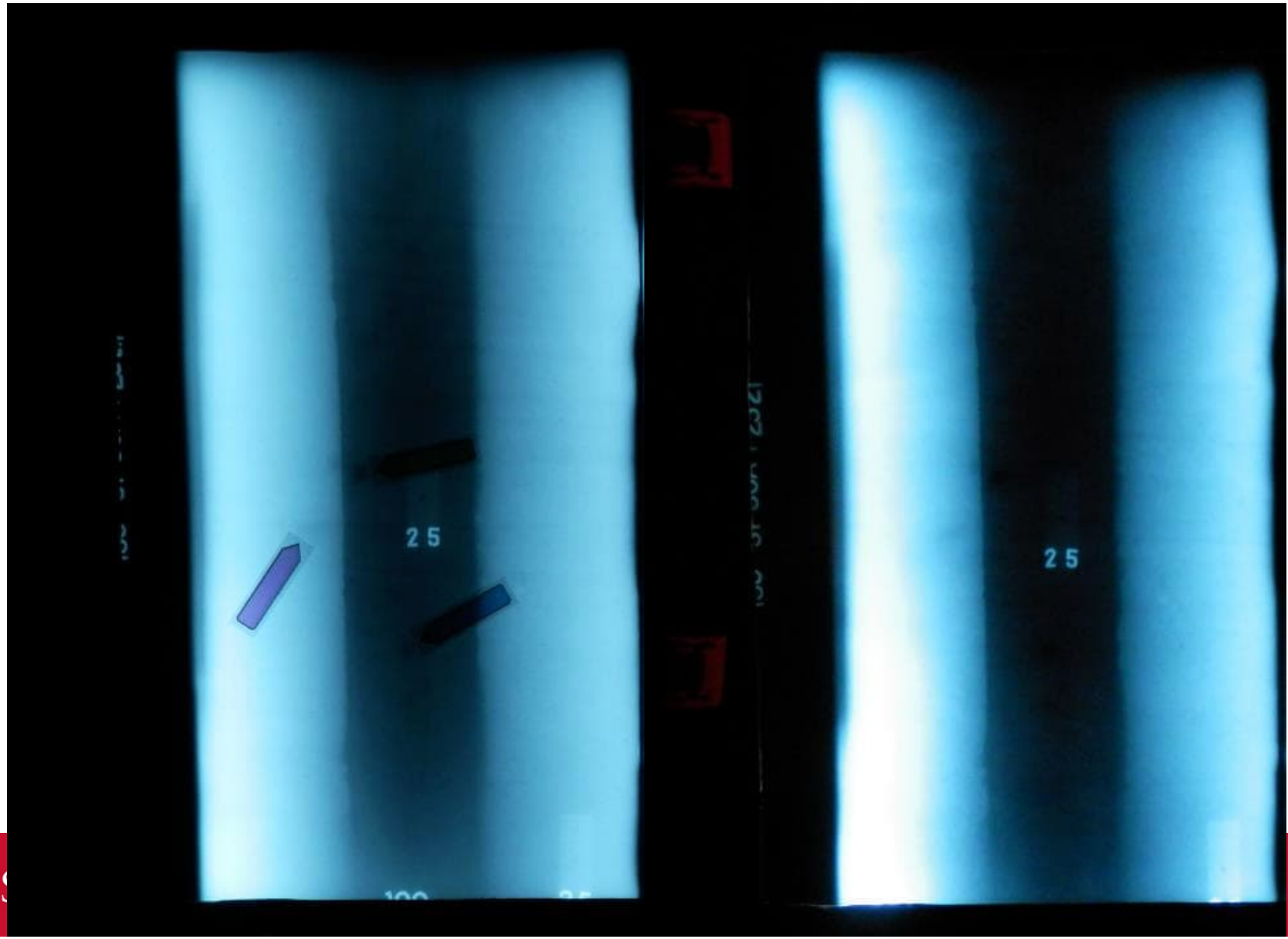
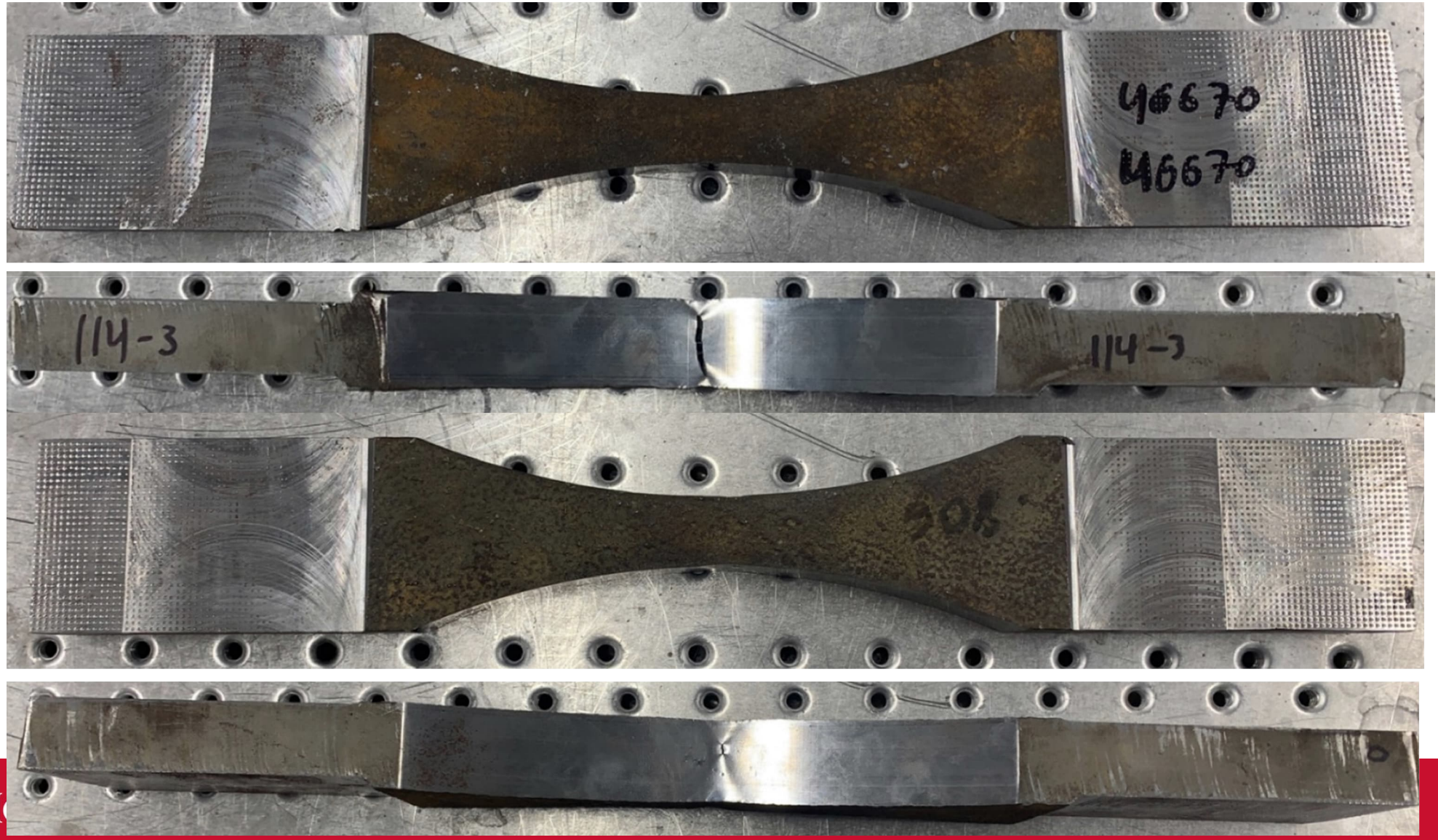


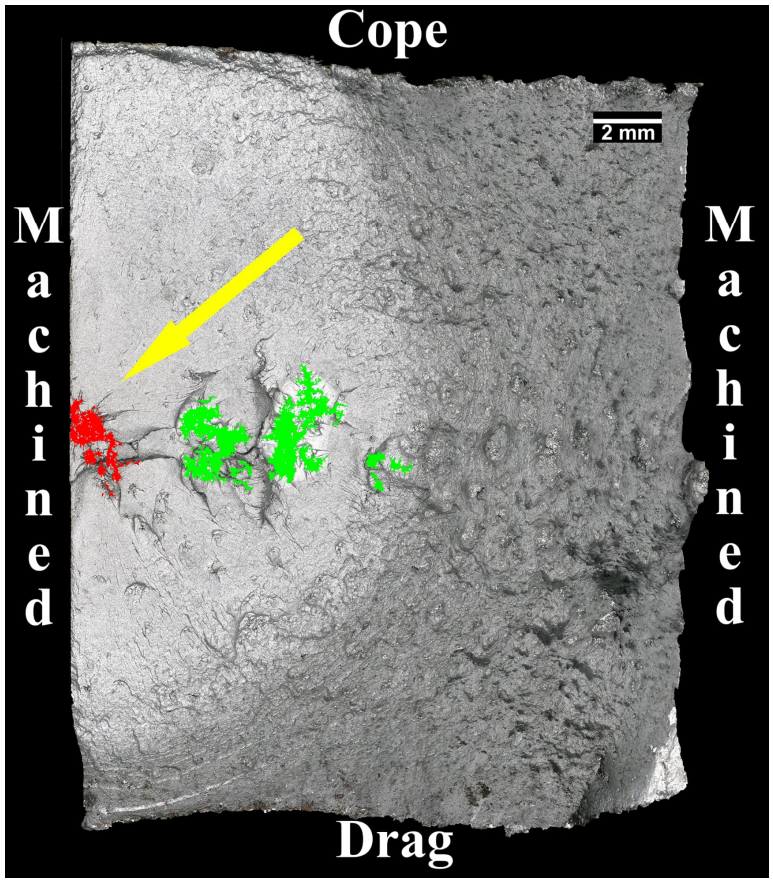
Plate #
100

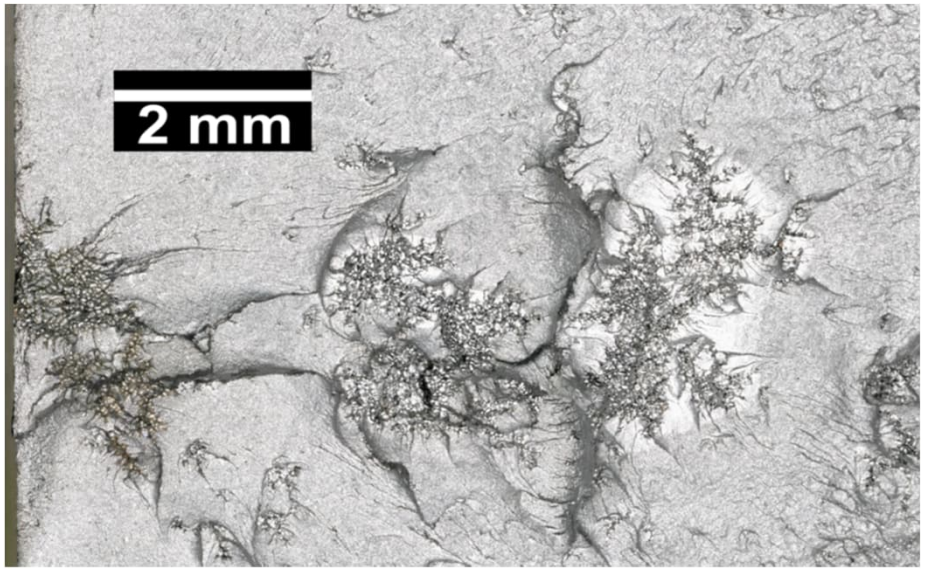
Plate #
100
A B




46670
46670
114-3
114-3

Set 5 Specimen 100-1

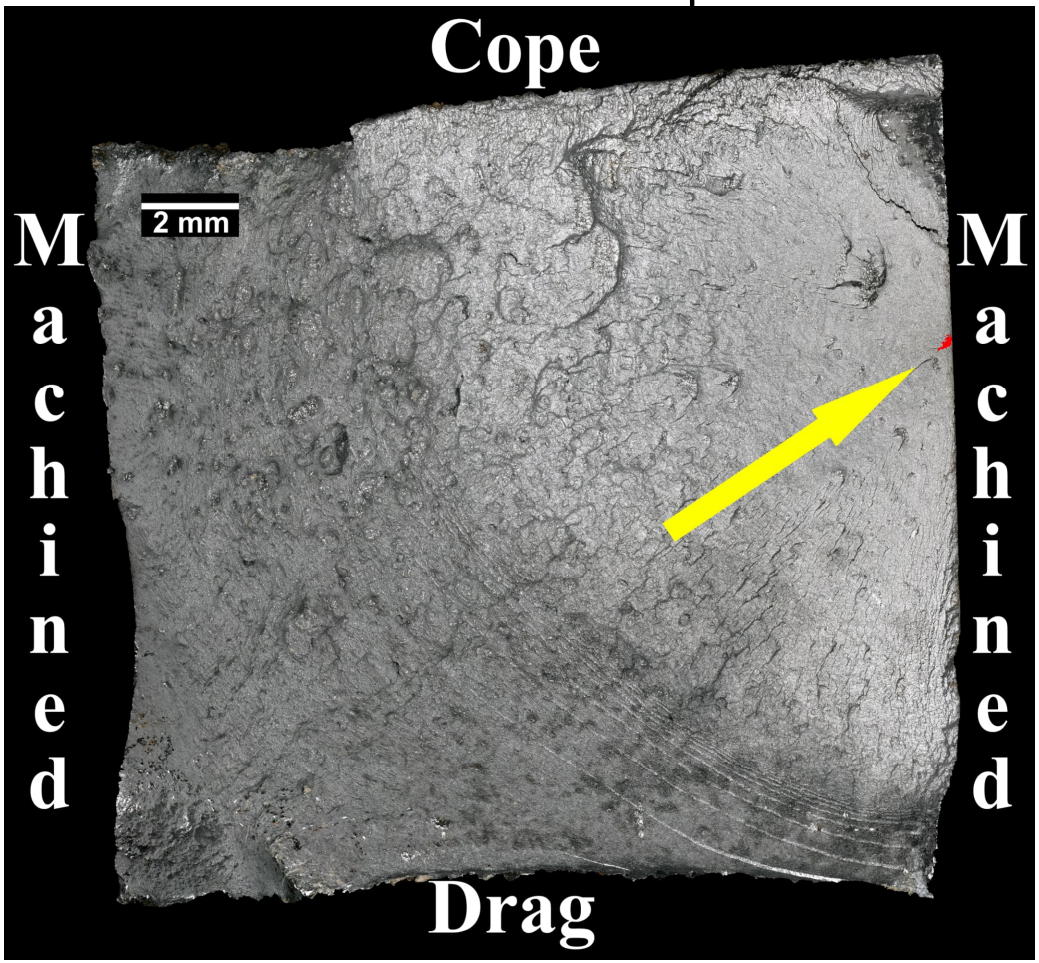


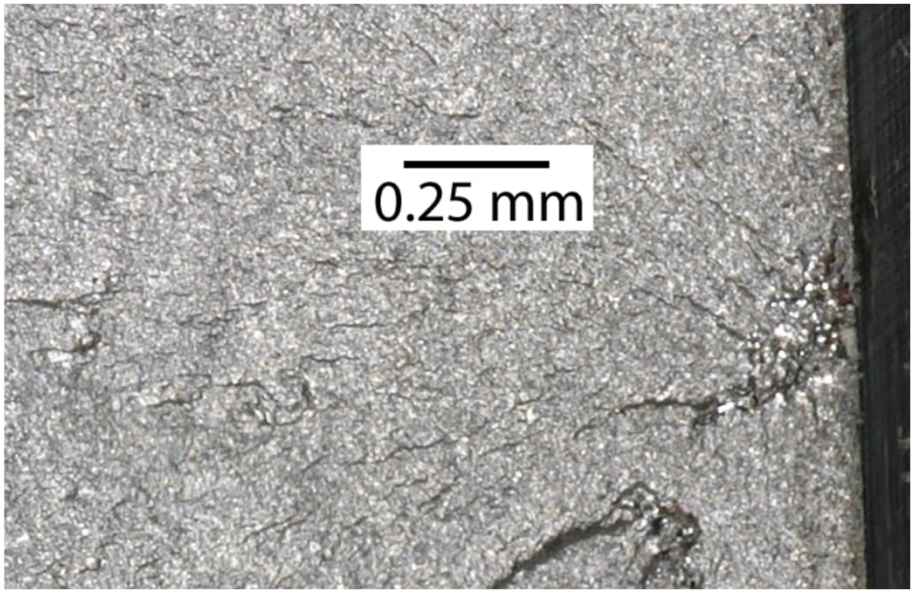


Zoom of Initiation Site

Yellow arrow points to initiation site
Red area is porosity at initiation site
Green area is porosity at secondary cracks

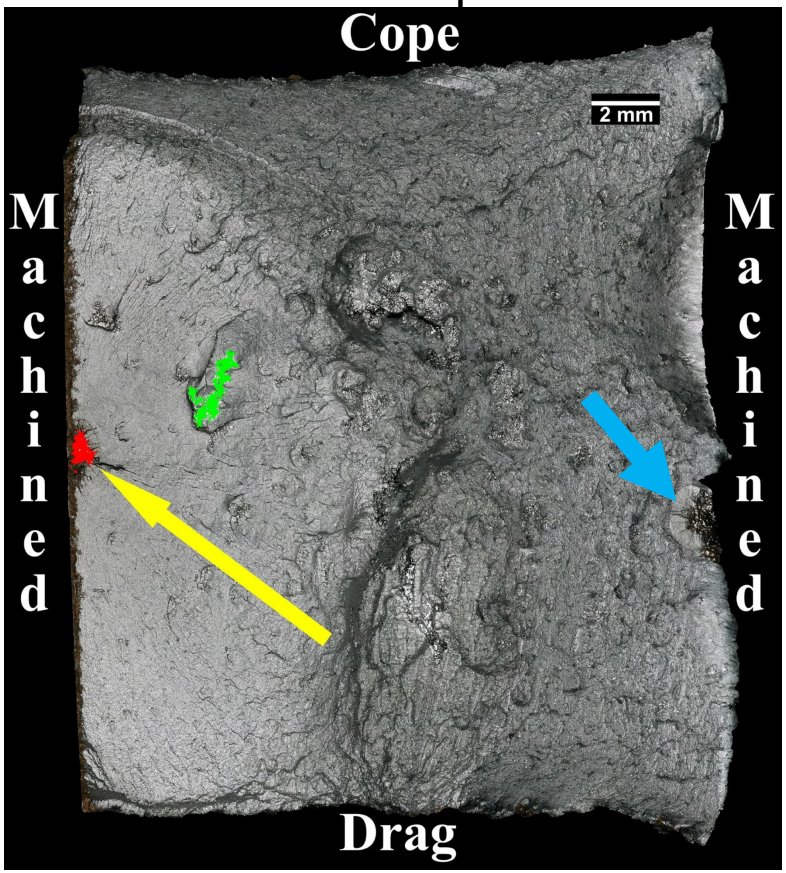
Set 5 Specimen 100-2 MIDDLE BAR



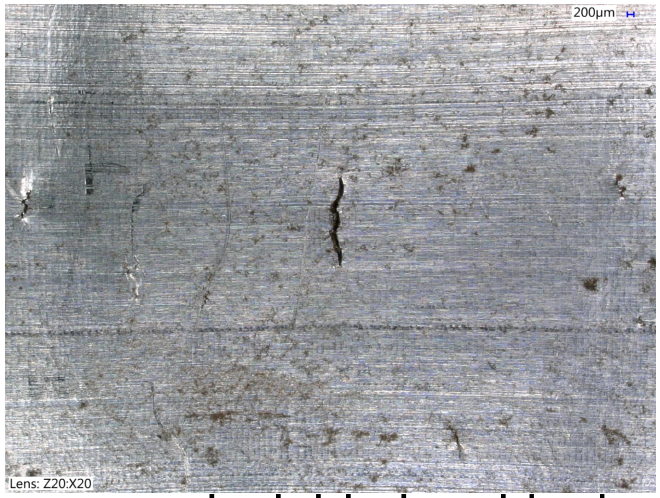


Yellow arrow points to initiation site
Red area is porosity at initiation site

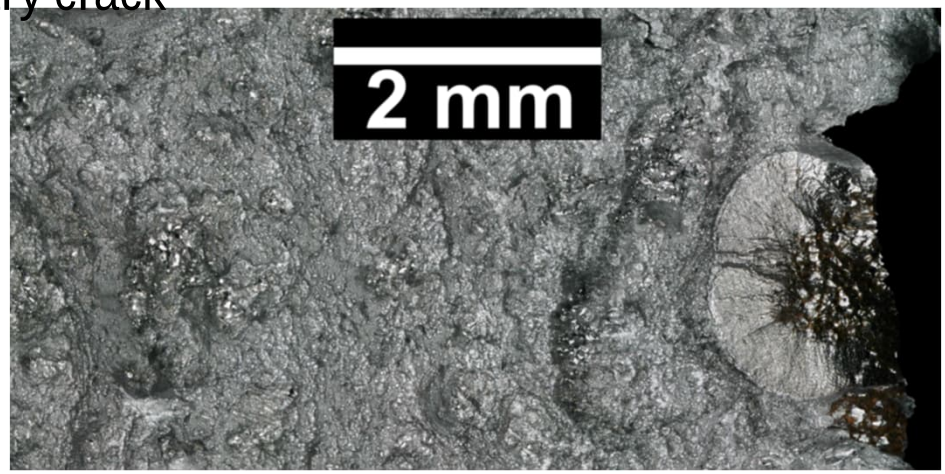
Set 5 Specimen 100-3



Blue arrow points to opened up secondary crack on machined surface opposite initiation side.

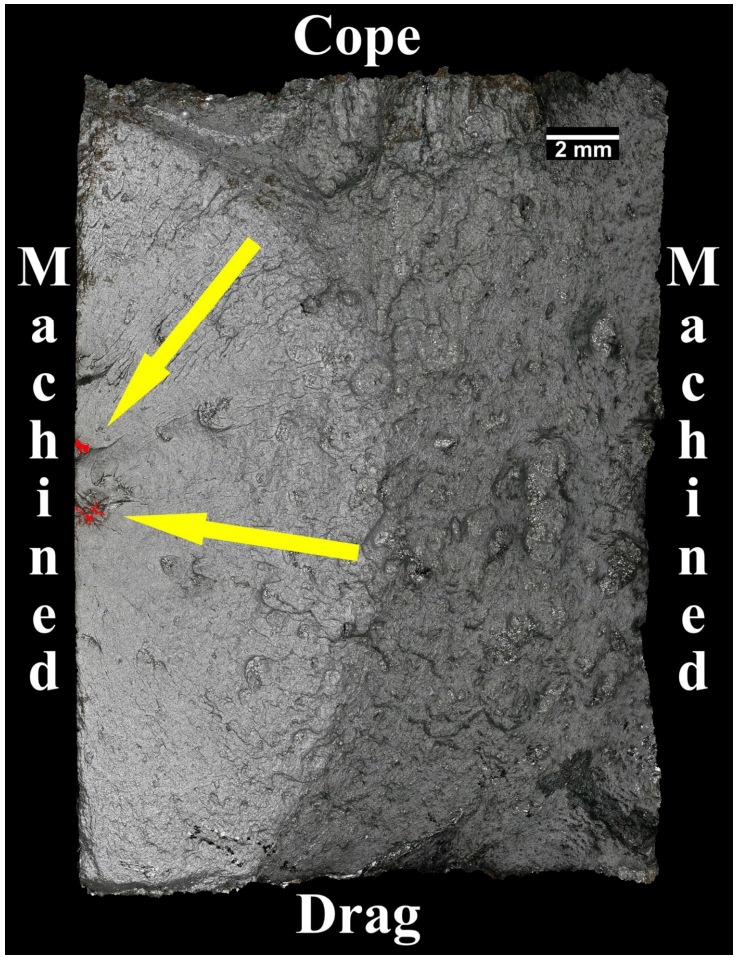


Machined surface opposite initiation side showing secondary crack

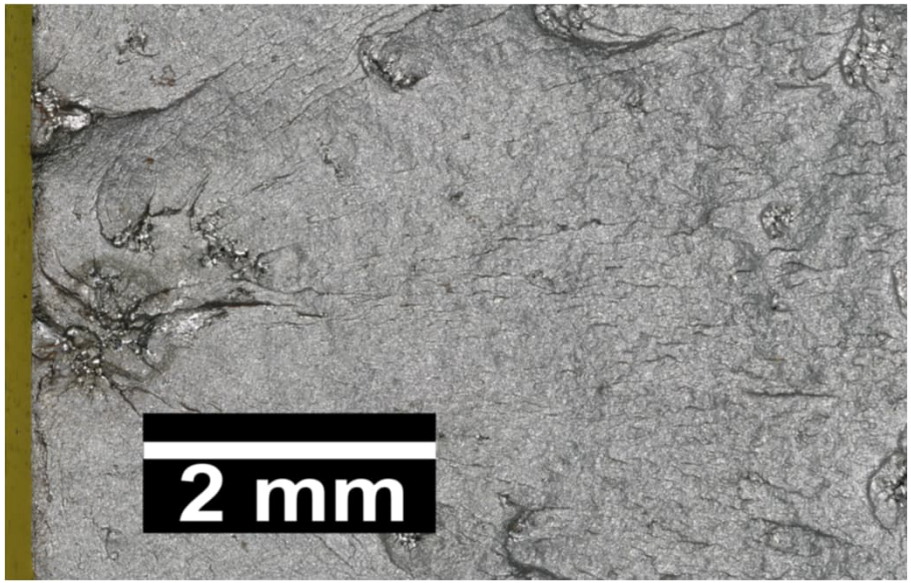


Zoom of opened-up secondary crack.

Set 5 Specimen 114-1

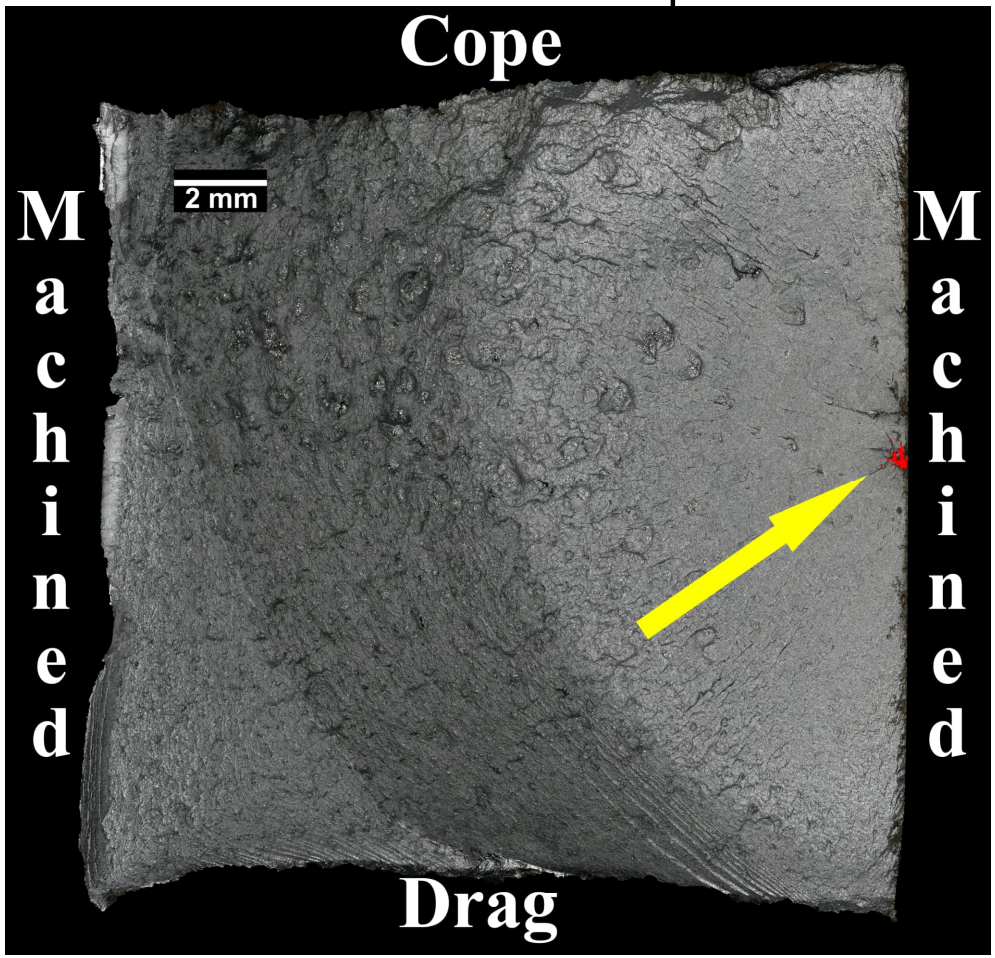


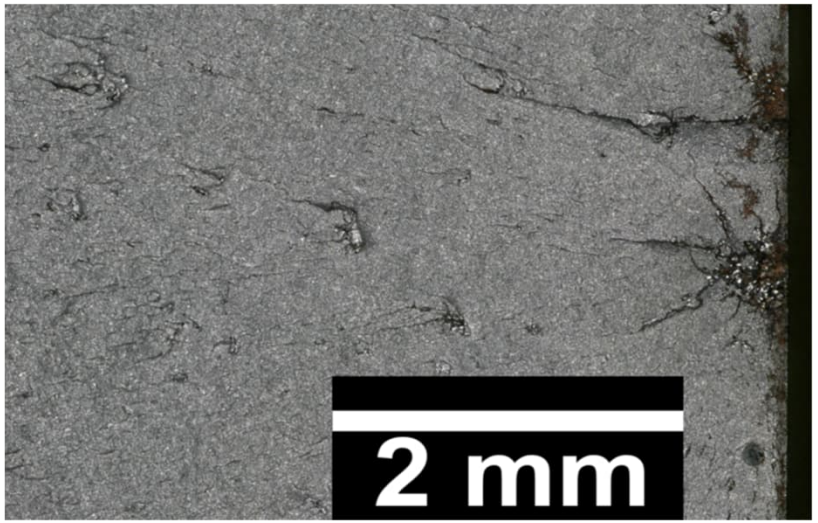
Yellow arrow points to initiation site
Red area is porosity at initiation site



Zoom of initiation site

Set 5 Specimen 114-2 MIDDLE BAR

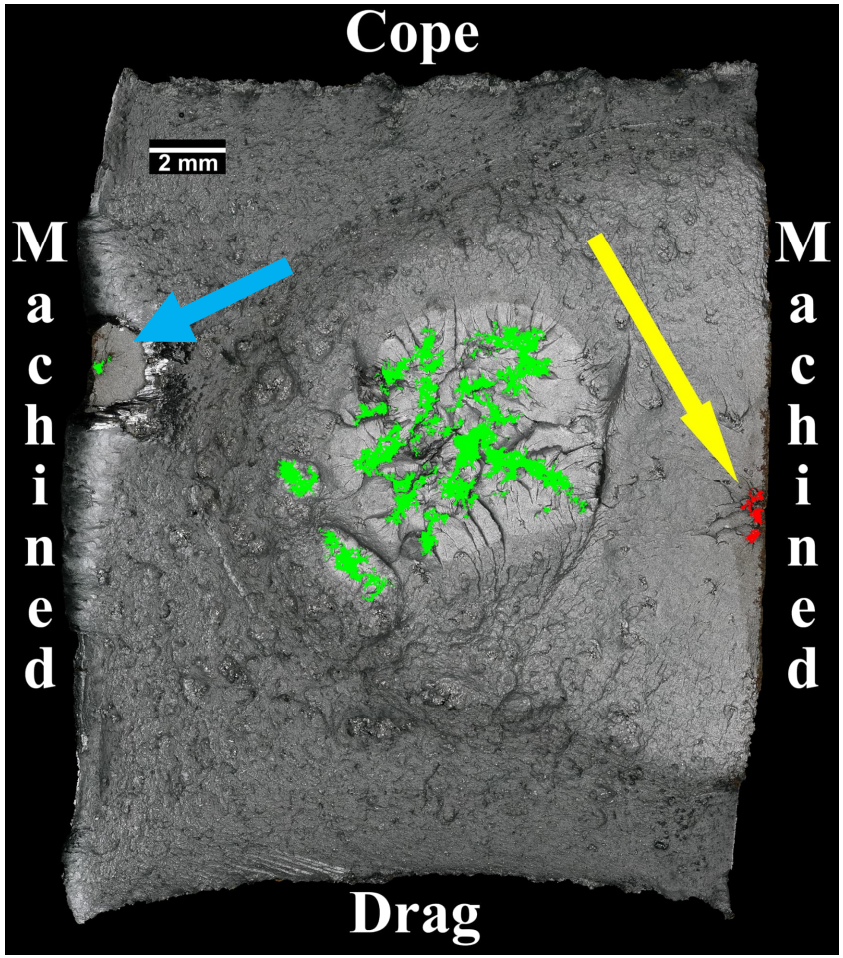




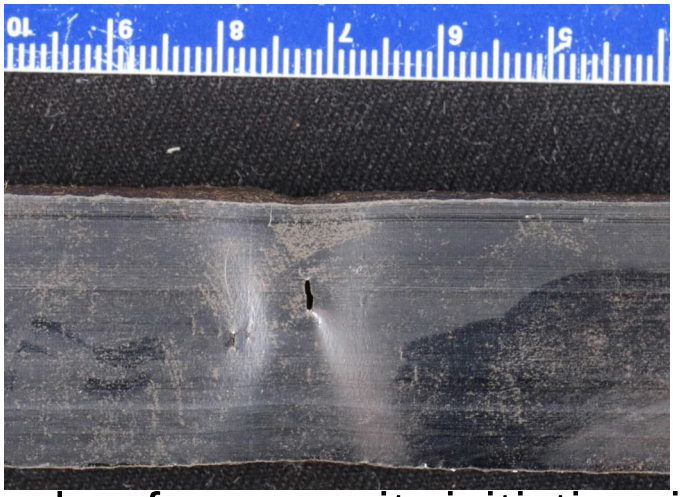
Yellow arrow points to initiation site

Red area is porosity at initiation site

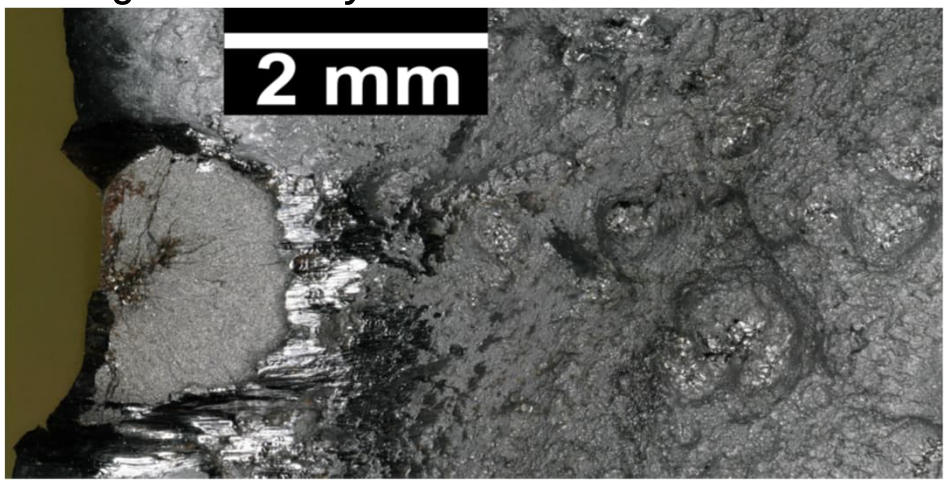
Set 5 Specimen 114-3



Blue arrow points to opened up secondary crack on machined surface opposite initiation side.



Machined surface opposite initiation side showing secondary crack



Zoom of opened-up secondary crack.

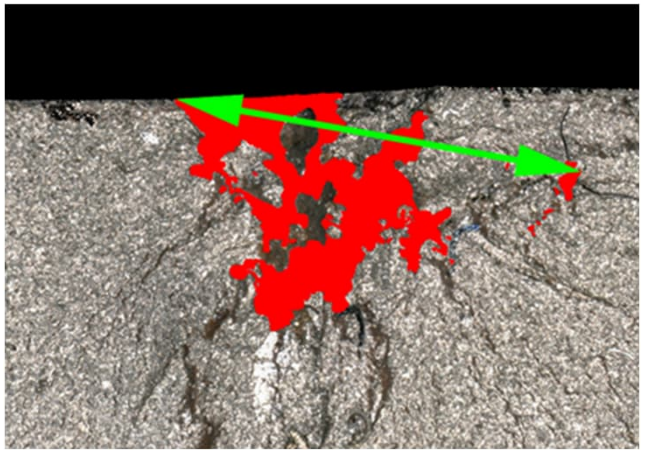
Measurements – Initiation Site

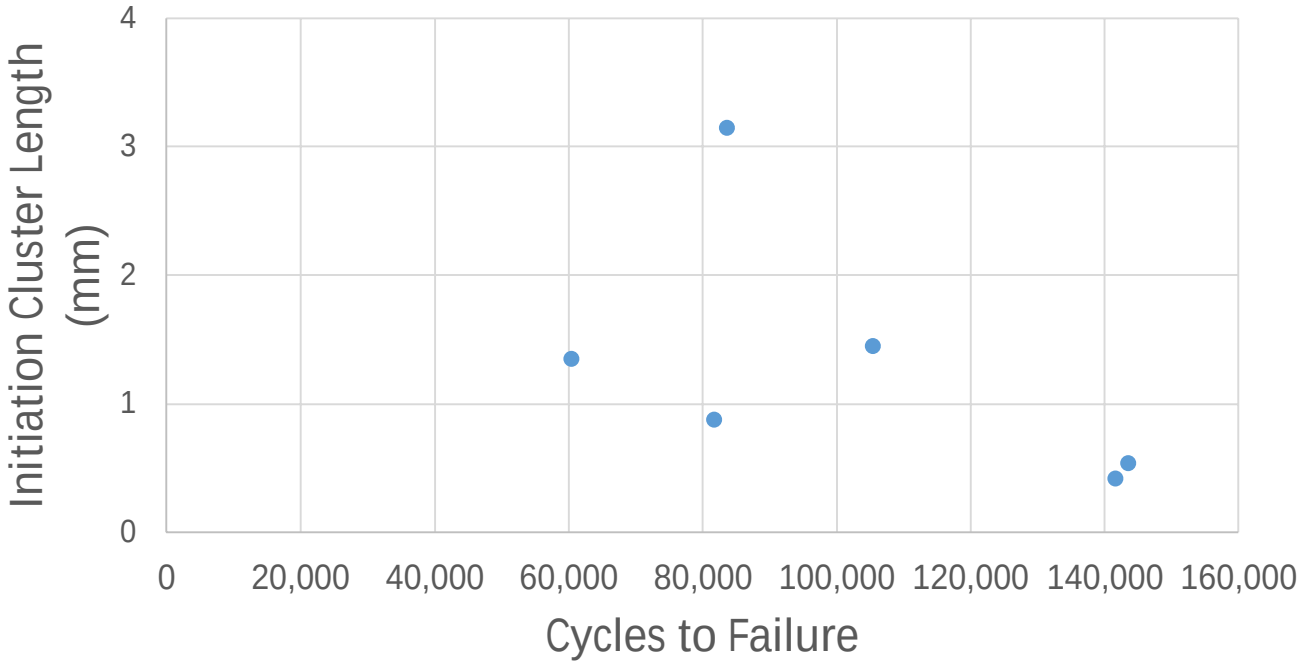
	Max Distance into Sample, mm	Initiation Area, mm^2	Initiation Cluster Size, mm	Cycles to Failure
100-1	2.09	1.46	3.15	83,594
100-2	0.31	0.04	0.42	141,655
100-3	0.88	0.44	1.35	60,446
114-1	0.86	0.10	0.88	81,734
114-2	0.46	0.09	0.54	143,511
114-3	0.67	0.27	1.45	105,374

Measurements Initiation and Secondary Cracks

Sample	Initiation Site	Secondary Crack 1		Secondary Crack 2		Secondary Crack 3		Total Crack Pore Area, Includes Initiation Site
	Initiation Area, mm^2	Initiation Area, mm^2	Initiation Cluster Size, mm	Initiation Area, mm^2	Initiation Cluster Size, mm	Initiation Area, mm^2	Initiation Cluster Size, mm	
100-1	1.46	2.33	3.02	2.64	3.56	0.38	1.37	6.82
100-2	0.04							0.04
100-3	0.44	2.48	0.90					2.92
114-1*	0.17							0.17
114-2	0.09							0.09
114-3	0.27	7.84	6.82	0.51	1.35	0.79	2.51	9.41

Cycles to Failure by Cluster Length

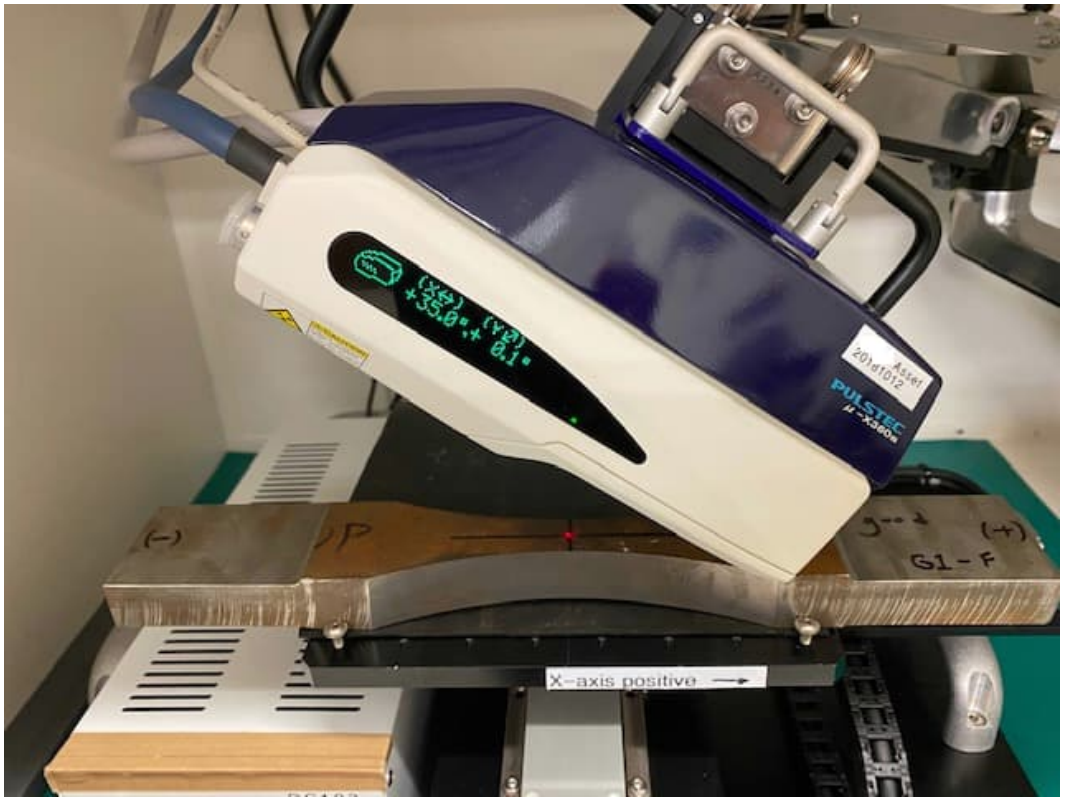




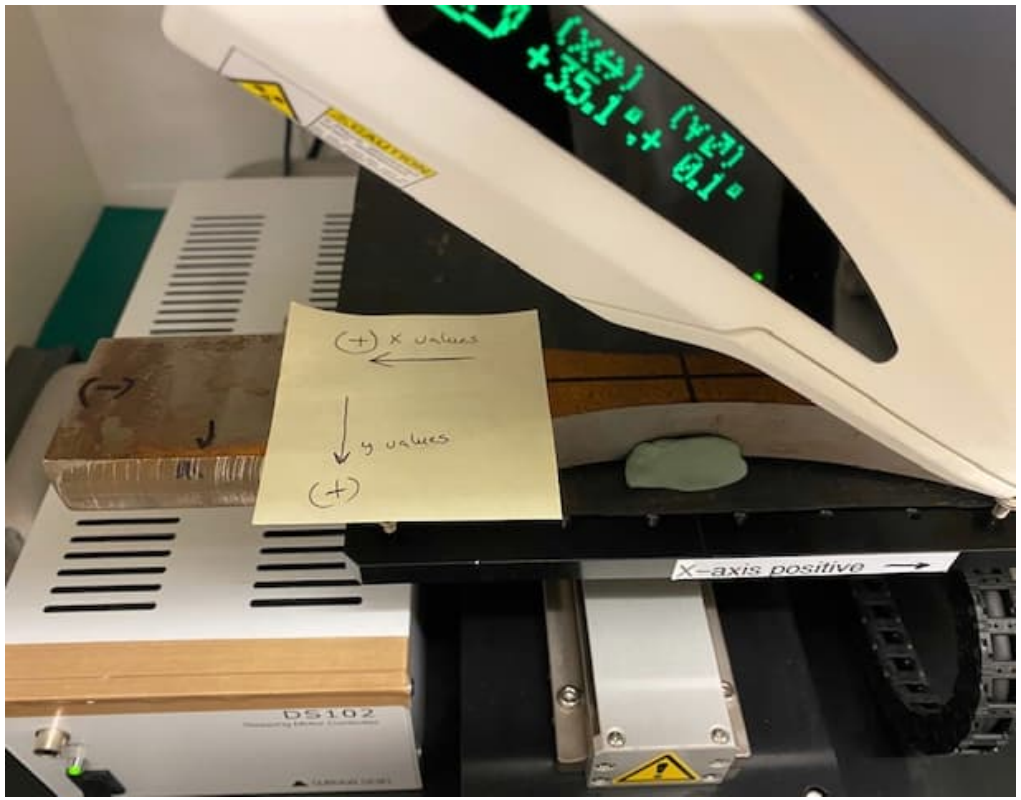
Rick Lopez
John Deere
Oct 2021

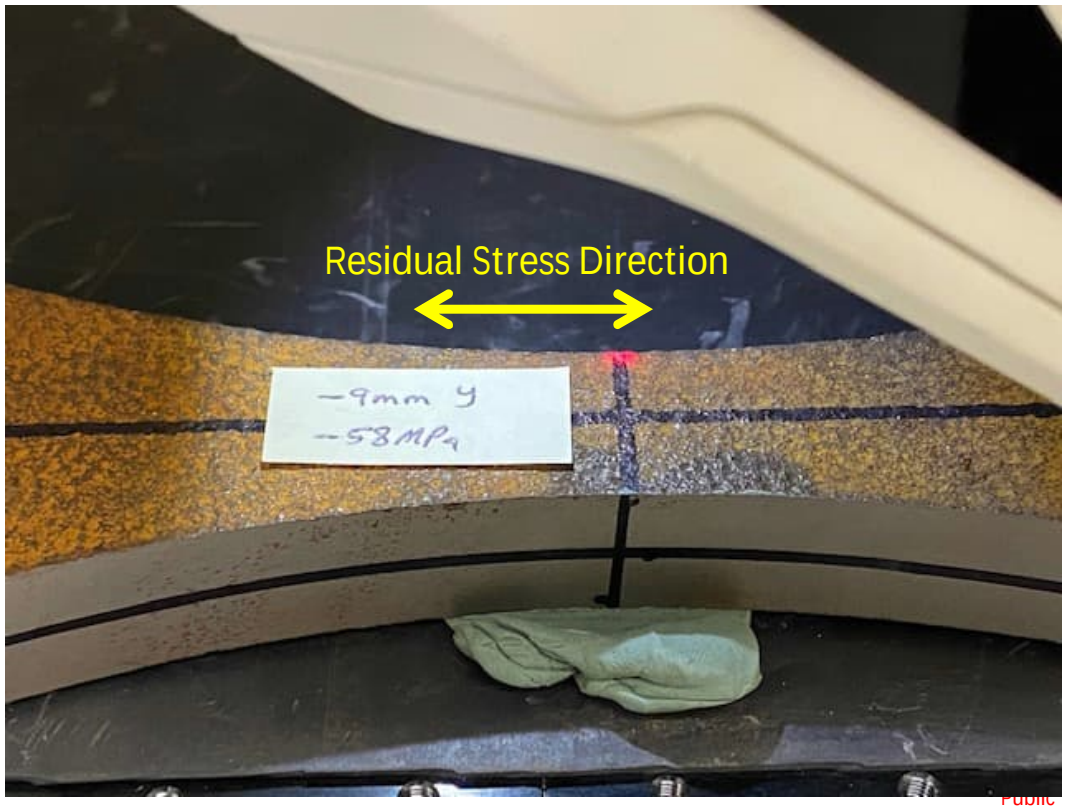
Pulstec µ-360s x-ray diffractometer (chromium tube)
Cosine α approach with area detector*
Sample surface is held horizontal so that incident angle of x-ray beam is controlled
X-Y positioning table is used to collect area scans or line scans

* Most XRD equipment instead uses $\sin^2$ theta approach

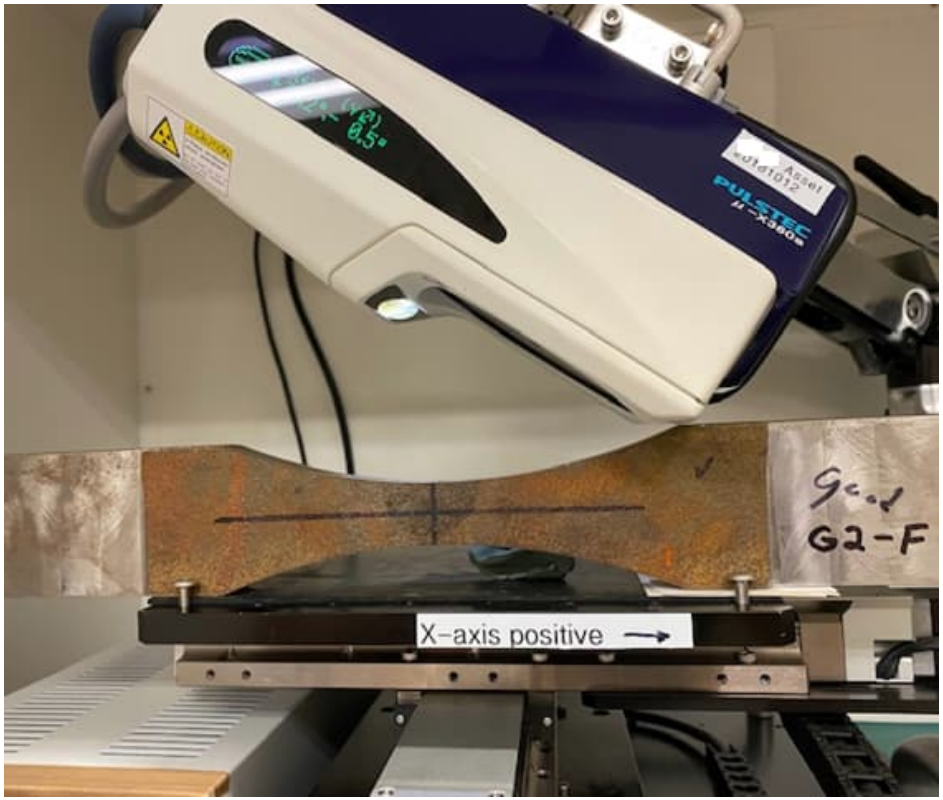


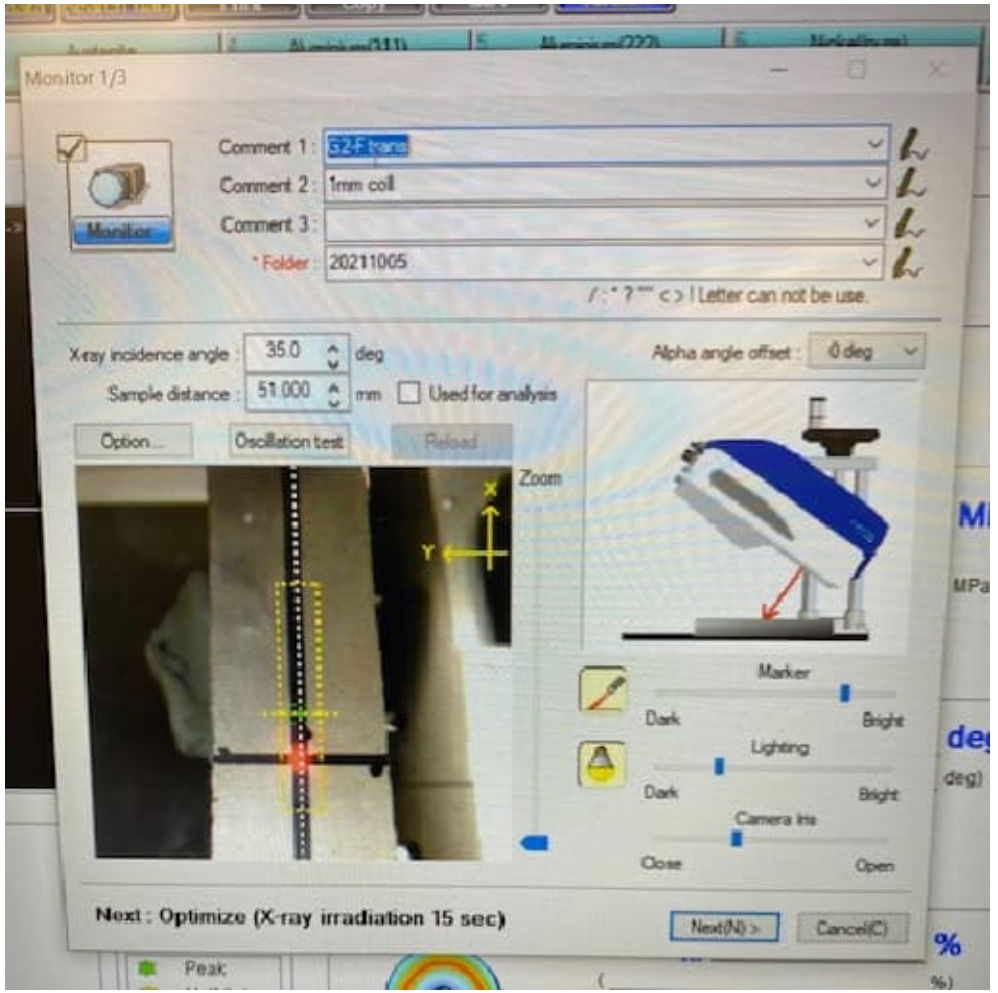
Location polarity within area and line scans is indicated below (left)
Example of typical value at a location is highlighted by laser dot (right)
Stress direction for all measurements was along the tensile testing longitudinal direction



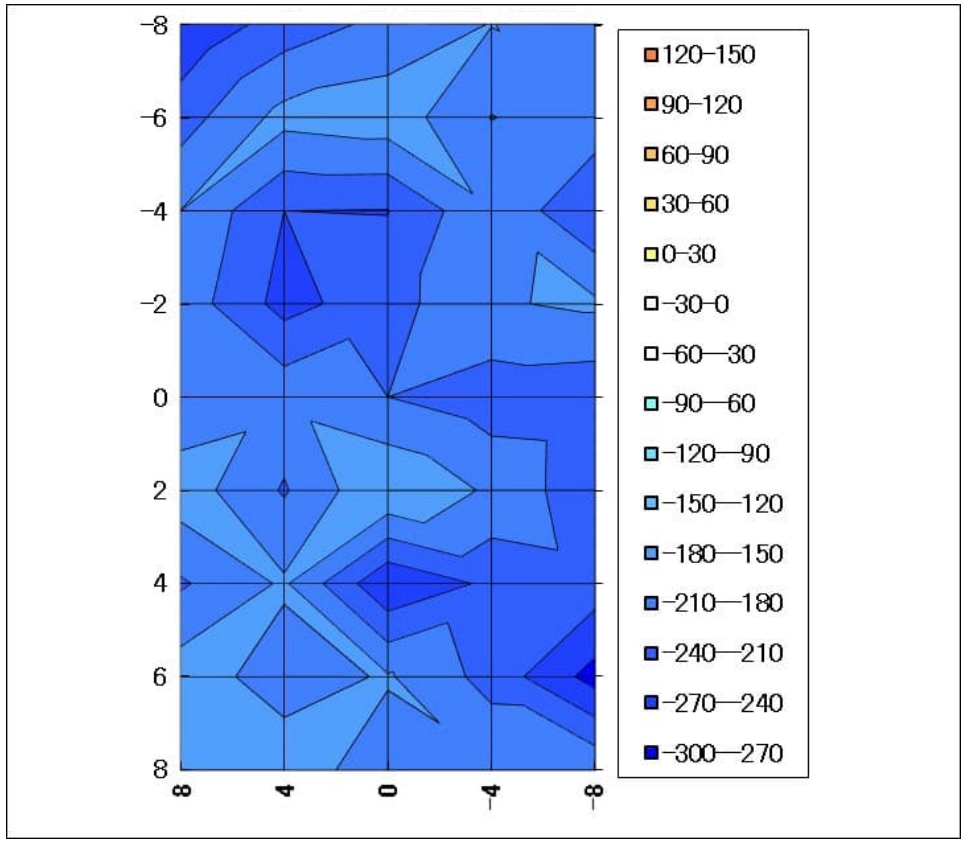


The measurement head was as close as possible to the sample for side locations
This caused sample distance to be slightly longer than preferred, but still allowable for valid data





Sample “G1” Front
Min: -282 MPa
Max: -151 MPa



Sample “G1” Back
Min: -282 MPa
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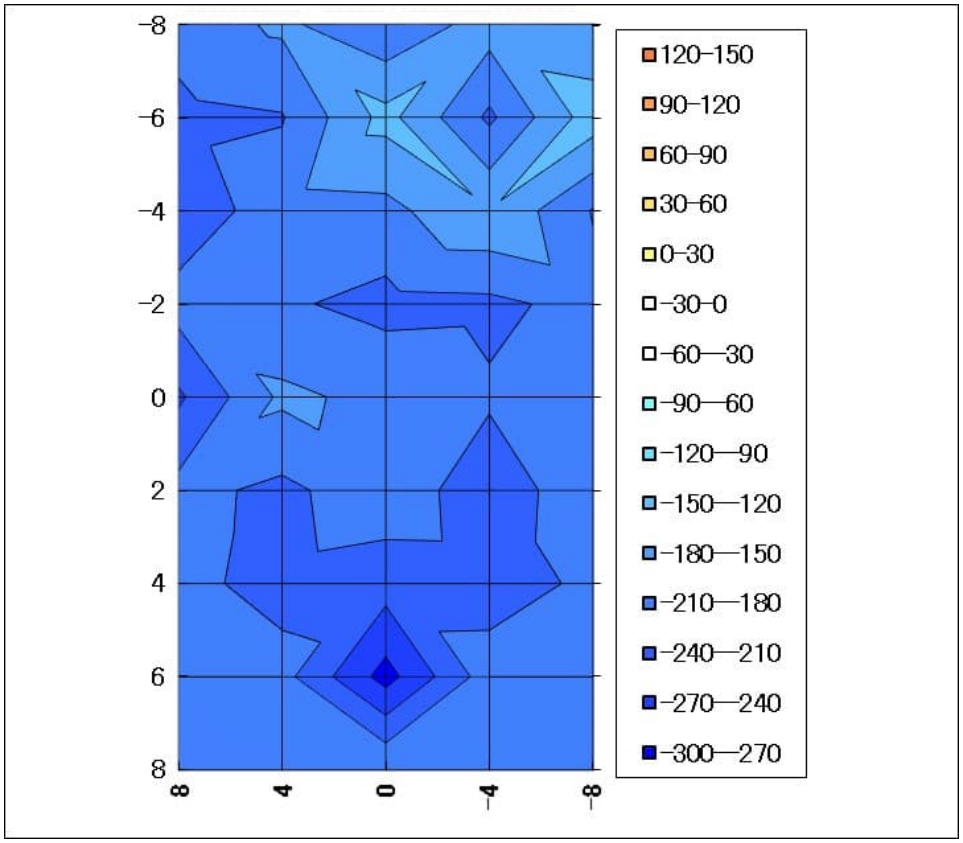
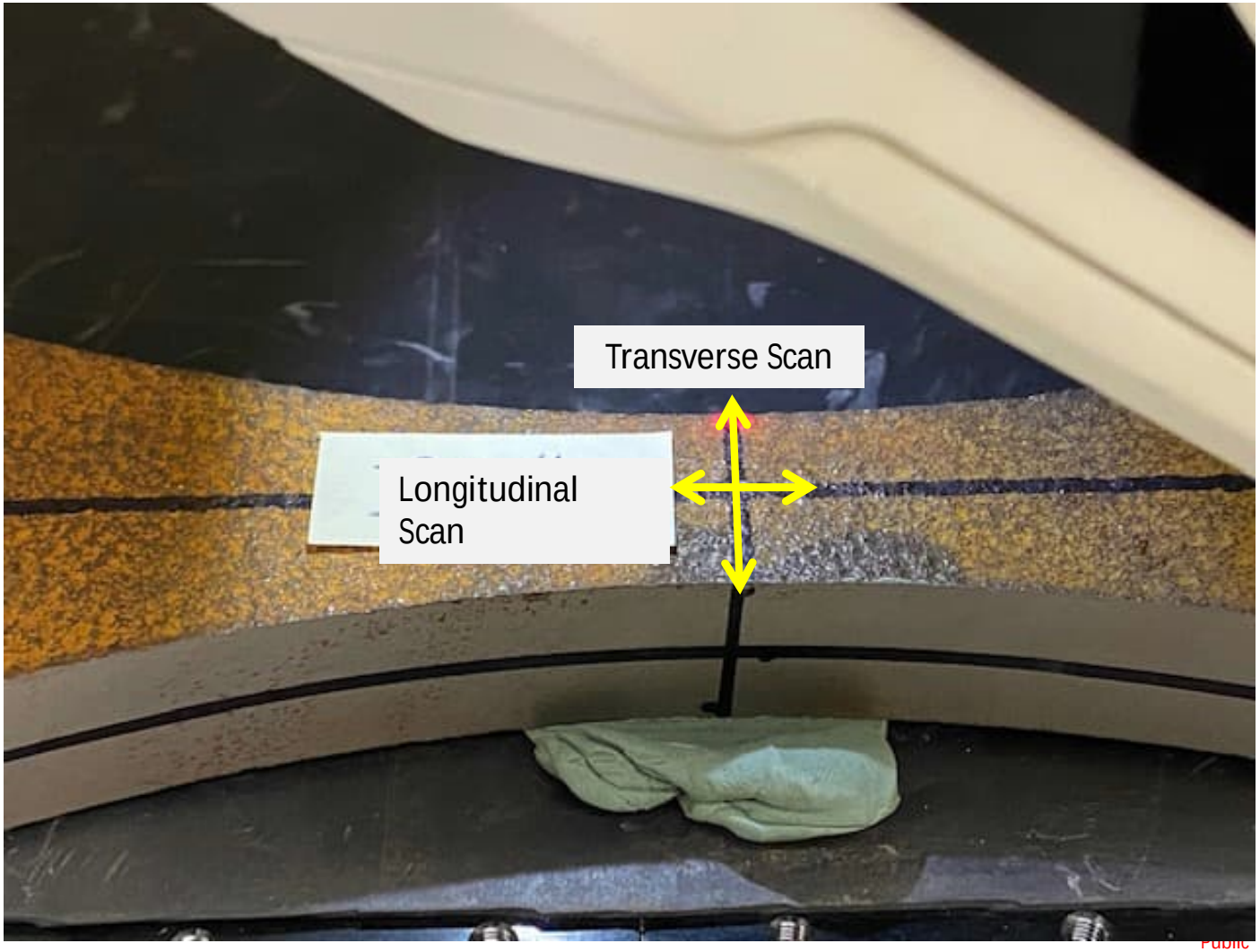
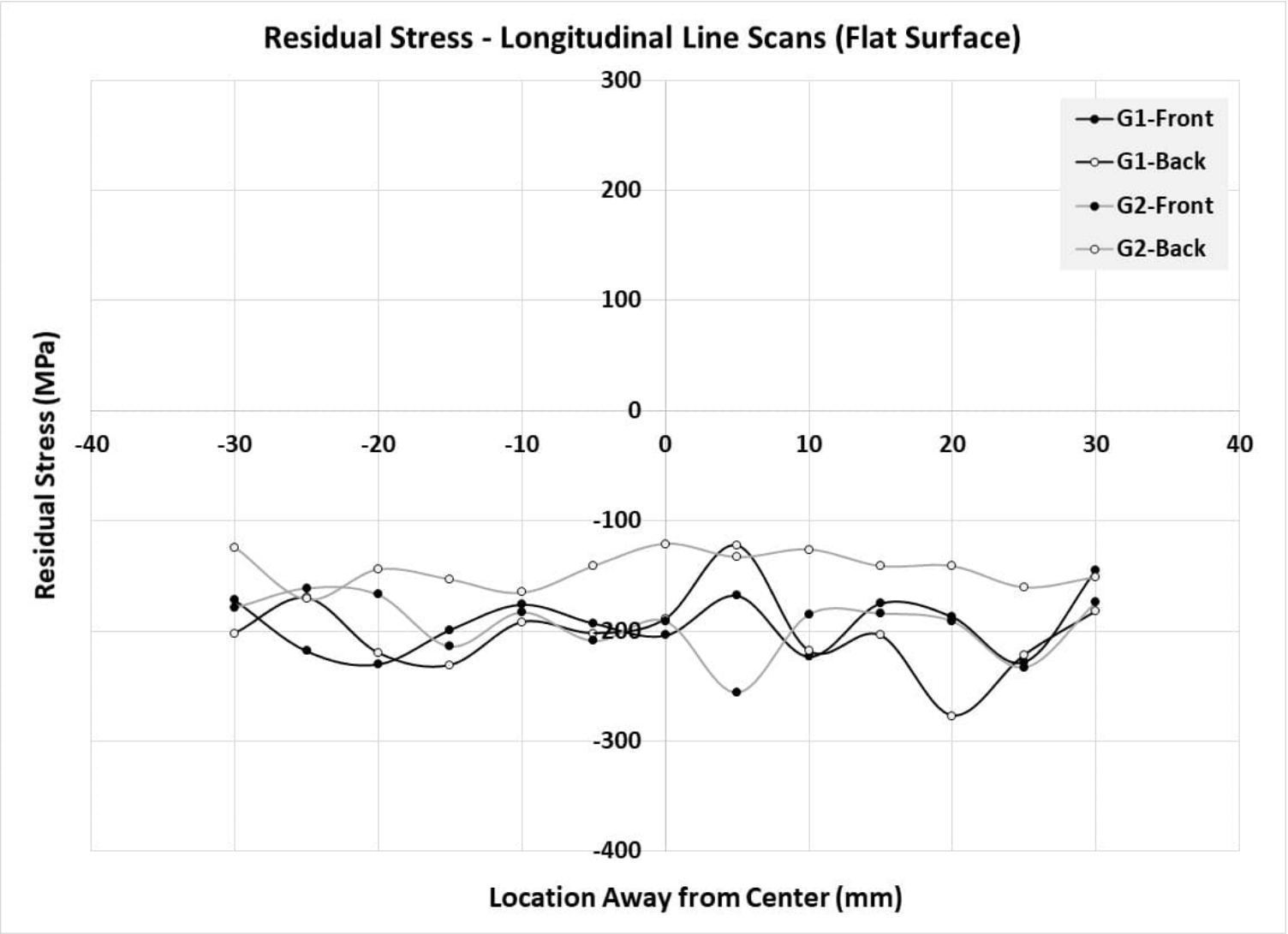




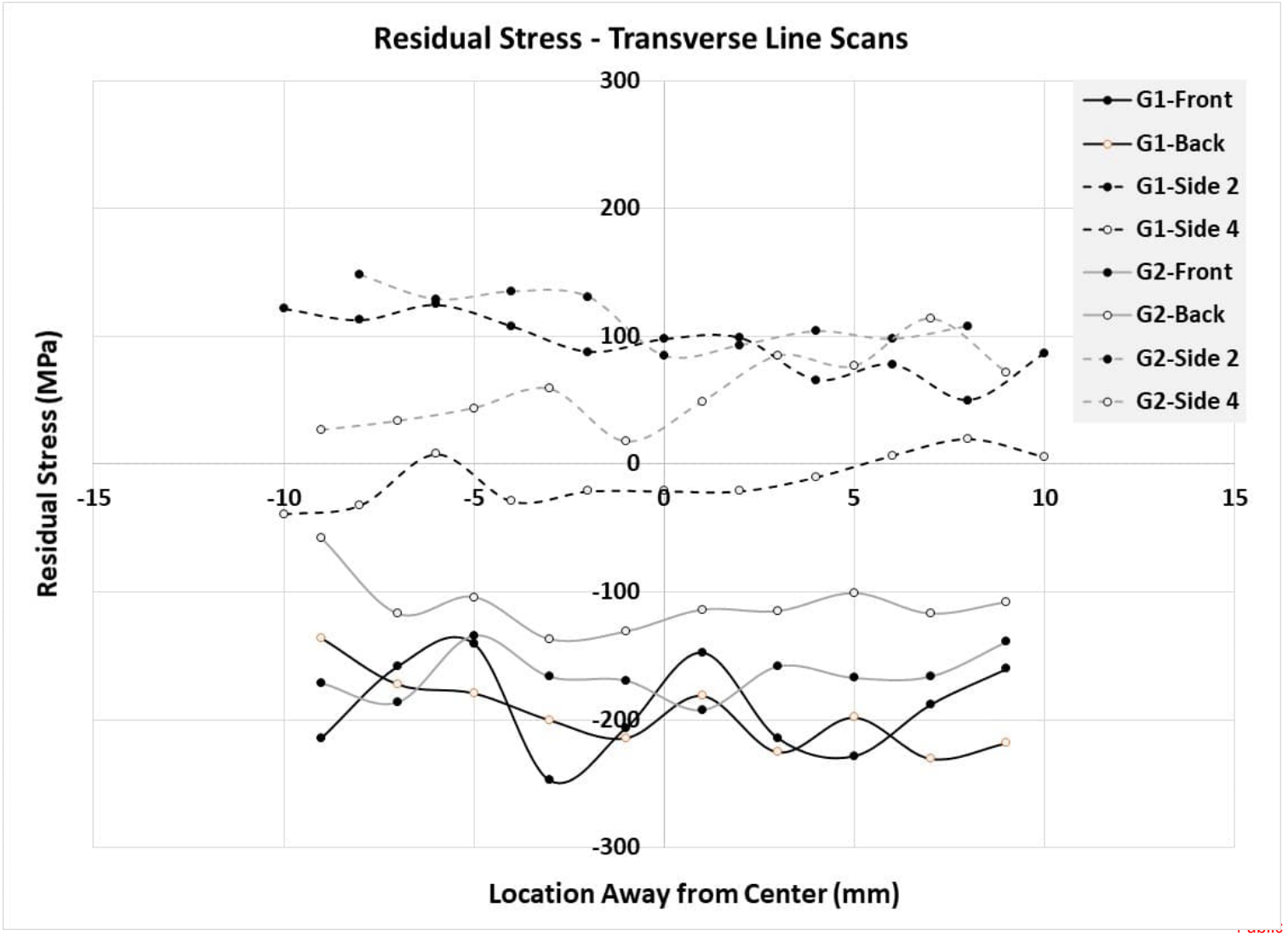
Longitudinal lines scans, which were only possible on the flat as-cast surfaces

As-cast surfaces exhibited a lower (more compressive) residual stress. This is likely due to abrasive blast cleaning.

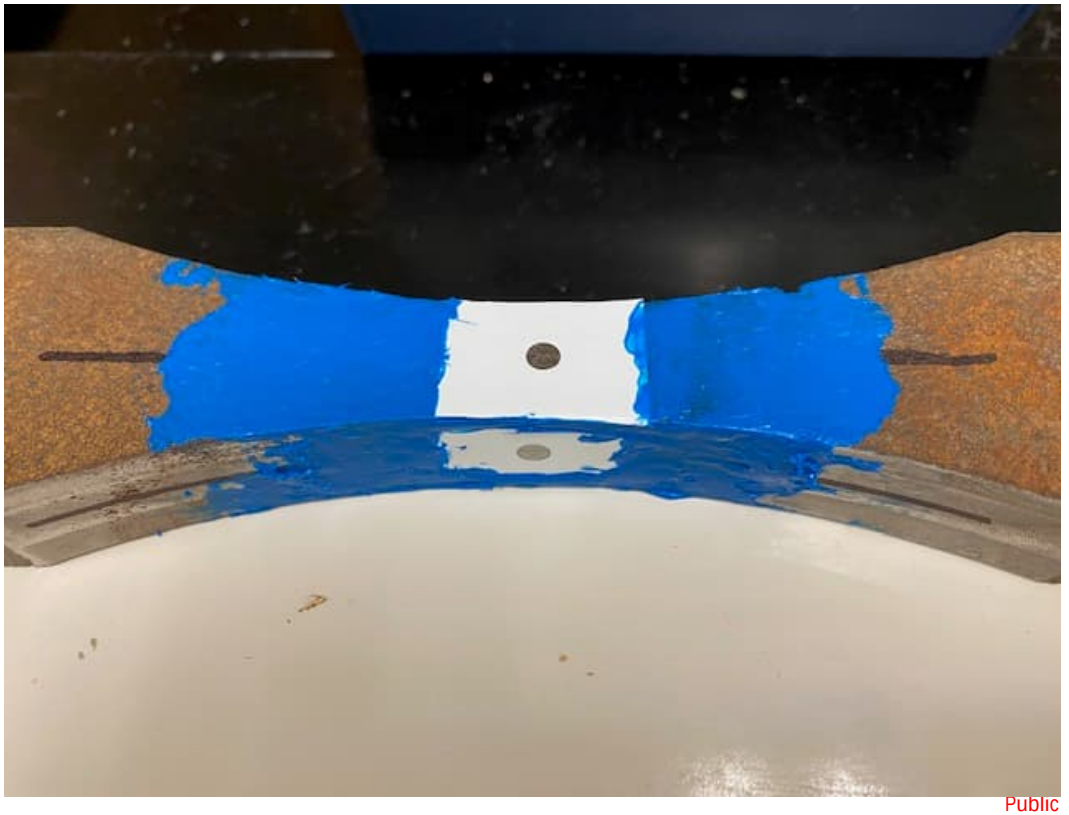


Transverse lines scans, which were possible on <u>all</u> sides

Machined surfaces exhibited a higher (more tensile) residual stress



For one sample, a single location on the as-cast surface, and a single location on the water-jet cut and milled surface, was depth-profiled. A sticker mask with 5mm hole, and additional rubber masking, limited electropolishing to only this area. Depth measurements were taken with a physical depth gage, and measurements were quite variable initially on the as-cast surface (likely error).



G3-Front (As-Cast Surface): Depth Profile Data After SAE HS-784 Flat Plate Correction

Compressive stress continued to increase in magnitude to a depth of ~60 microns. At deeper depths the compressive stress decreased in magnitude, but remained compressive (negative values) through all depths tested.

Material Removal Correction - FLAT PLATE

H [mm]	σm(H) [MPa]
18	-185

Δz depth [mm]	σm(z) Meas. [MPa]	σ(z) (Evans theory) [MPa]
0.00	-185	**-185.0**
0.01	-248	**-247.6**
0.04	-272	**-270.4**
0.06	-367	**-364.5**
0.10	-317	**-312.9**
0.15	-240	**-233.8**
0.18	-156	**-148.6**
0.30	-70	**-57.7**
0.35	-52	**-37.6**
0.49	-107	**-86.9**
		0.0
		0.0
		0.0
		0.0
		0.0
		0.0
		0.0
		0.0
		0.0

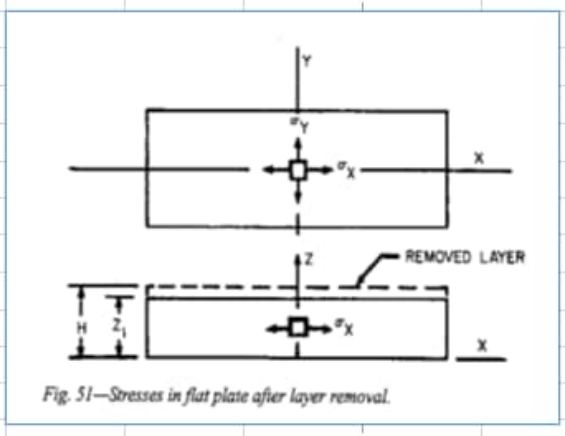
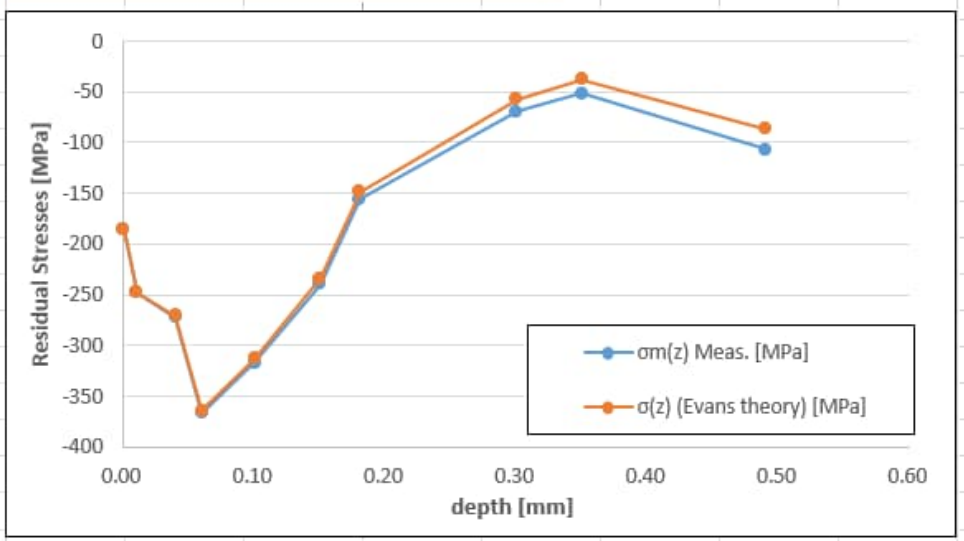


Fig. 51—Stresses in flat plate after layer removal.



G3-Side (Water Jet + Milled): Depth Profile Data After SAE HS-784 Flat Plate Correction

Tensile stress appeared to oscillate from tensile at the surface, to compressive (peaking at a depth of ~90 microns), and then tensile again at deeper depths.

Material Removal Correction - FLAT PLATE

H [mm]	σm(H) [MPa]
60	67

Δz depth [mm]	σm(z) Meas. [MPa]	σ(z) (Evans theory) [MPa]
0.00	67	**67.0**
0.05	-17	**-17.2**
0.09	-77	**-77.4**
0.12	87	**86.5**
0.14	119	**118.4**
0.25	33	**31.9**
0.33	34	**32.5**
		0.0
		0.0
		0.0
		0.0
		0.0
		0.0
		0.0
		0.0
		0.0
		0.0
		0.0
		0.0

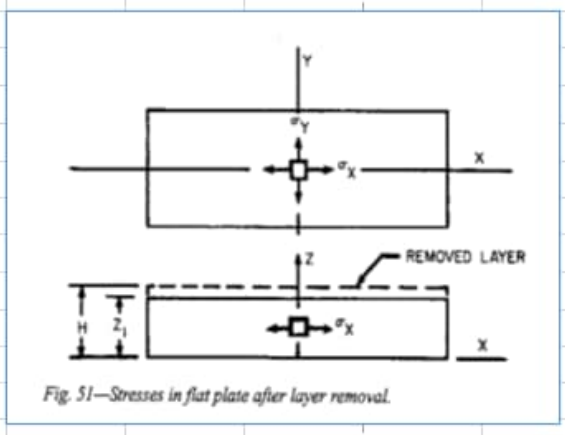
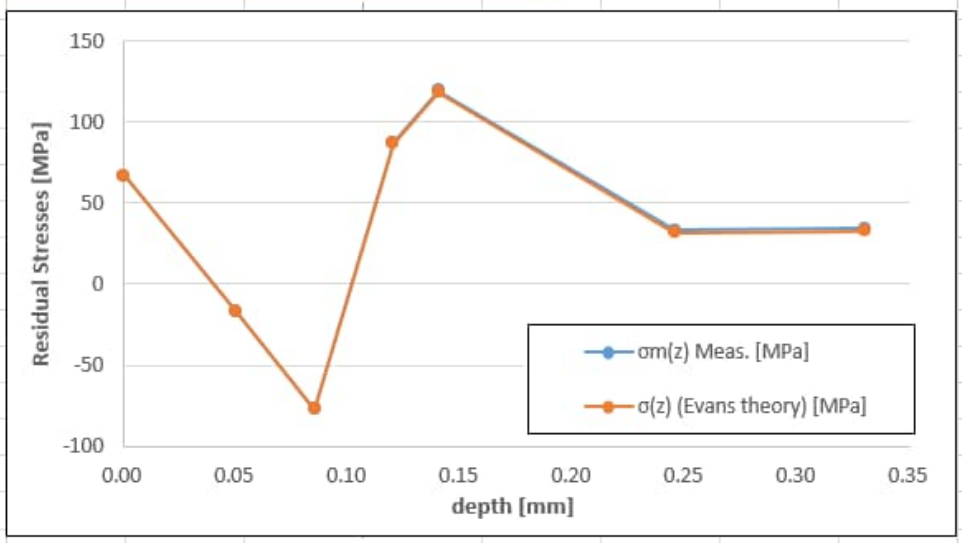


Fig. 51—Stresses in flat plate after layer removal.



Observations:

- As-cast surfaces exhibited longitudinal residual surface stresses as low as -282 MPa, and as high as -58 MPa.
- Water jet cut and milled surfaces exhibited longitudinal residual surface stresses as low as -39 MPa, and as high as +148 MPa.
- Depth profiles were performed on the as-cast and milled surfaces. These depth profiles were mathematically treated in a simple way to correct measurements for the relaxation due to removal of metal.