Evaluation of Cold Spray for Aircraft Repair

Sarah Galyon Dorman-SAFE Inc
Justin Rausch-SAFE Inc
Moriah Ausherman-SAFE Inc
Gregory Shoales-CAStLE Director

Program Goals and Objectives

- Show that cold spray can be used to improve fatigue life in repaired aluminum alloy 7050-T7451
- Demonstrate a cold spray repair can be used for structural repair of 7xxx series aluminum alloys
- Develop samples for use in validating structural repair using cold spray

Program Goals and Objectives

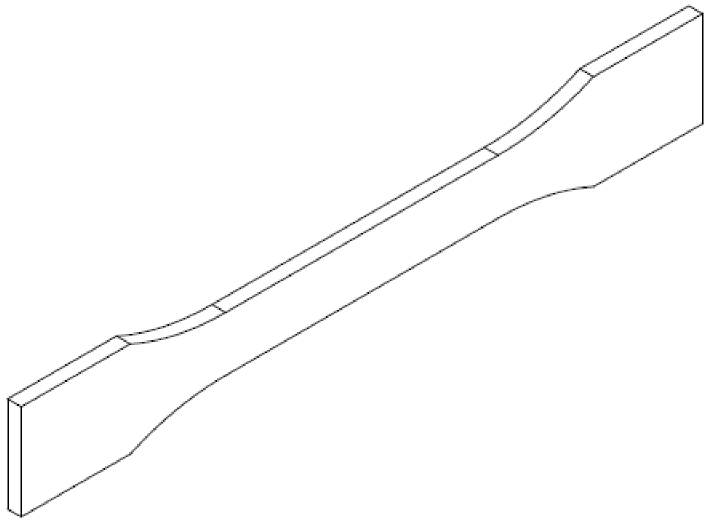
- Cold spray or other additive manufacturing evaluations have often only relied upon evaluation of the pure cold spray material.
- However, often these processes are expected to be used as a repair, meaning the repaired system needs to be evaluated.
- Sample design of relevant but still standard testing related samples is difficult and was the aim of this project to allow for a better understanding of a cold spray repair on high strength aluminum alloys (7075 and 7050) would perform under the following mechanical loading conditions.
- These tests would allow for cold spray to be evaluated for use on structural aircraft repairs.

Repair Performance

- Tensile
- Compression
- Three Point Bend
- Bearing
- Fatigue

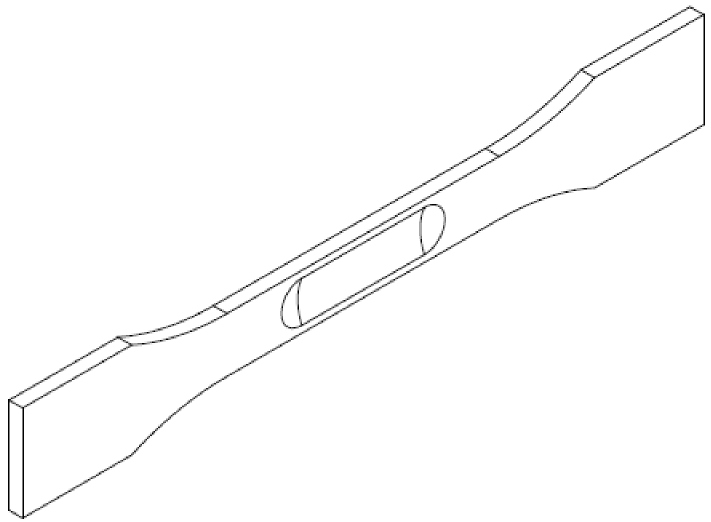
Tension – ASTM E8/E111

Pristine Coupon Geometry
After repair by cold spray with raster pattern parallel to long direction of sample, Repaired samples would have sample final dimension.



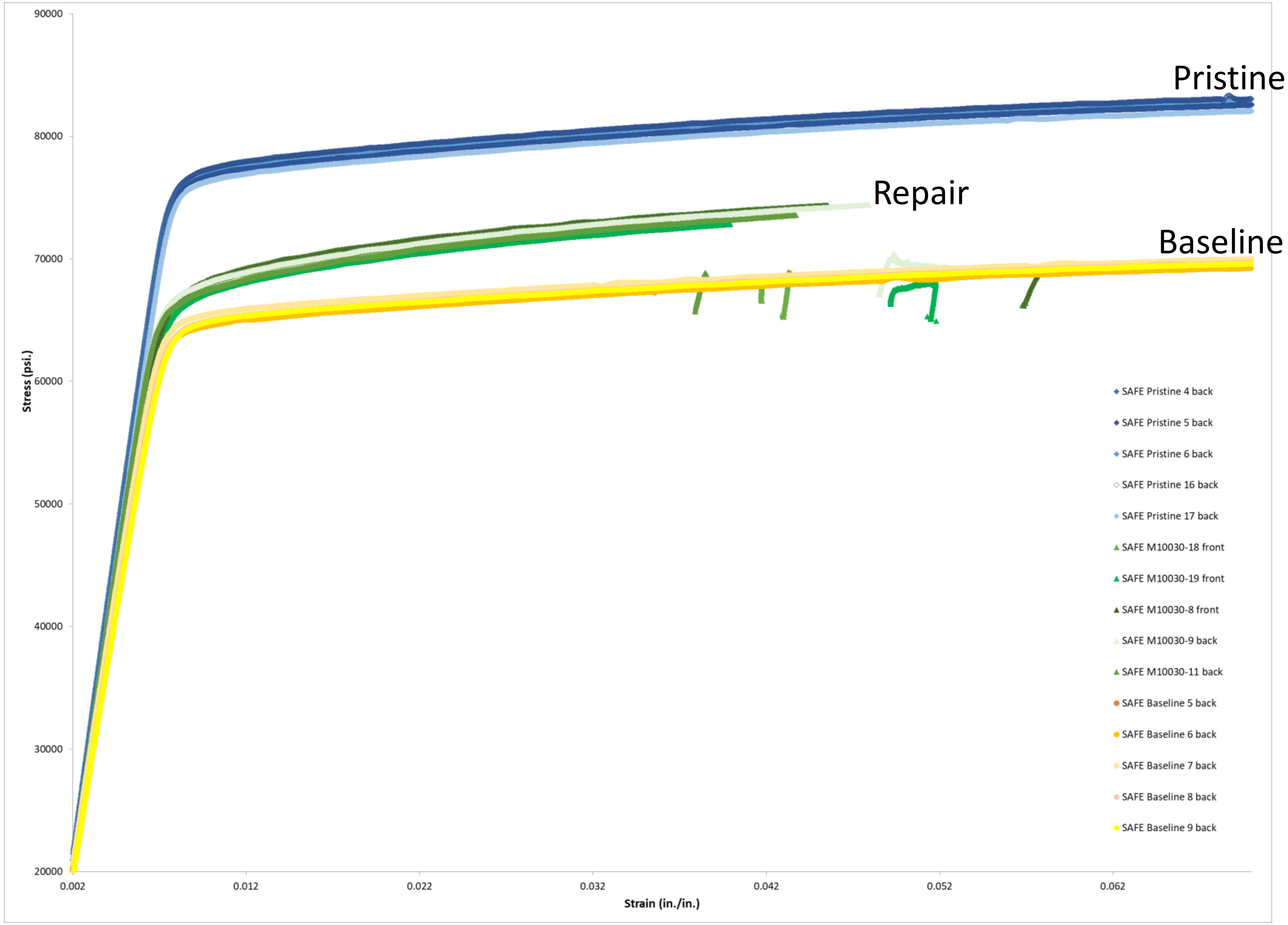
All samples are 0.25 inch thick, 12.5 inches long, the defect is 2.5 inches long, 1 inch wide and 30% of the sample depth.

Baseline Coupon Geometry
This geometry was repaired by cold spray with a raster pattern parallel to long direction of sample to make the final Repair geometry.



This geometry is repaired and then machined to the dimensions of the Pristine geometry.

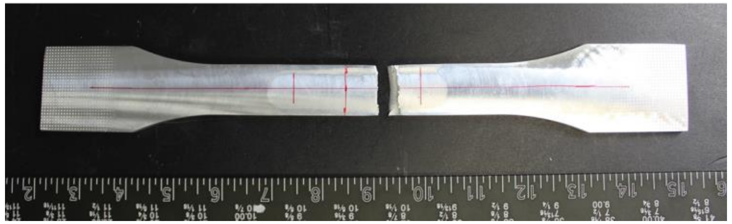
Tension – ASTM E8/E111



Tensile Property Comparison

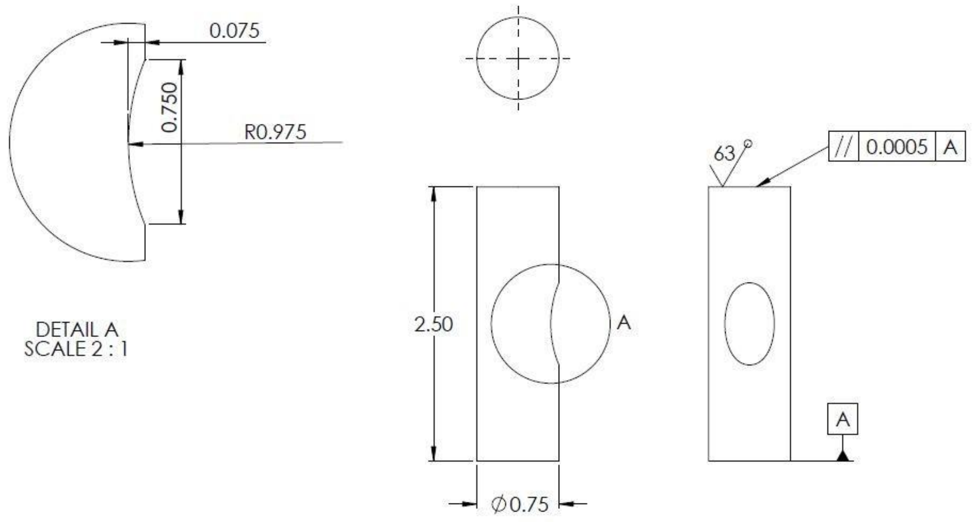
	Yield	UTS	Modulus
Pristine	77.12	83.53	10.30
Baseline	64.19	70.07	11.25
Repair	67.44	73.22	10.08

Posttest Repair Failure

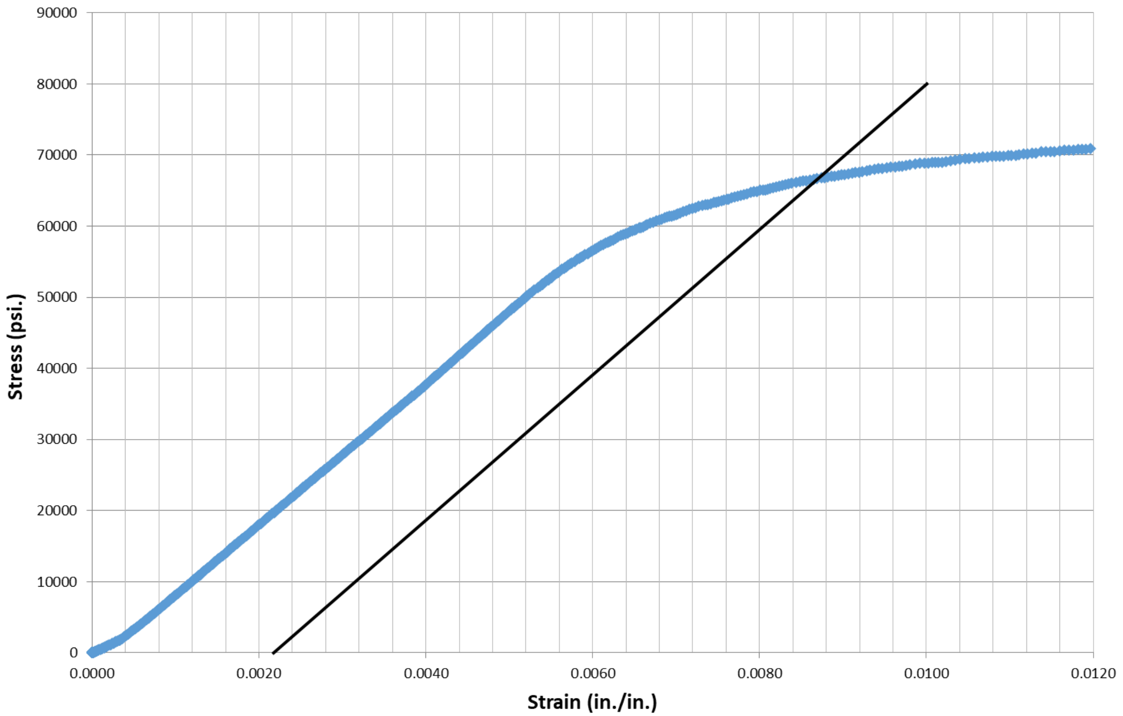


- Repaired coupons have a yield and ultimate tensile strength 87% of pristine coupons.
- The cold spray does not cause propagating fast fracture in the sample.
- The cold spray remains adhered during fracture.

Compression-ASTM E9



Schematic of Compression Specimen, showing simulated damage

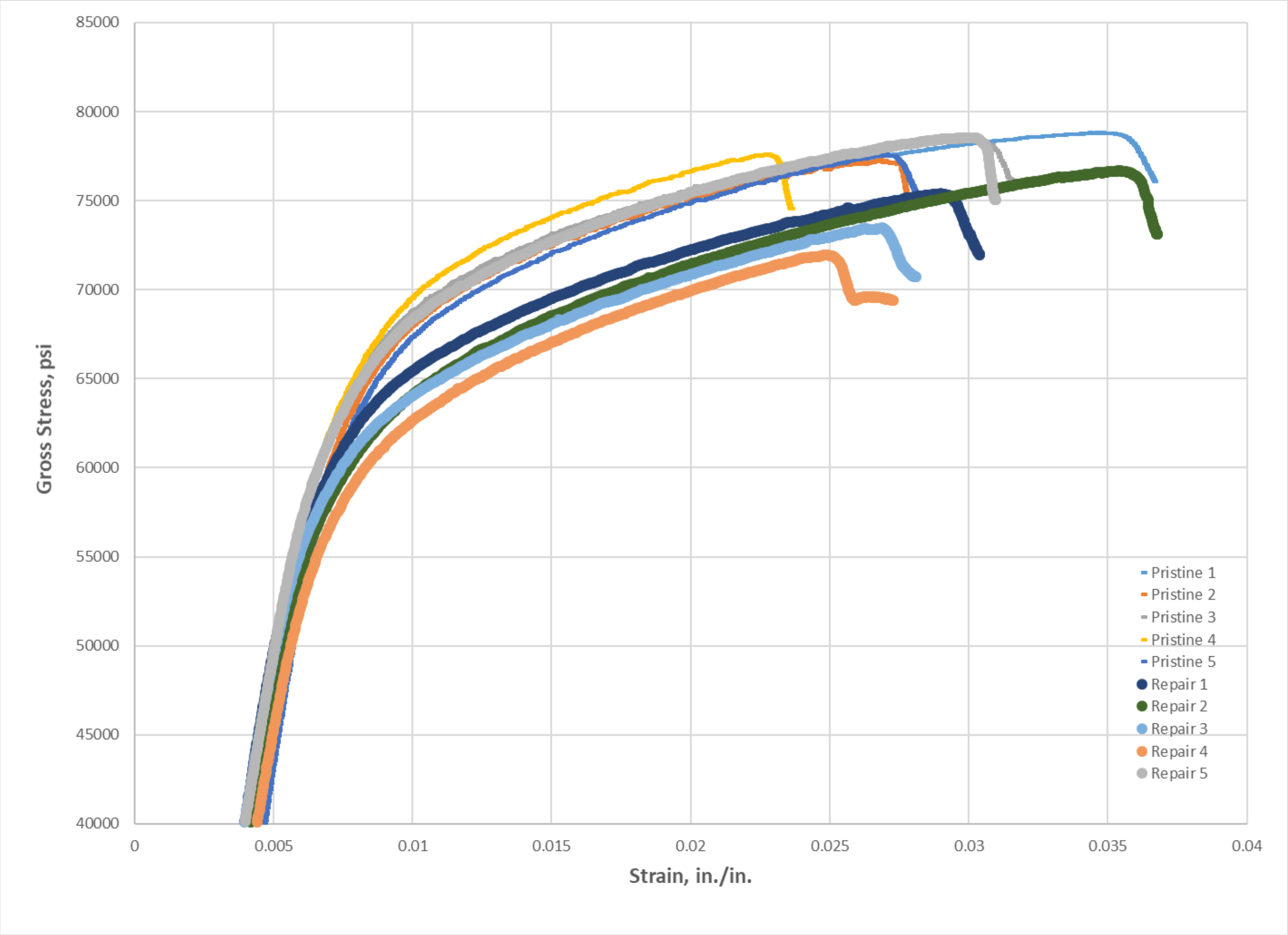


Typical Pristine Stress-Strain Plot

Compression Testing-Comparison

- Repaired compression specimens exhibit similar stress-strain response to the pristine specimens
  - Compressive Yield Strength
    - 66 ksi for Pristine vs. 62 ksi for Repaired
    - 94% of Pristine
  - Stress at Failure Load
    - 78 ksi for Pristine vs. 75 ksi for Repaired
    - 96% of Pristine

- No failure of Cold Spray
  - No fracture
  - No delamination

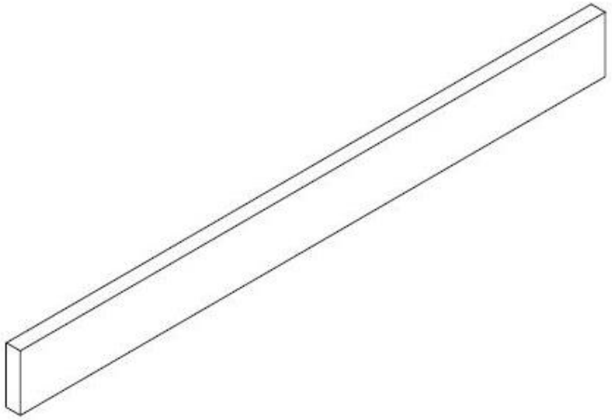


Comparison of Stress – Strain curves between Pristine and Repaired Specimens

Bending – ASTM E290

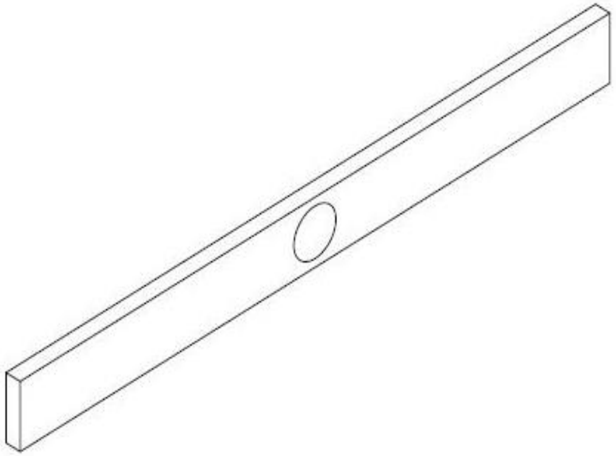
Pristine Coupon Geometry

After Cold Spray repair, samples would have same final dimension.



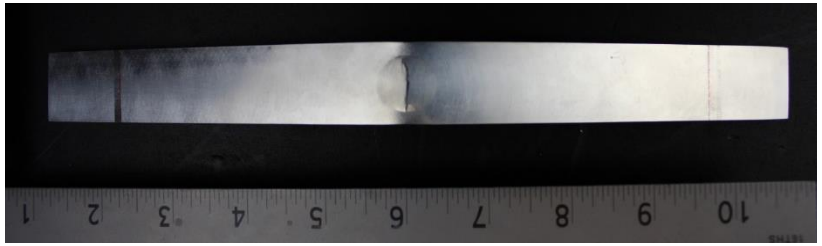
Baseline Coupon Geometry

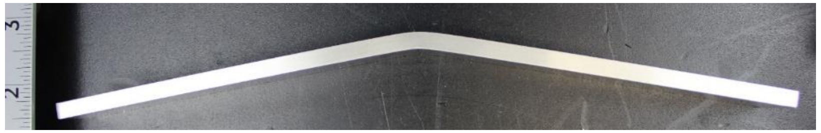
This geometry was used for Repair specimens prior to Cold Spray.

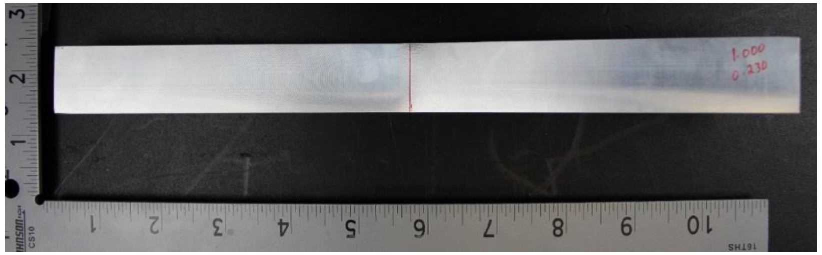


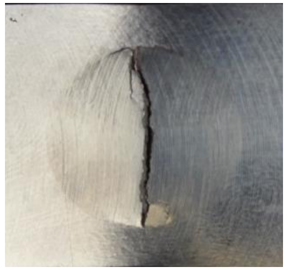
Posttest Images

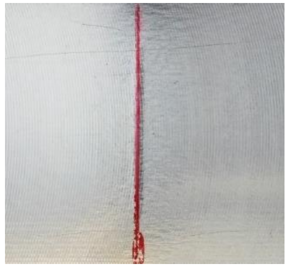
Cold spray is allowed to crack, but not disbond.
No cracking on the substrate side is allowed.











All samples are 0.25 inch thick, 10.5 inches long, the defect is a 0.75 inch spherical divot and 30% of the sample depth.

Testing is 3-point bend with cold spray in maximum tensile loading.

Bending Final Data

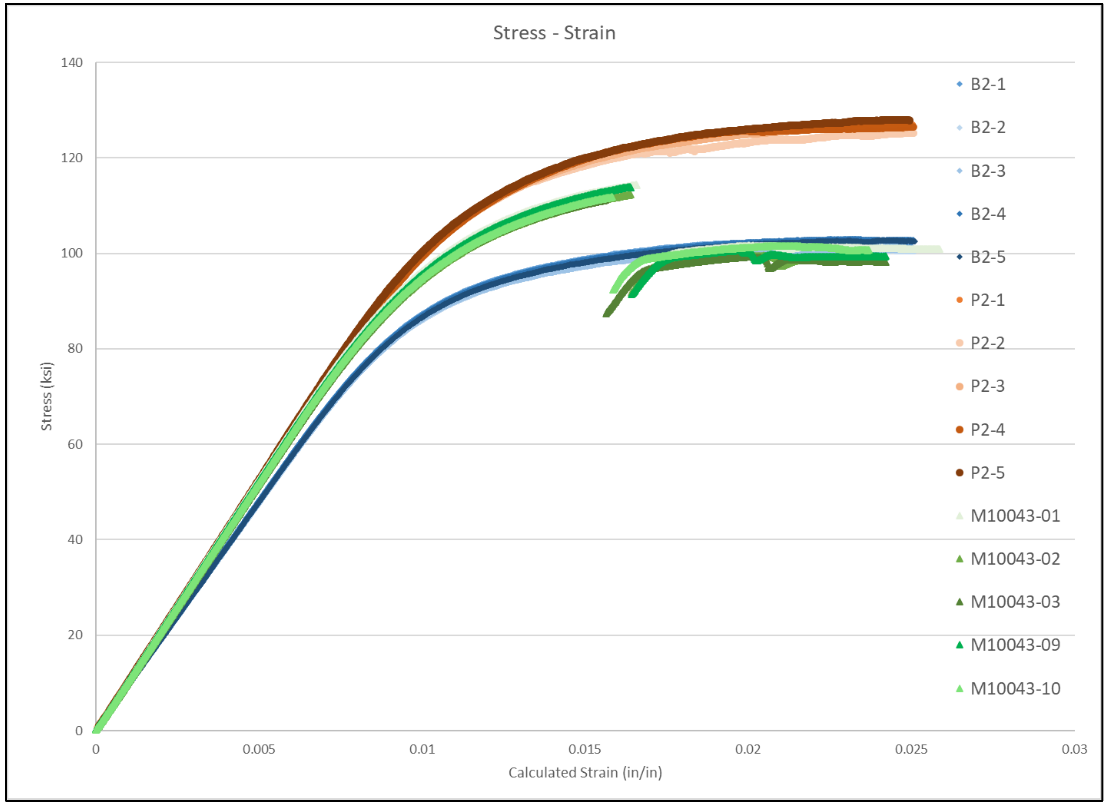
	Average P_{max}	*Average S_{max} (ksi)
Pristine	621.09	127
Baseline	500.99	102
Repair	507.02	113
*Not a design value		

All repaired samples passed with no disbondment noted.

Cracking of the cold spray was noted in all samples.

Stress strain curves were used to show the comparison of the sample performance.

- Note: The reason for the lack of design values is the assumption that the bending stress in this test remains elastic. The stress-strain curves generated by this method are based on elastic deformation only, however the test progresses into heavy plastic deformation to evaluate the cold spray. Therefore, the resulting stresses are higher than what would be expected for the material



Red Data-Pristine

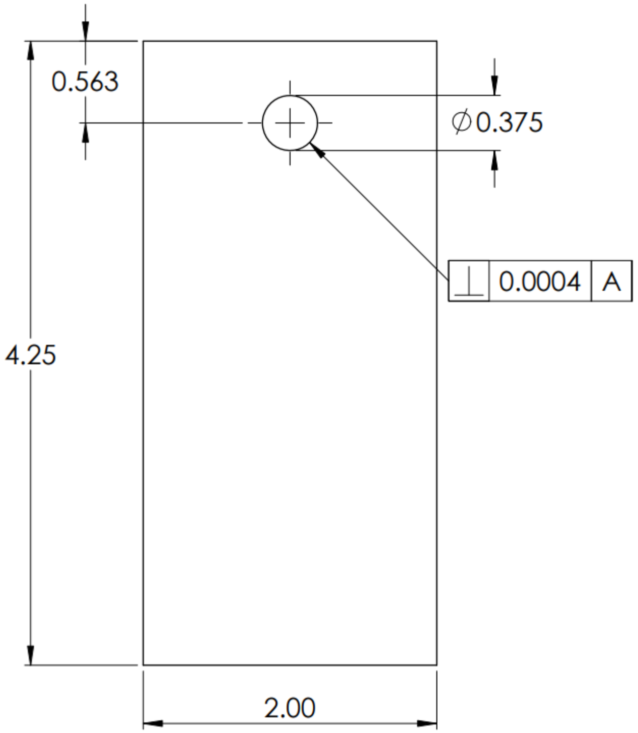
Blue-Baseline

Green-Repair

Bearing – ASTM E238

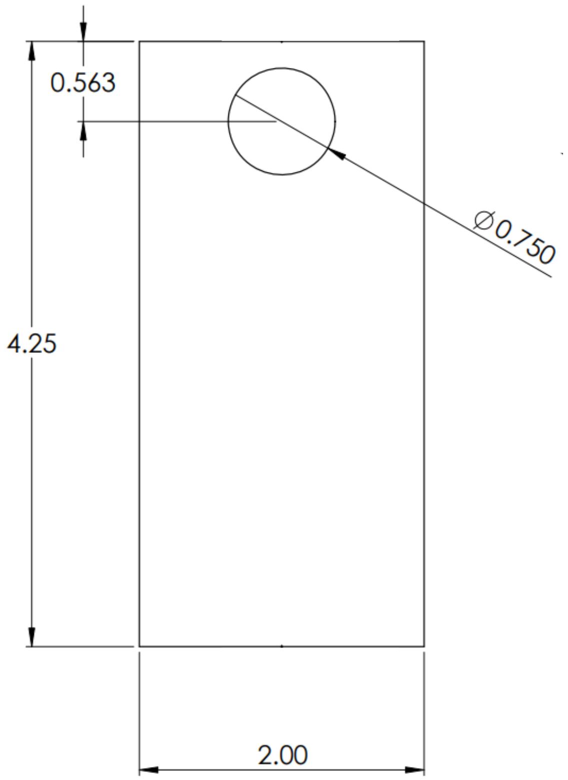
Pristine Coupon Geometry.

Repair Coupon final dimensions.

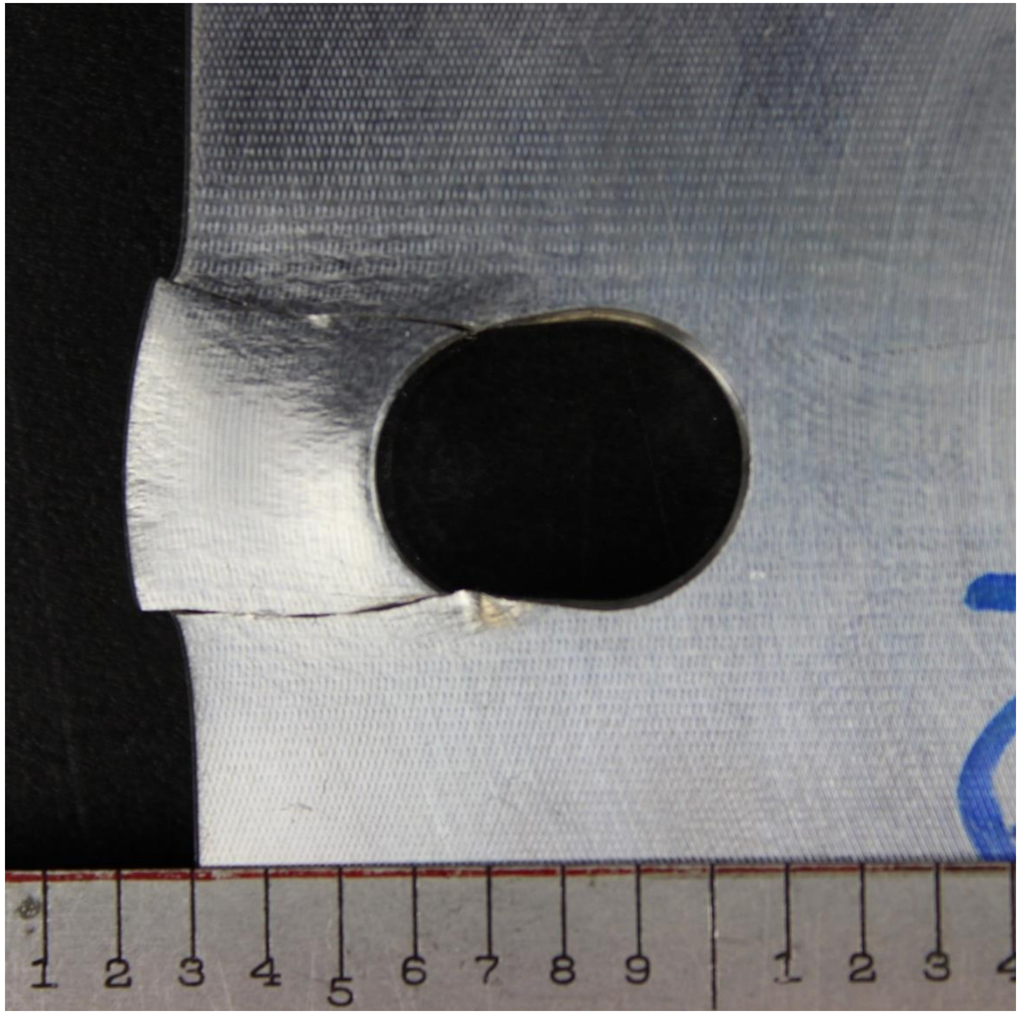


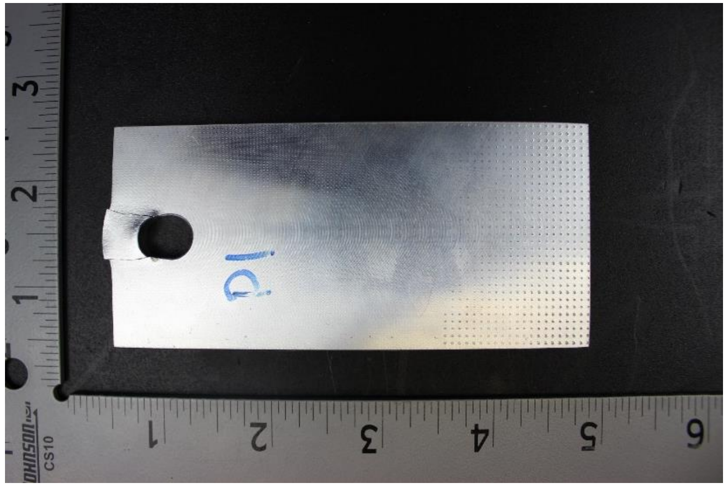
Baseline Coupon Geometry prior to final hole.

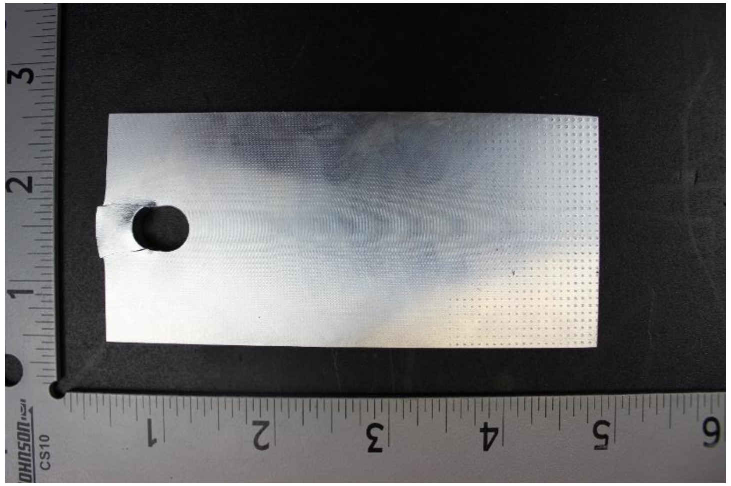
Repair Coupon Geometry prior to CS repair and final hole. Repair raster parallel to sample length.



Pristine Bearing

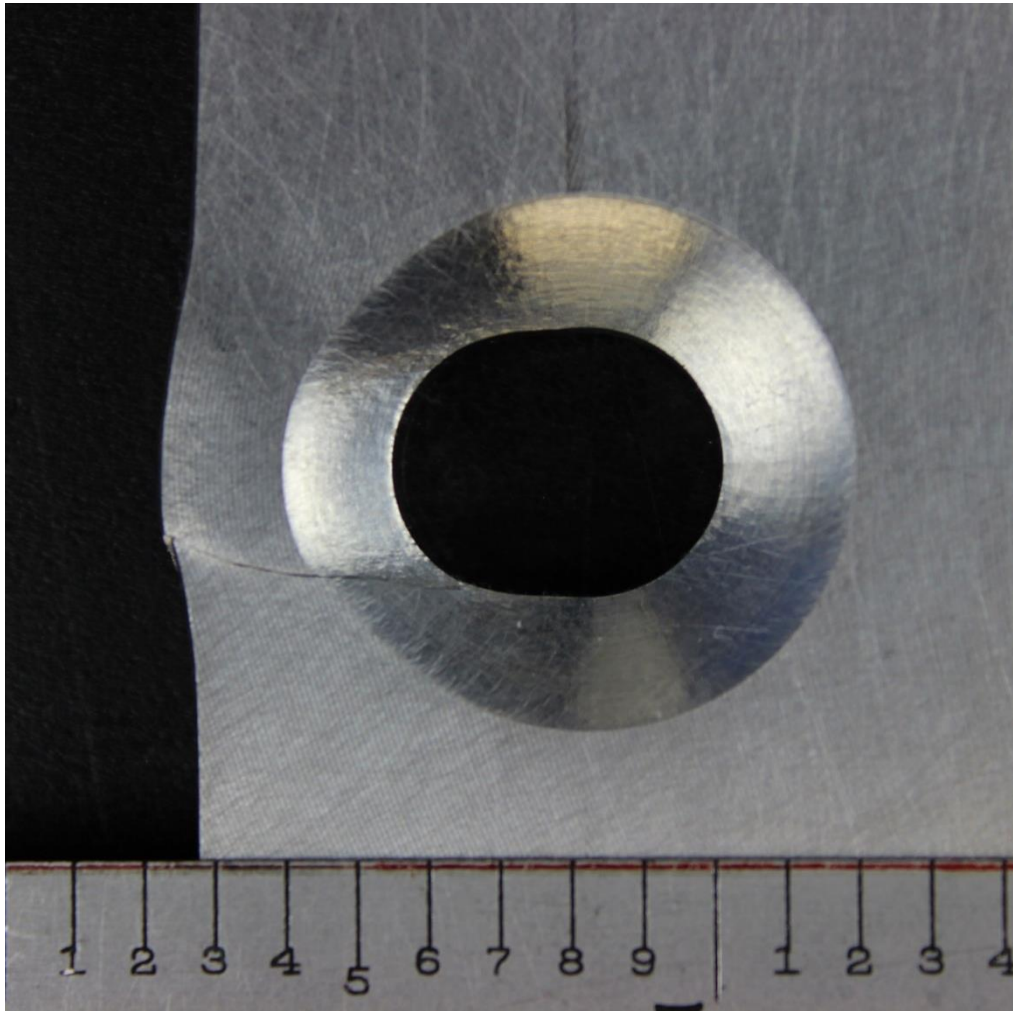


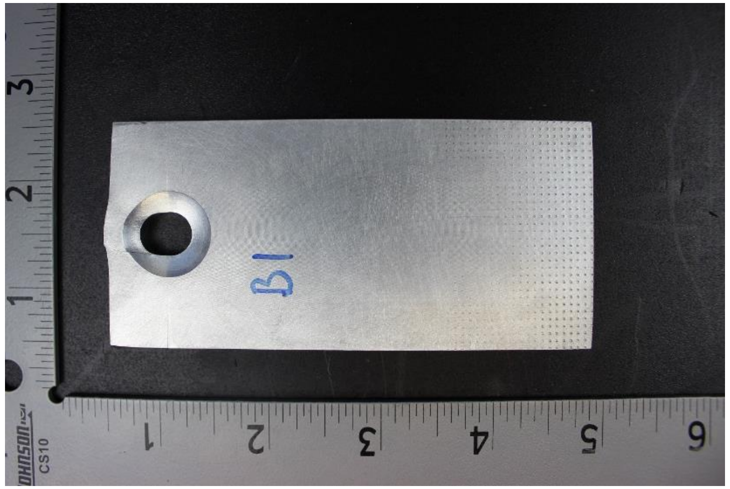


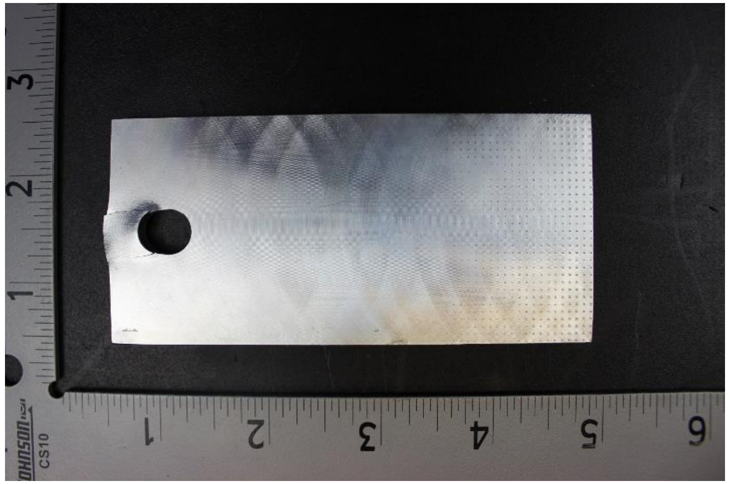


SAFE ENGINEERING

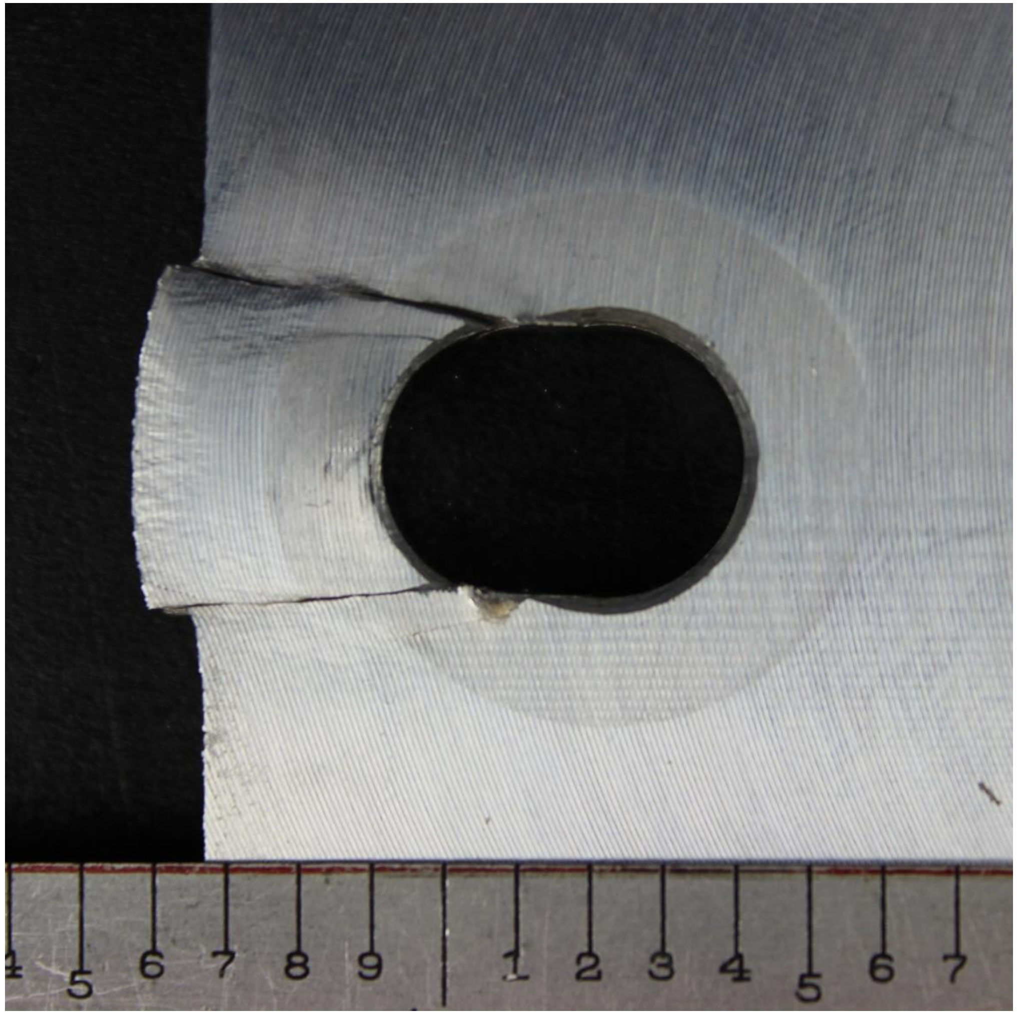
Baseline Bearing

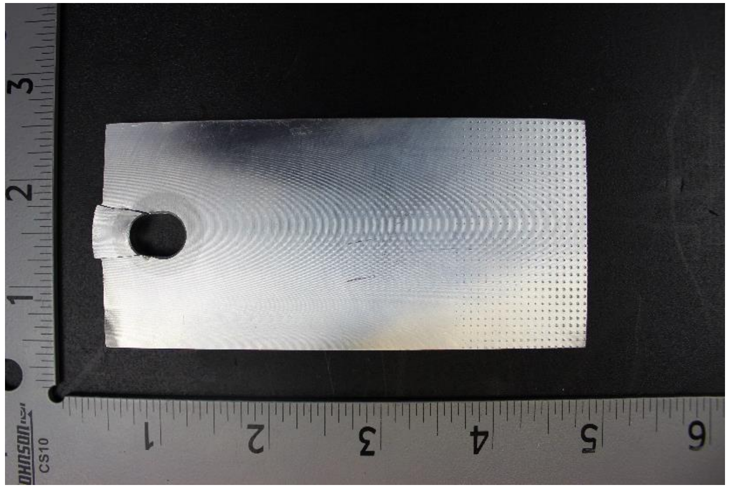


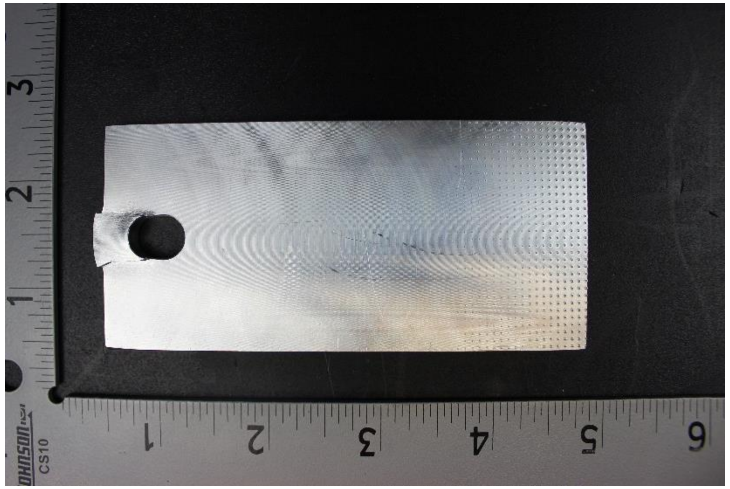




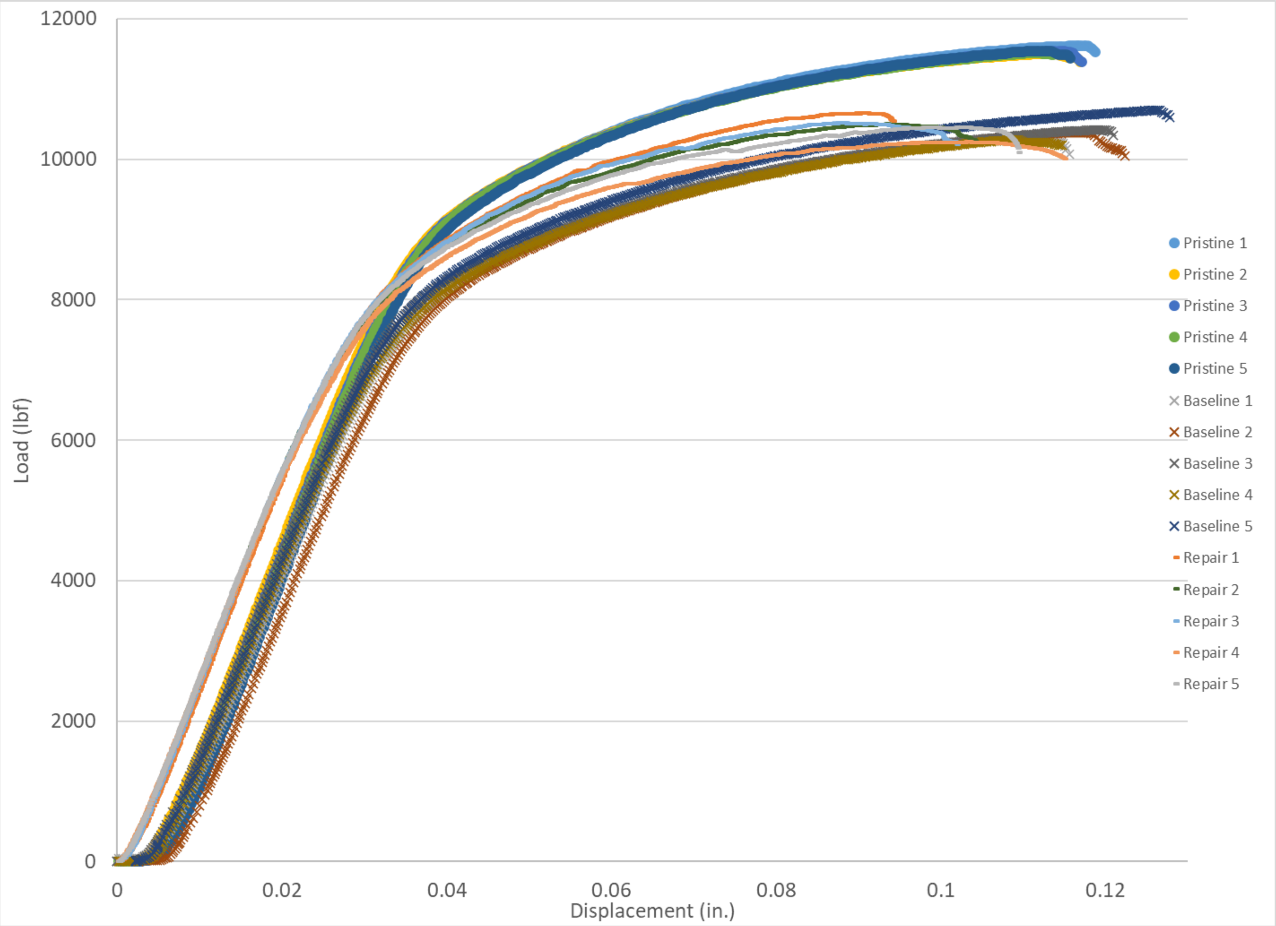
Repair Bearing







Bearing Property Summary



No disbondment for any repaired sample.

Specimen	Pmax (lbf.)	t (in.)	d (in.)	Fbru (ksi.)
P-1	11620	0.241	0.379	127.2
P-2	11512	0.241	0.377	126.7
P-3	11542	0.242	0.378	126.2
P-4	11515	0.241	0.378	126.4
P-5	11547	0.241	0.379	126.4
Average	11547			126.6

Specimen	Pmax (lbf.)	t (in.)	d (in.)	Fbru (ksi.)
B-1	10306	0.245	0.376	111.9
B-2	10386	0.242	0.377	113.8
B-3	10421	0.244	0.377	113.3
B-4	10279	0.243	0.376	112.5
B-5	10702	0.245	0.376	116.2
Average	10418.8			113.5

Specimen	Pmax (lbf.)	t (in.)	d (in.)	Fbru (ksi.)
R-1	10660	0.242	0.379	116.2
R-2	10502	0.242	0.38	114.2
R-3	10516	0.244	0.38	113.4
R-4	10248	0.243	0.379	111.3
R-5	10459	0.2445	0.38	112.6
Average	10477			113.5

Bearing stress is dominated by the yield strength making the baseline and repair data almost the same due to the earlier yield properties of cold spray.

Fatigue Sample Geometries

15% Blend Geometry

Pristine

Baseline

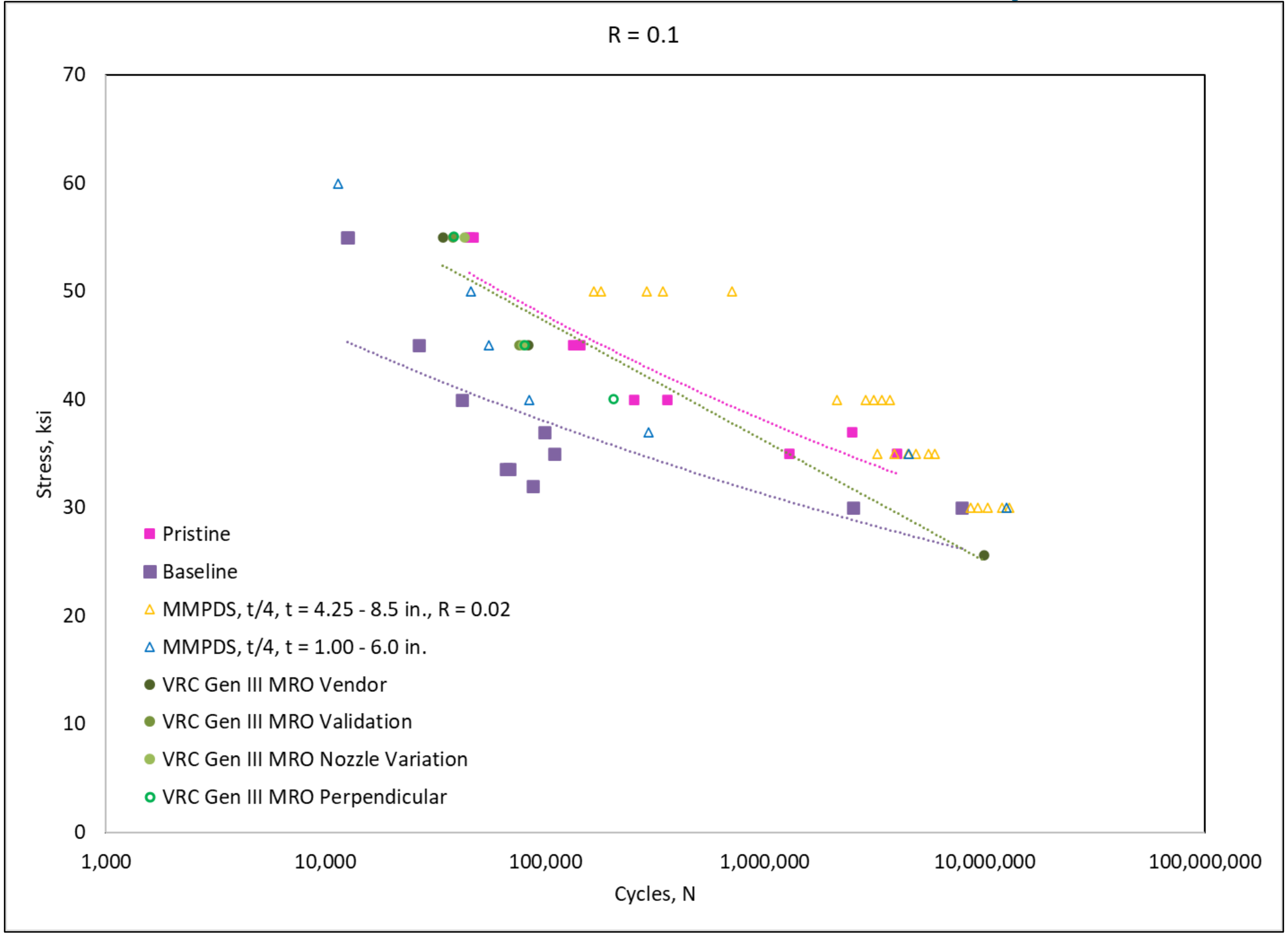
Repair

30% Blend Geometry

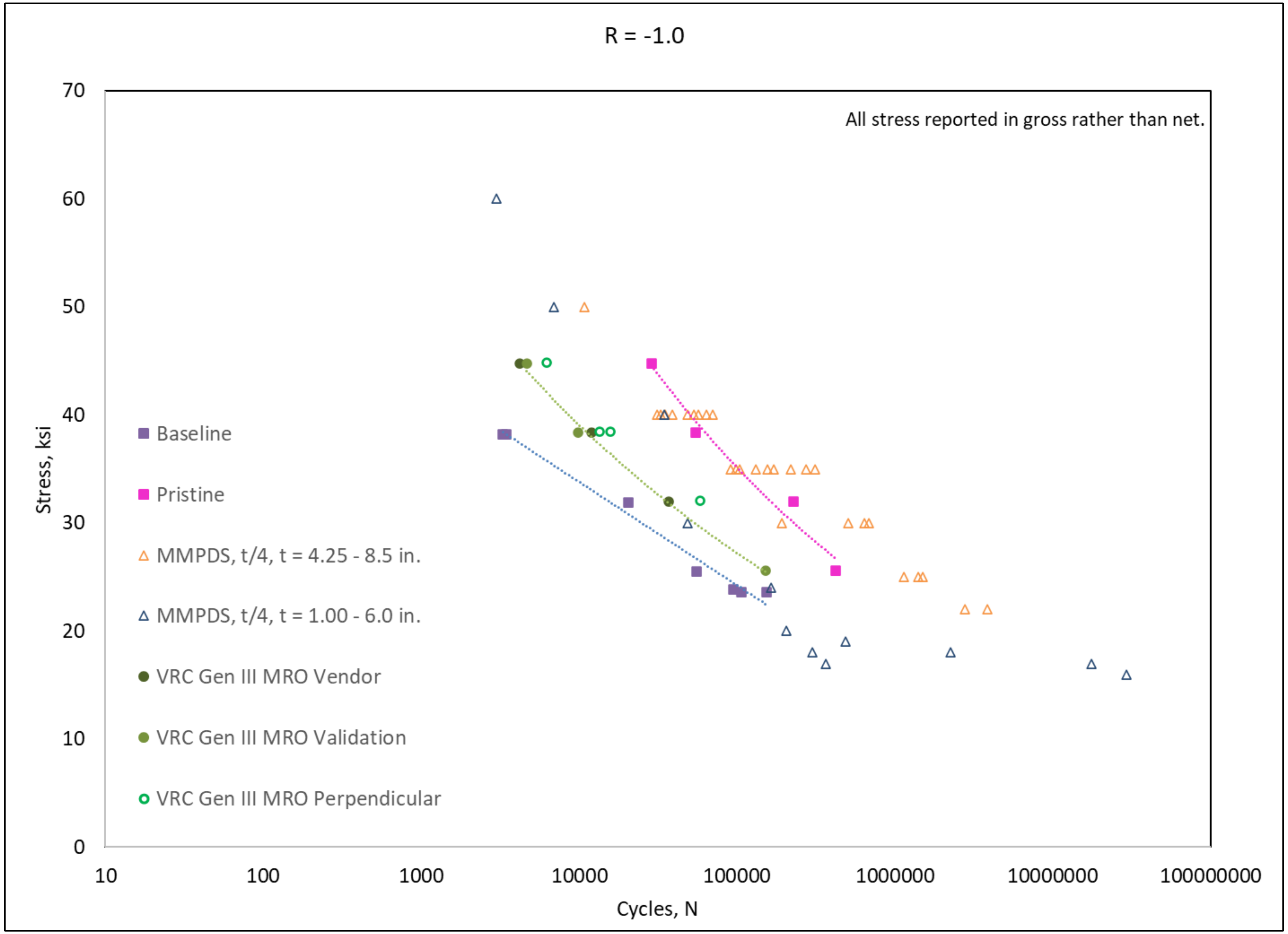
Baseline

Repair

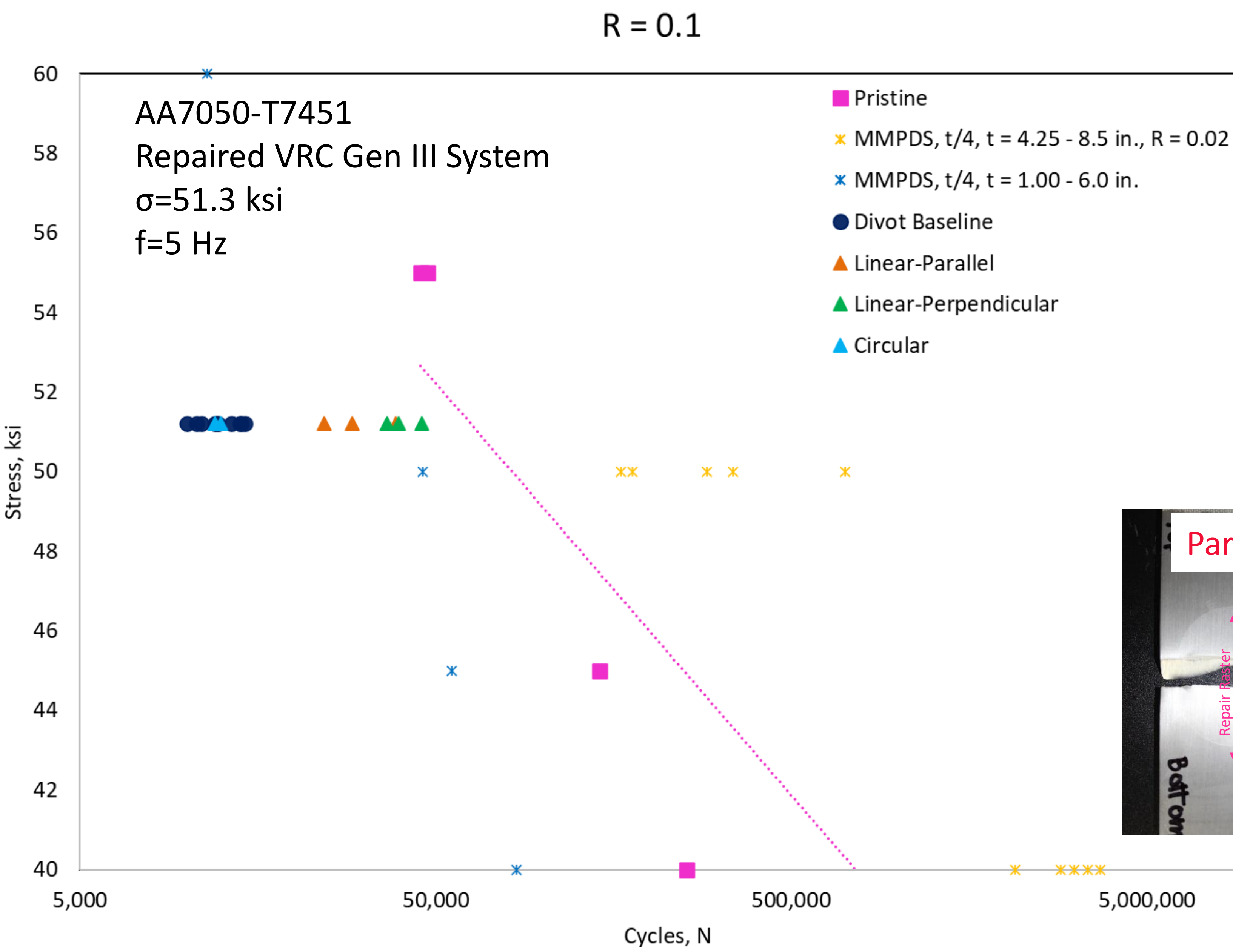
15% Blend Geometry

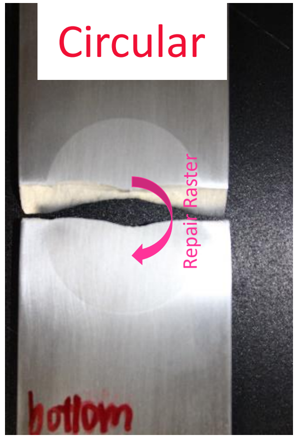


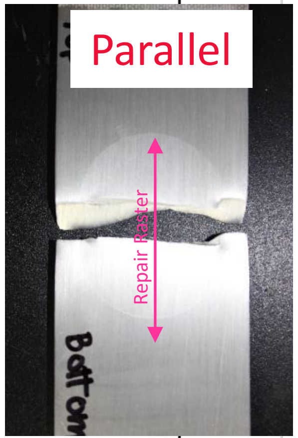
15% Blend Geometry



30% Divot Geometry

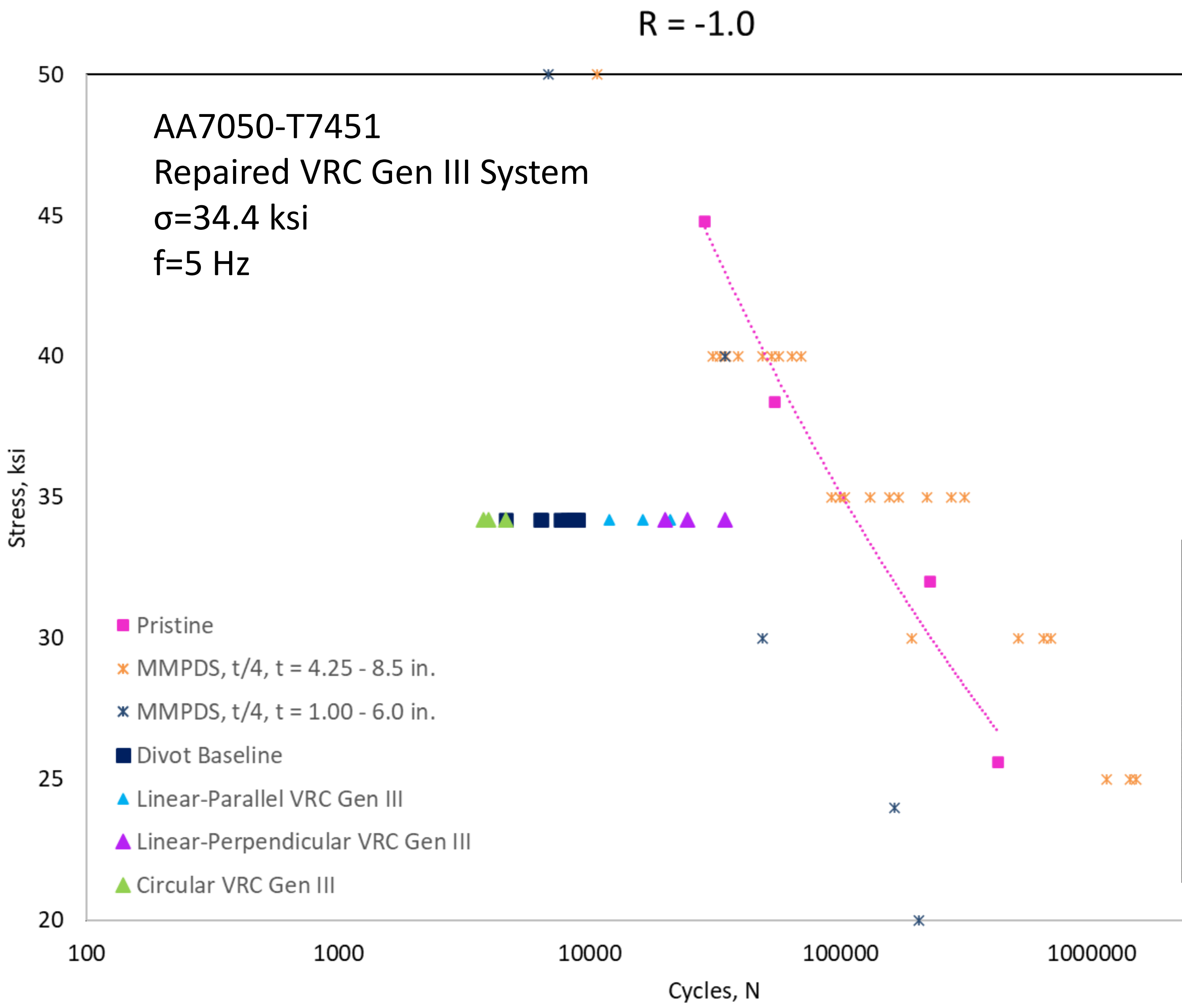


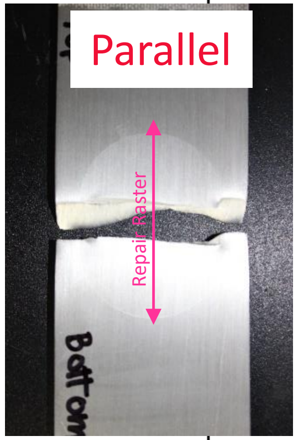


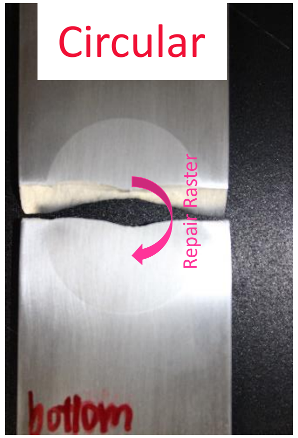


Perpendicular

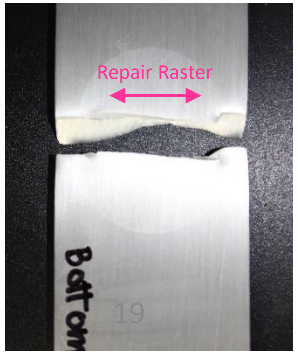
30% Divot Geometry



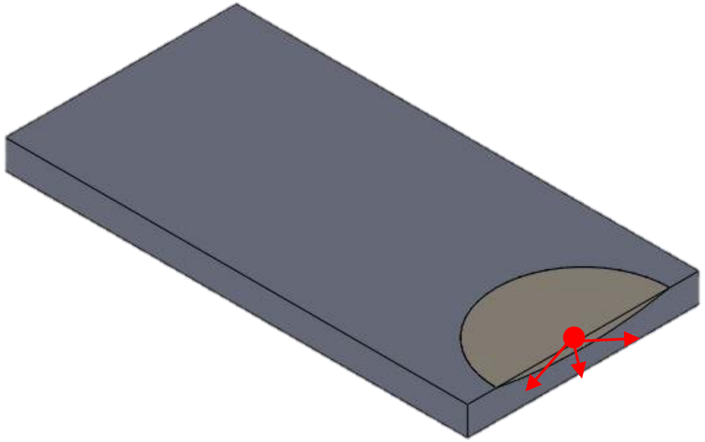




Perpendicular

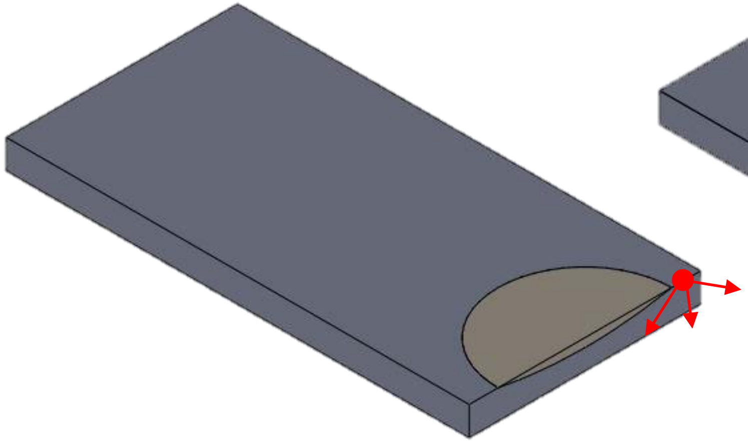


Fracture Nucleation Location



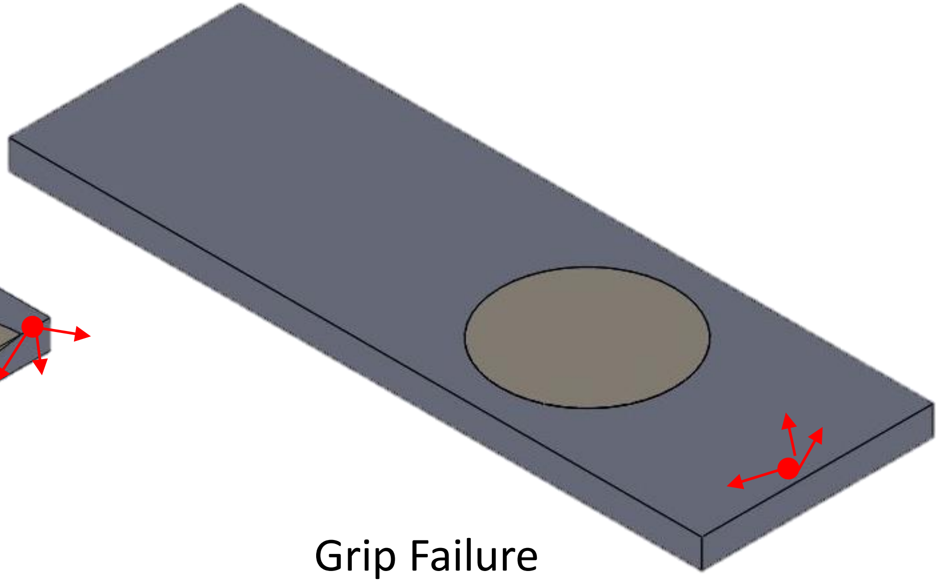
Divot Failure

Fracture nucleation at the center of the divot, where the Cold Spray is thickest.



Edge Failure

Fracture nucleation at one or both sides of the divot, completely in the wrought material. Not noted in these samples.

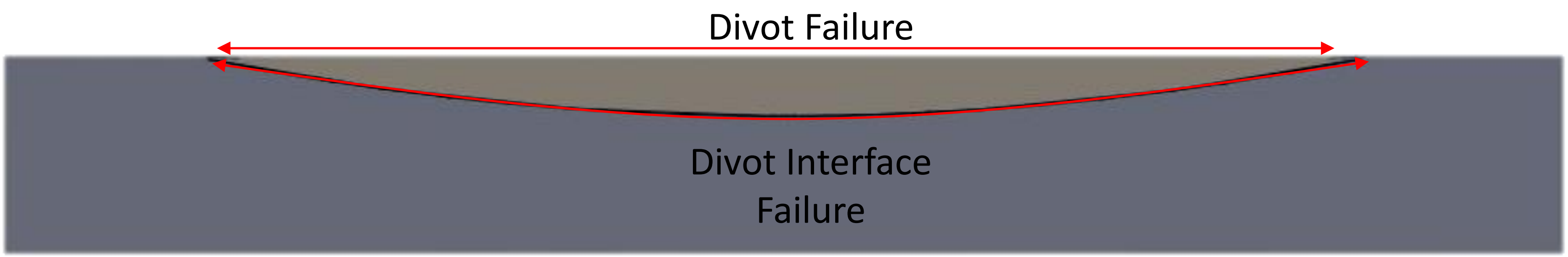


Grip Failure

Fracture can nucleate from any location, in any direction.

Failure nucleation location can highlight information about how the load is being transferred between the cold spray and wrought material. For an unrepaired sample, the failure should start near the base of the divot due to the highest stress localization. If the cold spray is able to carry load equivalent to the wrought material the nucleation location could move into the cold spray or to other locations within the sample. Other features such as porosity, limited particle deformation or other features can also influence these events.

Fracture Nucleation Location - Thickness



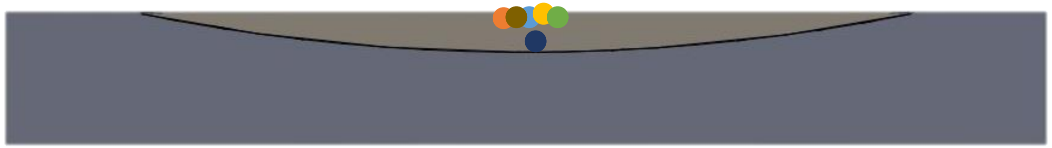
Divot Failure

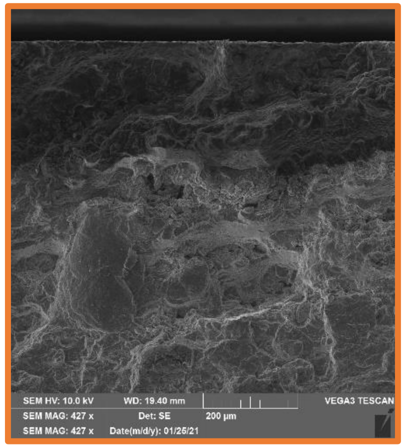
Occurs within the cold spray, generally at or near the surface

Divot Interface Failure

Occurs at the bond between the wrought and cold spray.

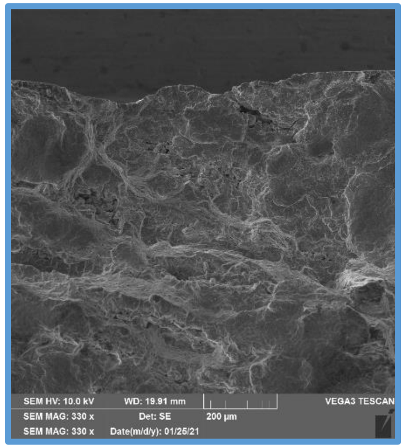
Crack Nucleation-Circular Repair



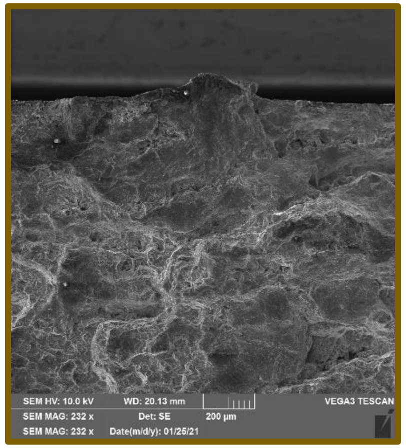


Divot Failure
R= -1
N= 3,785 cycles

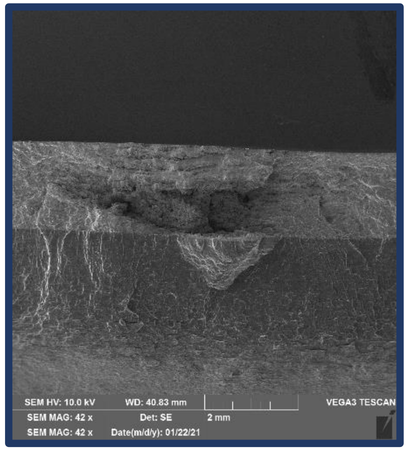
1.65mm from interface



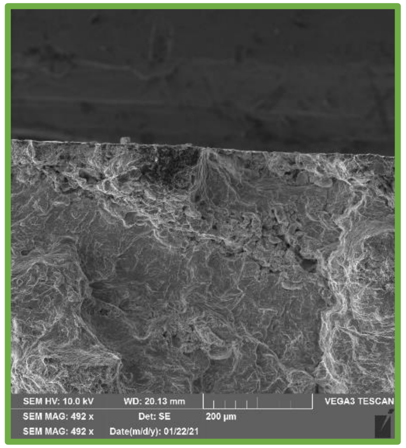
Divot Failure
R= -1
N= 3,964 cycles



Divot Failure
R= -1
N= 4,661 cycles

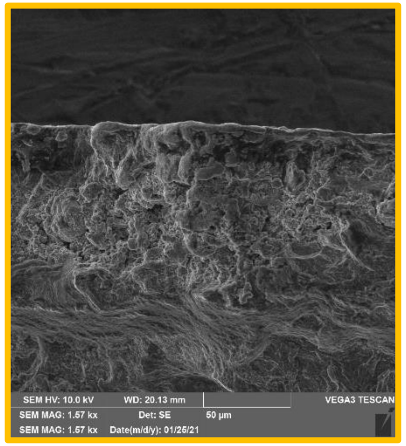


Divot Failure
R= 0.1
N= 1,298 cycles



Divot Failure
R= 0.1
N= 11,991 cycles

1.75mm from interface

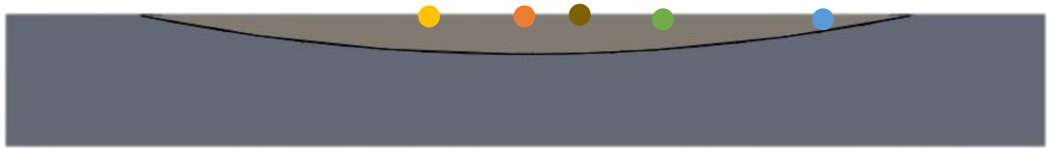


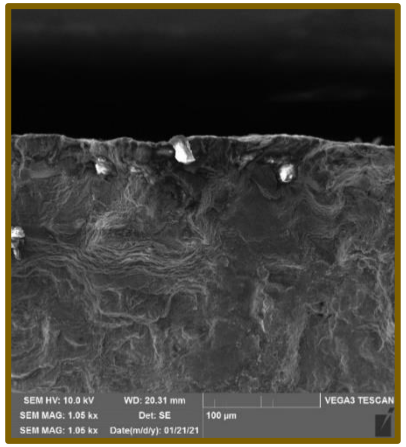
Divot Failure
R= 0.1
N= 12,458 cycles

1.80mm from interface

- In all six circular samples, fracture nucleated within the cold spray due to incomplete bonding of cold spray particles.
- Distance from initiating feature to interface measurements were not taken for three samples due to incomplete bonding of cold spray particles throughout the coating and multiple initiation sites.

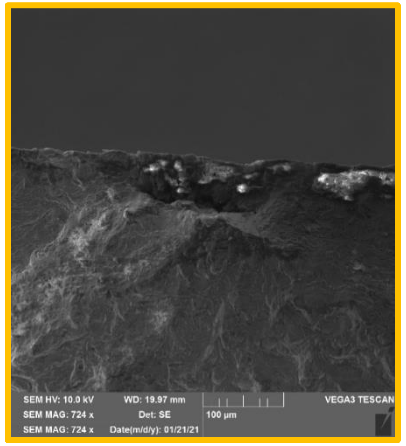
Crack Nucleation Linear – Parallel





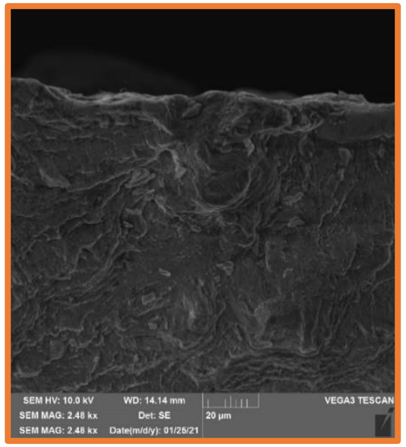
Divot Failure
R= -1
N= 11,997 cycles

1.75 mm from interface



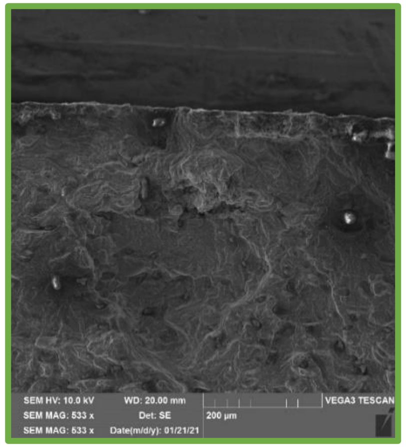
Divot Failure
R= -1
N= 15,343 cycles

1.55 mm from interface



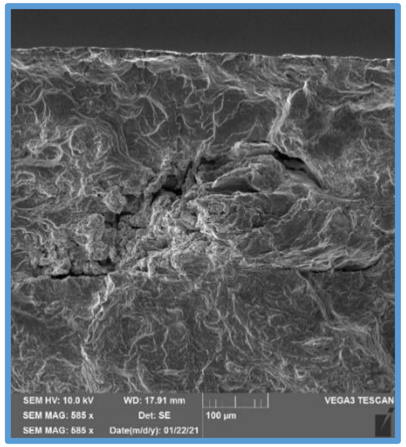
Divot Failure
R= -1
N= 21,033 cycles

1.40 mm from interface



Divot Failure
R= 0.1
N= 24,348 cycles

1.50 mm from interface



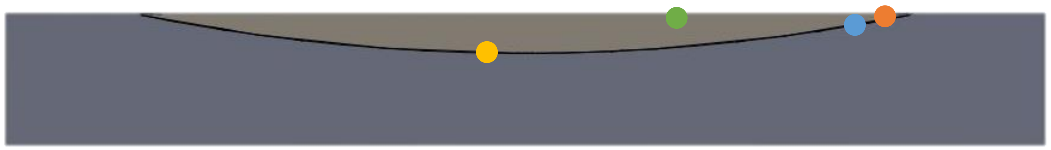
Divot-Edge Failure
R= 0.1
N= 29,197 cycles

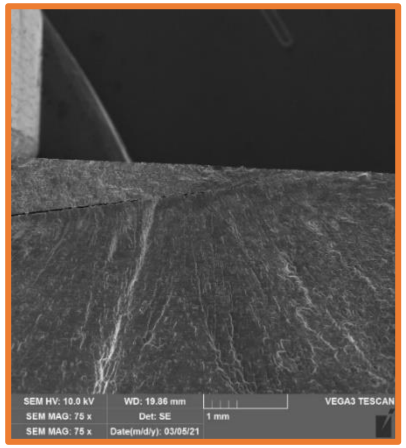
0.35mm from interface

Grip Failure
R= 0.1
N= 38,524 cycles

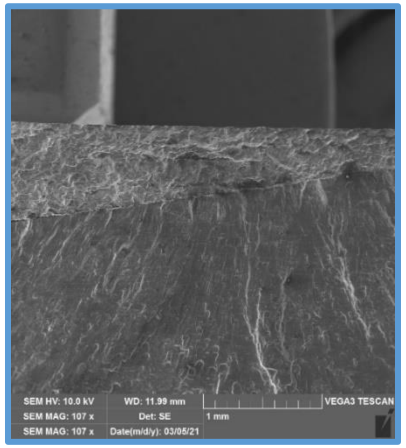
- In most of the linear-parallel samples, sprayed parallel to the length of the coupon, fracture initiated within the cold spray. No obvious signs of consistent porosity within the cold spray were noted in center cold spray. The correlates with the increased cycles to failure over the baseline.

Crack Nucleation Linear – Perpendicular Repair



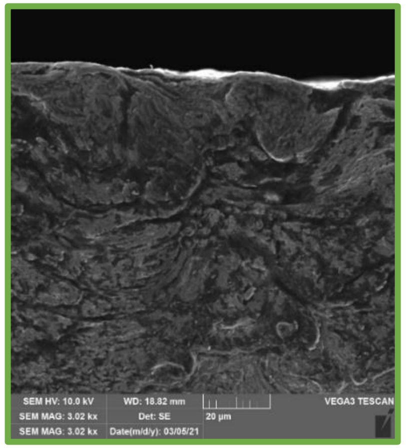


Divot-Edge Interface Failure
R= -1
N= 20,060 cycles



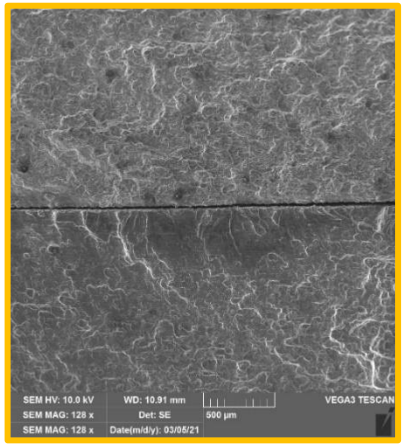
Divot-Edge Failure
R= -1
N= 24,590 cycles

0.36mm from interface

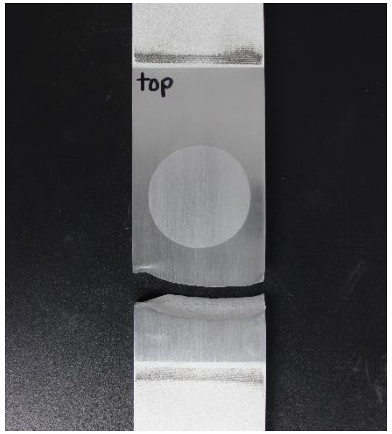


Divot Failure
R= -1
N= 34,693 cycles

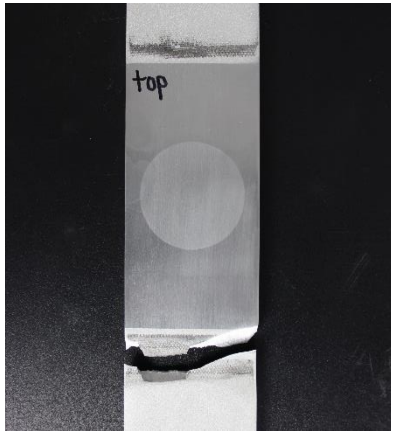
1.45mm from interface



Divot Interface Failure
R= 0.1
N= 39,202 cycles



Grip Failure
R= 0.1
N= 35,611 cycles

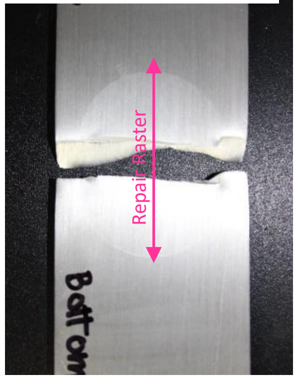


Grip Failure
R= 0.1
N= 45,580 cycles

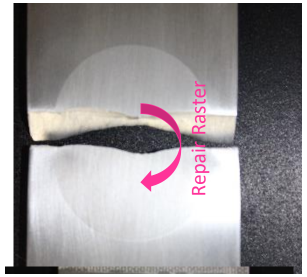
- Linear samples sprayed perpendicular to the length of the coupon performed better than the other raster patterns. This led to a range of initiation locations.
- Two samples initiated in the divot center (one at the CS surface and one in the interface), two broke at the divot-edge (one higher and one at the interface), and two broke within the grip section.

Hardness Analysis

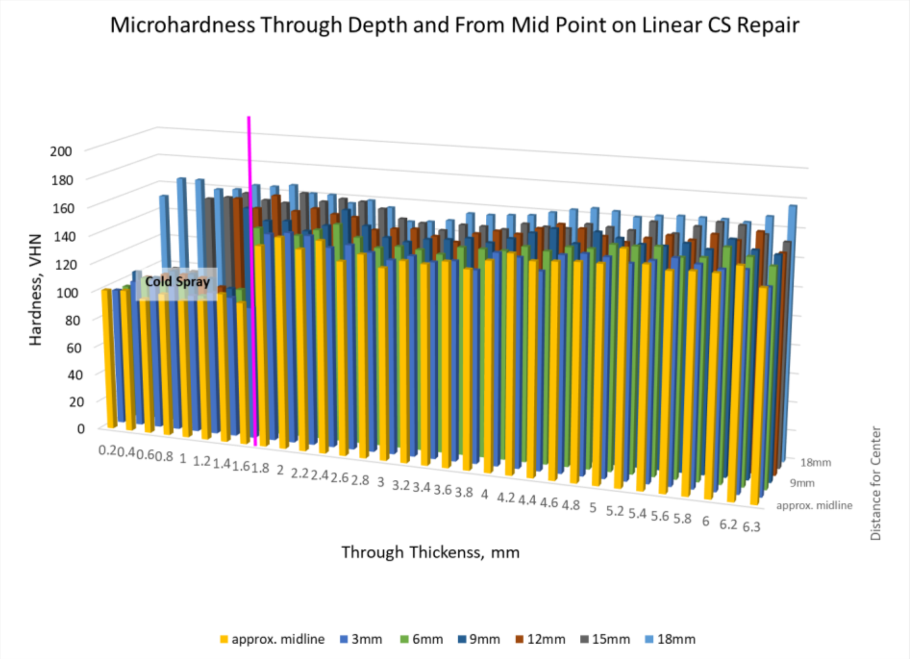
Linear Repair



Circular Repair

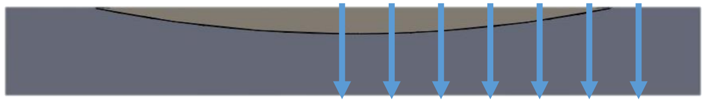


Perpendicular



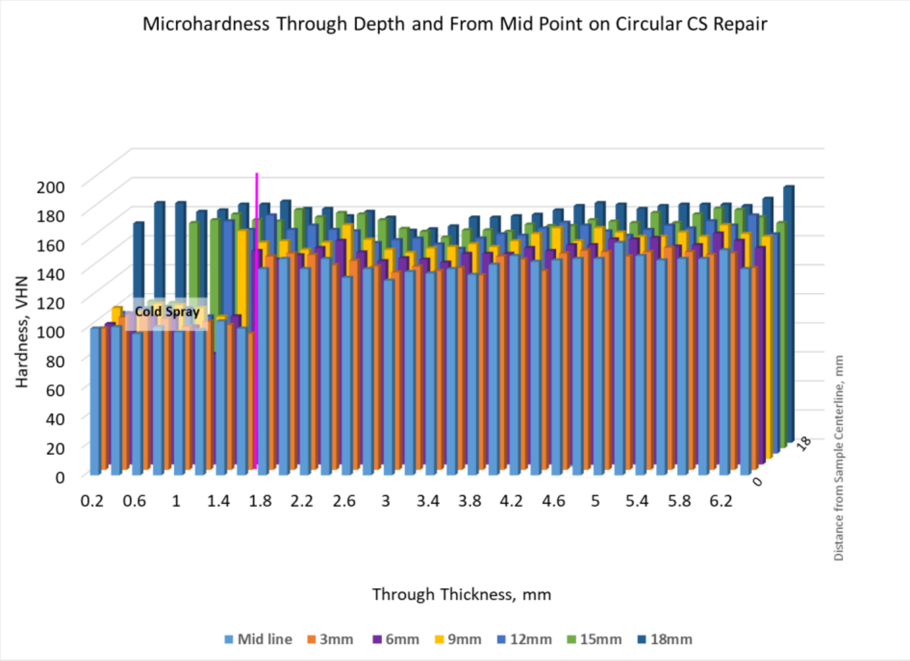
Hardness Average at 2mm Depth (just over deepest CS repair)								
Distance from Center	Midline	3mm	6mm	9mm	12mm	15mm	18mm	21mm
Linear	156	156	157	157	159	158	159	160
Circular	146	144	149	152	153	156	160	
Perpendicular	159	157	157	157	161	158	159	160

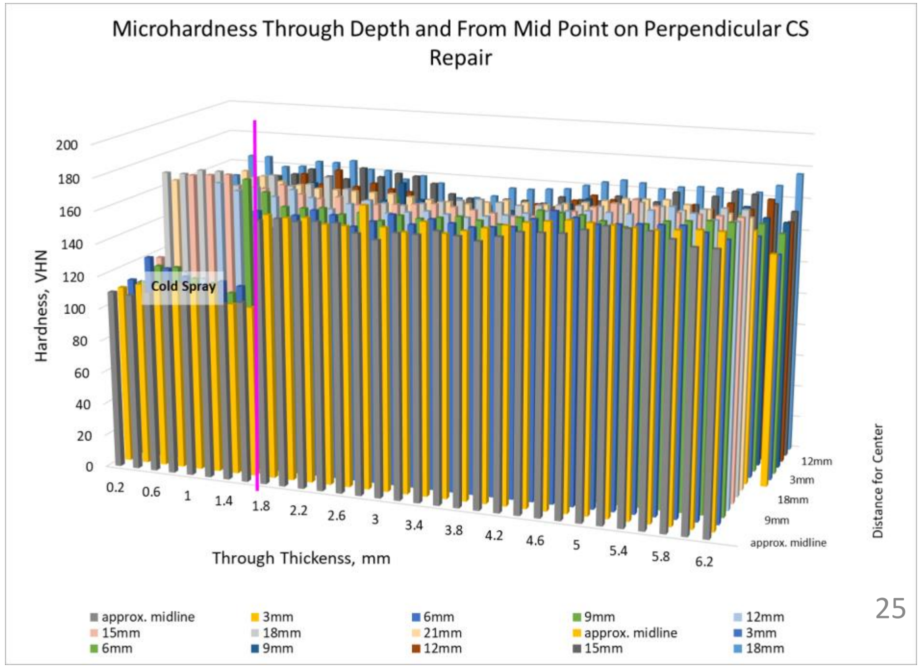
Measurement Made Through Sample Thickness from CS Centerline



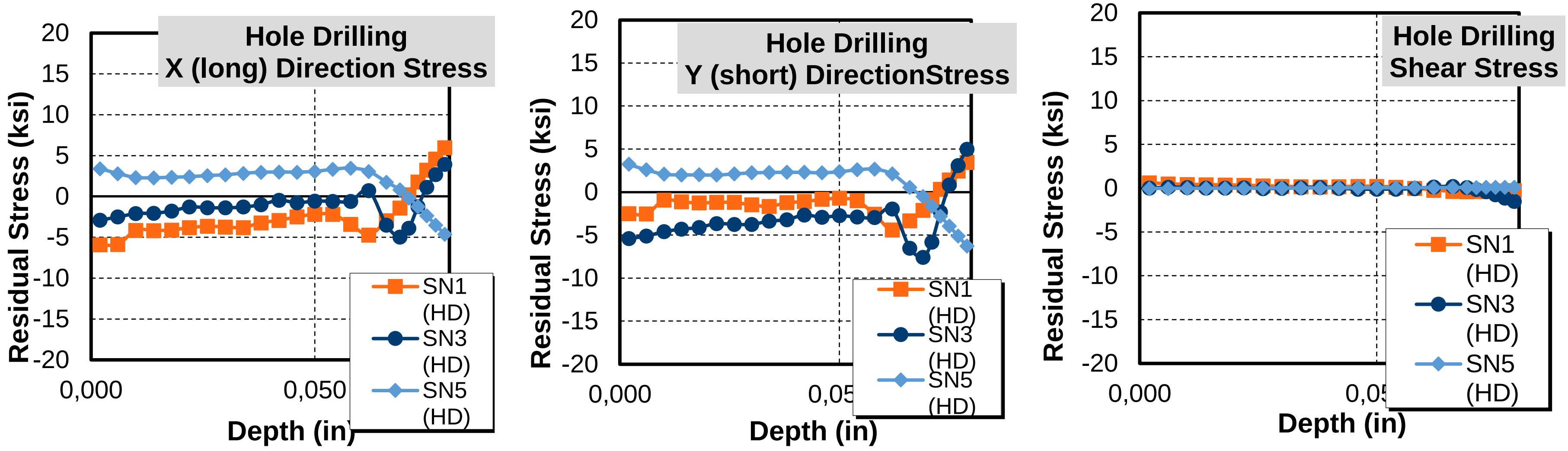
Cold Spray Hardness	
Linear	104.3
Circular	99.9
Perpendicular	110.3

The linear sprays showed limited to no change in hardness: suggesting heat input is acceptable





Hole Drilling – Residual Stress



The coupons with a circular raster pattern had tensile residual stress up to the transition from cold spray to wrought (SN5). The parallel (SN3) and perpendicular (SN1) coupons each showed compressive residual stress with increased compressive residual stresses occurring in sprays nominal to the stress direction, (ie. Y direction (perpendicular) sprays and X direction stress.)

Conclusions

- AA7050-T7451 and 7075-T651 were repaired using high pressure cold spray
- The 30% repair had ultimate and yield tensile strength approximately 87% of the wrought material
- The compression properties were over 94% of the pristine coupon
- Bending samples showed increased load carrying ability with the repair and no disbondment of the cold spray or cracking through the substrate
- Bearing performance was limited by the yield strength of the cold spray.
- Fatigue performance was investigated
  - Two repair depths were investigated 15% and 30%; both showed an improvement in fatigue life at R=0.1 and R=-1 over unrepaired samples
  - The spray raster that showed the greatest improvement in fatigue life was perpendicular to the loading direction of the sample
    - This fatigue life improvement based on raster direction was greater for samples with wrought material surrounding the repair compared to the repairs with free cold spray edges
    - The majority of the fatigue crack initiated within the cold spray and propagated across the interface into the wrought material
- No heat effect was noted in the samples from microhardness measurements suggesting the heat input is well controlled
- Residual stress does not appear to be greatly changed by the linear raster direction, but other patterns can be detrimental to residual stress.

Questions

- This work is funded by the Office of Naval Research under contract FA70001820015 and subcontract on FA700021D0002 through the Center for Aircraft Structural Life Extension (CAStLE) at the United States Air Force Academy.

- The views and conclusions contained herein are those of the authors and should not be interpreted as necessarily representing the official policies and endorsements, either expressed or implied of the US Air Force Academy or the US Government.