iMAST
Institute for Manufacturing and Sustainment Technologies

NAVY MANTECH
manufacturing technology program

# A2647 – Additive Manufacturing for NAVAIR

## Repair of AV-8B F402 Engine Component due to Fretting Wear

Principle Investigator: Steve Brown

The Aircraft Airworthiness and Sustainment Conference

24 Mar. 2016

AV-8B Harrier



PennState Applied Research Laboratory

CIMP-3D

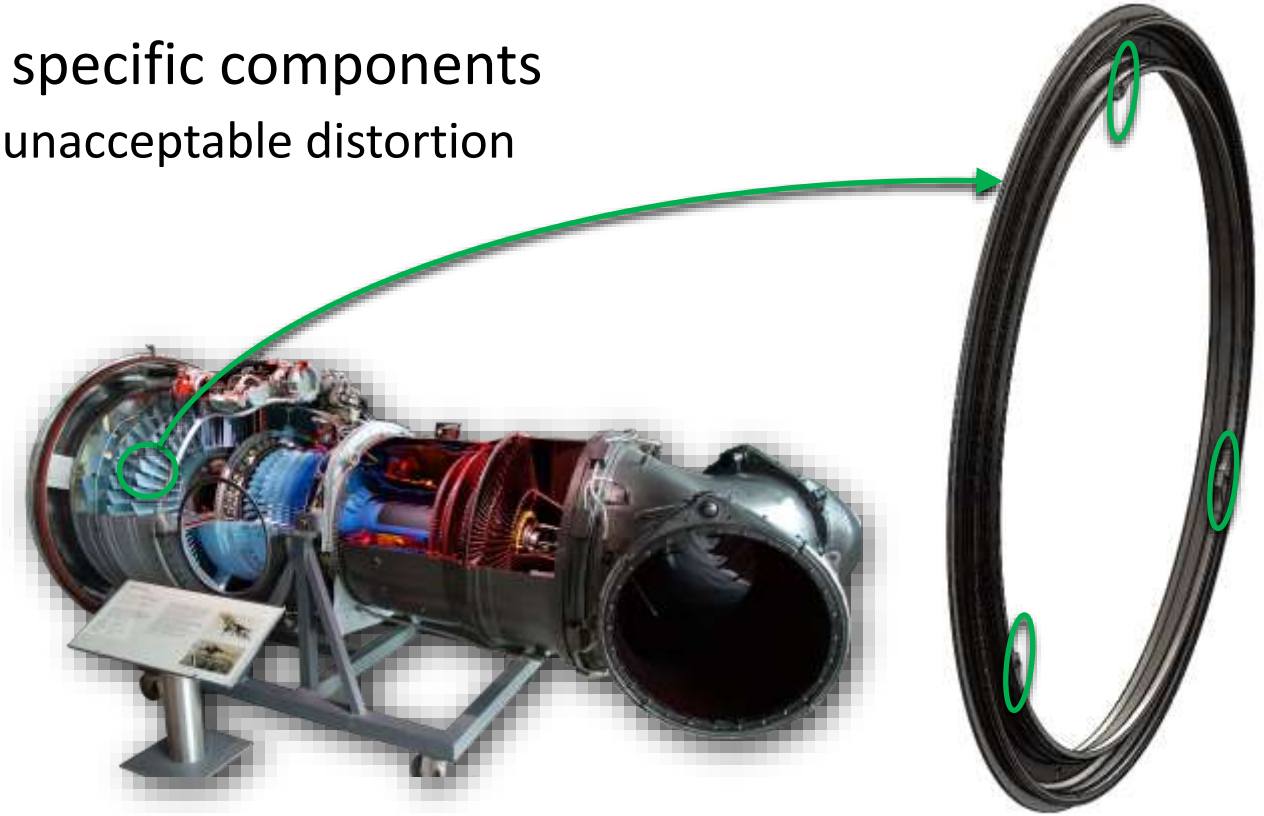
# Issue Description / Project Objective



- Replacement parts, if available, have long (cf. 2 yr) lead times
- Repair procedures are not available on specific components
  - Prior arc-based repair attempts produced unacceptable distortion

## Objective:

- Develop and demonstrate AM repair qualification and certification procedures on a targeted, high-priority component
  - F-402 low pressure compressor (LPC) 2nd stage rear seal ring



# Specific Technical Goals



## Develop a suitable repair process for the F-402 engine's LPC 2nd stage rear seal ring

- Optimize laser-based AM repair processes to meets qualification standards
- Generate, vet, and revise a Qualification Test Plan (QTP)
- Test coupons and full scale articles to reinforce and finalize the QTP
- Generate a technical data package to enable transfer of the process to FRC East

# Benefits / Payoff



## Provide FRC East with a qualified repair for quick implementation

- Replacement sources are limited
- FRC awaits an approved seal ring repair procedure
  - Prior repair attempts via arc-based processes were unsatisfactory

## Provide NAVAIR with a low heat input / low distortion laser-based repair methodology that may be applied to other components

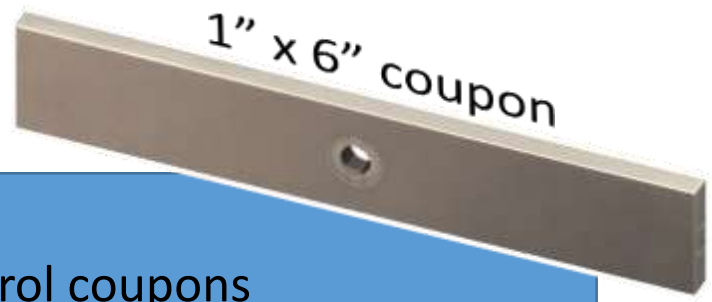
- FRC East regularly repairs parts that are no longer manufactured
- Limited stock of replacement parts may result in delays
- An approved in-house method to produce laser-based repairs is desired

# Project Status / Issues



## Qualification Testing compressed from 9 months to 3 months

- All results appear good; some tests will be repeated




**Initial Test Metrics** (will be changed):

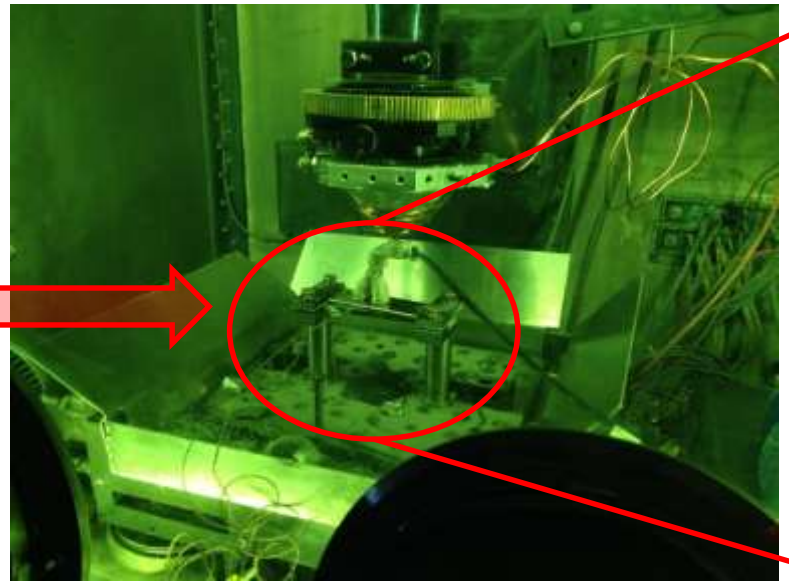
- ✓ X-Ray (limit based on machine resolution)
  - No spherical voids greater than 0.004"
- ✓ Liquid Penetrant
  - No observable defects
- ✓ Overall Distortion
  - Tolerances within 50% from "as-received"
- ✗ Guided Bend
  - Defects ≤ control coupons
- ✓ Macro-Etch (per MIL STD 248)
  - Buildup discontinuities ≤ 10% thickness
- ✗ Wear
  - Wear rate/condition ≤ control coupons

# Test Coupon Preparation



## 1” x 6” x 0.225”

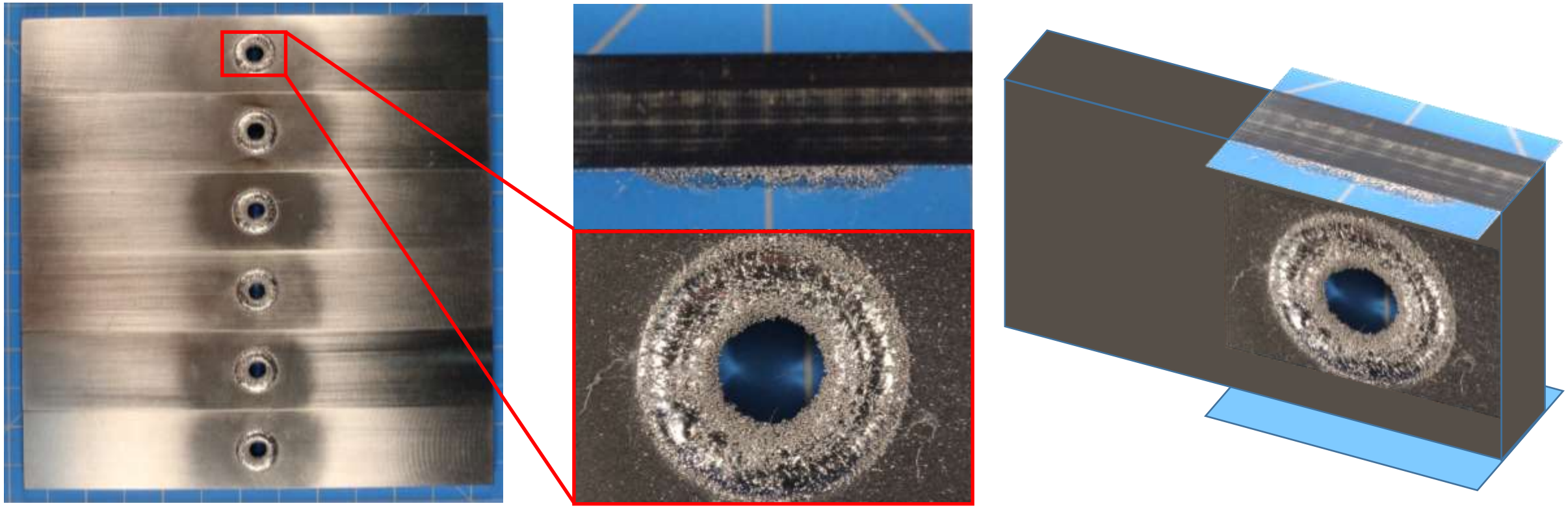

## Optomec LENS system



## Fixture w/ preheater

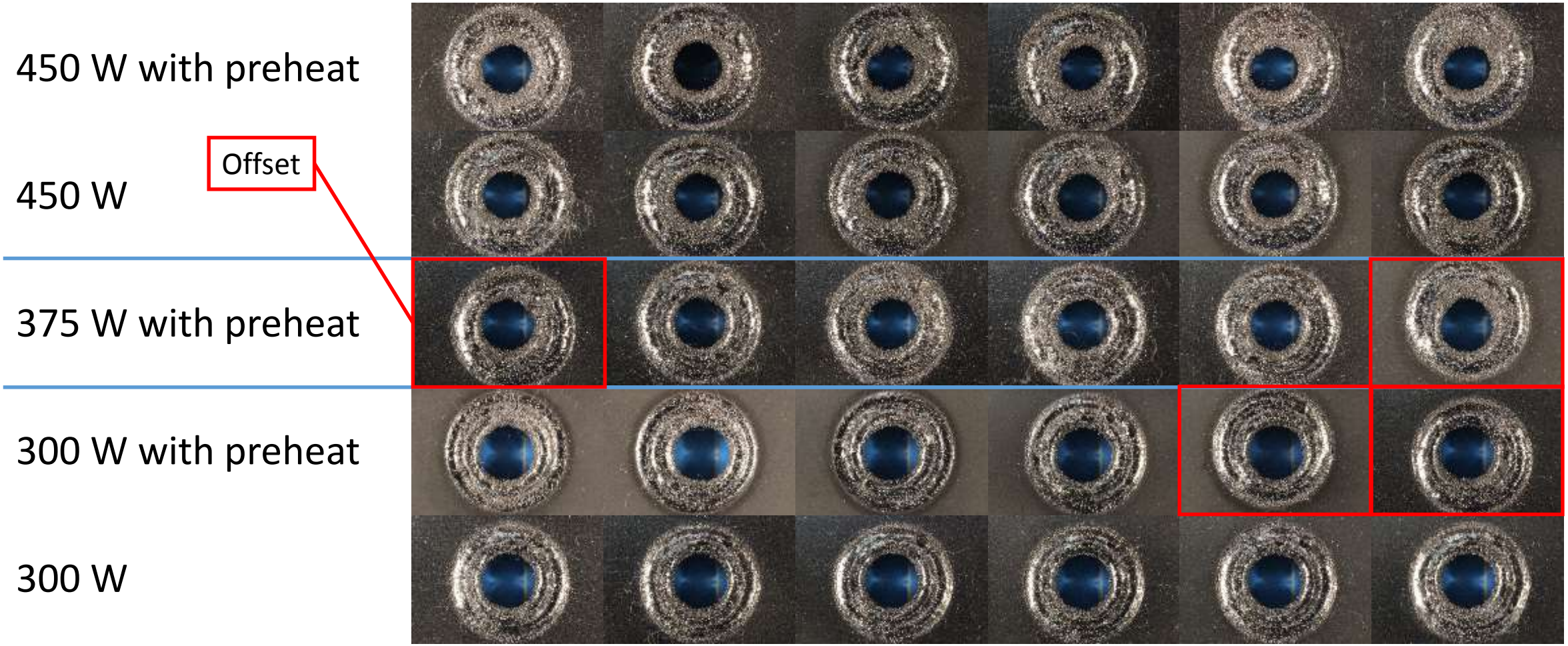
# Coupon Deposition Images





# Coupon Deposition Images





# Coupon Deposition Images



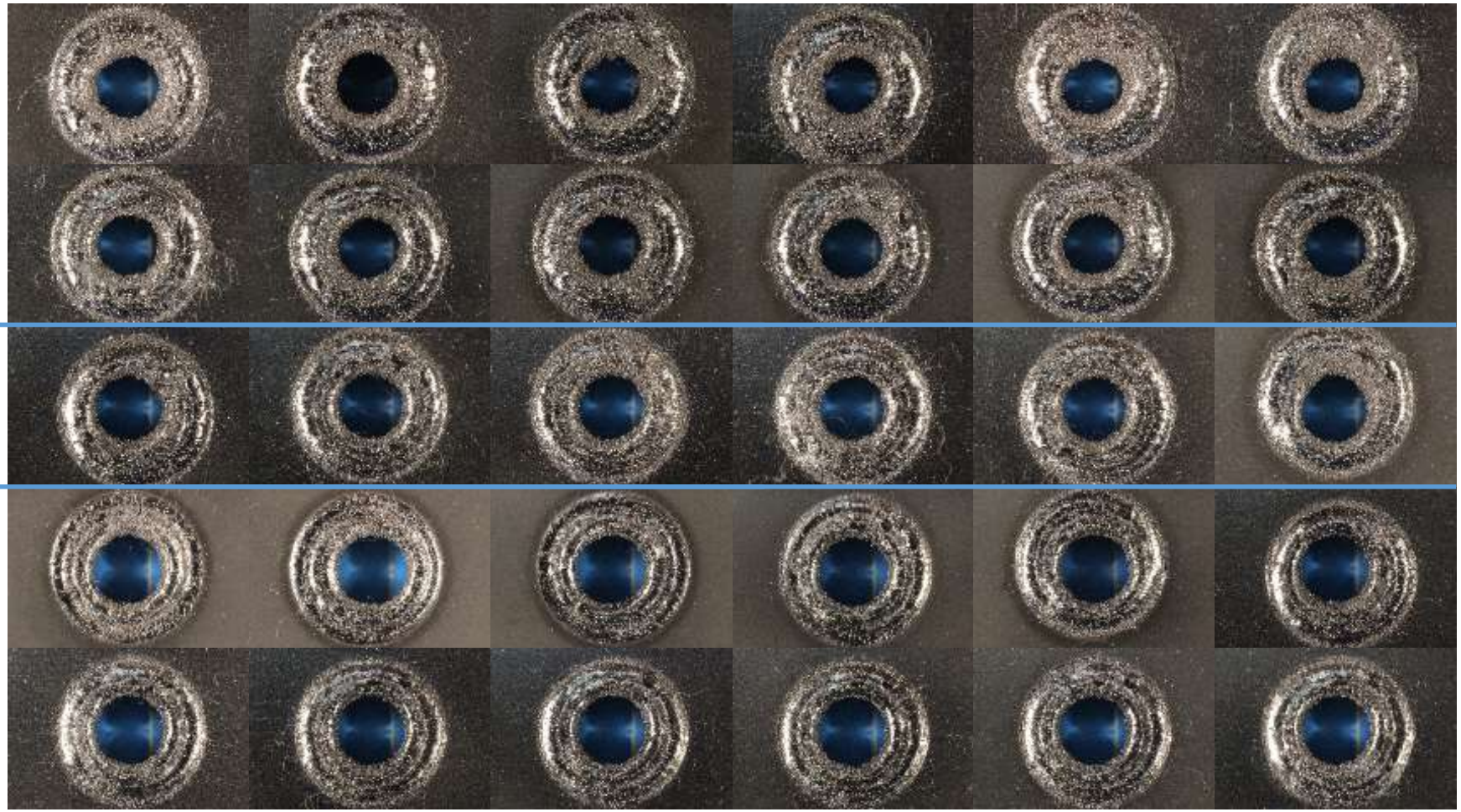
450 W with preheat

450 W

375 W with preheat

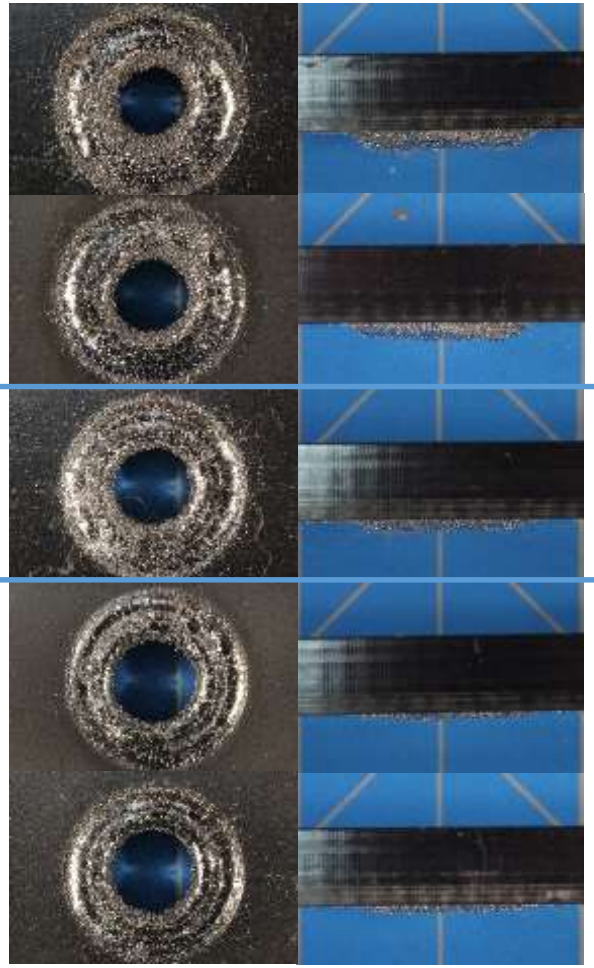
300 W with preheat

300 W



# **Deposition Height** & Layer Thickness





| | |
|---|---|
| 450 W with preheat | **0.059 in**, 4 layers, 0.020 in/layer |
| 450 W | **0.050 in**, 4 layers, 0.017 in/layer |
| 375 W with preheat | **0.035 in**, 4 layers, 0.014 in/layer |
| 300 W with preheat | **0.027 in**, 5 layers, 0.009 in/layer |
| 300 W | **0.023 in**, 5 layers, 0.009 in/layer |

# Predicted Distortion using CUBES



450 W
with preheat

375 W
with preheat

300 W
with preheat


450 W

300 W

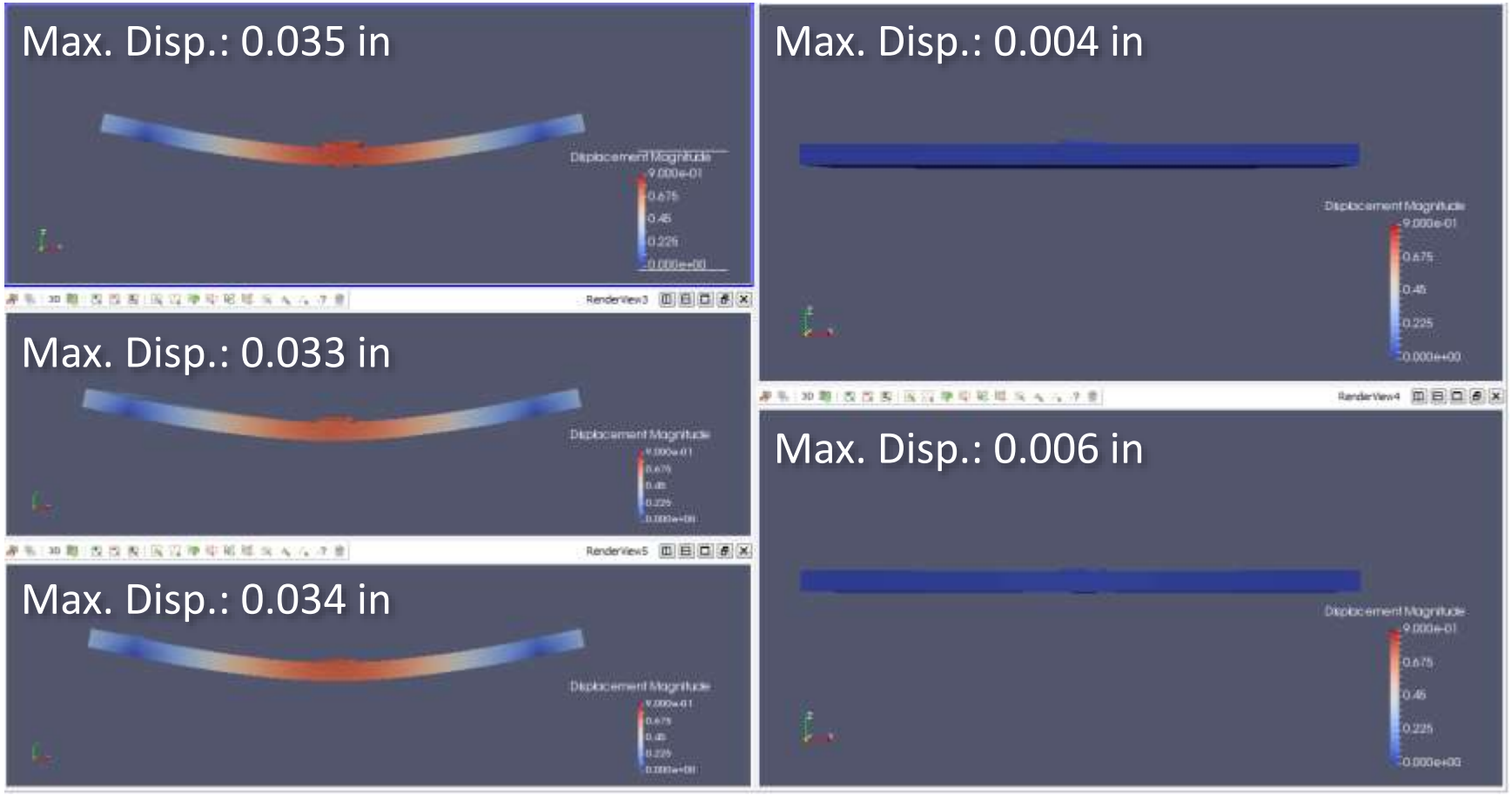
# Predicted Distortion using CUBES



450 W with preheat

375 W with preheat

300 W with preheat

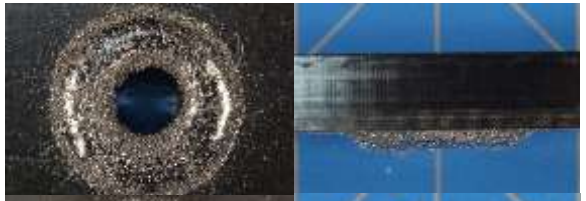
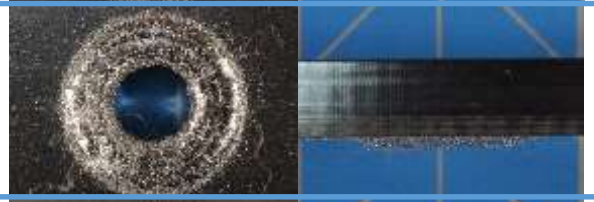
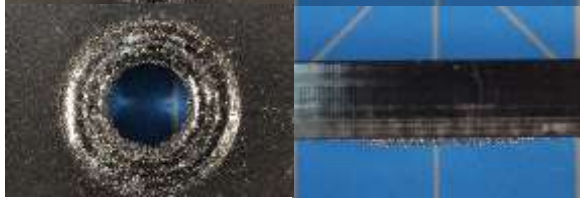



450 W

300 W

# Measured Distortion



| | | |
|---|---|---|
| 450 W with preheat |  | **0.013 in** |
| 450 W |  | **0.019 in** |
| 375 W with preheat |  | **0.016 in** |
| 300 W with preheat |  | **0.024 in** |
| 300 W |  | **0.019 in** |

# Distortion for Parameter Selection

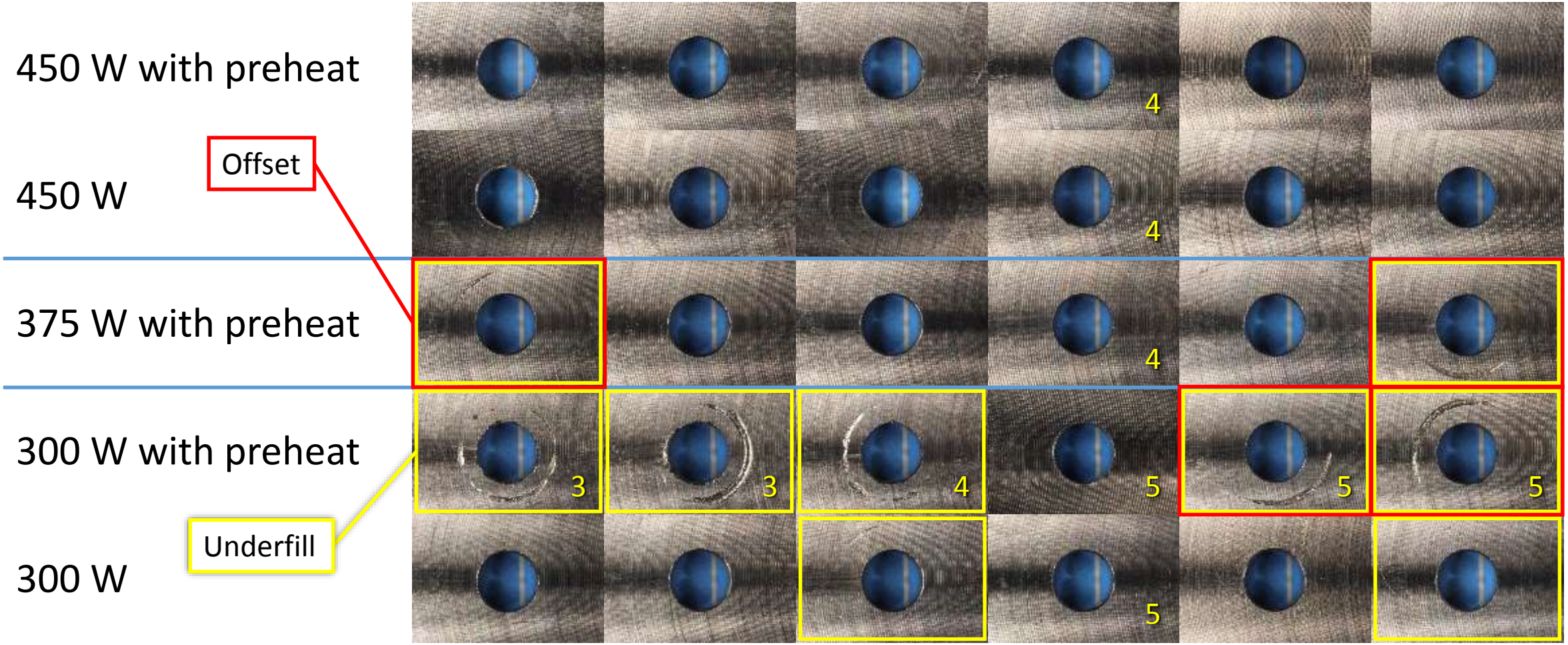


## Conclusions

- CUBES thermo-mechanical finite element analysis (FEA) software is new and tailored specifically to additive manufacturing
- Trend of predicted distortion was unlike trend of measured distortion
- Minimum distortion, as measured from test coupons, corresponded to 450 W with preheat condition
- Acceptability of qualification test metrics will correlate with results specific to 450 W with preheat parameters
- Overall Distortion test will only be conducted using 450 W with preheat parameters

# Machined Coupon Images






Inset numbers: Deposition layers in repair

# X-Ray (Computed Tomography) (Test 1/6)



## Qualification Metric

- No voids greater than 0.004”

# X-Ray (Computed Tomography) (Test 1/6)



# X-Ray (Computed Tomography) (Test 1/6)



## Conclusions

- All coupons were X-Ray (CT) tested
- No porosity greater than 0.004” in 450 W with preheat samples was observed ✓
- Porosity smaller than scan resolution (0.004”) is suspected in most samples, but could not be confirmed
- One pore of ~0.004” was observed in a 450 W (without preheat) sample
- One pore of ~0.005” was observed in a 300 W with preheat sample

# Liquid (Dye) Penetrant (Test 2/6)

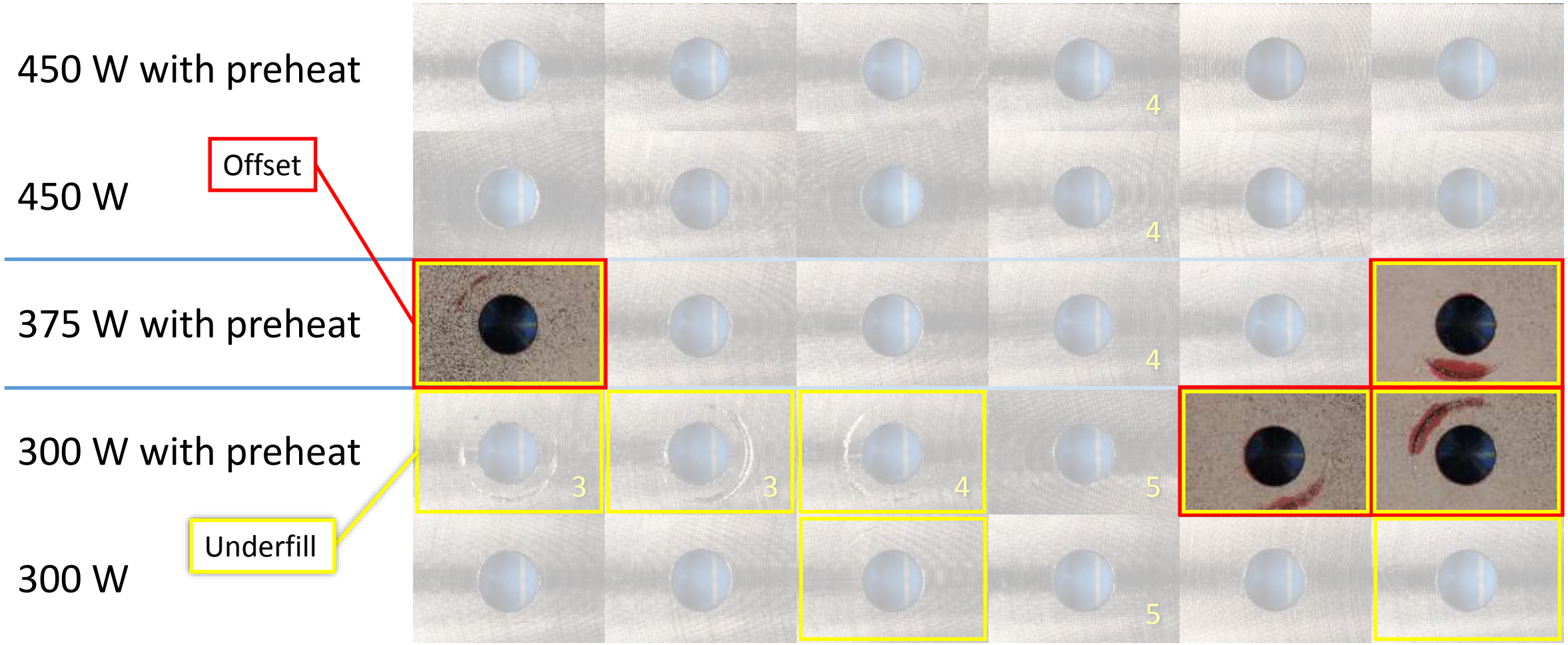


## Qualification Metric

- No observable defects (unaided viewing)

# Liquid (Dye) Penetrant (Test 2/6)





# Liquid (Dye) Penetrant (Test 2/6)



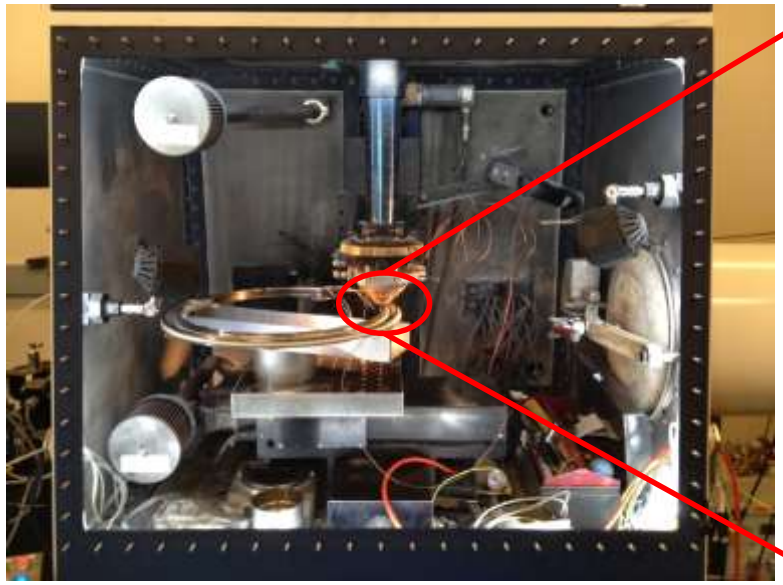
## Conclusions

- All test coupons were dye penetrant (PT) tested
- No indications were observed in 450 W with preheat samples 
- Indications were only observed in the four samples that were repaired with a significant offset between the deposit and the hole/excavation
  - These indications mark lack-of-fusion areas where the deposit did not adequately overlap the substrate excavation wall
  - No lack-of-fusion surface cracks or porosity is thus expected for any of the tested parameters where the deposit is properly aligned with the excavated area, per design

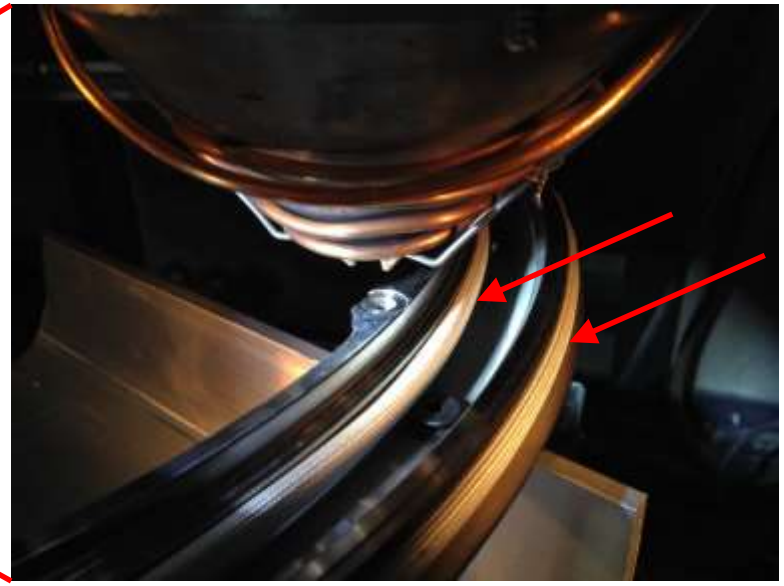
# Seal Ring Preparation

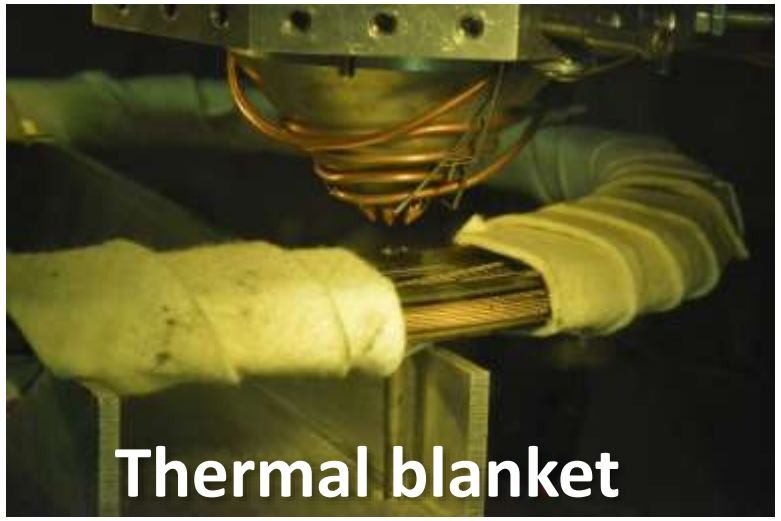



## Optomec LENS system



## Heating cords





# Seal Ring Deposition Images



450 W with preheat






# Radiography of Seal Ring Repairs



## Observation

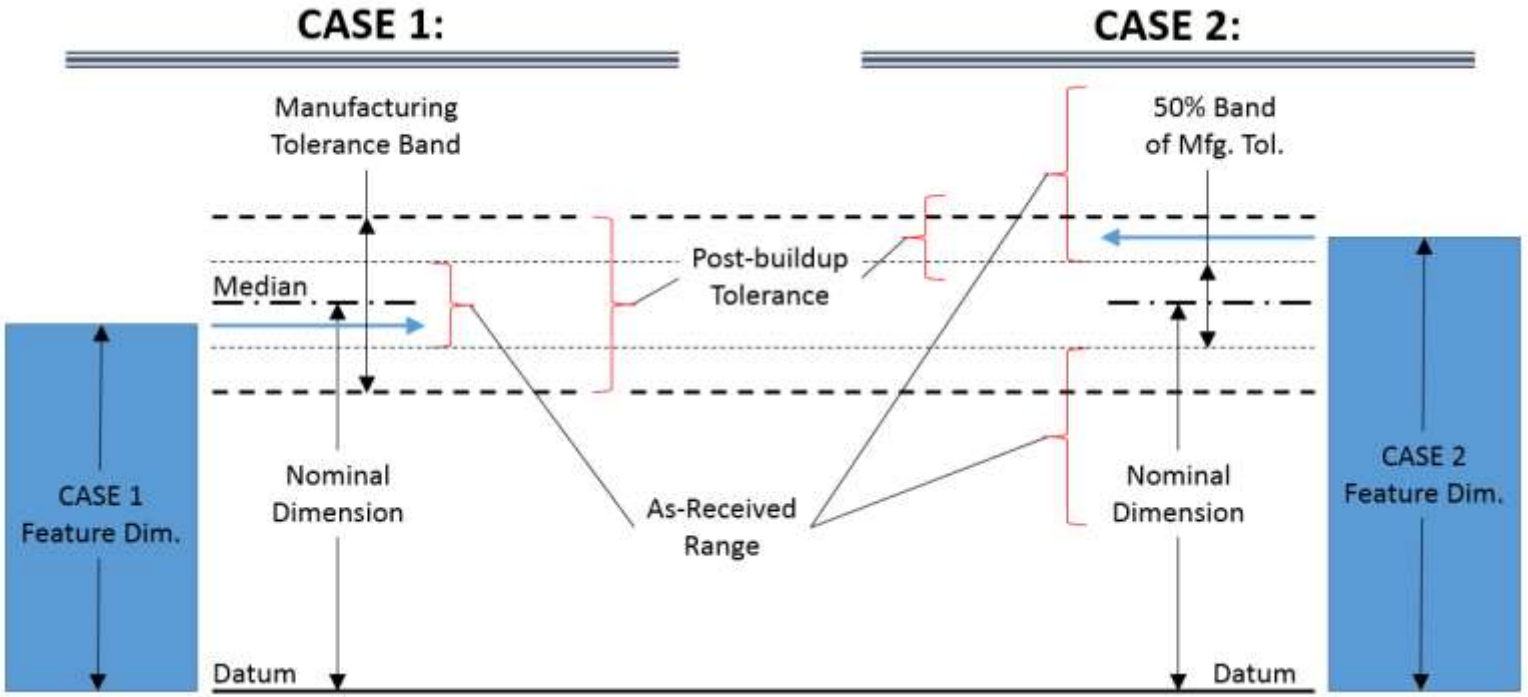
- No voids greater than 0.004” were detected

# Overall Distortion (Test 3/6)



## Qualification Metric

- Tolerances within 50% from “as-received”



# Overall Distortion (Test 3/6)



## Before Repair

QMAC QUALITY MACHINING

PART NAME : 6613011 | January 12, 2016 | 15:26
REV NUMBER : | SER NUMBER : 001 | STATS COUNT : 1

18.6801 DIAMETER

DIM LOC1= LOCATION OF CIRCLE CIR-18.68 UNITS=IN

| AX | NOMINAL | +TOL | -TOL | MEAS | DEV | OUTTOL |
|---|---|---|---|---|---|---|
| D | 18.6801 | 0.0008 | 0.0008 | 18.6791 | -0.0010 | 0.0002 <--------- |

TOP TO DATUM A PARALLELISM

DIM PARL1= PARALLELISM OF PLANE PLN-UNDER,RFS TO PLANE PLN-TOP,RFS UNITS=IN

| AX | NOMINAL | +TOL | -TOL | MEAS | DEV | OUTTOL |
|---|---|---|---|---|---|---|
| M | 0.0000 | 0.0020 | 0.0000 | 0.0023 | 0.0023 | 0.0003 <--------- |

FLATNESS

DIM FLAT1= FLATNESS OF PLANE PLN-UNDER UNITS=IN

| AX | NOMINAL | +TOL | -TOL | MEAS | DEV | OUTTOL |
|---|---|---|---|---|---|---|
| M | 0.0000 | 0.0020 | 0.0000 | 0.0023 | 0.0023 | 0.0003 <--------- |

DIM FLAT2= FLATNESS OF PLANE PLN-TOP UNITS=IN

| AX | NOMINAL | +TOL | -TOL | MEAS | DEV | OUTTOL |
|---|---|---|---|---|---|---|
| M | 0.0000 | 0.0020 | 0.0000 | 0.0014 | 0.0014 | 0.0000 ------#-- |

## After Repair

QMAC QUALITY MACHINING

PART NAME : 6613011 | February 10, 2016 | 14:19
REV NUMBER : | SER NUMBER : 001 | STATS COUNT : 1

18.6801 DIAMETER

DIM LOC1= LOCATION OF CIRCLE CIR-18.68 UNITS=IN

| AX | NOMINAL | +TOL | -TOL | MEAS | DEV | OUTTOL |
|---|---|---|---|---|---|---|
| D | 18.6801 | 0.0008 | 0.0008 | 18.6794 | -0.0013 | 0.0005 <--------- |

TOP TO DATUM A PARALLELISM

DIM PARL1= PARALLELISM OF PLANE PLN-UNDER,RFS TO PLANE PLN-TOP,RFS UNITS=IN

| AX | NOMINAL | +TOL | -TOL | MEAS | DEV | OUTTOL |
|---|---|---|---|---|---|---|
| M | 0.0000 | 0.0020 | 0.0000 | 0.0001 | 0.0001 | 0.0001 <--------- |

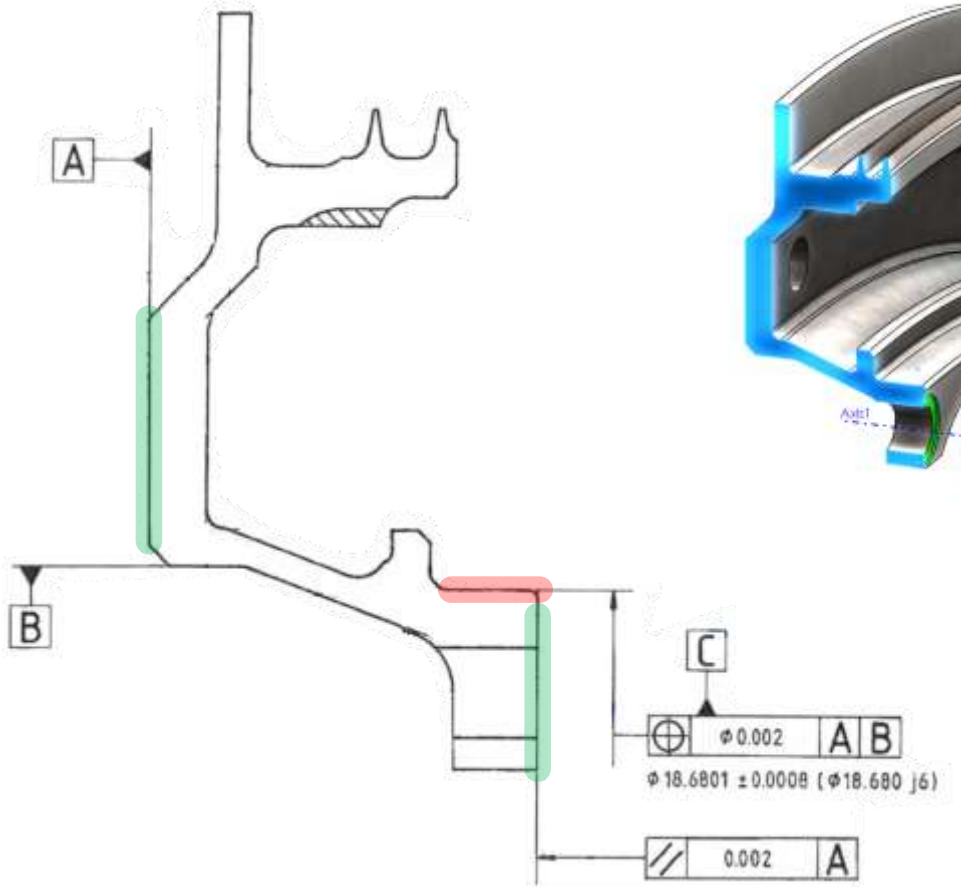
FLATNESS

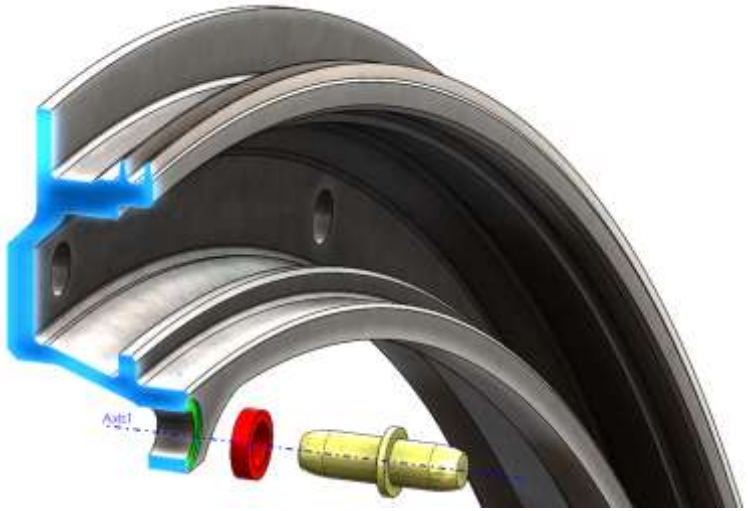
DIM FLAT1= FLATNESS OF PLANE PLN-UNDER UNITS=IN

| AX | NOMINAL | +TOL | -TOL | MEAS | DEV | OUTTOL |
|---|---|---|---|---|---|---|
| M | 0.0000 | 0.0020 | 0.0000 | 0.0021 | 0.0021 | 0.0001 <--------- |

DIM FLAT2= FLATNESS OF PLANE PLN-TOP UNITS=IN

| AX | NOMINAL | +TOL | -TOL | MEAS | DEV | OUTTOL |
|---|---|---|---|---|---|---|
| M | 0.0000 | 0.0020 | 0.0000 | 0.0013 | 0.0013 | 0.0000 -----#--- |



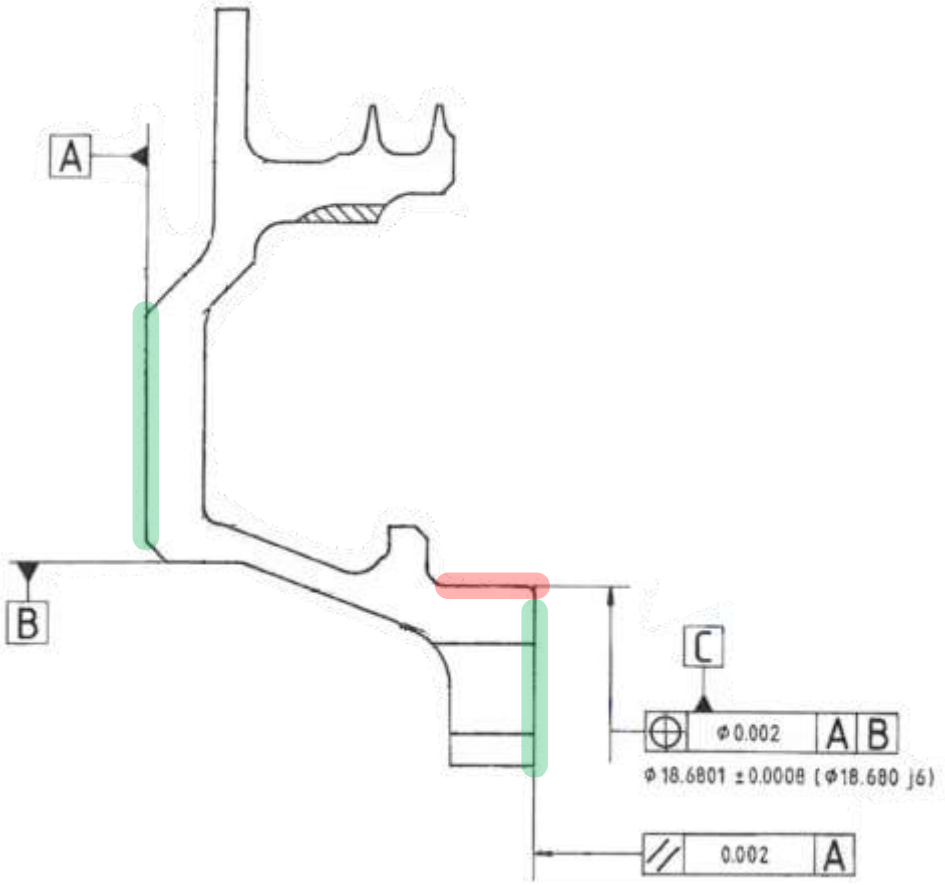



# Overall Distortion (Test 3/6)



| BEFORE REPAIR (Manufacturing Criteria) | | | | | |
|---|---|---|---|---|---|
| | Nominal | Tol. | Meas. | Dev. | Out-of-Tol. |
| Diameter | 18.6801 | + 0.0008<br>– 0.0008 | 18.6791 | – 0.0010 | – 0.0002 |
| Parallelism | 0.0000 | + 0.002<br>– 0.000 | 0.0022 | + 0.0022 | + 0.0002 |

| AFTER REPAIR (Overall Distortion Criteria) | | | | | |
|---|---|---|---|---|---|
| | Nominal | Tol. | Meas. | Dev. | Out-of-Tol. |
| Diameter | 18.6791 | + 0.0004<br>– 0.0004 | 18.6788 | – 0.0003 | |
| Parallelism | 0.0022 | + 0.0005<br>– 0.0005 | 0.0021 | + 0.0001 | |



# Overall Distortion (Test 3/6)



## Conclusions

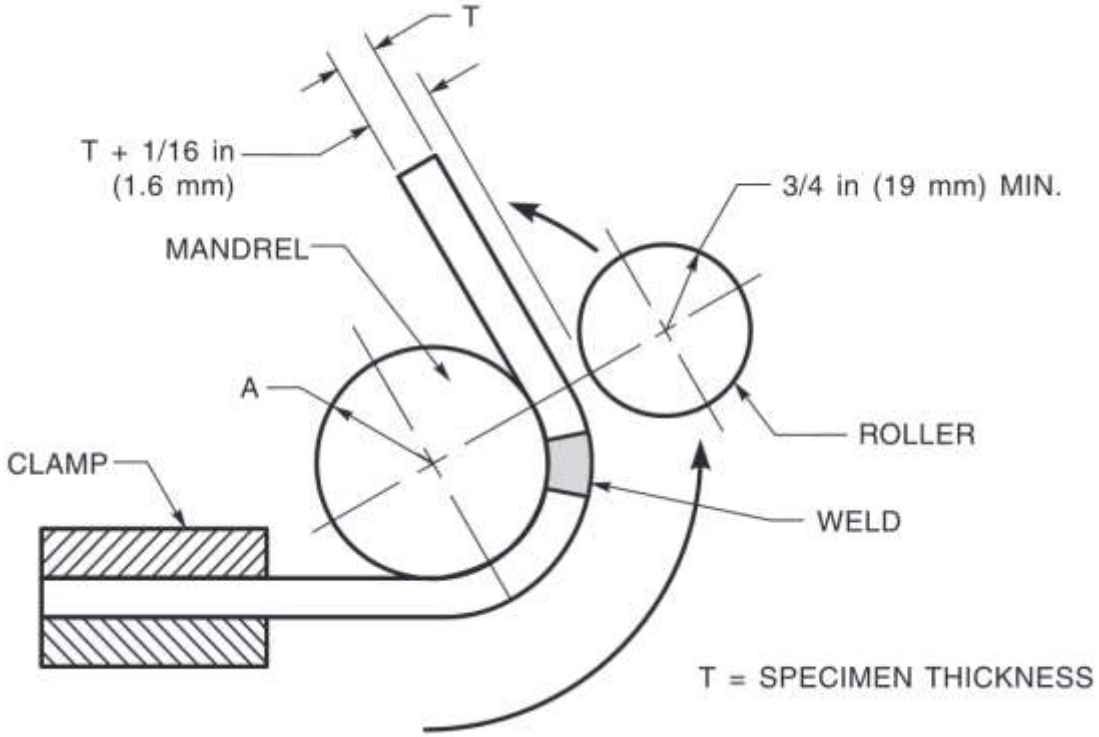
- One seal ring was received for testing
- Diameter and parallelism requirements were both out-of-tolerance upon receipt
- Diameter and parallelism deviations following repair deposition and machining were both within 50% of the manufacturing tolerance band from the as-received state ✓

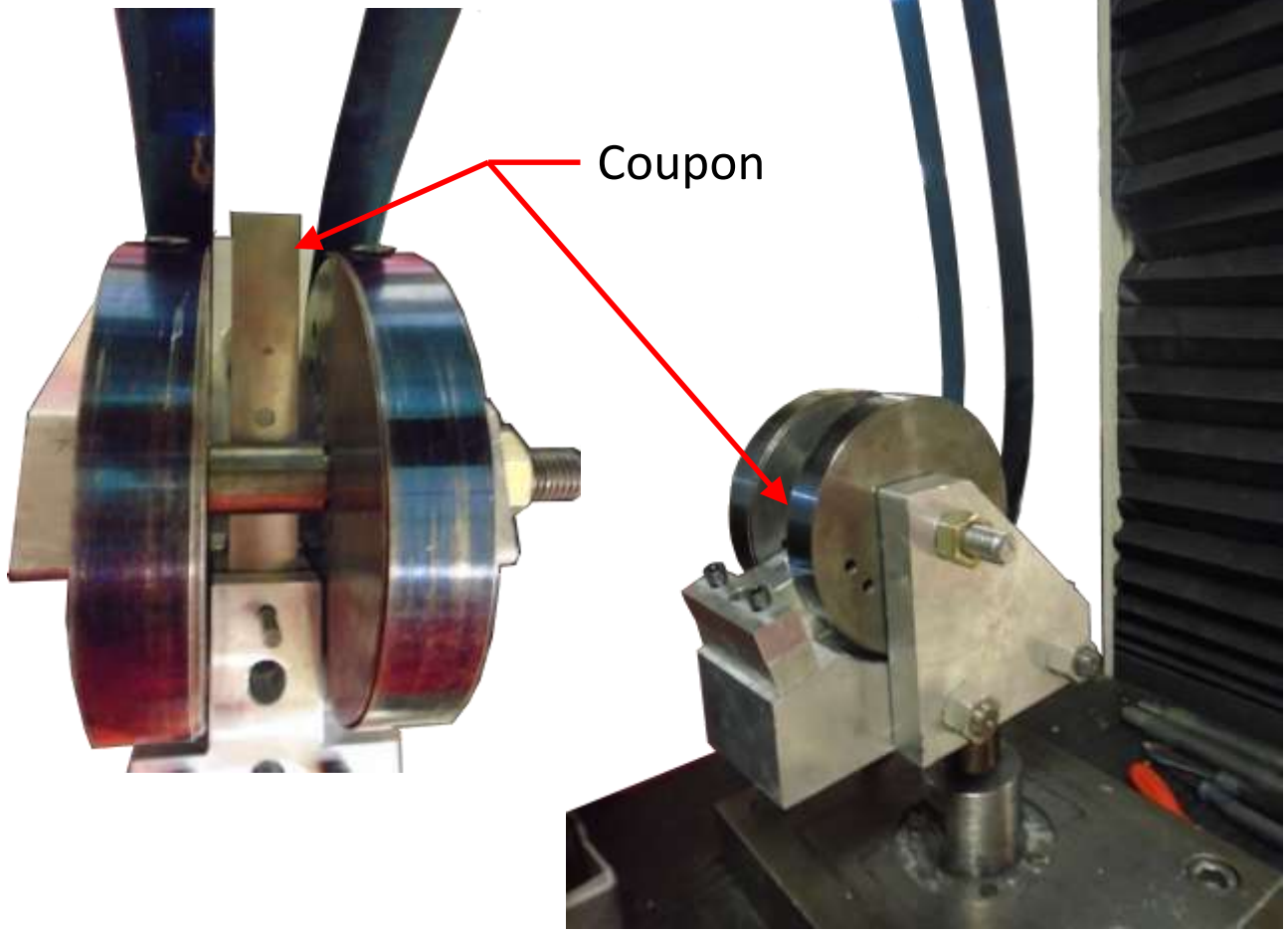
# Guided Bend (Test 4/6)



## Qualification Metric

- Defects ≤ control coupons



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# Guided Bend


(Test 4/6)

NAVY MANTECH manufacturing technology program

450 W with preheat

450 W

375 W with preheat

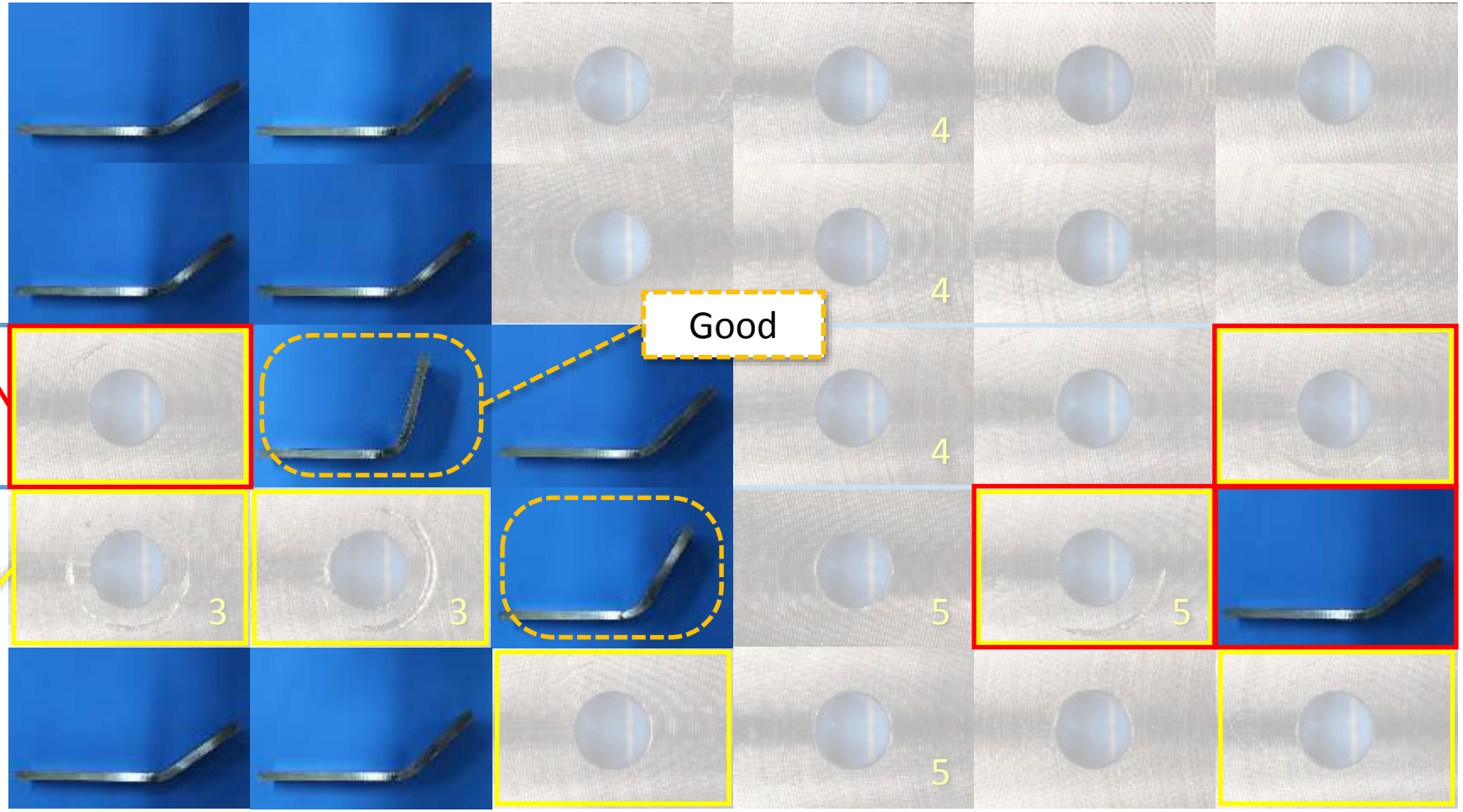
300 W with preheat

300 W

Offset

Underfill

Good



# Guided Bend


(Test 4/6)



450 W with preheat

450 W

375 W with preheat

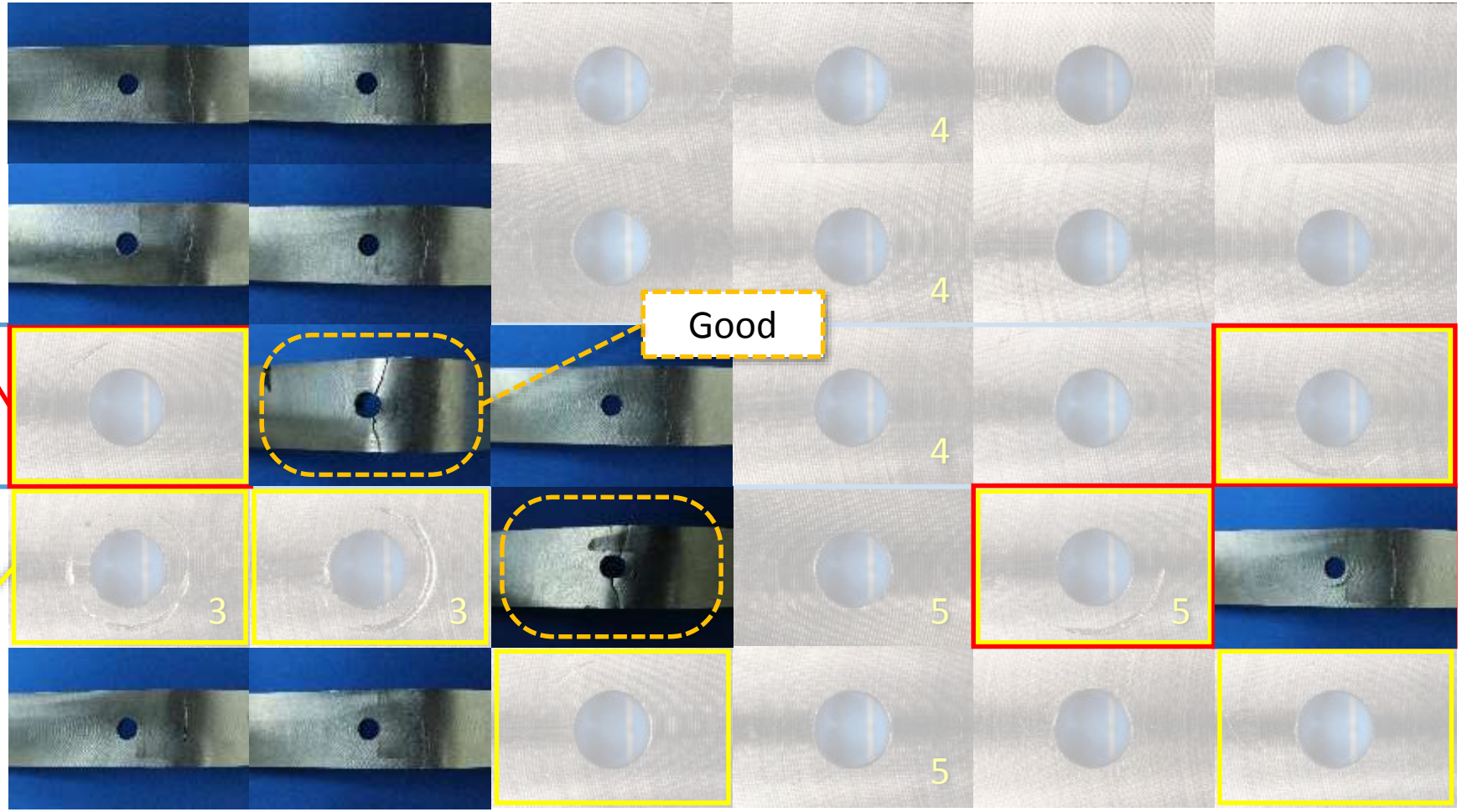
300 W with preheat

300 W

Offset

Underfill

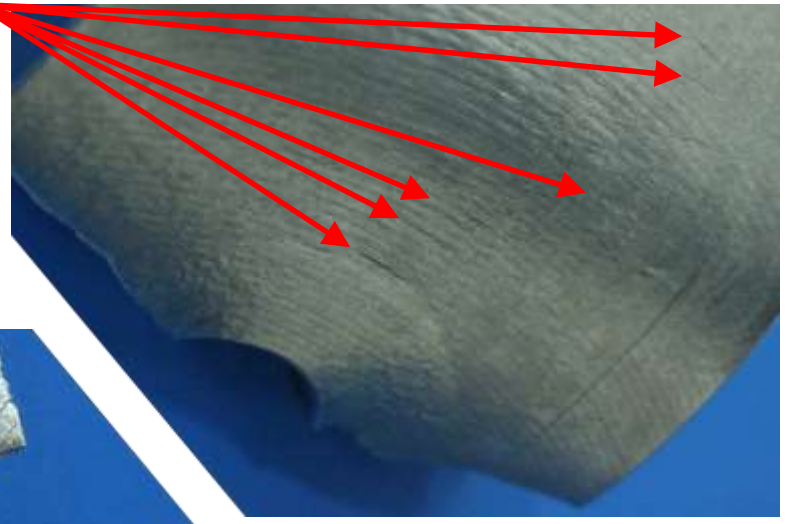
Good



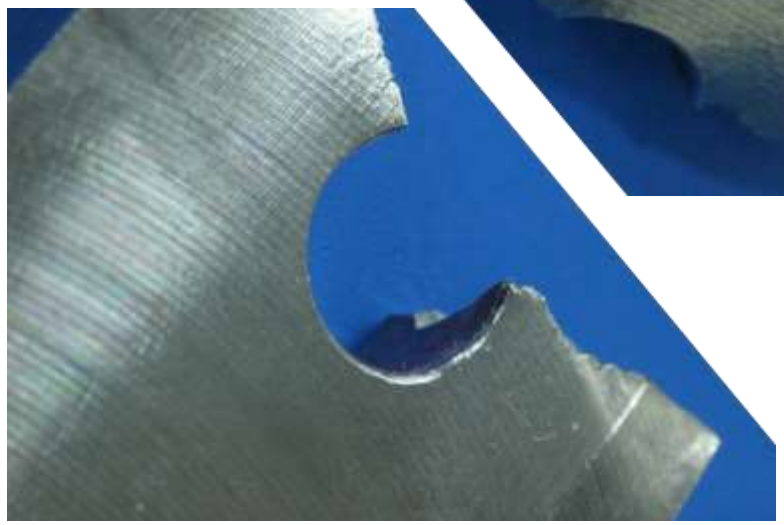
# Guided Bend (Test 4/6)



Cracks



375 W with preheat



# Guided Bend (Test 4/6)



## Conclusions

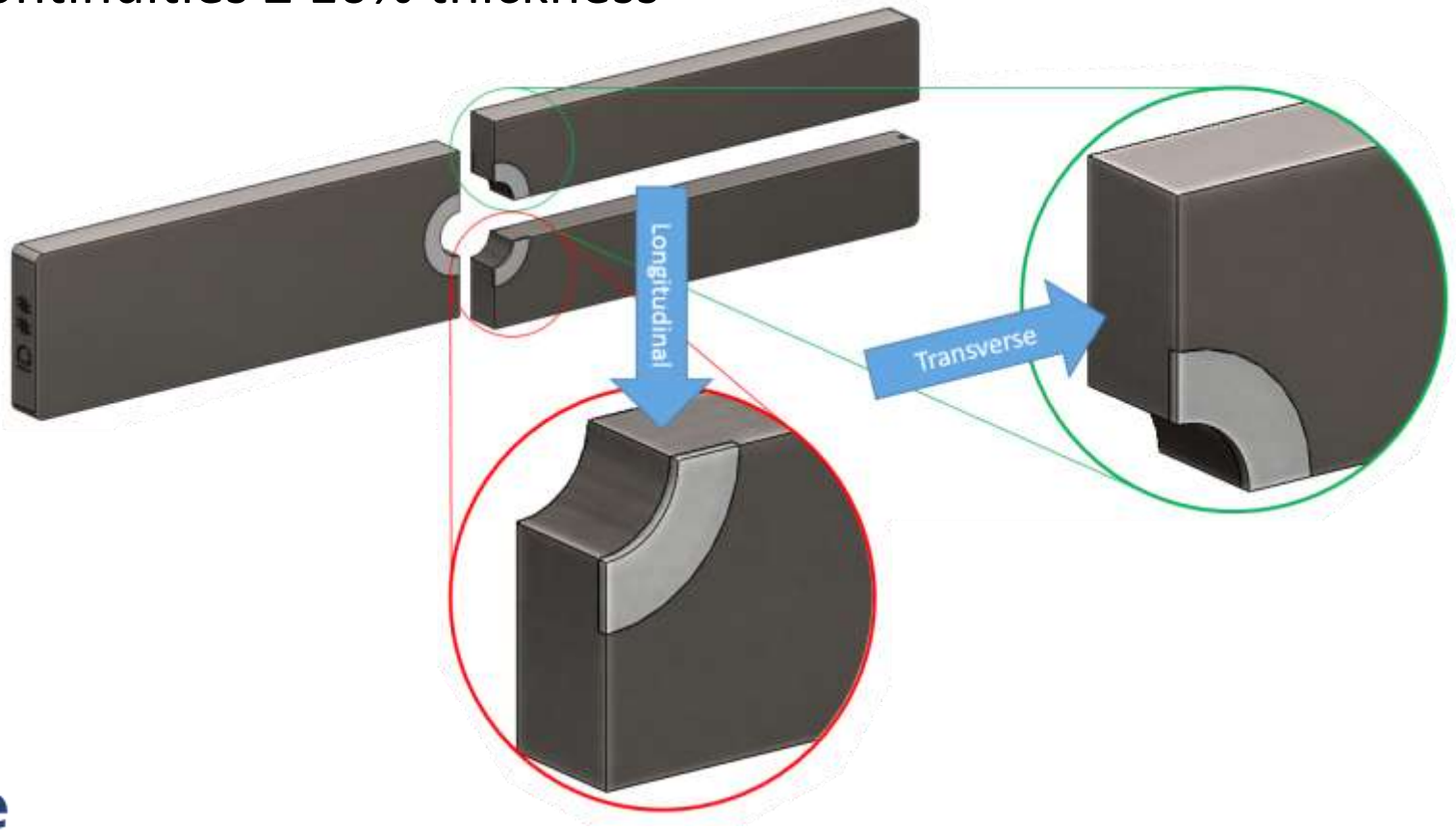
- Two coupons from each parameter set and two control coupons were tested
- All but two coupons yielded prematurely within the substrate providing insufficient insight into the potentially more ductile region beneath the repaired areas
- Coupons (1 ea) prepared at 375 W with preheat and at 300 W with preheat were bent successfully through their repaired regions. Cracking was evident at the onset of bending, well before the repaired regions were stressed
- Cracking was observed at the suspected more-ductile perimeter of the repair region, but was unremarkable compared to prior yielding on the same sample
- Additional bend testing is recommended using a larger mandrel to reduce the elongation and early onset of yielding within the substrate

# Macro-Etch (Test 5/6)



## Qualification Metric

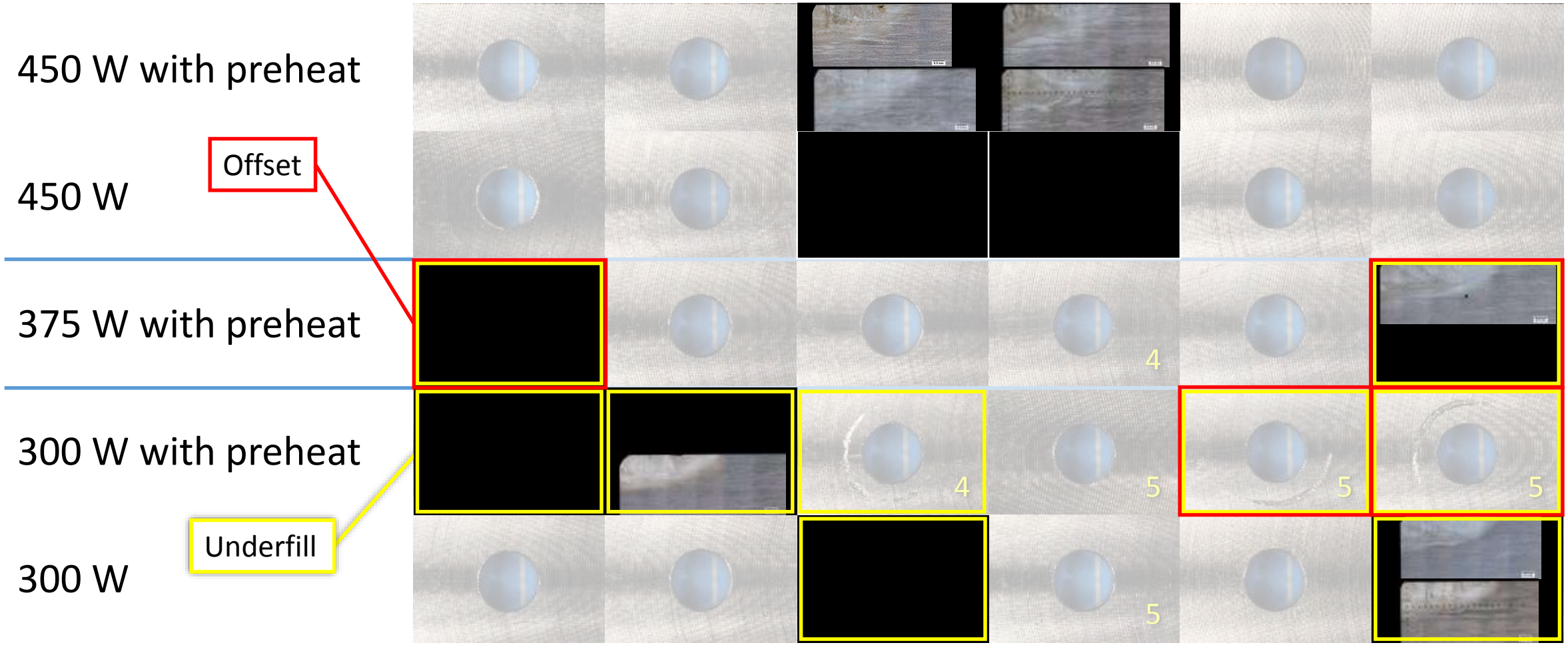
- Buildup discontinuities ≤ 10% thickness



# Macro-Etch

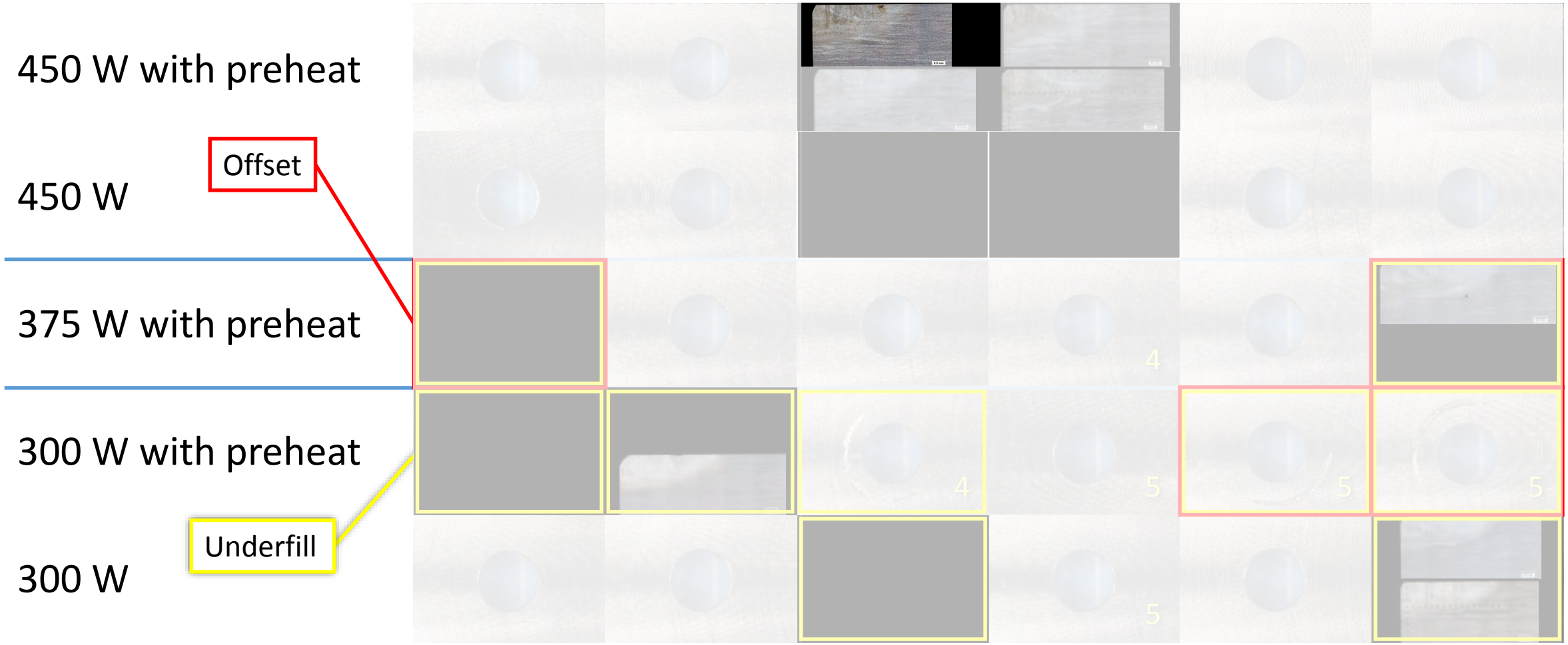
Controls [redacted] (Test 5/6)





# Macro-Etch

Controls [redacted] (Test 5/6)



# Macro-Etch (Test 5/6)



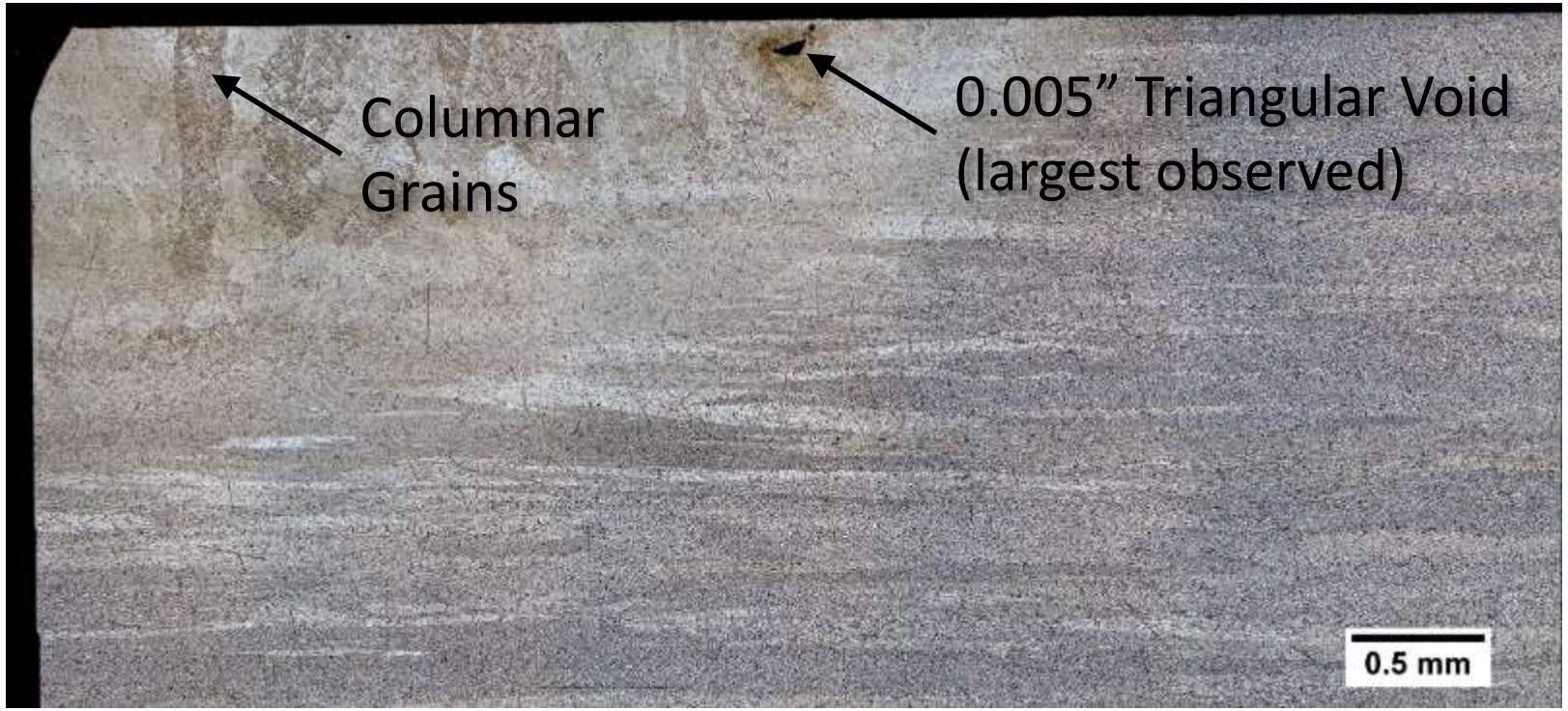
**450 W with preheat**

450 W

375 W with preheat

300 W with preheat

300 W



# Macro-Etch

Controls

(Test 5/6)



450 W with preheat

450 W

375 W with preheat

300 W with preheat

300 W

Offset

Underfill

# Macro-Etch (Test 5/6)



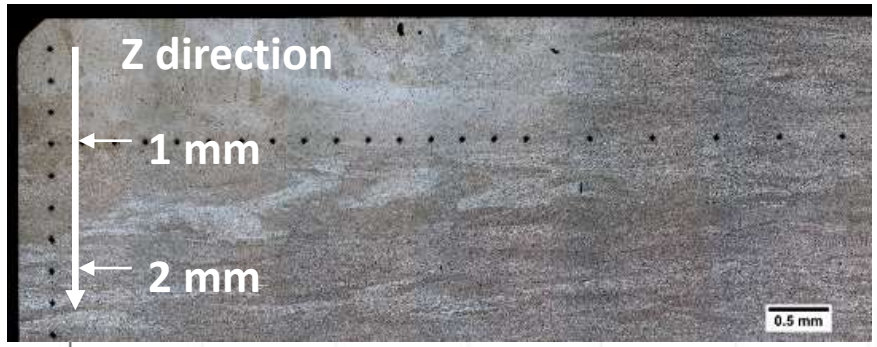
**450 W with preheat**

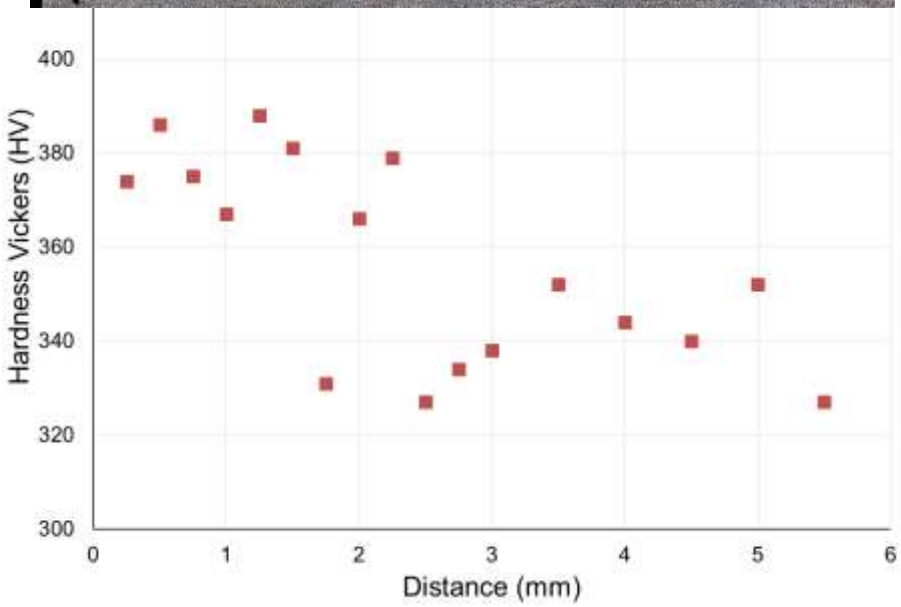
450 W

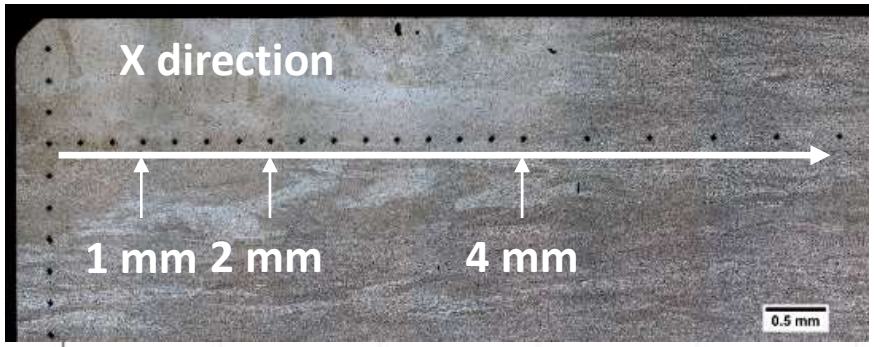
375 W with preheat

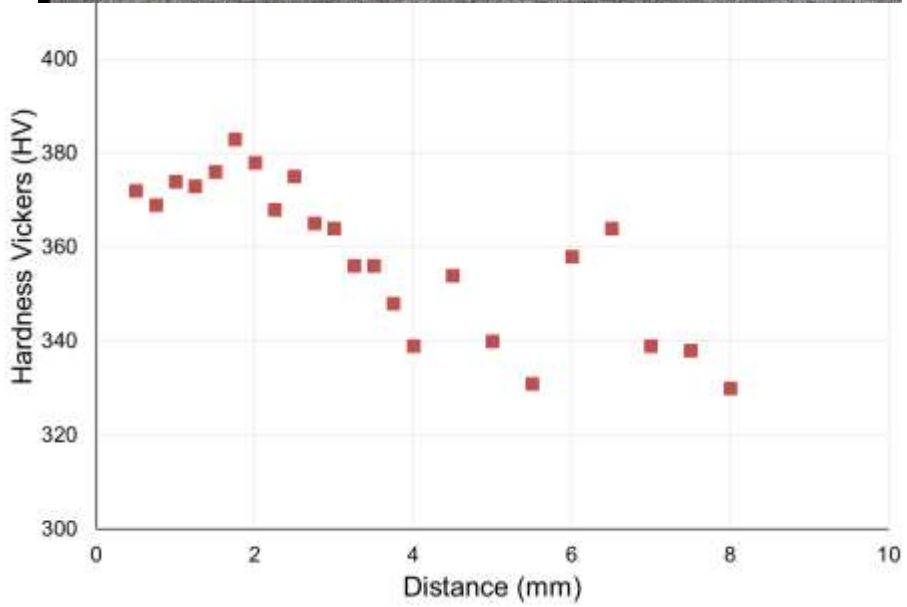
300 W with preheat

300 W



# Macro-Etch

Controls

(Test 5/6)



450 W with preheat

450 W

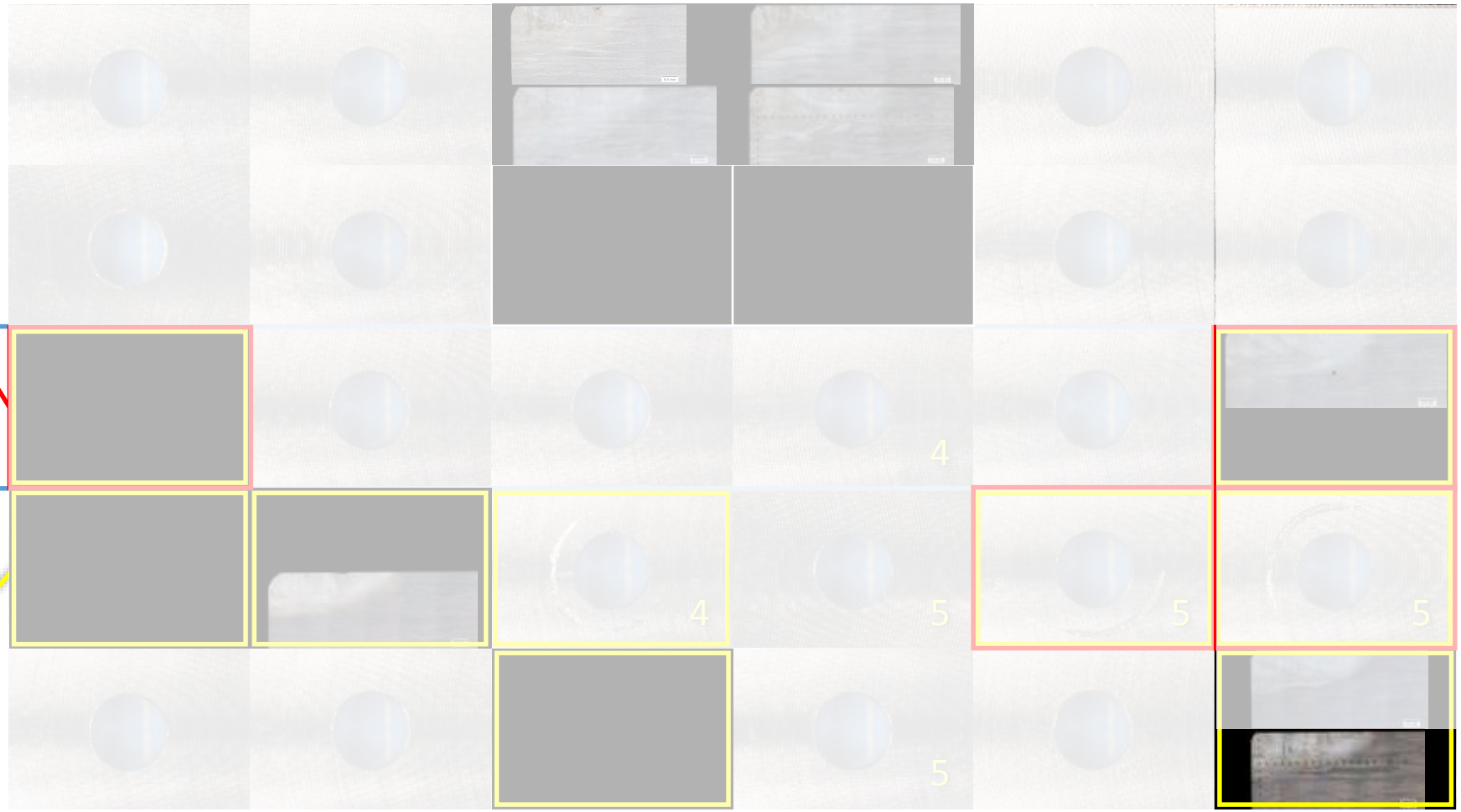
375 W with preheat

300 W with preheat

300 W

Offset

Underfill



# Macro-Etch (Test 5/6)



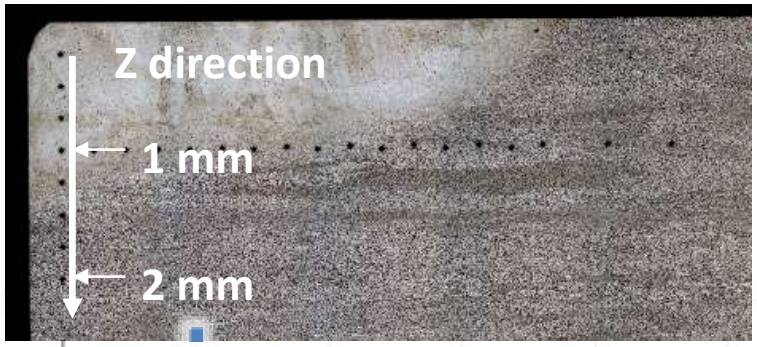
450 W with preheat

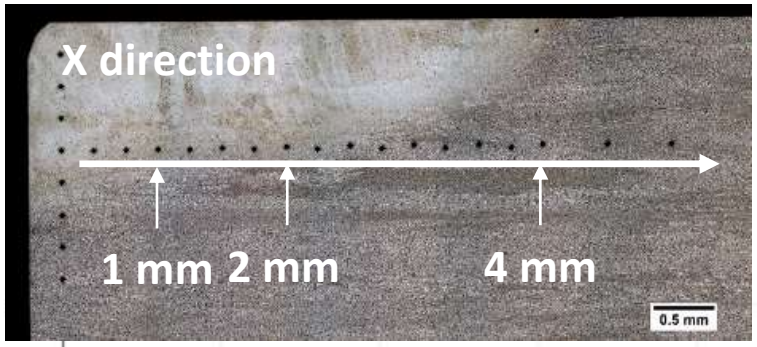
450 W

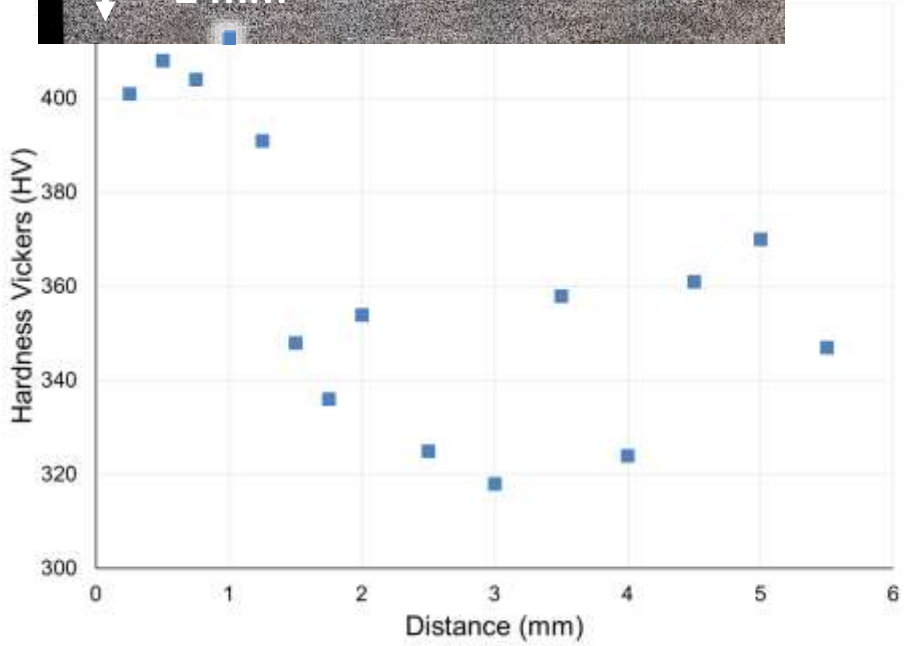
375 W with preheat

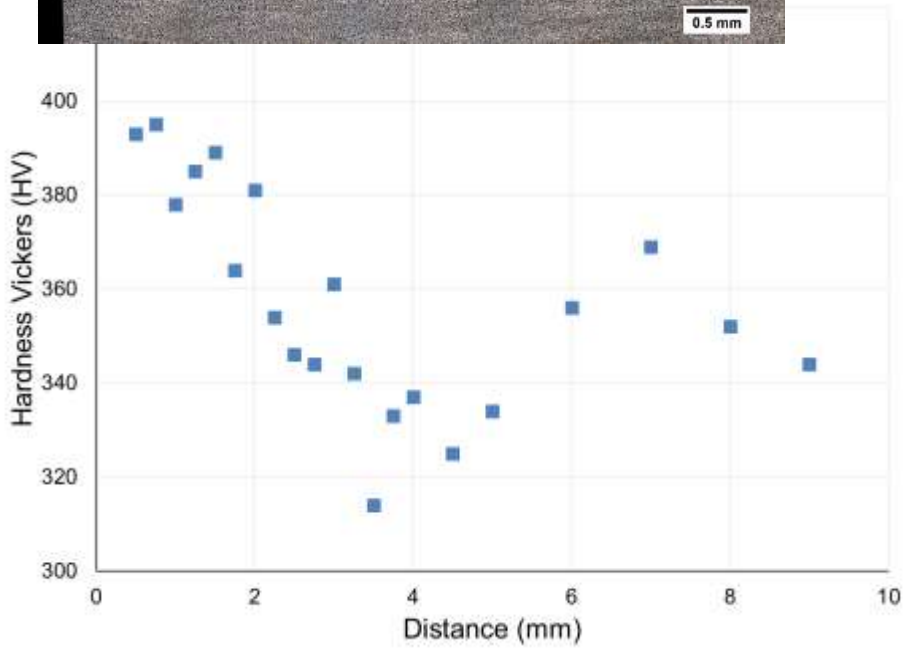
300 W with preheat

**300 W**



# Macro-Etch (Test 5/6)



## Conclusions

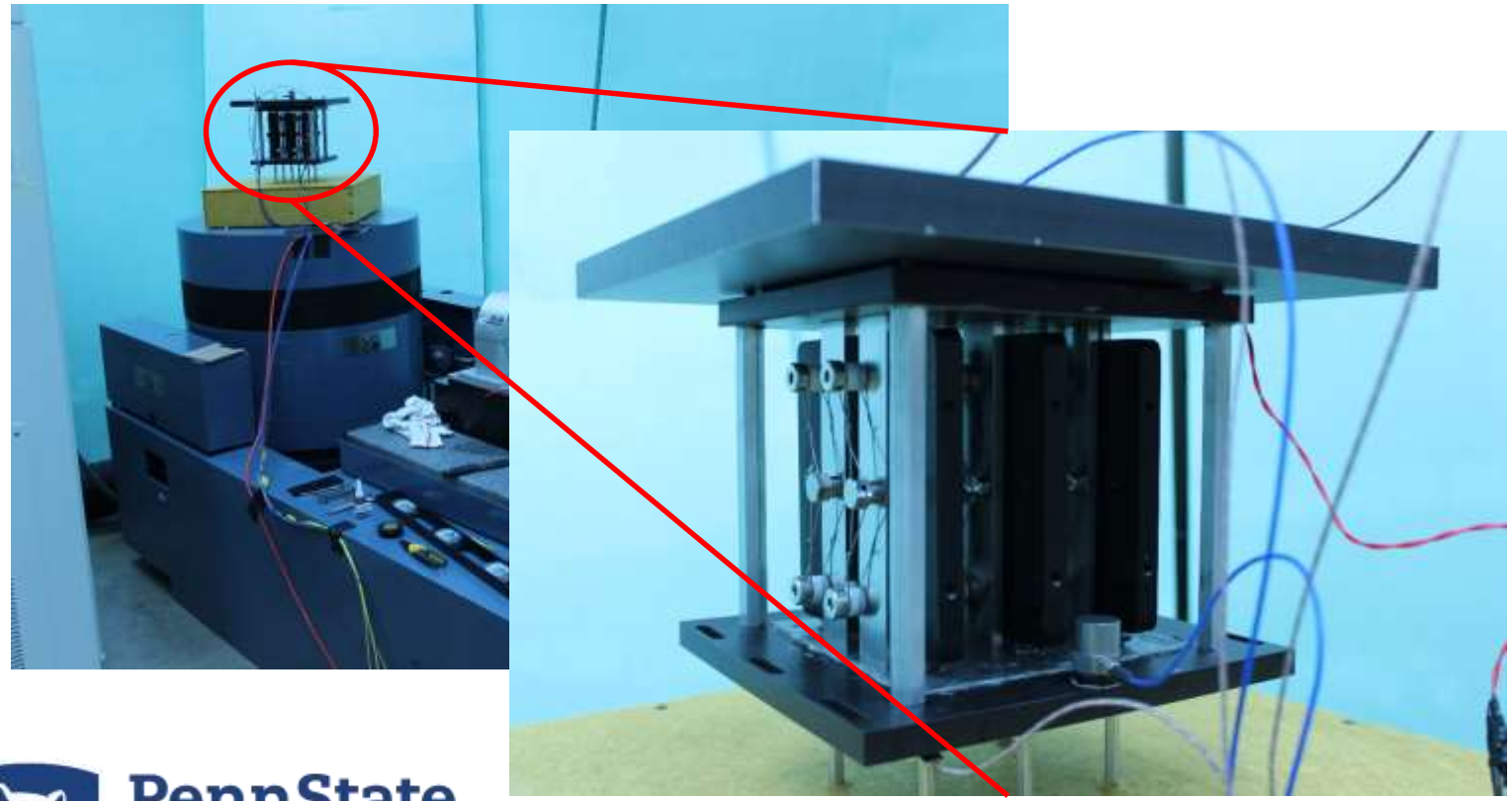
- Ti-6Al-4V repair consisted of columnar prior beta grains oriented in the Z-direction
- Microstructure of the Ti-6Al-4V repair exhibited martensitic like structure
- Hardness in the repair area was higher in the 350 W (no preheat) sample with an average hardness of 407 ± 5 HV
- Hardness in the repair area for the 450 W with preheat sample averaged 378 ± 9 HV
- Hardness for the substrate region for both samples were similar at 348 ± 14 HV
- Possibly some softening observed below the fusion zone in the heat effected zone with hardness dropping to values between 320 and 340 HV
- Some minor porosity was observed within the repair region
- Qualification metric may be updated to reflect Class A acceptance criterion of AWS D17.1, which allows subsurface porosity less than 0.007”

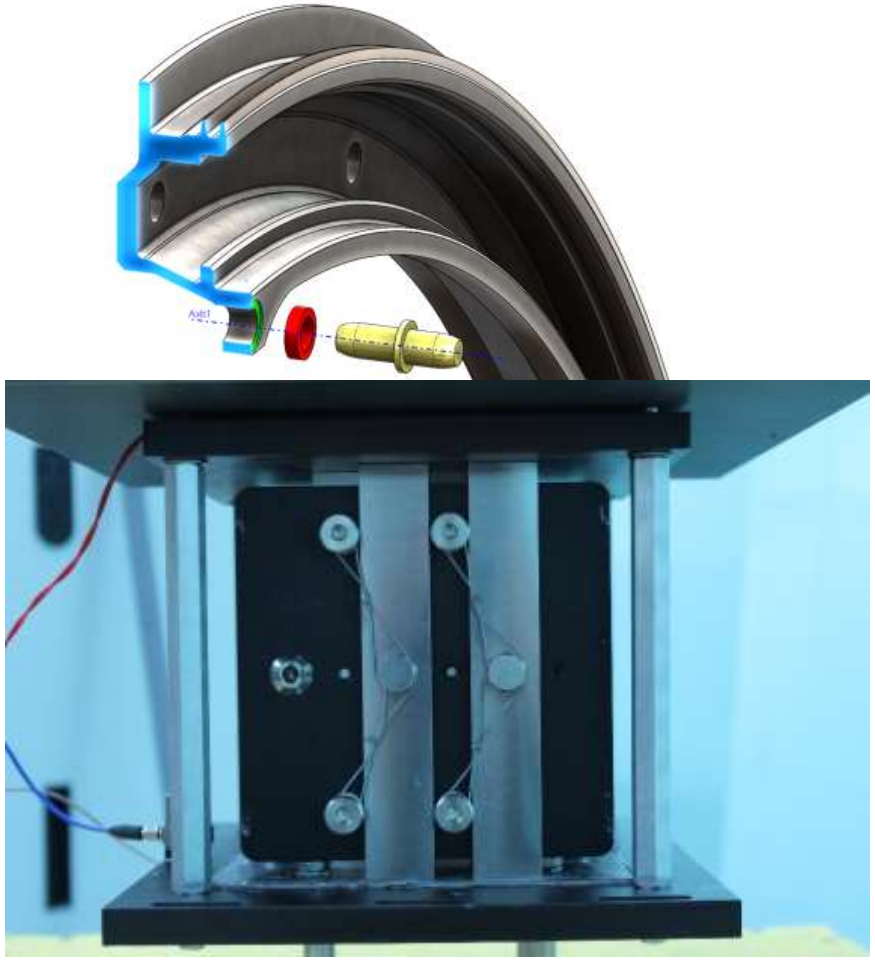
# Wear (Test 6/6)



## Qualification Metric

- Wear rate/condition ≤ control coupons



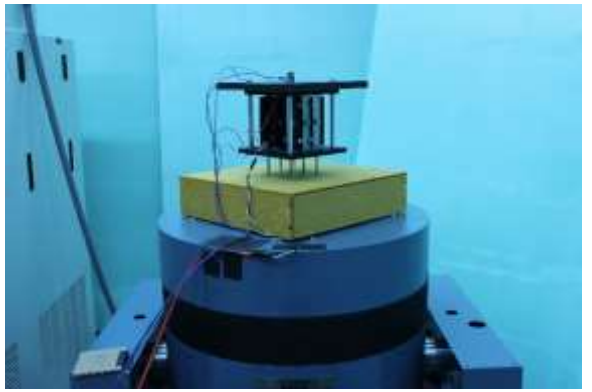


# Wear (Test 6/6)

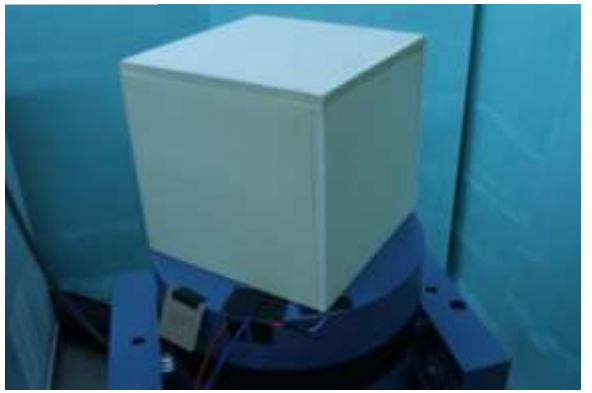


| TEST PARAMETERS | | | |
|---|---|---|---|
| Excitation | Frequency | 100% NL | (nominal engine speed) |
| | Acceleration | > 1 g | (used actual service condition) |
| Temperature | | > 200 °F | (used actual service condition) |
| Test Duration | | 340 hrs | (1/3 service life) |
| Clamping Force | | 260 lbs | (service condition unknown) |

TEST FRAME



OVEN



# Wear (Test 6/6)



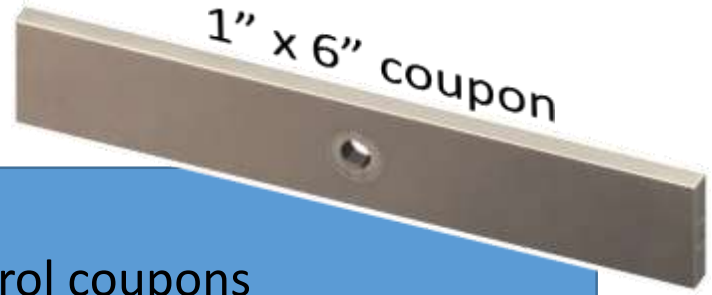
## Conclusions

- Preliminary test coupons tested 12 hrs under clamping force of ~190 lbs showed clear signs of slipping, but samples also seemed unnecessarily loose after test
- Clamping force increased to 260 lbs to accelerate wear of formal coupons
- No evidence of wear was present in any of the test samples after 340 hr test ✓...
- Wear testing must be repeated with verifiable slipping for use in QTP
- Alternate test facilities will be necessary due to competing demands for ARL equipment/facilities

# Updated Qualification Parameters



**Test Metrics** (Updated per AWS D17.1)**:**




- X-Ray
  - Subsurface porosity < 0.33T (0.007")
- Liquid Penetrant
  - No observable defects
- Overall Distortion
  - Tolerances within 50% from "as-received"
- Guided Bend
  - Defects ≤ control coupons
- Macro-Etch
  - Subsurface porosity < 0.33T (0.007")
- Wear (necessity of test in question)
  - Wear rate/condition ≤ control coupons

# Current Project Results



## Conclusions

- Distortion may be used for parameter down-selection, but should come from measured test articles until AM simulation software is improved for titanium
- X-Ray (CT) minimum resolution should be less than minimum porosity requirement (0.007”) to bolster confidence in non-spherical void detection
- Dye-Penetrant and Overall Distortion testing results were satisfied by “450 W with preheat” parameter set
- Guided Bend test showed robustness of additive repairs, but (2T) bend radius was too severe and should be increased to 4T to gather additional results
- Macro-etch testing showed minor porosity at excavation wall that might be alleviated by increasing excavation mill radius
- Wear testing results were non-conclusive, but hardness data and bend test results suggest wear rate would decrease (improve) for additively repaired conditions