Fatigue Life of a NiCr-Coated Powder Metallurgy Disk Superalloy After Varied Processing and Exposures

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1. NASA Glenn Research Center, 2. DVTI, Inc., 3. Vantage Partners, LLC

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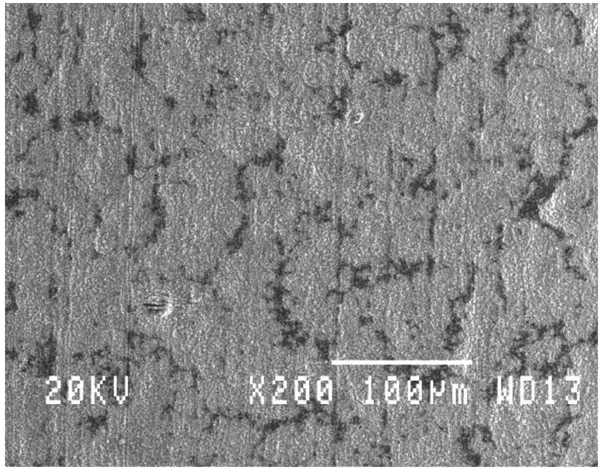
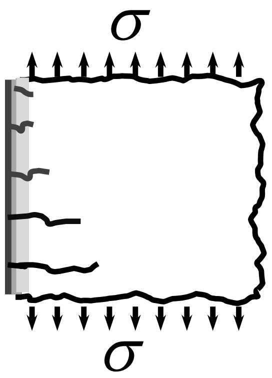
Effects of Oxidation and Corrosion on a Disk Superalloy

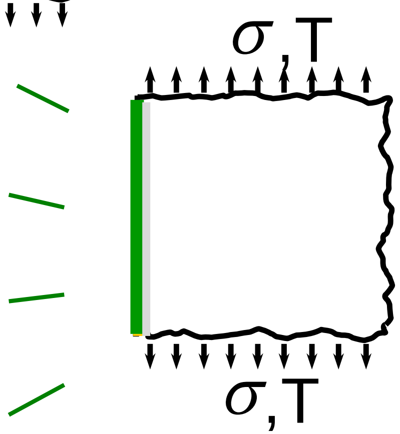
- **Environmental attack by oxidation and corrosion can occur on disk superalloys at temperatures above 700 °C, to impair disk fatigue resistance.**
- **A protective coating could potentially prevent this.**
- **This coating would have to protect disk features at varied stresses and temperatures, and continue to provide protection throughout service life.**

Oxidation Attack



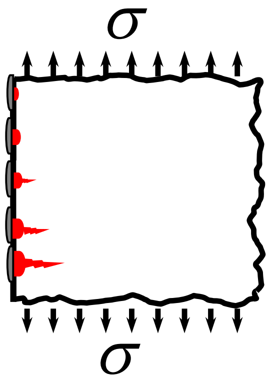


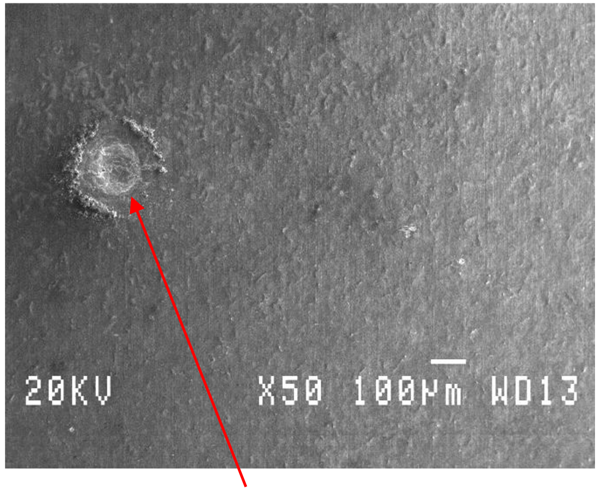
<u>Oxide Scales on Surface</u>: Up to *98 %* Reduction in Uncoated Fatigue Life



<u>Protective Coating</u>

Hot Corrosion Attack

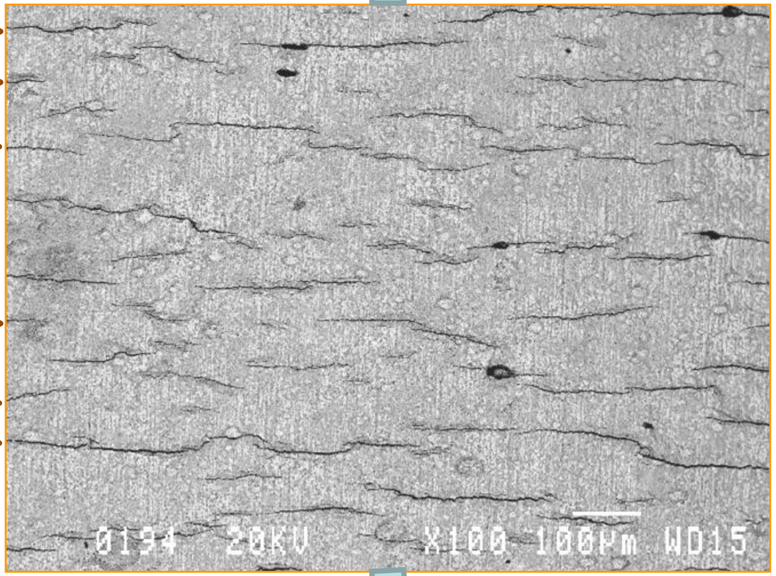




<u>Corrosion Pit on Surface:</u> Up to *98 %* Reduction in Uncoated Fatigue Life

Statement of Problem

Enhanced fatigue cracking



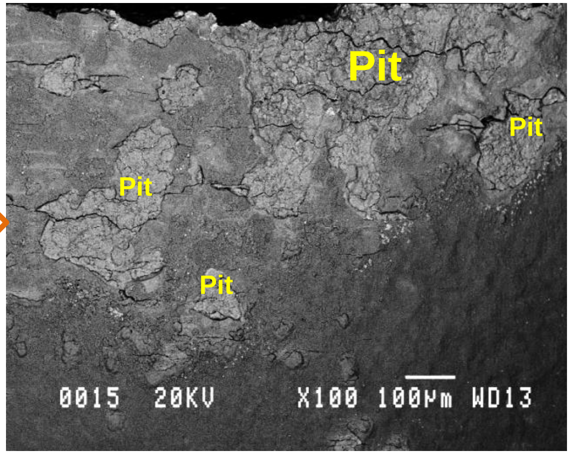
We evaluated a baseline coating process on a disk superalloy using grit blasting to roughen the surface, coating with a Ni45CrY $\gamma + \alpha$ phase coating, shot peening plus heat treatment. In fatigue tests, this gave increased fatigue cracking at the coated surface.

- ***Could this process, possibly with variations, applied with a more ductile NiCr γ phase coating experience less fatigue cracking at the surface?***

Objective

- **Assess this baseline coating process with a more ductile NiCr γ phase coating, considering fatigue life and failure modes, before and after oxidation plus hot corrosion.**
- **Then determine the effects of alternative pre-coating and post-coating process conditions on fatigue life and failure modes.**

Process

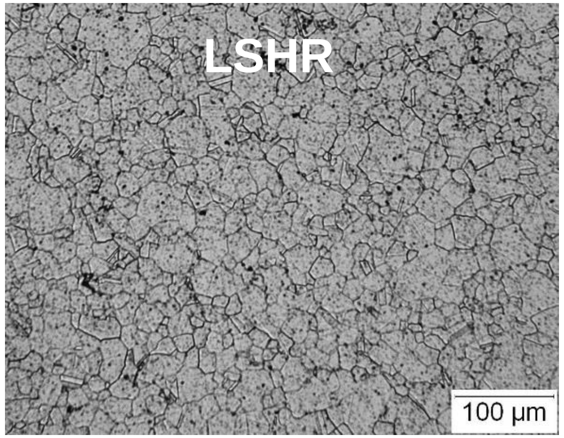


Properties

Processing Procedures

Substrate: Powder Metal Superalloy LSHR

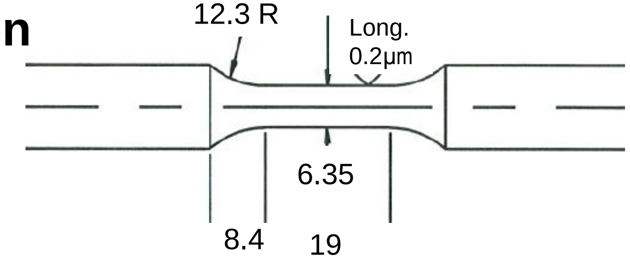
Alloy – weight percent	Al	B	C	Co	Cr	Fe	Hf	Mn	Mo	Ni	Nb	O	Re	Si	S	Ta	Ti	V	W	Y	Zr
LSHR (s)	3.54	0.027	0.045	20.4	12.3	0.1	0.0	0.0	2.71	Bal.	1.49	0.02		0.012	<.0010	1.52	3.45	0.006	4.28	<.0005	0.049



Supersolvus solution heat treated 1171 °C - 2 h, aging heat treated 855 °C for 4 h + 775 °C / 8 h results in 15 µm grain size

Pre-Coat Surface Preparation:

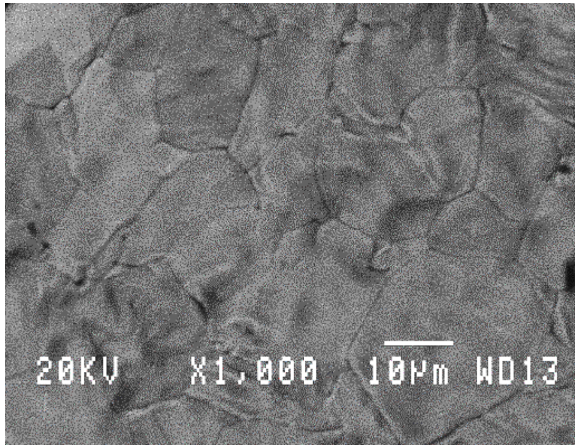
- Cylindrical specimens low stress ground, polished in the axial direction
  - (A) Baseline : grit blasted
  - (B) Alternative treatments: wet blasted or grit blasted + wet blasted?



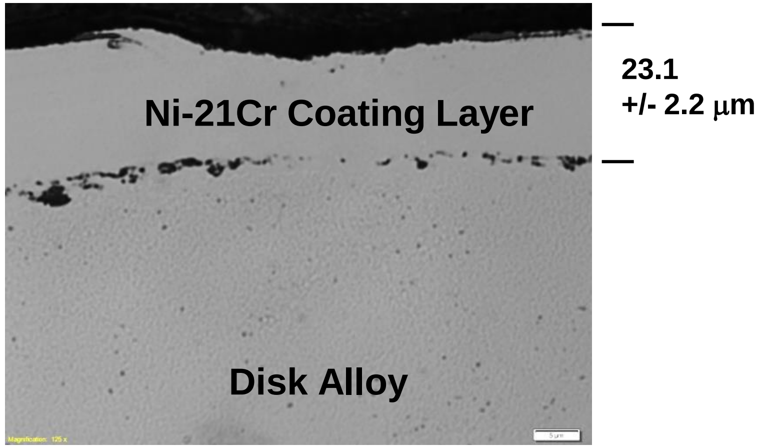
Coating:

- Directed vapor deposition was used by DVTI, Inc. to apply coating of Ni-21Cr (wt. %)

As-Coated Surface



Coated+Shot Peened+Heat Treated



Post-Coat:

- Coated LCF specimens were shot peened with CCW14 steel shot
  - (A) Baseline: 16N intensity, 200 % coverage,
  - (B) Alternative Treatment: 8N-150% coverage?
- Heat treated 760 °C-8 h-low pO_2.

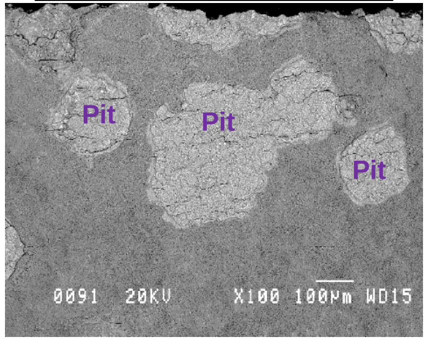
Testing Procedures

- Surface evaluations:
  - Imaging: Scanning Electron Microscope (SEM) JEOL 6100
  - Roughness: Optical interferometer Zygo NewView 7200
  - Residual stresses: X-ray diffraction using a Bruker D8 Discover with GADDS area detector, Mn tube, (311) plane diffraction, target area of 1.25 mm^2 and sampled depth of 13.5 μm (90 % of diffracted rays).

- Oxidation: 760 °C – 500 h in lab air

- Hot Corrosion:
  - A mixture of 59 wt. % Na_2SO_4 - 41 wt. % $MgSO_4$ salt, at 2.0 mg/cm^2.
  - Specimens were exposed in air at 760 °C for 50 h: this consistently produced pits in uncoated specimens.

Uncoated, Corroded



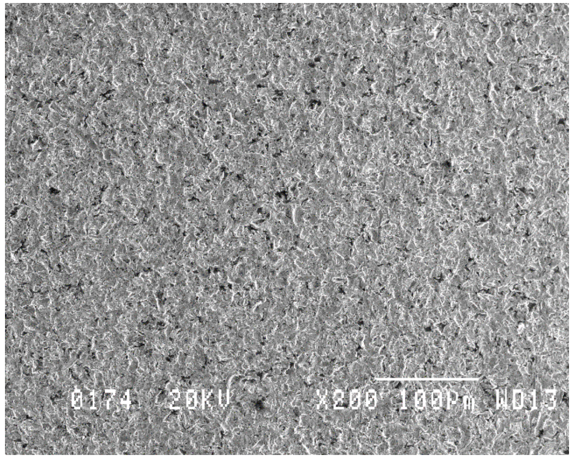
- Fatigue cycling:
  - Axial stress cycled between +841 MPa / -427 MPa at 0.33 hertz, 760 °C.

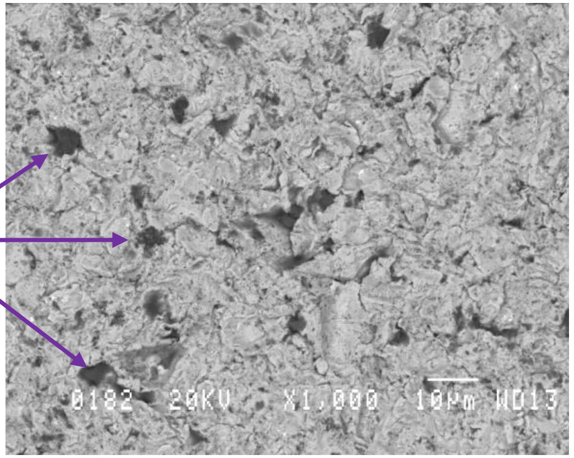
Results

A. Effects of (A) baseline preparation steps (Pre-Coat grit blast, Coated, shot peened) on surface conditions and fatigue life.

↑ **Axial Loading Direction** ↓

Pre-coating

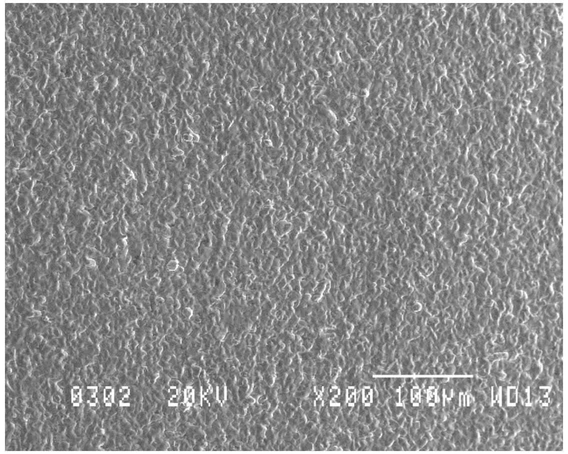


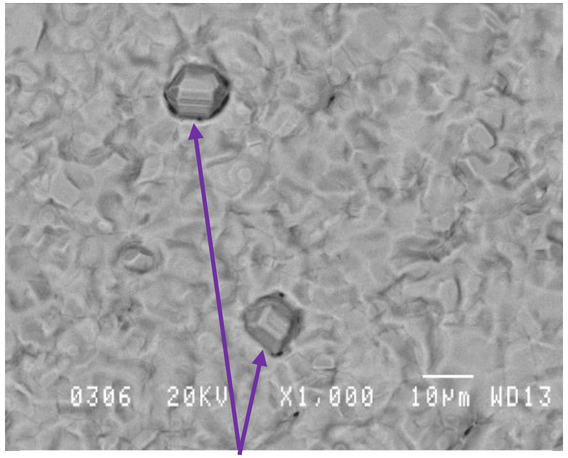


Grit: Dark particles are embedded alumina grit

Grit Blasted 220 grit Alumina

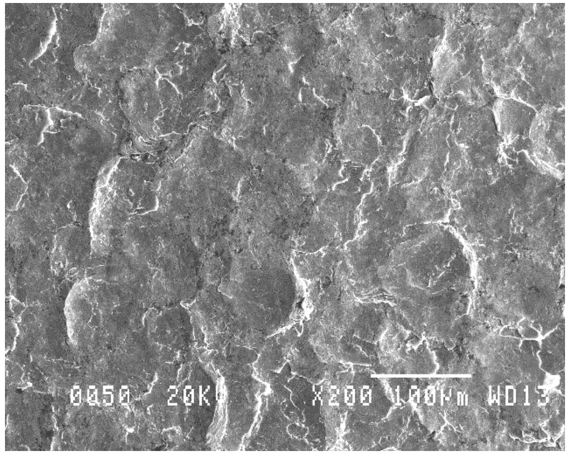
Coated

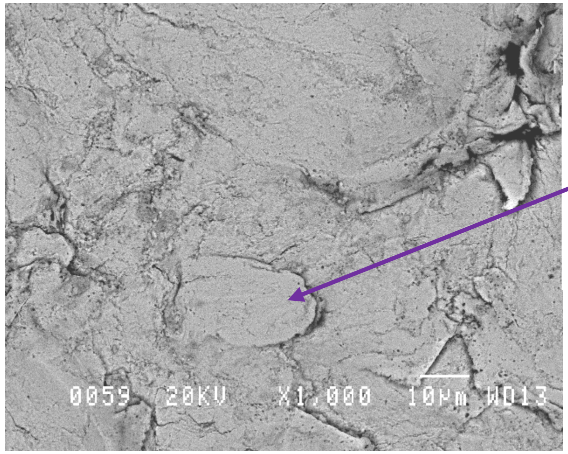




"Spit": Produced by occasional arcing event in the coating plasma

Post-coating





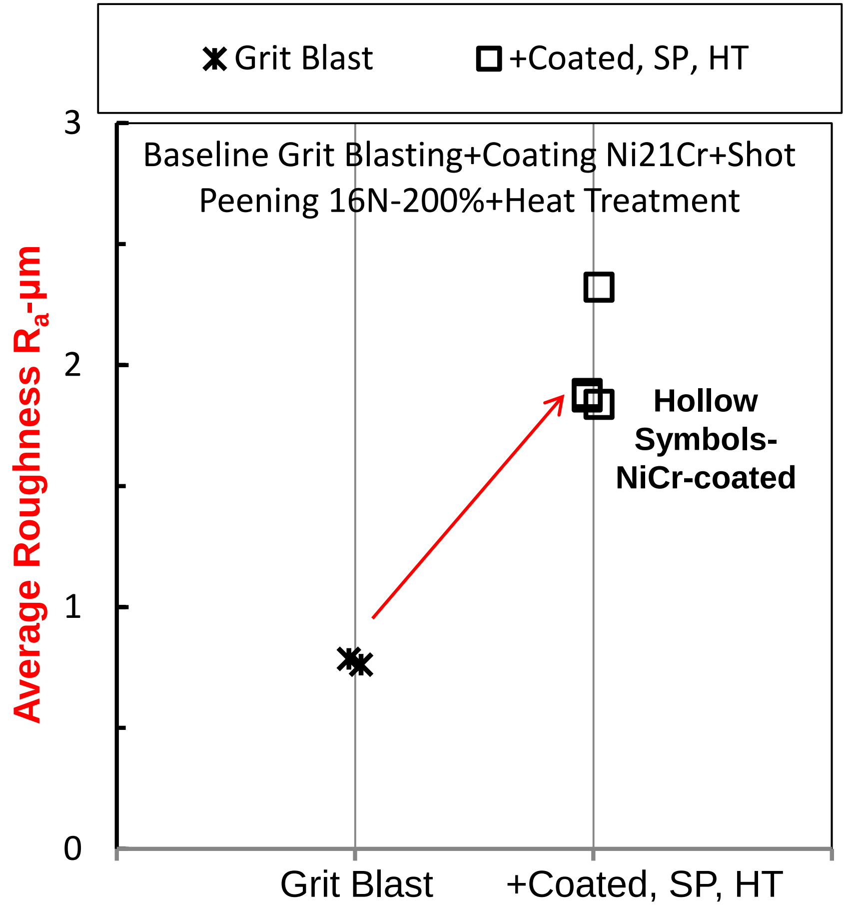
Lap: Folded rim of dimple from shot impact

Shot Peened & Heat Treated

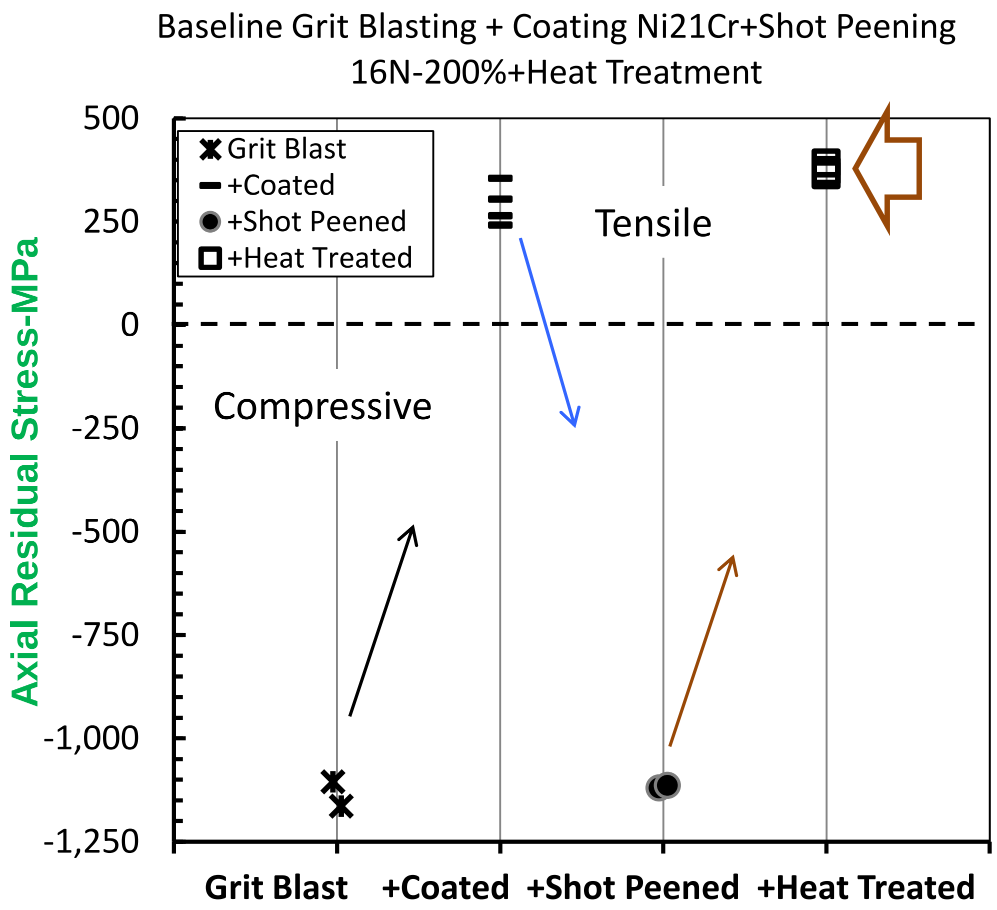
Surface Roughness Was Increased After Coating + Shot Peen + Heat Treat

(A) Baseline Processing: Pre-coat Grit Blast + Coating + Shot Peen + Heat Treat

Average Roughness-R_a



Axial Residual Stresses

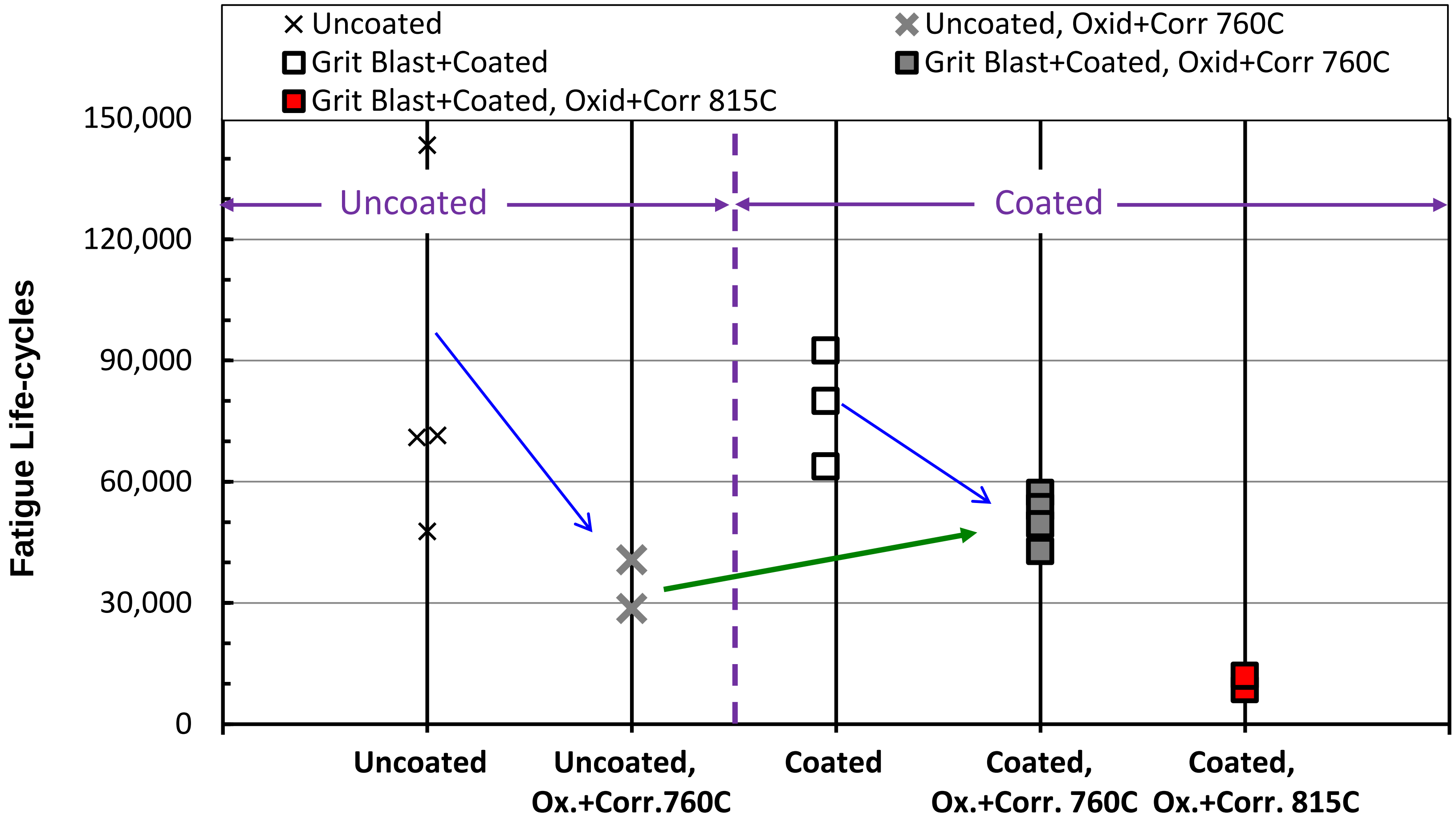


- The coating was in tension, but shot peening produced large compressive residual stresses at the surface of the coating.

- Heat treatment at 760 °C for 8 h relaxed out the compressive residual stresses, resulted in tensile stresses at the surface.

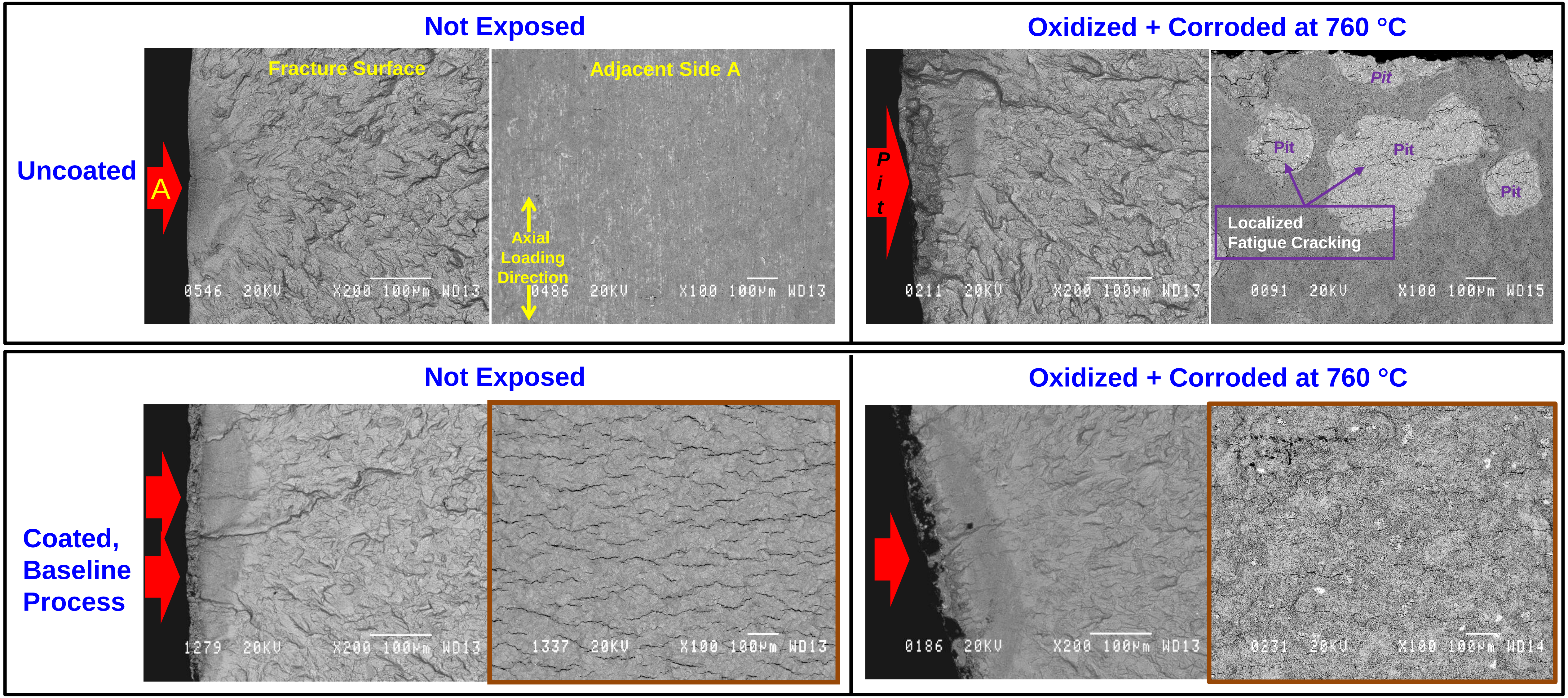
Comparison of Fatigue Lives For Uncoated Versus Coated
Specimens Prepared Using the Baseline Process

(A) Baseline Process = Pre-Coat Grit Blast + Coated Ni21Cr + Shot Peened 16N-200% + Heat Treated 760 ºC/8h/low pO_2



- **Combined oxidation plus corrosion exposures reduced fatigue lives for uncoated <u>and</u> coated specimens.**
- **Coating gave a modest benefit after oxidation + corrosion**

Fatigue Failure Modes Were Shifted By the Exposure and By the Coating



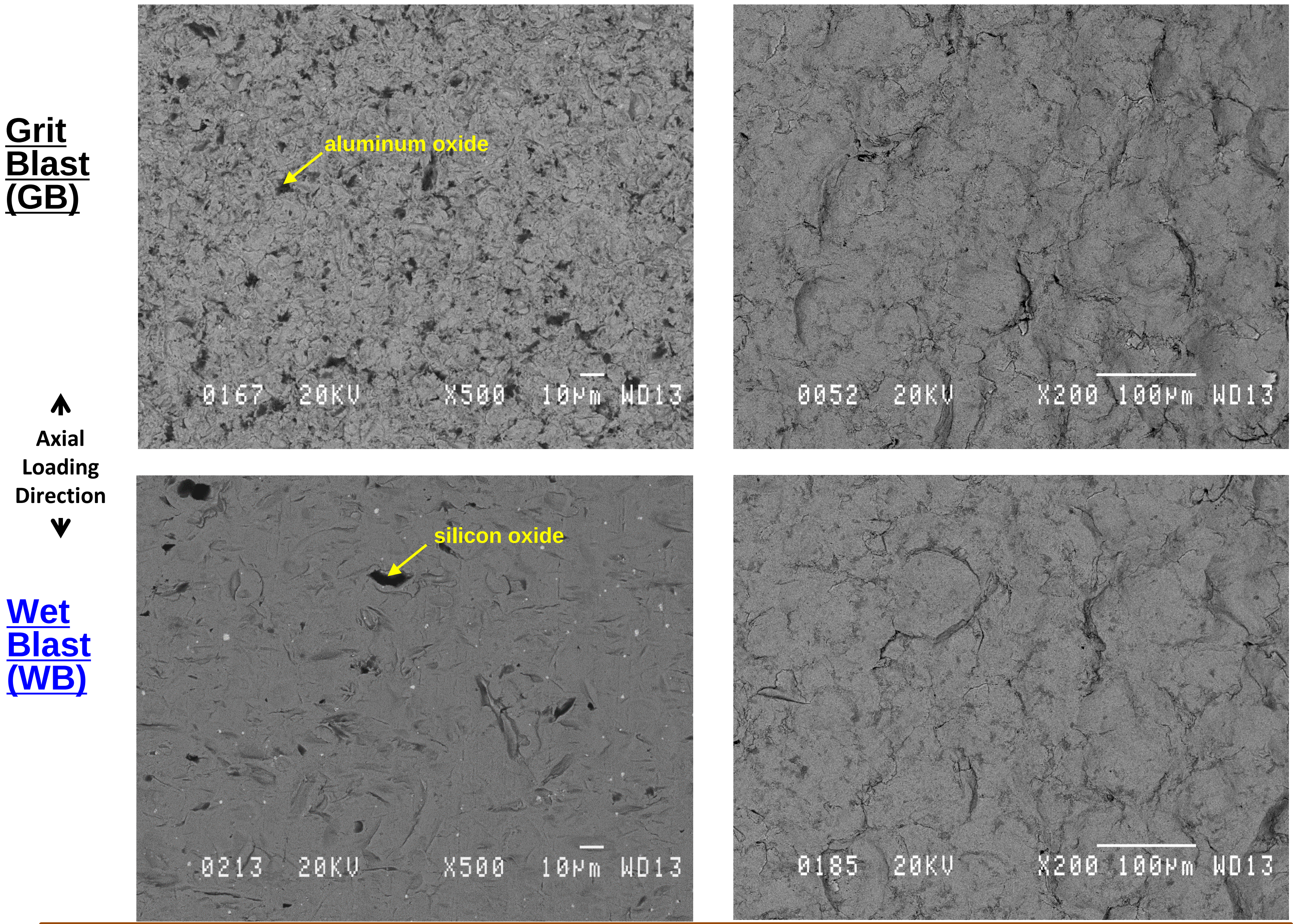
-Uncoated specimens had localized fatigue cracking at corrosion pits.

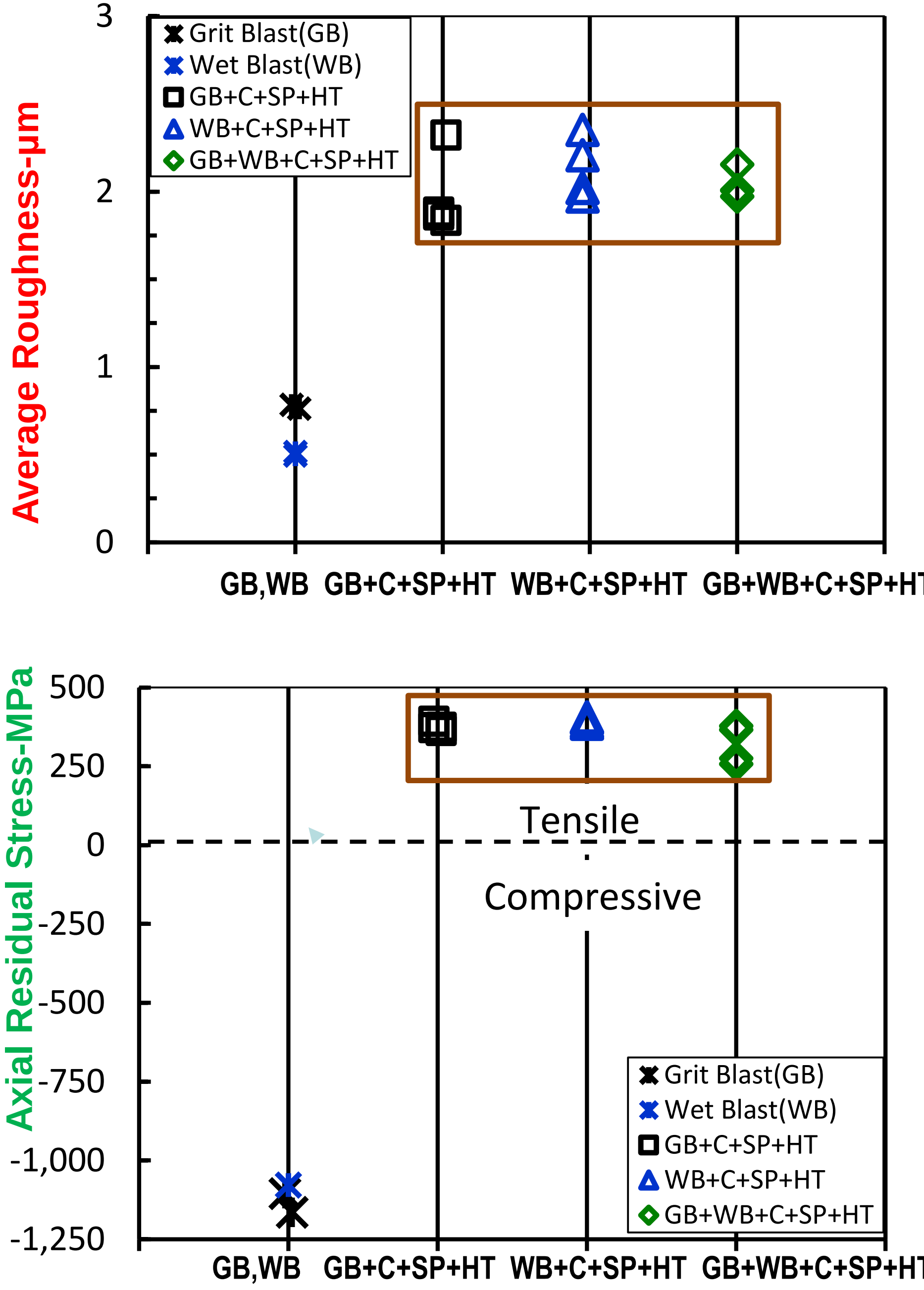
-The surfaces of coated specimens did not display distinct corrosion pits, yet had increased fatigue cracking, even without oxidation plus corrosion at 760 °C.

A more ductile coating did not eliminate the increased surface cracking, at the coating.

Could an alternative pre-coat treatment embed less grit, to reduce surface fatigue cracking of the coating?

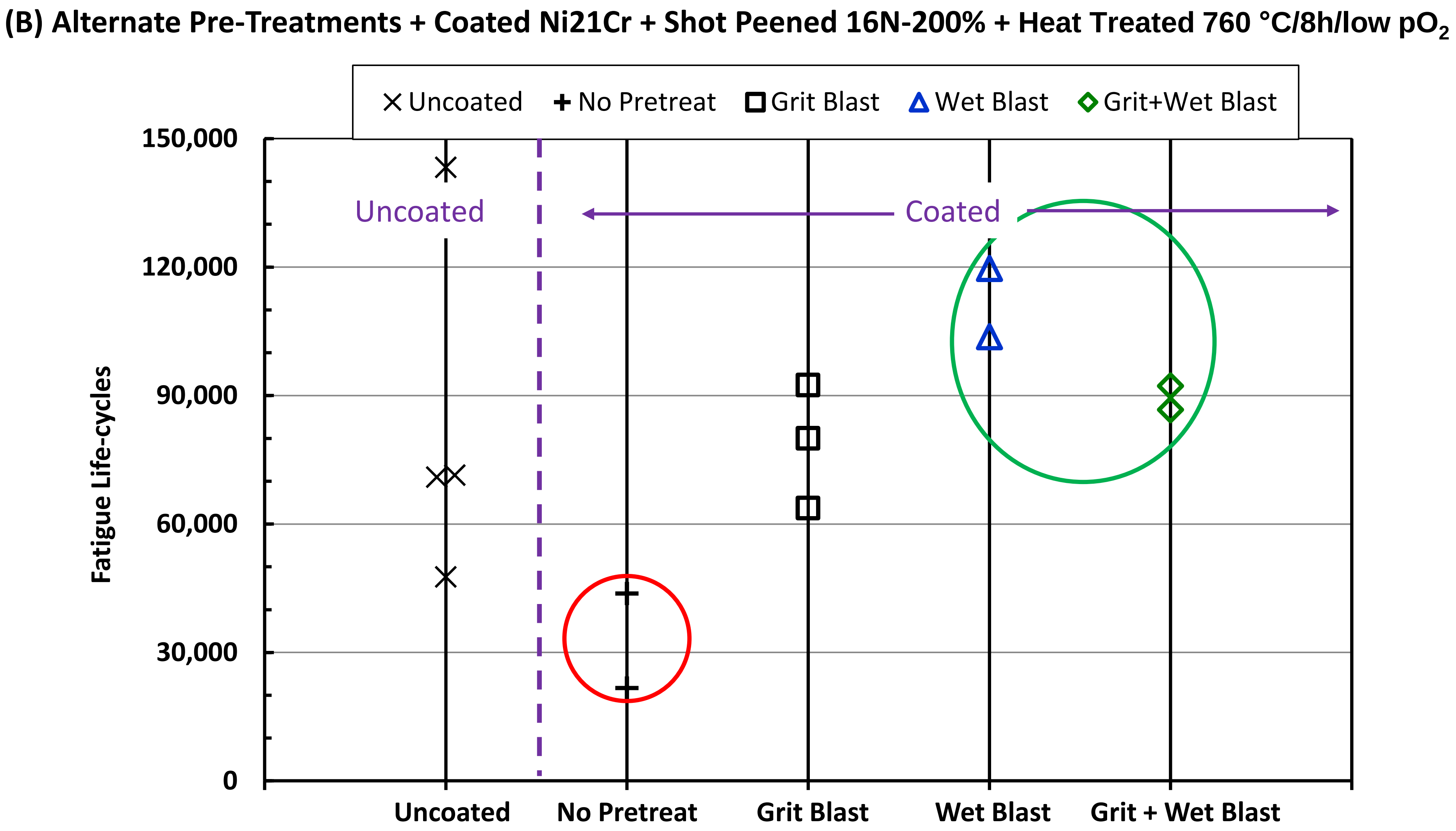
B: wet blasting - 300 grit silica





- After baseline coating (C), shot peening (SP), and heat treatment (HT) processes, similar tensile residual stresses were measured at the surface for all conditions.

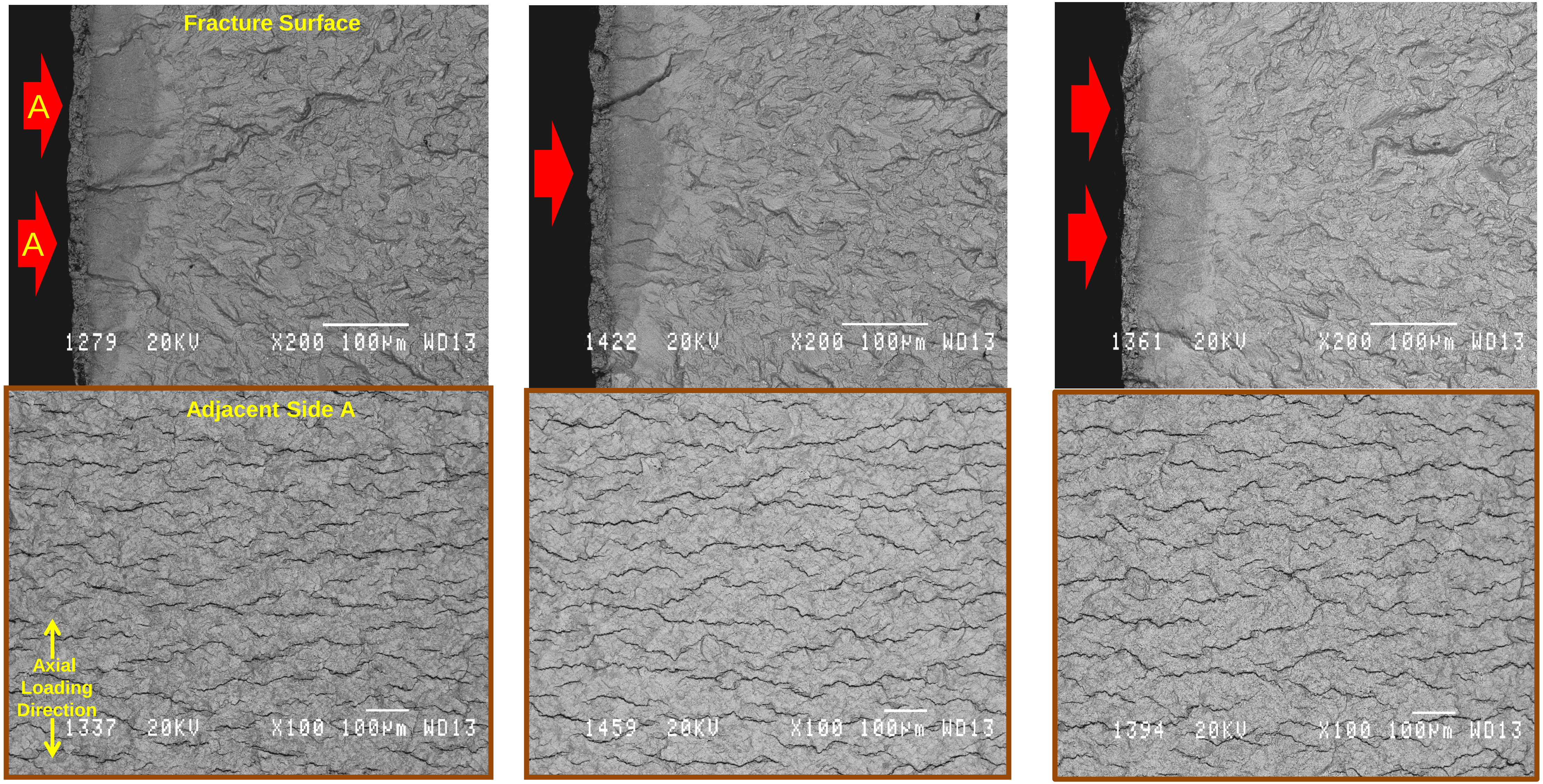
After Different Pre-Treatments, Fatigue Lives of Coated Specimens With No Exposures Varied



- Coated with no pre-coat treatment had unacceptable fatigue lives.
- Coated with wet blast pre-coat treatment gave highest coated fatigue lives.

Associated Fatigue Failure Modes, After No Exposures

Grit Blast | Wet Blast | Grit + Wet Blast

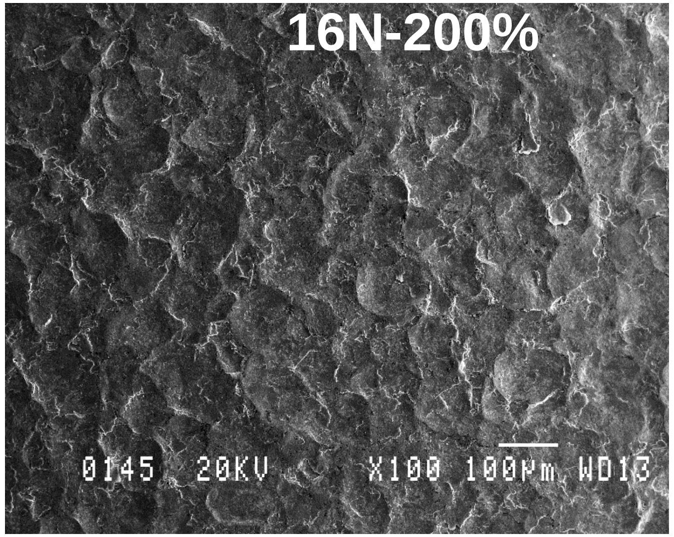


Application of all pre-coating treatments still resulted in increased surface fatigue cracking, at the coating.

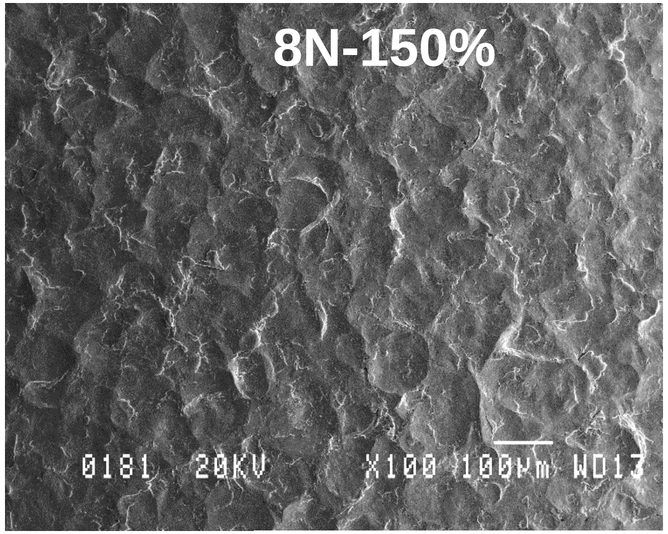
Could more gentle shot peening conditions reduce surface fatigue cracking of the coating?

C. Alternative Post-coat treatment, gentler 8 N-150 % shot peening

Baseline
16N-200%

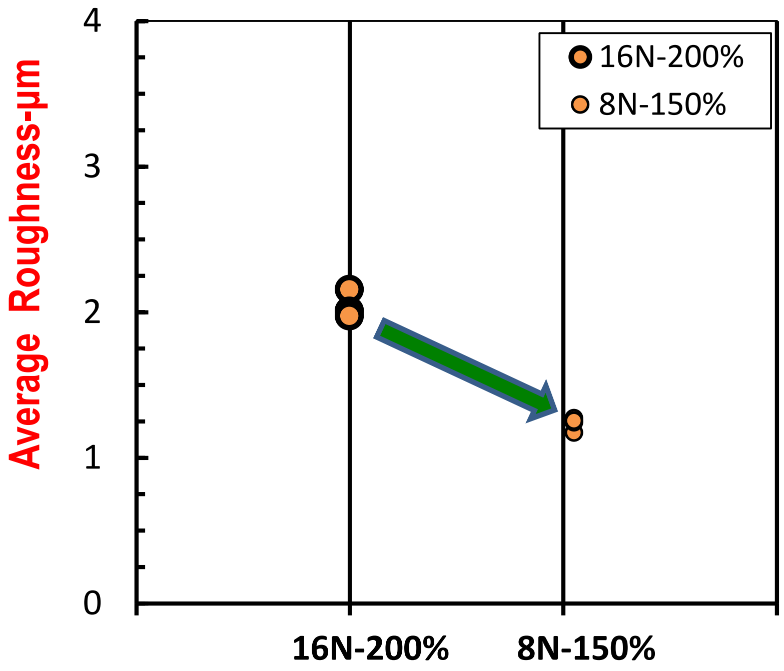


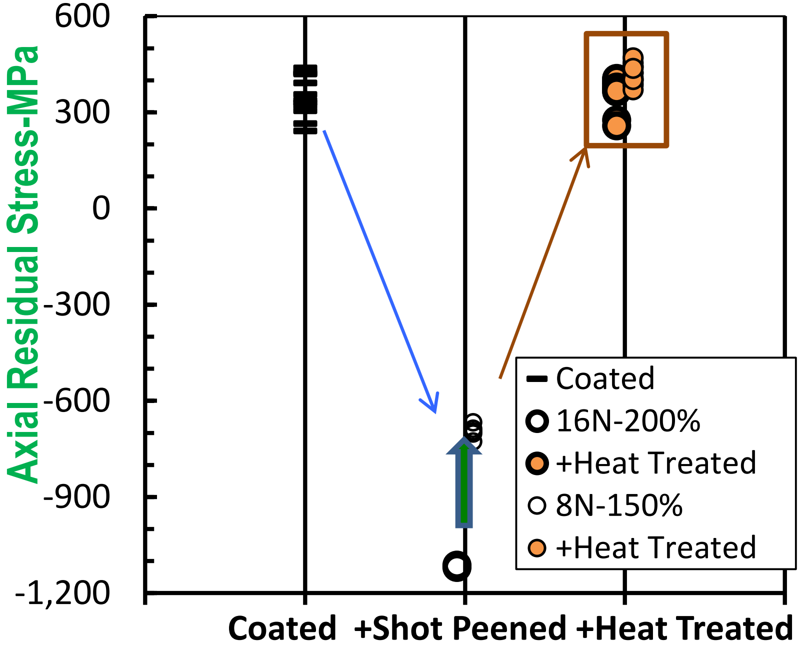
8N-150%



Axial Loading Direction

After Shot Peening





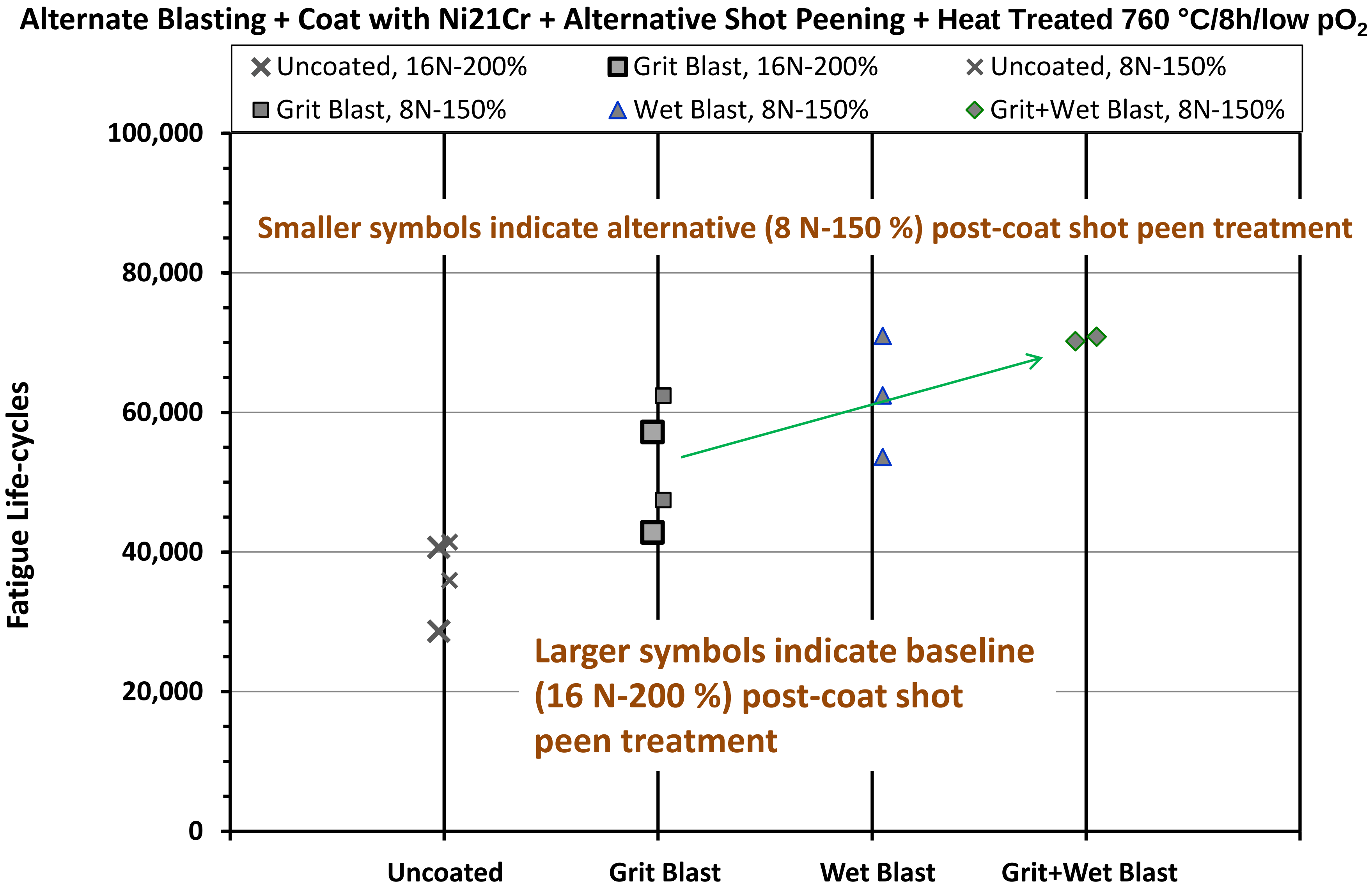
-Average roughness after shot peening reduced about 40 %.

-Magnitude of axial compressive residual stress from shot peening reduced about 35 %.

- Alternative post-coat shot peen treatment reduces roughness and compressive residual stress.

- Yet, heat treatment still relaxed residual stresses to comparable values.

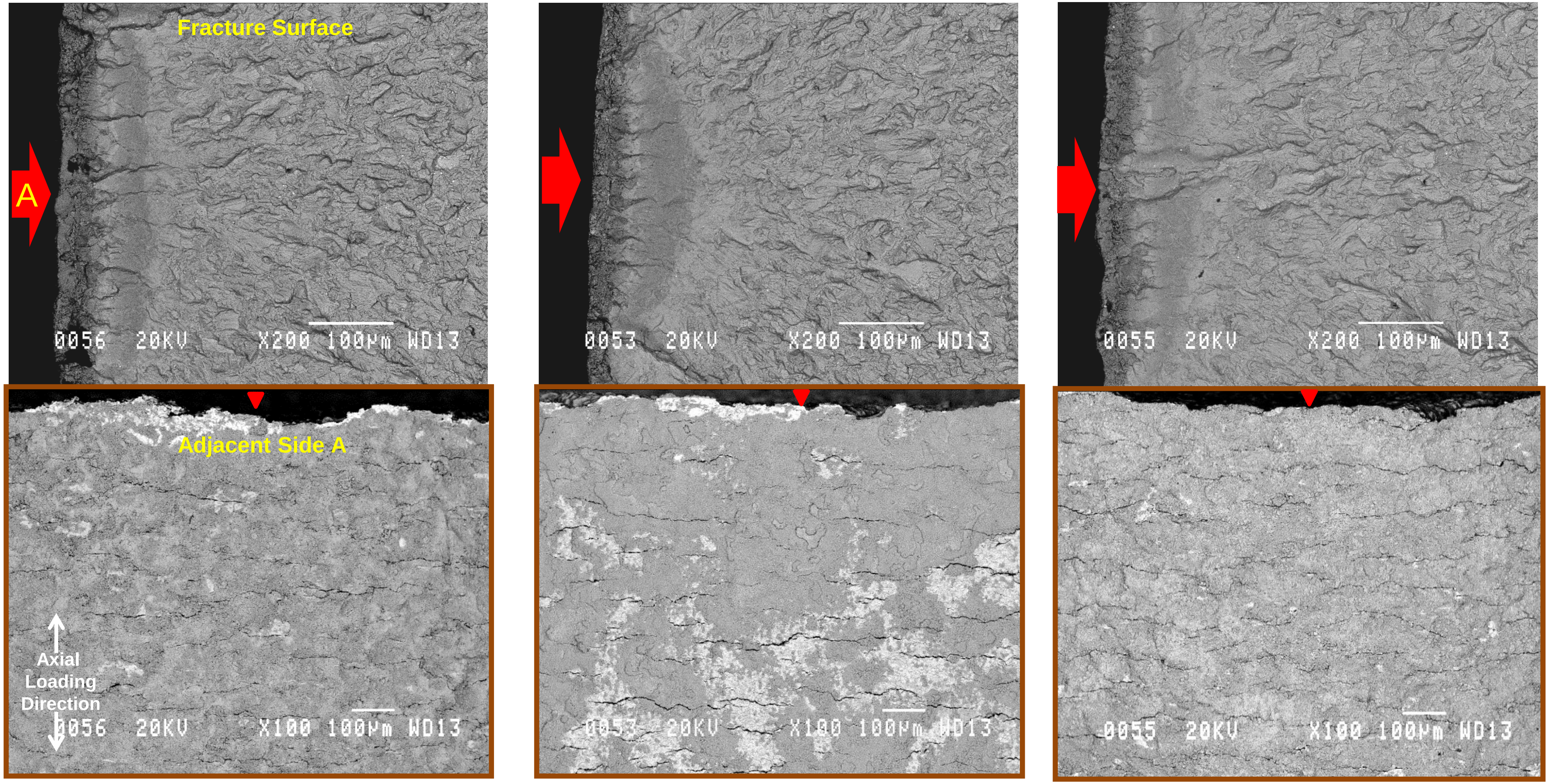
Comparison of Fatigue Lives After Oxidation + Corrosion



- Alternative post-coat shot peen treatment gave modestly improved coated fatigue lives after oxidation plus corrosion.

Fatigue Failure Modes With Reduced Shot Peening of 8 N-150 % After Oxidation + Corrosion

Grit Blast | **Wet Blast** | **Grit+Wet Blast**



Could varied treatments applied to a more ductile NiCr γ phase coating reduce surface fatigue cracking?

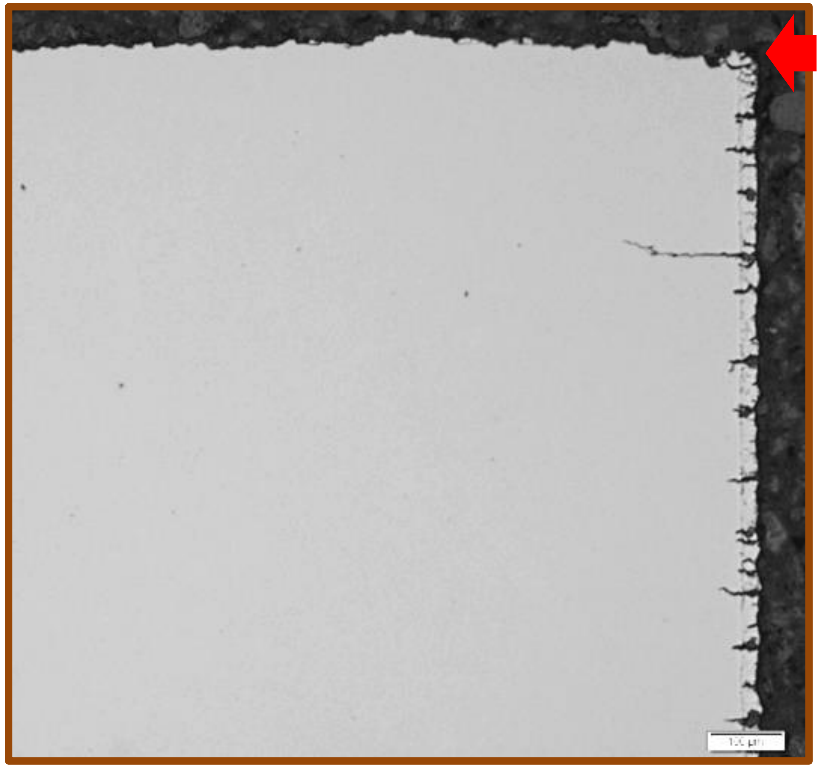
No, increased surface cracking of this ductile coating was still prevalent for all pre-coating treatments combined with a gentler post-coating shot peen treatment.

Metallographically Prepared Longitudinal Cross-Sections Adjacent to the Failure Initiation Sites

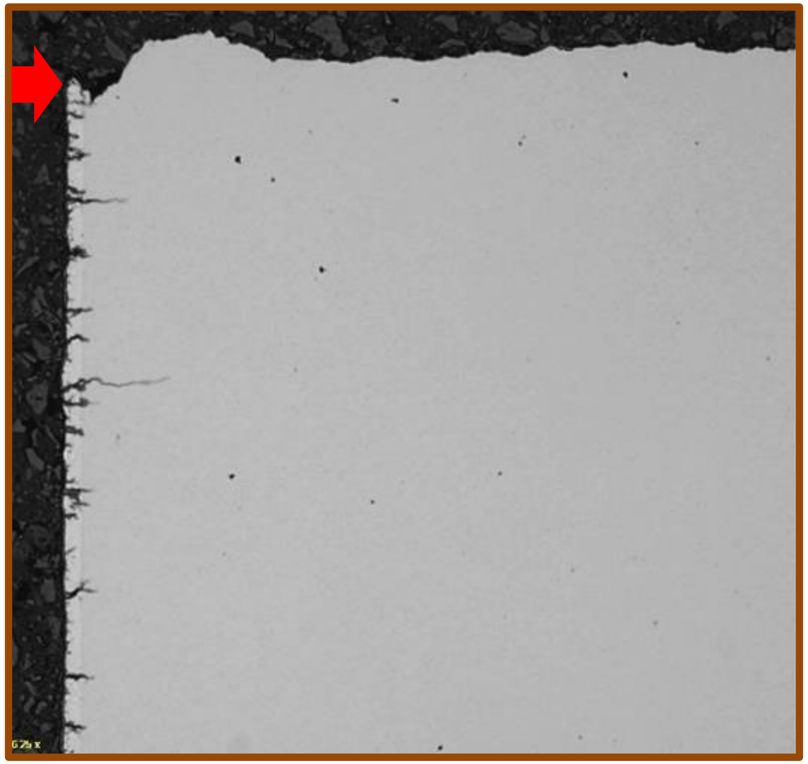
Axial Loading Direction

Shot Peened 8 N-150 % + Heat Treated 760 °C/8h/low pO_2 + Oxidized 760 °C/500h + Hot Corroded 760 °C/50 h + Fatigue at 760 °C

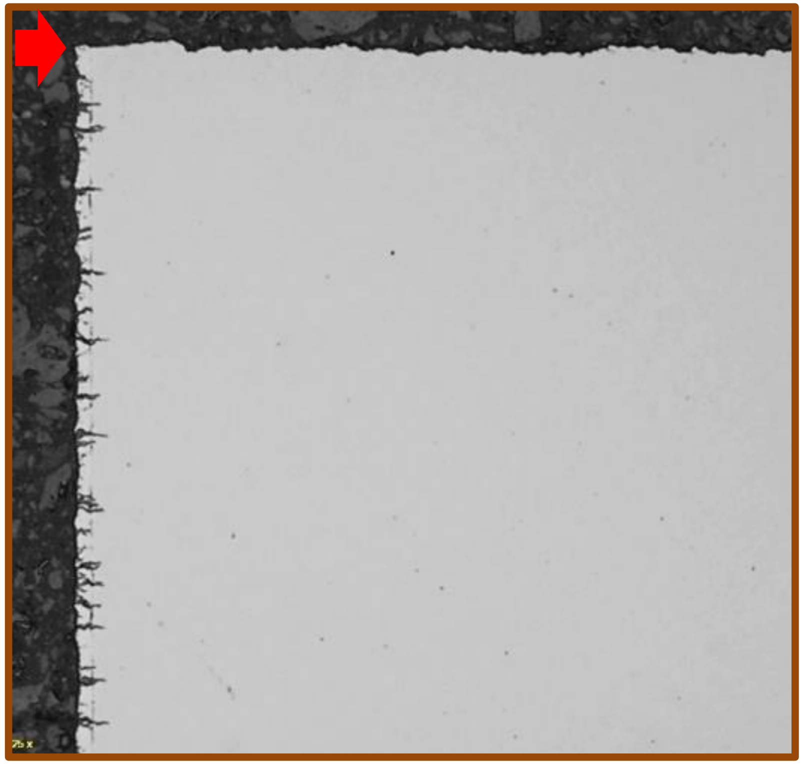
Grit Blast



Wet Blast



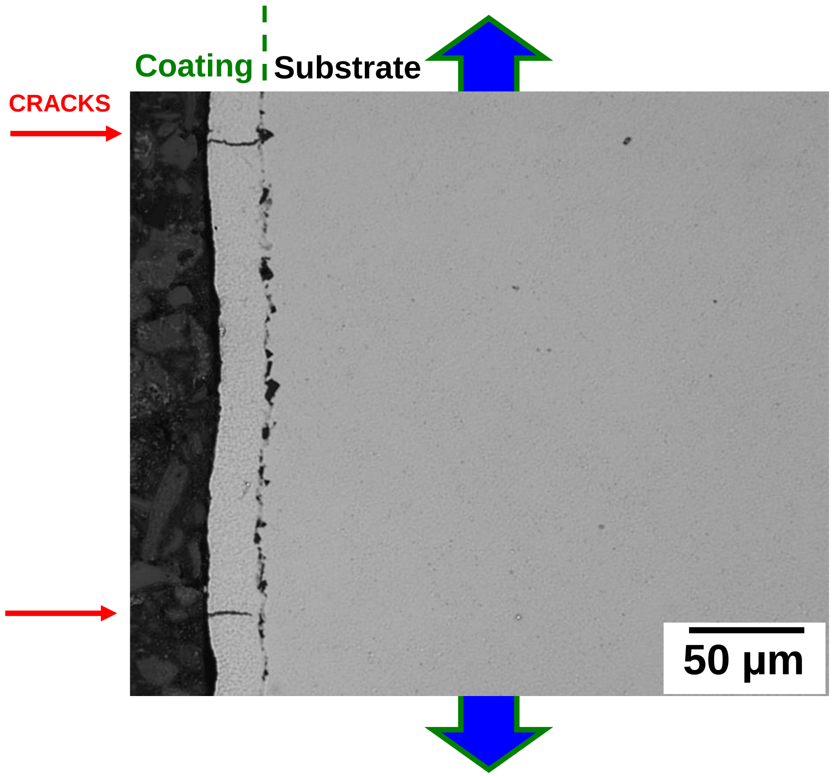
Grit+Wet Blast



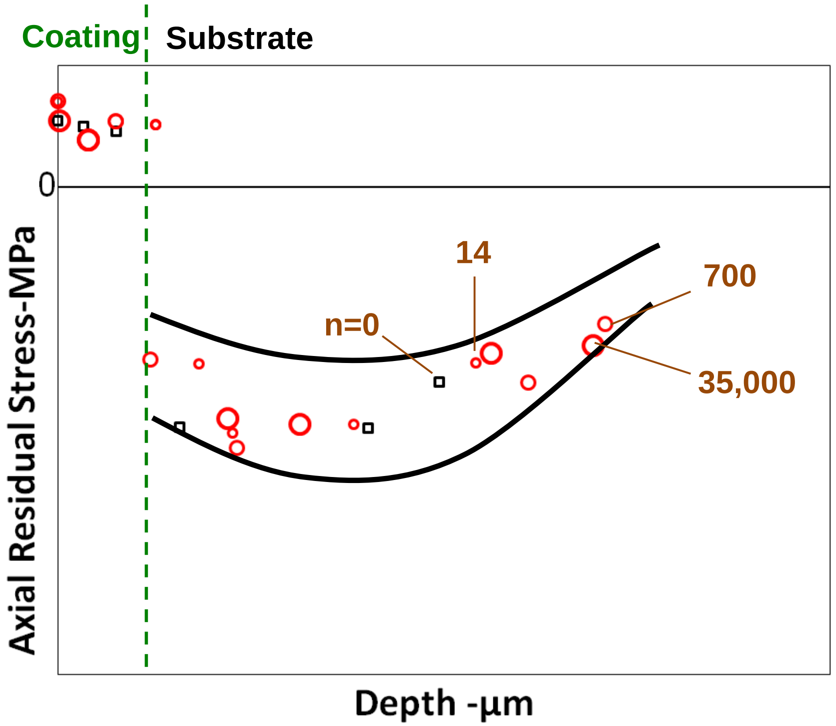
- Very many cracks are present at the coated surface.
- Yet, a majority of the coating cracks did not grow far into the superalloy substrate.
- ***Very similar response had been observed for the Ni45CrY $\gamma + \alpha$ phase coating on this disk superalloy.***

Why do we get increased surface cracking for all these coated specimens, yet good fatigue lives, even after exposures? (i.e., it looks worse than it is, why?)

- Longitudinal Section of Ni45CrY-Coated LSHR Fatigue Specimen (Baseline Process) Tested at 760 °C for up to 35,000 Cycles Compared to Measured Residual Stresses[1]



Residual Stresses in NiCrY-Coated Specimens, After Various Numbers of Fatigue Cycles - n



- Cracks can begin to form sooner in these weak coatings, where no compressive residual stresses from shot peening remain at 760 °C.

- Yet, the adjacent substrate can retain sufficient stable compressive residual stresses to resist most crack growth there, enabling good fatigue life.

Ref. 1. T. P. Gabb, R. B. Rogers, J. A. Nesbitt, R. A. Miller, B. J. Puleo, D. Johnson, J. Telesman, S. L. Draper, I. E. Locci, "Influences of Processing and Fatigue Cycling on Residual Stresses in a NiCrY-Coated Powder Metallurgy Disk Superalloy", J. of Materials Engineering and Performance, V. 26(11), 2017, pp. 5237-5250; DOI 10.1007/s11665-017-3005-z.

Summary of Results

- A baseline process path was evaluated of grit blasting and NiCr-coating fatigue specimens of a disk superalloy, then shot peening and heat treating them

- Coated and uncoated specimens were fatigue tested at 760 °C, after oxidation plus hot corrosion exposures:

  - Uncoated specimens- fatigue cracks initiated from corrosion pits to reduce life.

  - Coated specimens- no deep corrosion pits were formed, so life improved.

  Increased surface cracking occurred in this ductile coating.

- Alternative pre-coating surface pre-treatments were screened:

  - Wet blasting gave lower roughness and fewer imbedded abrasive particles, and coated fatigue life improved.

  Increased fatigue cracking of the coating still predominated.

- Alternative post-coating shot peening conditions were screened:

  - Gentler shot peening gave lower roughness, comparable residual stresses after heat treatment, moderately improved fatigue life after exposures.

  Increased surface cracking of coating still remained.

Conclusions

- **Effects of baseline coating process on disk superalloy fatigue life at 760 °C:**

  - Unexposed- Fatigue life comparable to uncoated can be attained, yet increased fatigue cracking of the coating can occur.

  - Oxidized + Corroded at 760 °C - The coating can prevent deep corrosion pits to benefit fatigue life, but is prone to increased surface cracking.

- **Varied surface pre-coat treatments:**

  Wet blasting can improve coated fatigue life, but still allows increased fatigue cracking of the coating.

- **Varied post-coat shot peening treatments:**

  Reduced shot peening intensity and coverage can improve coated plus exposed fatigue life, yet will not suppress increased fatigue cracking of the coating.

- **Why can there be increased fatigue cracking of the coating, yet good fatigue lives:**

  → Cracks can form sooner in NiCr γ phase and $\gamma + \alpha$ phase coatings, where no compressive residual stresses from shot peening remain at 760 °C.

  → Yet, the adjacent superalloy substrate can still retain some compressive residual stresses, to help suppress crack growth there.