U.S. ARMY COMBAT CAPABILITIES DEVELOPMENT COMMAND –
ARMY RESEARCH LABORATORY

Fatigue of Coated Structures

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FATIGUE THEORY

Fatigue is a process of material failure below the static strength of a material through repeated cycles of loading.

- Fatigue crack initiation
- Fatigue crack growth
- Final rupture

https://www.slideshare.net/DineshGupta45/metal-fatigue-ppt-70984837

U. Zerbst: Fracture Mechanics in Railway Application

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Fatigue failures often result in dramatic failures as part function is often unaffected until rupture and separation.

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FATIGUE THEORY: STEPS FROM INITIATION TO FAILURE

<u>Step 1: Crack Initiation</u>

During this step dislocation motion along slip planes cause a step or defect to form near the surface acting like a stress concentration and initiating a crack.

<u>Complicating Factors</u>

- Surface roughness
- Defects in the structure (dislocations, pores, unfused particles, loading case, etc.)
- Residual Stresses
- Surface damage (fretting, corrosion, etc.)

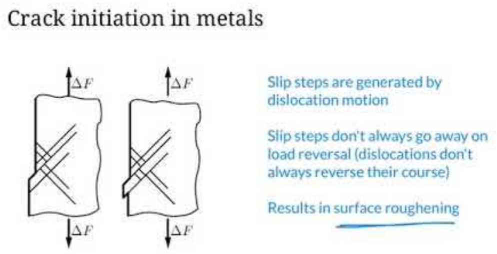

Figure from *Mechanical Behaviour of Engineering Materials* by Roesler, Harders, and Baeker.
Dr. Megan Frary
Micron School of Materials Science and Engineering
Boise State University

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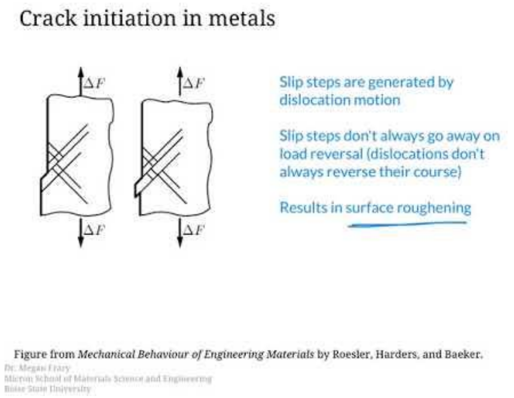


Step 2: Crack Propagation

During this step the initiated crack will propagate through a process of incremental growth. As crack length increases stress intensity at the crack tip increases creating larger incremental tearing with each cycle.

Complicating factors

- Residual stress
- Crack closure (plasticity or roughness)
- Interfaces
- Defects in the crack path
- Embrittlement

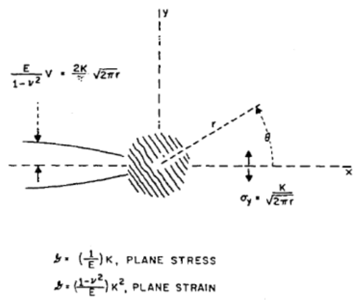
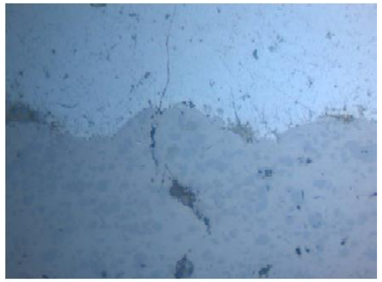


Fig. 1 - The leading edge of a crack

IRWIN, KRAFFT, PARIS, AND WELLS



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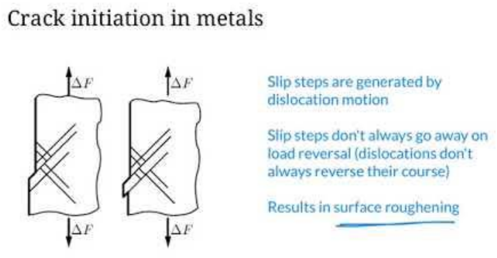

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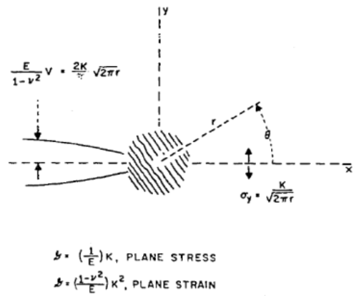

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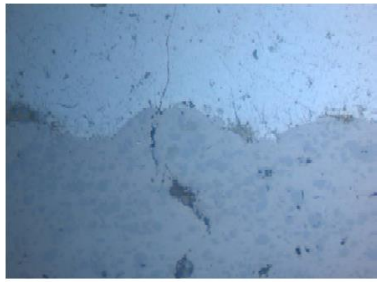

Step 3: Final Rupture

Once a fatigue crack reaches a critical length where the stress intensity factor exceeds a critical, unstable crack growth and separation will occur.

Complicating factors

- Constraint (plane stress, plane strain)
- Embrittlement

http://www-materials.eng.cam.ac.uk/mpsite/properties/non-IE/toughness.html

COATED STRUCTURES AND LOAD SHARE

Typical coated structures have a coating applied much thinner than the substrate providing only a fraction of the load support, but experiencing the same strains as the substrate.

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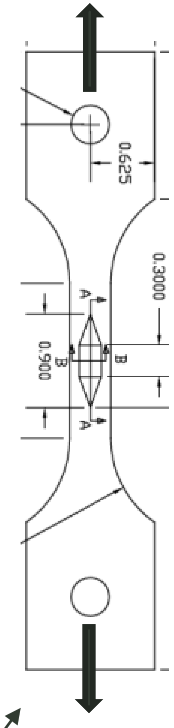

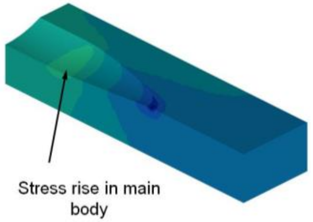

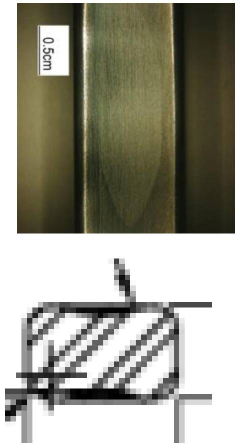

Coated specimens are typically designed with proportions approaching those of the real parts although that is often not possible

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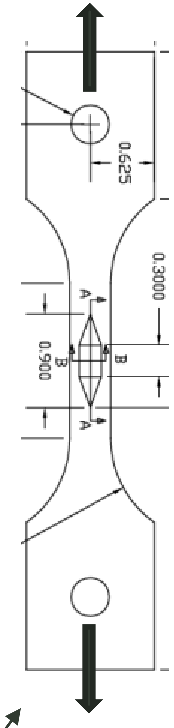

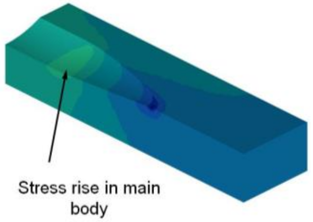

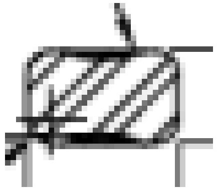

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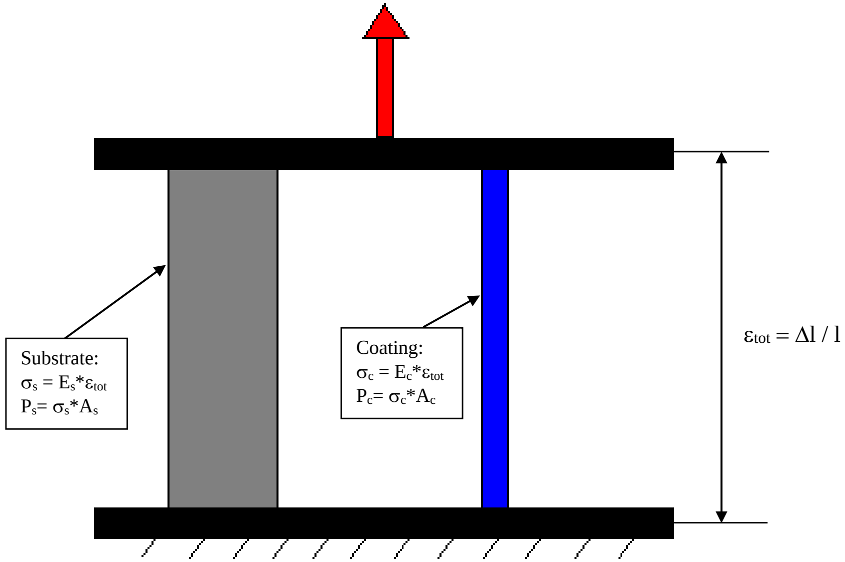
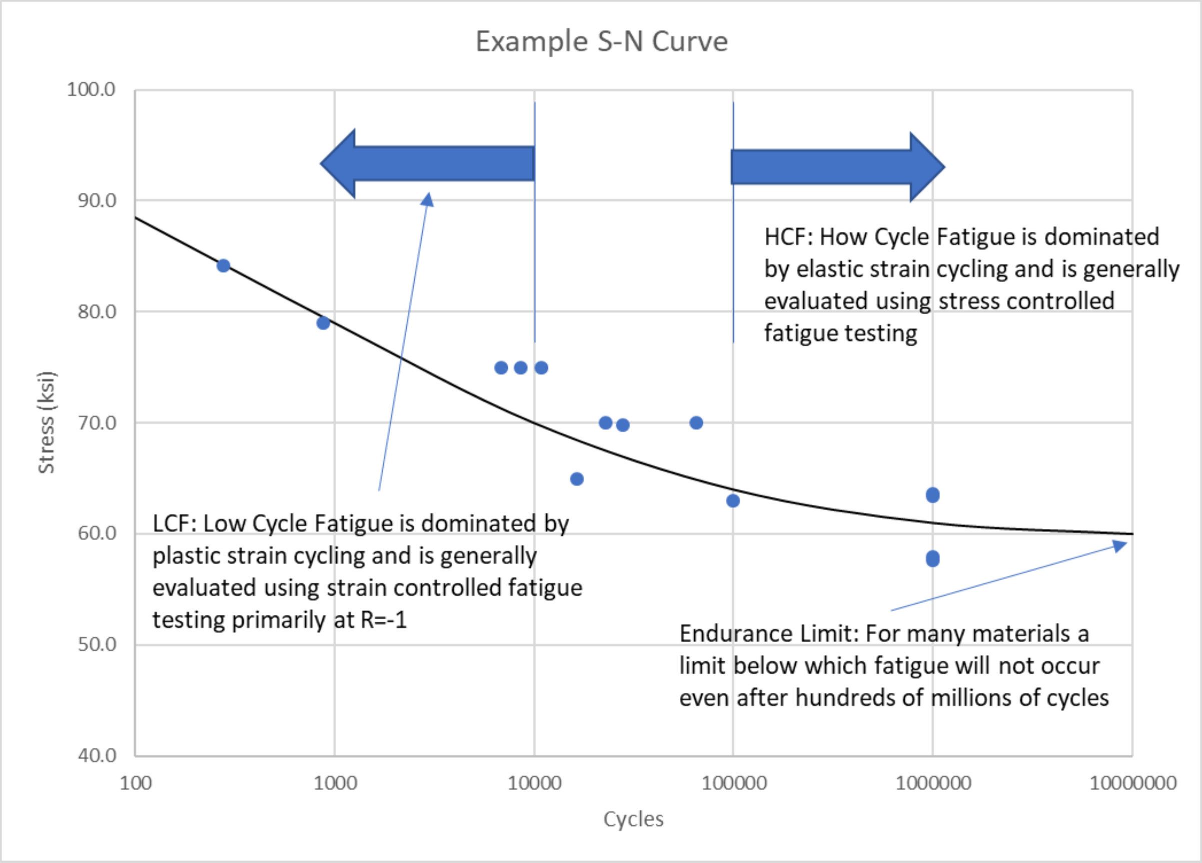
A 2 bar mechanism model provides insight into the relationship between stress, strain, and load carrying of a coating during elastic deformation



HIGH CYCLE FATIGUE

S-N curves show the number of cycles that can be sustained prior to either initiation or failure at a given stress level for a particular test setup, specimen design, and stress ratio.



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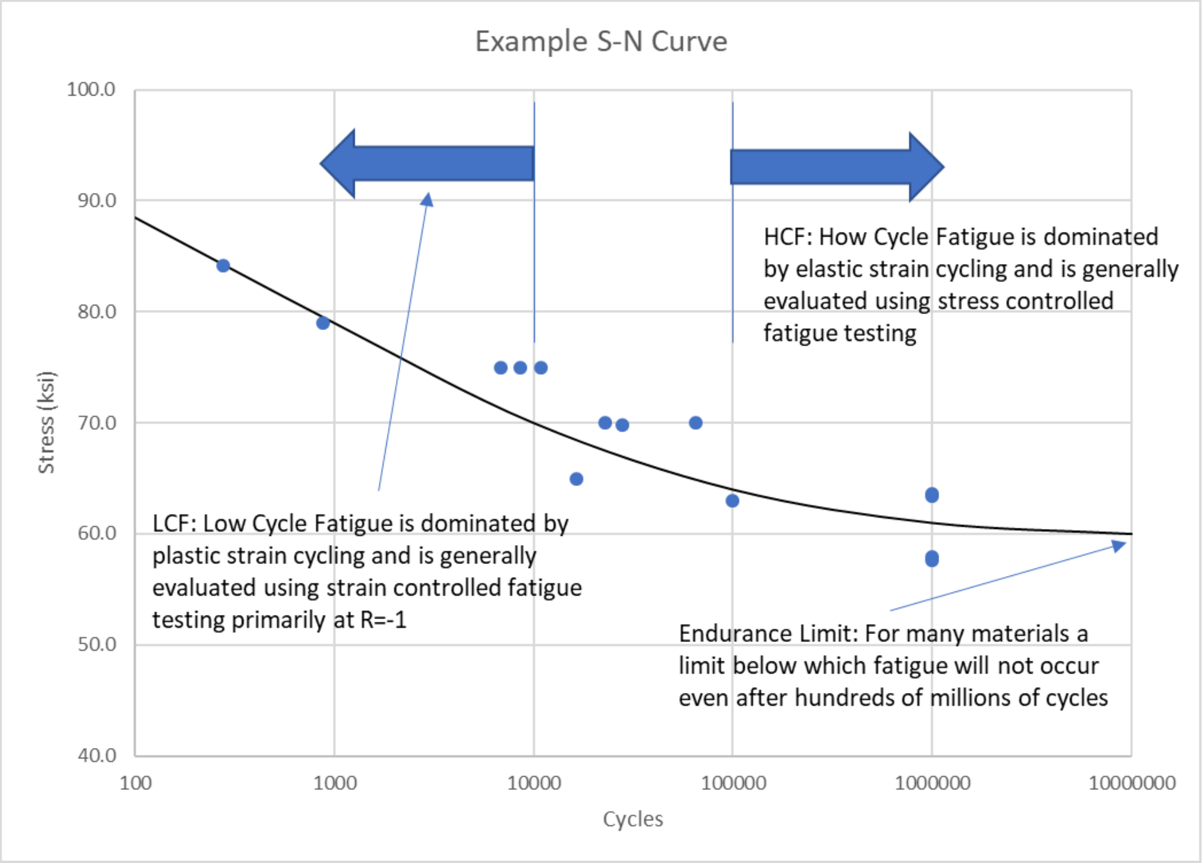
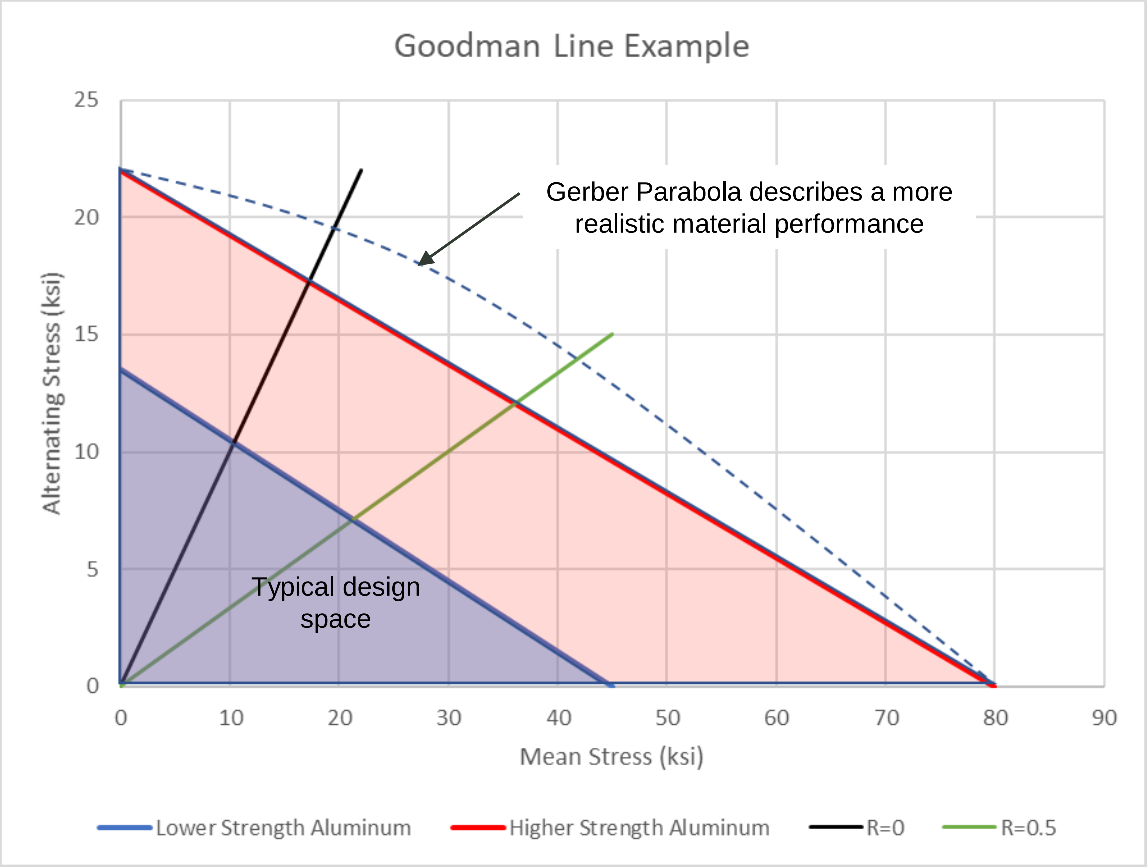
Constant life plots provide insight into the design space at a given life limit. If HCF is the concern, you might construct a Goodman Line plot for the endurance limit of the material by connecting the R=-1 fatigue strength with the UTS to bound the design space.

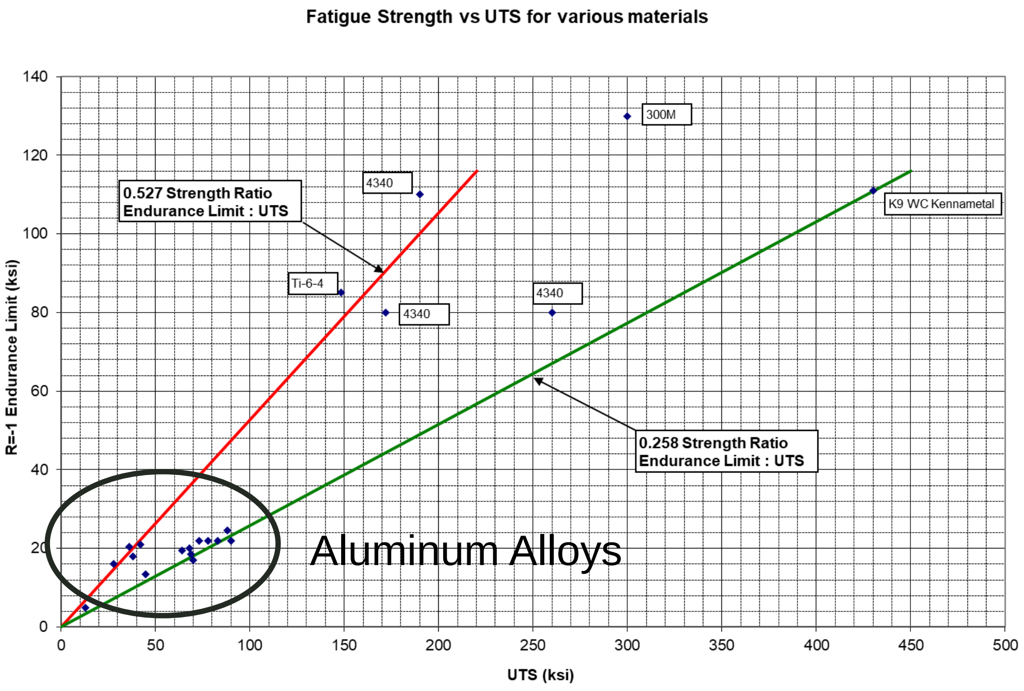




HIGH CYCLE FATIGUE

High Cycle Fatigue of a coating is very much like any other material

- Most materials can be bounded between roughly 0.25 and 0.5 as the ratio of R=-1 endurance strength and Ultimate Tensile Strength
- Aluminum alloys fall between the same relative bands where increasing UTS for an alloys



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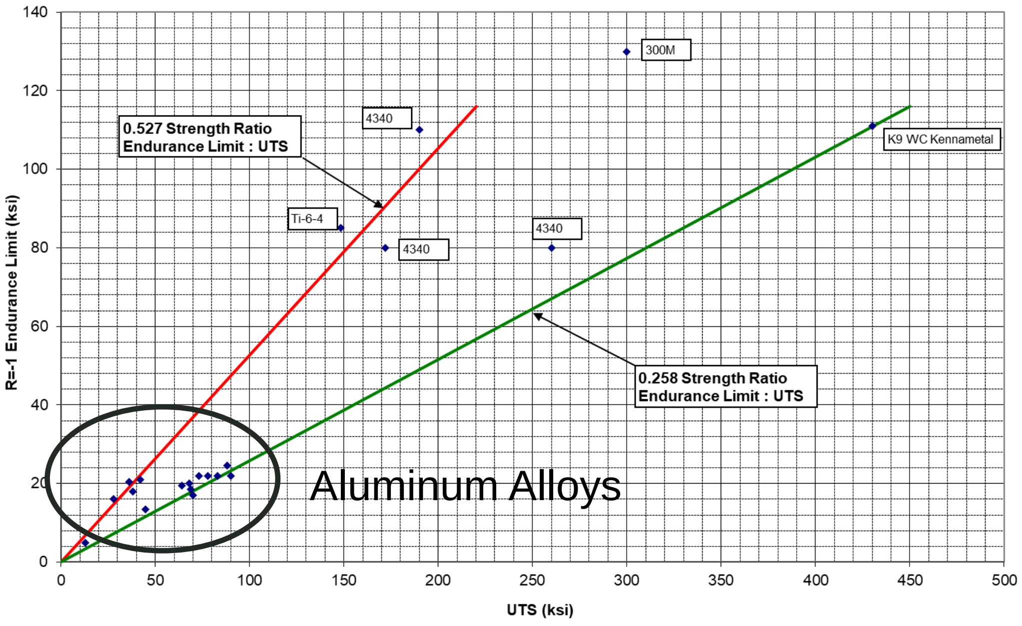
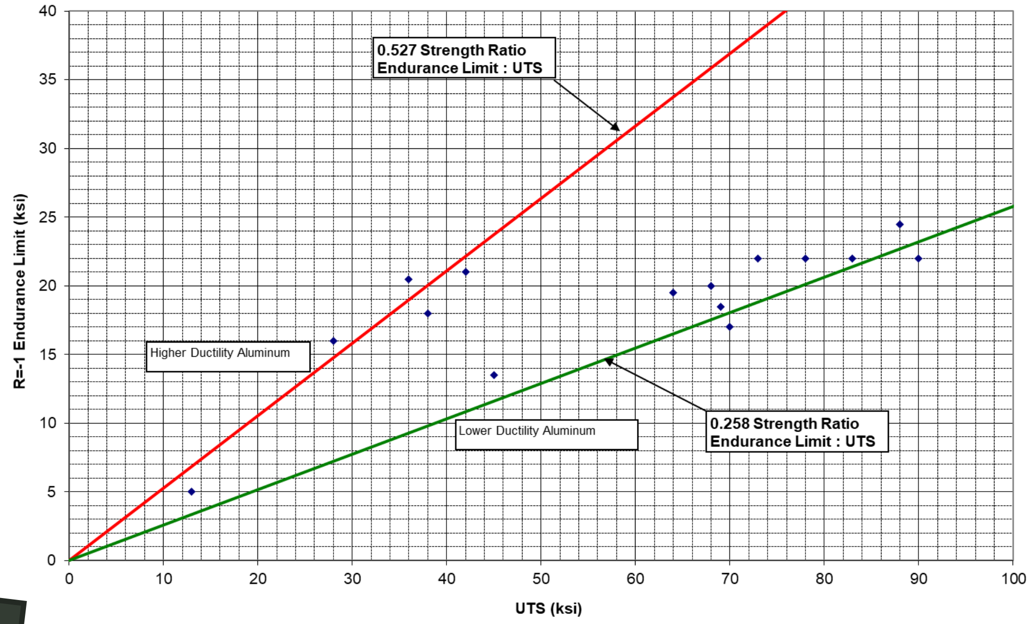
Fatigue Strength vs UTS for various materials



Fatigue Strength vs UTS for Aluminum Alloys



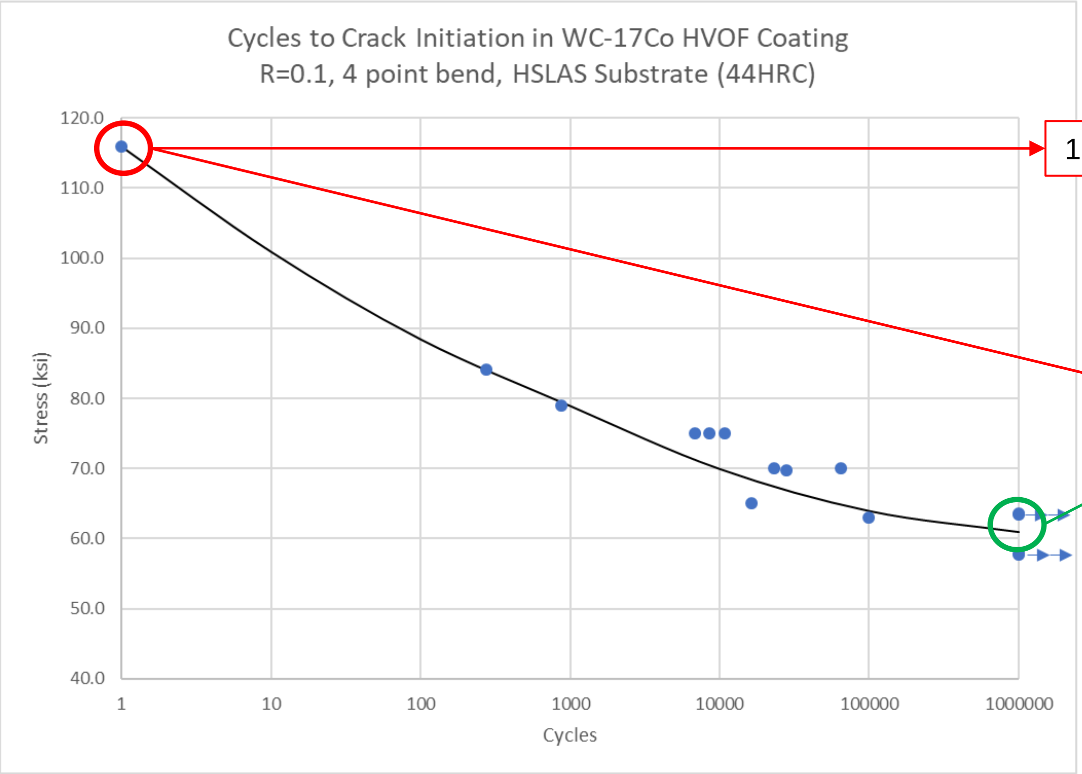
It is possible to provide a bounding condition based on static data alone to define the low end of a materials fatigue capability based on this relationship

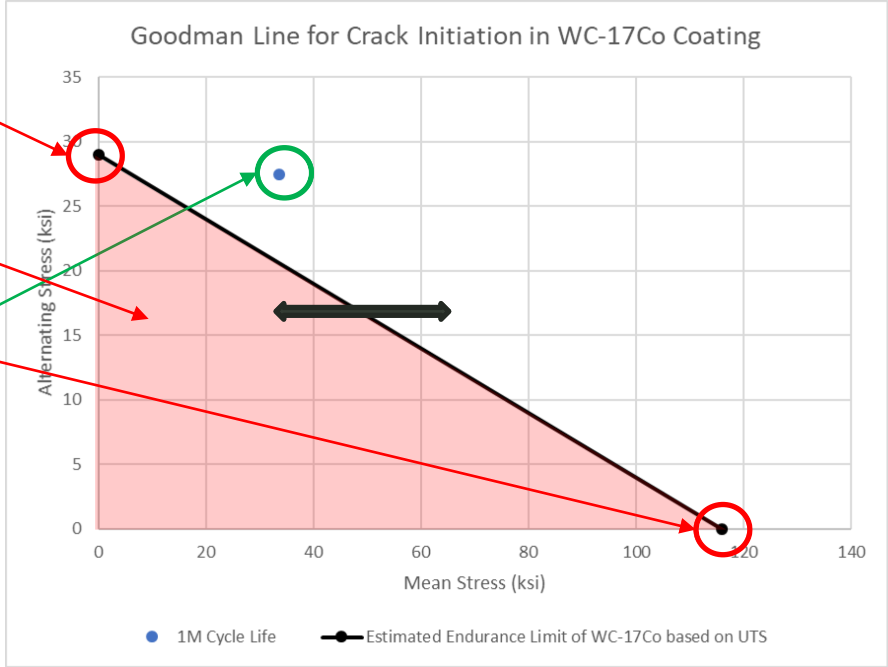
EXAMPLE OF FATIGUE IN HVOF WC-17CO

- Fatigue Testing was performed on WC-17Co coated High Strength Low Alloy Steel (4340, 44 HRC equivalent)
- AE was used to monitor cracking of the coating during static loading and fatigue testing to identify crack initiation

Building of a Goodman Type Constant Life Diagram

- Use static performance (UTS) of the coating to identify mean stress 0 alternating point
- Use 0.25 factor from generic material fatigue estimate
- If coating and substrate are decoupled, shift the curve in the x axis by the magnitude and direction of the residual stress in the expected coating





COLD SPRAY 6061 FREE STANDING COUPON EXAMPLE

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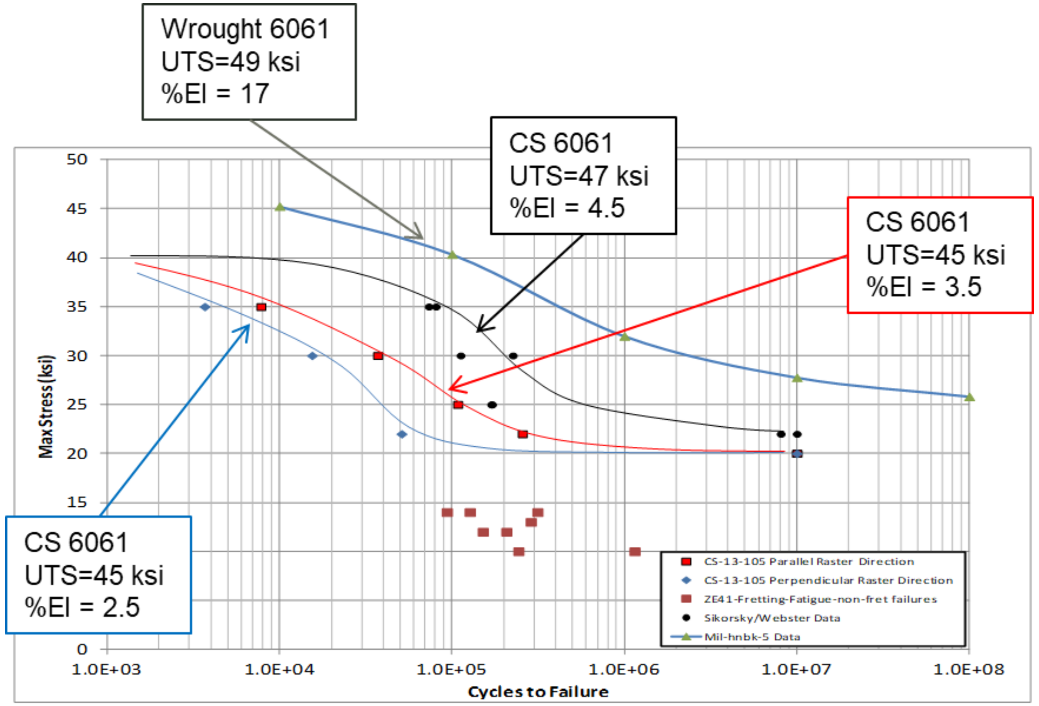
Goodman Type Constant Life Diagram at Endurance Limit

- Same procedure using UTS Data
- Note demonstrated properties close to but exceeding expected



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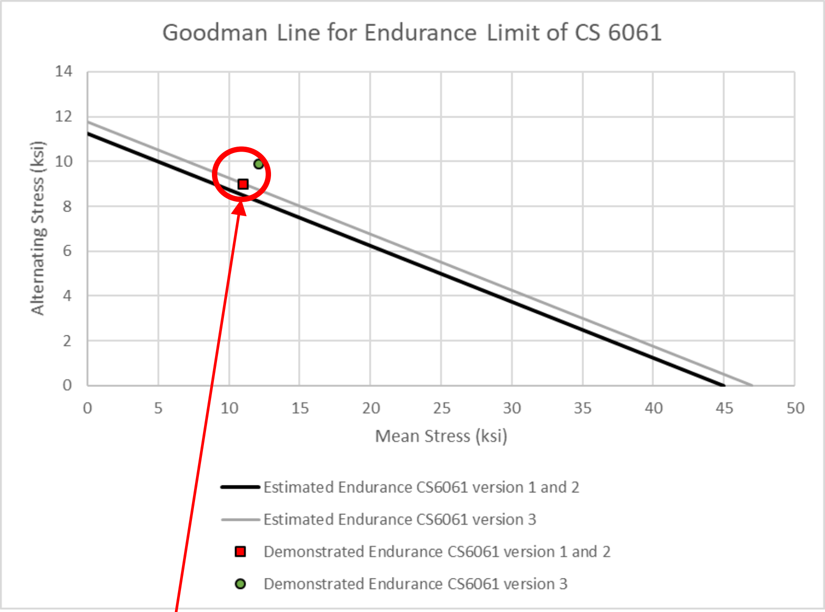

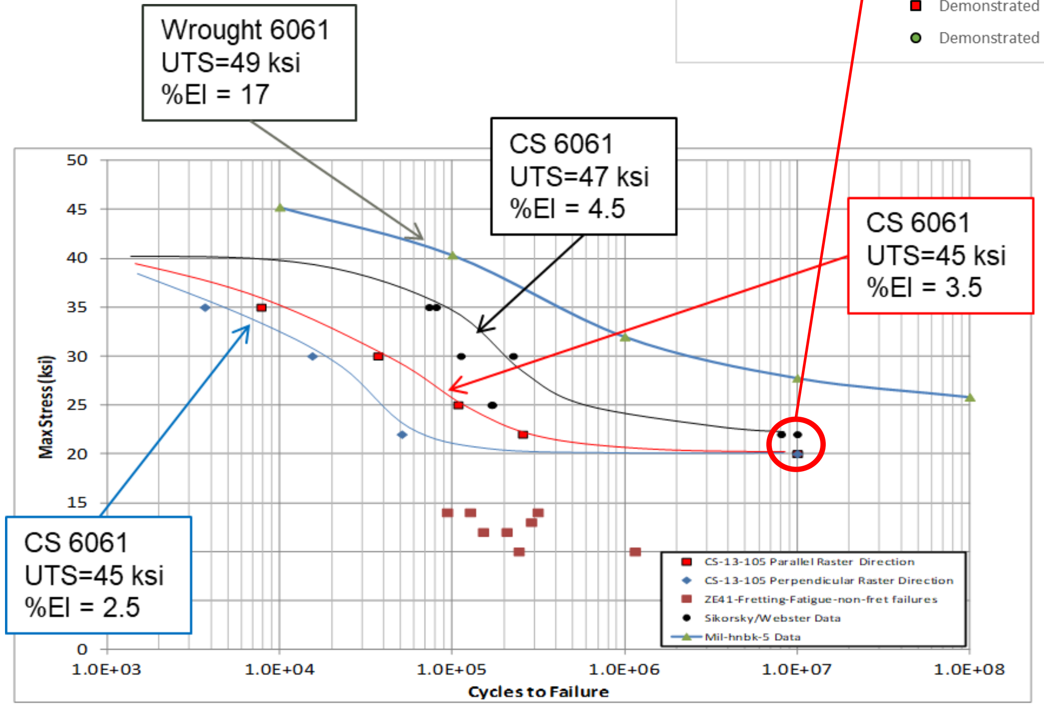

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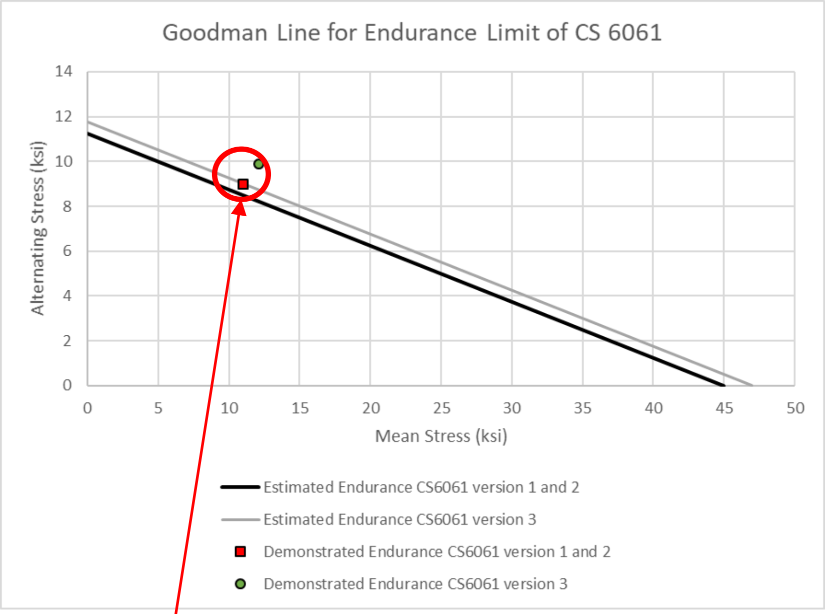
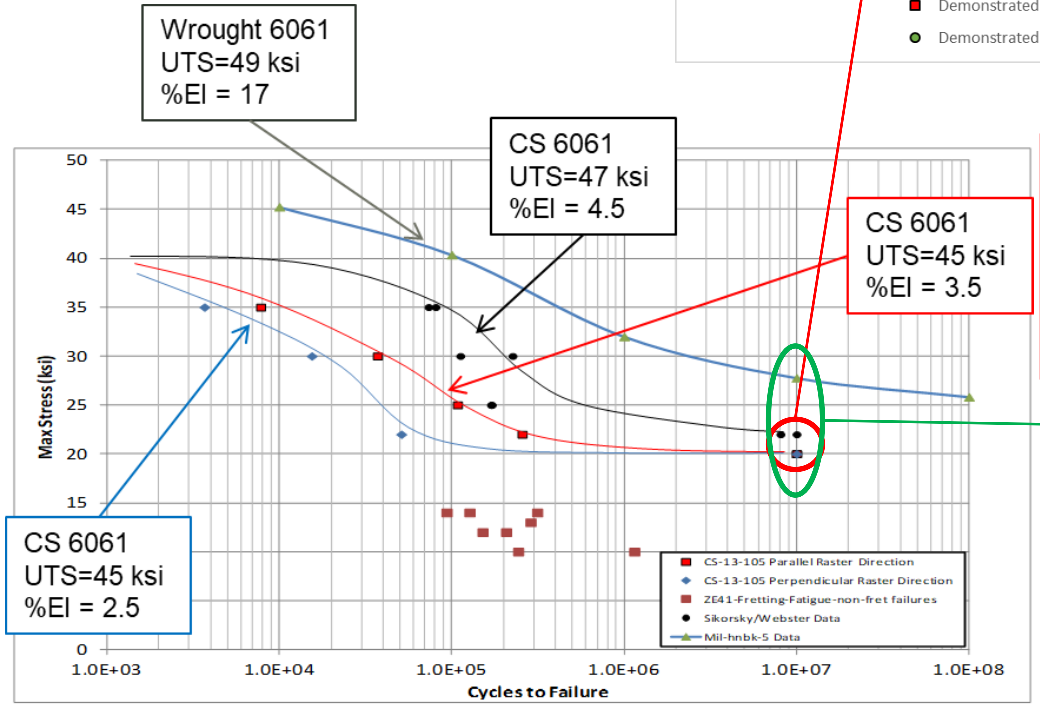
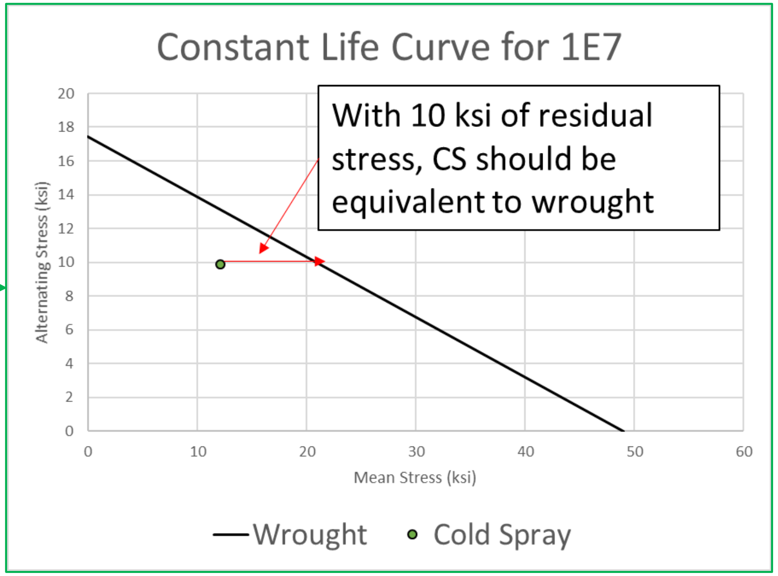




Corrections for Residual stress in the deposit suggest debit may be minimized if applied as coating



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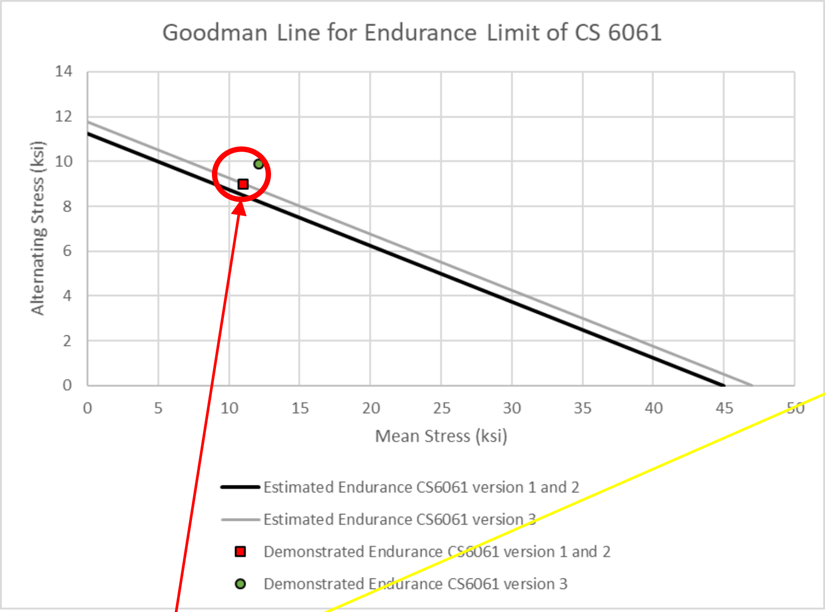

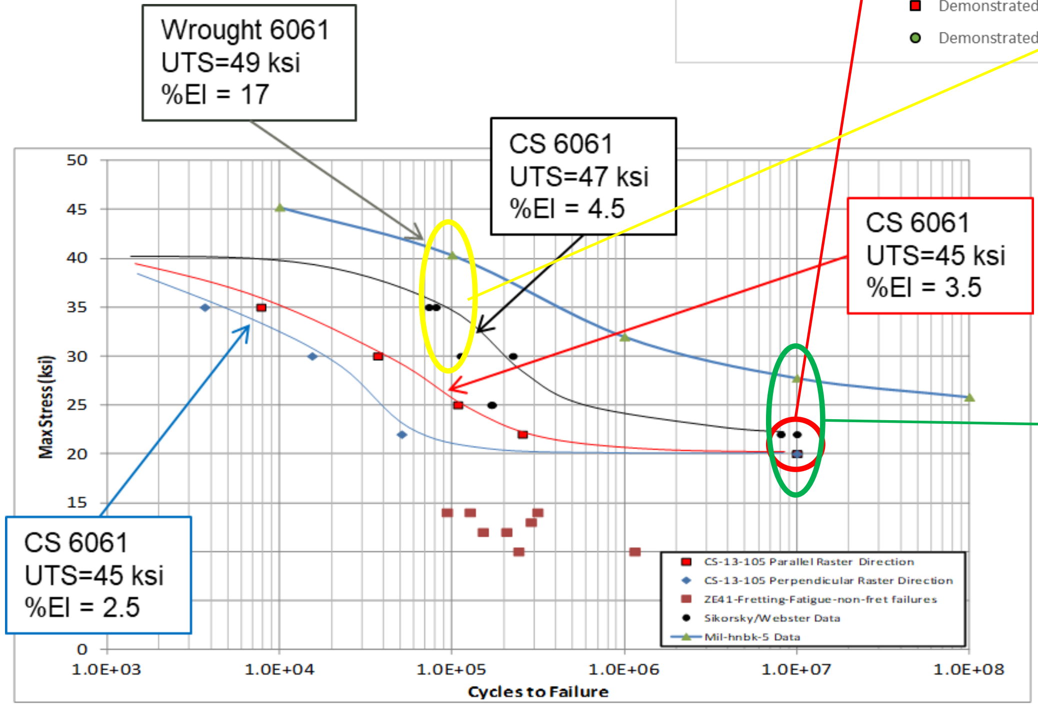

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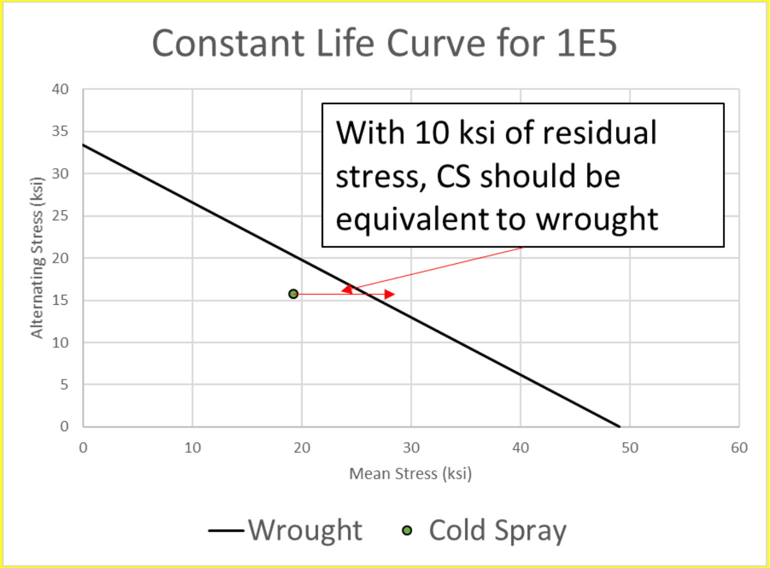
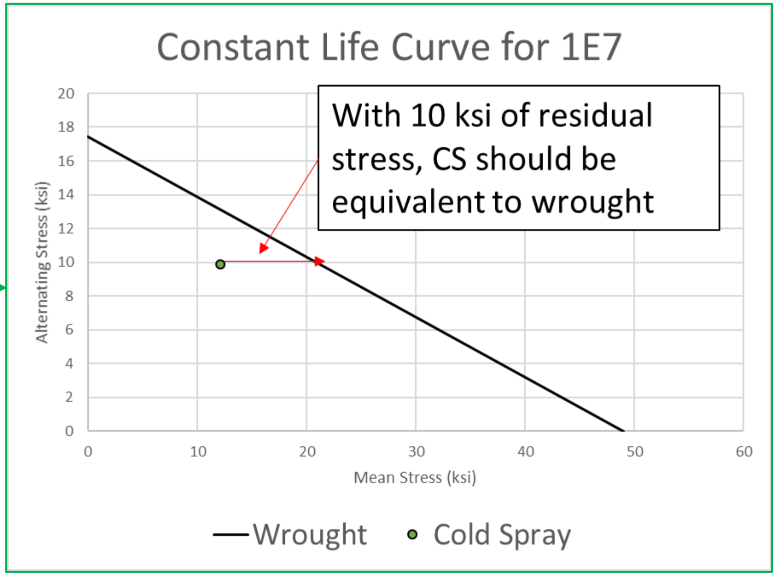
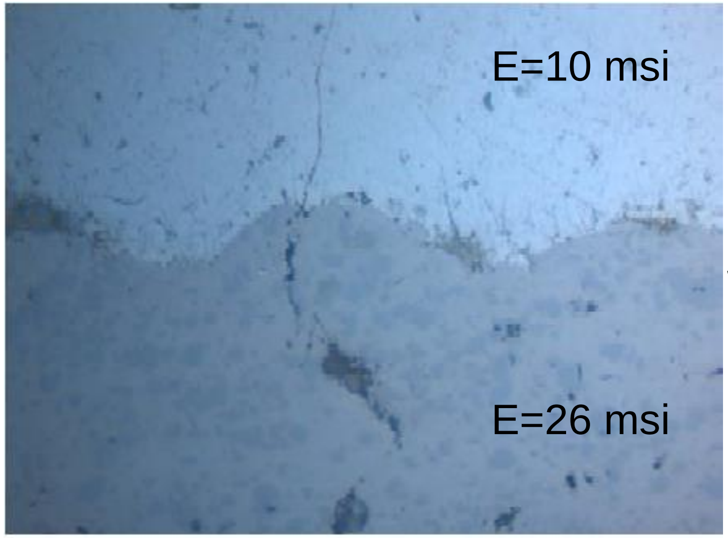
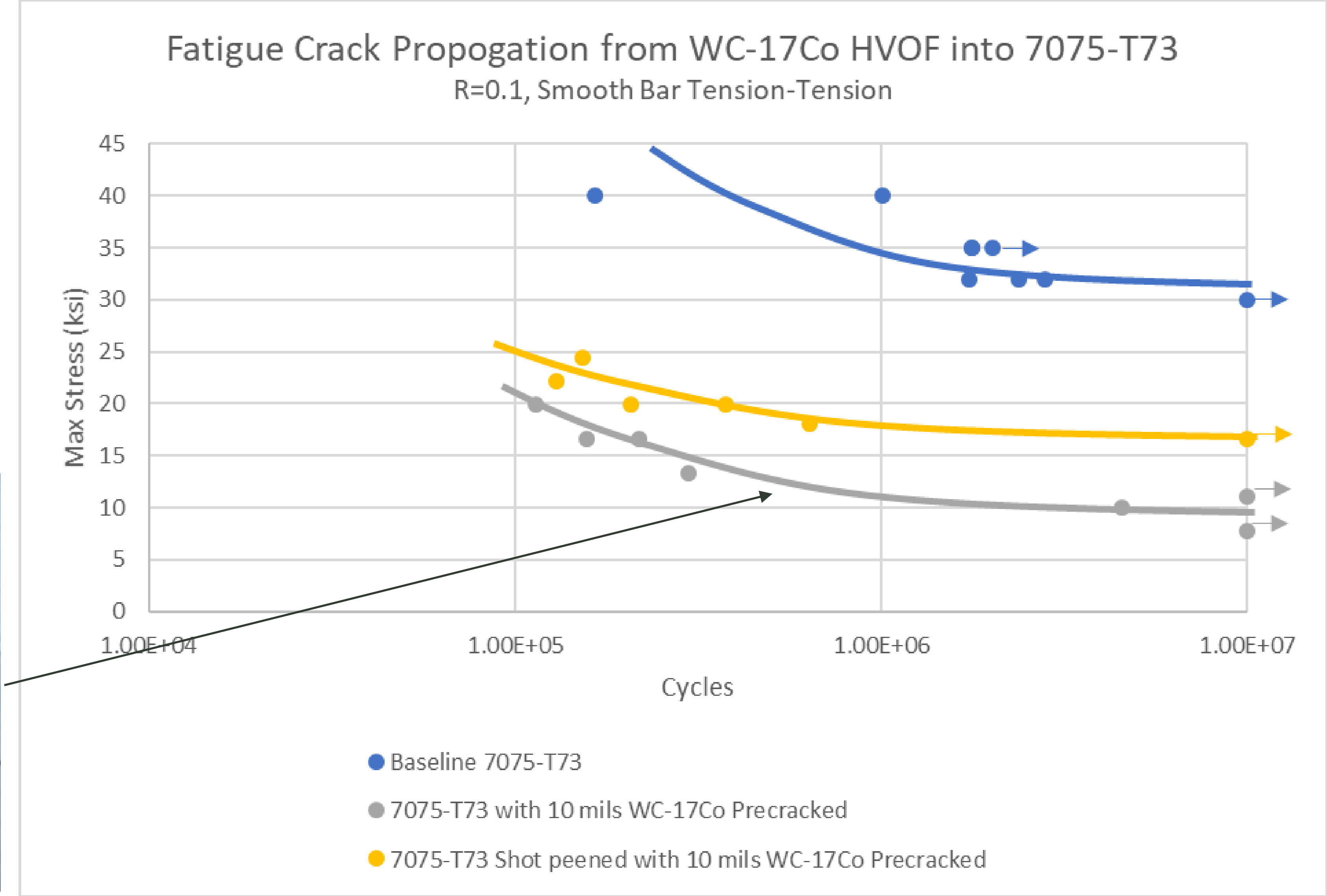




CRACK PROPAGATION FROM HIGH MODULUS COATING INTO 7075-T73

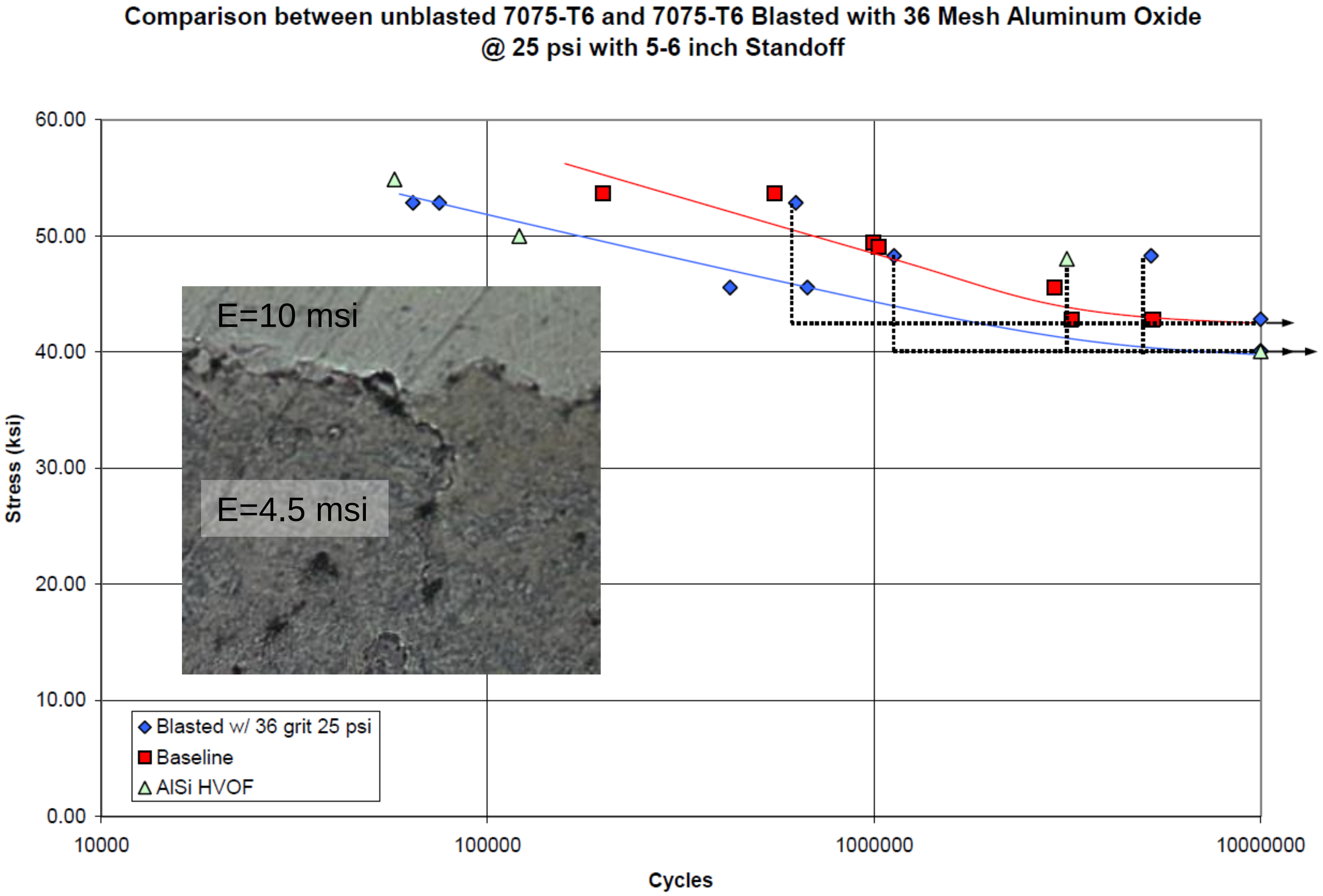
- Pre-cracking the WC-17Co allows understanding of crack transition across interface
  - Modulus difference changes traction stress at interface
- Shot peening shifts performance in HCF with less effect in LCF





EFFECTS OF GRIT BLASTING ON FATIGUE OF HIGH STRENGTH ALUMINUM

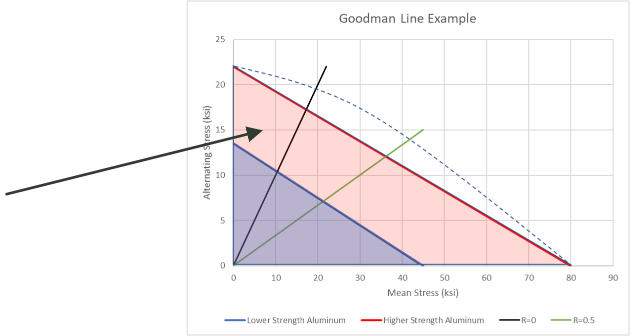
- Grit blasting is often critical for achieving high bond strength in thermal spray coatings
- Grit blasting can contribute to a compressive stresses
- Grit imbedding and surface damage can drive early initiations
- Al-Si is a relatively low quality aluminum coating with low modulus of elasticity and bond strength



SUMMARY

- Fatigue is a critical consideration for Cold Spray repairs as we transition to critical structure repairs especially in aircraft

- May need to consider dissimilar materials in some cases (eg. 7075 to repair 6061)
    - High quality 6061 with high ductility and high UTS and with compressive residual stress may meet typical performance of the substrate
    - Nitrogen sprayed “good” quality 7075 may meet the typical performance requirements of 6061 due to a generally higher UTS



- “Low Quality” repairs may not show debit to substrate in do-no-harm repairs, but likely will not provide load support or sufficient quality for many critical applications