Fatigue Life of Haynes 188 Superalloy in Hydrogen

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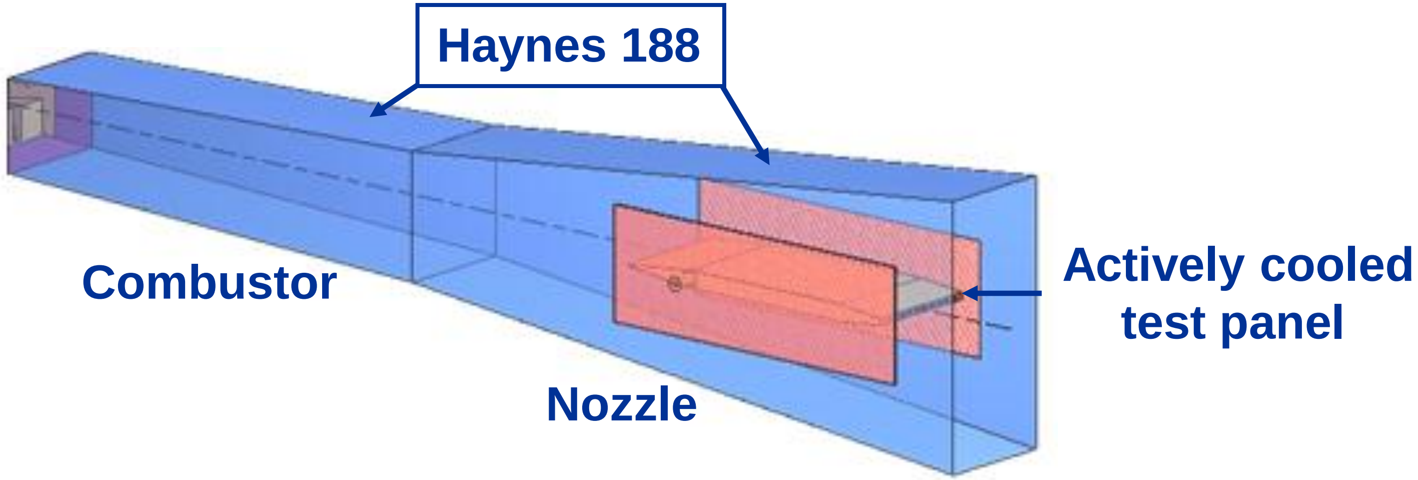
- The Durable Combustor Rig (DCR) provides a flexible and efficient test bed to demonstrate the durability of actively cooled scramjet engine structures, static and dynamic sealing technologies, and thermal management techniques.
  - DCR is hydrogen fueled and cooled
  - Flight-like structural test panels also hydrogen cooled
  - Testing at NASA Langley Research Center



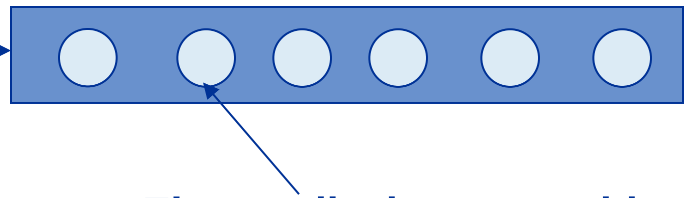
T. D. Drozda, D. P. Capriotti, R. L. Gaffney, "Modeling and Simulation of Mach 6 Tests of NASA's Durable Combustor Rig with VULCAN", 58th JANNAF Propulsion Meeting / 44th CS / 32nd APS / 32nd EPSS / 26th PSHS Joint Subcommittee meeting, April 2011, Crystal City, VA.

A. H. Auslender, K. L. Suder, S. R. Thomas, "An Overview of the NASA FAP Hypersonics Project Airbreathing Propulsion Research", AIAA Proceedings,19-22 Oct 2009.

- Statement of Problem: Actively cooled combustor walls of Haynes 188 superalloy shall encounter severe conditions that could challenge low cycle fatigue durability in repeated runs

<u>Haynes 188 Panel Cross-section</u>

- **Temperatures up to 650°C**
- **High thermal gradients**
- **High pressure hydrogen environment**
- **Surface finish variations**



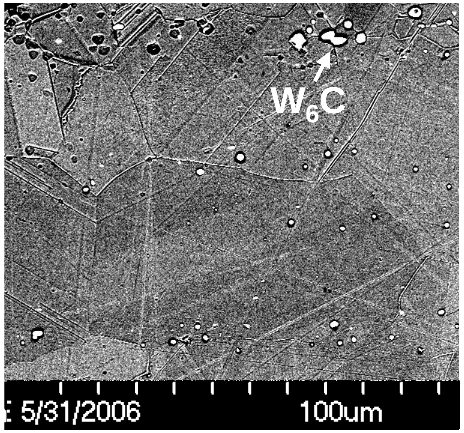
Electro-discharge machined (EDM) hydrogen cooling passages

- Objective: Assess low cycle fatigue capability of Haynes 188 for DCR application
  - 25 and 650°C
  - Hydrogen and helium environments
  - Low stress ground (LSG) and electro-discharge machined (EDM) finish

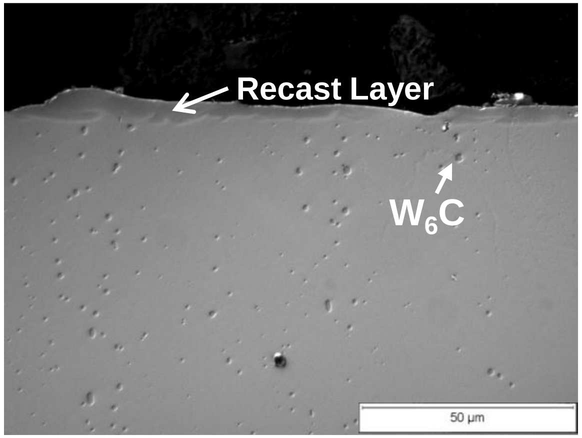
- Material: Haynes 188

Element	B	C	Cr	Fe	La	Mn	Ni	Si	W	Co
Weight %	0.015*	0.10	22.0	3.0*	0.03	1.25*	22.0	0.35	14.0	39 (bal.)

* Maximum



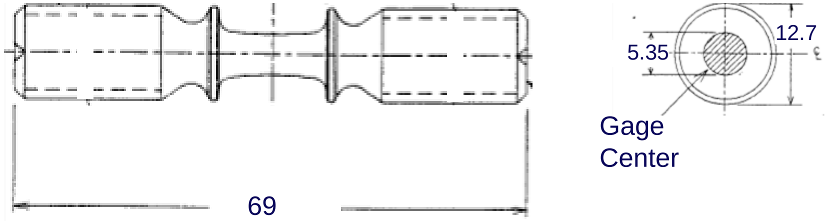
40 μm Grain Size



LCF Specimen EDM Surface

- Specimens machined from remnants of DCR structural panels
- EDM finish of cooling holes reproduced on specimens surfaces
- No cracks observed in EDM recast layer

LSG and EDM Finished Fatigue Specimens



• Roughness and Residual Stress of Fatigue Specimens

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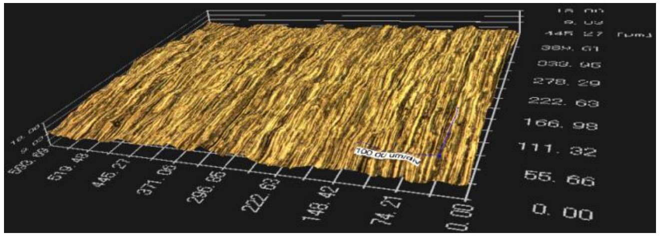
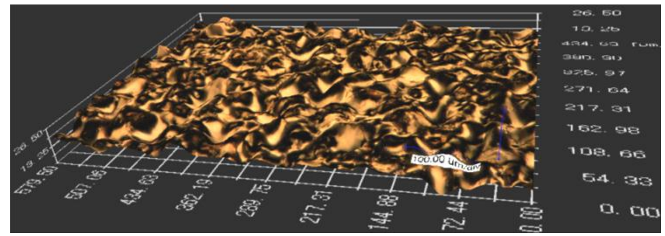
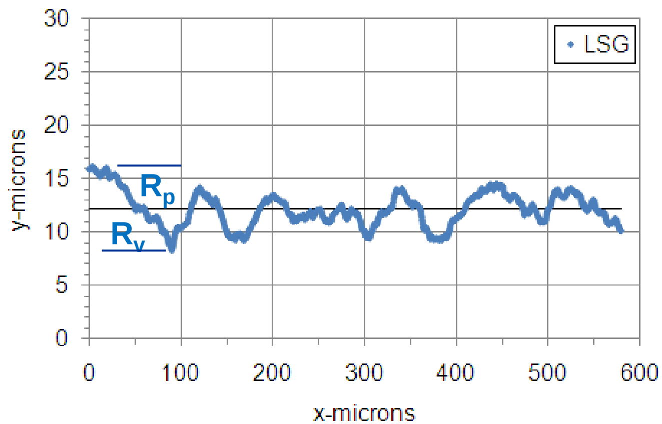
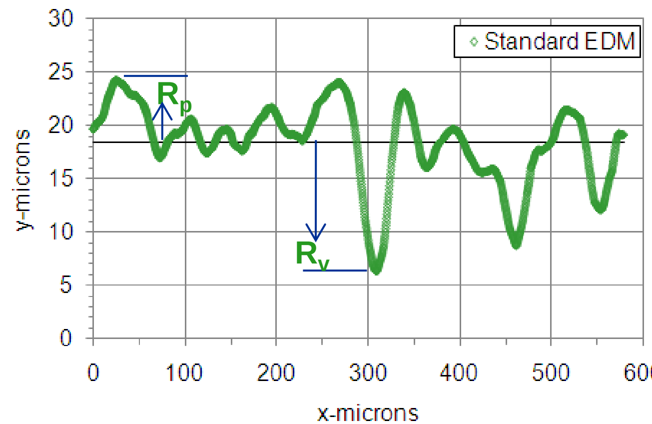
Low Stress Ground(LSG)



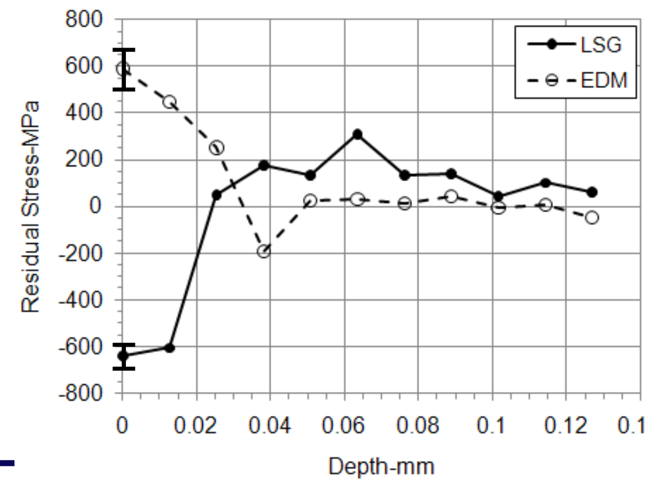
Electro-Discharge Machined(EDM)







The EDM finish gave higher roughness and tensile residual stresses near the surface in comparison to LSG specimens

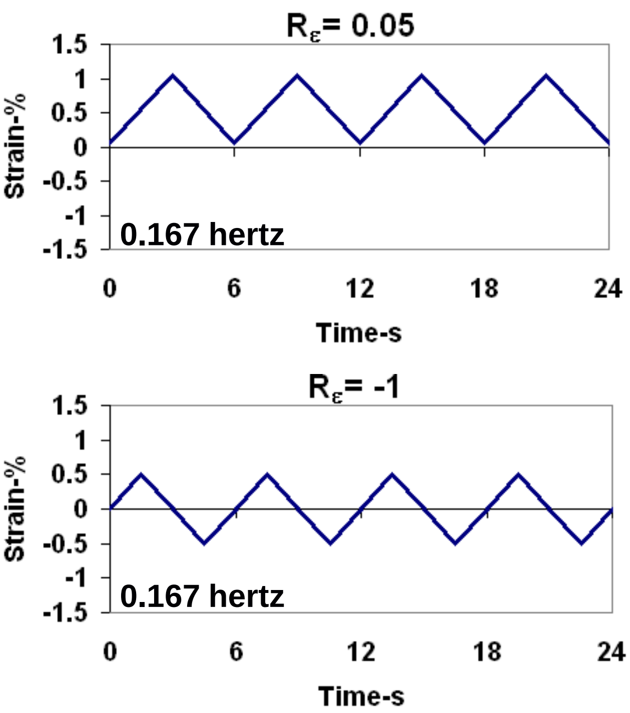


- Fatigue Testing: Performed at the NASA Marshall Space Flight Center, hydrogen test facility
  - 25 and 650°C, hydrogen and helium gas environments at 34.5 MPa pressure
  - Constant total strain range ($\Delta\varepsilon_t$) tests, min./max. strain ratios (R_ε)=0.05 and –1
  - Lives compared using the Smith-Watson-Topper stress parameter,

    $$\mathbf{SWT = (\sigma_{max}\Delta\varepsilon_t E/2)^{0.5}}$$

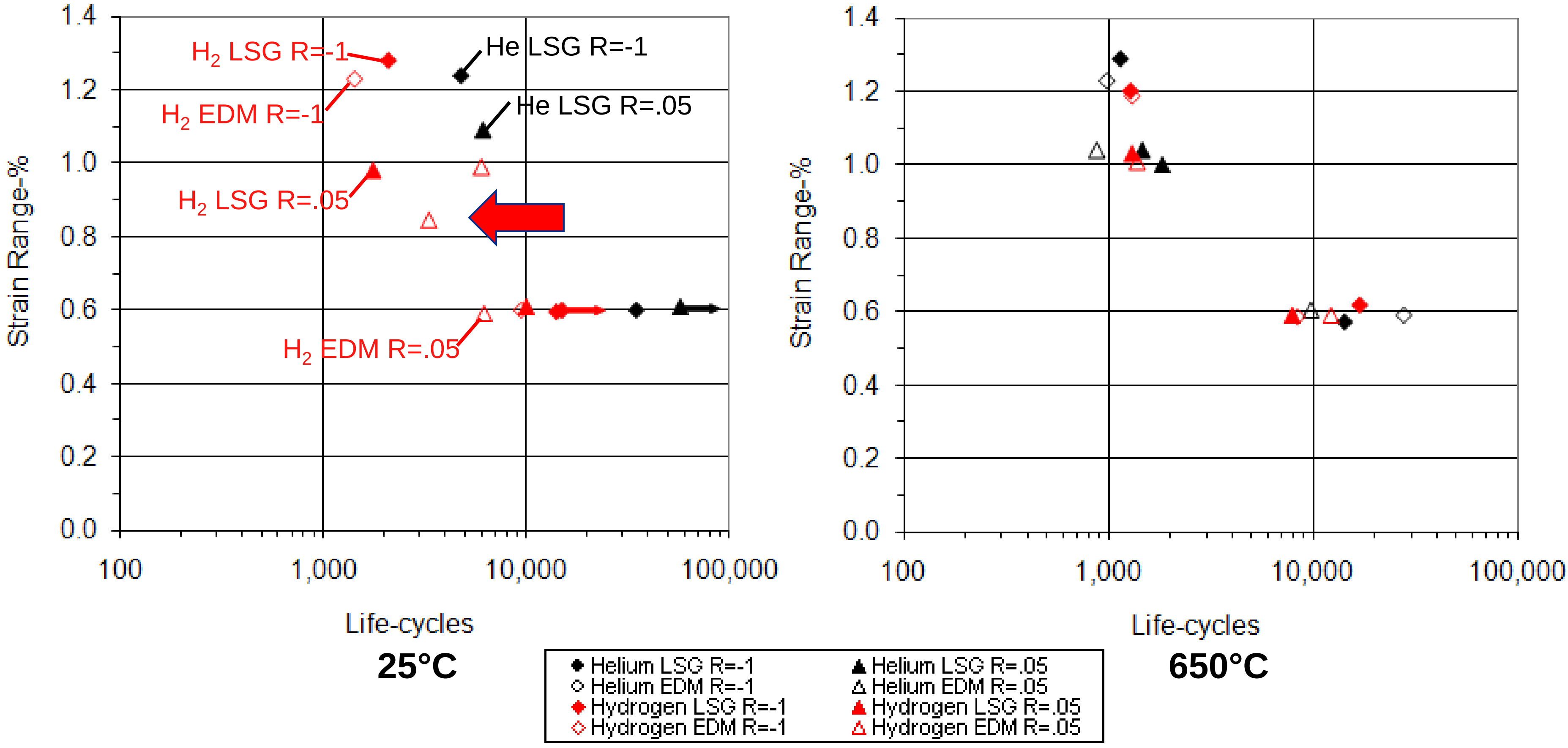
  - Accounts for variations in:
    - Total strain range $\Delta\varepsilon_t$
    - Maximum stress σ_{max}
    - Elastic modulus **E**
  - NASA GRC has successfully used this fatigue parameter in past studies (1) of Haynes 188

Strain Control Waveforms



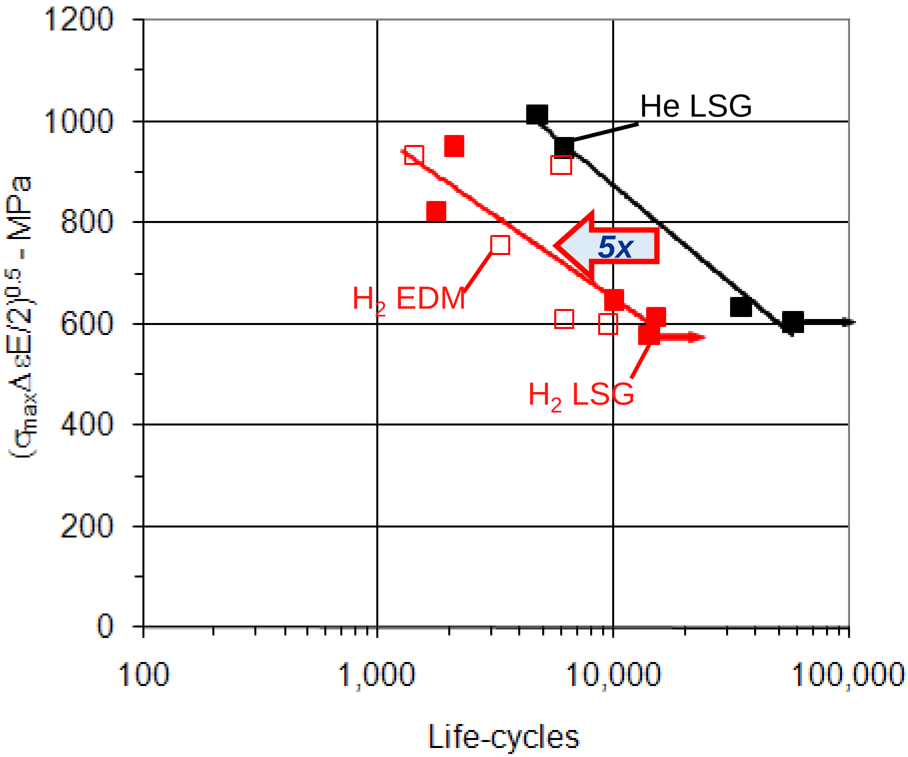
1. S. Kalluri, M. A. McGaw, G. R. Halford, "Fatigue Life Estimation Under Cumulative Cyclic Loading Conditions", <u>ASTM STP 1389</u>, ASTM, West Conshohocken, PA, 2000, pp. 94-109.

Results: Hydrogen Reduced Fatigue Life At Room Temperature

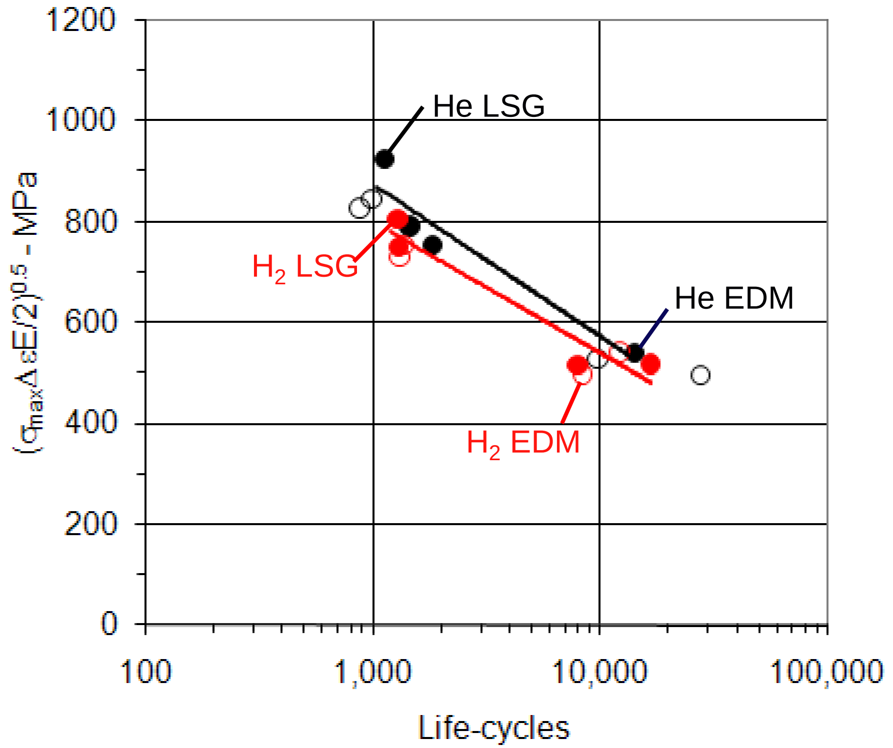


Higher strain ratio consistently reduced life at 650°C

Hydrogen Reduced Mean Fatigue Life 5x
At Room Temperature



25°C



650°C

EDM finish did not strongly degrade mean fatigue life, but increased scatter at 25°C

Multiple Linear Regression

- Continuous variables of temperature, σ_{SWT}, roughness, and residual stress were scaled to be -1 to +1 so magnitudes of regression constants could be used to rank their influences:

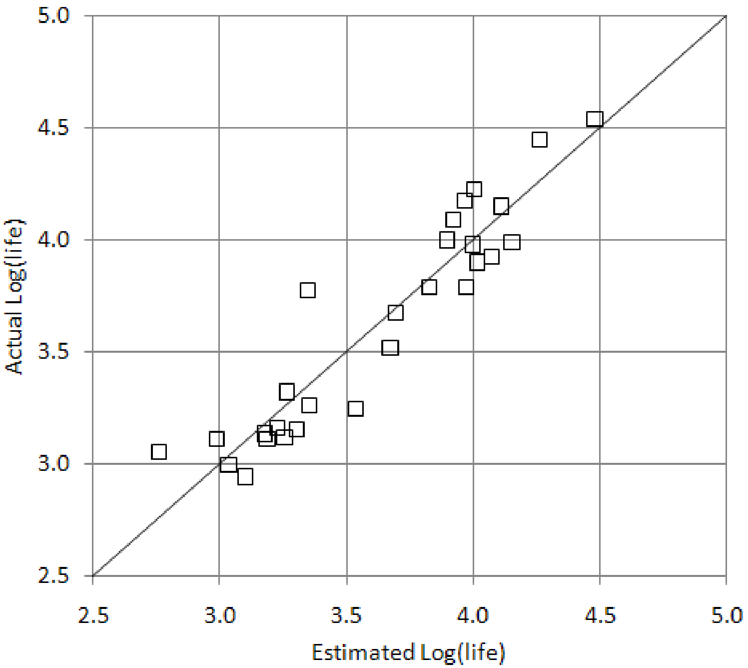
$$\mathbf{V'} = (V - V_{mid})/(\Delta V/2)$$

- Environment was included as a discrete variable (helium-0, hydrogen-1)

$$\text{Log(life)} = 3.7901 - 0.3678\,e - 0.4373\,\mathbf{T'} - 0.7213\,\boldsymbol{\sigma}_{\mathbf{SWT}}' + 0.1843\,e\,\mathbf{T'} - 0.1876\,\mathbf{T'}\,\boldsymbol{\sigma}_{\mathbf{SWT}}'$$

$R^2_{adj} = 0.855$,
rms Error = 0.1846

Multiple linear regression indicated SWT stress (σ_{SWT}') , temperature (T'), and environment (e) significantly influenced life, but not roughness or residual stress



Fatigue Failure Initiation Sites Varied With Environment At Room Temperature

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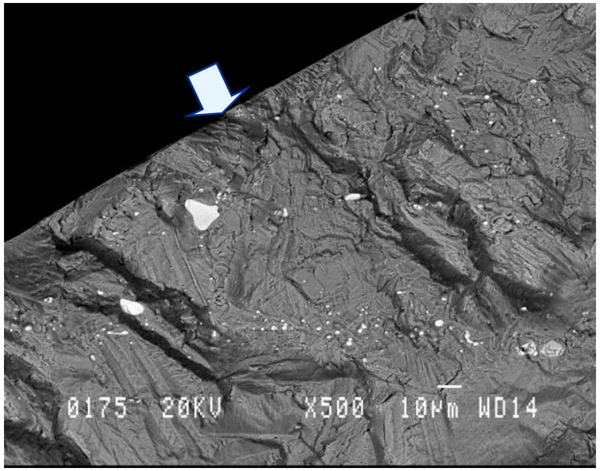
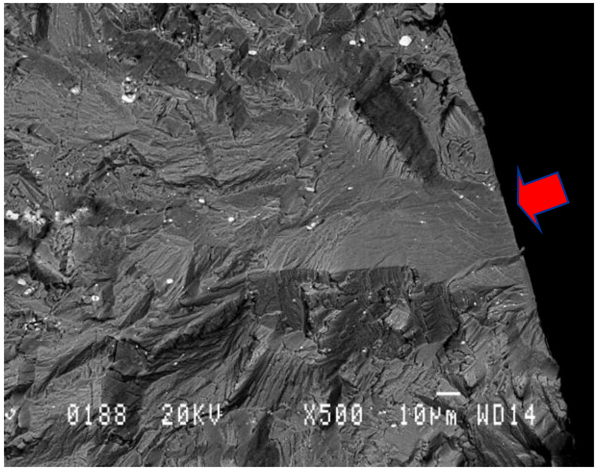
LSG / 1% Strain / He



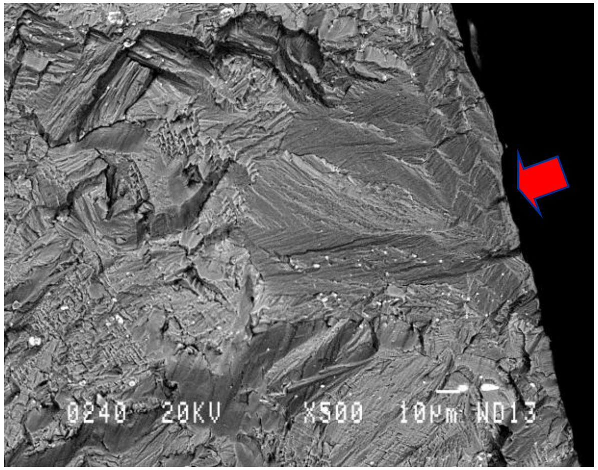
Normal to Load Axis

LSG / 1% Strain / H



Grain Facet

EDM / 1% Strain / H



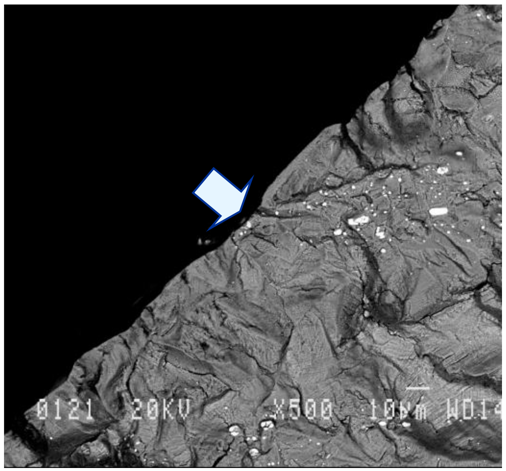
Grain Facet

Crystallographic grain facets initiated surface cracks in hydrogen

- Subsequent crack growth was transgranular, but not faceted (brittle)

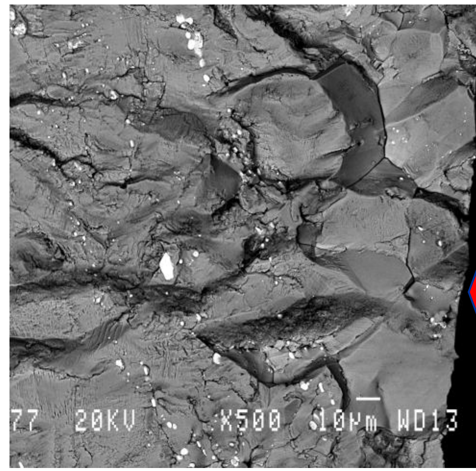
Fatigue Failure Initiation Sites Varied With Environment At 650°C

EDM / 1% Strain / He



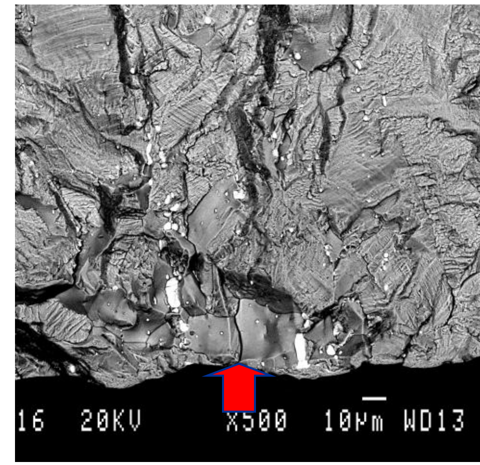
Normal to Load Axis

LSG / 1% Strain / H



Grain Boundary

EDM / 1% Strain / H



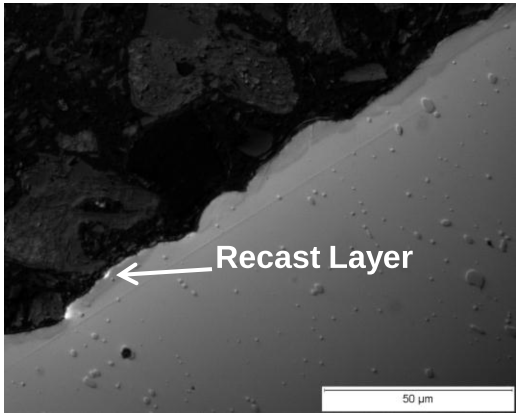
Grain Boundary

Grain boundary cracking at the surface was encouraged by hydrogen

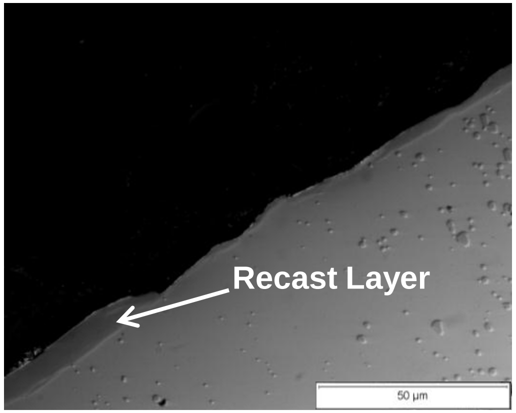
- Subsequent crack growth was transgranular, did not appear faceted

Additional Samples Were Prepared With Purposefully Varied EDM Finish and Resulting Roughness

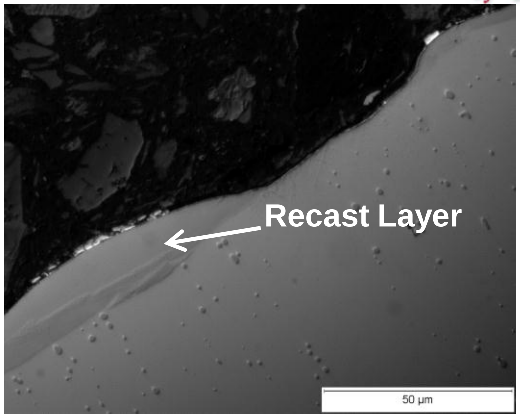
Low



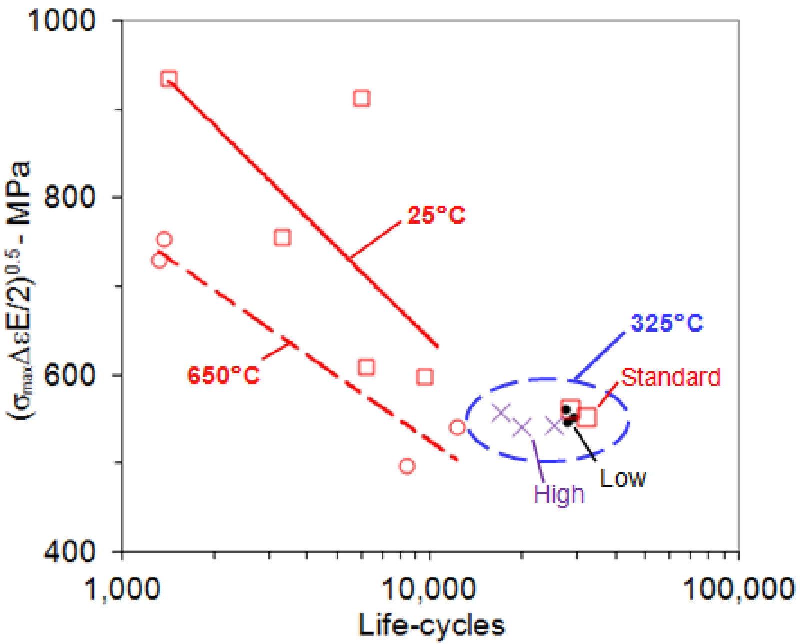
Standard



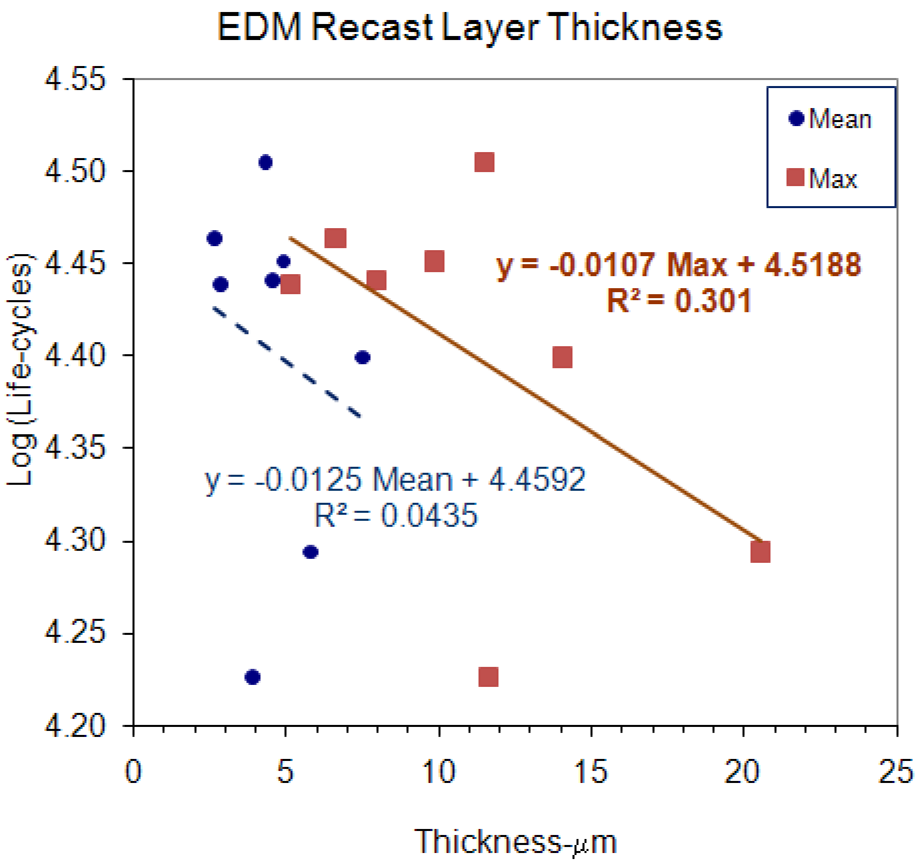
High

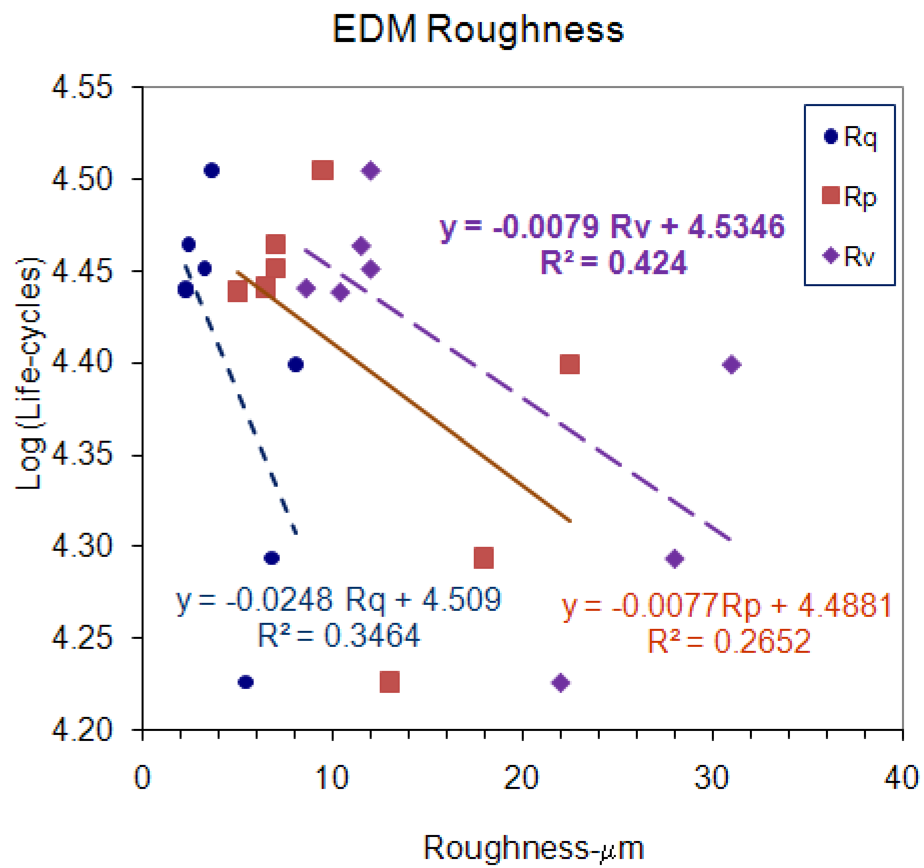


Tests performed in hydrogen at an intermediate temperature of 325°C indicated "high" EDM conditions reduced life



EDM Recast Layer Thickness and Surface Roughness Versus Fatigue Life in Hydrogen at 325°C



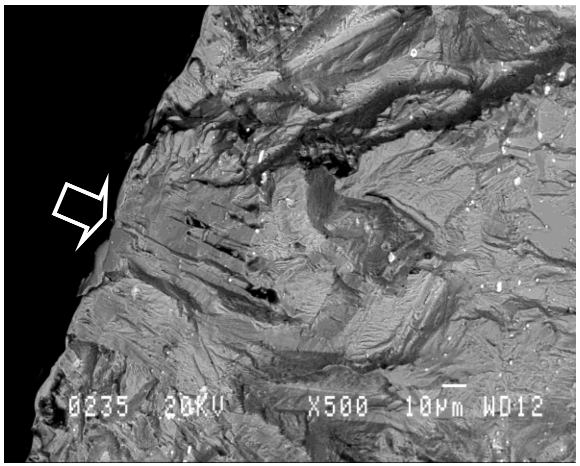


Valley roughness (Rv) had the strongest correlation with fatigue life

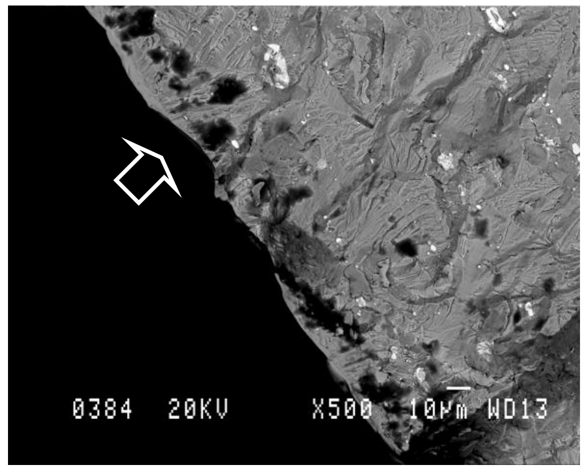
- Substantial scatter remained, suggesting other factors at "high" have influence

Fatigue Failure Initiation Sites Did Not Consistently Vary With EDM Condition for Tests in Hydrogen at 325°C

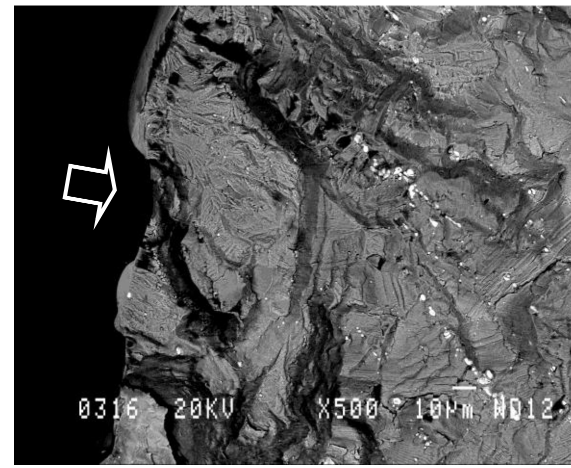
Low



Standard



High



Cracking at surface facets was less prevalent than at 25°C, and often occurred normal to the loading axis at valleys

- **Subsequent crack growth was transgranular, did not appear faceted (brittle)**

- Summary: Low cycle fatigue capability of Haynes 188 was assessed for DCR application
  - 25 and 650°C
  - Hydrogen and helium environments
  - Low stress ground and electro-discharge machined finish
- Conclusions: Low cycle fatigue life capability of Haynes 188 in hydrogen looks quite satisfactory for DCR application
  - Capability moderately decreased by hydrogen at low temperature
  - Capability not decreased with controlled EDM machining
  - Failures indicate retention of ductility during crack growth

- **Acknowledgements**

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