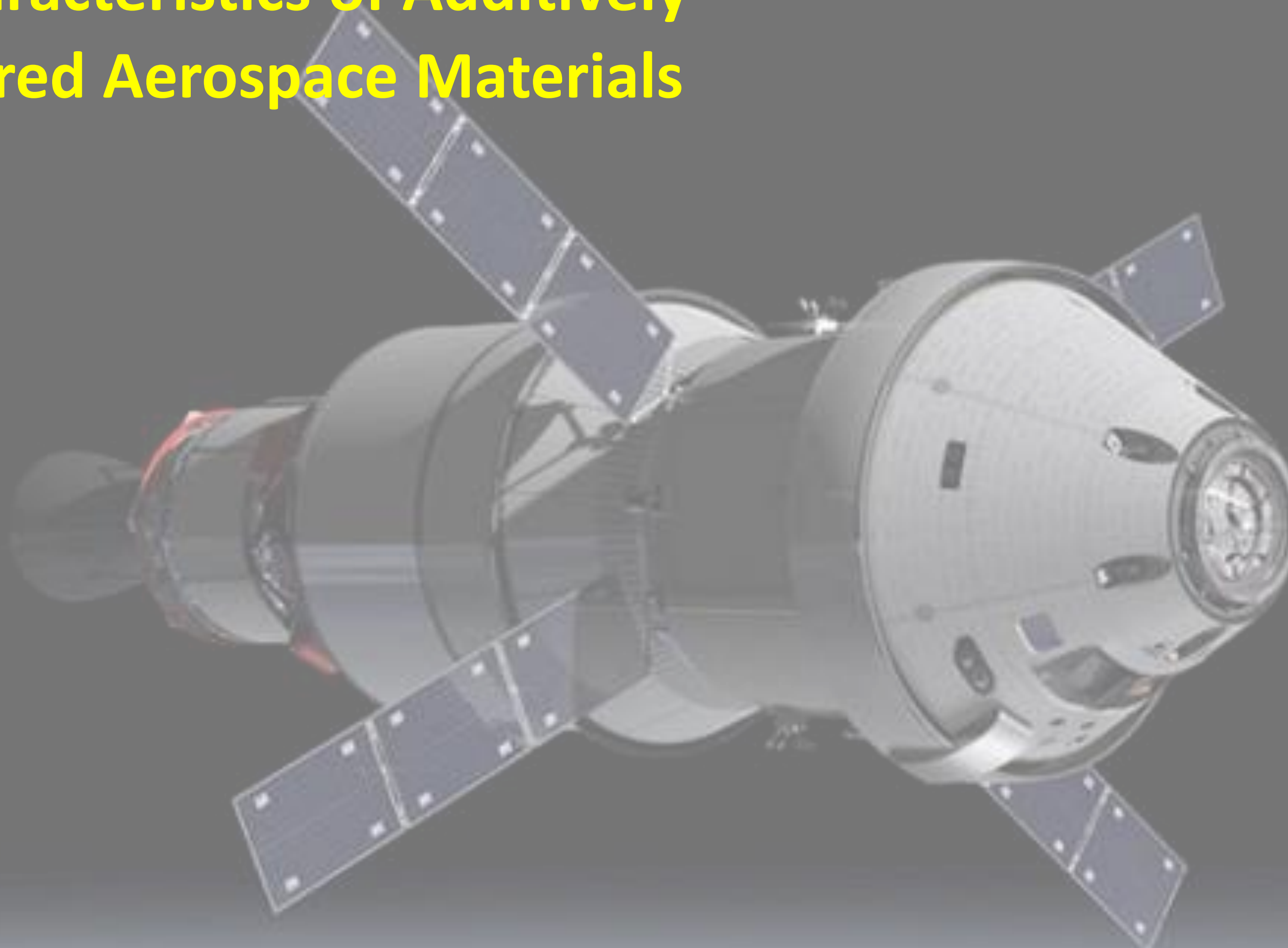
Fatigue Characteristics of Additively Manufactured Aerospace Materials



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Additive Manufacturing (AM) finding many uses in NASA's missions

AM allows design flexibility, decreases parts, increases affordability, and reduces manufacturing time.

Drawbacks:

Limited number of alloy powders

Limited understanding of AM parameters, including powder characteristics

Very limited processing and feedstock specifications

Scarce knowledge of process control on component properties

Limited databases for AM materials

Difficulty in qualification and certification

Space Launch System RS-25 Affordability Strategy

33% Reduction in Cost

> 700 Welds Eliminated
> 700 Parts Eliminated

35 AM Opportunities

Current study on materials made by powder bed additive manufacturing methods

Alloy 718 and GRCop-84 made using Selective Laser Melting (SLM)

Ti-6-4 made using Electron Beam Melting (EBM)

Test coupons built with either as-fabricated or machined surfaces

High Cycle Fatigue (HCF) and Low Cycle Fatigue tests conducted at 20 ^{o}C

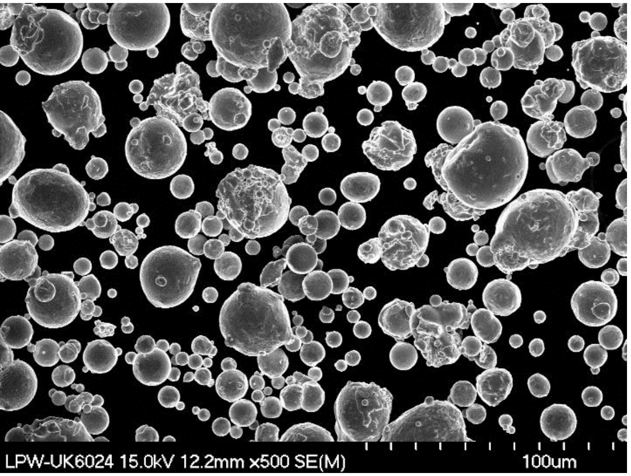
Fractography and metallography performed to document initiation sites

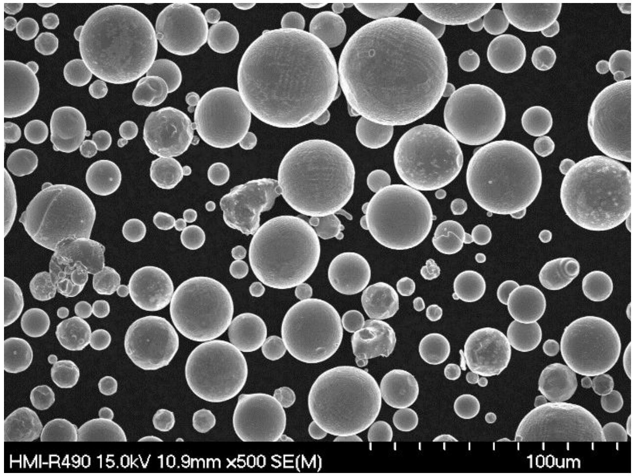
GRCop-84 Combustion chamber

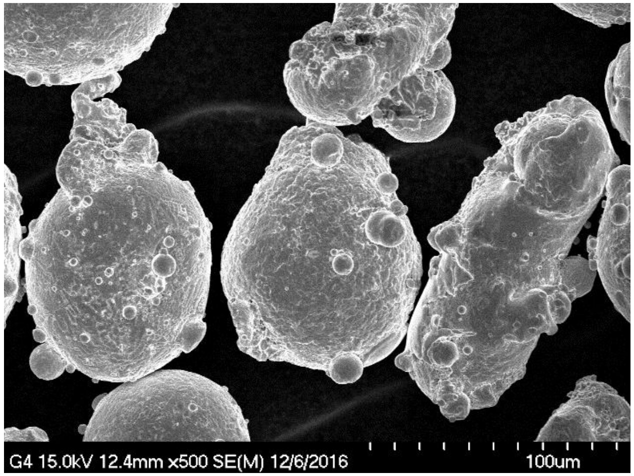
Additively Manufactured Alloy 718

Additive Manufacturing Structural Integrity Initiative

- Purchased 18 commercially available powder lots
- Performed extensive powder characterization
- Built test coupons (SLM) with either as-fabricated or low stress ground gauge surfaces.
- Samples HIPed and heat treated
- Variety of tests and conditions conducted
- Extensive microscopy performed on material and tested samples
- Showing high cycle fatigue (HCF) results from tests at 20 ^{o}C

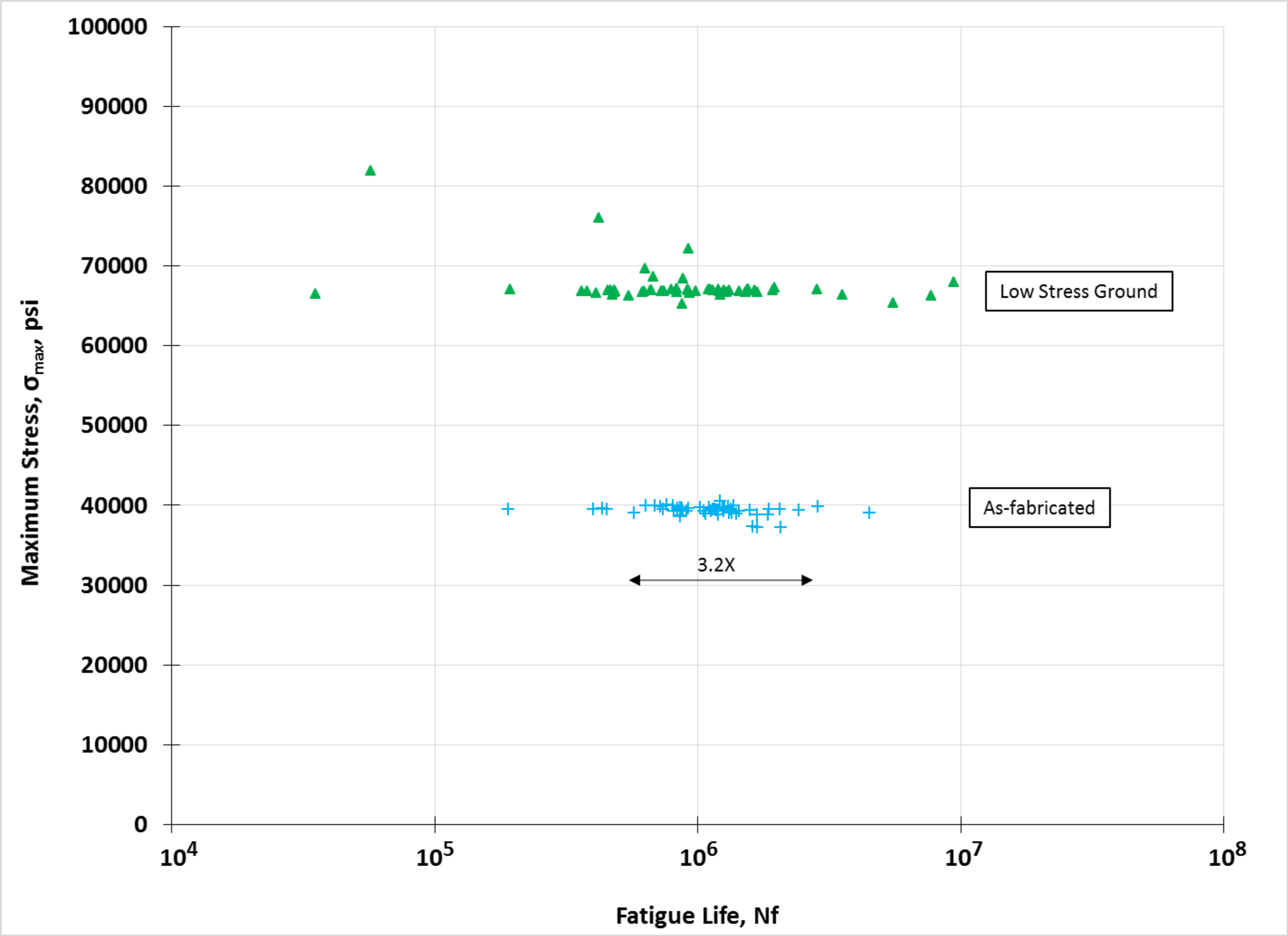




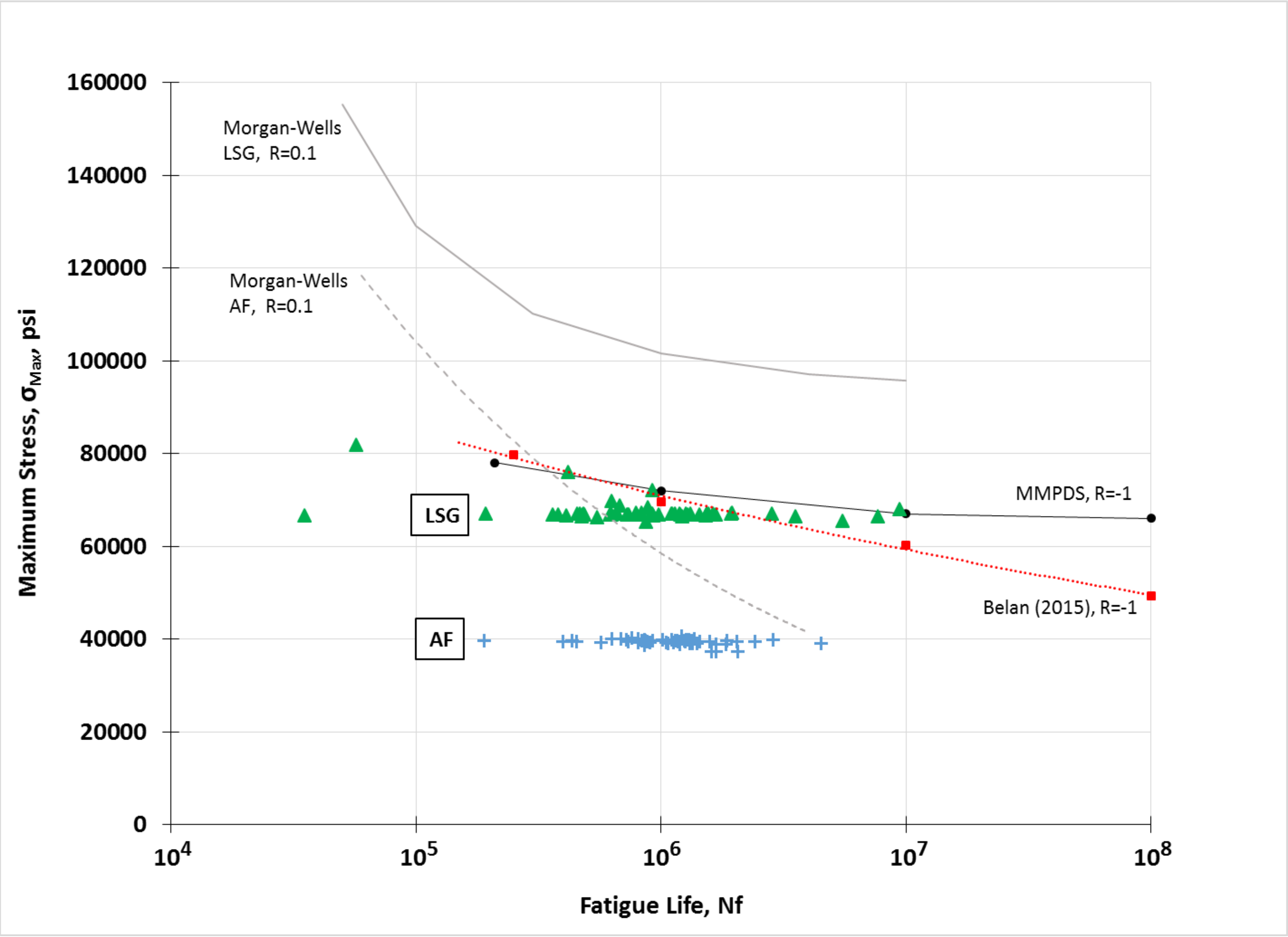


Alloy 718 Powder differences

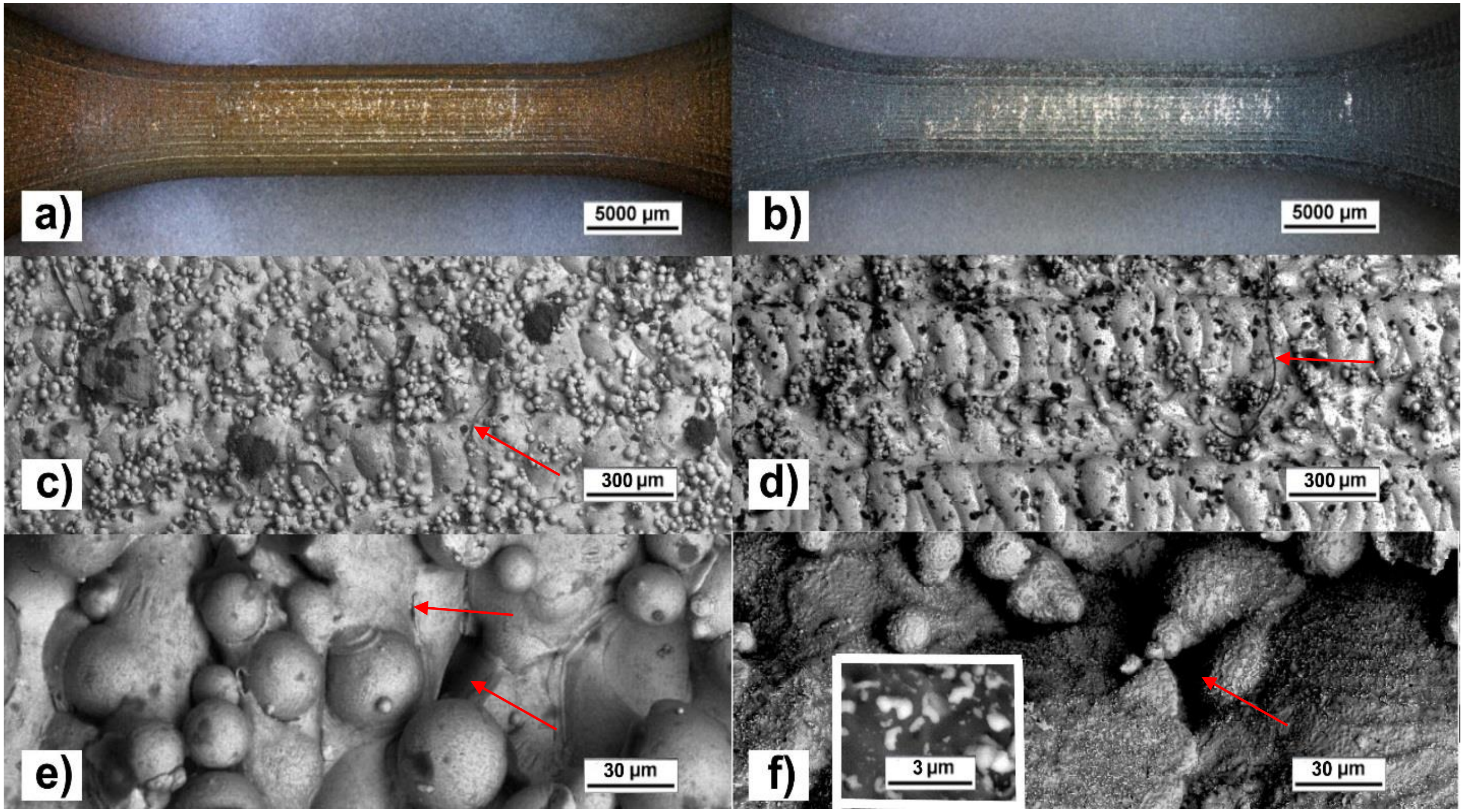
Fatigue of AM 718 tested at R_σ = -1 and 20 ^oC with two surface conditions.



Fatigue of AM 718 compared to literature data.

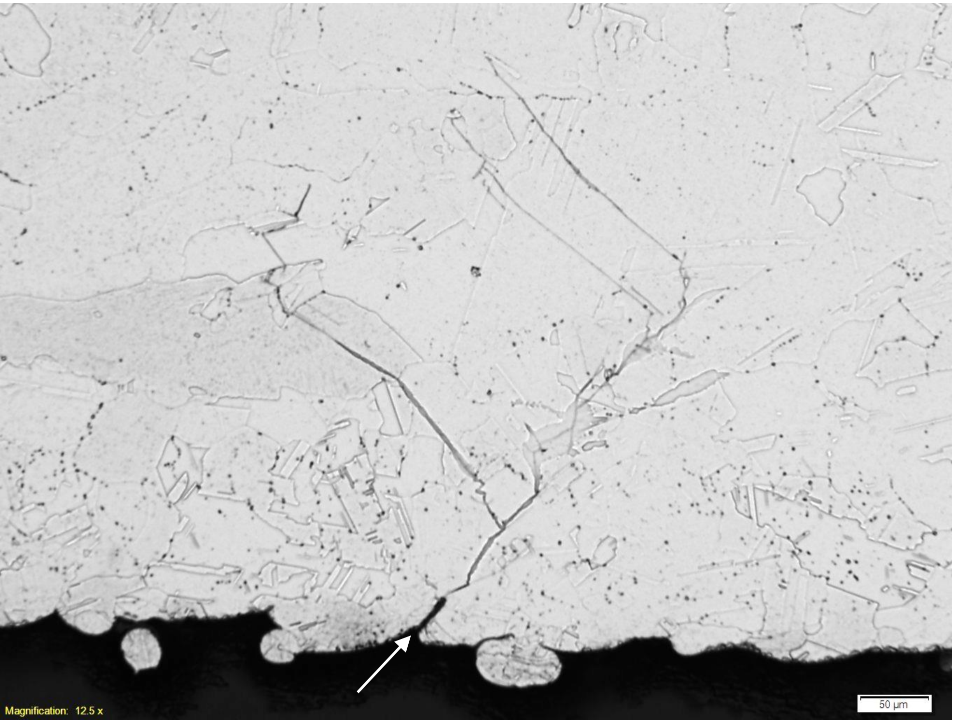


Gage surfaces of AM 718

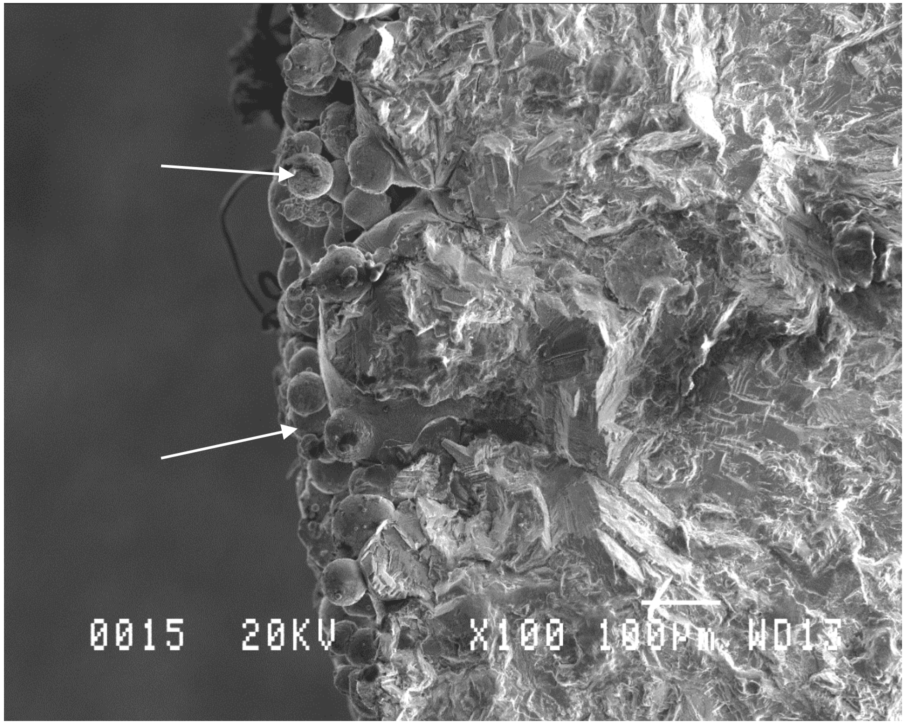


As-fabricated finish

Fatigue Crack Initiation Sites



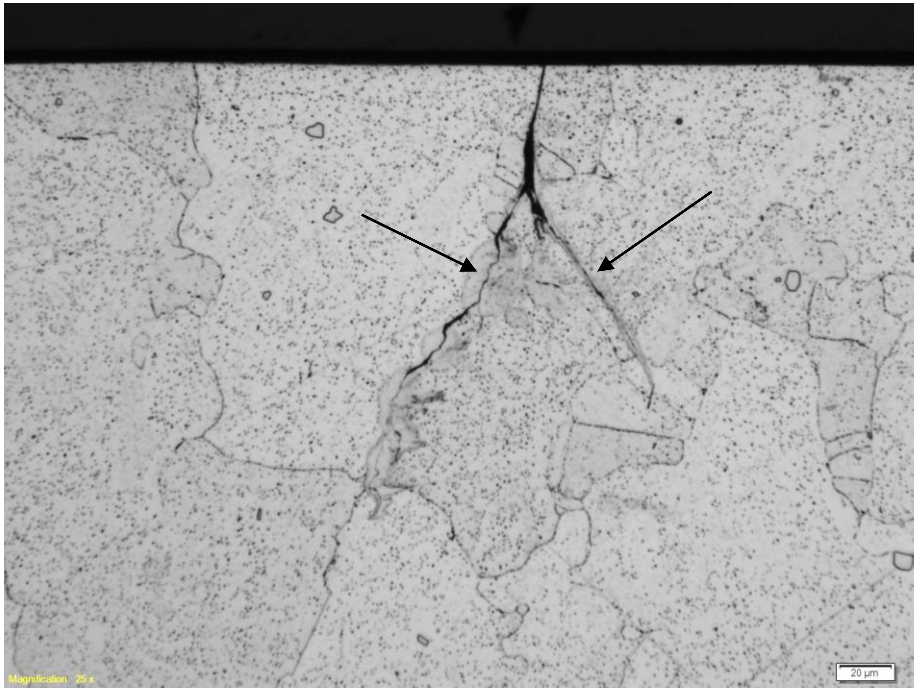
G2-2-3



G4-4-5

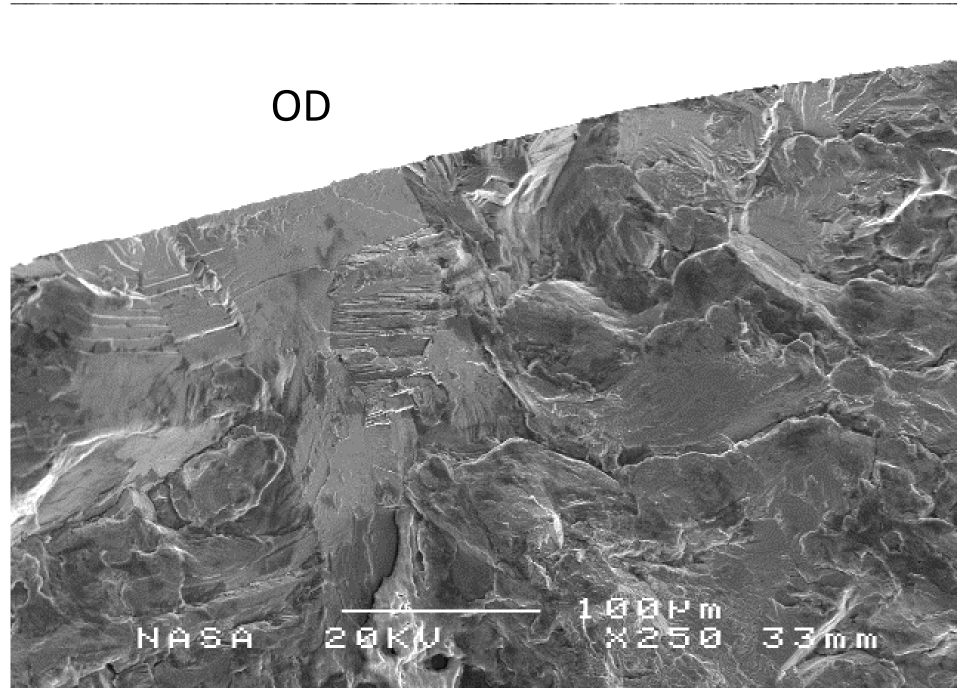
As-fabricated surface

Fatigue Crack Initiation Sites



V3-2-8

OD



H1-2-8

Low stress ground surface

Additively Manufactured GRCop-8Cr-4Nb

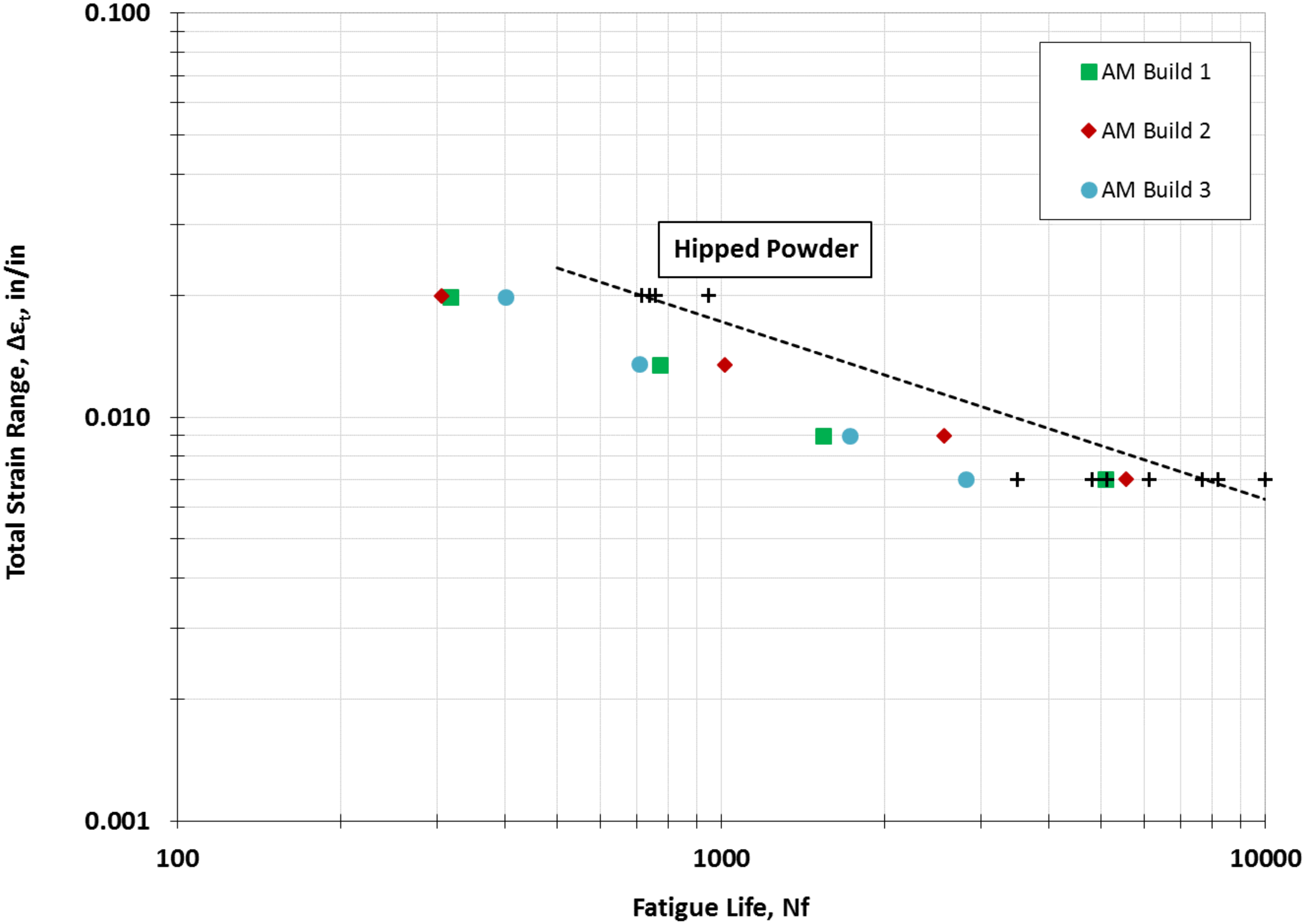
Low Cost Upper Stage-class Propulsion Combustion Chambers

- Purchased one large lot of powder and performed limited powder characterization
- Built test coupons (SLM) with internal hole to produce as-fabricated surface.
- Samples HIPed and heat treated
- Variety of tests (tensile, LCF, creep, toughness, FCP) and conditions conducted
- Extensive microscopy performed on material and tested samples
- Showing low cycle fatigue (LCF) results from tests at 20 ^{o}C

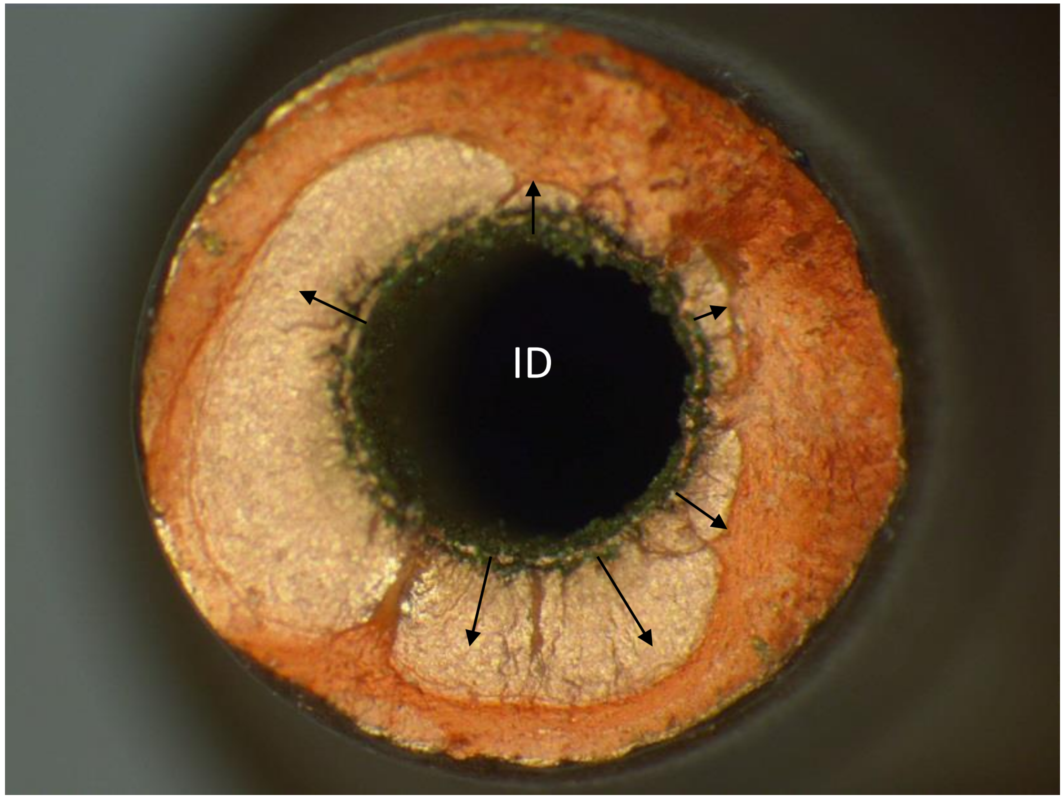
Chamber builds with coupon samples

LCF samples with welded ends

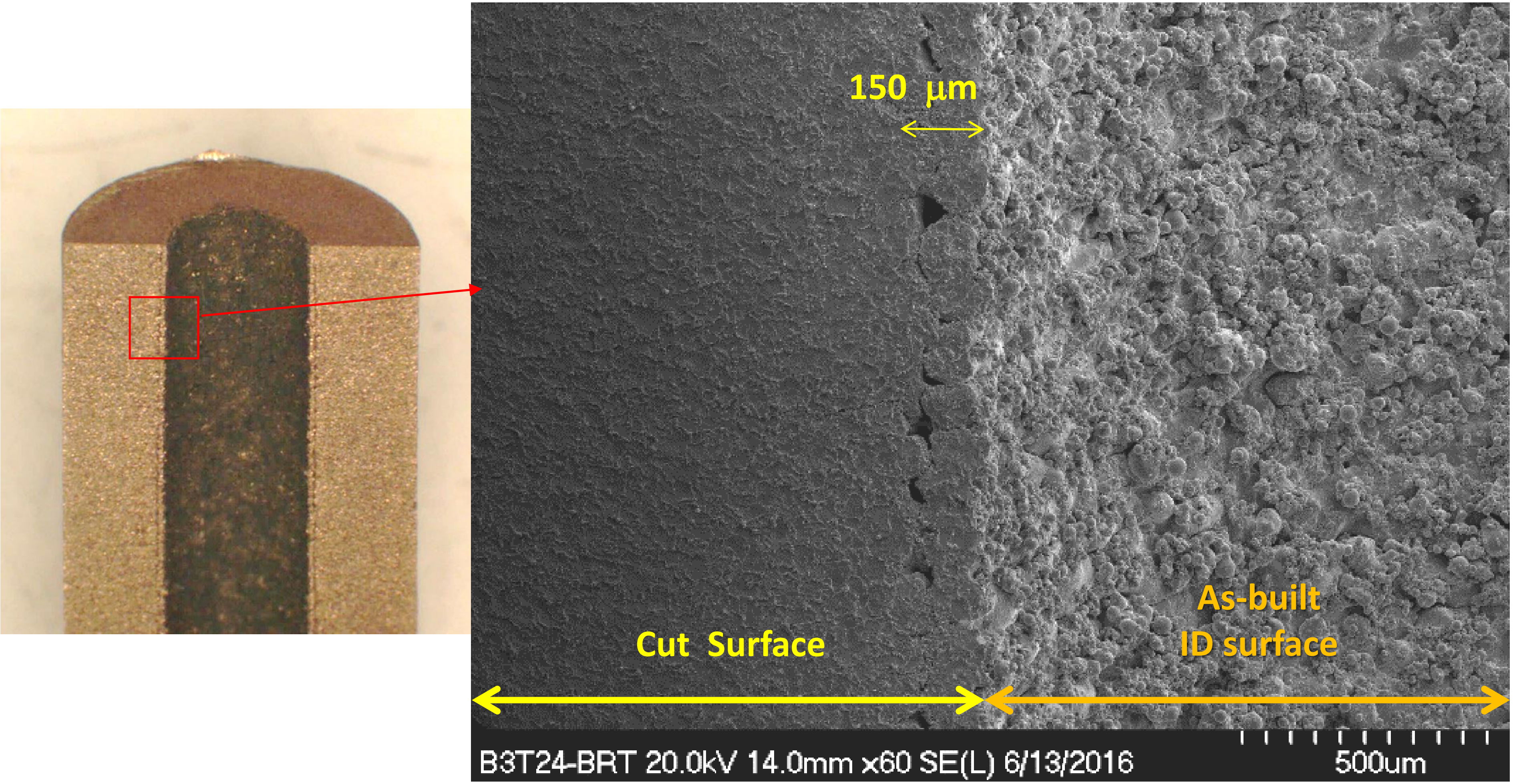
Fatigue of GRCop-84 tested at R_ε = -1 and 20 ^{o}C



Fatigue cracks initiating at the as-fabricated, inner diameter

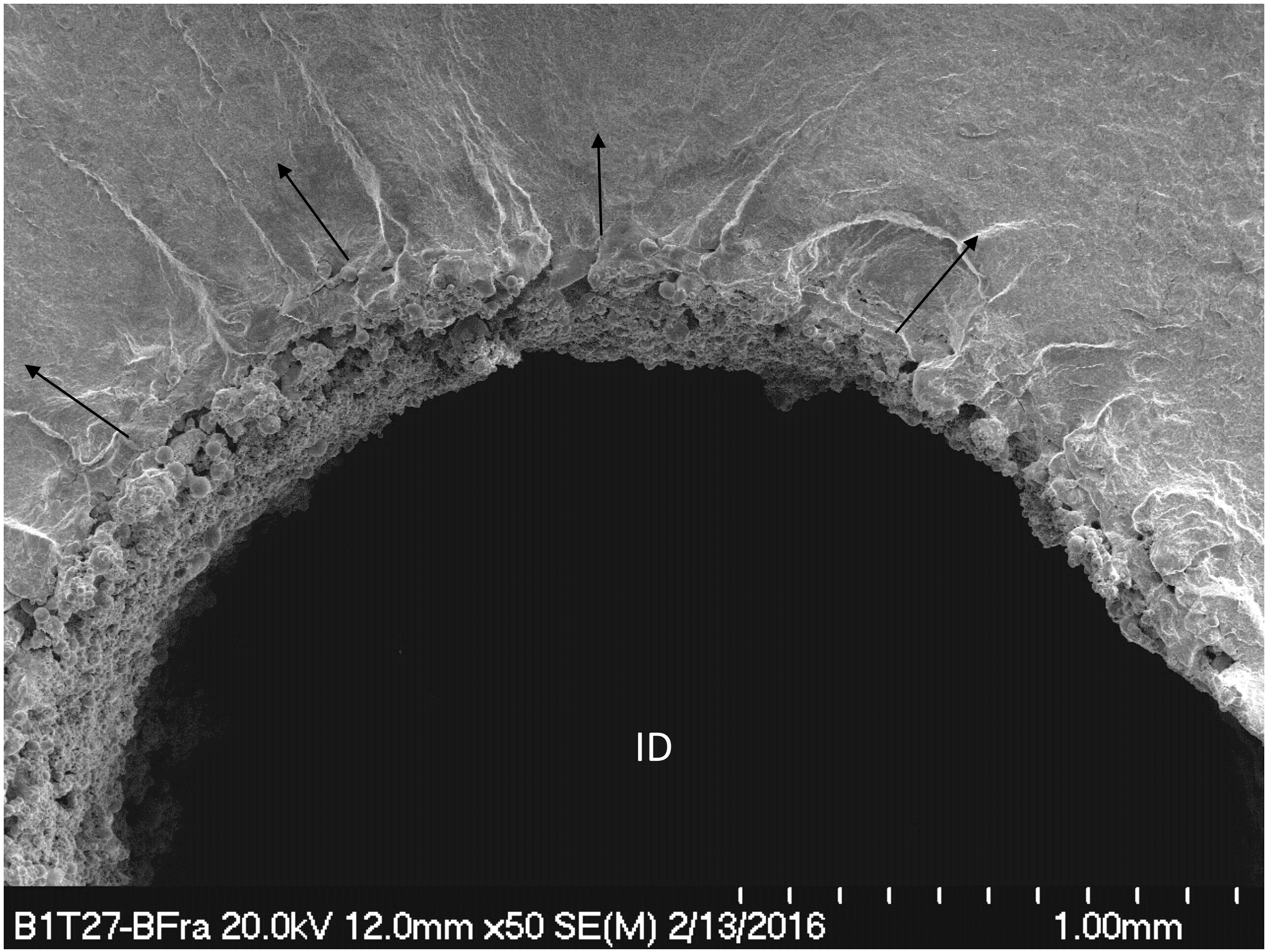


Surface finish of as-fabricated, inner diameter

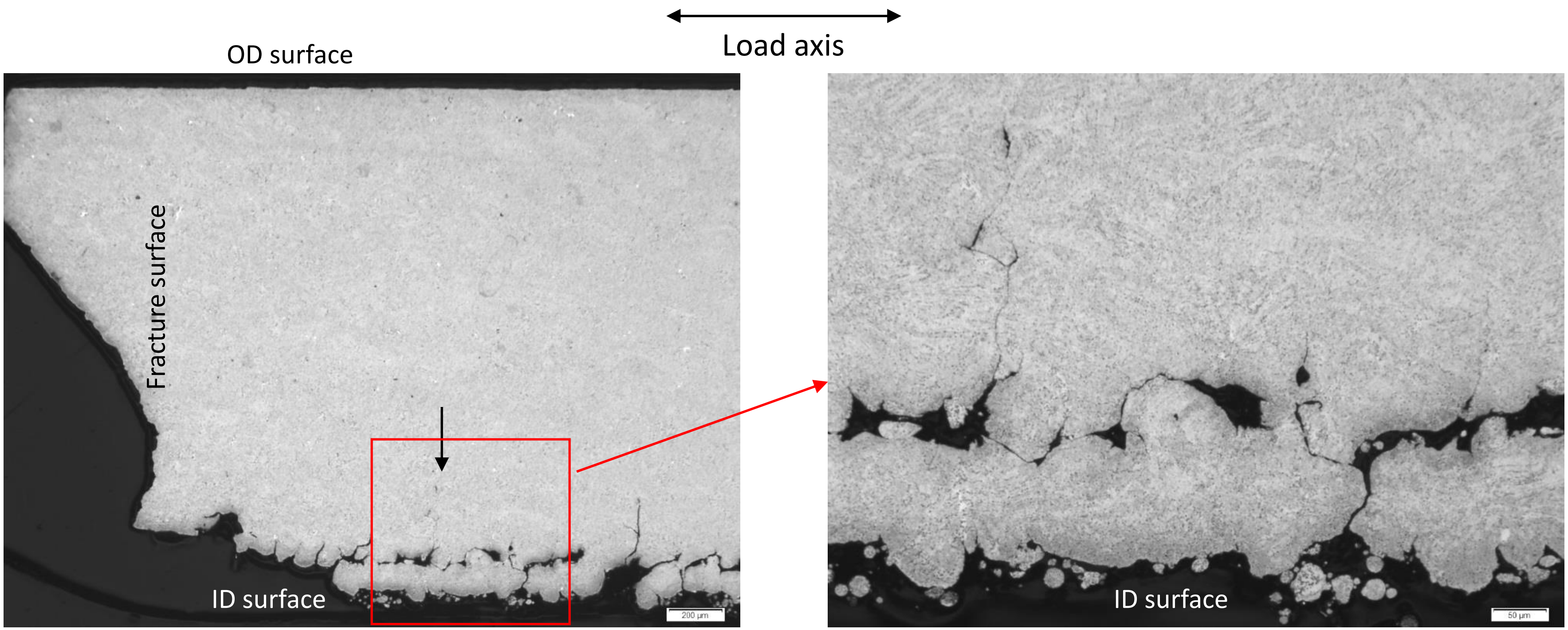


Rough as-built surface and subsurface voids and cracks

Fatigue cracks initiating at rough ID surface



Crack initiation from ID surface and row of porosity.



Additively Manufactured Ti-6Al-4V

USAF, Aerojet-Rocketdyne

Two lots of samples manufactured (EBM)

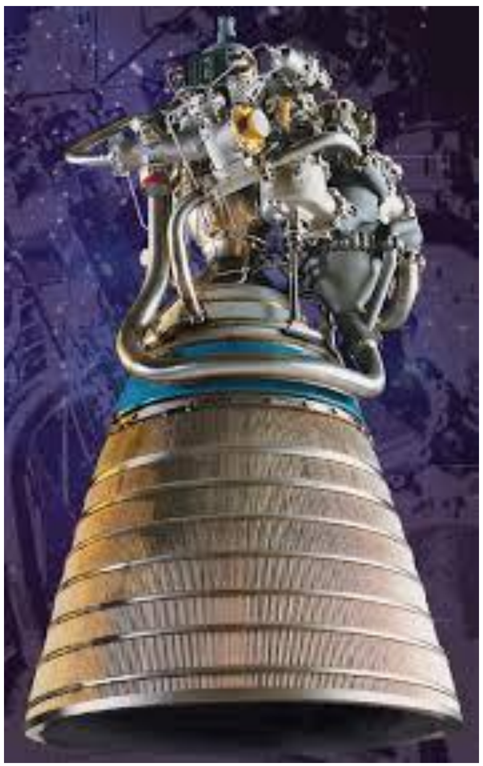
Minimal powder characterization performed

Samples were HIPed

Variety of tests and conditions conducted

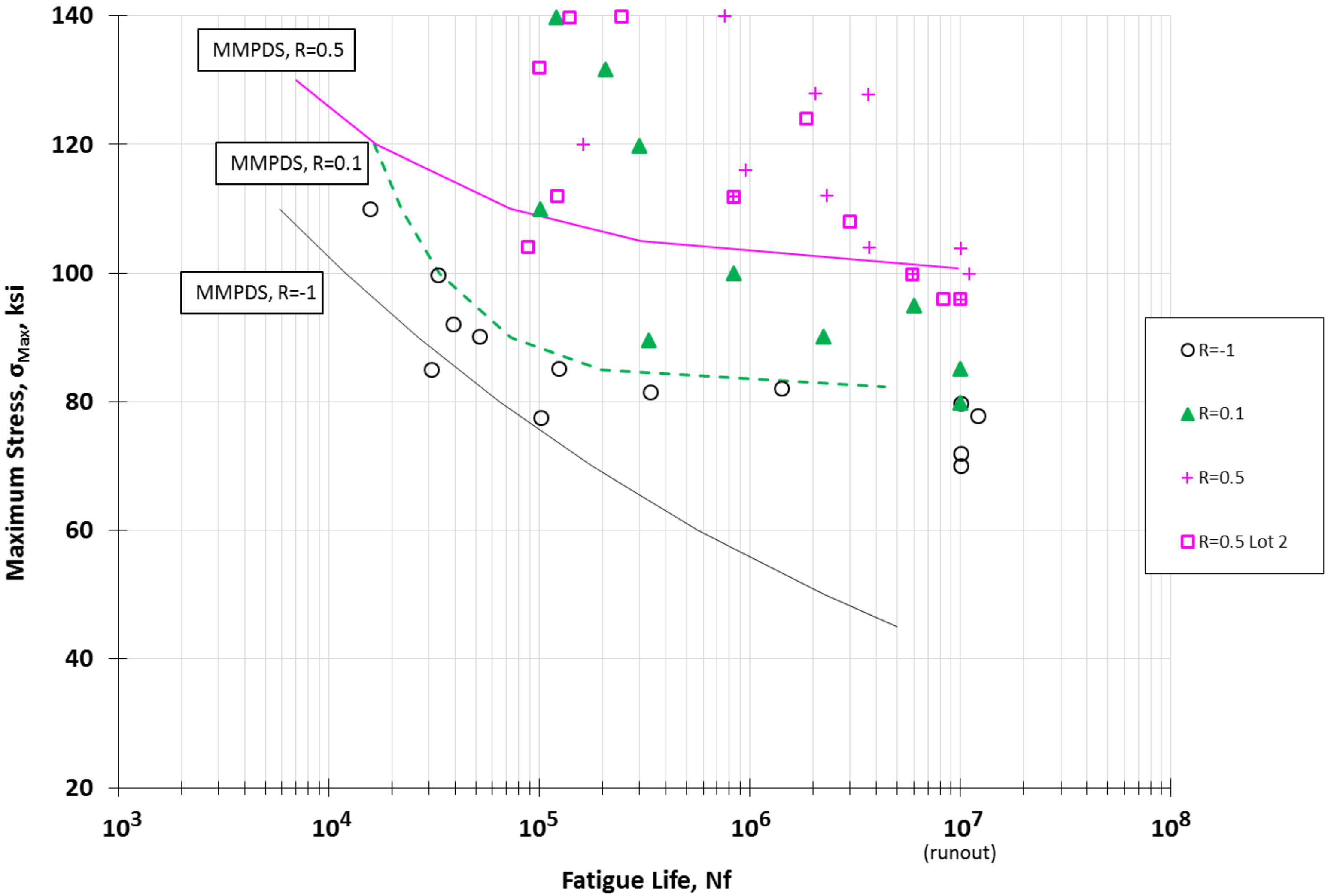
Extensive microscopy performed on material and tested samples

Showing high cycle fatigue (HCF) results from tests at 20 ^{o}C



RL-10 engine

Fatigue of AM Ti-6-4 compared to literature data.



Texture in AM Ti-6-4

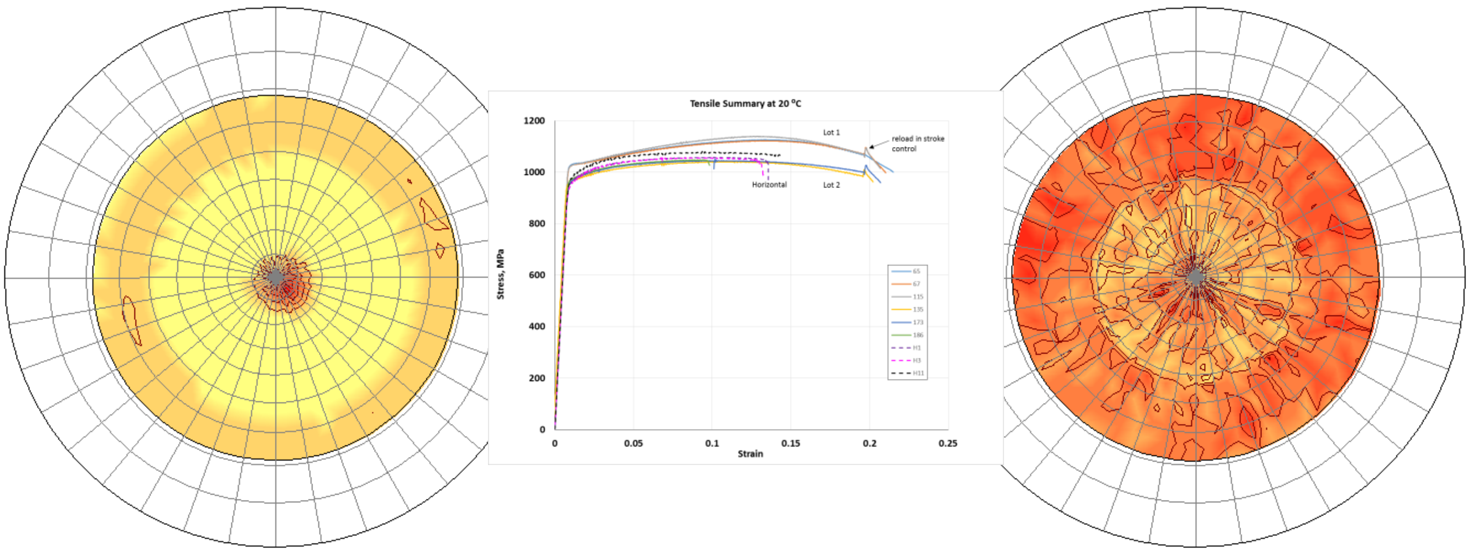
Lot 1

Fiber texture

(002)

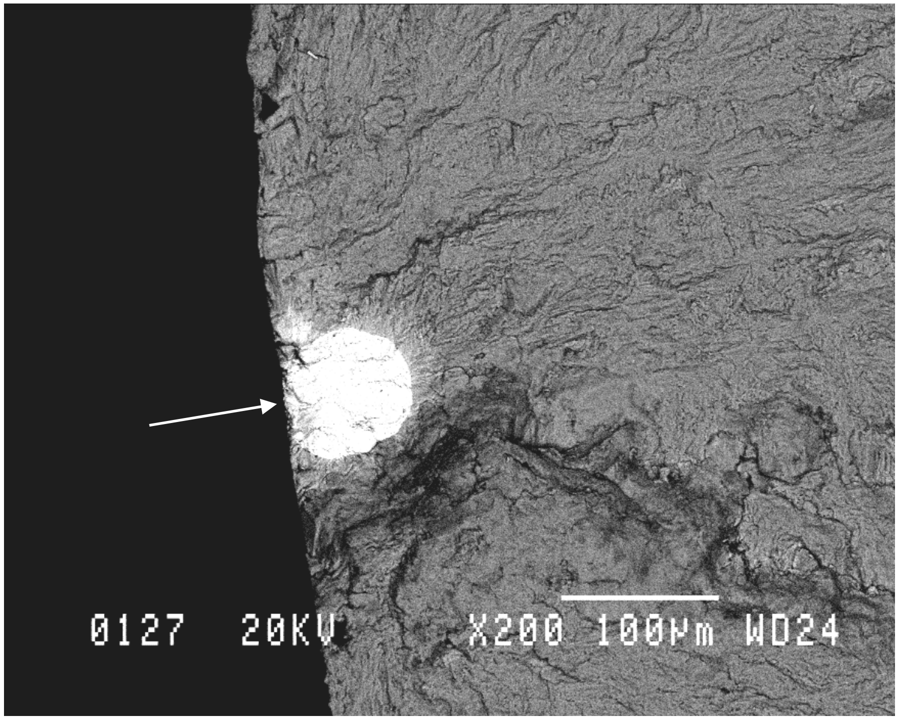
Lot 2

Random texture

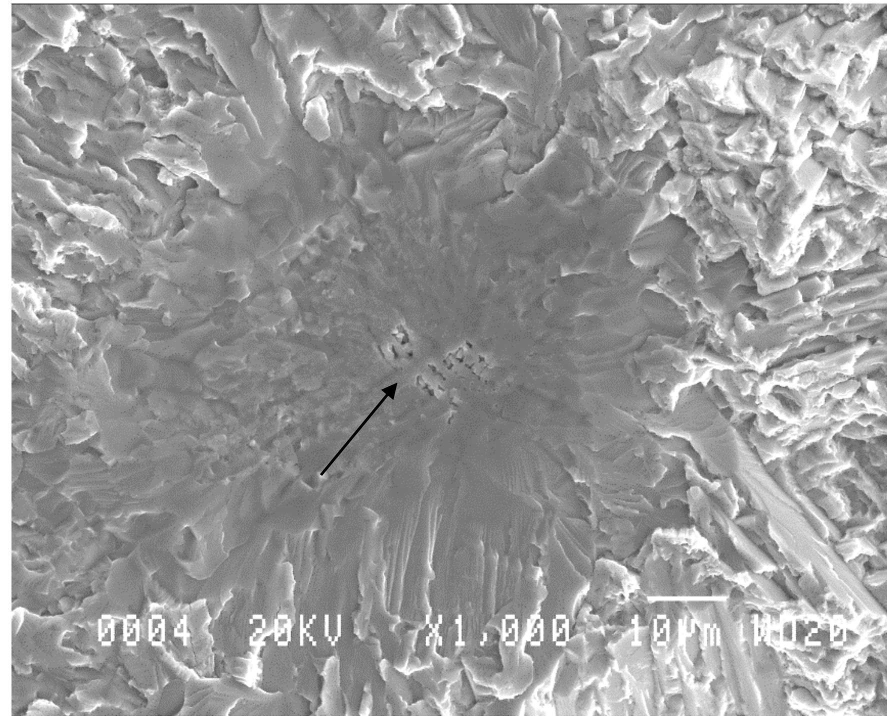


Pole figures showing fiber texture in (002) direction responsible for higher tensile and fatigue strength for lot 1.

Fatigue Initiation Sites – Ti-6-4

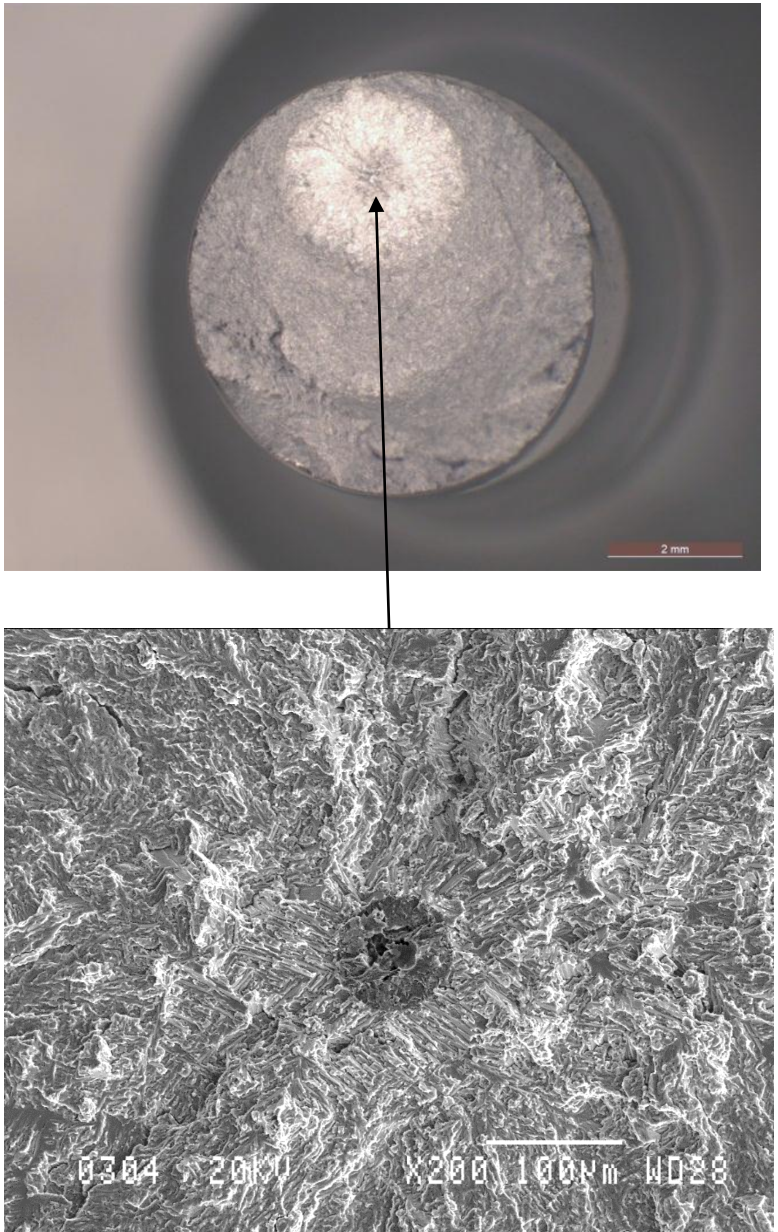


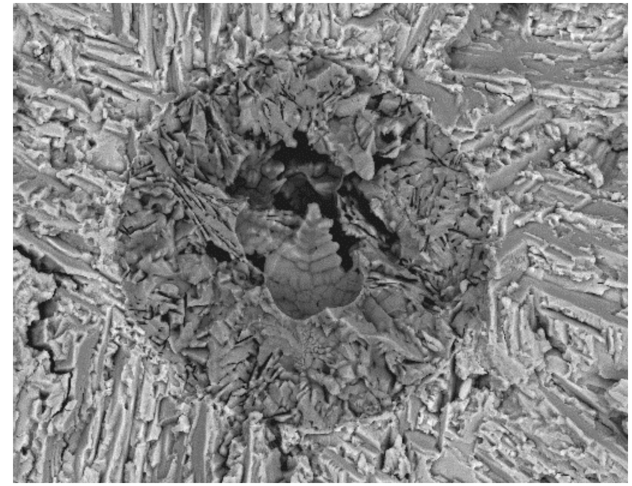
Nb inclusion at initiation site

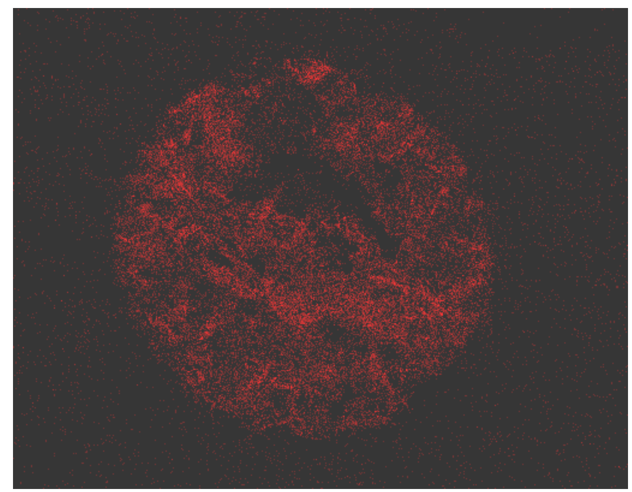


Initiation at pores probably a result of argon entrapment during powder processing

Fatigue Initiation Site – Ti-6-4



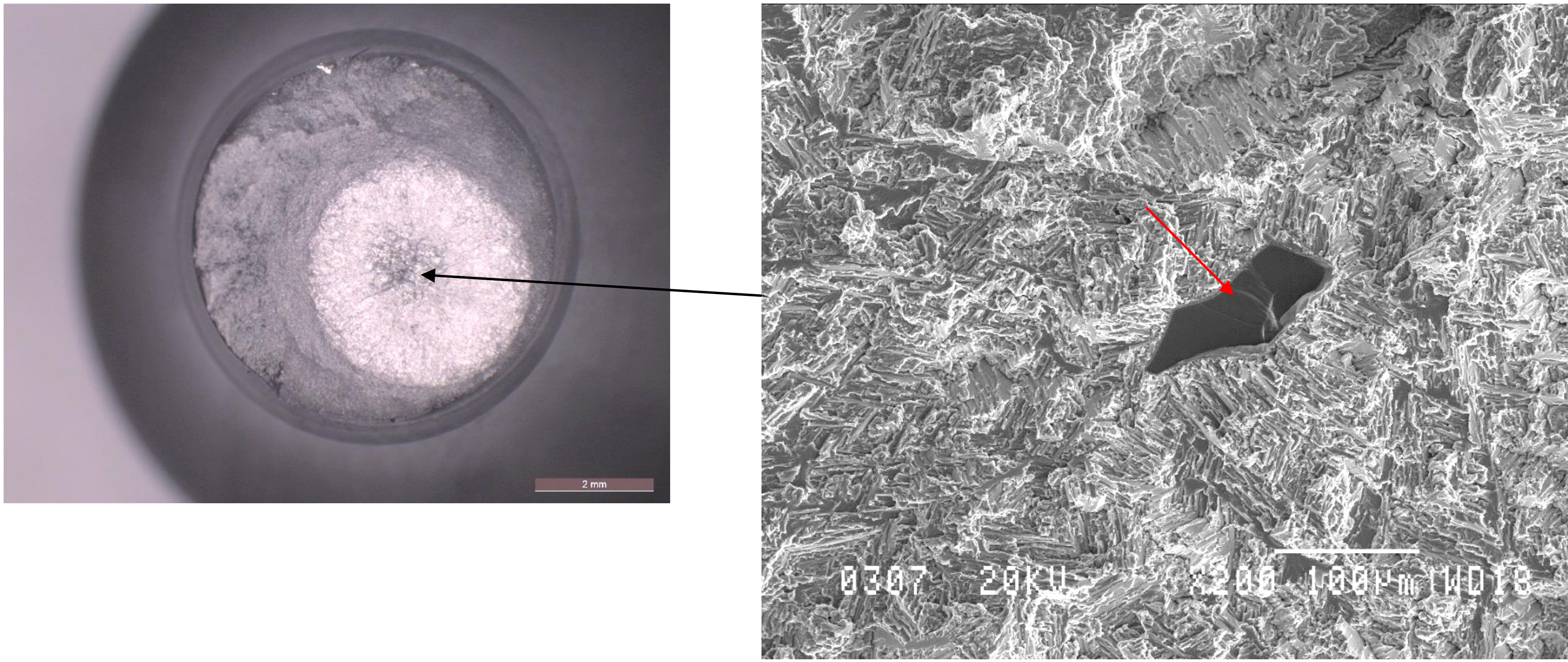




C

Internal initiation at a WC particle

Fatigue Initiation Site – Ti-6-4



Internal initiation at a Si-rich particle

Summary

AM can yield properties equivalent to, or better than, materials processed by conventional techniques

- Samples must be HIPed
- Surfaces must be well-machined

Powder cleanliness could be an issue, but no more so than that for bulk powder metallurgy

Various defects may initiate fatigue cracks, but they are usually small enough to still yield good fatigue lives

Location in build and lot variation do not necessarily affect properties.

However, development of a crystallographic texture can influence properties

Publications

Alloy 718

Industry Comparison of Powder Variability of Selective Laser Melted Ni-based Superalloy 718, C. K. Sudbrack, D. L. Ellis, B. A. Lerch, T. M. Smith, I. E. Locci, A. C. Thompson, J. M. Tylka, W. Tilson, R. E. Boothe, K. F. Cooper, B. Richards, P. Chao, A. Hinojos and M. Kloesel, In preparation, NASA/TM-2018.

Impact of powder variability on the microstructure and mechanical behavior of selective laser melted Alloy 718, C.K. Sudbrack, B.A. Lerch, T.M. Smith, I.E. Locci, D.L. Ellis, A.C. Thompson, B. Richards, Superalloy 718 and Derivatives, 2018.

GRCop-84

Development and Hot-fire Testing of Additively Manufactured Copper Combustion Chambers for Liquid Rocket Engine Applications, Gradl, Paul R.; Greene, Sandy Elam; Protz, Christopher S.; Ellis, David L.; Lerch, Bradley A.; Locci, Ivan E., AIAA Paper 2017-4670, M17-6113

Mechanical Properties of Additively Manufactured GRCop-84, Ellis, David L.; Lerch, Bradley A.; Locci, Ivan E., In preparation, NASA/TM 2018

Ti-6-4

Materials Characterization of Electron Beam Melted Ti-6Al-4V, S.L. Draper, B.A. Lerch, J. Telesman, R.E. Martin, I. Locci, A. Garg and A.J. Ring, NASA/TM 2016-219136.

GRCop-84 Hot Fire Test

Click image to activate video.