National Aeronautics and Space Administration

Material Characterization of Additively Manufactured Titanium Parts for an Environmental Control and Life Support System in Space Flight Hardware

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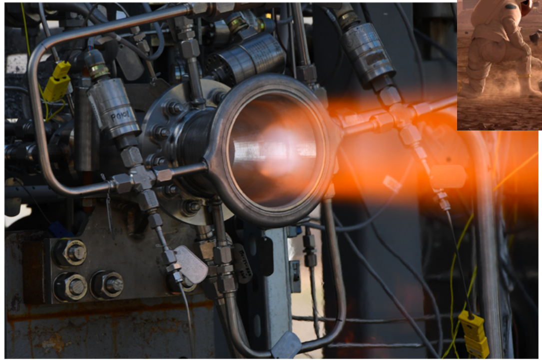
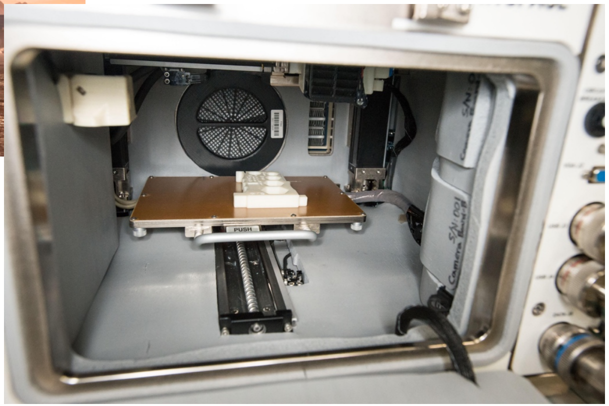
Introduction

3-D Printed Habitat Challenge first place in the Phase 3: Level 4
Credits: Team SEArch+/Apis Cor



Hot-fire testing of additively manufactured nozzle.
Credits: NASA/MSFC/David Olive



Additive Manufacturing Facility aboard ISS
NASA Image: ISS047E152501

Introduction: Continued…

Advantages:

- Altered Design Space
- Fast Production Time
- Potential Cost Reductions
- Potential Weight Reductions
- *In-Situ* Resource Utilization
- Rapid Design Iteration

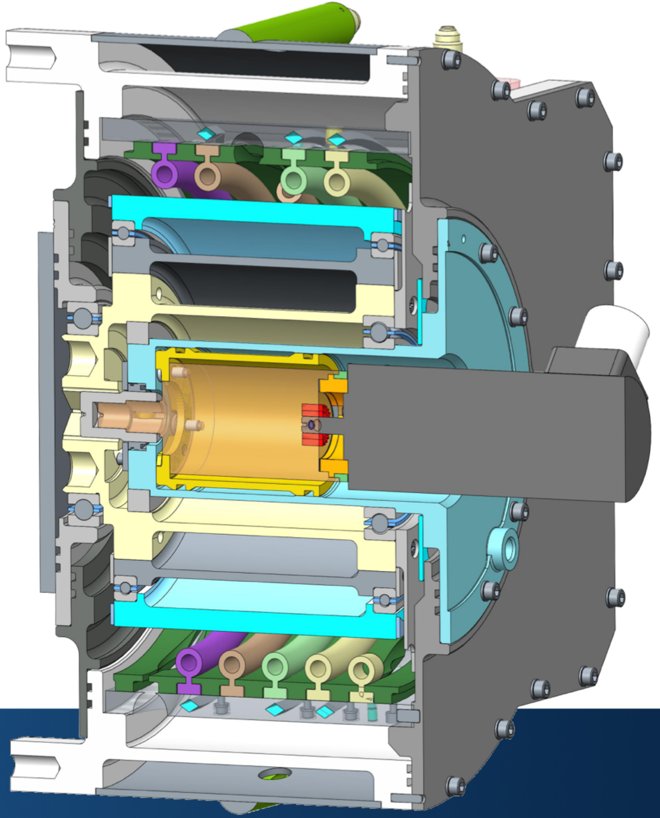
Disadvantages:

- New Design Constraints
- Difficult Inspection
- Limited Availability of Standards
- Limited Materials Data
  - “New Process”
  - Small Sample Sizes
- Limited Process knowledge

ECLSS PCPA

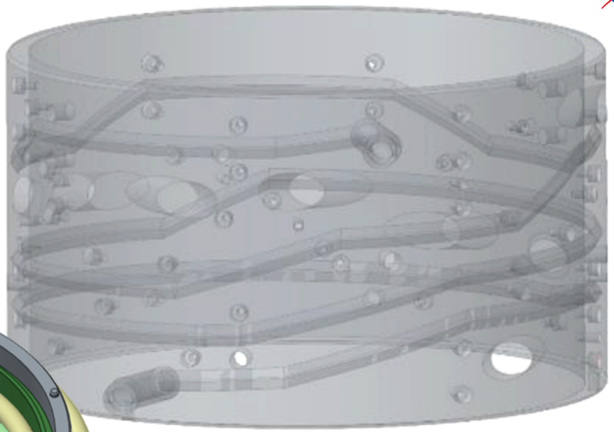
Environmental Control and Life Support System (ECLSS) Pressure Control Pump Assembly (PCPA)

- Peristaltic pumps in the Urine Processor Assembly (UPA)
  - Maintains vacuum pressure on the Distillation Assembly (DA)
  - Provide a two phase flow to the Separator Pump Assembly (SPA)
- Short lifespan

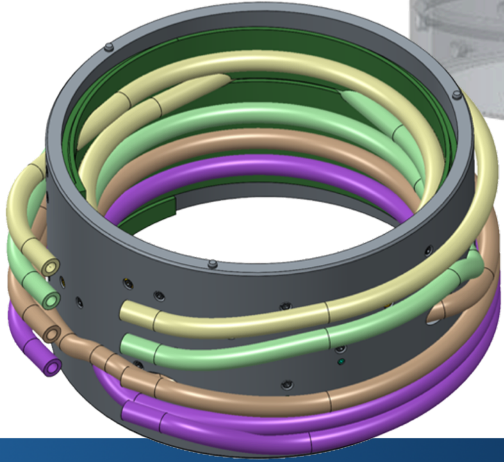


Part Design & Production

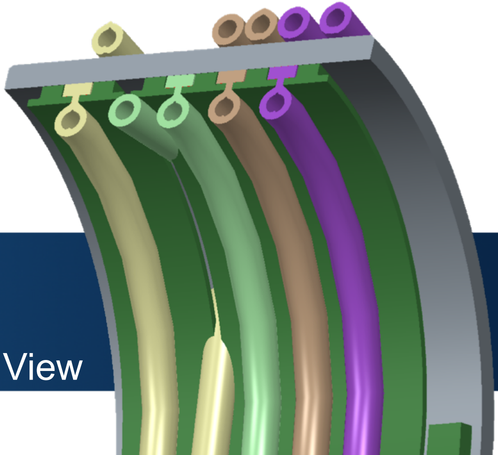
- PCPA shell was replaced with an additively manufactured component
- Selective Laser Melting (SLM)
  - EOS M290
  - Argon
  - 60 µm
  - Titanium Grade 5
- Stress Relieved
- Hot Isostatic Pressed



PCPA Shell



New Assembly

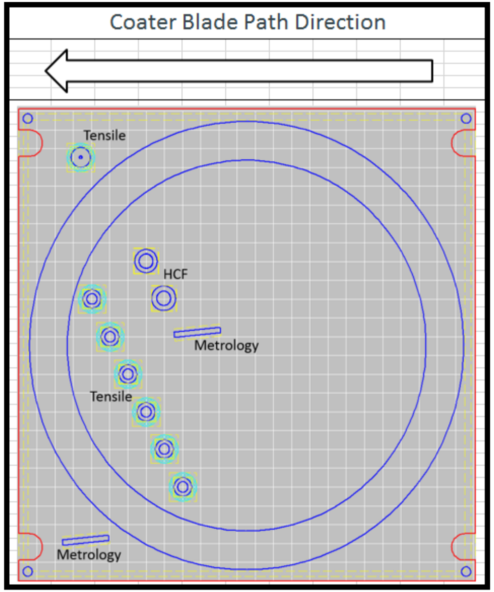


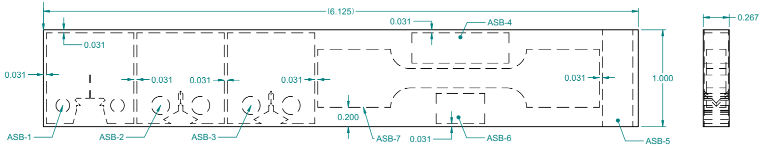
Old Assembly Section View

Part Design & Production

- Manufactured before MSFC-SPEC-3717 and MSFC-STD-3716 were released

Type	Quantity		Metrology Sample
	HIP	As Built	
Tensile	6	1	
Poisson's Ratio	1	1	•
High Cycle Fatigue	2	-	
Metallography	3	3	•
da/dN	2	2	•
Fracture Toughness	1	-	•



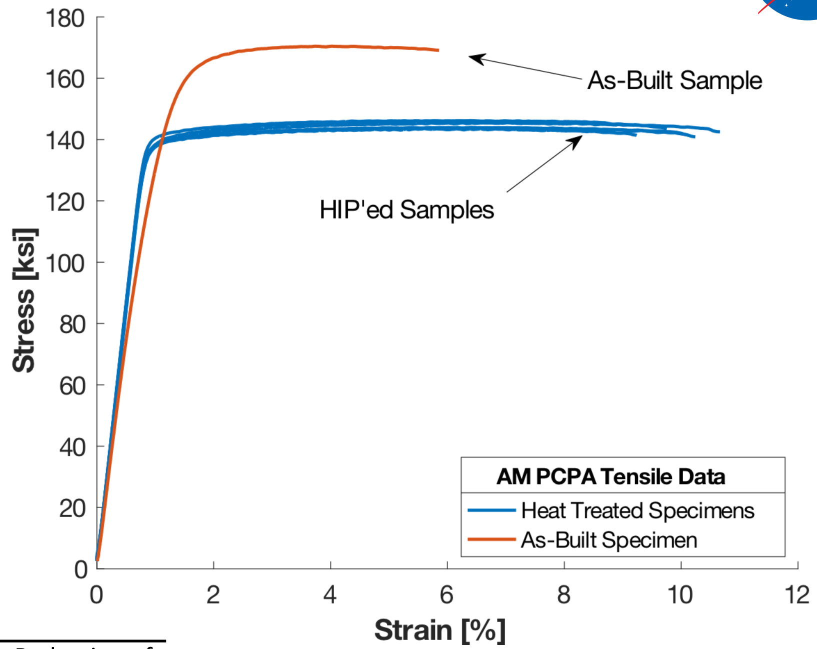


Testing Does Not Represent a Statistically Significant Dataset

- **Testing was used to support analysis assumptions**

Tensile Testing

- Samples Tested to ASTM E8/E8M
- HIP Samples showed reduced tensile and yield strength comparable to traditional Ti64
- Fracture elongation, while improved by the HIP procedure still does not meet traditional values



Specimen ID	Tensile Stress [ksi]	Yield Stress [ksi]	Inelastic Strain [%]	Modulus of Elasticity	Fracture Elongation [%]	Reduction of Area [%]
Heat Treated[a]	145.0	138.5	8.8	17.1[b]	9.8	10.6
As-Built	170.6	140.5	4.7	15.2[b]	5.8	5.4

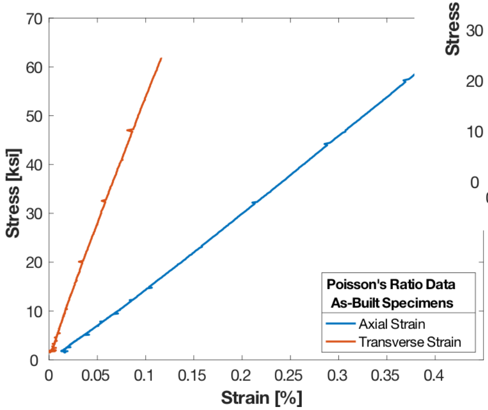
[a] *Data represents mean values*

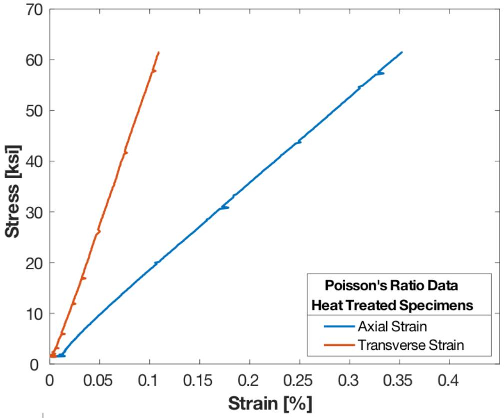
[b] *Modulus of elasticity value is for reference only. Specific modulus tests are required for true value.*

Poisson's Ratio Testing

- Tested per ASTM E132
- Three runs
- Slope was calculated using linear least squares regression on the portion of the curve between 500 lbf and 2500 lbf

Sample	Poisson's Ratio
Heat Treated	0.296
As-Built	0.306





High Cycle Fatigue: Conditions

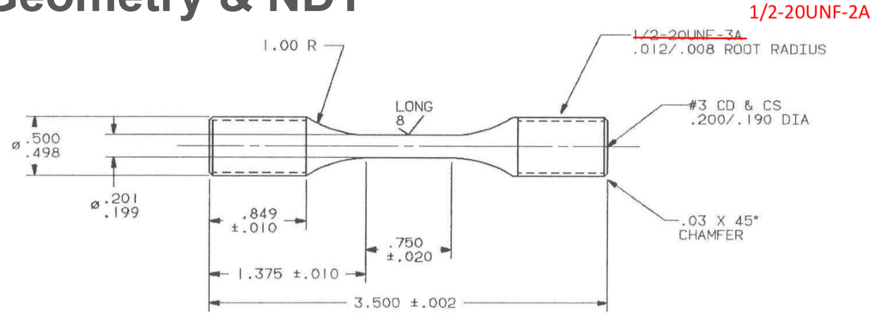
- Design life dictated testing to 20 million cycles
- Room temperature and pressure
- Samples were tested under 2 conditions in load control
  - Sample 1 tested at 75% of yield strength
  - Sample 2 tested at 40% of yield strength

Specimen ID	Alternating Stress [ksi]	Max Stress [ksi]	Mean Stress [ksi]	Min Stress [ksi]	R-Ratio
HCF-1†	103.8	103.8	0.0	-103.8	-1
HCF-2	55.3	55.3	0.0	-55.3	-1

† Sample previously cycled at low stress levels

High Cycle Fatigue: Sample Geometry & NDT

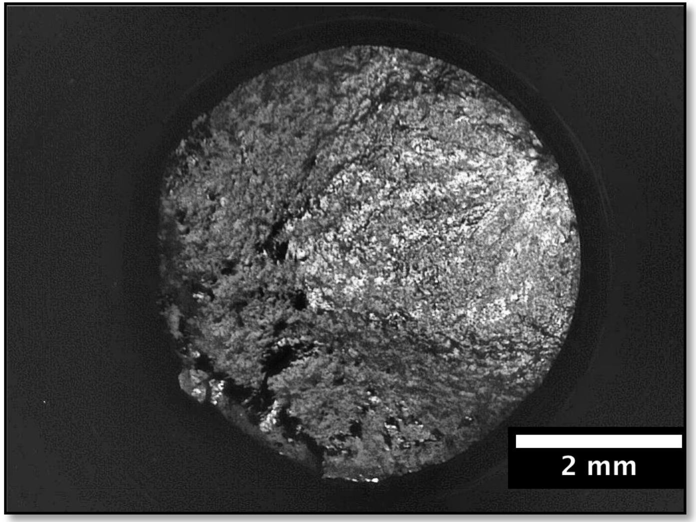
- Samples were produced in a low cycle fatigue geometry
  - Analogue samples were produced of wrought Ti64 to ensure acceptable alignment and temperature rise
- AM samples were machined to a final finish of RMS 8
- AM samples inspected by eddy current (calibrated to a 0.080”L x 0.010”D notch specimen)
  - No crack-like indications noted



High Cycle Fatigue: Results & Fracture Surface

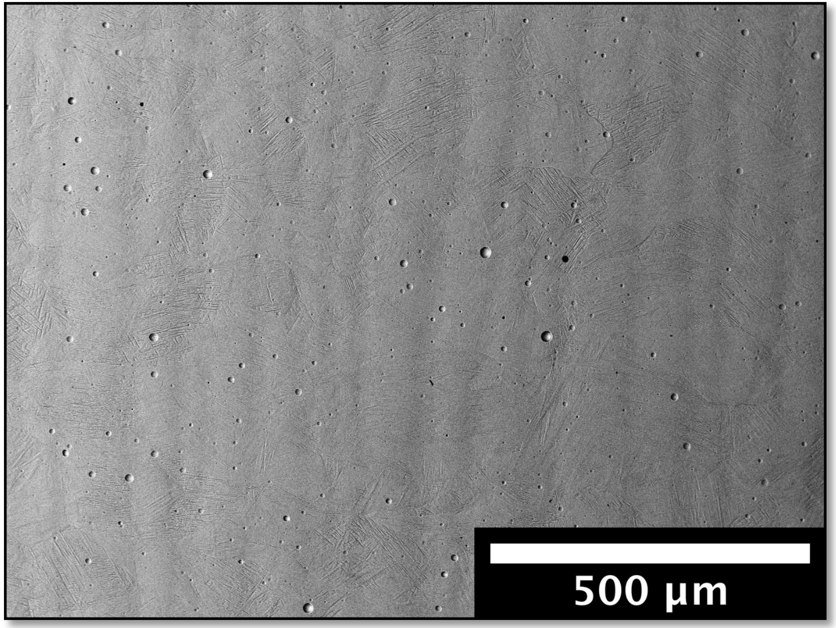
Specimen ID	Relative Stress	Alternating Stress [ksi]	Max Stress [ksi]	Mean Stress [ksi]	Min Stress [ksi]	R-Ratio	Cycle Count
HCF-1[†]	75% s_y	103.8	103.8	0.0	-103.8	-1	61,432
HCF-2	40% s_y	55.3	55.3	0.0	-55.3	-1	Runout @ 20M

† Sample previously cycled at low stress levels



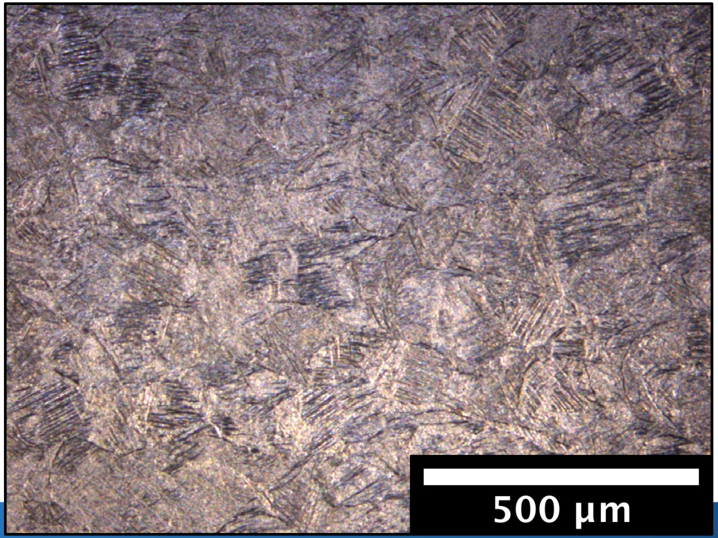
Microscopy: As-Built

- One sample from each local orientation was mounted, polished and imaged
- Entrapped gas porosity observed
- Evidence of layering was observed

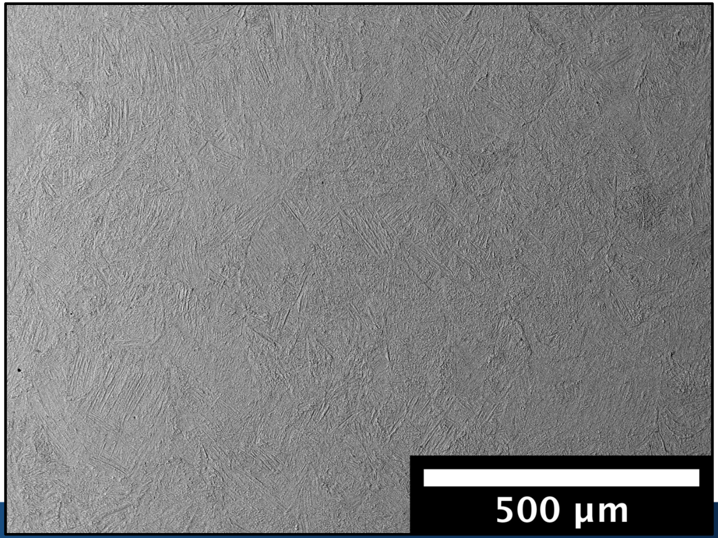


Microscopy: HIP’ed Samples

- HIP’ed samples showed no evidence of layering or visible porosity



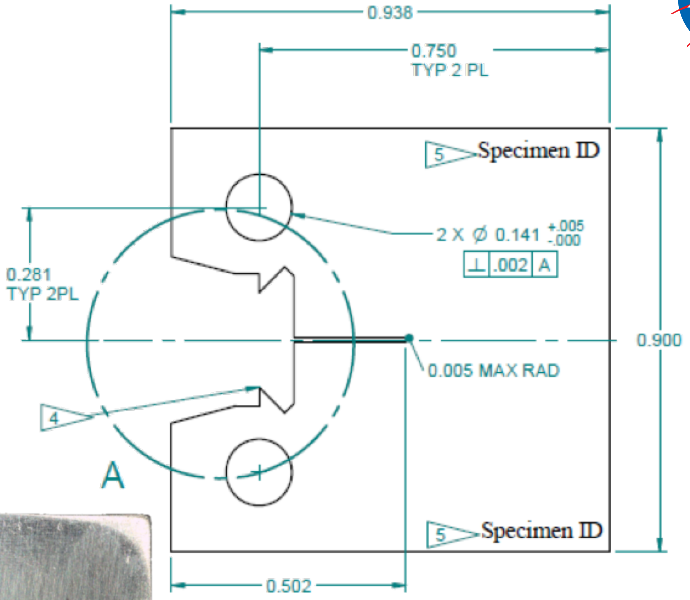
Optical Microscopy

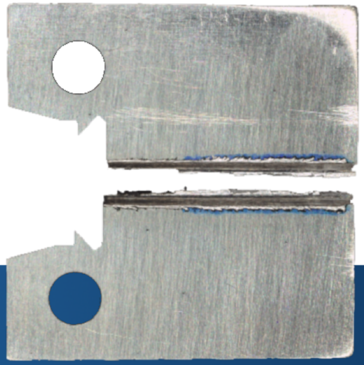


Secondary Electron Image

Fracture Toughness

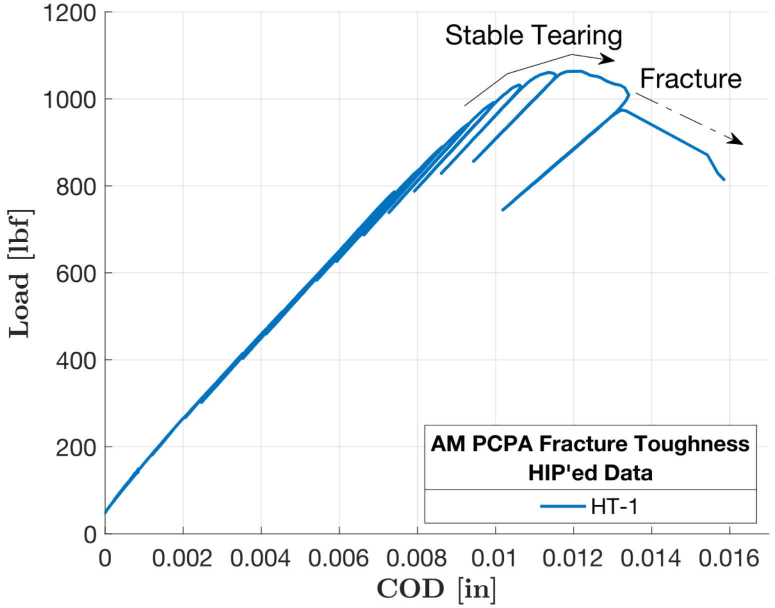
- One compact tension fracture toughness test, W = 0.75”, B = 0.25”
- Sample tested in the heat treated condition at room temperature and pressure per ASTM E1820
- Crack opening direction normal to build plane





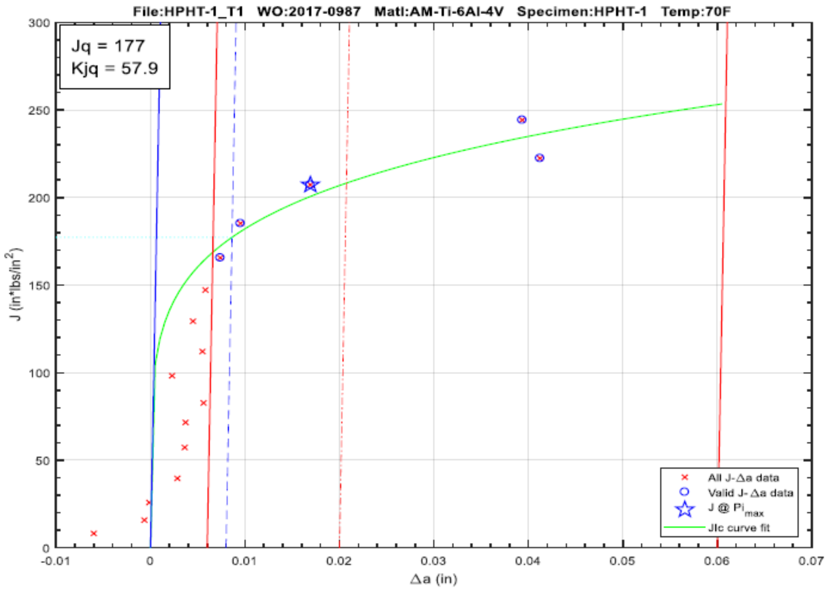
Fracture Toughness: continued

- Load-Crack Opening Displacement Curve with Compliance Unloading Cycles
- Stable tearing followed by fracture instability in the final load response



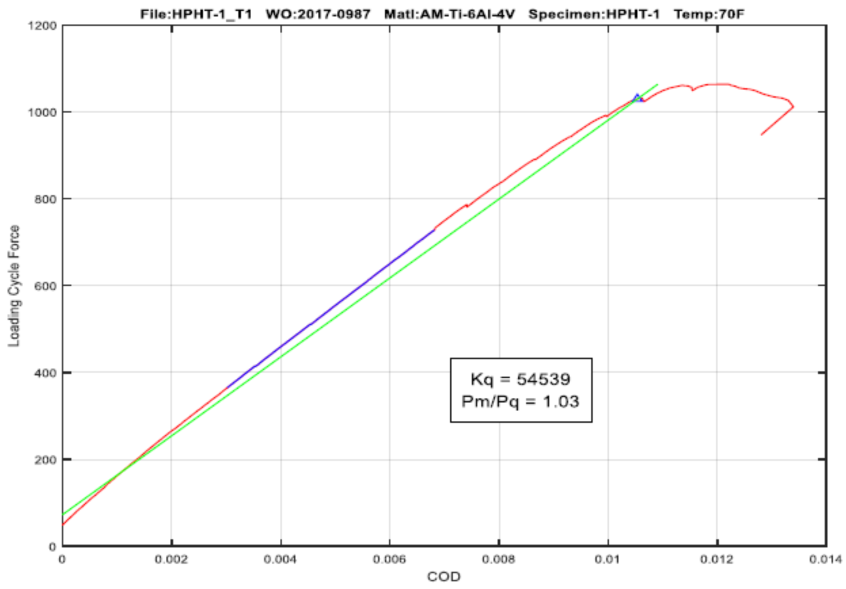
Fracture Toughness: continued

- ASTM E 1820 Evaluation
- Test did not produce a JIc value due to lack of well defined crack extension and R-curve regression curve fit invalidity
- Rising R-curve behavior reflecting stable tearing capability
- Fracture instability occurred after stable tearing.
- Jq = 177 in-lb/in^2
- Kjq = 57.9 ksi√in



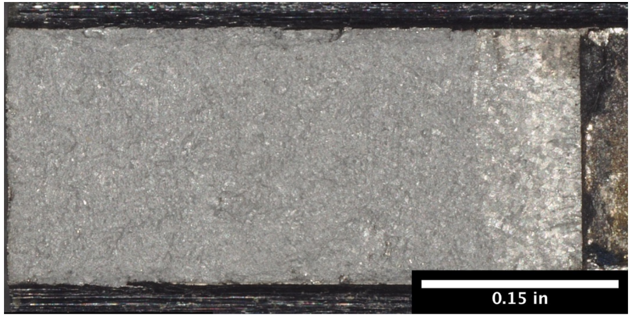
Fracture Toughness: continued

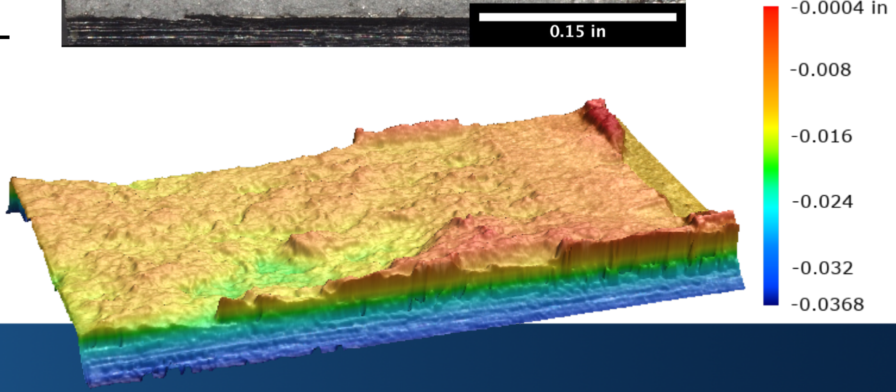
- ASTM E 399 Evaluation
- Test did not produce a KIc value due to sample ligament size.
- $(Kq/\sigma_{YS})^2 = 0.171$ in
- Required ligament = 0.42 in
- Actual ligament = 0.36 in
- The extended COD capability after Pq suggests some stable tearing capability
- Kq = 54.5 ksi√in
- Kq ≈ KJq



Fracture Toughness: continued

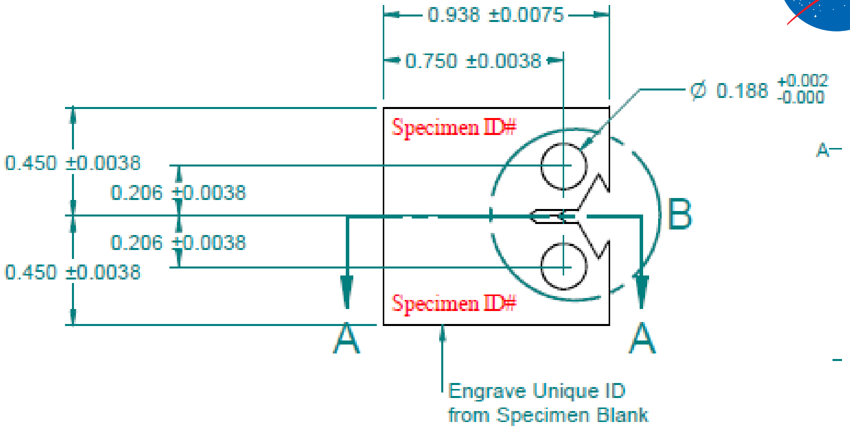
- Evaluations from a single data point are speculative, but…
- Fracture toughness in the build plane is approximately 55 ksi√in for 0.25” thick material at room temperature.
- Average fracture toughness for mill annealed forged bar titanium (yield strength range 124 – 145 ksi) is 57 ksi√in, COV=11.7 ksi√in (Ref: MMPDS-10)
- Material exhibits rising R-curve behavior
- Additional testing and fracture surface microscopy is needed to characterize material



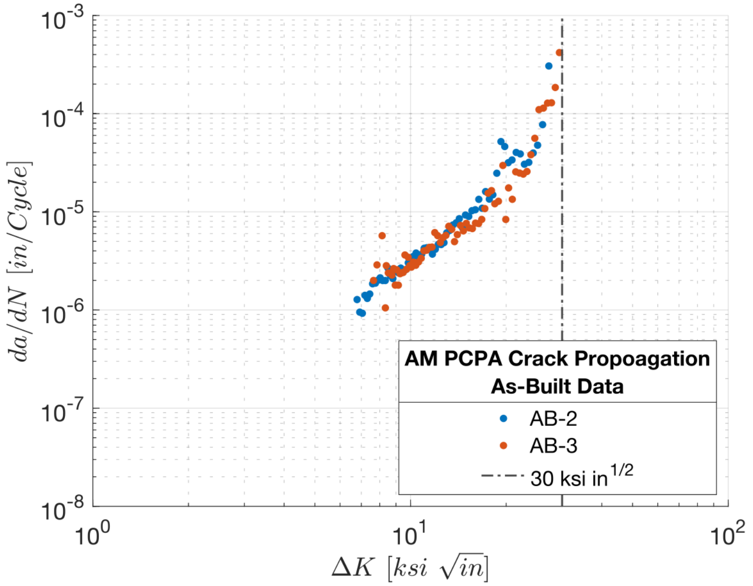


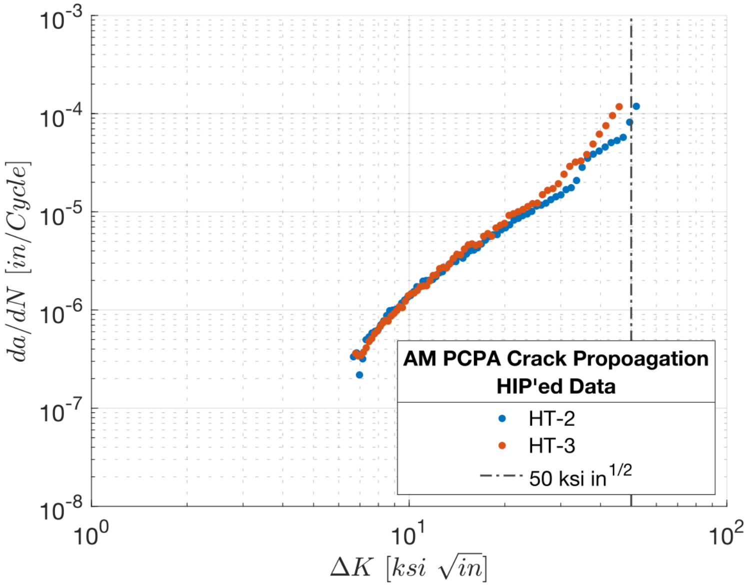
Fatigue Crack Growth

- Four compact tension fatigue crack growth rate (FCGR) specimens
  - Two heat treated
  - Two as-built samples
- Tested at room temperature and pressure per ASTM E647
  - ΔK increasing tests
  - R ratio = 0.1
- Objective to evaluate Paris region crack growth

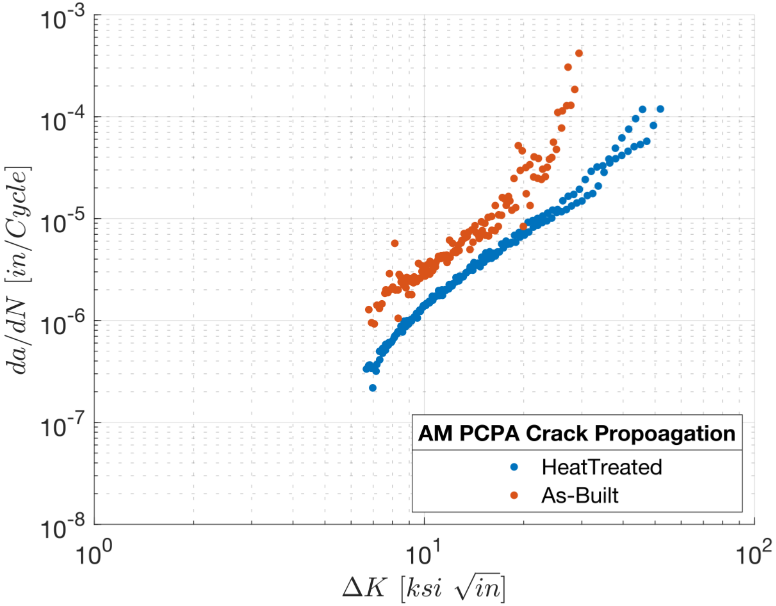


Fatigue Crack Growth: Continued



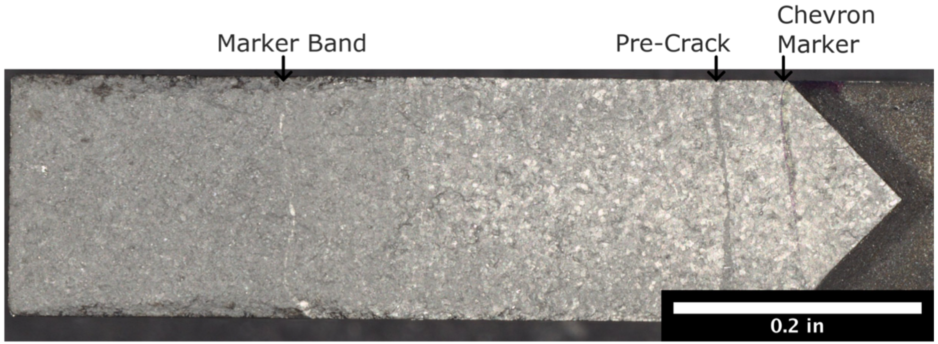


Fatigue Crack Growth: Continued



Fatigue Crack Growth: Continued

- As built material exhibits more scatter vs heat treated material
- As built material instability consistent with estimated fracture toughness
- Evaluation of crack growth rate at additional R-ratios recommended to establish mean stress effects



Work Going Forward

- Implementing MSFC-SPEC-3716 & MSFC-STD-3717
  - Qualified Metallurgical Process
  - More Samples per Build
  - Build Confidence in AM Technology
  - Work with ASTM on standards development

MEASUREMENT SYSTEM IDENTIFICATION METRIC/SI (ENGLISH) UNITS

National Aeronautics and Space Administration

MSFC-SPEC-3717
BASELINE
EFFECTIVE DATE: October 18, 2017

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

EM20

MSFC TECHNICAL STANDARD

SPECIFICATION FOR CONTROL AND QUALIFICATION OF LASER POWDER BED FUSION METALLURGICAL PROCESSES

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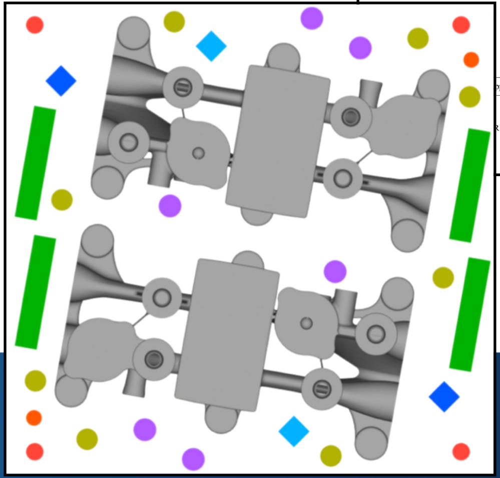
R LIST — VERIFY THAT THIS IS THE CORRECT VERSION BEFORE USE



Conclusions & Summary

- Samples compare reasonably well to wrought data
- The process is maturing to the point where it may provide viable alternatives to engineering challenges
- Going forward more work is needed to obtain a statistically significant dataset to allow for the development of robust design allowables

Questions

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MAKING HUMAN SPACE EXPLORATION POSSIBLE