EWI Project No. 55232GTH
Annual Review
March 22, 2017

Additive Manufacturing of Fuel Injectors

NETL – 2017 Crosscutting Research and Rare Earth Elements Portfolios Review

Prepared by:

Mahdi Jamshidinia[1], Daniel Ryan[2], Charles Drews[1]

[1]EWI, [2]Solar Turbines

EWI®
We Manufacture Innovation

The Project Team

EWI
We Manufacture Innovation

Mahdi Jamshidinia, (PI)
Charlie Drews, (PM)

Solar Turbines
A Caterpillar Company

Daniel Ryan, (PI)
Mark Lipschutz (Materials Technology)
David Teraji, (PM)

NETL

Sydni Credle (PM)

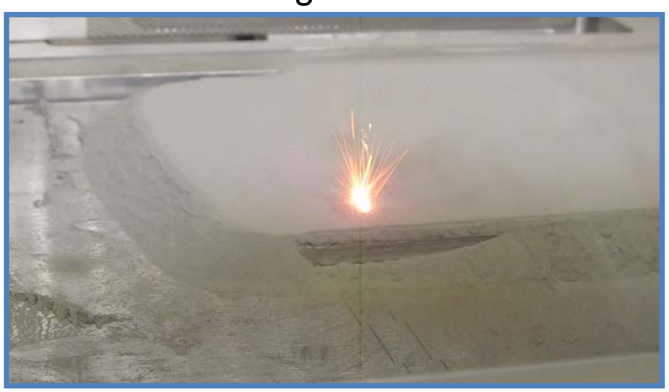
Process Equipment Overview

Laser PBF
EOS M280

Electron Beam PBF
Arcam A2X

Material Extrusion
Stratasys Fortus
450mc

Laser PBF – Open Architecture
EWI-Designed and Built

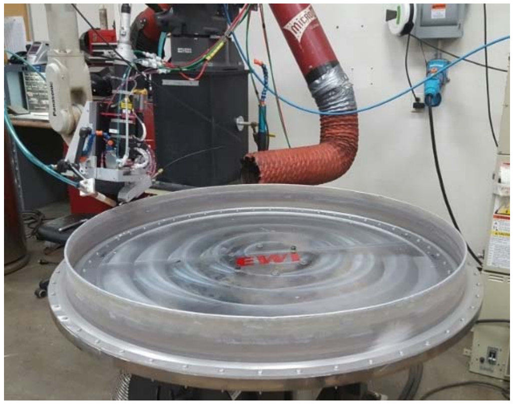


Binder Jetting
ExOne Innovent

Sheet Lamination UAM
Fabrisonic

Process Equipment Overview

Laser and Arc-DED
Commercial Robot



Laser DED
RPM 557

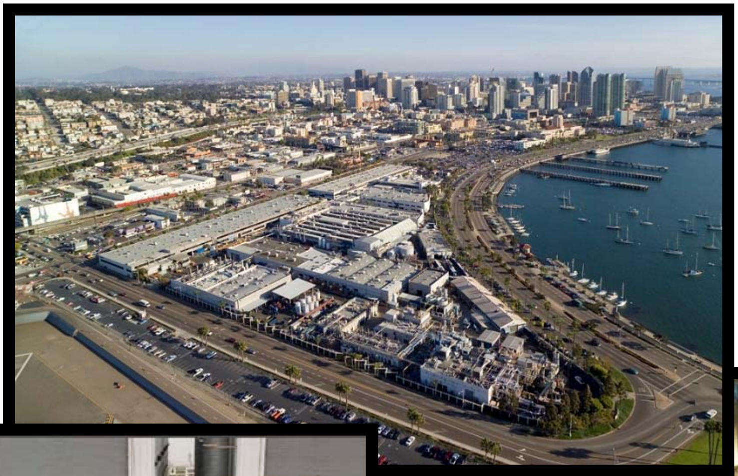
EB-DED
Sciaky EBAM

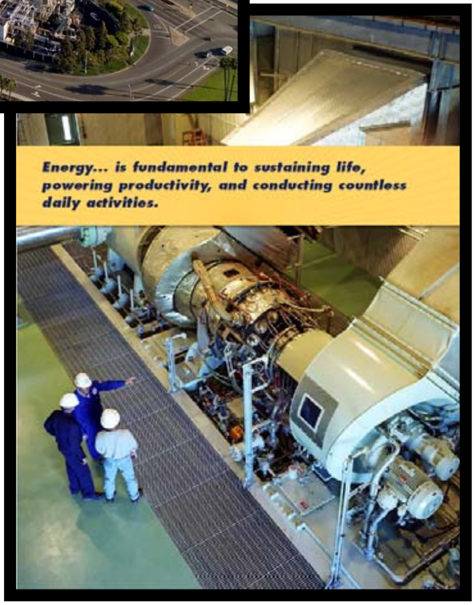
Targeting $10-$15M AM equipment investment in Buffalo

EWI
We Manufacture Innovation

Solar Turbines Overview

- World's Largest Manufacturer of Industrial Gas Turbines (1 to 22 MW)
- Over 15,000 Gas Turbines Sold
- Over 6,000 Gas Compressors Sold
- Installations in over 100 Countries
- Direct End-to-End Sales & Service
- More than 2 Billion Fleet Operating Hours
- Global Workforce (7,000) Employees
- Based in San Diego, California, U.S.A.
- Subsidiary of Caterpillar Inc. Since 1981





Solar Turbines
A Caterpillar Company

EWI
We Manufacture Innovation

Motivation

- **Gas turbine components**
  - Very specific design (difficult to cast)
  - Long lead time
- **Fuel injector tip**
  - Alloy X
    - Ni-Cr-Fe-Mo alloy
    - Solid Solution Strengthened

Additive manufactured fuel injector courtesy of Solar Turbines

Objective

- **Objective:**
  - To develop a novel process to qualify the AM technique of laser powder bed fusion (L-PBF) for complex gas turbine components made of high temperature nickel-based alloys
  - To investigate the effect of input powder stock and AM process variables on resultant microstructure and mechanical properties for the alloy material
  - Post-processing, including heat treatment and the use of finishing technologies will also be employed in order to achieve required dimensional and surface finish requirements for the component.

Relevance to Fossil Energy

- **Alloy-X is used in many industrial gas turbine applications.**
- **AM will enable design and energy efficiencies:**
  - Faster and less costly design optimization.
  - Future applications could enable more energy efficient designs by reducing design constraints
    - Increasing fuel efficiency
    - Providing higher operating temperature

EWI®
We Manufacture Innovation

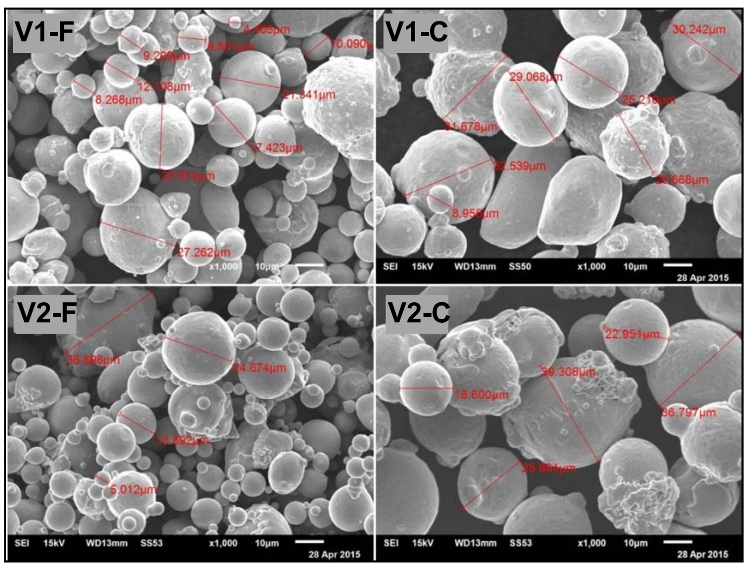
Milestones

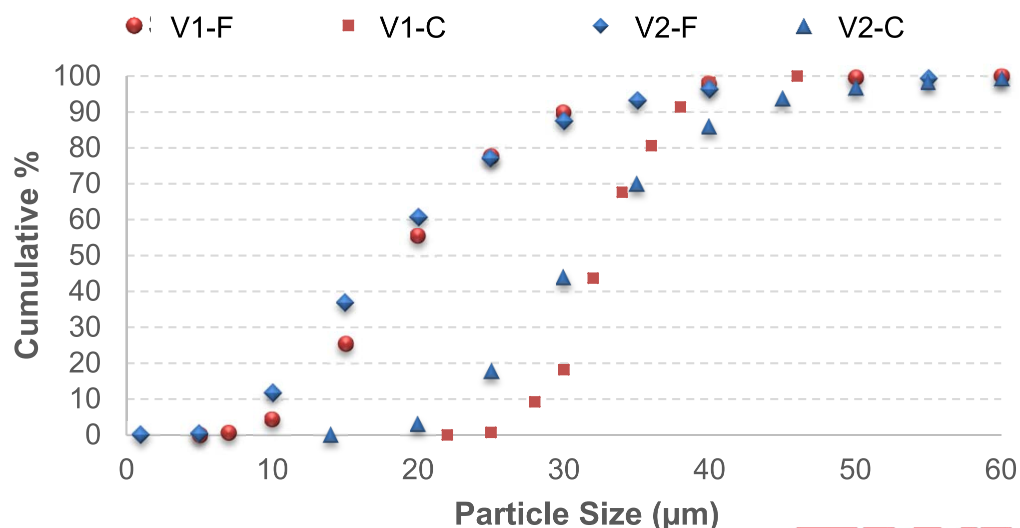
- **Milestone 1: Powder Characterization**
  - Complete
- **Milestone 2: NIST Test Artifacts Complete**
  - Complete
- **Milestone 3: Process Parameter Report Delivered**
  - Complete
- **Milestone 4: Property Data Curves Delivered**
  - In-progress
- **Milestone 5: Specification Document Delivered**

Milestone 1- Powder Evaluation

◆ Powder evaluation:

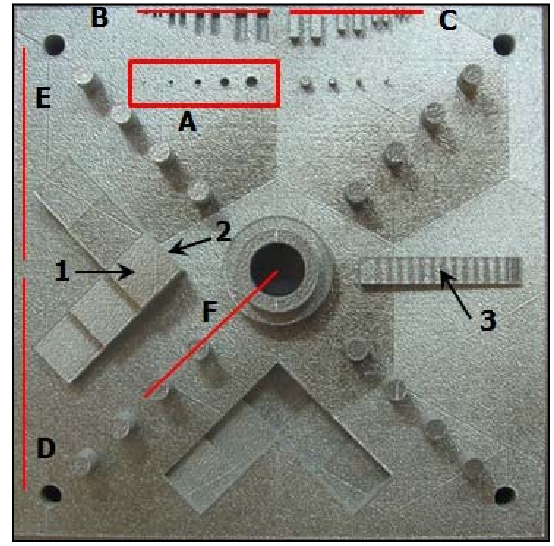
Vendor	Type	Min. Desired Size (µm)	Max. Desired Size (µm)	Fine (%)	Coarse (%)	Cost Comparison per lb. (350 lb order)
V1	Fine	5	38	0.1% < 5 um	0.8% > 38 um	100%
V1	Coarse	20	45	4.2% < 20 um	0.5% > 45 um	132%
V2	Fine	5	38	2% < 5.5 um	1 > 38 um	190%
V2	Coarse	16	45	1% < 16 um	1% > 45 um	195%

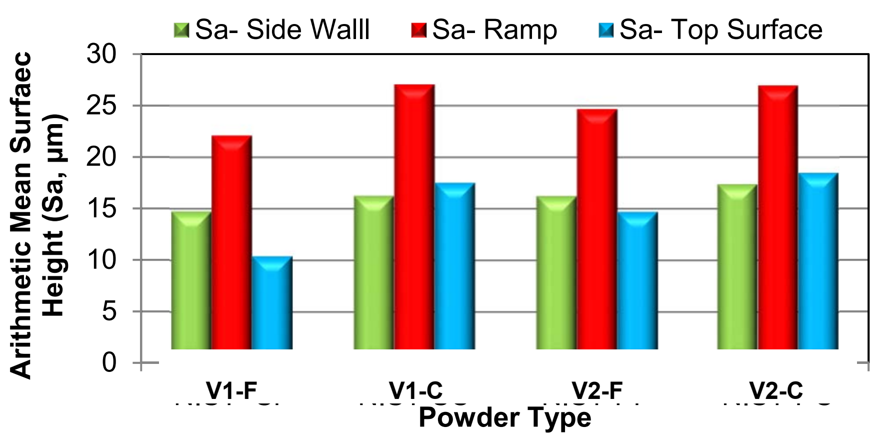


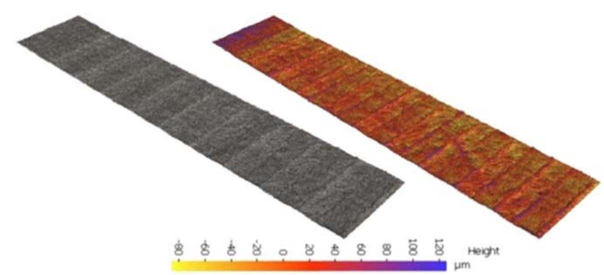


Milestone 2- NIST Test Artifacts Complete

- **Minimum Feature Size:**
  - The L-PBF process was capable of producing fine features, and met capabilities of investment casting
- **Surface roughness measurement:**
  - Fine powders were slightly better (S_a).
  - Typical allowable limit for the surface finish of investment casting
    - (Ra) less than 125 µin. (3.17 µm)







EWI
We Manufacture Innovation

Milestone 3- Process Parameter Report Delivered

- **Stress relief heat treatment:**
  - All of the specimens underwent the stress relief heat treatment, while still attached to the build plate
    - 2150°F
    - 1 hour
    - Rapid argon cooling.

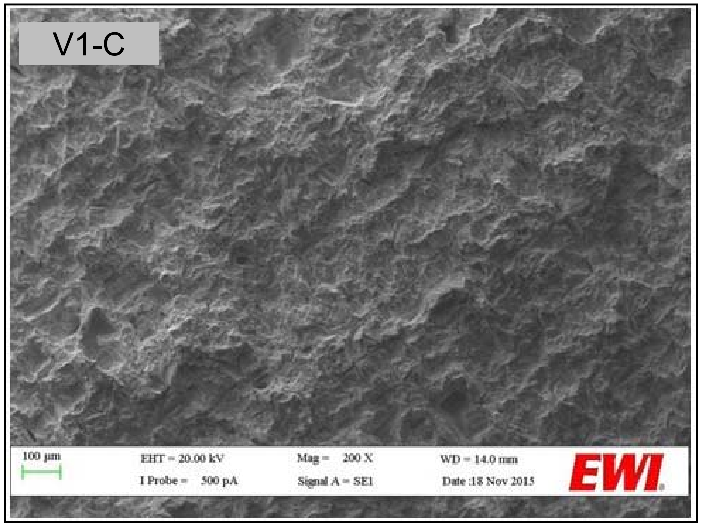
EWI®
We Manufacture Innovation

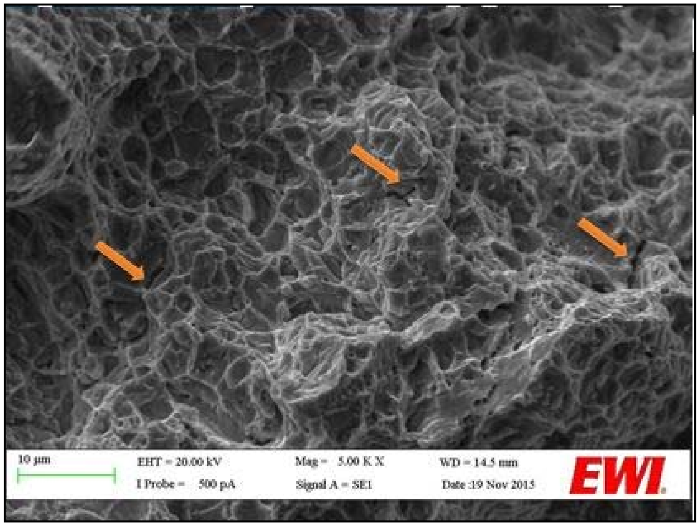
Milestone 3

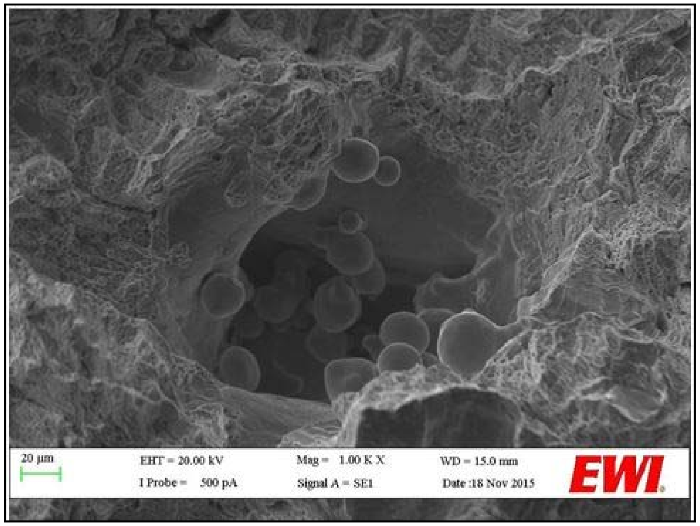
- **Mechanical test:**
  - Tensile
    - Room temperature
    - Elevated temperature (1500°F/815.5°C)
  - Creep
    - Elevated temperature (1500°F/815.5°C)
    - Stress: 15 ksi
  - Low cycle fatigue
    - Elevated temperature (1000°F/538°C).
    - Total strain range: 0.6%
    - Stress ratio: -1

Milestone 3

- **Fractography:**
  - Room temperature tensile test
    - Intergranular fracture morphology
    - Dimples on the fracture surfaces
    - Secondary cracking
    - LOF surrounded by un-melted powder particles.







EWI®
We Manufacture Innovation

Milestone 3

- **Powder down select:**

Powder / Properties	Cost Comparison	Powder Compatibility with AM Machine (ProX300)	Microstructure (Micro cracks)	RT- Tensile Test			ET- Tensile Test		Creep		Fatigue
				UTS	YS	El%	UTS	El%	Hrs (rpt.)	El% (rpt.)	Cycles
V1-C	100%										
V1-F	132%							No HT			
V2-C	190%										
V2-F	195%										

- Vendor 1
  - V1-C:
    - Lowest creep and fatigue properties
    - Powder leakage
  - V1-F
    - Low ductility at high temperature as well as the short creep rupture time could be improved using a proper heat treatment
    - Originally developed with the OEM.
    - Favorable powder cost

Milestone 3

- **Powder down select:**

Powder / Properties	Cost Comparison	Powder Compatibility with AM Machine (ProX300)	Microstructure (Micro cracks)	RT- Tensile Test			ET- Tensile Test		Creep		Fatigue
				UTS	YS	El%	UTS	El%	Hrs (rpt.)	El% (rpt.)	Cycles
V1-C	100%										
V1-F	132%							No HT			
V2-C	190%										
V2-F	195%										

- Vendor 2
  - V2-C
    - Powder leakage
  - V2-F
    - Similar or better tensile properties than those of V2-C
    - Longer fatigue life
    - Lower creep life.
    - Unfavorable powder cost
    - Unfavorable microstructure (micro-cracks)

EWI® We Manufacture Innovation

Milestone 3

- **Heat Treatment Optimization (Microstructure Screening)**
  - The team investigated eight HTs.
    - As printed (no HT)
    - Solution Annealing
      - Temperature (#2)
      - Time (#5)
    - HIP
    - Post annealing
  - Microstructural screening to downselect to four heat treatments for mechanical testing

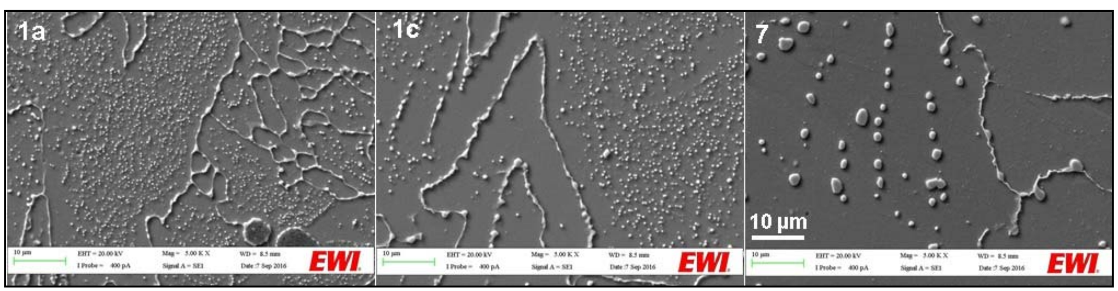
HT Procedure	Solution Annealing			HIP		
	Temp. (°F)	Time	Post Cooling	Temp. (°F)	Pressure (MPa)	Time (hrs)
1-a	2150	15 min.	AC	---	---	---
1-b	2150	40 min.	AC	---	---	---
1-c	2150	1 hr	AC	---	---	---
2	---	---	---	2150	100	4
6*	2150	4 hr	AC	---	---	---
7	2150	8 hr	AC	---	---	---
8	2200	1 hr	AC	---	---	---
AC: Argon cooling						

EWI®
We Manufacture Innovation

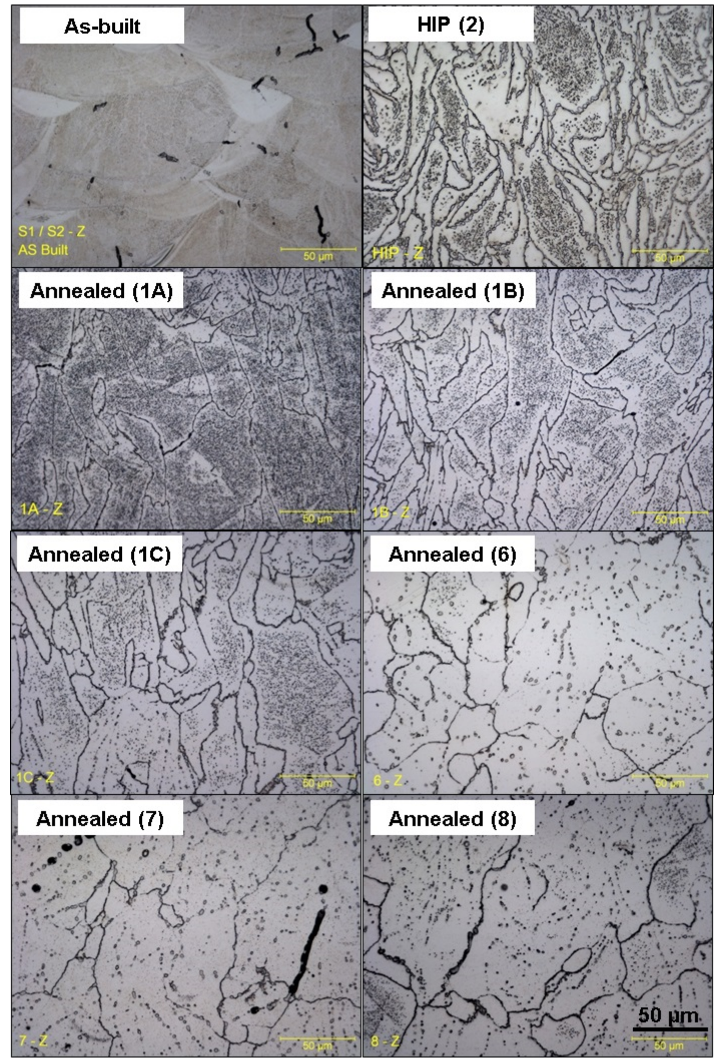
Milestone 3

- **Heat Treatment Optimization**
  - Annealing time
  - Annealing temperature
  - External pressure (HIP)

    - Grain growth
    - Dissolution of precipitates



1a, 1c, and 7 had an annealing temperature of 2150°F, but with the annealing times of 15, 60, and 240 minutes



Milestone 3

- **Heat Treatment Optimization (Mechanical testing)**
  - Additional test walls were produced.
  - Four heat treatment procedure were selected for the further analysis of mechanical properties.
    - Room temperature tensile test
    - Elevated temperature tensile test
    - Low cycle fatigue (LCF)
    - Creep

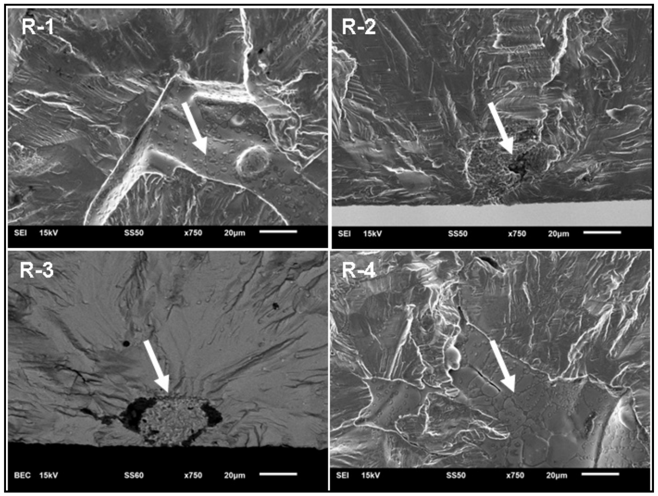
HT Procedure	Solution Annealing			HIP			Solution Annealing		
	Temp. (°F)	Time (hr)	Post Cooling	Temp. (°F)	Pressure (MPa)	Time (hrs)	Temp. (°F)	Time	Post Cooling
R1	2150	1	AC	---	---	---	---	---	---
R2	---	---	---	2150	100	4	---	---	---
R3	---	---	---	2150	100	4	2150	1	AC
R4	2150	4	AC	---	---	---	---	---	---

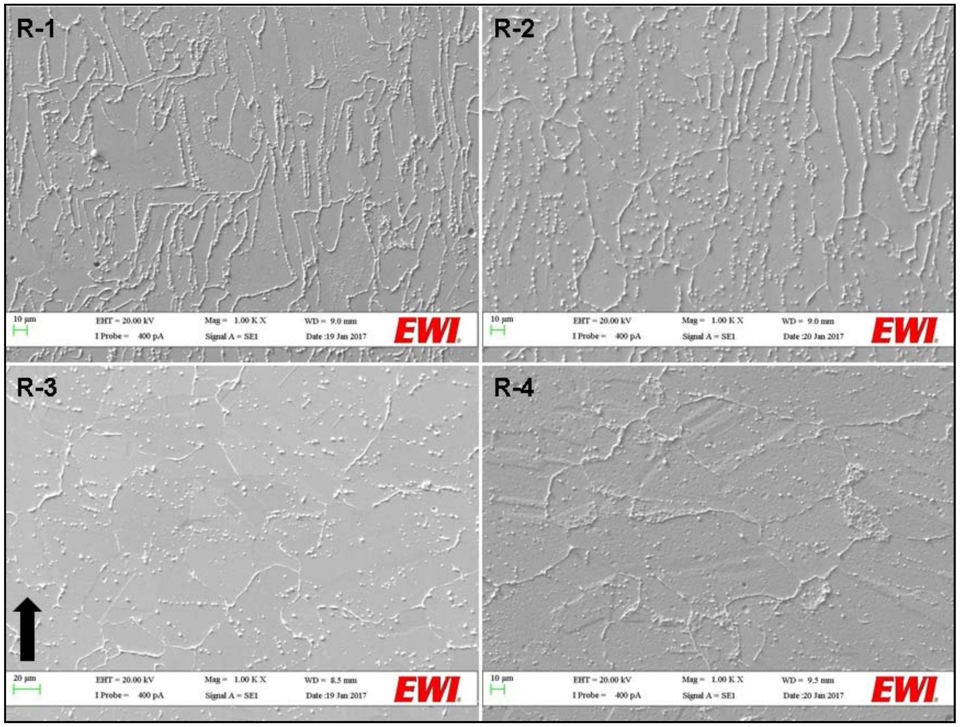
AC: Argon cooling

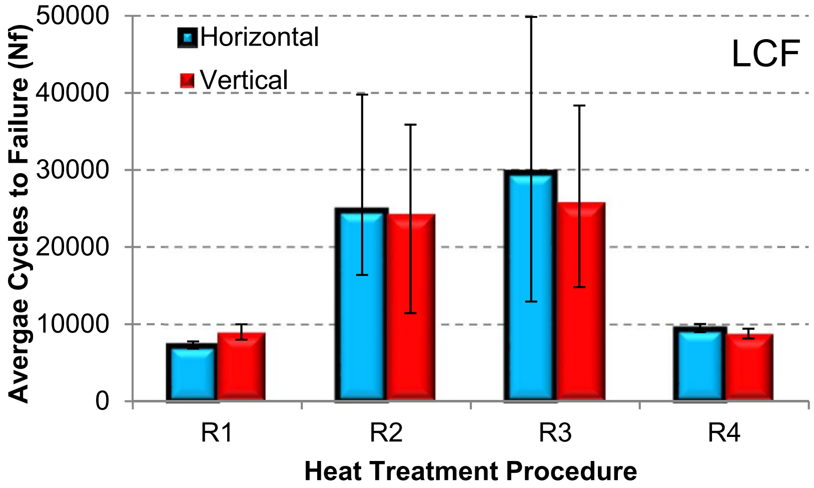
EWI® We Manufacture Innovation

Milestone 3

- **LCF**
  - Longer fatigue life in the HIP'd samples
    - Reduction of internal defects
    - Higher volume fraction of intergranular precipitates

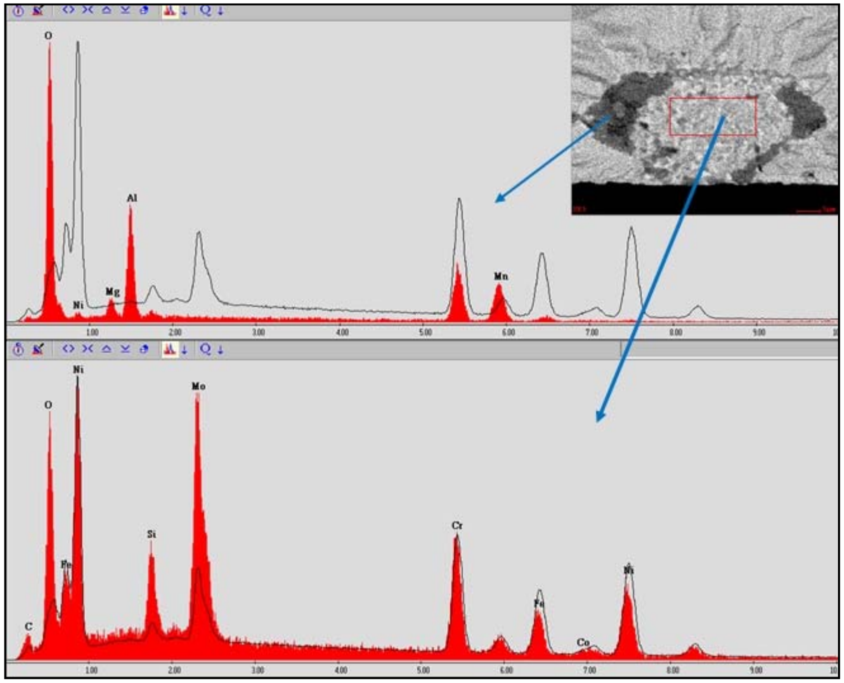


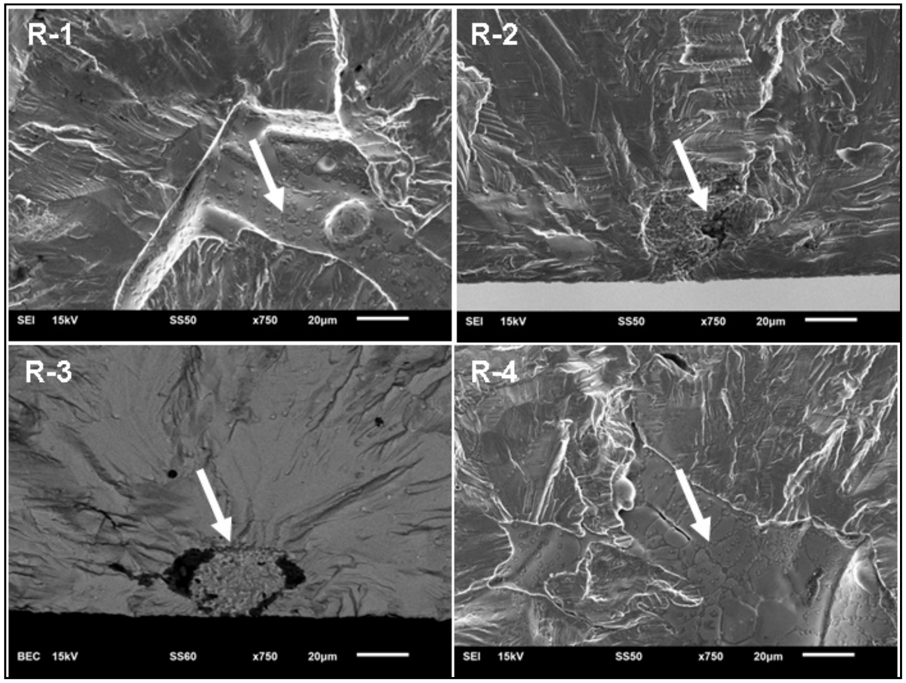




Milestone 3

- **LCF**
  - Small LOF and solidification crack discontinuities
  - Non-metallic SiMo and AlMnMg inclusions
    - New crack initiation mechanism
    - Scattering in the results





Milestone 3

- **Milestone 3: Optimized Heat Treatment Down-Select**
  - HIP improved both LCF and Creep properties
  - Post HIP reduced creep performance
  - R2 selected for Milestone 4 activities

HT Procedure	Solution Annealing			HIP			Solution Annealing			Mechanical Properties	
	Temp. (°F)	Time (hr)	Post Cooling	Temp. (°F)	Pressure (MPa)	Time (hrs)	Temp. (°F)	Time	Post Cooling	LCF	Creep
R1	2150	1	AC	---	---	---	---	---	---		
R2	---	---	---	2150	100	4	---	---	---		
R3	---	---	---	2150	100	4	2150	1	AC		
R4	2150	4	AC	---	---	---	---	---	---		

AC: Argon cooling

Milestone 4- Property Data Curves Delivered

- **Builds**
  - Complete
- **Heat treatment**
  - Complete
- **Mechanical Testing**
  - In-progress

Future Work

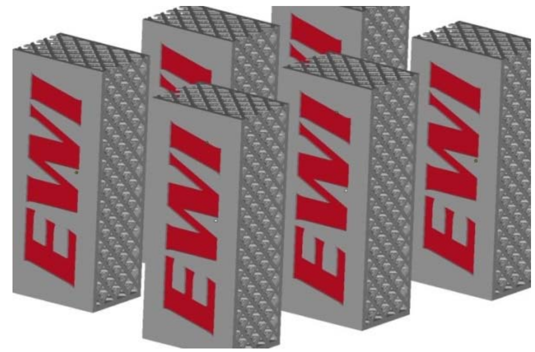
- **Milestone 4**
  - Generation of Property Data Curves
    - Room Temperature tensile
    - Elevated temperature tensile
    - LCF
    - Creep
- **Milestone 5**
  - Development of the specification document
    - Powder
    - Process Parameters
    - Design
- **Final report**

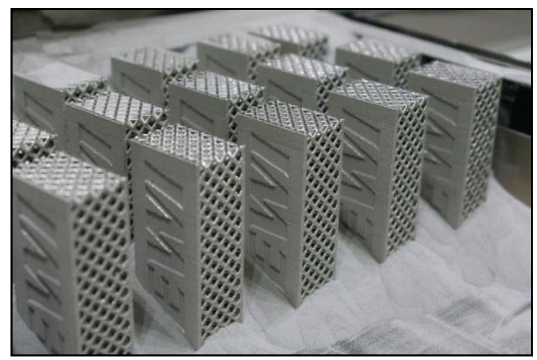
Summary

- **The influences of powder feed on the dimensional accuracy and mechanical properties of additively manufactured Hastelloy X were analyzed.**
  - One powder was down selected.
  - Process parameters were optimized.
- **Heat treatment procedure was optimized for the additively manufactured Hastelloy X.**
  - Eight heat treatment conditions were analyzed.
  - Microstructural and mechanical analysis were performed.
  - Improvements in LCF & Creep properties demonstrated

Questions

Mahdi Jamshidinia, Ph.D.
Applications Engineer, Additive Manufacturing
mjamshidinia@ewi.org
614.688.5153





http://ewi.org/technologies/additive-manufacturing/

EWI®
We Manufacture Innovation

Disclaimer

EWI disclaims all warranties, express or implied, including, without limitation, any implied warranty of merchantability or fitness for a particular purpose.

Under no circumstances will EWI be liable for incidental or consequential damages, or for any other loss, damage, or expense, arising out of or in connection with the use of or inability to use the report delivered under this engagement. This report may not be reproduced or disseminated to individuals or entities outside of your organization without the prior written approval of EWI.

EWI®
We Manufacture Innovation

EWI®

We Manufacture Innovation

EWI is the leading engineering and technology organization in North America dedicated to developing, testing, and implementing advanced manufacturing technologies for industry. Since 1984, EWI has offered applied research, manufacturing support, and strategic services to leaders in the aerospace, automotive, consumer electronic, medical, energy, government and defense, and heavy manufacturing sectors. By matching our expertise to the needs of forward-thinking manufacturers, our technology team serves as a valuable extension of our clients' innovation and R&D teams to provide premium, game-changing solutions that deliver a competitive advantage in the global marketplace.

ewi.org • 614.688.5000

EWI FACILITIES AND LABS

Columbus, Ohio
EWI World Headquarters
1250 Arthur E. Adams Drive
Columbus, OH 43221
614.688.5000
info@ewi.org

Buffalo, New York
Buffalo Manufacturing Works
847 Main Street
Buffalo, NY 14203
716.710.5500
mnutini@ewi.org

REGIONAL EXTENSION OFFICES

Metro DC
Jesse Bonfeld
703.665.6604
jbonfeld@ewi.org

Detroit, Michigan
Jon Jennings
248.840.6569
jjennings@ewi.org

Bay Area, California
Brian Victor
614.499.5544
bvictor@ewi.org

Tampa, Florida
Ian Harris
614.440.1277
iharris@ewi.org

EWI®

We Manufacture Innovation