Development of nuclear quality components using metal additive manufacturing

RadiaBeam Systems, LLC
The University of Texas at El Paso
W.M. Keck Center for 3D Innovation

RadiaBeam Systems – Introduction

- RadiaBeam has two core missions:
  - To manufacture high quality, cost-optimized accelerator systems and components
  - To develop novel accelerator technologies and applications
- Currently > 50 employees and growing & 30,000 sq. ft.
  - Consists of PhD Scientist (10), Engineers (18), Machinists (10), Technicians (8), and Administrative (4)

W.M. Keck Center for 3D Innovation - Introduction

- 13,000 sq. ft. of space with world-class capabilities in additive manufacturing
- Over 50 AM machines (polymers, metals, ceramics, electronics, composites)
- Multi-disciplinary research team with over 50 faculty, staff, and students
- Involved in education, research, outreach, technology development and commercialization and industrial partnership

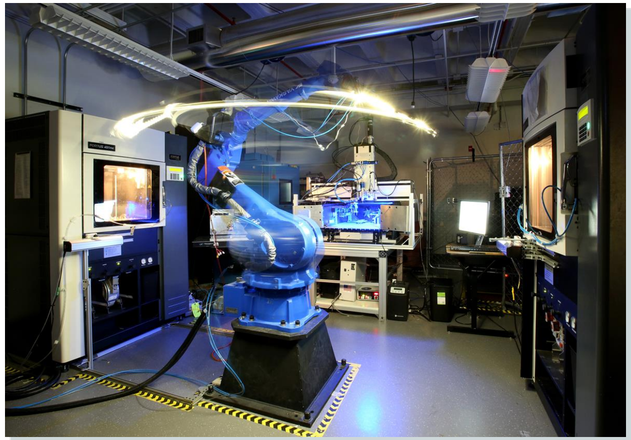
Capabilities

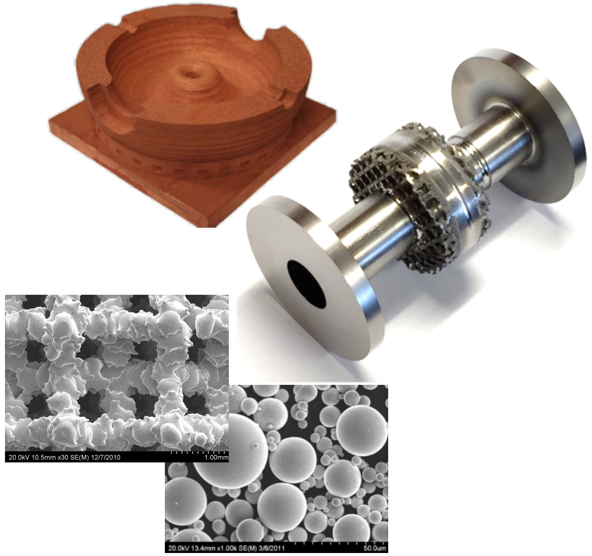
radiabeam SYSTEMS

- Design (RF, magnetic, thermal-mechanical)
- Engineering
- Fabrication
- Assembly
- Testing
- Installation
- Service

W.M. KECK CENTER FOR 3D INNOVATION

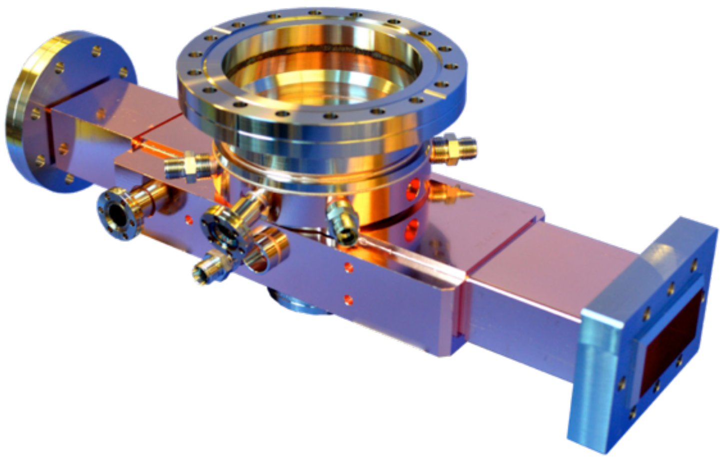
- Design for additive manufacturing
- Reverse engineering
- Mechanical Testing
- Materials characterization
- Hybrid manufacturing
- Materials processing



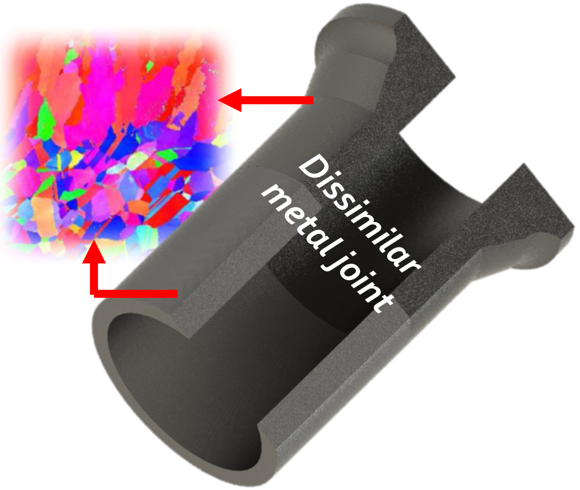


Products

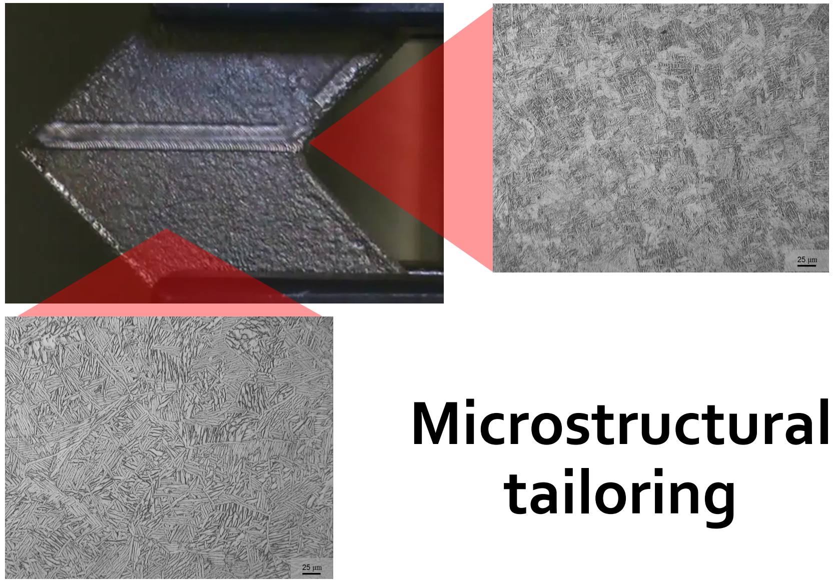
- Turnkey accelerators
  - Cargo inspection and Radiography
  - High-power Irradiation
  - Self-shielded irradiators
- E-beam diagnostics
  - Beam profile monitors
  - Bunch length monitors
  - Charge, emittance, etc.
- RF structures
  - RF photoinjectors
  - Bunchers
  - Linacs
  - Deflectors
- Magnetic systems
  - Electromagnets
  - Permanent magnets
  - Systems (chicanes, final focus, spectrometers)



Accomplishment in R&D of metals



Multi-material



Microstructural tailoring

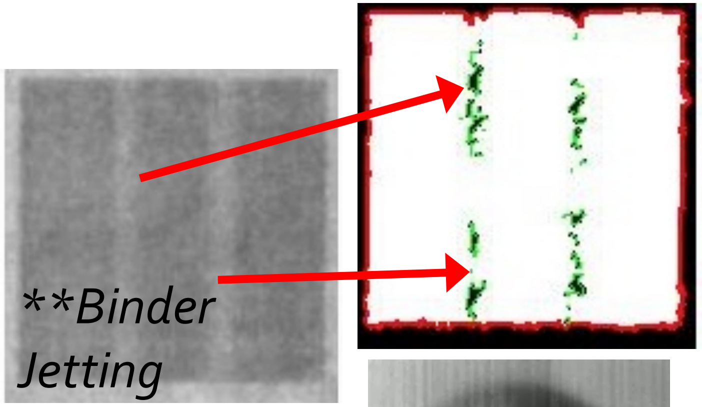
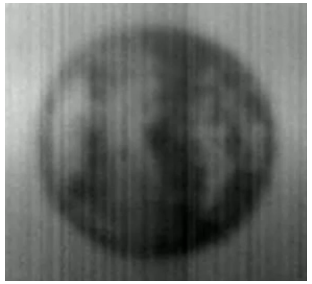
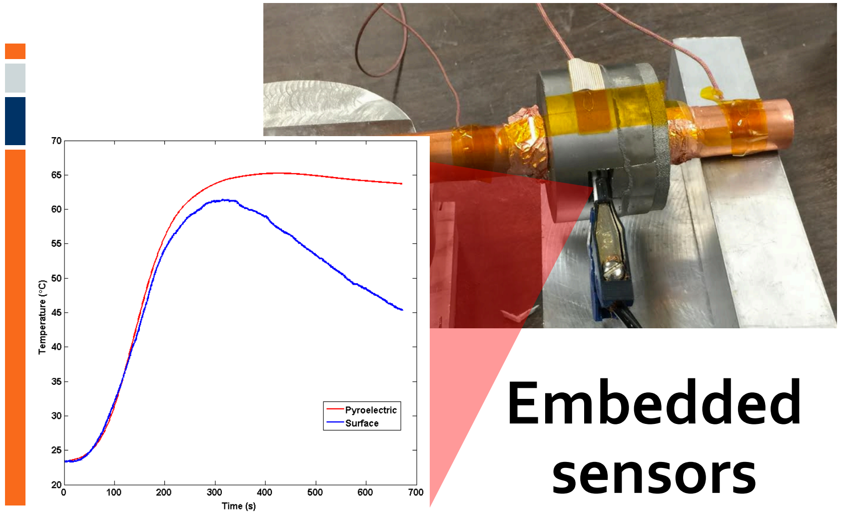


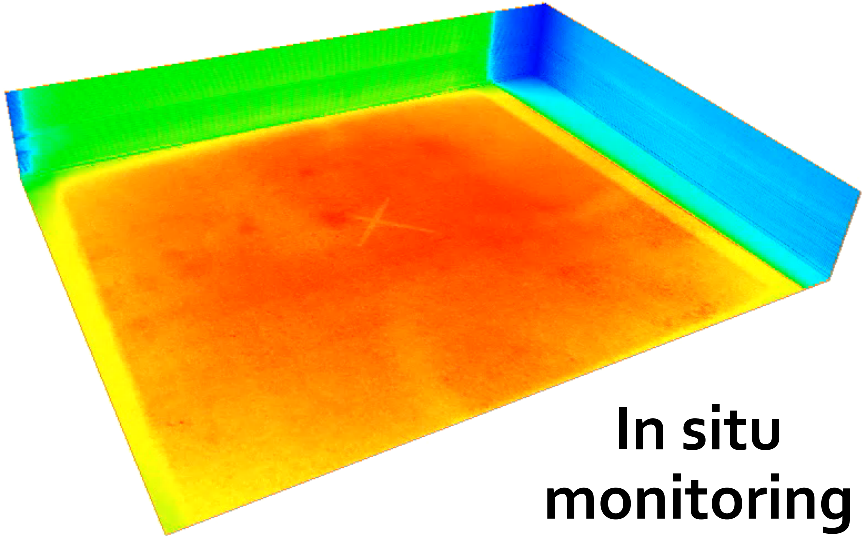
Image analysis & control



*Powder bed fusion



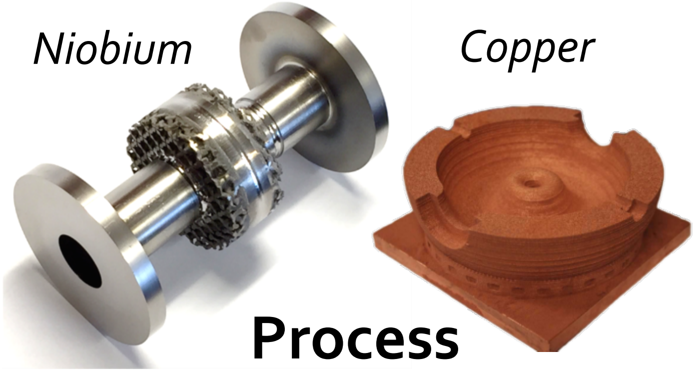
Embedded sensors



In situ monitoring

Niobium

Copper



Process parameter development

Growing list of customers for RadiaBeam…

Argonne NATIONAL LABORATORY
ISL
iba
SPARKLE RADIOPHARMACEUTICALS
CERN
NSRRC

CINEL
KAERI
healthcare for everyone TeamBest Your True Partner
University of Colorado
UNIVERSITY of HAWAI'I MĀNOA
UNIVERSITY OF Nebraska Lincoln

東京大学 THE UNIVERSITY OF TOKYO
NIOWAVE Accelerating Your Particles
Schlumberger
ACCURAY
Sterigenics
Fermilab
SIEMENS
Yale University
Lawrence Livermore National Laboratory
EUROTEK
Mizzou University of Missouri - Columbia
TRIUMF
excillum
BROOKHAVEN NATIONAL LABORATORY

UCLA
VETENSKAP OCH KONST KUNGL TEKNISKA HÖGSKOLAN
TRAD Tests & radiations
BERKELEY LAB
EUROPEAN SPALLATION SOURCE
LNLS Laboratório Nacional de Luz Síncrotron
INFN Istituto Nazionale di Fisica Nucleare

OAK RIDGE National Laboratory
WRIGHT STATE UNIVERSITY
Idaho Accelerator Center
CENTRE FOR ADVANCED TECHNOLOGY, INDORE
PAL
Canadian Light Source
Centre canadien de rayonnement synchrotron

ARIEL UNIVERSITY
ENEA ENTE PER LE NUOVE TECNOLOGIE, L'ENERGIA E L'AMBIENTE
INDIANA UNIVERSITY BLOOMINGTON
Sandia National Laboratories
CANDLE
Los Alamos NATIONAL LABORATORY
WISCONSIN UNIVERSITY OF WISCONSIN–MADISON

MICHIGAN
KIT Karlsruher Institut für Technologie
FERMI @elettra
SLAC NATIONAL ACCELERATOR LABORATORY
MAX IV
SOLEIL SYNCHROTRON
VANDERBILT UNIVERSITY
PAUL SCHERRER INSTITUT PSI

Growing list of small businesses for Keck Center

radiabeam SYSTEMS

CalRAM
A Division of Precision Holdings

radiabeam TECHNOLOGIES

ExOne
DIGITAL PART MATERIALIZATION

Swift Engineering Inc.

BENNETT ADVANCED RESEARCH™
CREATING YOUR FUTURE™

TIS Consulting Group

ADDAERO

and continues to grow….

Facilities

radiabeam SYSTEMS

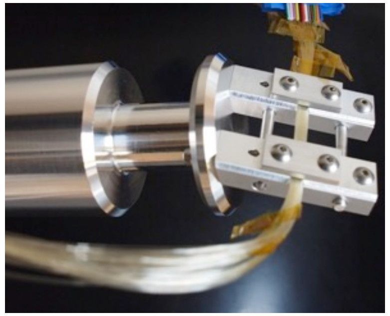
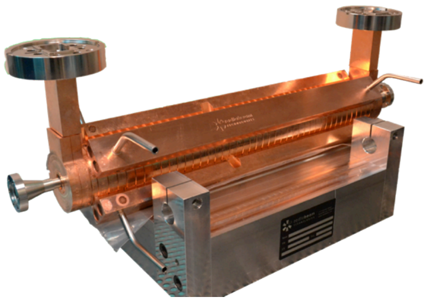
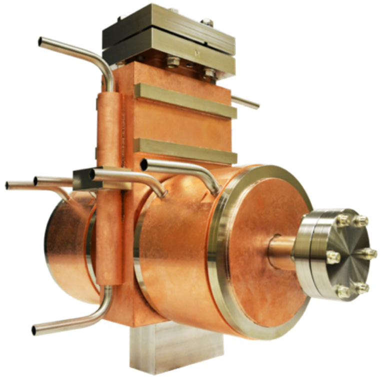
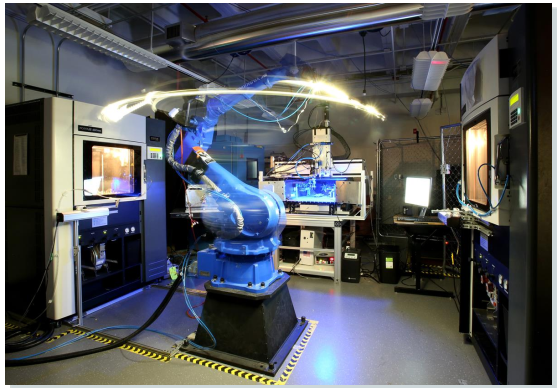
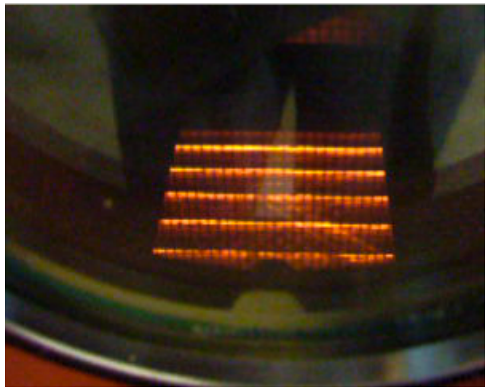
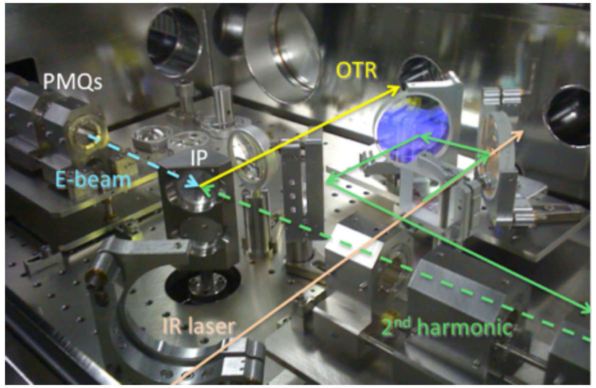
- Machine shops
- Magnetic measurement lab
- Optics Lab
- Clean room
- Hot test cell (up to 9MeV)
- Chemical processing
- RF test lab

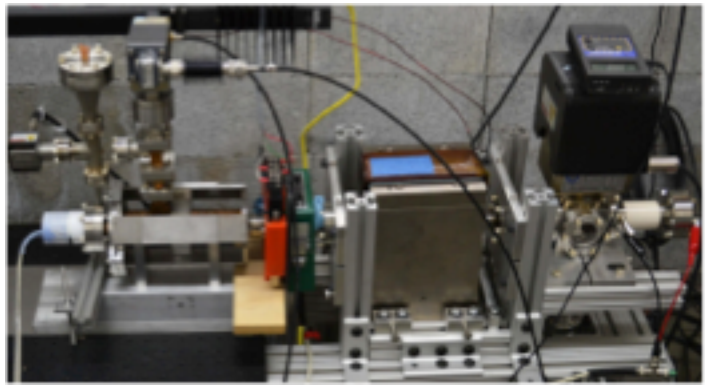
W.M. KECK CENTER FOR 3D INNOVATION

- CNC machining
- Mechanical testing
- Materials characterization
- Post-processing (heat treating, finishing)
- >50 additive manufacturing machines

Multiple funding agencies

- SBIR/STTR, BAA, commercial funded and self-funded R&D to develop new products and technical solutions

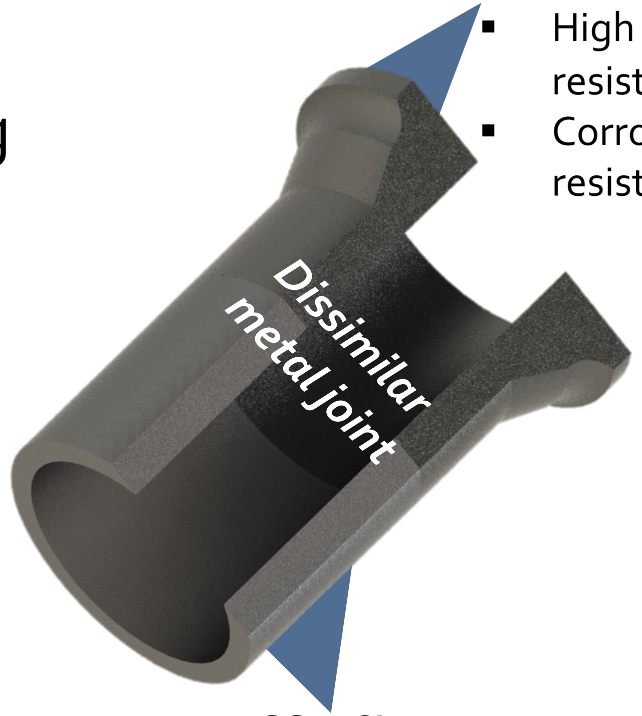










Project Goals and Relevance to DOE Nuclear Power

- Project Goal
  - Phase I – Experimentally demonstrate feasibility of joining dissimilar metals using EBM AM.
  - Phase II – Further the fundamental understanding of dissimilar metal joining using EBM AM
- DOE NE Relevance
  - Avoids use of filler materials
  - Vacuum (~10^{-4} Torr) limits contamination of oxides and nitrides
  - High quality joint while minimizing the thermal damage to surrounding material
  - Promise of realizing complex multi-material part

Inconel 718
- High temperature resistance
- Corrosion resistance



SS316L
- High strength at elevated temperature for structural and pressure-containing applications

Joining dissimilar metals – Directed Energy Deposition

- Sciaky's Electron Beam Additive Manufacturing
- Wire feedstock is fed onto a substrate and melted using an electron beam

- Optomec's Laser Engineered Net Shaping
- Powder is directed onto a substrate and melted using a laser beam

Research Focus: Electron Beam Melting (EBM)

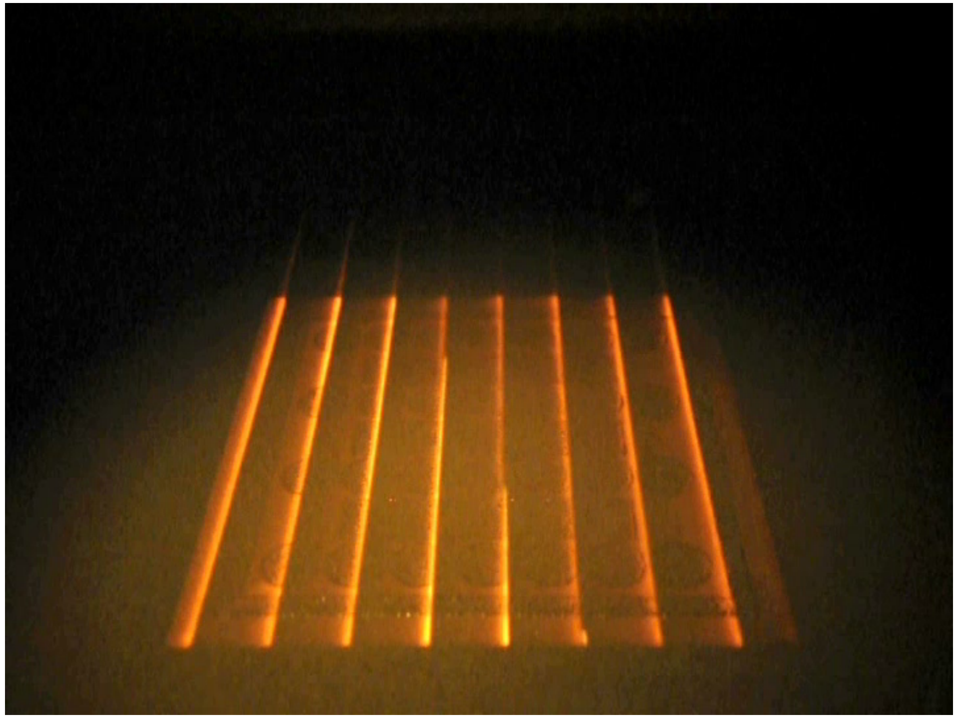
A2

Two Build Tanks
200 x 200 x 350mm
(7.8 x 7.8 x 13.75 in)
Ø = 300mm, h = 200mm
(Ø = 11.81, h = 7.8 in.)

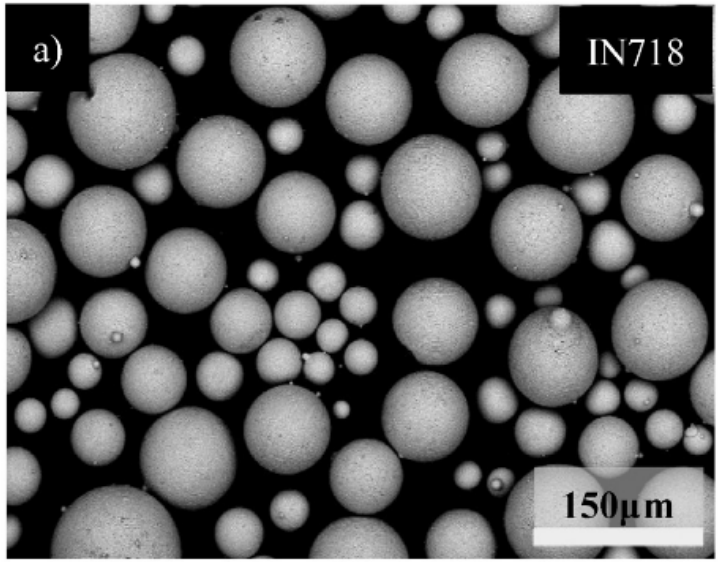
S12

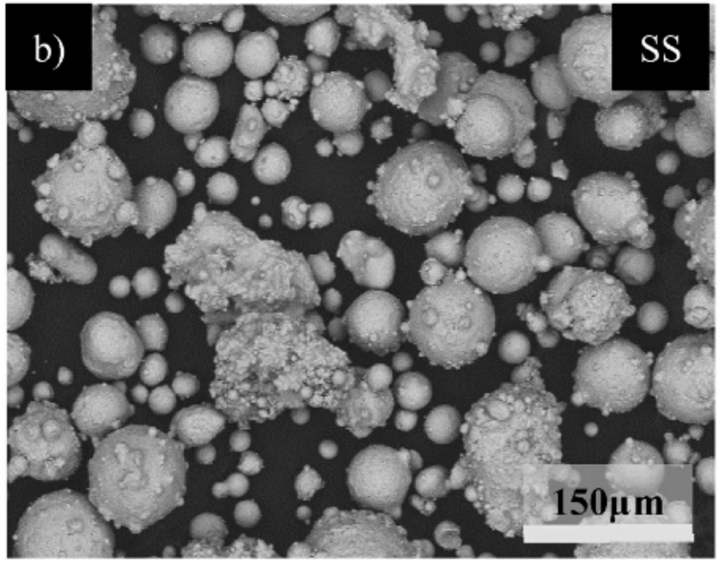
(modified for high temperatures)

One Build Tank
200 x 200 x 180mm
(7.8 x 7.8 x 7.0 in.)

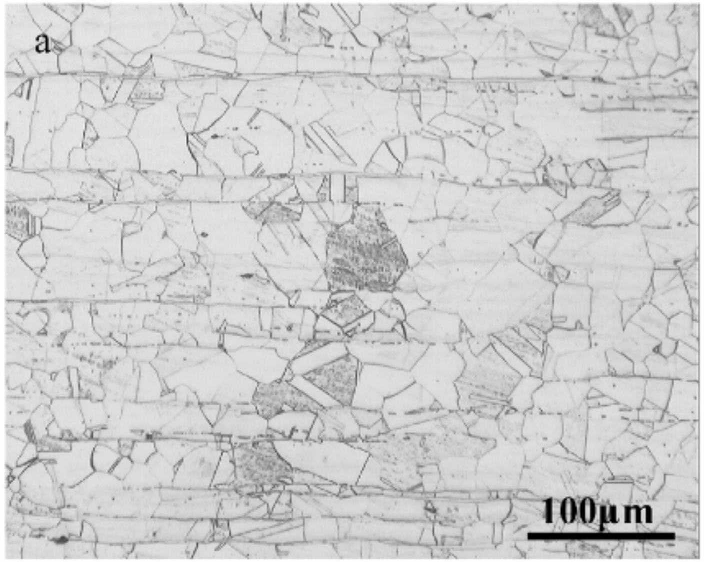


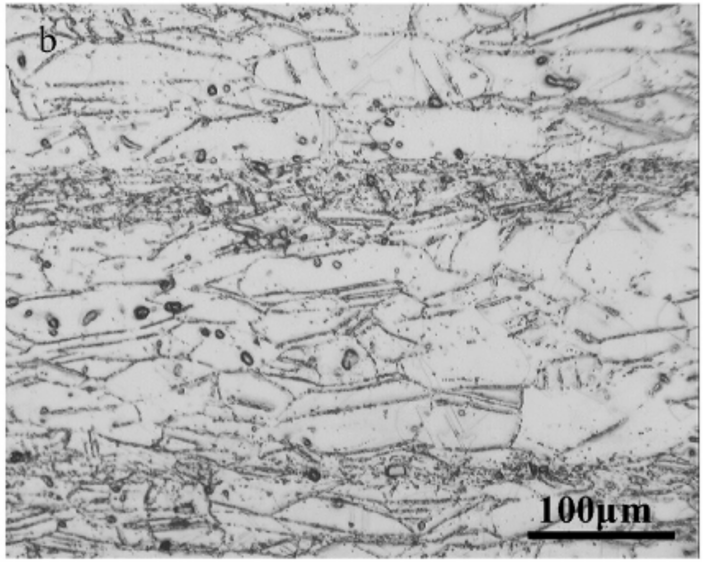
Joining dissimilar metals using EBM AM technology





- Purchased and characterized wrought and powder precursor material composed of SS316L and IN718
- Goal was to join precursor material onto dissimilar wrought material and characterize joint interface

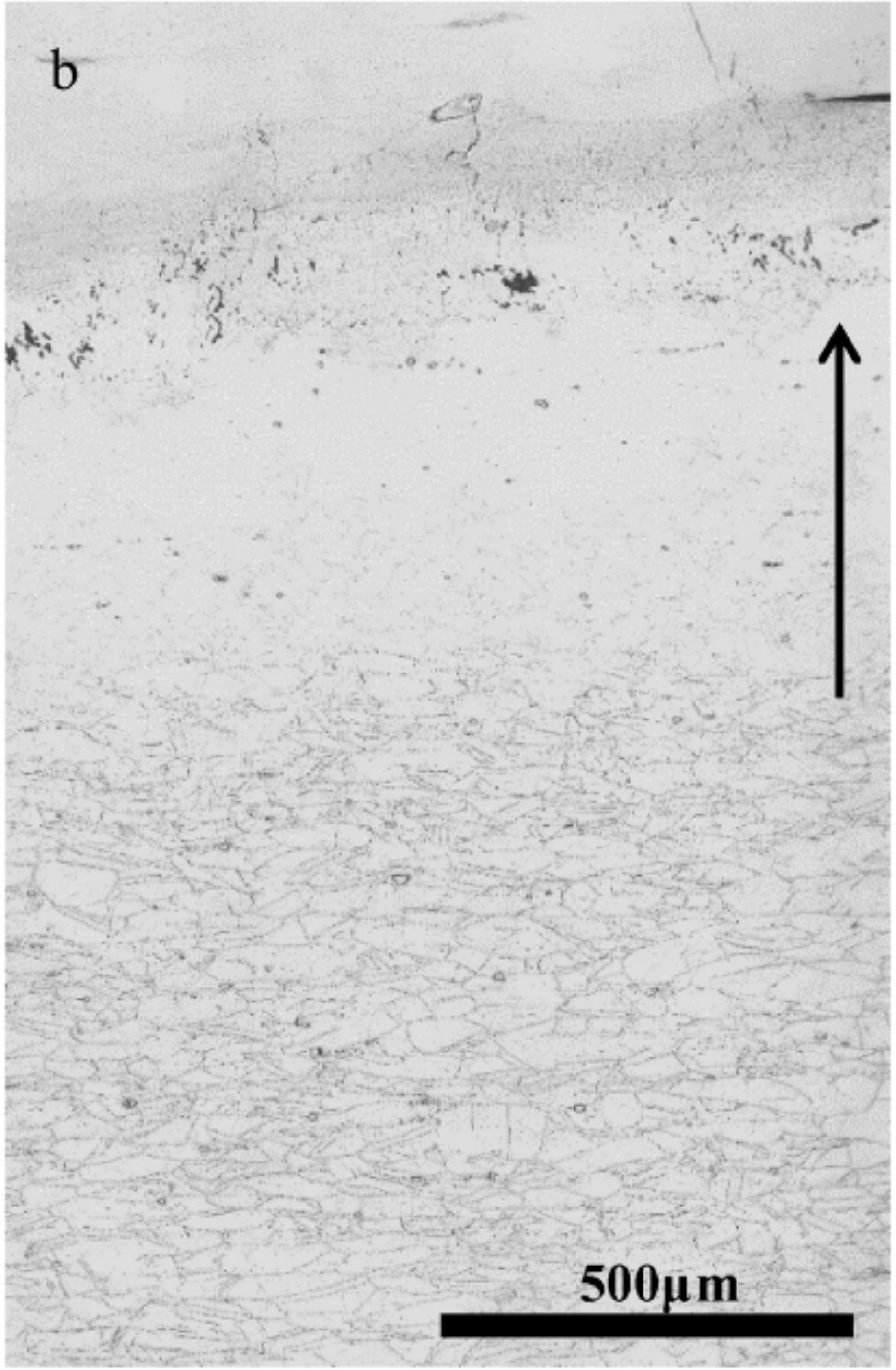




Hinojos, A., Mireles, J., Reichardt, A., Frigola, P., Hosemann, P., Murr, L.E., Wicker, R.B., (2016). *Joining of Inconel 718 and 316 Stainless Steel using electron beam melting additive manufacturing technology*. Materials and Design 94, 17-27.

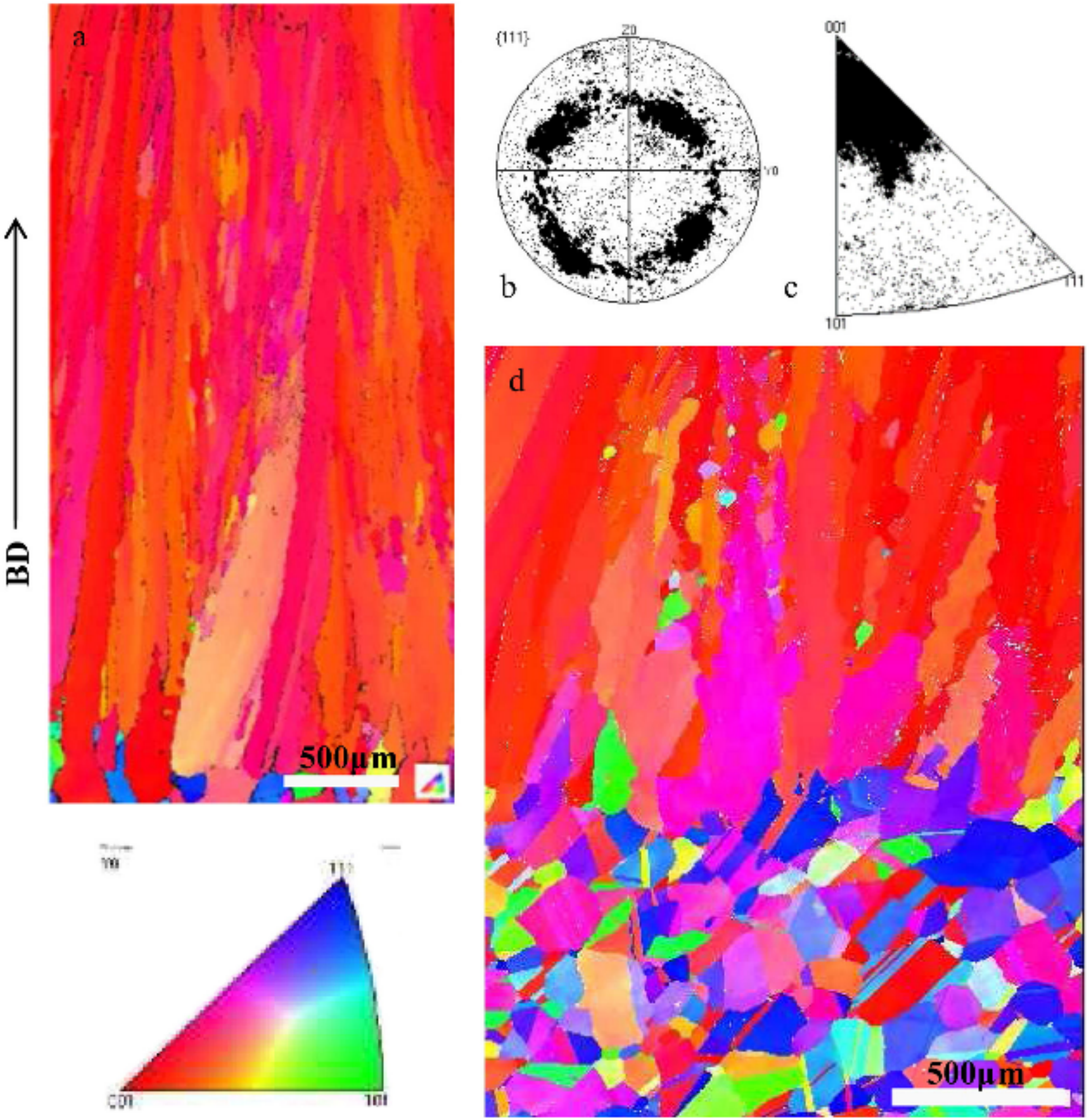
HAZ

- HAZ of SS316L had an average penetration depth of 2.61±0.4mm and 443±56μm for IN718 substrate
  - Features are smaller in comparison to classic joining techniques such as GTAW



EBSD

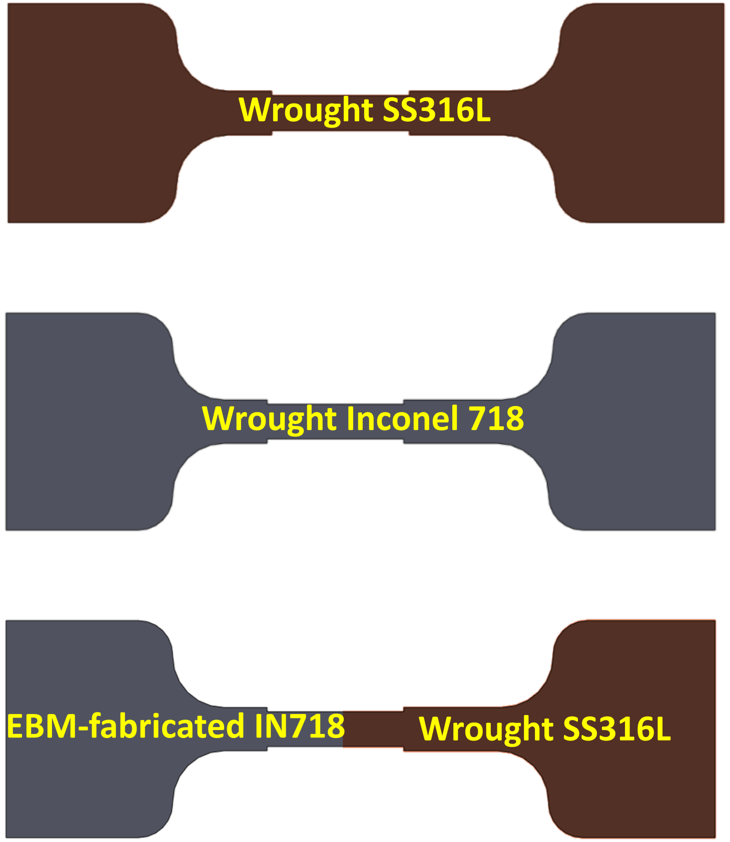
- Pole figures shown right of IN718 on SS316L
- Fabrication shows large columnar grains and strong texturing in the 001 direction
- Figure on right depicts joint interface where fabricated material grows from substrate grains

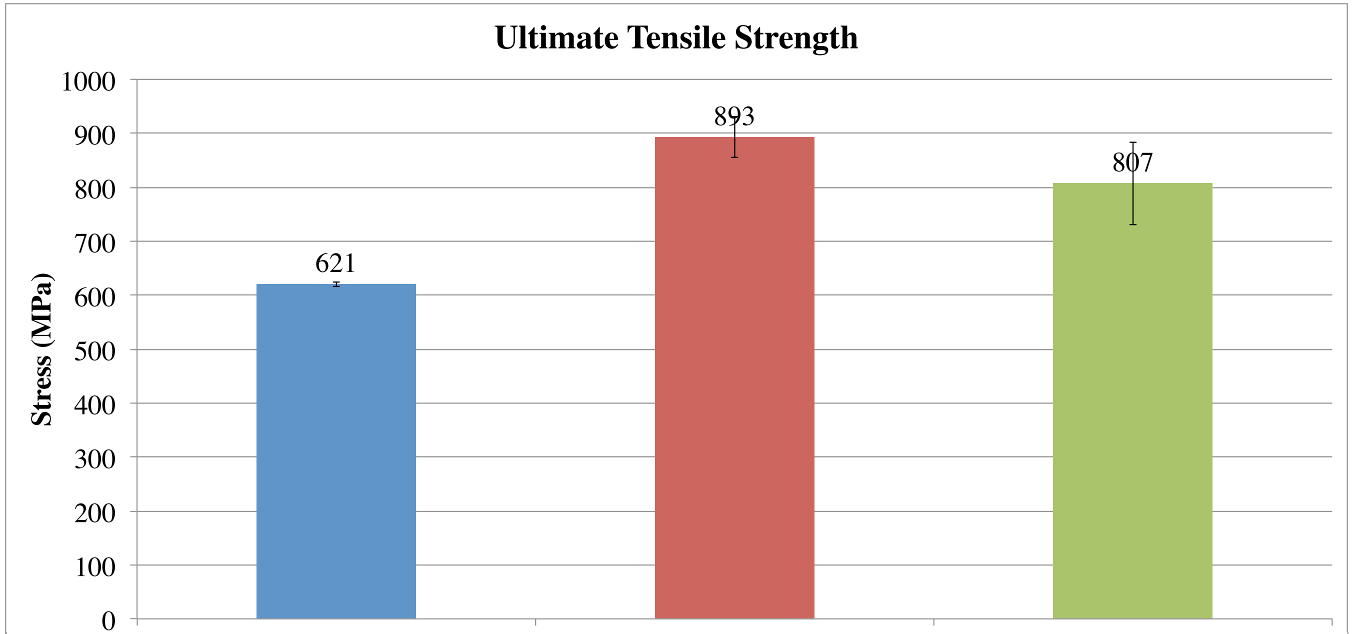


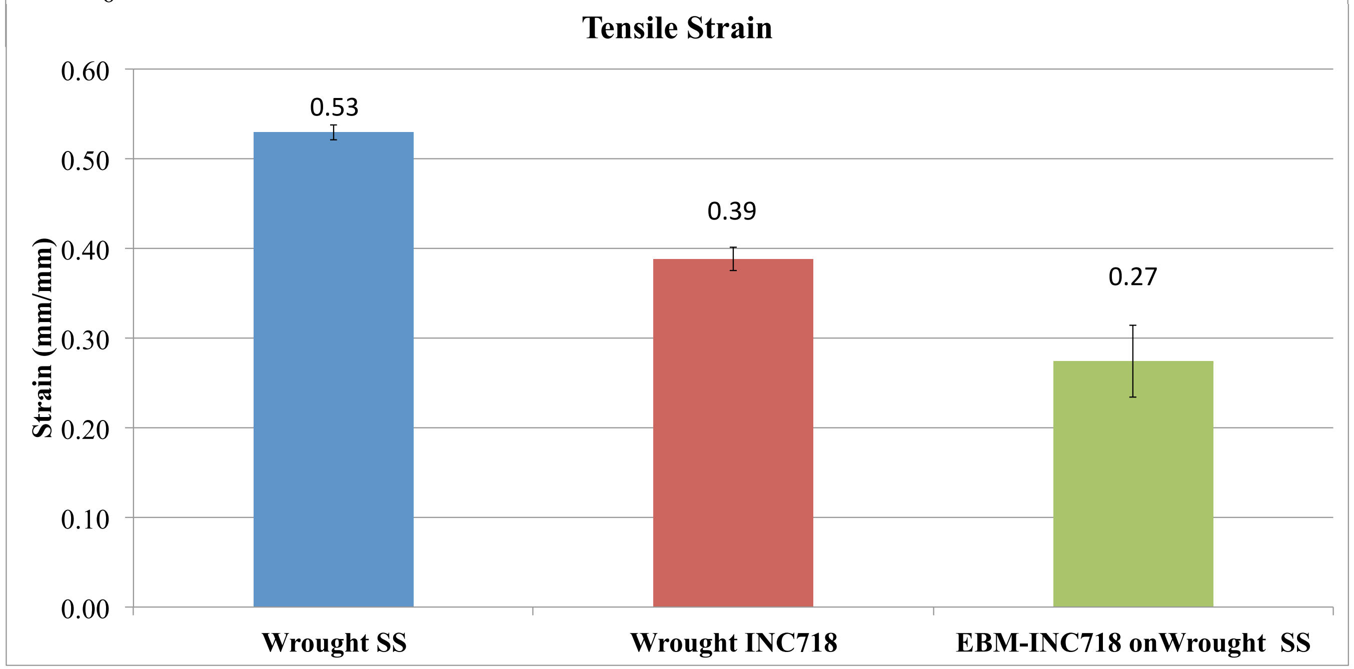
Phase 1 - Project summary

- Research explored the feasibility of joining Inc718 and 316L SS using EBM AM.
- Simple geometries suitable for material testing were fabricated (Inc718 on 316L and 316L on Inc718) using Arcam EBM, and the joints characterized
- Material testing showed reduced presence of precipitates and narrower HAZ when compared to traditional welding processes
- Change in mechanical properties in the HAZ and the substrate were not greatly affected
- A. Hinojos et. al., *Joining of Inconel 718 and 316L Stainless Steel using powder bed fusion additive manufacturing technology*, Materials and Design, 2016

Mechanical Properties

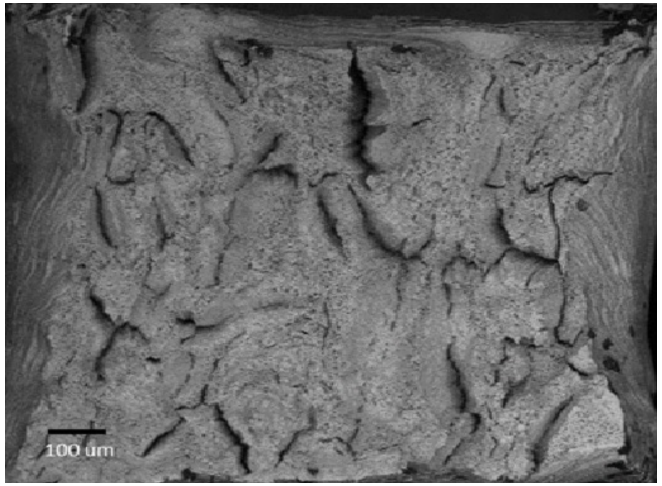




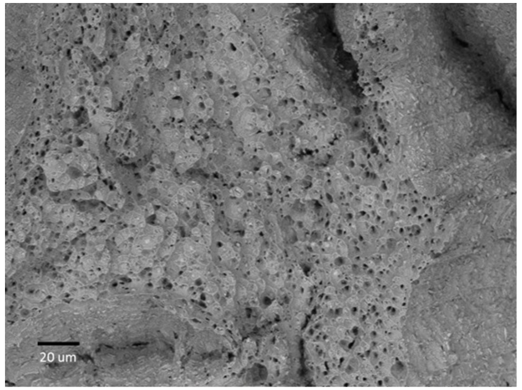


Fracture of EBM-fabricated IN718 on wrought SS316L

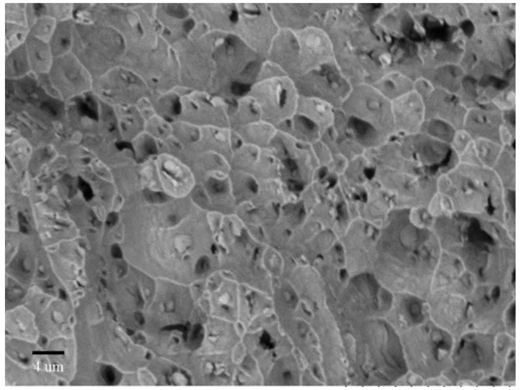
TOP Sample 1



X1000

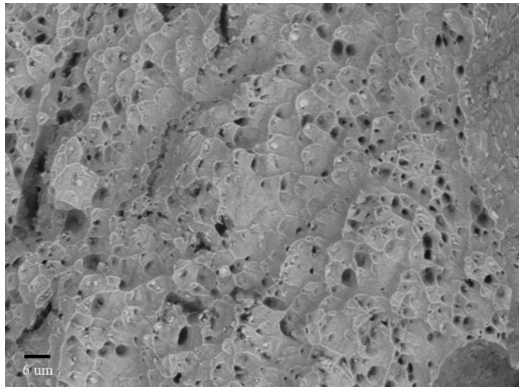


X4000

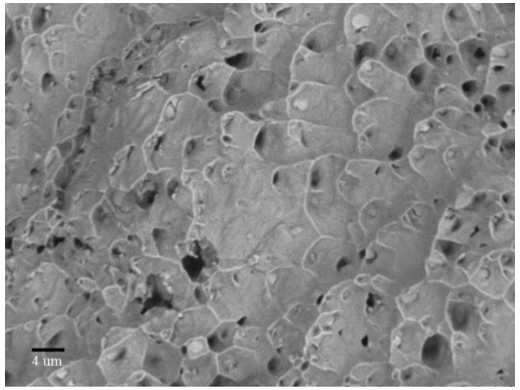


BOTTOM Sample 1

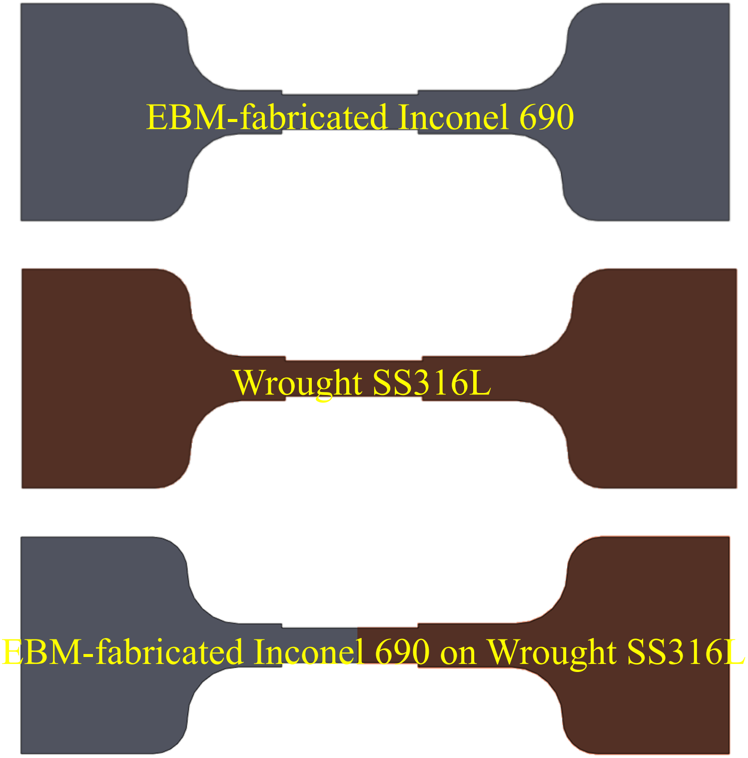
X2000

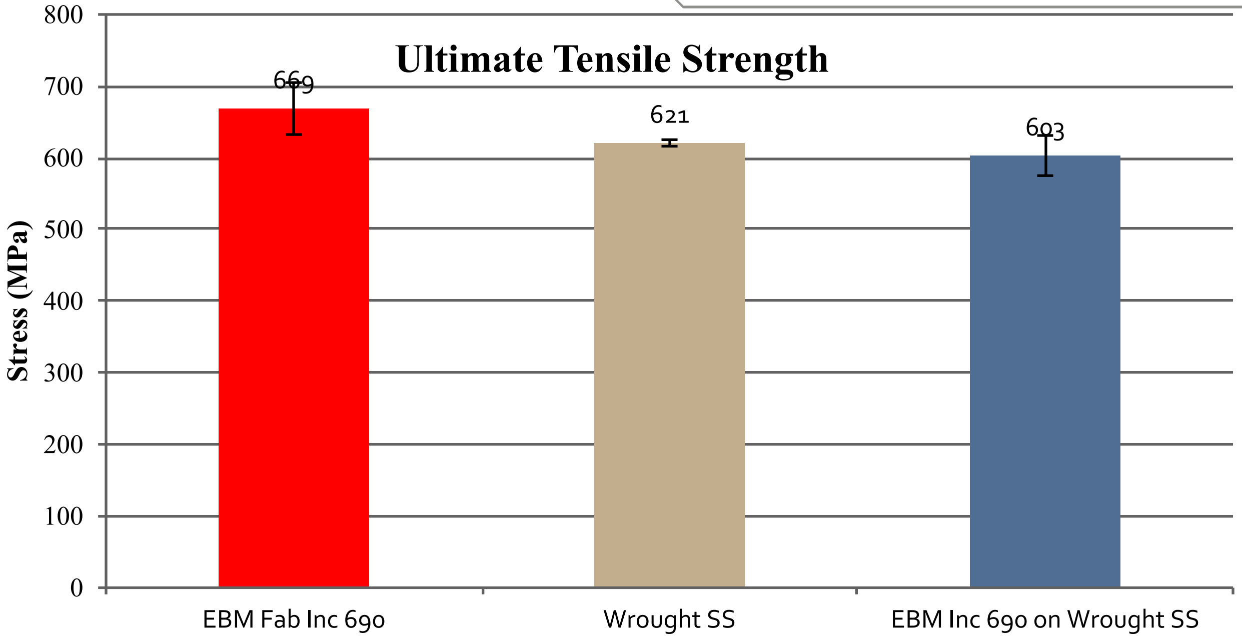


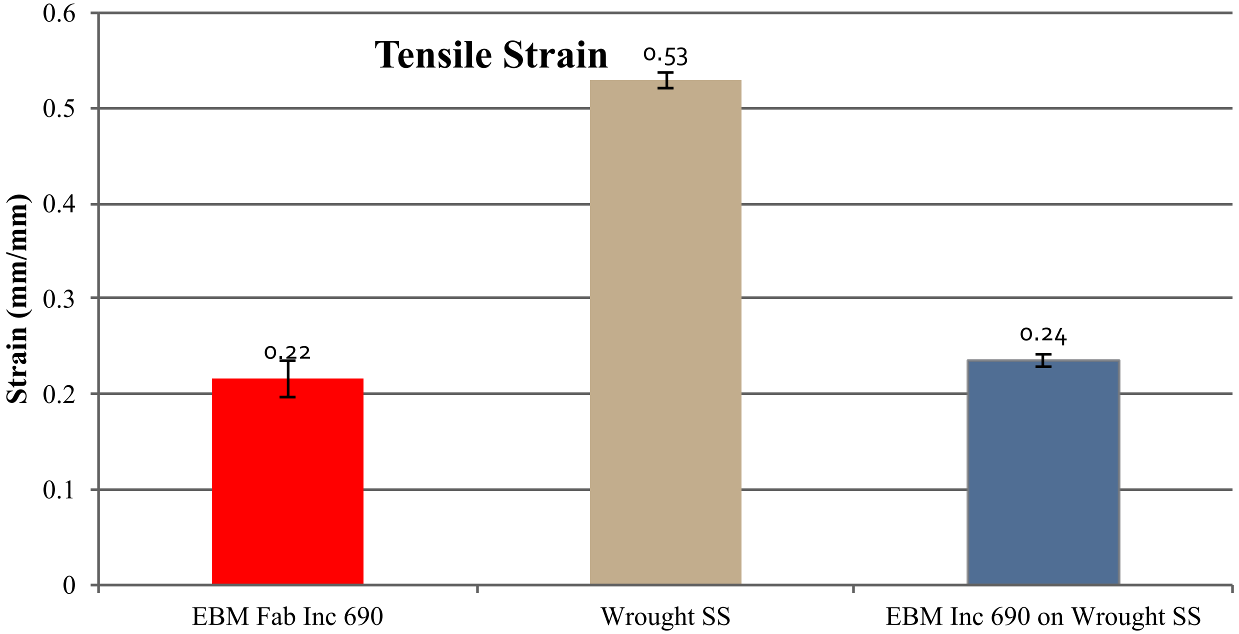
X4000



EBM-fabricated Inconel 690 on Wrought SS316L

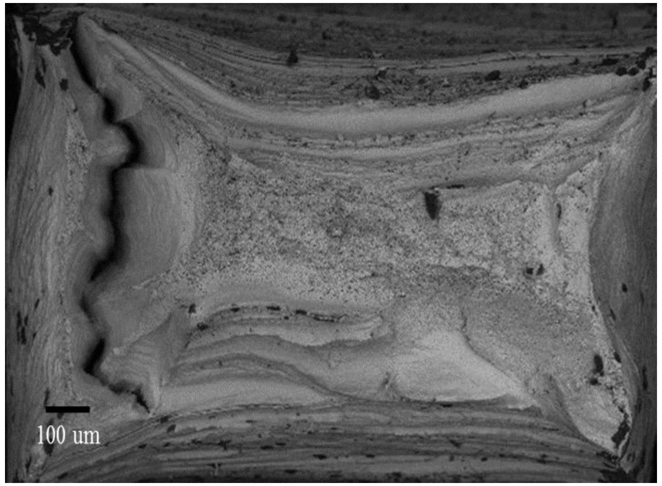






Fracture of EBM-fabricated IN690 on SS316L

TOP Sample 3



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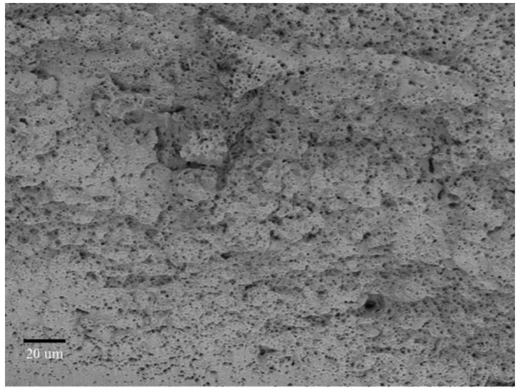

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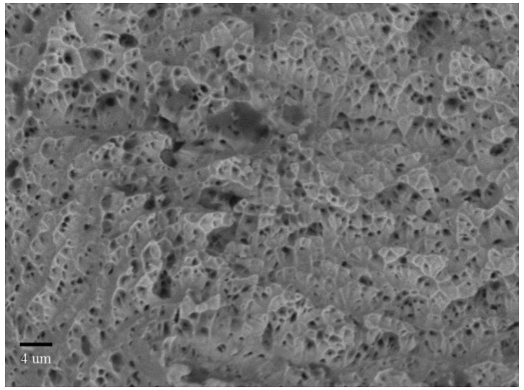
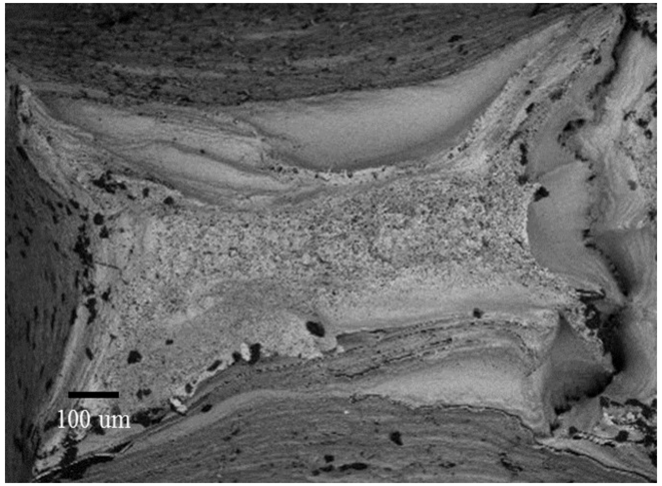
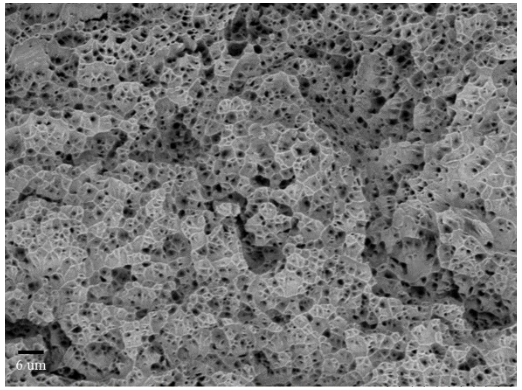


BOTTOM Sample 3



X2000



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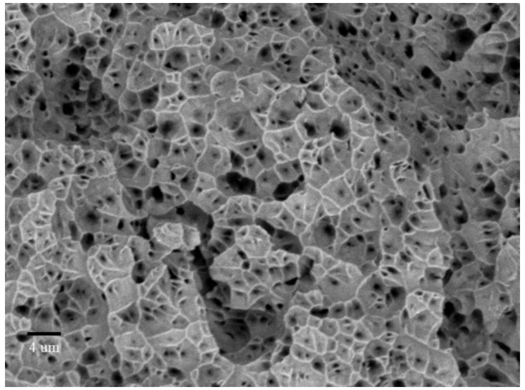
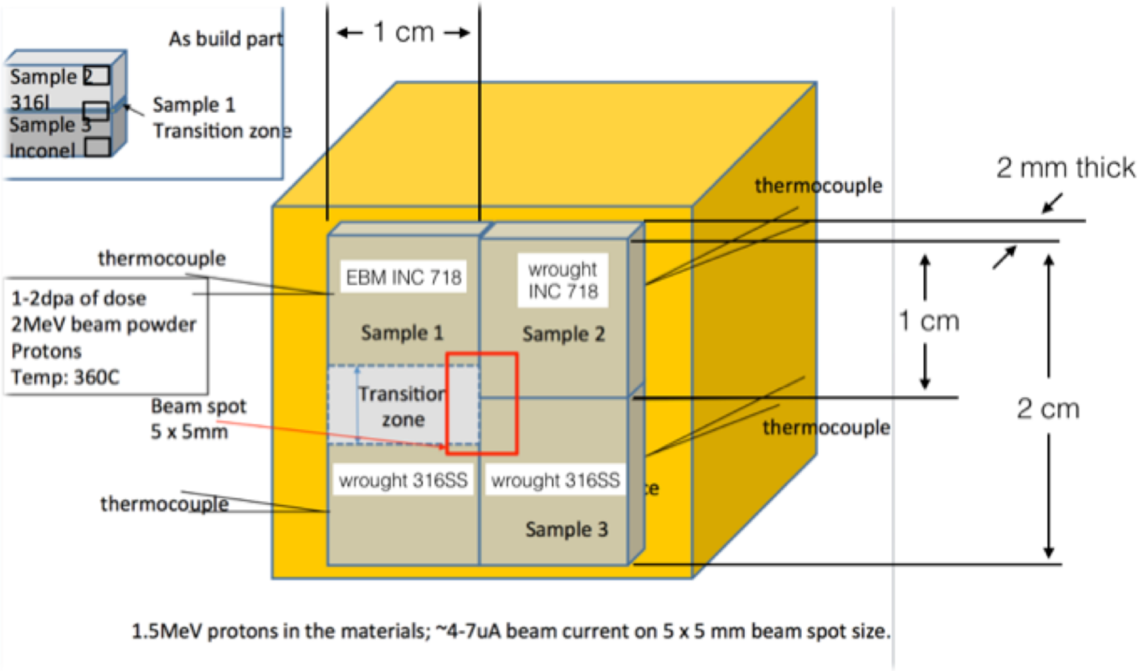


Phase II – Update summary

- Phase II goal: Further the fundamental understanding of dissimilar metal joining using EBM AM
  - Detailed materials testing
  - Introduce simulations to guide material choice in joint design and extend EBM processing to ferritic alloys
  - Extend material testing to nuclear reactor environmental conditions (high temperature, pressure, radiation)

Current research objective

- Continue mechanical testing and materials characterization
- Execute plan for irradiation studies



Acknowledgements

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STTR Collaborators:

- Alejandro Hinojos, Jorge Mireles, Sara M. Gaytan, Lawrence E. Murr, Ryan B. Wicker, W.M. Keck Center for 3D Innovation at the University of Texas at El Paso
- Ashley Reichardt, Peter Hosemann, Department of Nuclear Engineering at the University of California Berkeley
- Stuart Maloy, Ion Beam Materials Laboratory at Los Alamos National Laboratory

QUESTIONS/COMMENTS

W.M. KECK CENTER
FOR 3D INNOVATION

radiabeam
SYSTEMS

UTEP