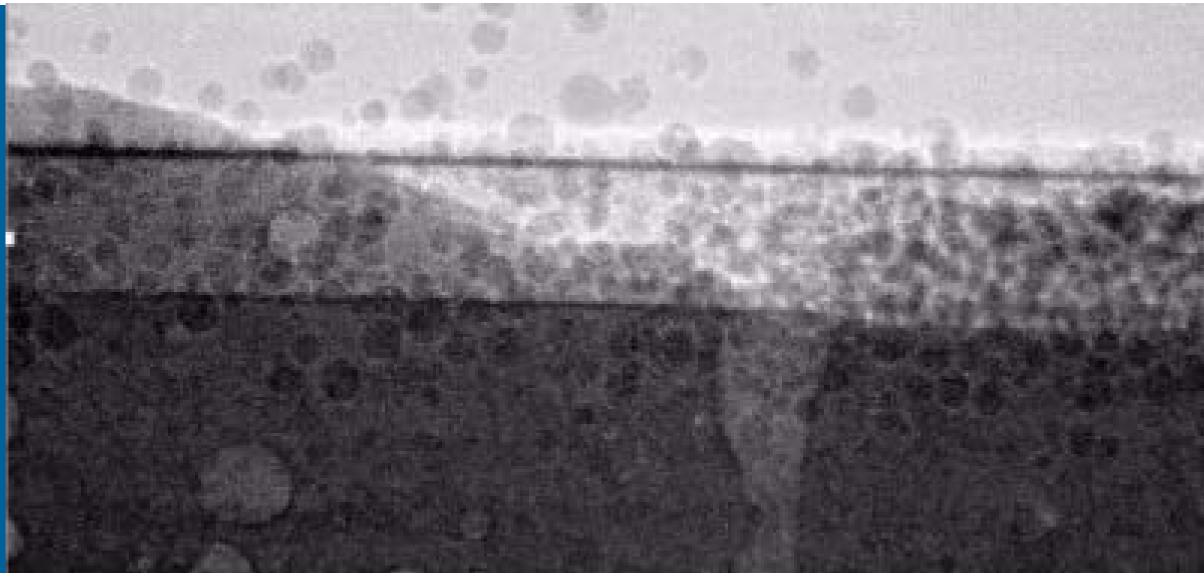
LIGHTMAT

PROJECT ID#: MAT230

LASER POWDER BED FUSION PARAMETER DEVELOPMENT FOR NOVEL STEEL AND ALUMINUM POWDERS USING IN SITU SYNCHROTRON IMAGING AND DIFFRACTION



AARON GRECO
Argonne National Laboratory

ANDREW BOBEL
GM R&D

2021 Vehicle Technology Office Annual Merit Review

June 24th 2021

OVERVIEW

Timeline

Project start date: Jan 2020
CRADA end date: Sept 30 2021, NCTE to June 30 2022

Budget

DOE funds: $250,000
GM in-kind cost share: $250,000

Barriers & Technical Targets

- Powertrain weight reduction through use of additive manufacturing
- Current printable aluminum alloys lack strength at elevated temperatures for use in dynamically loaded components; current printable steels are too high cost
- New alloys require significant time and resources to properly tune printing parameters

Partners

Argonne National Laboratory
General Motors

RELEVANCE/OBJECTIVE

Additive Manufacturing for Automotive Components

- **Opportunity:** Additive manufacturing (AM) offers significant potential for reducing the weight of components and systems through optimization of design and use of low density/high strength materials
- **Challenge:** Current AM alloys lack strength and fatigue performance at elevated temperatures for use in critical automotive applications
- **Objective:** Optimize the printing parameters for several advanced alloys (AlSiCu, FeCu, Fe393, AlTi, etc)

AlSiCu

Performance at Elevated temperatures (300C)
15% increase* in Yield Strength at 300C
25% increase* in Ultimate Tensile Strength @ 300C
160% increase* in fatigue strength
*compared to AlSi10Mg

Application:
Super charger rotors
45% weight reduction 40% inertia reduction

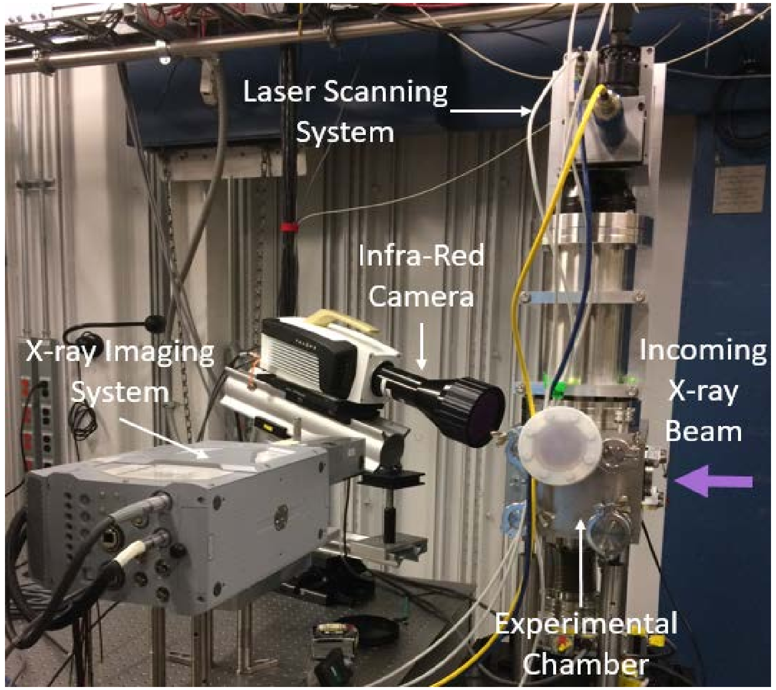
FeCu

50% cheaper than 17-4PH SS
Maintains key performance metrics

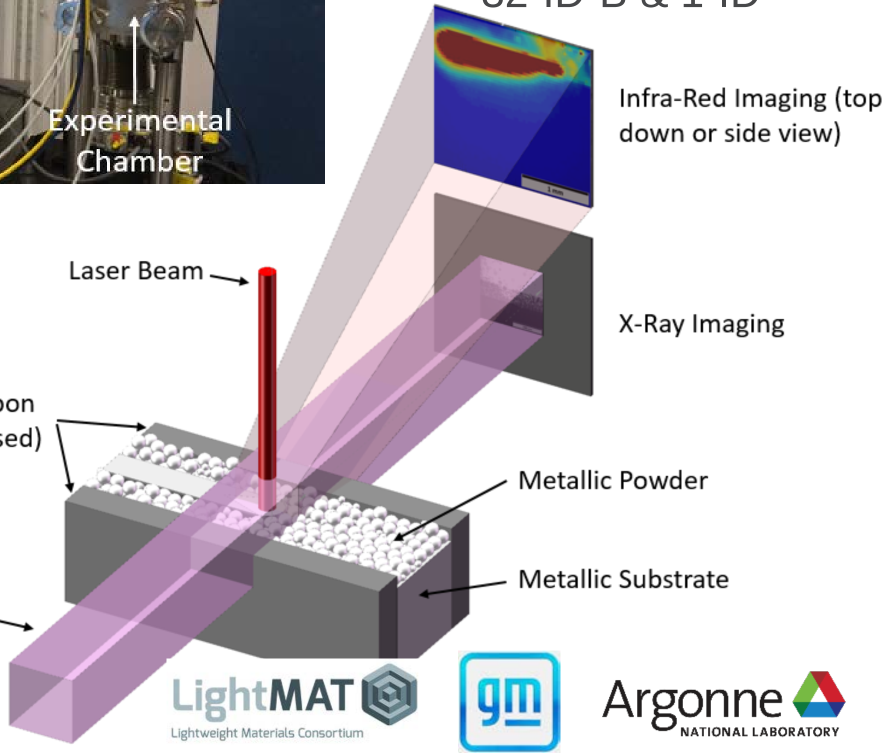
Application:
Connecting rods
15% weight reduction

APPROACH

- **In-situ AM Experiments:**
  - Subsurface porosity formation
  - High speed infrared (IR) measurements
  - X-ray diffraction
- **Modeling:**
  - Thermal model for porosity risk (high throughput / computationally efficient)
  - Integrated Computational Materials Engineering (ICME) modeling, microstructural validation
- **Post test material characterization:**
  - Microstructural characterization: electron backscatter diffraction (EBSD)
  - Porosity/density



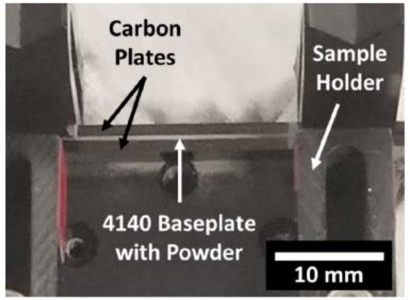
APS Beamline 32-ID-B & 1-ID

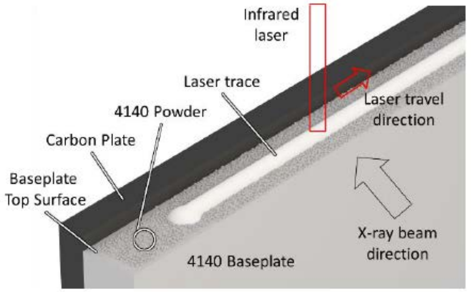


Gould, Wolff, et al. In-Situ Study of laser powder bed fusion using simultaneous high speed infra-red and X-ray imaging, JOM

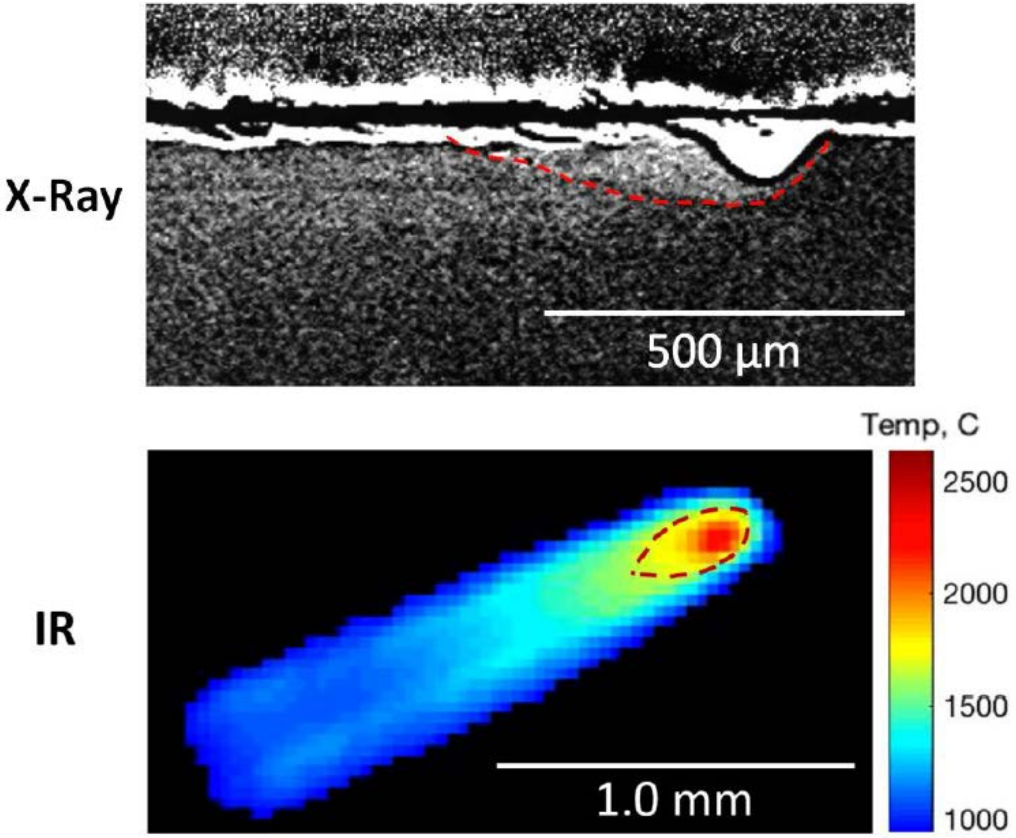
APPROACH

In-situ Experiments





2mm Laser Scans on Shim



- Simulating laser powder bed fusion (LPBF) metal AM
- Simultaneous IR and x-ray collection
- IR calibration and melt pool identification
  - Matching melt pool geometry with x-ray images to fit the correct melt pool boundary temperatures

Bobel, A. et al, "In-situ X-ray, IR, and Diffraction Measurements of Automotive Grade Steel During Laser Powder Bed Fusion", TMS 2020 invited talk

PROJECT MILESTONES

Task Number & Brief Description	Year 1 (Alloy set #1)				Year 2 (Alloys set #2)			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Task 1: Sample preparation	■	■			■	■		
Task 2: *In-situ* LPBF experiments	■	■	■		■	■	■	
Task 3: Experiment data processing/analysis		■	■	■		■	■	■
Task 4: Post experiment sample analysis			■	■			■	■

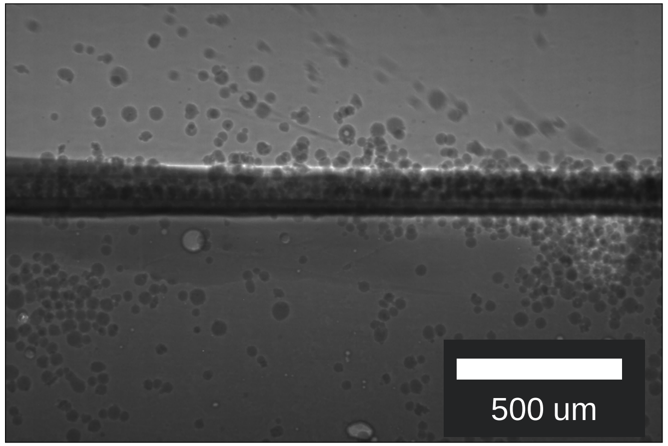
Milestones/Deliverables:	
Milestone 1:	Complete sample preparation for in-situ experiments for Alloy Set #1 (complete by end of Year 1 Q2, ANL and GM), **Completed**
Milestone 2:	Complete in-situ experiments and data collection for Alloy Set #1 (complete by end of Year 1 Q3, ANL), **Completed**
Milestone 3:	Complete data processing and posttest sample analysis for Alloy Set #1 (complete by end of Year 1 Q4, ANL and GM). Prepare report with GM. **75% complete**
Milestone 4:	Complete sample preparation for in-situ experiments for Alloy Set #2 (complete by end of Year 2 Q2, ANL and GM)
Milestone 5:	Complete in-situ experiments and data collection for Alloy Set #2 (complete by end of Year 2 Q3, ANL)
Milestone 6:	Complete data processing and posttest sample analysis for Alloy Set #2 (complete by end of Year 2 Q4, ANL and GM)
Milestone 7:	Derive quantitative relationships between LPBF processing parameters and probability of defect formation for the two alloy sets (end of project milestone, ANL and GM). Prepare report with GM.

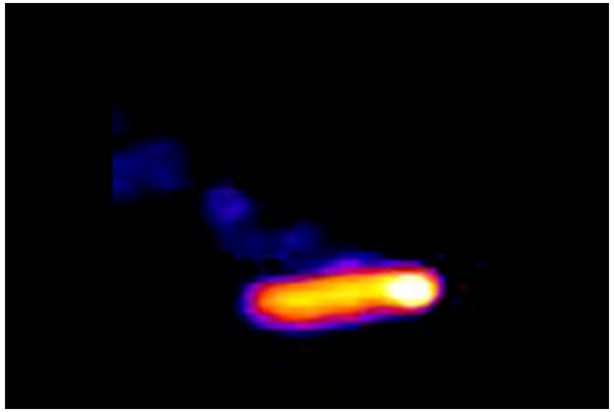
TECHNICAL ACCOMPLISHMENTS

- Alloys: AlTi, AlSiCu, FeCu, Fe393
- In-Situ experiments - *complete*
  - (106 experiments – 32 hrs beam time)
- IR thermal analysis - *complete*
- Diffraction measurements – *next beam cycle*
- Modeling – *started*
- Microstructural analysis – *complete on FeCu*

- Highlights:
  - Oxide vaporization porosity formation Al
  - Correlation IR and porosity

Materials Tested	Laser Power Tested (W)	Laser Scan Speeds Tested (mm/s)
AlTi (on printed substrate)	260, 302, 395, 520	300, 800, 1000, 1300, 1600
AlTi (on cast substrate)	302, 520	300, 800, 1000, 1300
AlSiCu (on printed substrate)	260, 364, 520	800, 1300, 1400, 1600, 2000
FeCu (on printed substrate)	213, 348	190, 300, 400, 500
Fe393 (on printed sustrate)	213, 348	300, 400, 700

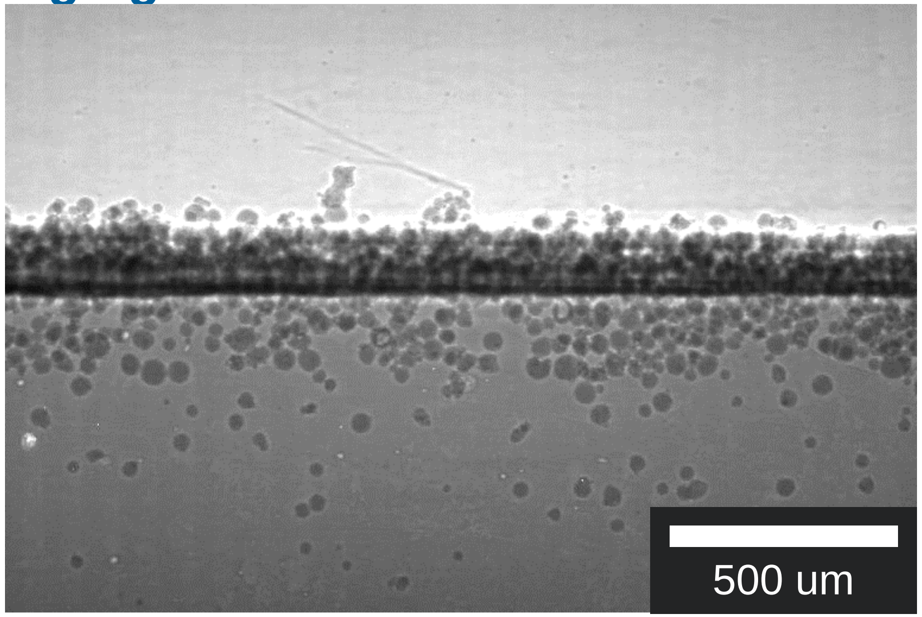


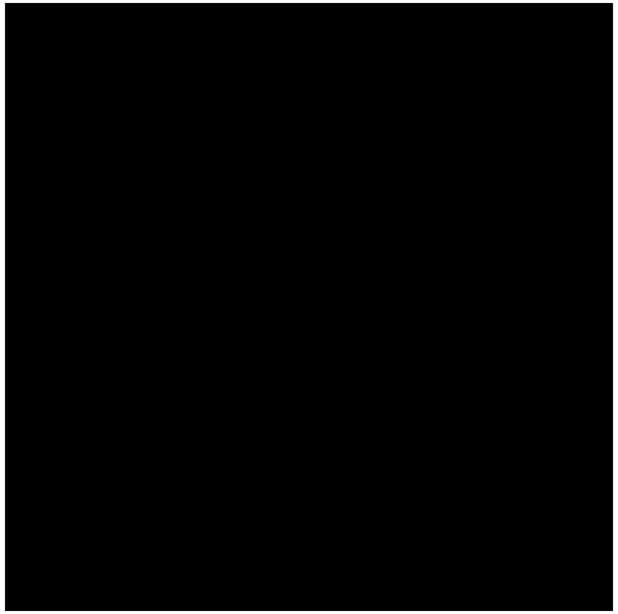


TECHNICAL PROGRESS

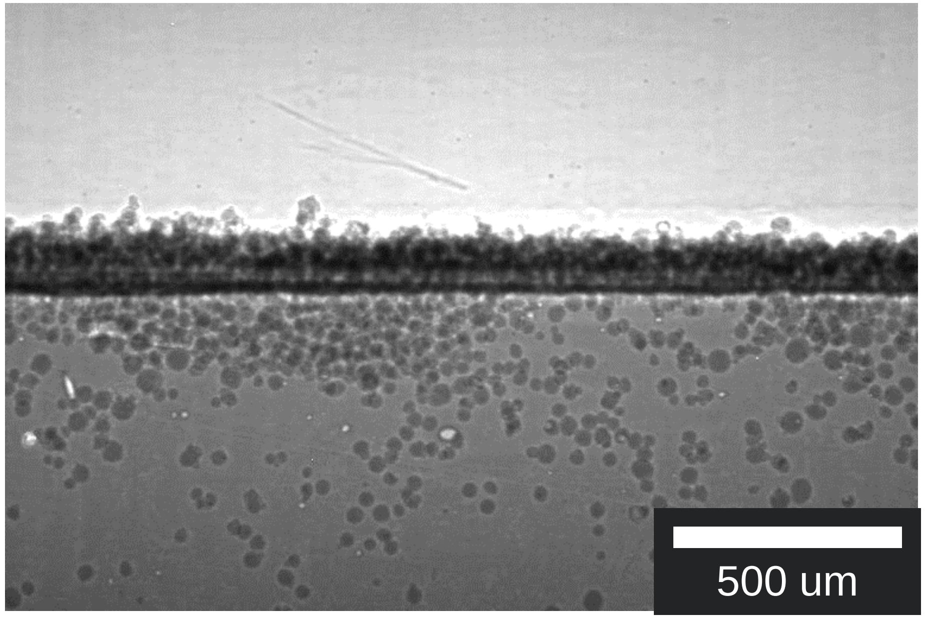
FeCu – X-ray and IR imaging

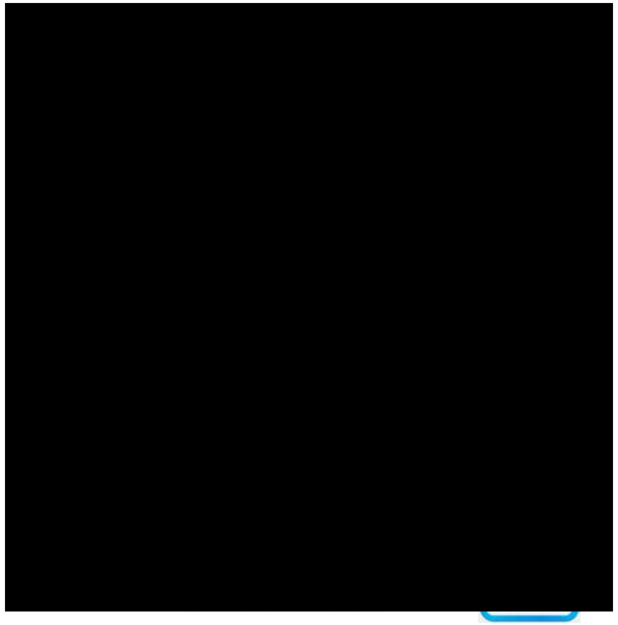
- High Energy (Exp72)





- Low Energy (Exp 74)

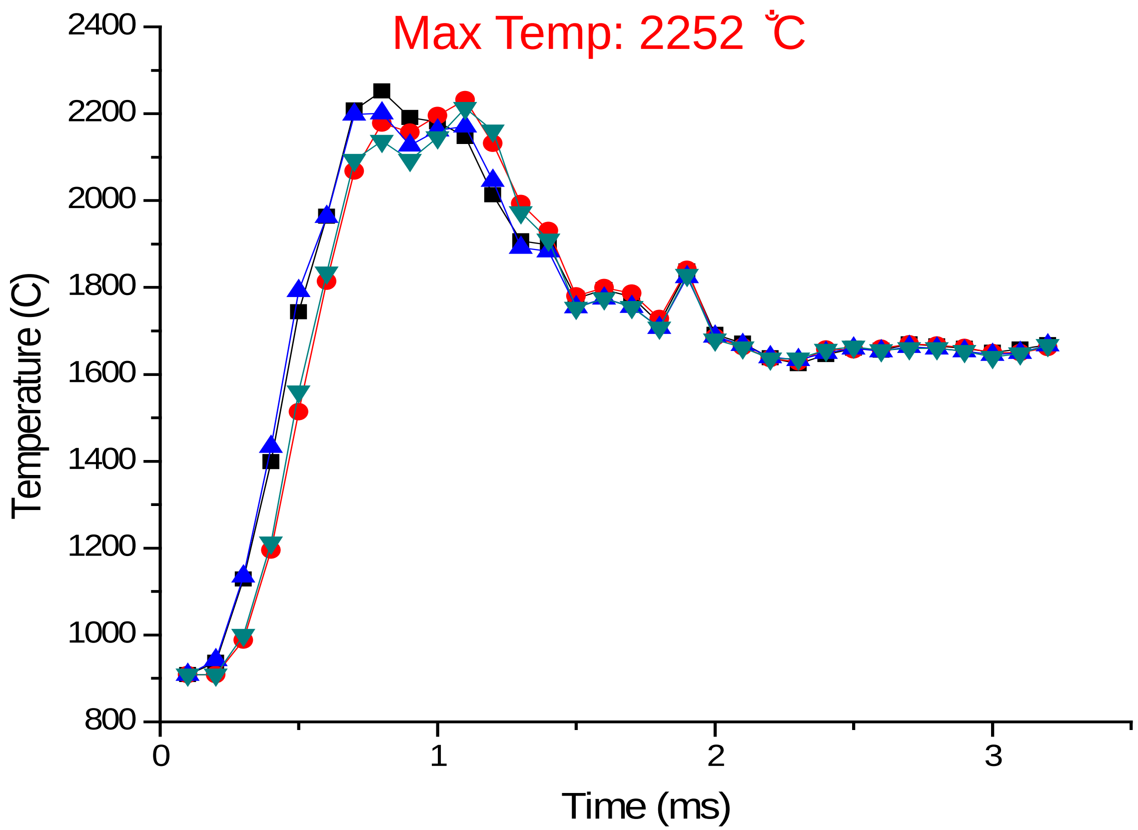


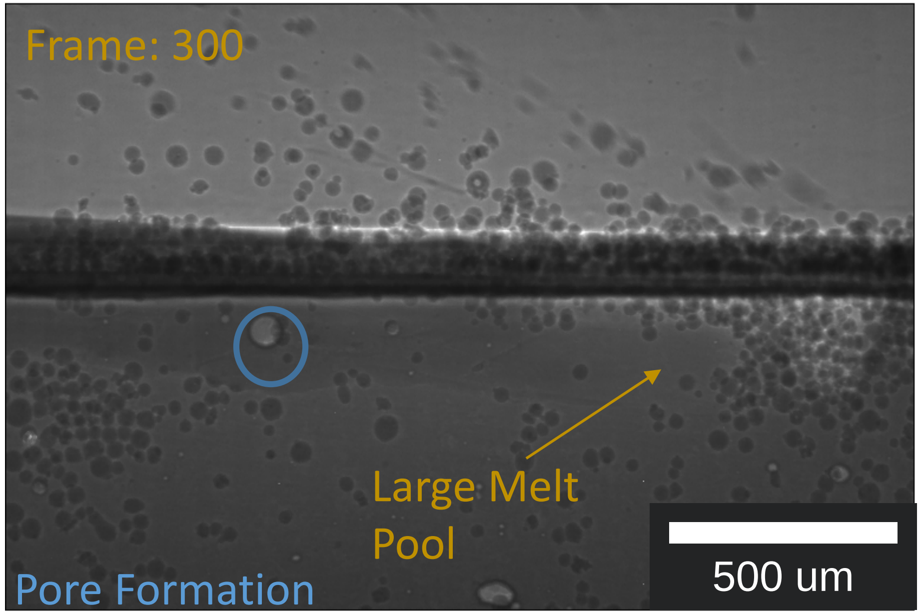


TECHNICAL PROGRESS

FeCu – Thermal Analysis (Pore formation)

Calibrated IR temperature measurements @ center of scan





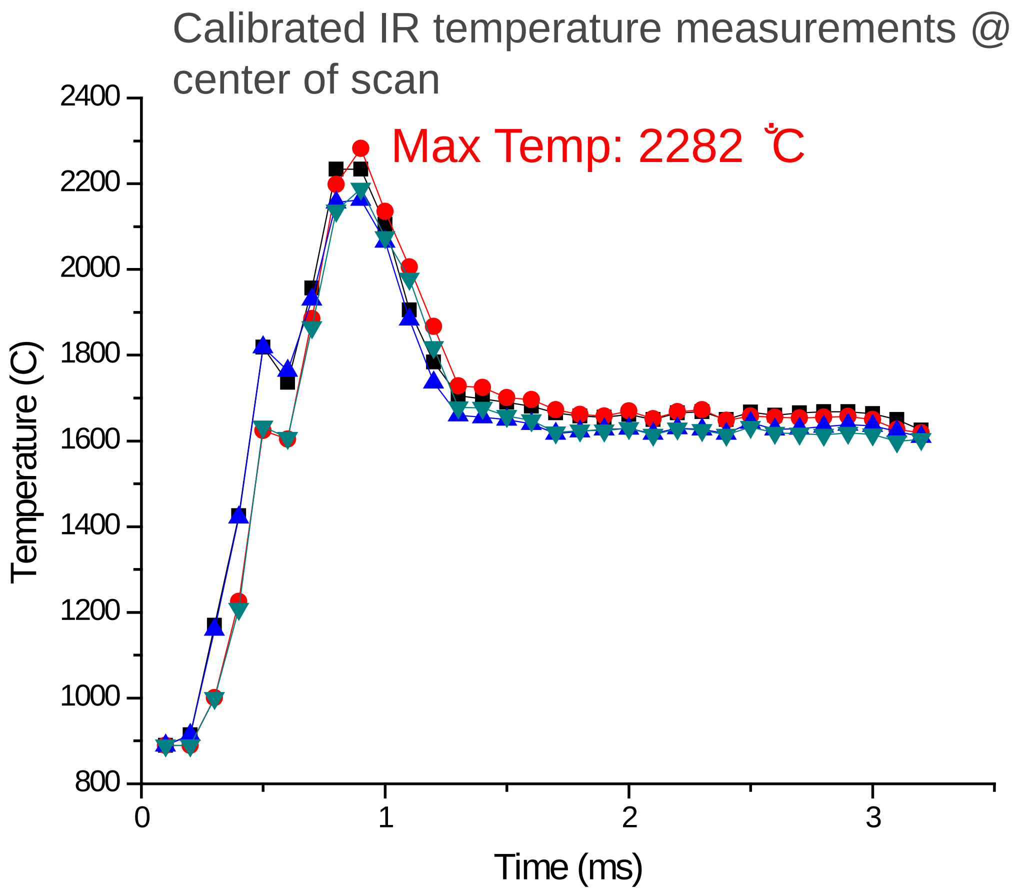
Laser Power: 350 W

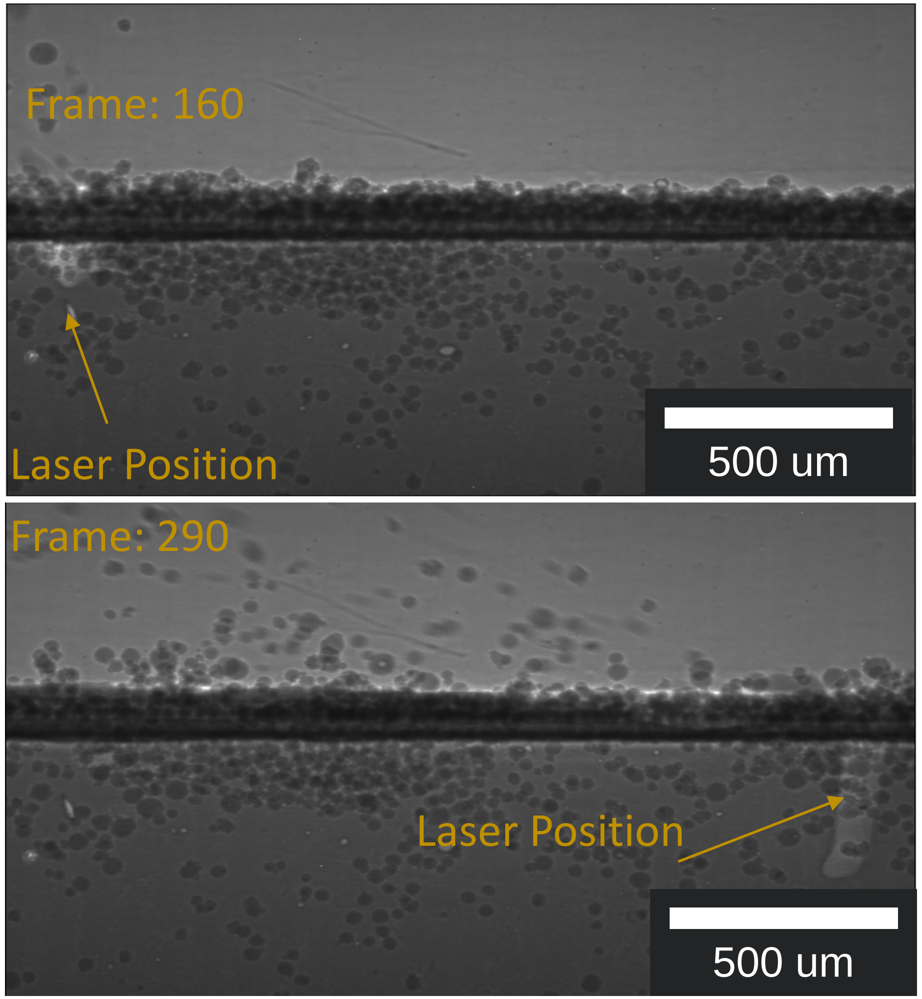
Scan Speed: 400mm/s

LightMAT Lightweight Materials Consortium gm Argonne NATIONAL LABORATORY

TECHNICAL PROGRESS

FeCu – Thermal Analysis (No Pore Formation)





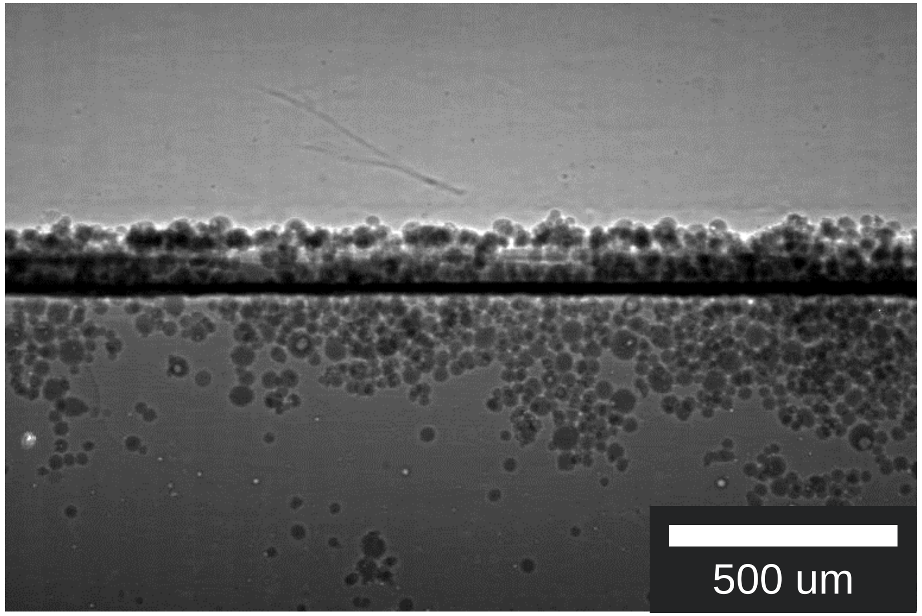
Laser Power: 350W

Scan Speed: 500mm/s

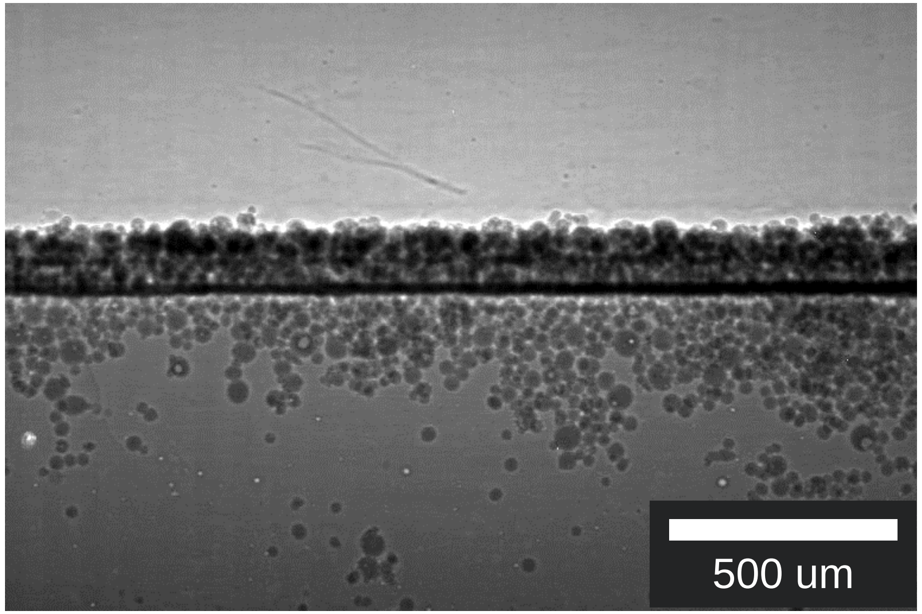
TECHNICAL PROGRESS

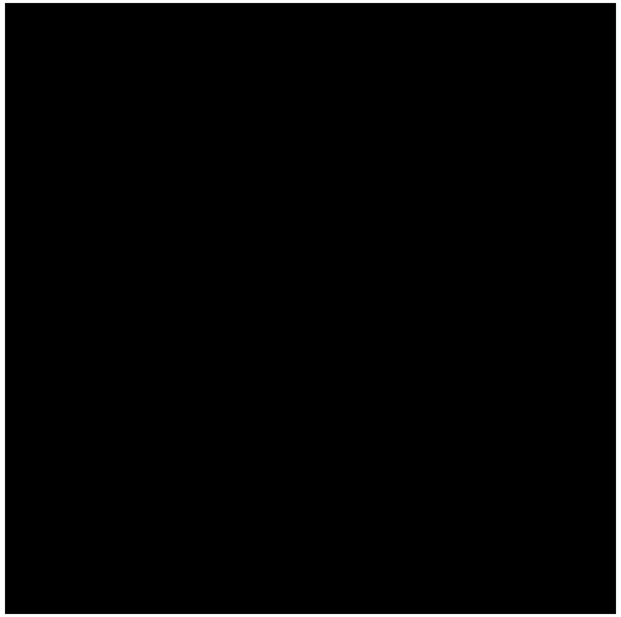
Fe393 – X-ray and IR imaging

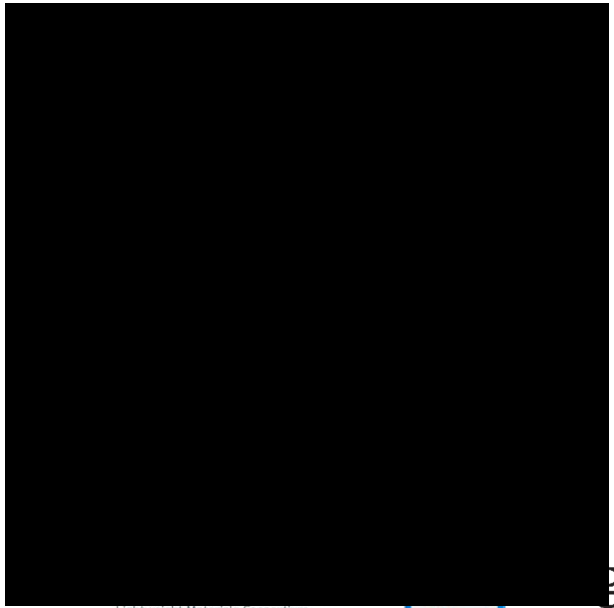
High energy (52)



Low energy (51)



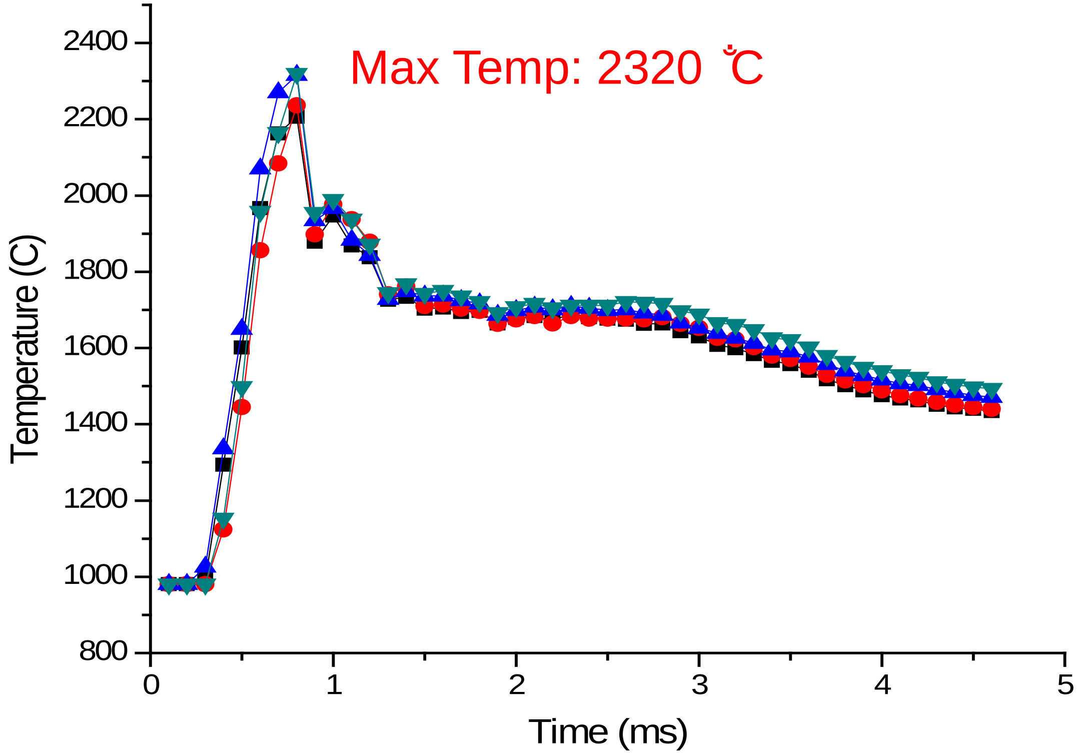


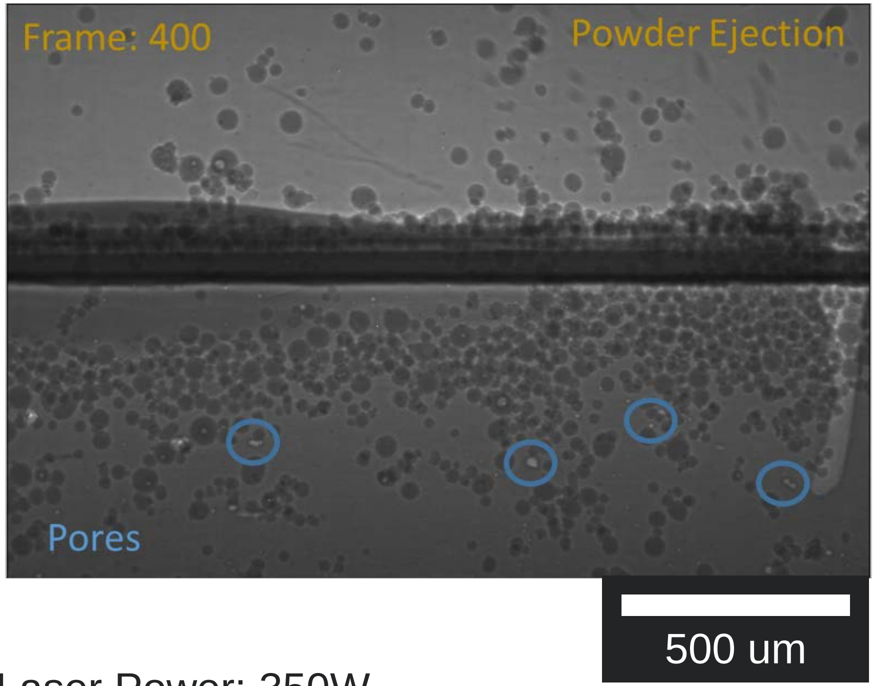


TECHNICAL PROGRESS

Fe393 – Thermal Analysis (Pore formation)

Calibrated IR temperature measurements @ center of scan





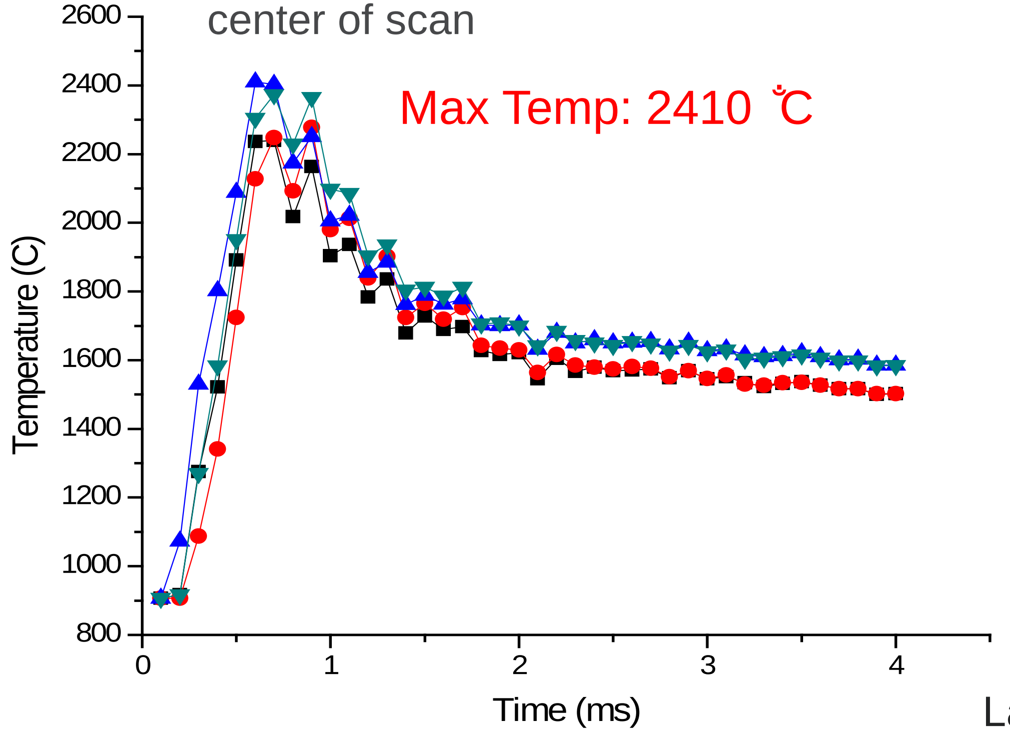
Laser Power: 350W

Scan Speed: 300 mm/s

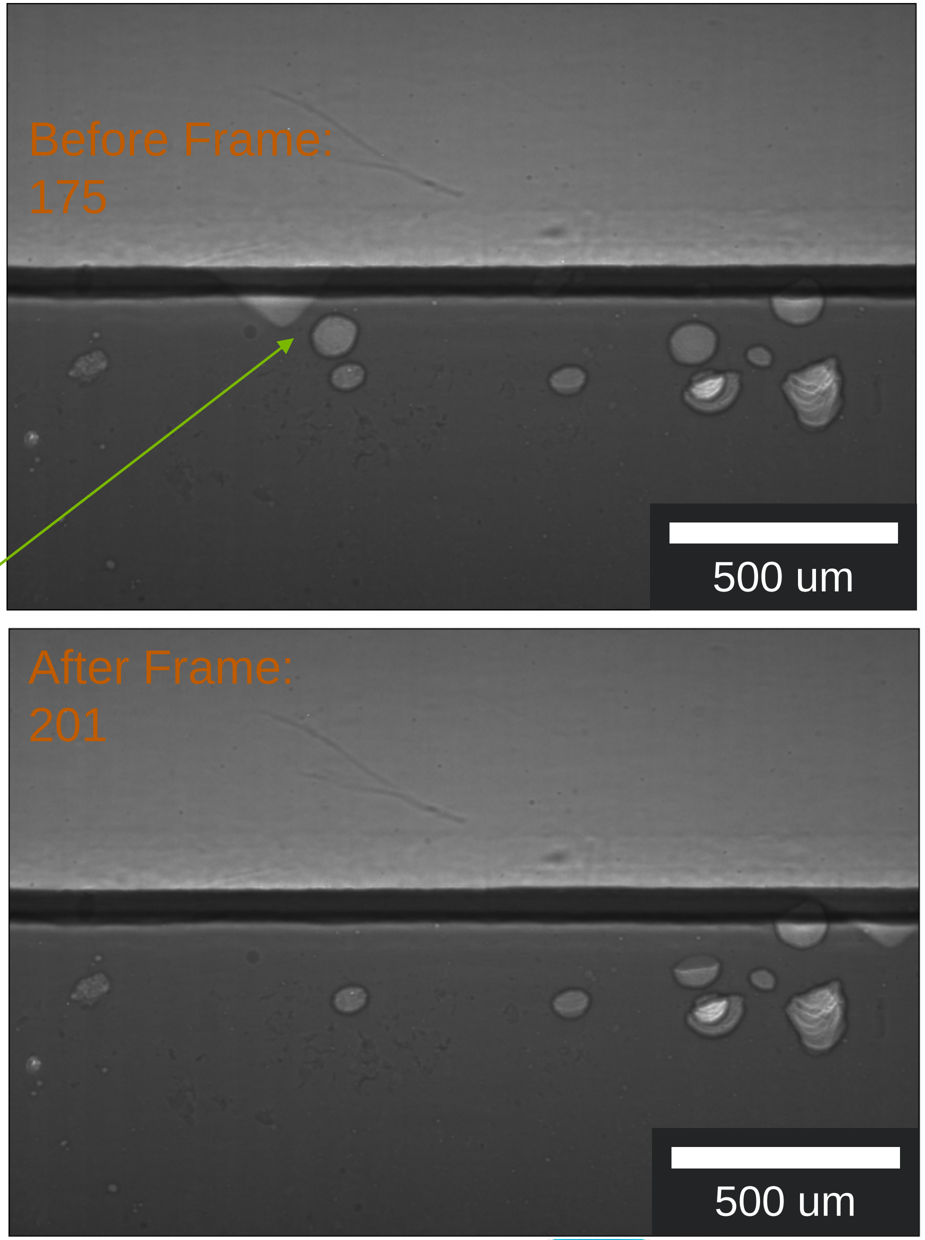
TECHNICAL PROGRESS

Fe393 – Thermal Analysis (No Pore Formation)

Calibrated IR temperature measurements @ center of scan



Pore removal after laser passes through substrate.

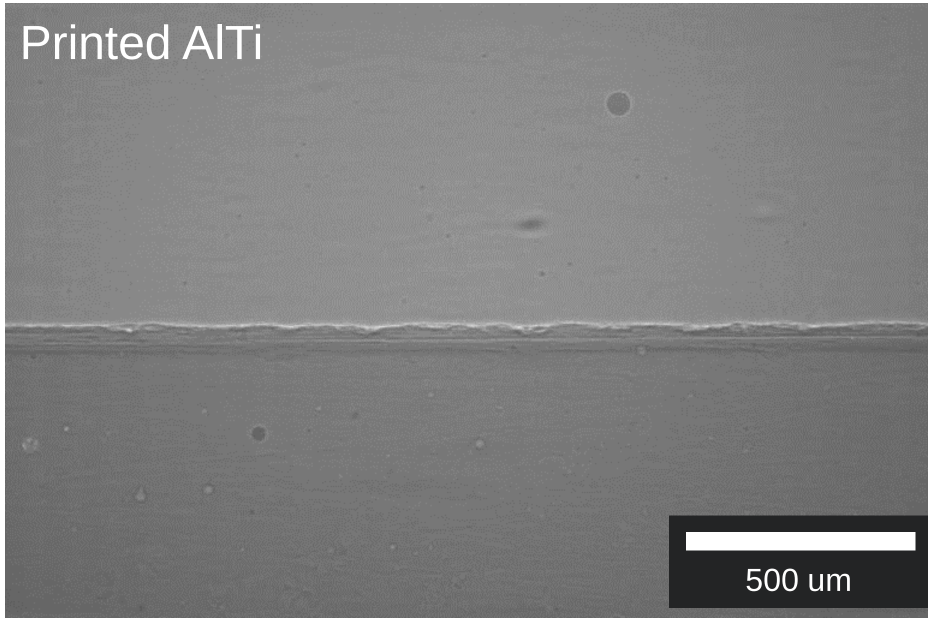


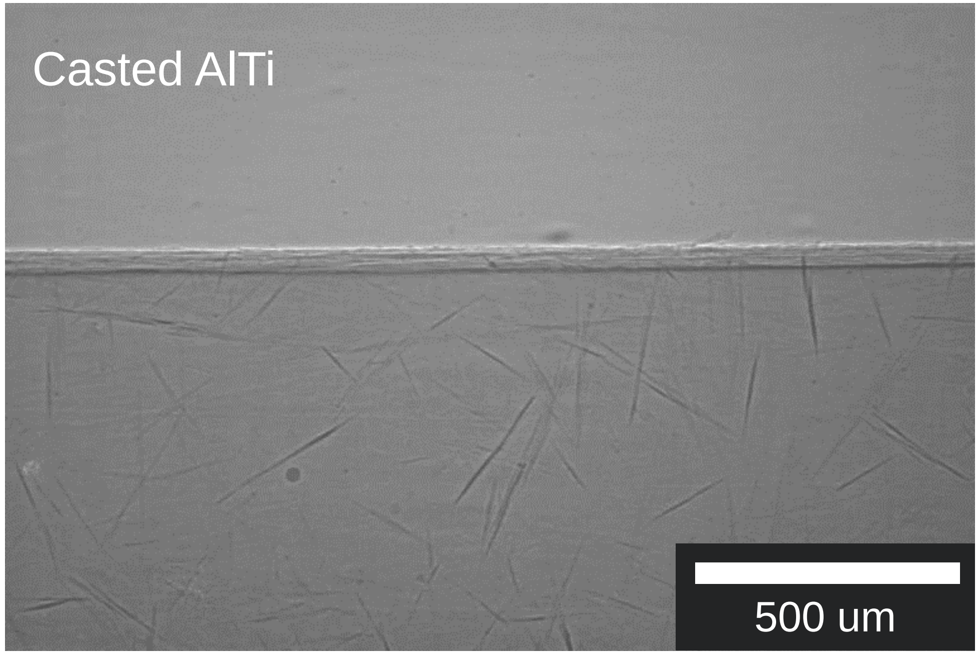
Laser Power: 350W

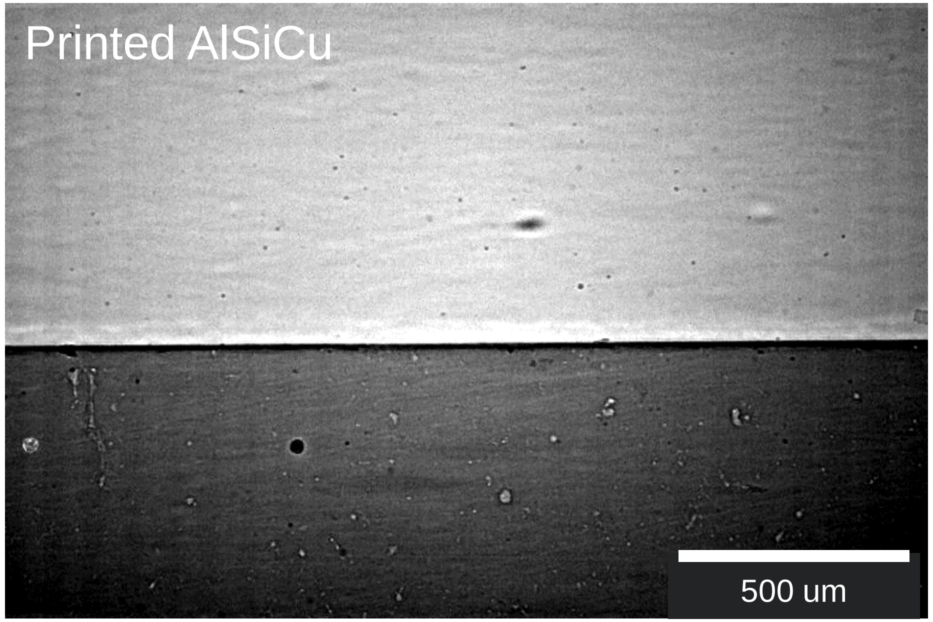
Scan Speed: 700mm/s

TECHNICAL PROGRESS

Porosity Formation in Aluminum Alloys
Casted vs Printed







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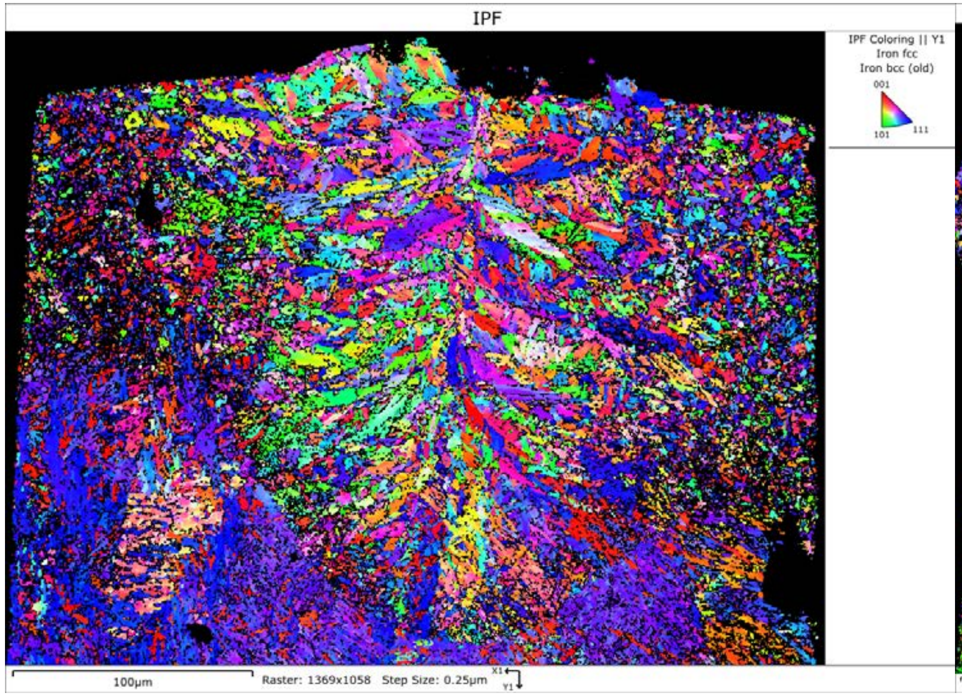
TECHNICAL PROGRESS

Microstructural Analysis

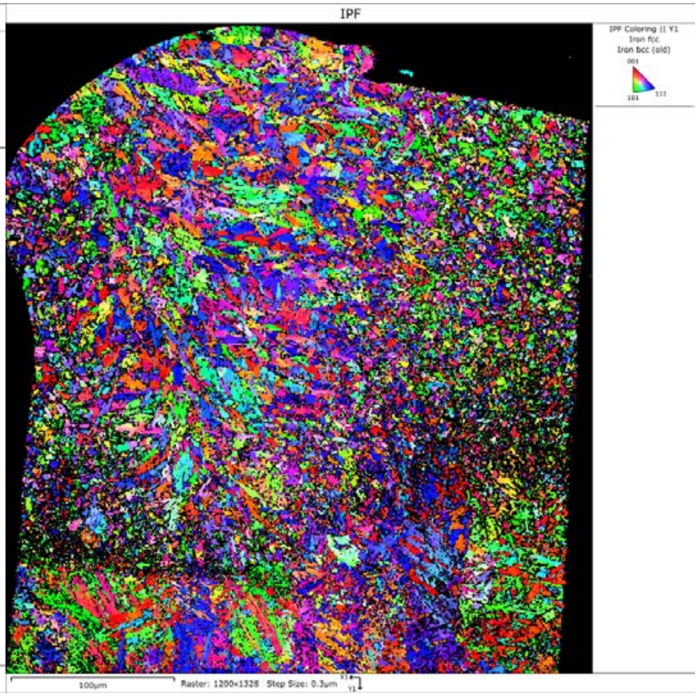
- Electron backscatter diffraction (EBSD) analysis was performed on the printed samples (FeCu samples complete to date)
- More microstructural anisotropy observed in low energy density test as compared to high energy density conditions

Parameter Set	Spot Size (µm)	Power (W)	Speed (mm/s)	SED (J/mm²)
FeCu High	80	350	300	14.6
FeCu Mid	80	350	400	10.9
FeCu Low	80	350	500	8.75
FeCu Slow	80	200	190	13.2

FeCu Low



FeCu High



COLLABORATION WITH PARTNER

- GM Research & Development
  - CRADA partner
  - Provides alloy powders and shim samples
  - Participates in experiments at Argonne APS
  - Thermal modeling to predict porosity risk
  - ICME modeling for microstructural validation
  - Microstructural analysis of samples post-test (EBSD and optical)
  - Co-author journal articles and conference presentations

REMAINING CHALLENGES AND SCHEDULING ISSUES

- Technical challenges:
  - Establish relation between AM machine processing parameters and parameters used in in-situ experiments
- Scheduling issues:
  - Argonne/APS
    - APS access limitations due to COVID19, subject to DOE guidance
    - Beam time for in-situ experiments has been granted and request are submitted for summer cycle
  - GM
    - Limited access to microstructural analysis lab
    - Staff on rotations till July
    - Next alloy set samples are delayed (making shims)

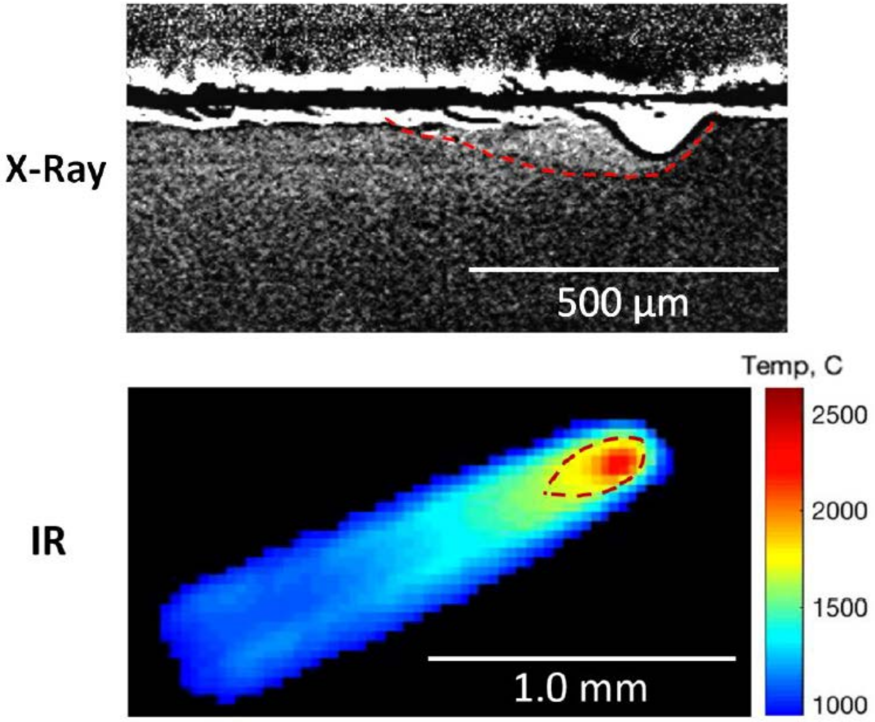
FOLLOW-ON RESEARCH

- Perform in-situ experiments and post test analysis for alloy set #2
- Complete simulations of the parameter set/alloy combinations using thermal model
- Perform in-situ x-ray diffraction experiments and correlate with ICME modeling
- Complete correlation of in-situ experiments to AM printer parameters aided by thermal model
- Derive quantitative relationship between AM print parameters to probability of defect formation for the studied alloys

Any proposed future work is subject to change based on funding levels

SUMMARY

- Demonstrated that advanced high energy x-ray in-situ experimentation is a useful tool for accelerating the development of advanced alloy for additive manufacturing
- Completed analysis for Fe-based alloys, identified processing parameters that related to defect formation
- Aluminum-based alloys exhibit unanticipated result of secondary porosity formation, possibly due to vaporization of trapped oxides



TECHNICAL BACKUP SLIDES

4140 CASE STUDY

Experimental Conditions

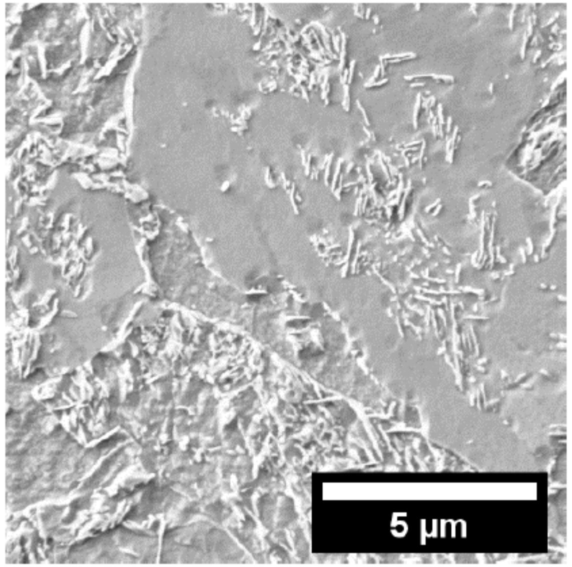
4140 Powder: Fe-0.4C-1.1Cr-0.86Mn-0.26Si-0.19Mo wt%

Baseplates/shims from conventional bar stock primarily **ferrite-bainite** microstructure

Parameter Set	Spot Size (µm)	Power (W)	Scan Speed (mm/s)	SED (J/mm)
Fill	100	250	500	5.0
Fill 1.5x	100	374	750	5.0
High Energy	100	364	500	7.3
Keyhole	80	208	300	8.7

$$\text{Specific Energy Density}\left[\frac{J}{mm^2}\right] = \frac{Power\,[W]}{Speed\,[mm/s] * \; Spot\ Size\,[mm]}$$

4140 Baseplate/Shim

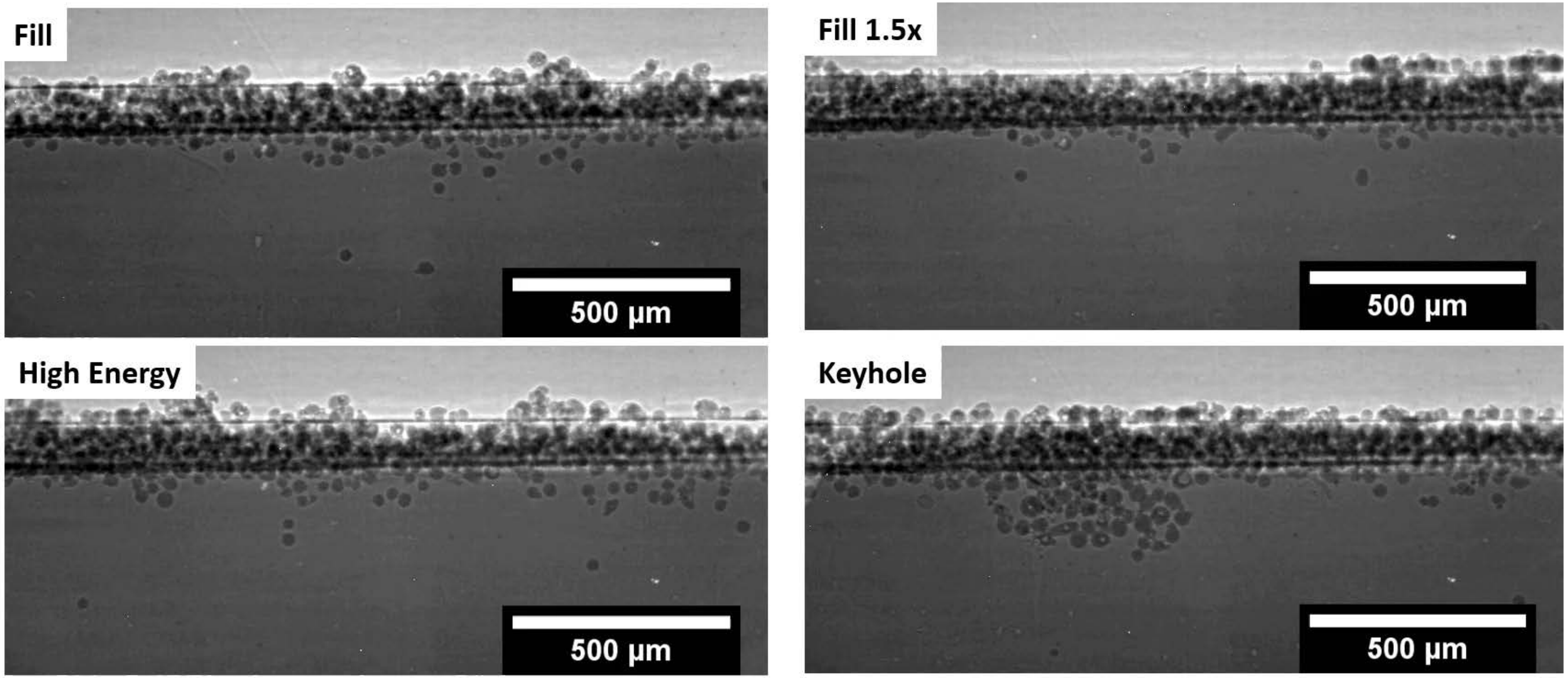


Bobel, A. et al, “In-situ X-ray, IR, and Diffraction Measurements of Automotive Grade Steel During Laser Powder Bed Fusion”, TMS 2020 invited talk

4140 CASE STUDY

X-ray imaging of porosity

4140 X-ray Imaging



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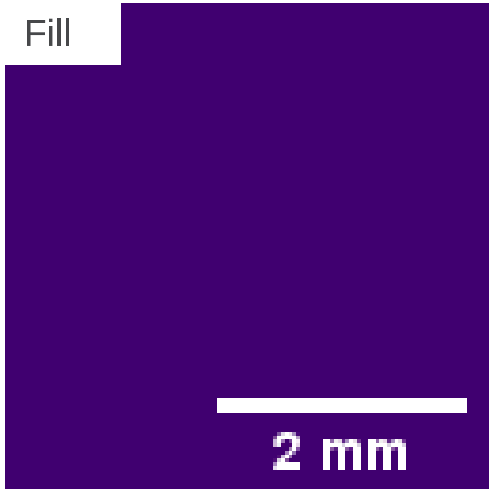
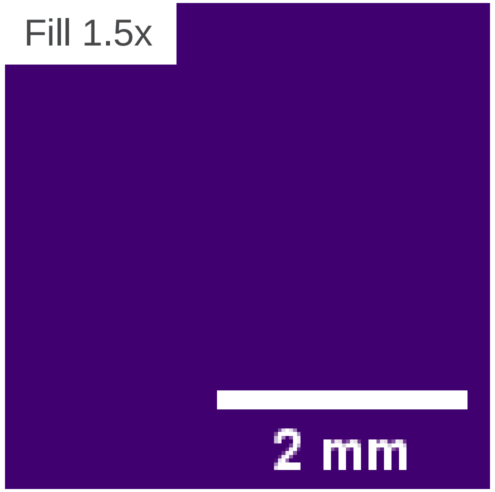
4140 CASE STUDY

IR thermal maps

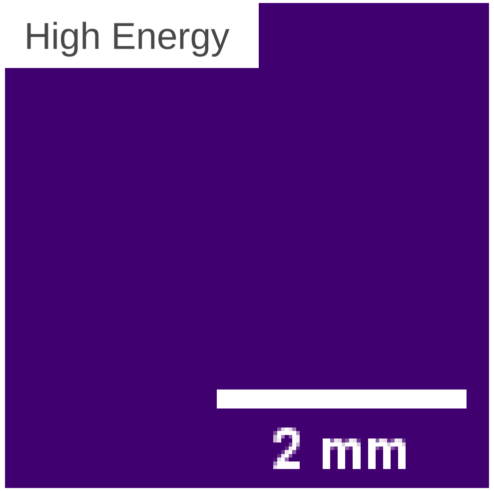
Fill



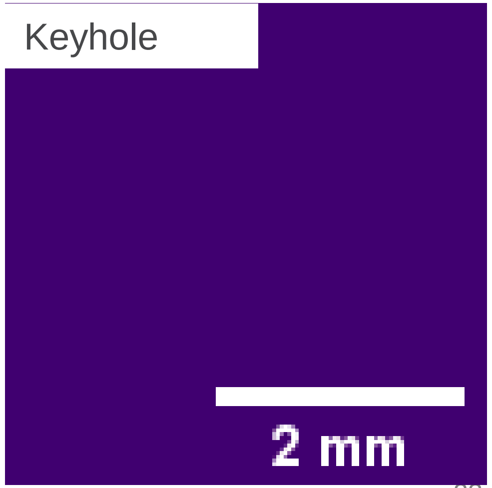
Fill 1.5x

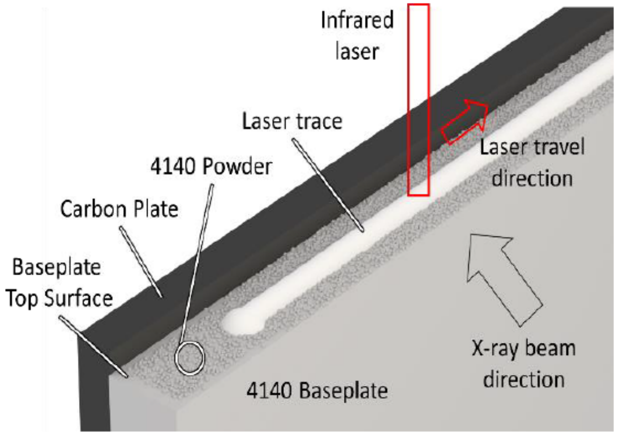


High Energy



Keyhole





Parameter Set	Spot Size (µm)	Power (W)	Scan Speed (mm/s)	SED (J/mm)
Fill	100	250	500	5.0
Fill 1.5x	100	374	750	5.0
HE	100	364	500	7.3
Key	80	208	300	8.7

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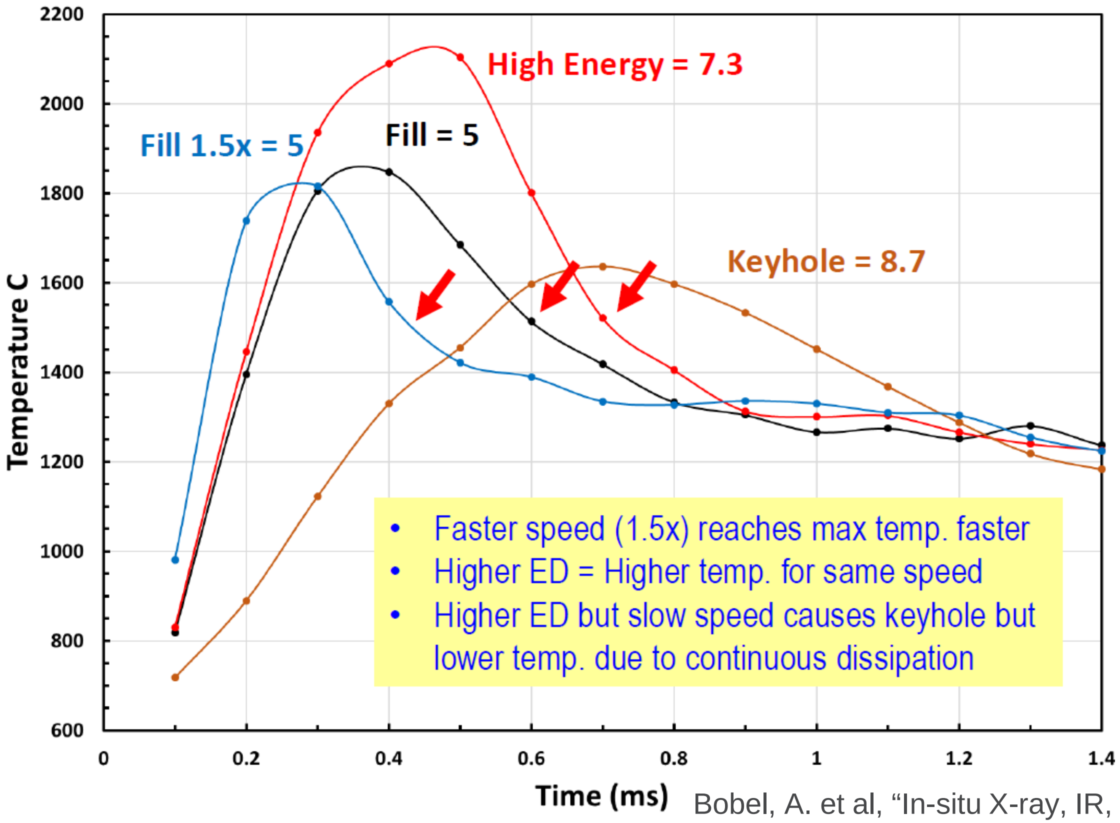
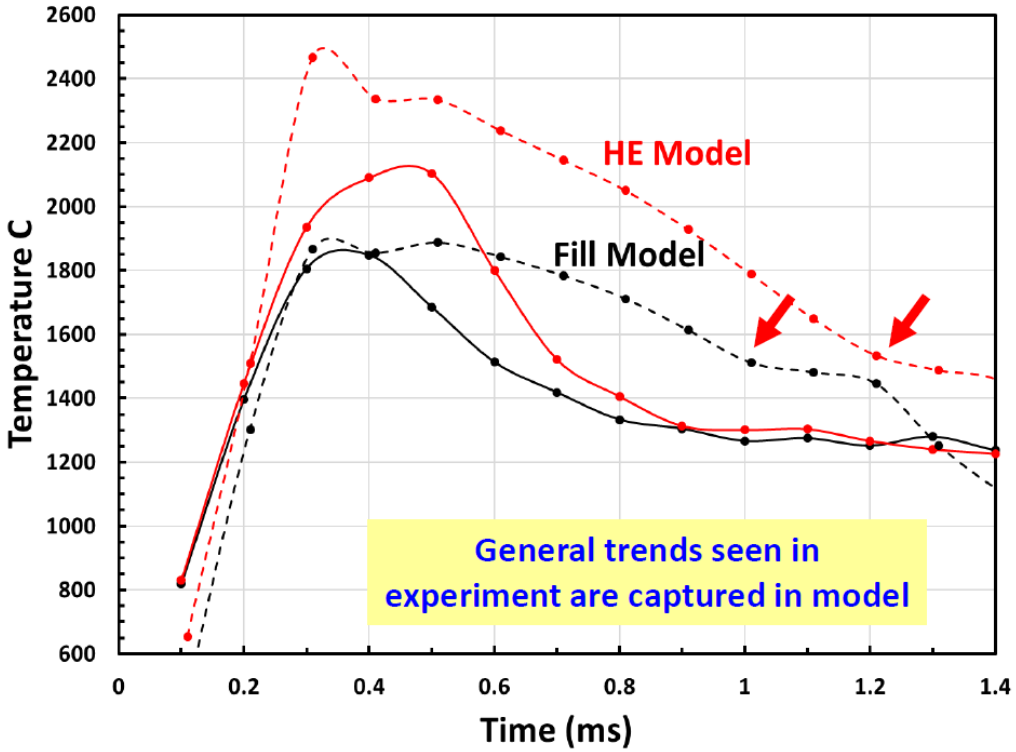
4140 CASE STUDY

Temperature plot and comparison to model



Only using input from melt pool geometry for Fill parameter



Bobel, A. et al, “In-situ X-ray, IR, and Diffraction Measurements of Automotive Grade Steel During Laser Powder Bed Fusion”, TMS 2020 invited talk

HOT CRACKING CASE STUDY

Aluminum 6061