Advanced Methods for Manufacturing

DEC 2 – 3, 2020

Laser Additive Manufacturing of Grade 91 Steel for Affordable Nuclear Reactor Components

Award Number: 19-17206

Award Dates: 9/2019 – 9/2022

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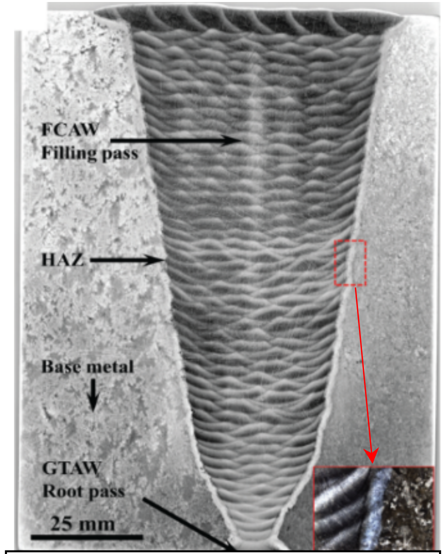
Team Members: Dr. Tom Lienert- Optomec Inc., Prof. Tarasankar DebRoy- Penn State U., Prof. Peter Hosemann- UC Berkeley

Project Objectives

- The primary objective of this project is to develop a *method and process model* that provides *in-situ tempering* of a *Grade 91* (Gr 91) steel, a radiation tolerant steel, during *laser additive manufacturing* (LAM).
- A second objective will involve *fabrication* of a subscale *grid spacer* prototype for fast reactors using LAM.

Background

- Modified 9Cr–1Mo–V–Nb steel is a 2nd generation creep-resistant F/M steel with 9% Cr, 1% Mo, 0.1 C with V & Nb.
- To produce the desired combination of strength, ductility, creep resistance and radiation tolerance required for service, the *Martensite in Gr 91 weldments must be tempered*.
- To optimize the properties in reactor applications where post-weld heat treatment is not practical, *special welding techniques such as the temper bead method* may be used.
- We propose that LAM can be used to fabricate reactor components of Gr 91 with *engineered microstructures* that provide *equal or improved properties* relative to wrought components.
- Moreover, we propose that LAM parameters *can be tailored to provide effective in-situ tempering during deposition*, *like with temper bead welding*. Precludes the need for post-fabrication heat-treatment (*greater affordability*).

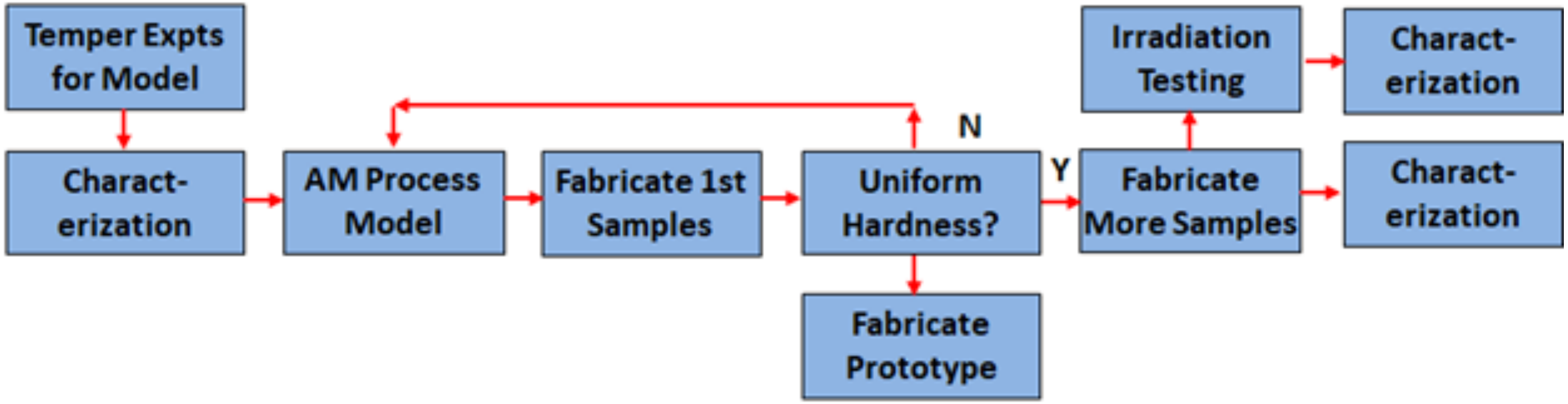


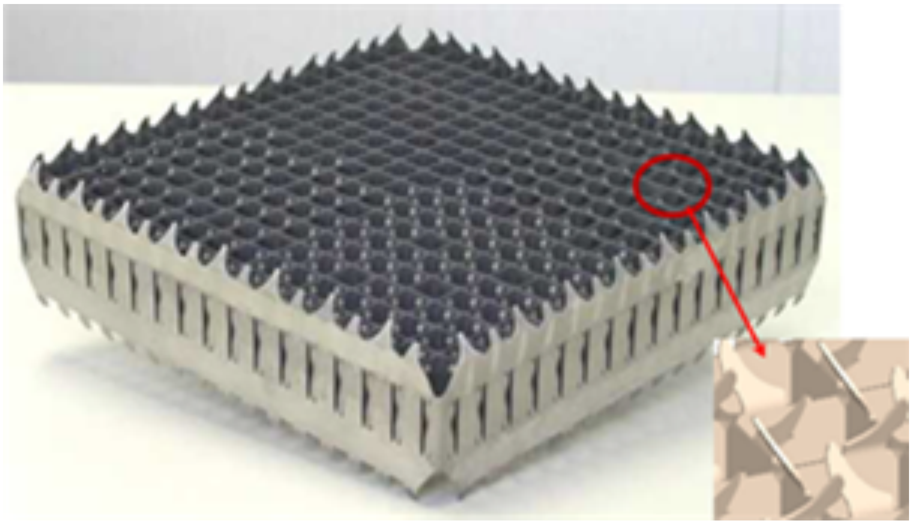
Macrograph showing structures of temper beads in multi-pass arc welded component.

Project Plan

- LAM Process Model including in-situ tempering model using *Johnson-Mehl-Avrami* (JMA) framework.
- Isothermal Tempering Studies will be conducted on wrought samples to *allow calibration* of the JMA equation.
- LAM Processing using an IR camera & beam profiling data as inputs to the process and tempering models.
- Mechanical Testing with large scale & micro-scale samples of LAM Gr 91 in as-deposited and irradiated conditions.
- Irradiation Testing (Fe^{2+}(high dose) & proton(low dose)) initial information on the radiation tolerance of the LAM produced Gr 91.
- Microstructural Characterization OM, SEM, EBSD & TEM/STEM: (a) morphology, location, volume fraction, composition and crystal structure of the various phases; and (b) presence and density of radiation-induced defects such as dislocations, vacancies and clusters

Project Plan – Flow Chart





Grid Spacer

Project Gantt Chart

Task	Resource	FY 20				FY21				FY 22			
Year 1		Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Complete Sub-Contracts	LANL	■											
Order Gr 91 Powder and Materials	Optomec	■											
Kickoff Meeting	All	■											
Temper Experiments for Model Calibration	LANL, UCB	■											
Initial Characterization of Temper Samples (LOM & hardness)	LANL, UCB		■										
Process Modeling-Use Results of Experiments	PSU	■	■	■									
Fabricate 1st set of samples using calibrated model	Optomec				■								
Year 2													
Initial Characterization of samples (Is hardness uniform?)	LANL, UCB					■							
Validate/Modify Model using Characterization Results	PSU					■	■						
Fabricate Samples for Testing	Optomec							■					
Full Characterization of validation samples (Non Rad)	LANL, UCB								■	■	■		
Irradiation Studies	LANL								■	■			
Year 3													
Full Characterization of validation samples (Rad)	LANL, UCB										■	■	■
Fab & test micro-samples	UCB										■	■	■

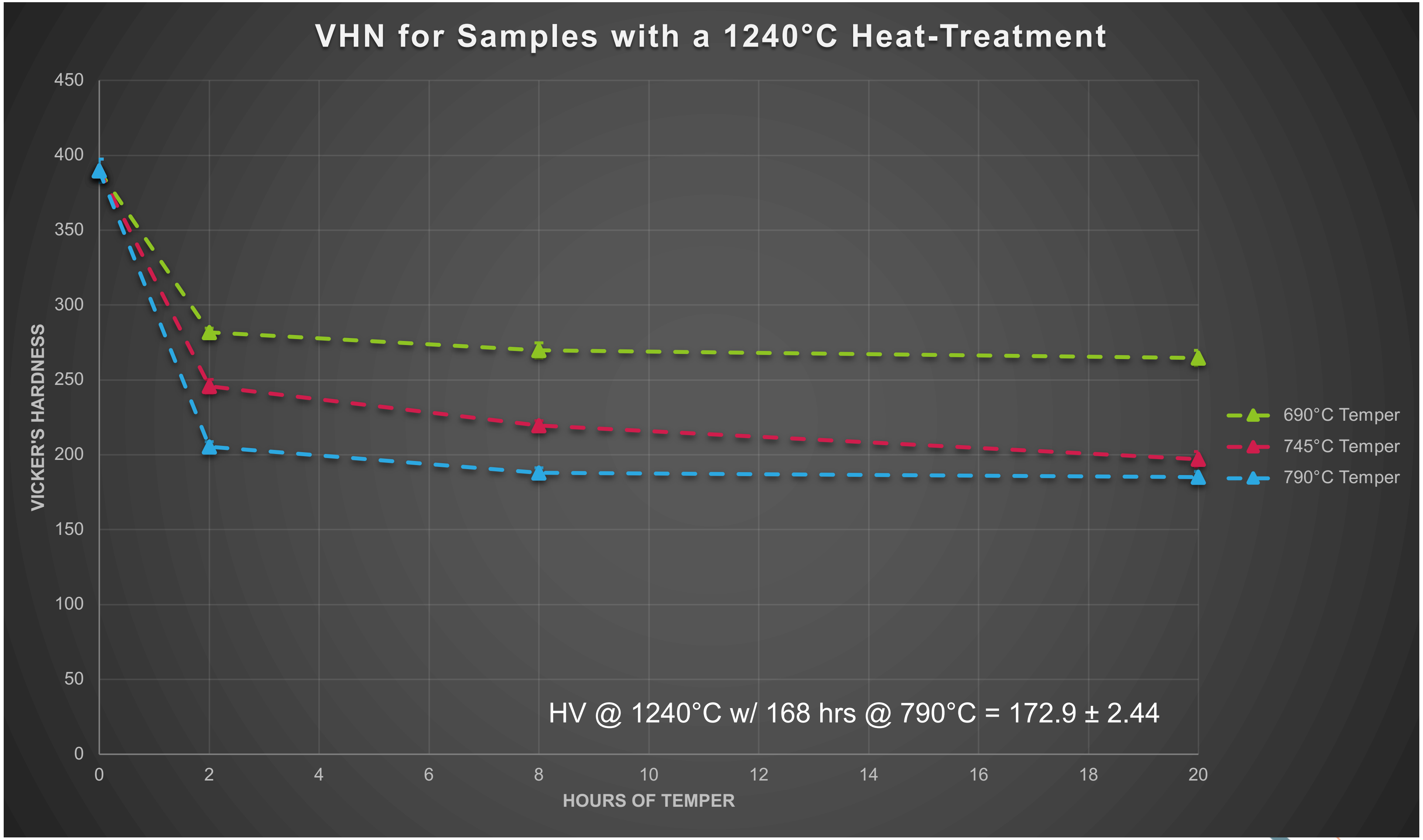
Technical Progress/Accomplishments

- Temper Experiments completed on Grade 91 samples with range of normalization temperatures and tempering times.
- Data is being used for Model Development
- Powders of Grade 91 ferritic/martensitic steel were obtained
- Initial Fabrication of samples was performed using DED-L at Optomec Inc.
  - Characterization is underway

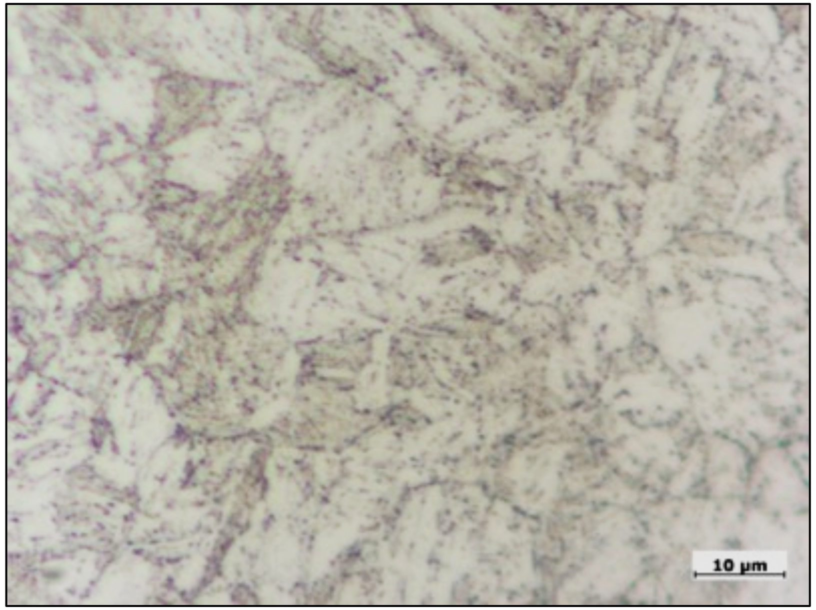
Summary of Temper Experiments

Vicker's Hardness					
HV @ 1040°C Heat-treat					
	0 hrs	**2 hrs**	**8 hrs**	**20 hrs**	**168 hrs**
690°C	352.3 ± 23.70	271.1 ± 4.94	247.7 ± 5.74	223.7 ± 11.36	--
745°C	352.3 ± 23.70	202.0 ± 16.50	187.5 ± 6.77	185.2 ± 15.18	--
790°C	352.3 ± 23.70	192.1 ± 3.33	180.4 ± 3.38	188.8 ± 3.81	160.6 ± 3.87
HV @ 1140°C Heat-treat					
	0 hrs	**2 hrs**	**8 hrs**	**20 hrs**	**168 hrs**
690°C	427.2 ± 14.95	284.2 ± 15.76	265.2 ± 4.33	261.3 ± 12.59	--
745°C	427.2 ± 14.95	244.6 ± 8.39	198.8 ± 11.33	203.4 ± 4.50	--
790°C	427.2 ± 14.95	197.0 ± 5.12	188.9 ± 4.17	167.2 ± 11.98	159.7 ± 3.51
HV @ 1240°C Heat-treat					
	0 hrs	**2 hrs**	**8 hrs**	**20 hrs**	**168 hrs**
690°C	389.7 ± 7.76	281.6 ± 2.87	269.7 ± 5.07	264.6 ± 5.05	--
745°C	389.7 ± 7.76	245.7 ± 4.61	219.7 ± 3.02	197.0 ± 5.07	--
790°C	389.7 ± 7.76	205.4 ± 3.33	187.9 ± 3.38	185.1 ± 3.81	172.9 ± 2.44

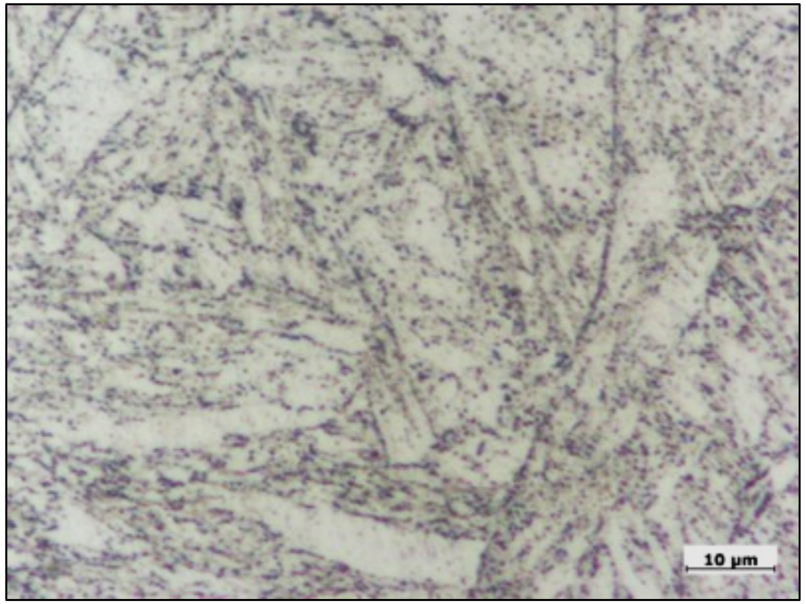
Summary of Temper Experiments



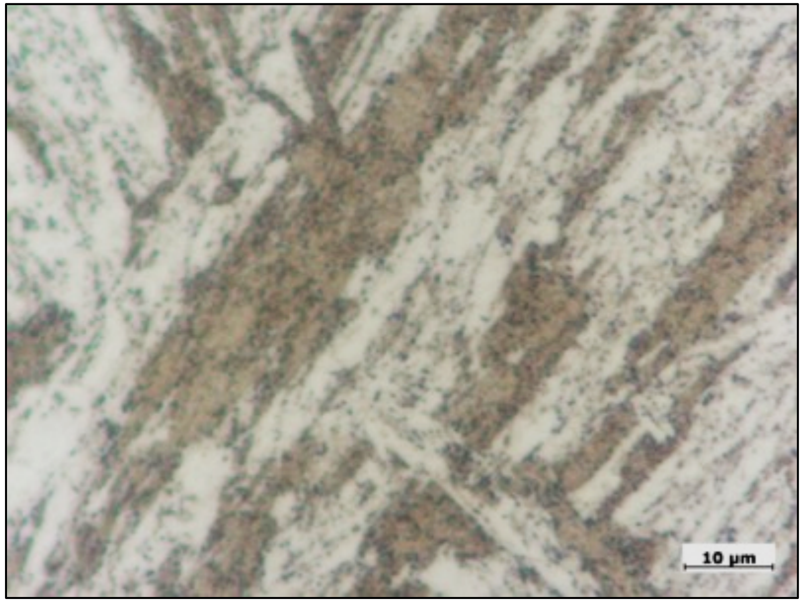
Optical Metallography for Temper Experiments



1040C Austenitize
2 hr 690C Temper

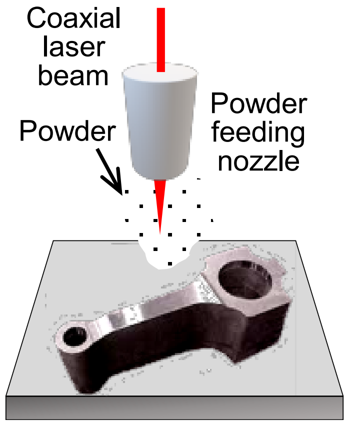


1140C Austenitize
2 hr 690C Temper



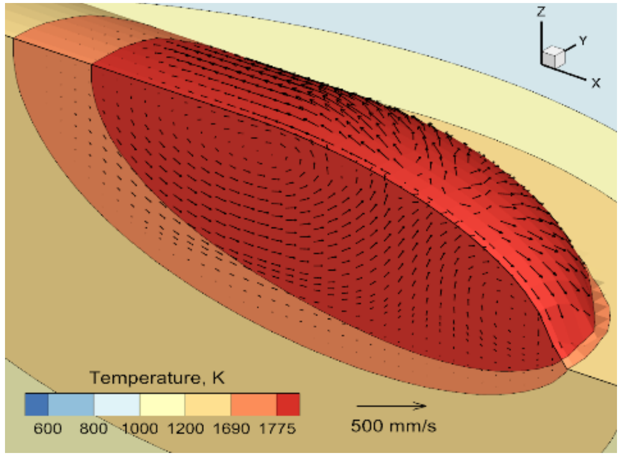
1240C Austenitize
2 hr 690C Temper

Methodology of Model Development



DED-L process

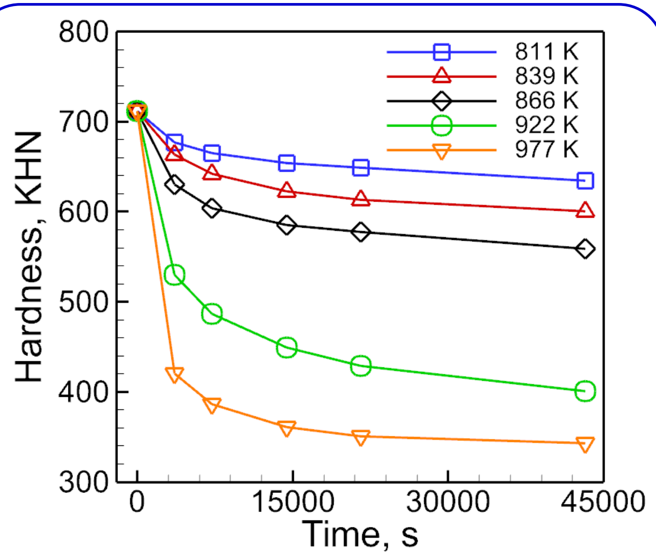
Process conditions



Heat transfer and fluid flow model

Alloy properties

Thermal cycles

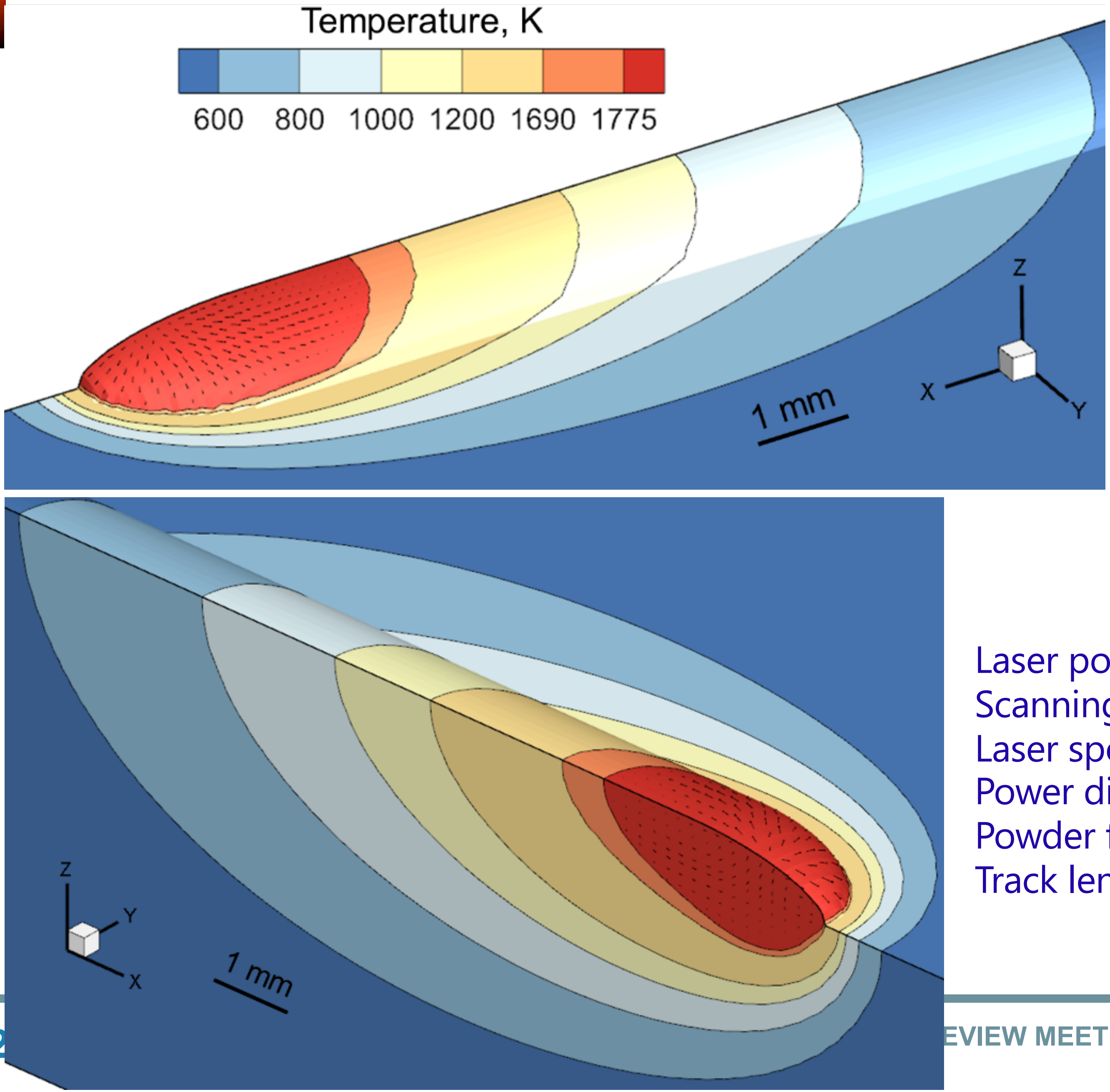


Isothermal aging data

JMA parameters

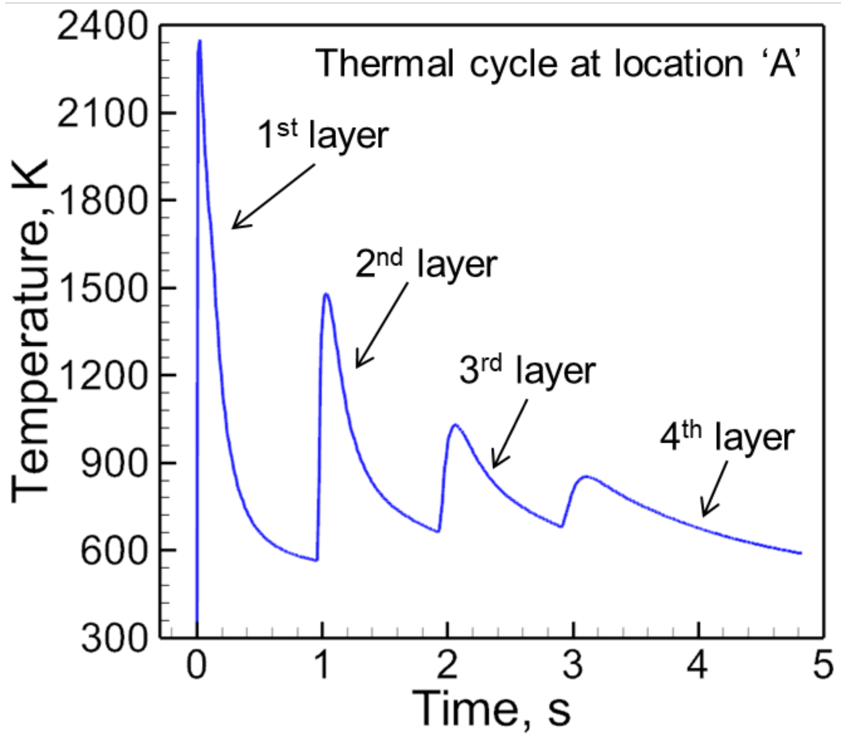
Hardness prediction to understand the effect of in-situ tempering

3D transient temperature and velocity distributions



Laser power: 500 W
Scanning speed: 10 mm/s
Laser spot radius: 1.0 mm
Power distribution parameter: 3.0
Powder feeding rate: 0.22 g/s
Track length: 20 mm

Hardness variation with repeated thermal cycle



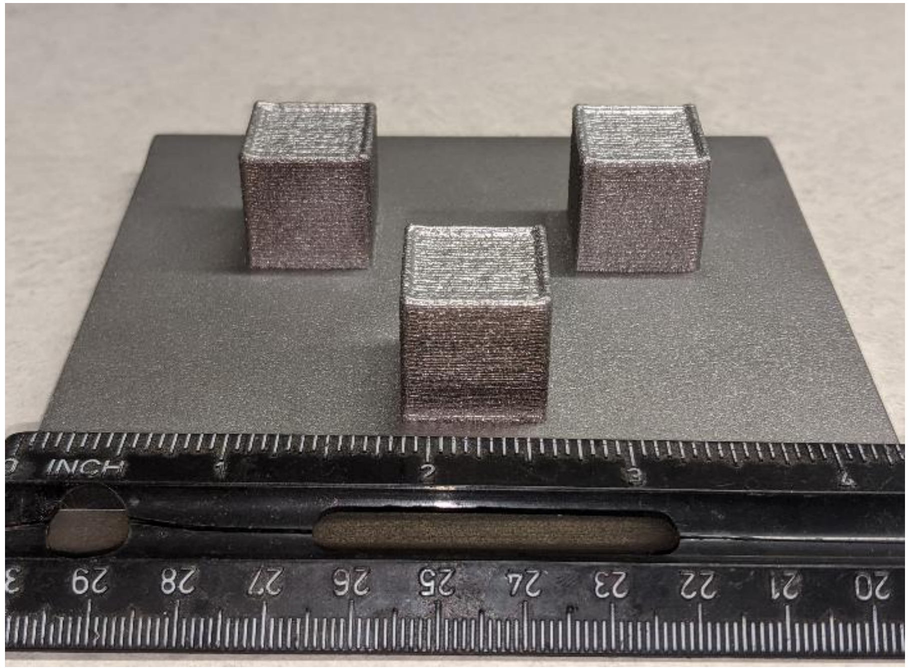
Location 'A' is at the mid-length, mid-width and on the top of layer 1

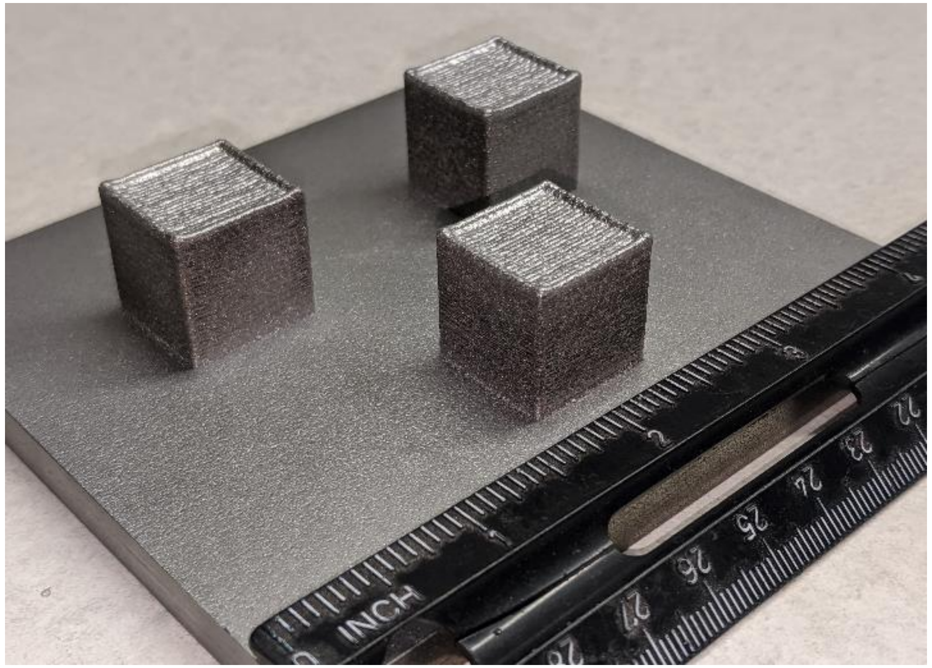
Hardness decreases at the same location in the component experiencing repeated heating and cooling during multi-layer deposition

Location	After deposition of layer #	Hardness, VHN
A	1	325.0
	2	295.5
	3	288.4
	4	285.6

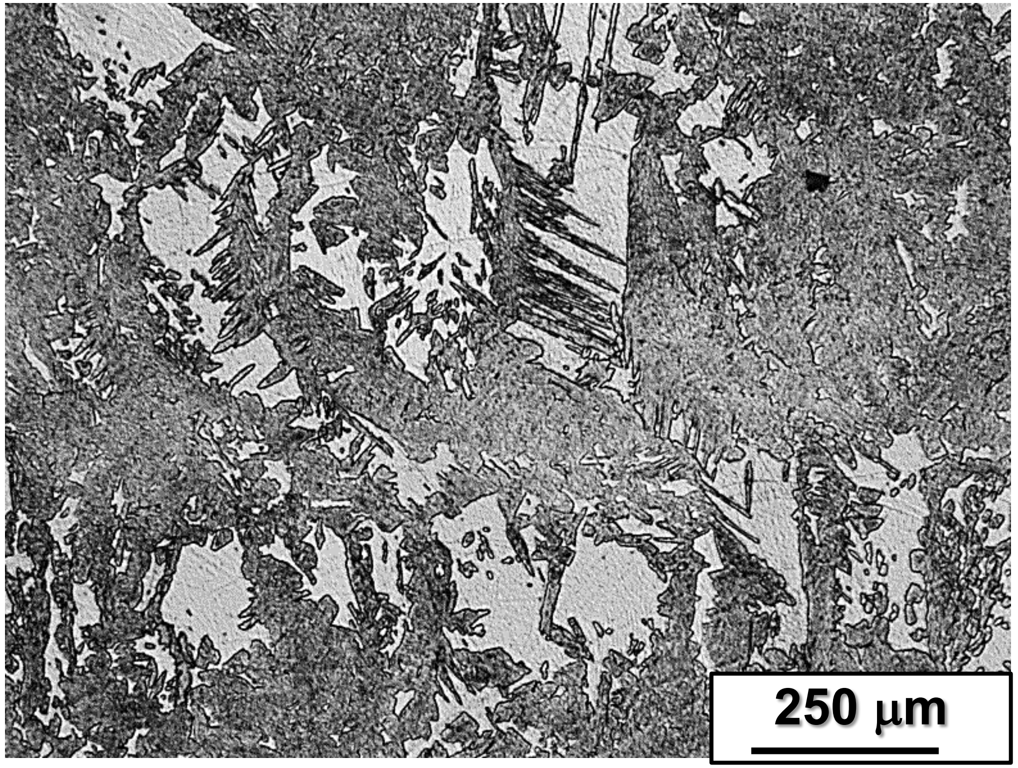
Laser power: 500 W
Scanning speed: 10 mm/s
Laser spot radius: 1.0 mm
Power distribution parameter: 3.0
Powder feeding rate: 0.22 g/s
Track length: 20 mm

First Samples produced using DED-L at Optomec



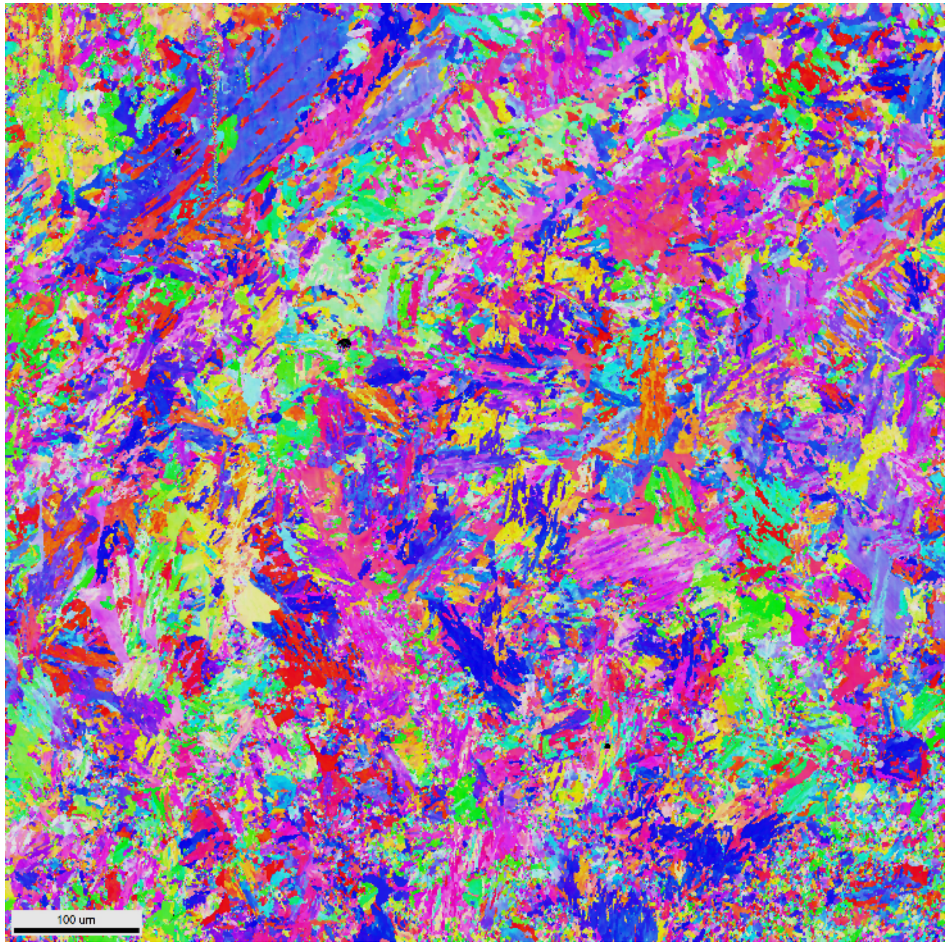


Initial Optical Microscopy and SEM Analysis



No Pre-Heat
Build Top

Build
Direction



Project Impacts

- Journal Publications
  - Paper submitted for publication in a peer review journal– Mukherjee, DebRoy, Lienert, Maloy, Hosemann, “**Spatial and temporal variation of hardness of a printed steel part” 11/2020**
- Conference Presentation
  - Abstract accepted for TMS 2021 - **Laser Additive Manufacturing of Grade 91 Steel for Affordable Nuclear Reactor Components with Improved Radiation Tolerance, Maloy, Lear, El-Atwani, Hosemann, Bickel, Lienert, DebRoy and Mukherjee**

Milestones and Deliverables for FY-20

- Report on Acquisition of Grade 91 powders – completed on time, 5/22/2020
- Report on Temper Experiments performed at LANL and UC Berkeley-completed on time, 8/22/20
- Report on Optomec Fabrication of first set of samples using G91 powder-completed on time, 9/30/20

Issues and Concerns

- COVID-19 caused some initial delays especially at national labs but through leaning on university collaborators, milestones were met.
- Plan to continue strategy into FY21 to meet future milestones and keep project on schedule.

Milestones and Deliverables for FY-21

- Report on Characterization Results of Additive Manufactured Materials – 6/18/21
- Report on Samples Fabricated by Additive Manufacturing – 6/30/21
- Report on Model Calculations of Microstructural Processes during Additive Manufacturing – 9/30/21

Possible Areas/Industries/Programs (and Readiness) for Adoption

- Presently the estimated Technology Readiness Level is 3-4
- Strong collaboration with Optomec Inc. as part of this project
- Possible future nuclear energy connections as project progresses

Contact Information and Questions

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