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

AMM Technical Review Meeting Webinar

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Introduction

- According to the Nuclear Energy R&D Roadmap Report, one of the key challenges facing the nuclear energy industry involves development of innovative reactor designs with reduced capital costs.
- Two related R&D objectives outlined further in the report include:
  - Making improvements in the affordability of any new reactors
  - Development of structural materials to withstand irradiation for longer periods.

Objectives to Address Challenges

- 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.

Project Team

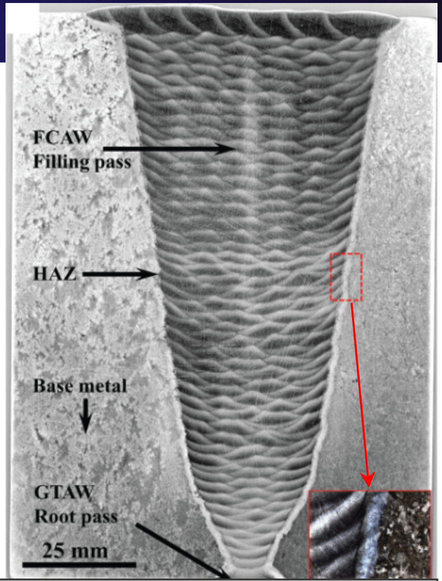
- S.A. Maloy (PI) - Los Alamos National Laboratory
- Dr. T. Lienert (Co-I) – Optomec, Inc.
- Prof. T. DebRoy (Co-I) - The Pennsylvania State University
- Prof. P. Hosemann (Co-I) - University of California Berkeley

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.
- Now employed widely in fossil fuel power plants operating at temperatures up to ~650°C.
- Current "workhorse" alloy approved under ASME Boiler and Pressure Vessel Code. Considered for structural applications in nuclear reactors.
- Typical joining of steels used for nuclear reactors can use manual, multi-pass welding processes
- 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*.

Background (cont.)

- 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.
- Specifically, the thermal cycles of temper beads are exploited to *improve the properties* of the underlying metal.
- 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 <u>*can be tailored to provide effective in-situ tempering during deposition*</u>, <u>*like with temper bead welding*</u>. Precludes the need for post-fabrication heat-treatment (*greater affordability*).

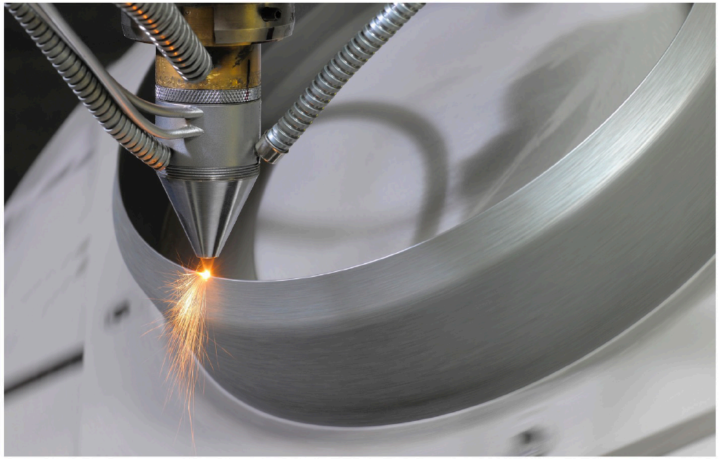


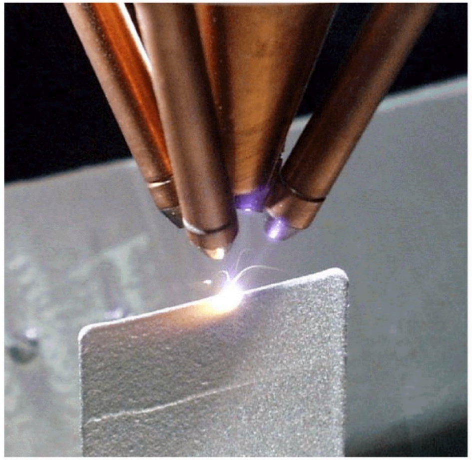
Macrograph showing structures of temper beads in multi-pass arc welded component.

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





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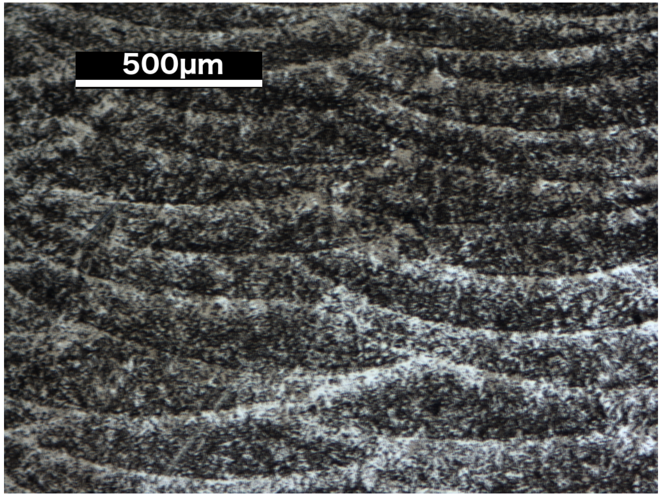
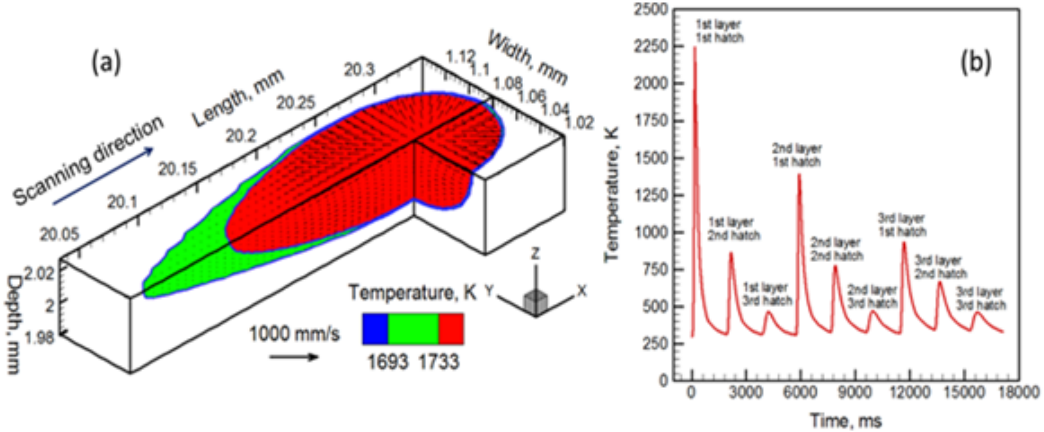
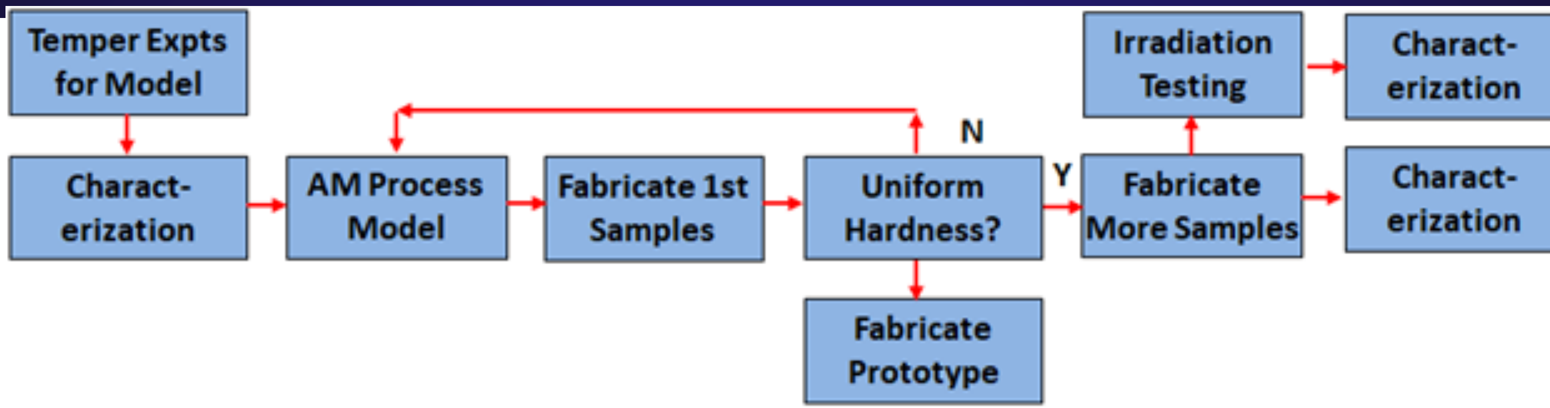


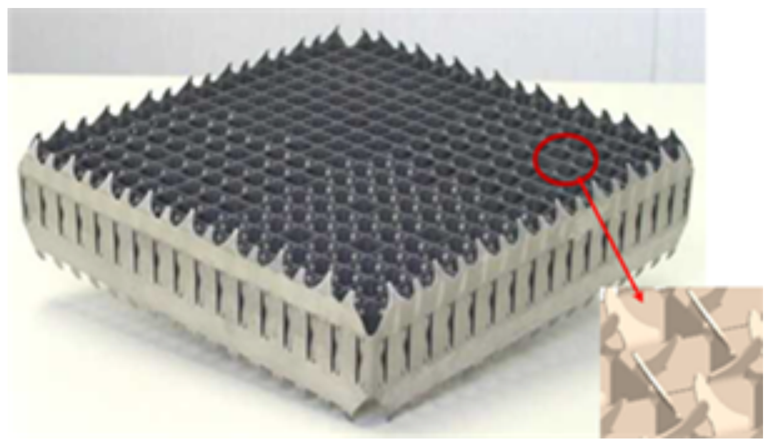
Build Direction



Preliminary Process JMA Model Results

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										■	■	■

Project Status - Milestones

- Year 1: Heat-treating studies to calibrate model, Initial characterization, Begin process modeling, Fabricate DED LAM samples.
- Year 2: Continue process modeling, Fabricate DED LAM samples to validate the tempering model, Start irradiation studies, Start characterization.
- Year 3: Complete process modeling, Complete irradiation studies, Complete characterization, Fabricate prototype part.

Project Status

- Tasks Completed:
  - Contracts placed with all participants recently.
  - Quote for AM powder has been received.
- Next Steps:
  - Place order for powder.
  - Kickoff meeting right after holiday break.
  - Start process modeling in January
  - Start tempering experiments in January.
  - Start LAM experiments in March.

Risk and Mitigation Strategies

- Challenge: time and effort to validate temper model on wrought Gr 91 via an iterative process (loop in flow chart).
- Challenges may arise if hardness map shows variations outside the target range.
- Mitigation: If OM results show melt pool dimensions & overlap spacings are consistent with the process model, then the problem lies with details of the tempering model.

- The tempering model will then be run iteratively using different values of k, the fitting constant for the JMA eqn.