Numerical Study of Microstructural Evolution of IN625 During Pulsed Laser Welding

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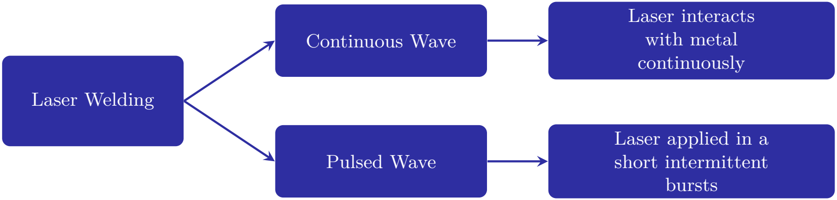
Outline

Introduction

Laser Welding

One of the most preferred welding techniques due to excellent precision and high energy density – produces excellent quality joints.



Our work

Why Pulsed Laser welding

It enables finer control of heat input and melt-pool dynamics – thus controlling the cooling rate and grain growth.

Why Nickel Based Alloy

They have excellent properties like low density yet high toughness, bio-compatibility, and excellent resistance to creep, corrosion, and high temperatures

Our Work

This work utilizes a **Cellular Automata (CA)** based microstructural simulation to establish *predictive process-structure relationships*, directly informing the optimization of weld quality in the alloy **Inconel 625**.

Mathematical modeling

Thermo-fluid Transport Equation

$$\nabla \cdot (\mathbf{u}) = 0$$

$$\rho \left[\frac{\partial \mathbf{u}}{\partial t} + \nabla \cdot (\mathbf{u}\mathbf{u}) \right] = \nabla \cdot (\mu \nabla \mathbf{u}) - \nabla p + \rho \beta (T - T_0)\mathbf{g} - \mu \frac{180}{\lambda^2} \frac{f_s^2}{(1 - f_s)^3} \mathbf{u}$$

$$\rho c_p \left[\frac{\partial T}{\partial t} + \nabla \cdot (\mathbf{u}T) \right] = \nabla \cdot (k \nabla T) + \rho L_f \frac{\partial f_s}{\partial t} + Q$$

Gaussian Heat Source

$$Q(x, y, z) = \frac{2\eta P}{r_{xy}^2 d \pi^{3/2}} \exp\left(- \left(\frac{2(x - x_0)^2}{r_{xy}^2} + \frac{2(y - y_0)^2}{r_{xy}^2} + \frac{2(z - z_0)^2}{d^2} \right) \right)$$

Heterogeneous Nucleation

$$f(\Delta T) = \frac{1}{\Delta T_\sigma \sqrt{2\pi}} \exp\left(-\frac{1}{2} \left(\frac{\Delta T_\mu - \Delta T}{\Delta T_\sigma} \right)^2 \right)$$

Model Validation

The numerical model was validated using experimental data from the *NIST Additive Manufacturing Benchmark 2018 Challenge* across 3 distinct welding conditions:

Case	**Power (W)**	**Speed (mm/s)**
A	137.9	400
B	179.2	800
C	179.2	1200

Table: Welding Process Parameters

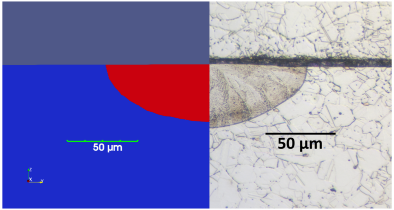
Validation Metrics

- Melt pool geometry
- Cooling rates
- Microstructure predictions

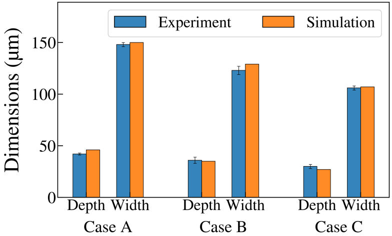
** NIST AM Bench is an international benchmark series for validating computational models against standardized additive manufacturing experiments.*

Thermo-Fluid Validation

The thermo-fluid model was validated by comparing predicted melt pool dimensions (depth and width) against experimental measurements through qualitative and quantitative analysis.

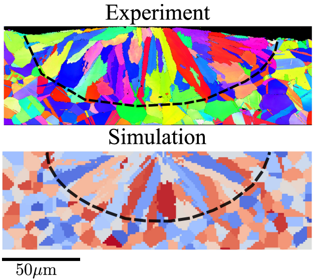


(a) Qualitative comparison of melt pool morphology for case B

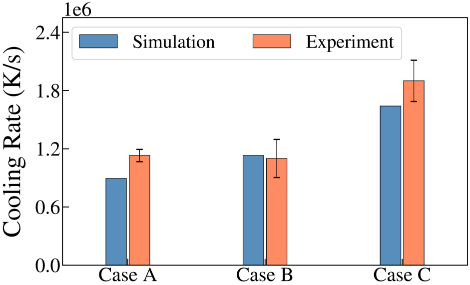


(b) Quantitative validation of melt pool dimensions for all 3 cases

Microstructure Validation



(a) Qualitative comparison of grain structure (Case B)

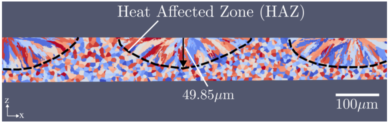


(b) Quantitative validation of grain dimensions

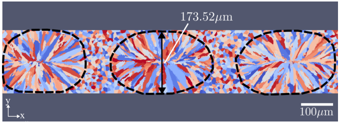
Pulse Laser Setup

- Four pulsed welding cases: 2, 8, 20, and 50 kHz
- AMMT Case B parameters with 0.5 duty cycle
- Peak power doubled to maintain equivalent average power

Results



(a) 2 KHZ ZX Plane



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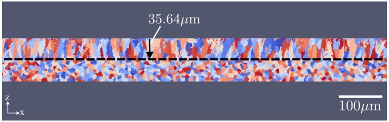
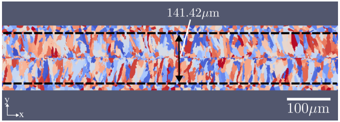


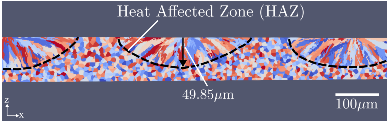
(a) 50 KHZ ZX Plane



(a) 50 KHZ XY Plane

Figure: Caption

Results



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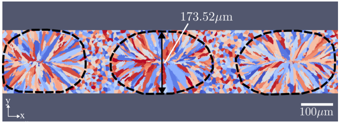

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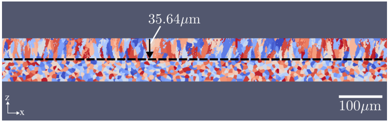

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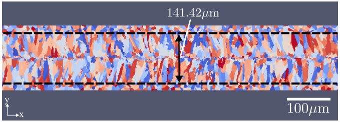

(a) 50 KHZ XY Plane

Figure: Caption

Conclusion