U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

AMMTO & IEDO JOINT PEER REVIEW

May 16th-18th, 2023

Washington, D.C.

Machine Learning (ML) Enhanced Development of Functionally Graded Materials (FGMs) Enabled By Directed Energy Deposition (DED)| AMMTO

Alex Kitt, EWI

DE-EE009118| 09/01/2020 – 07/31/2023

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Project Overview

- **Primary Innovation:**
  - Development of Inconel 718 to René 41 Functionally Graded Material for Hot and Harsh Gash Path (HGP)
- **AMMTO Mission Alignment:**

Energy, Emissions, & Environment: • Reduced Buy:Fly- Lower Embodied Energy • Expanded Design Space: Potential for Higher Efficiency Designs	**Cost & Competitiveness:** • Current Manufacturing in China • Reduced Lead Time • Capabilities not Available In China
Technical & Scientific: • ICME + ML to Accelerate Development • AM of "Unweldable" Alloys	**Other Impacts:** • Five peer reviewed publications • Full-Scale, FGM Jet Engine Component Build

- **Support:**
  - Neutron Scattering Measurements at ORNL, X-ray Scattering Measurements at Sandia National Lab, Computations to be Performed on NREL High Performance Computing

Project Outline

Innovation: ML Enabled Development of Hot and Harsh Gas Path FGMs
Project Lead: EWI
Project Partners: GE Research, University of South Carolina

Timeline: 09/01/2020 – 07/31/2023, 80% complete
Budget: BP1 – DOE Funded: $2,578,782 Cost Share: $813,632
BP2 – DOE Funded: $1,361,459 Cost Share: $367,433

	FY21 Costs	FY22 Costs	FY23 Costs	Total Planned Funding
DOE Funded	$1,368,389	$1,160,538	$1,411,313	$3,940,240
Project Cost Share	$523,696	$328,182	$329,187	$1,181,065

End Project Goal:

1. DED technologies to manufacture high γ'-low/no γ' strengthened Ni alloy FGMs with proper selection of the high γ'-low/no γ' strengthened Ni superalloys ✓
2. FGM coupons shows comparable strength and oxidation resistance and at least 20-30% LCF improvement compared to welded coupons
3. Demonstration case shows at least 10-20% cost reduction compared to the current manufacturing methods; and
4. ML methods to optimize DED printing parameters and predict microstructure and defects of high γ'-low/no γ'strengthened Ni alloy gradients. ✓

Current State of Manufacturing

- **HGP Component Life Limited by High Temperature Performance**
- **Current State Design Constraints:**
  - High γ’ Ni-Based Superalloys (René 41, René 80, etc.)
    - Meet Durability Requirements
    - Penalized by Cost and Manufacturability
    - Often only required in a region of a part
  - Low/No γ’ Ni-Based Superalloys (Inconel 625, Inconel 718)
    - Do not Meet Durability Requirements
    - Lower Cost, Simpler Manufacturing
- **Welding Low/No γ’ to High γ’ is Generally Avoided**
  - High γ’ Alloys are Often Challenging to Weld
  - Welded Interface is a Stress Concentrator, has CTE Mismatch

Project Goals

Program Team

Edison Welding Institute

- *FGM DED technology development*
- *Coupon & demonstration case printing & testing*

GE Research

- *FGM gradient design*
- *Characterization*
- *Multi-material DED process modeling*
- *Machine learning*

Univ. of South Carolina

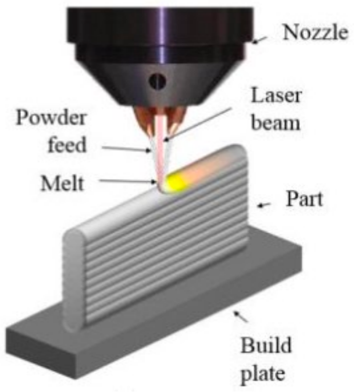
- *Microstructure & defects modeling*

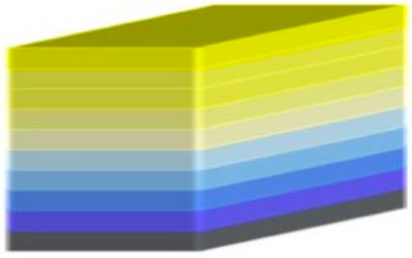
Field of Research:

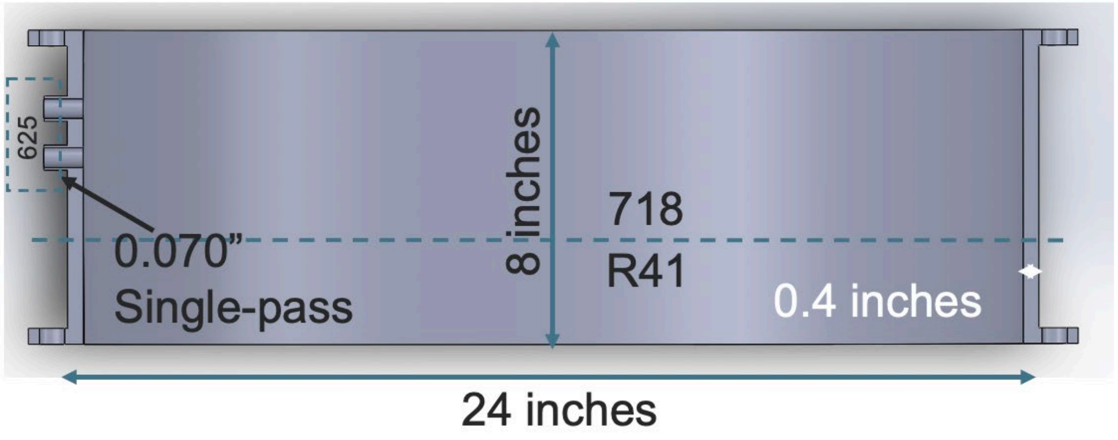
- **Maturation of Materials and DED Technology for HGP FGM Parts in Gas Turbines or Jet Engines (TRL 3 to TRL5)**
  - FGM Allows “Best of Both Worlds”-Durability and Cost Effectiveness
  - DED Simplifies Powder Mixing and Process Monitoring

Target Metrics:

- **BP1: >99.9% Dense, Crack Free, Coupon Scale FGM (Complete)**
- **BP2: Reduce Material and Manufacturing Costs by 10-20%**
- **BP2: Improve Durability by 20-30%**

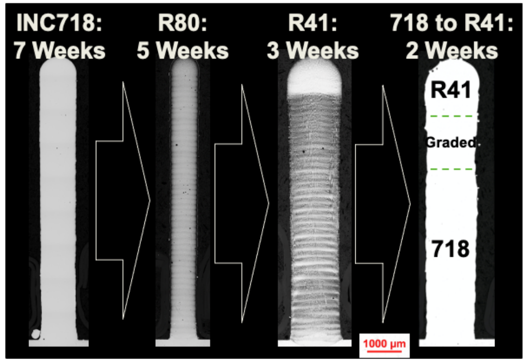


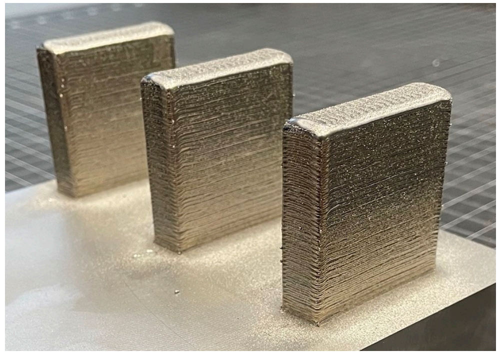




Project Strategy

BP1

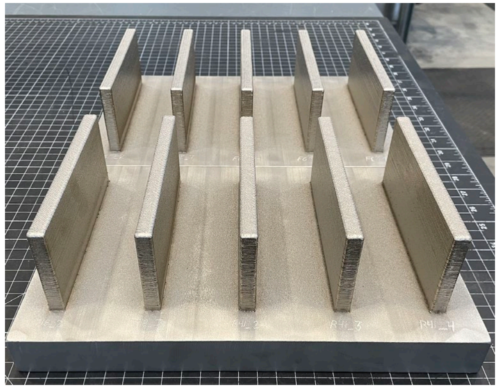


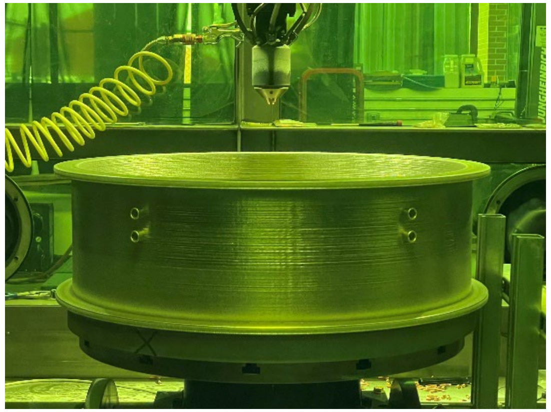


Achieved:
- Rapid Development
- Crack Formation Models

Achieved:
- >99.9% Dense
- Crack Free
- HT Optimized

BP2





TBD:
- Elevated Temp Tensile
- Elevated Temp Fatigue
- Oxidation

TBD:
- Elevated Temp Tensile
- Density
- Cost Comparison

Progressive Development:

1. *Innovation 1 and 2:* Rapid Iteration of Single-Pass Walls for Initial Development
2. Representative Coupons for BP1 Validation
3. Relevant Environment Mechanical Testing
4. *Achievement:* Demonstration Component

Key Tools:

- Advance DED Process for FGMs: Powder Mixing, Process Monitoring, Heated Build Plate
- Range of ICME Tools: Thermodynamic, DED Models, Cellular Automata
- ML/AI: GE BHM, GE IDACE

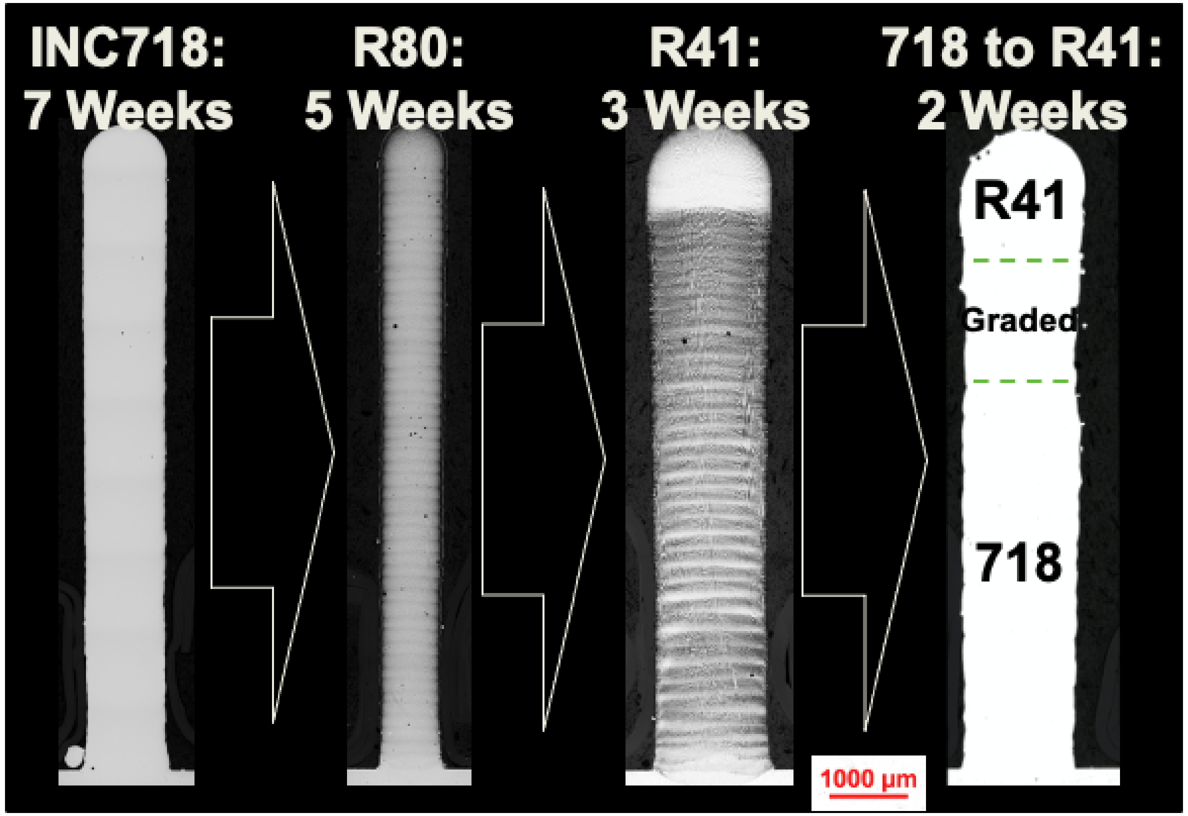
Innovation 1: Accelerated, Data Driven, Alloy Development

Transfer Learning Based Development:

- Inconel 718 Developed “From Scratch” Using Traditional Design of Experiments
- High Fidelity Gaussian Process Trained
- Low Fidelity Discrepancy Function used to Quickly ”Learn” new Alloys:
  - René 80
  - René 41
- FGM Process Window Parameters from Inconel 718 and René 41 Probabilistic Process Windows Overlap

Impact:

- *Project:* Achieved BP1 Go/No-Go: 99.9% Dense, Crack Free
- *AMMTO:* Rapid Alloy Development Combining Digital, Materials, and Process Expertise



Innovation 2: Physics Driven Crack Formation Prediction

Limitations to Data Driven ML:

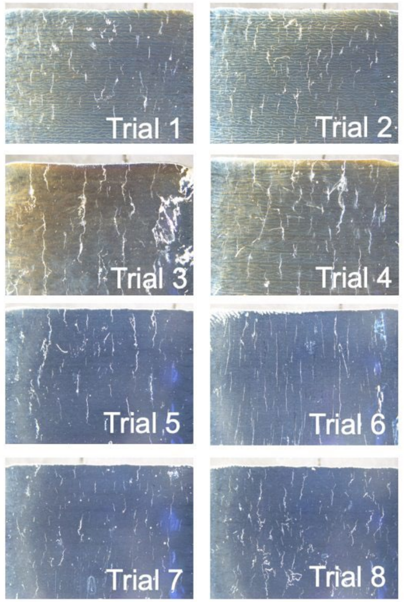
- Crack-prone René 80, Failed when Extrapolating to Thick Walls

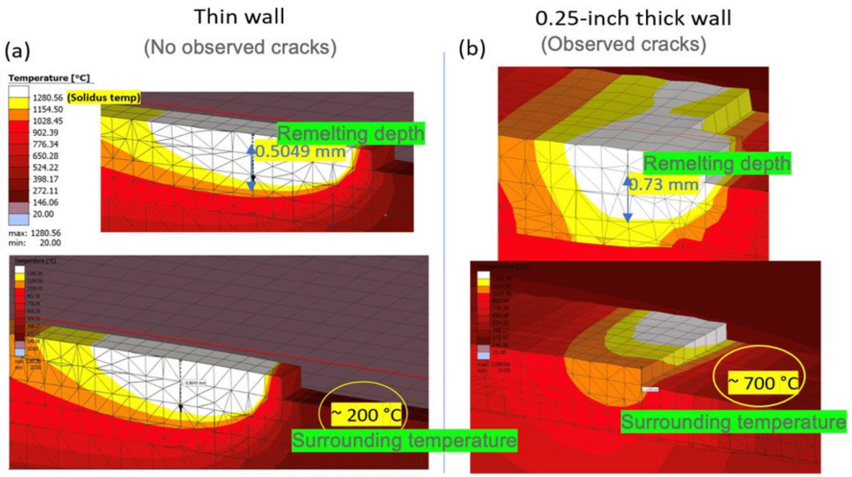
Hybrid Physics/ML Approach:

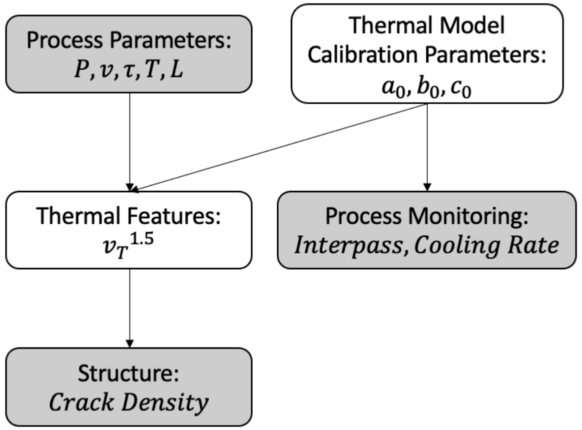
- *Process to Thermal:* Computationally Efficient Multi-Source Rosenthal Model Calibrated Against Process Monitoring
- *Thermal to Crack Formation:* Simplified Physics Based Criteria
- Calibration and Crack Formation Prediction using ML

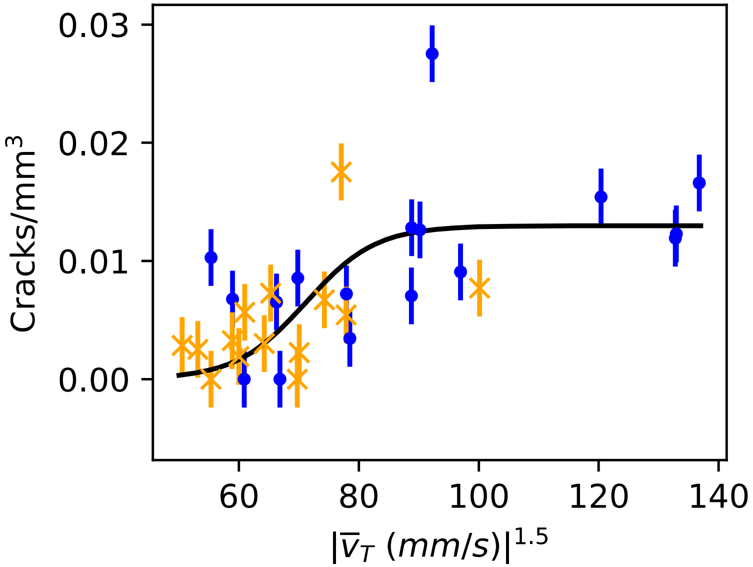
Impact:

- *Project:* Achieved Defect Prediction >90% Milestone









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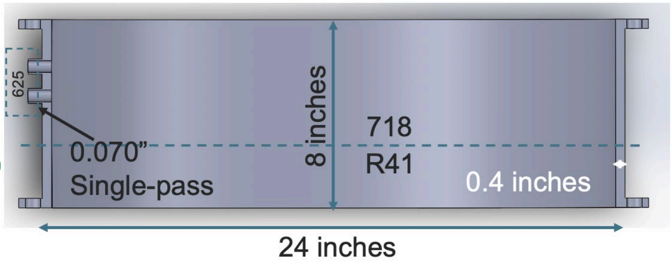
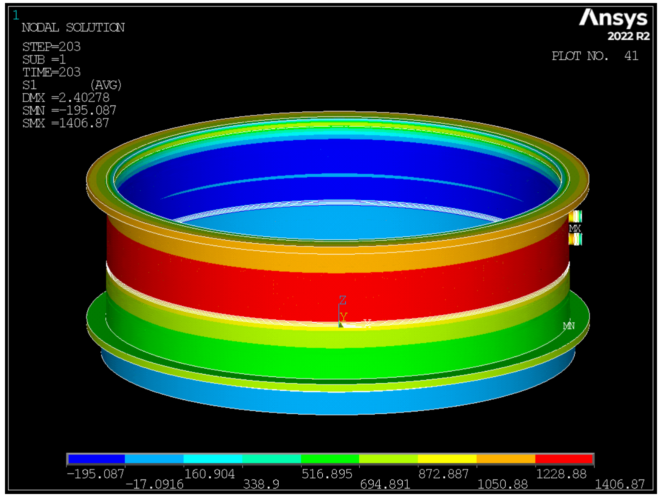
Achievement: Commercially Scaled Demonstration



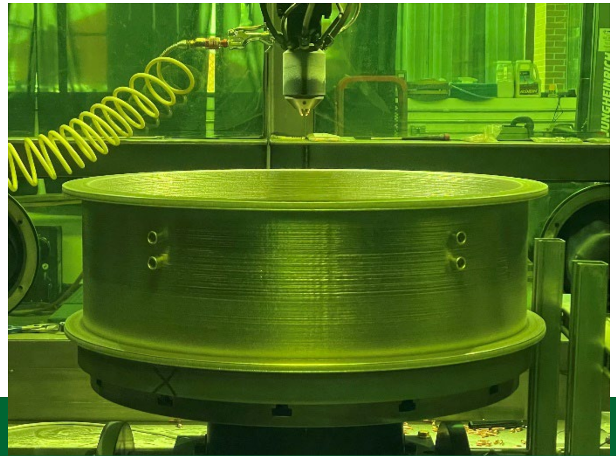
Demonstration:

- Design Based on a Full Scale 737 Jet Engine Case
- FGM on Main Cylinder and Side Ports
- Design Modifications Based on Process Model for First Time Buildability
- Roughly 11 Days of Build Time



Impact:

- *Project:* Required for Sample Excision for Density and Elevated Temperature Tensile Testing
- *AMMTO:* Significant Step Towards Commercialization



Future Work, Technology Transfer, & Impact

Future Work:

- Complete Coupon Level Mechanical Testing
- Operational Temperature Tensile, Fatigue, Oxidation Testing
- Complete Cost Comparison

Technology Transfer:

- Quarterly Updates to GE Aviation
- GER to Develop Technology Transition Plan
- Peer Reviewed Publications for Wider Adoption (5 submitted)

Impact:

- Developed and Demonstrated Two Methods of Accelerated Advanced Material Development:
  - Data Driven Transfer Learning
  - Hybrid (Physics/ML) Learning
- Demonstration Path to Industrial Application through Full Scale Demonstration Build

Questions?

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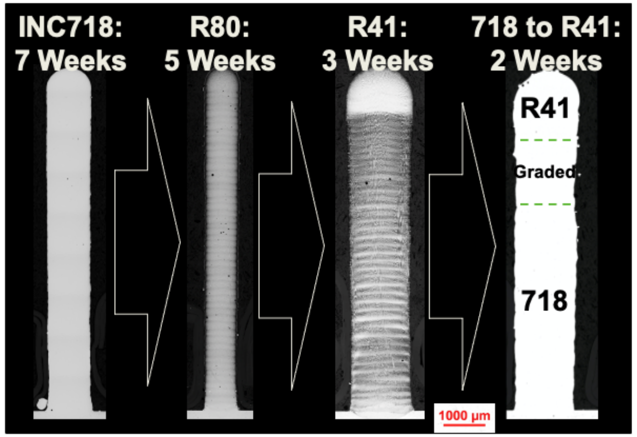
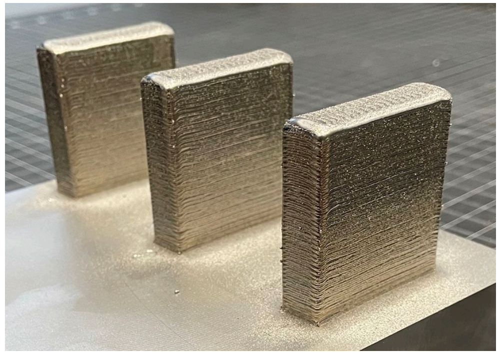
BP1





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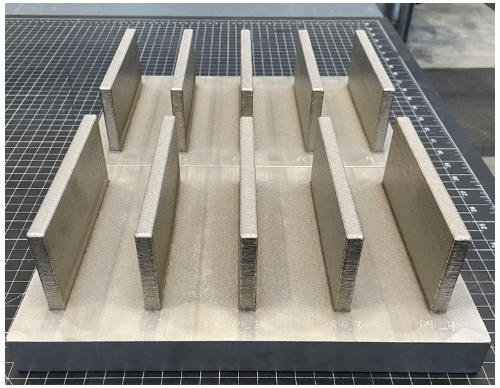

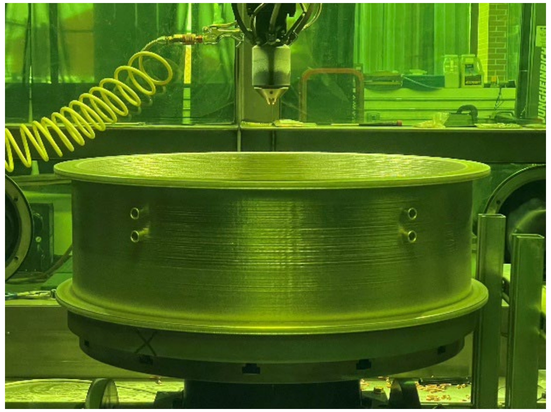

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