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ORNL/TM-2025/3784
CRADA/NFE-20-08390

Design of Novel Hot Gas Component for Gas Turbine Engines Enabled by Materials and Additive Manufacturing Process Development

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March 2025

OAK RIDGE
National Laboratory

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Manufacturing Science Division

DESIGN OF NOVEL HOT GAS COMPONENTS FOR GAS TURBINE ENGINES ENABLED BY MATERIALS AND ADDITIVE MANUFACTURING PROCESS DEVELOPMENT

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March 2025

Prepared by
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managed by
UT-BATTELLE LLC
for the
US DEPARTMENT OF ENERGY
under contract DE-AC05-00OR22725

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ABSTRACT

1. Background

This CRADA project was the result of a project award under FOA-DOE-0001980. The overarching FOA project team consisted of researchers from Carpenter Technology Corporation (CTC), Solar Turbines Incorporated (Solar), Pennsylvania State University (PSU), University of California-Santa Barbara (UCSB), and Oak Ridge National Laboratory (ORNL). Evaluations were conducted on two high-γ' superalloys that were designed by CTC and the UCSB. One alloy named GammaPrint-700 (GP-700) is a cobalt-base superalloy. The other alloy named GammaPrint-1100 (GP-1100) is a nickel-base (Ni-base) superalloy. PSU provided expertise and experimental testing of the thermal performance of AM micro-cooling architectures. ORNL provided expertise with the AM superalloy materials characterization and AM processing science. Solar provided turbine component design expertise. The focus of this CRADA report is to document the efforts between ORNL and CTC towards the development of superalloys designed for AM.

The project goal was to use an AM processable high-temperature superalloy and design for Additive Manufacturing (DfAM) techniques to design an efficient turbine component (i.e. a turbine tip shoe) with enhanced cooling features that can only be fabricated through additive manufacturing (AM). The efficiencies of existing combined heat and power (CHP) engines are capped by both component design and materials limitations. However, AM of a tip shoe component from a γ'strengthened superalloy offers the design flexibility to increase the efficiency and power of an industrial gas turbine.

This project brought about advancements in the DfAM tip shoe design space and in the area of high temperature superalloys processable through laser powder bed fusion (LPBF) AM. State of art computation design tools were utilized to optimize unique cooling features into a tip shoe component design. A two-prong materials development approach was taken to support development of the AM tip shoe geometry. The first approach centered on investigating the processability and the appropriate process science for the industry standard high-γ' nickel-base (Ni-base) superalloy Mar-M247. This superalloy is typically cast and considered non-weldable by traditional welding standards. In the course of this work, the alloy was not deemed feasible for process scale-up due to significant cracking issues during printing. The second approach focused on the development and evaluation of a novel cobalt-base superalloy, GammaPrint™-700 (GP-700 and a Ni-base superalloy, GammaPrint™-1100 (GP-1100) designed to mitigate the significant AM processing issues with Mar-M247. The processability of these two alloys were investigated through electron beam melting (EBM) binder-jet AM (BJAM), and LPBF as a risk mitigation for manufacturability. To be considered a candidate material for down-selection to proceed to full-scale AM tip shoe engine testing trials, the high temperature creep rupture strength was required to achieve at a minimum, a Larsen Miller Parameter (LMP) increase of 10.9% over the baseline material LPBF AM Hastelloy X.

2. TECHNICAL RESULTS

2.1 PRINTING

Initially this project focused on evaluation of three alloys (GP-700, GP-1100, and Mar-M247) across three AM technologies (LPBF, EBM, and BJAM). Mar-M247 was found to be too crack prone across all three printing technologies. Processing of both GP-700 and GP-1100 via EBM-AM was successful, however, the need for fine spatial resolution in the tip shoe components favored the use of LPBF. Binder-jet AM was found to require significant binder development to allow for successful sintering of the alloys. Hence, this report focuses on the LPBF processing of both the Ni and Co based superalloys, GP-700 and GP-1100 respectively.

Builds consisting of design of experiments (DoE) for both materials (GP-700 and GP-1100) were executed at ORNL utilizing the EOS M290 LPBF machine platform. Several DoEs were performed to assess the calibration of the machines used for printing and the repeatability of the process parameters for each material (Figure 1). These DoE's were performed to investigate both bulk material density, overhang printability, microstructure, as well as surface roughness characteristics.

2.1.1 GP-700 Printing

A total of 10 prints were completed using GP-700. Multiple parameter studies were performed using a central composite design (CCD) to investigate the design space for GP-700. Based on density and microstructural data, a parameter set that optimized print speed observed that was significantly faster than that of the process set initially identified by CTC during feasibility trials early in the program. While a high throughput process window was identified, with these parameters a significant difference in texture was observed in the as-printed material (Figure 2). As a result, both the CTC and fast process parameters were utilized to print mechanical test bar samples. The material from the CTC process parameters is referred to as "coarse" microstructure and the high throughput material as "fine" microstructure GP-700 based on the observed microstructure attributes. The high throughput process parameter window had the potential to yield a 50% increased throughput, which on the actual tip shoe components this would reduce a print from one week to three days.

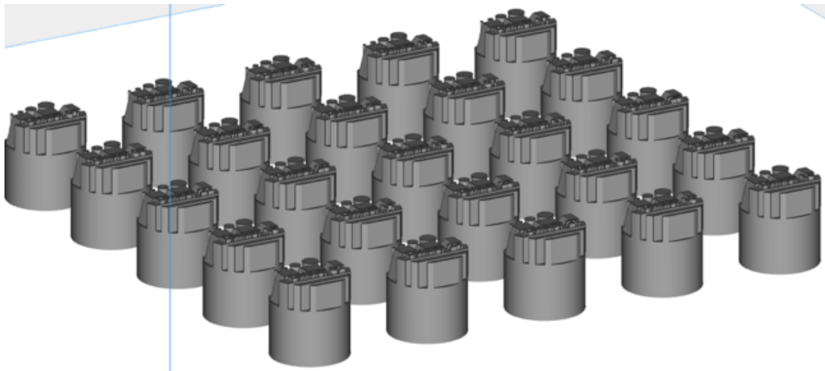

Figure 1 Representative example of the arrays of the geometry utilized for the process parameter development.

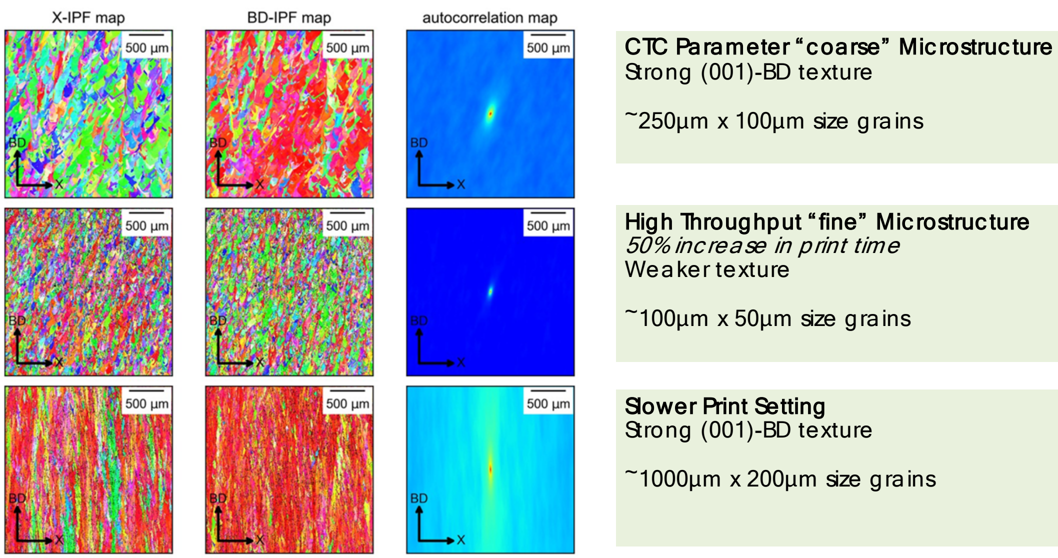

Figure 2: LPBF printed DMREF10 Co-superalloy material. (top) CTC printed material (middle) ORNL 'fast' setting (bottom) ORNL 'slow' settings.

2.1.2 GP-1100 Printing

A total of 25 prints were completed using GP-1100 material in an EOS M290 LPBF system utilizing the geometry previously shown in Figure 1 of 2.1.1. Multiple CCD parameter studies were performed to analyze the impact of process parameters on microstructure, mechanical properties, and surface finish of applicable geometries (overhanging pin fins). Based on initial microstructural comparison, the optimal parameters for density and speed remained the parameters developed at CTC early in the initial development efforts of the project and were utilized for all subsequent mechanical test bars prints and the component prints discussed in 2.4.

2.2 HEAT-TREATMENT & MICROSTRUCTURE CHARACTERIZATION

Heat-treatment studies were conducted on GP-700 to understand the recrystallization behavior of the as-printed material, with a desire to retain the columnar grain structure while maximizing the fraction of precipitates that are solutioned, and also to look at maximizing the ductility of the material in the historical superalloy ductility dip regime of 700-800 ^{o}C. Lower temperature stress relief (1000˚C, 1050˚C and 1100˚C) treatments followed by subsolvus (1190˚C) or supersolvus (1215˚C or 1250˚C) treatments were first investigated, Figure 3. The stress relief treatments did not suppress the tendency for recrystallization during supersolvus treatment, even for short times just above the solvus. Subsolvus aging resulted in a fine-scale bimodal precipitate structure that is related to the original cellular structure in the as-printed material.

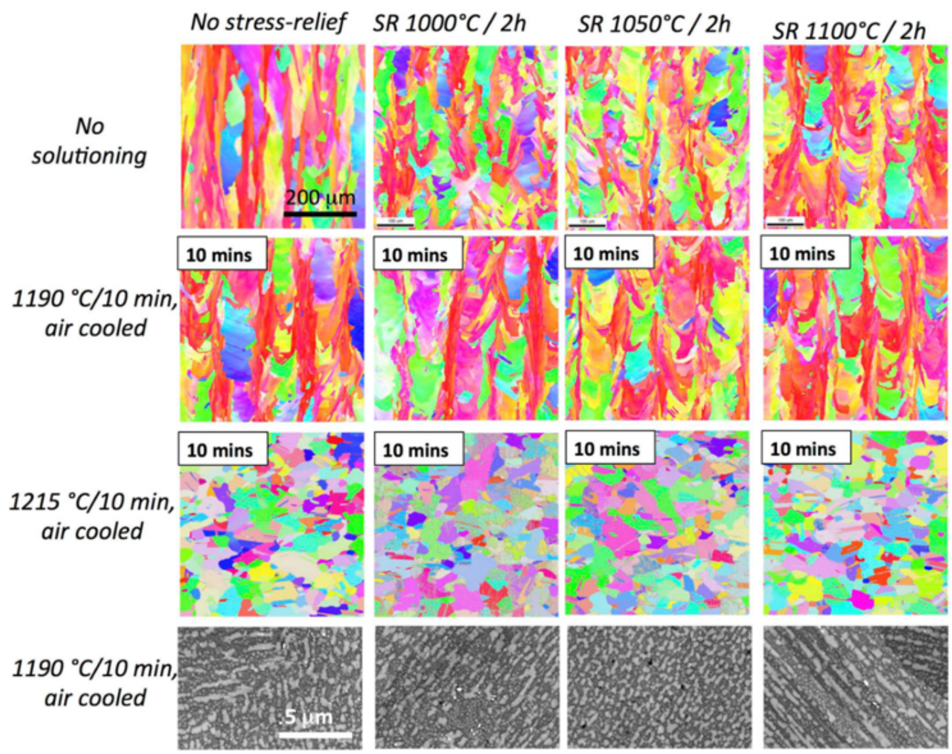

Figure 3: Results of heat treatments of as-printed Co-based superalloy. Top 3 rows are EBSD analyses showing columnar structure retained in subsolvus heat treatments and complete recrystallization in supersolvus. Bottom row shows morphology of strengthening precipitates for each combination of stress relief and heat treatment.

Similar to GP-700, the heat-treatment study for GP-1100 focused on retention of the as-printed columnar structure and examining the recrystallization temperature of the material. Based on differential scanning calorimetry (DSC) the critical temperature for GP-1100 were determined to be: 1162 °C (γ' solvus onset), 1191 °C (γ' solvus completion), 1297 °C (solidus temperature) and 1371 °C (liquidus temperature). Through the heat-treatment study (Figure X), the grain structure of GP-1100 was found to remain stable below the solvus temperature when solutioned at both 1177 and 1190 ^{o}C. Above the solvus temperature when solutioned at 1215 ^{o}C, the grain structure underwent recrystallization (Figure Xc) with moderate grain growth during the thermal exposure.

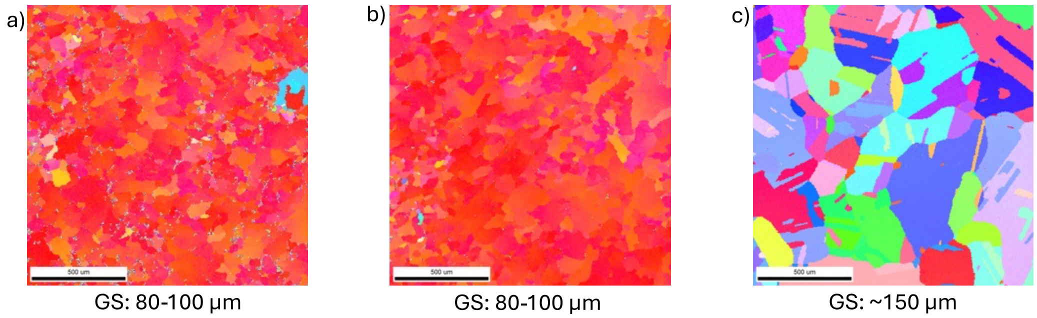

Figure 4: EBSD micrographs of GP-1100 after solution treatments (ST) and air cooling (AC) subsolvous and supersolvous temperatures a) 1177 °C ST and 4hrs AC b) 1190 °C ST and 1hr AC c) ST 1215 °C and 1hr AC

2.3 MECHANICAL TESTING

The mechanical integrity of the LPBF fabricated GP-700 and GP-1100 were evaluated via an experimental plan considering high temperature quasi-static tensile, fatigue, and creep tests to which the performance of the alloys was base-lined against LPBF Hastelloy X.

Tensile Properties

The summary of the 0.2% yield stress measured through quasi-static tensile tests for GP-700 and GP-1100 across various temperatures can be seen in Figure 5. Both alloys exhibits the classic ductility dip regime, driven by precipitate-scale deformation mechanisms, in the 750 ^{o}C+ regime. At 800 ^{o}C+ GP-700 and GP-1100 perform similarly to one another.

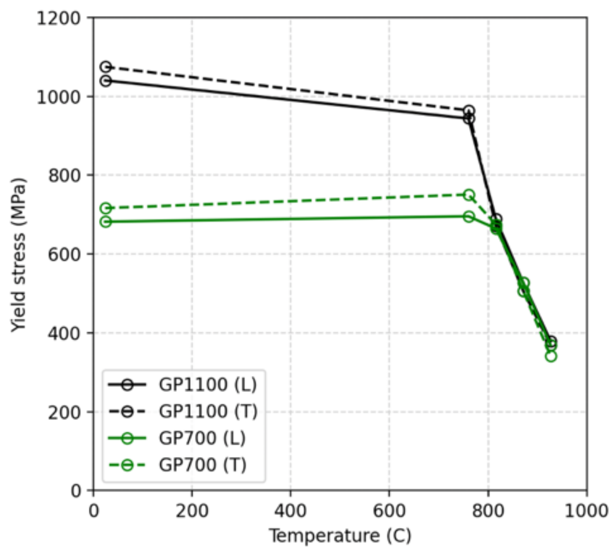

Figure 5. Yield stress of GP-700 and GP-1100 parallel (L) to the build direction and trasnverse (T) to the build direction.

Creep Properties

Creep testing results, summarized via the Larson-Miller parameter, are shown in Figure 6. Reference curves are included for AM Hastelloy X [1], a 10% curve used as a target in this project, and a 22% stretch goal corresponding to MarM247 behavior [2]. Prior single crystal Co-based superalloy reference points are also included to give context. Transverse and longitudinal tests are included. Several points are still 'incomplete' indicating that they may fall even further towards the right of the plot. In summary, the minimum targeted properties were achieved and at higher stress values the 10% reference curve is exceeded for both GP-700 and GP-1100 alloys.

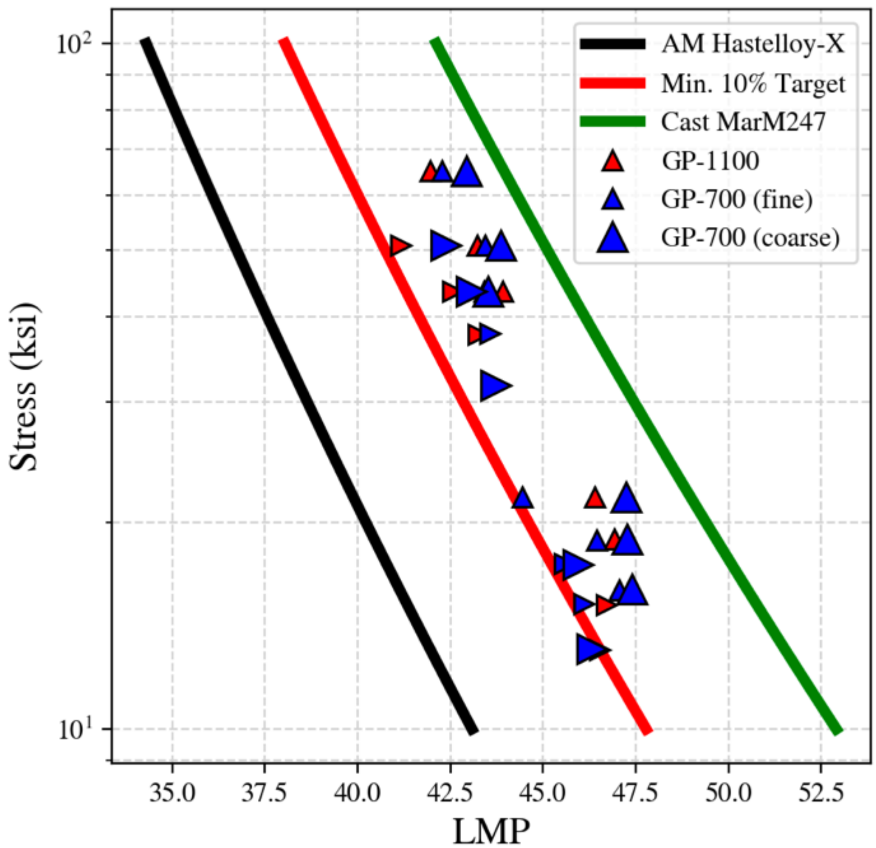

Figure 6. Creep rupture of GP-700, GP-1100, and reference data/curves [1,2]. Two microstructures are included for GP-700. Horizontal markers indicate loading transverse to the BD, vertical markers indicate loading in the BD.

Fatigue Properties

Fatigue results are shown in Figure 7. It should be noted that two sets of GP-700 were fabricated using differing LPBF parameters to produce the two distinctly different microstructures discussed previously. For the purpose of the mechanical testing these are referred to as 'fine' and 'coarse' in relation to the grain sizes. As a reference Hastelloy X fatigue points at 760 ^{o}C, the fatigue testing temperature, are also included [3]. The GP-1100 data, in both longitudinal and transverse directions, exceeds the Hastelloy-X behavior. Longitudinally tested coarse grain GP-700 demonstrates exceptionally good fatigue performance, however, the transversely loaded material exhibits a significant debit.

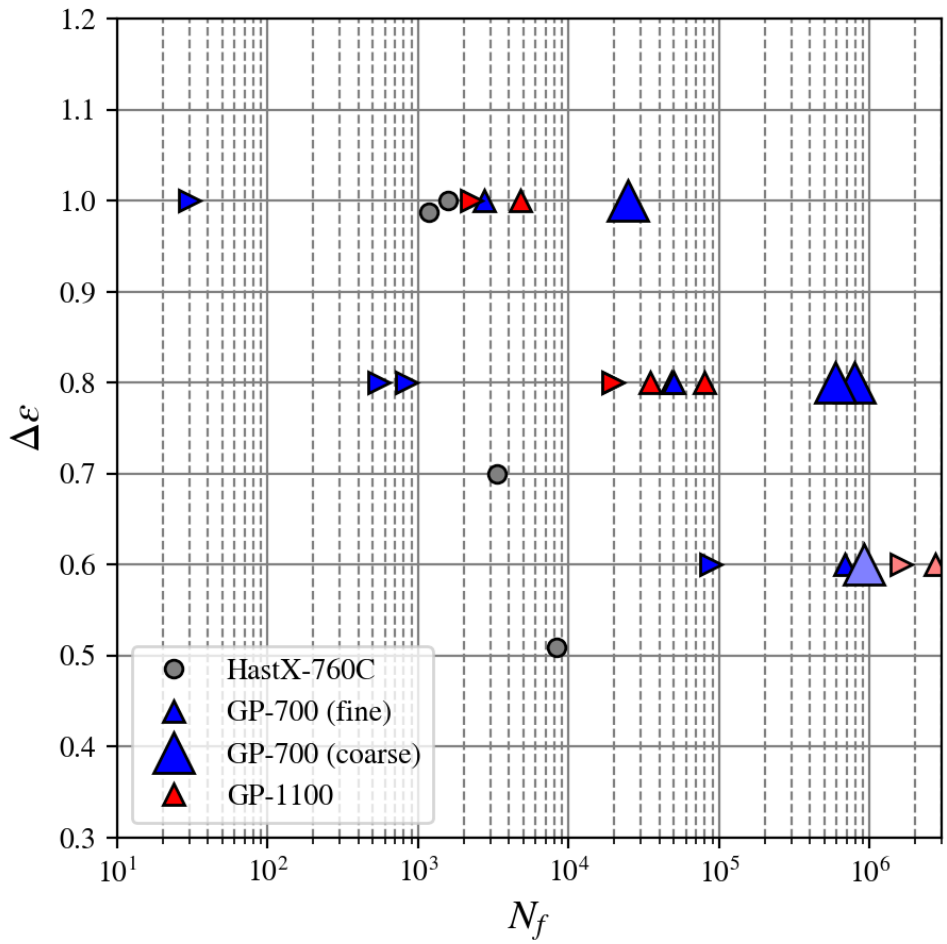

Figure 7. Fatigue results for GP-700 and GP-1100. Vertical traingles denote material aligned with the print direction. Horizontal triangles reference material built perpdenicular to the build direction. Reference Hastelloy X included [3].

3. IMPACTS

CTC's newly developed GP-700 and GP-1100 are AM-processable superalloys with demonstrated high temperature mechanical performance. Development of these alloy systems are important because (1) processability via AM enables their use for the design, fabrication, and use of advanced design gas turbine engine components and (2) novel materials solutions inherently provide operational benefits. Combined these two factors (better designs via AM, better performance via advanced alloys) enables significant performance boosts for gas turbine technologies. The benefits of these advances impacts operational performance e.g. improvements in energy conversion to provide greater power, improvements in component reliability which minimize operational costs and safety risks, and manufacturing advances which enable more streamlined fabrication routes needed for rapidly expanding gas turbine engine fleets deployed domestically in the U.S.. Furthermore, while these material were considered here for gas turbine engine applications, other applications (oil and gas, geothermal, hydro-power, fission and fusion) may also benefit from these advances thereby boosting domestic energy generation capacity.

4. CONCLUSIONS

This project focused on the co-development of novel materials and AM processing solutions for optimizing the performance of gas turbine engine tip shoes. Two novel material systems, Co and Ni based superalloys, processable via laser powder bed fusion, were developed. Alloy MarM-247 was found to be unprocessable. Processing experiments revealed that the Co-based superalloy's microstructure is extremely sensitive to processing conditions. Optimal heat treatment conditions were identified for producing optimized microstructures. Tensile, fatigue, and creep mechanical testing were performed to assess material behavior representative of gas turbine engine operation conditions. While tensile anisotropy is minor, non-negligible anisotropy was observed in creep and fatigue tests.

This work reveals that high strength Co and Ni based superalloys, designed specifically for mitigating against additive manufacturing processing defects, are achievable. The AM process history, controlled via user imposed process parameters, are critically important for controlling final material properties/performance. Extensive mechanical testing has demonstrated this sensitivity to process history and microstructure. A key outcome of this project has been the demonstration that these materials are processable via AM. Critically, process induced defects, such as solidification cracks, which plague most high strength Ni-based superalloys (MarM247), have been eliminated by careful alloy design. However, adoption of these materials and manufacturing routes for fabricating complex critical components requires de-risking materials uncertainties. Uncertainties can arise from intrinsic materials process-structure-properties relations which have been shown to be highly sensitive in this project. Additional uncertainties can arise from processing specific uncertainties e.g. laser powder bed fusion defects such as soot, balling, porosity, delamination. Hence, future efforts could build upon this work to further explore the process-structure-property relations and establish in-situ monitoring protocols for de-risking the adoption of these technologies and materials.

5. PARTNER BACKGROUND

Carpenter Technology Corporation (CTC) is a global leader in specialty alloy materials solutions for applications in aerospace, transportation, defense, energy, industrial, medical and consumer electronics markets. Domestically founded in Pennsylvania in 1889 CTC has grown to be a global leader with locations across the globe. CTC is a leading supplier of feedstocks for powder metallurgy (PM) of cobalt superalloys, stainless steels, alloy steels, and tool steels. PM products are specialty designed for a range of next generation manufacturing solutions including powder forging, metal injection molding, hot isostatic pressing, and additive manufacturing.

6. REFERENCES

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