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Evaluation of AddUp Precision L-PBF Technology for Tooling and Other Industrial Applications

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ABSTRACT

ORNL (Contractor) and AddUp Inc. (Participant) collaborated to enable the adoption of laser powder bed fusion for tooling applications, critical for reshoring the manufacturing sector in the U.S. Most of the work on laser powder bed fusion has focused on high value materials such as Ti-6Al-4V and Inconel 718 for niche applications in aerospace, biomedical and energy sectors. In this collaboration, ORNL and AddUp worked laser powder bed fusion of maraging steels for tooling applications while leveraging the unique ability of the AddUp laser powder bed fusion system to deposit fine powders. We demonstrated that the AddUp technology is capable of depositing complex artifacts and features such as overhangs within desired tolerances. We also showed that direct aging of the deposited parts result in simultaneously higher strength and elongation compared to the conventional two step heat treatments, which could result in significant energy savings. Finally, we developed thermos-kinetic models to enable design of heat treatments for optimal material properties compared to the energy intensive empirical methods currently used. The report summarizes the detailed findings of this collaboration.

1. EVALUATION OF ADDUP PRECISION L-PBF TECHNOLOGY FOR TOOLING AND OTHER INDUSTRIAL APPLICATIONS

This Manufacturing Demonstration Facility (MDF) technical collaboration project was started on May 18, 2019 and was completed on May 21, 2021. The collaboration partner for this project was AddUp Inc. In this project ORNL and AddUp evaluated the AddUp FormUp350 laser powder bed fusion (LPBF) system for the deposition of maraging steels for tooling and other industrial applications. The focus of this work was understanding the material properties in as deposited and heat-treated conditions as well as demonstrating its used for the fabrication of tools for injection or compression molding applications.

1.1 BACKGROUND

The tooling industry is a vital indicator of the health of the manufacturing sector of a nation. Over the course of the last few decades, majority of the tooling has been offshored from the U.S. that has eventually led to the loss of expertise as well as productivity. Even globally, the tooling industry often suffers from long lead times and geometric limitations for the tool and subsequently part geometries. Additive manufacturing (AM) technologies such as laser powder bed fusion offer a unique opportunity for tool and die manufacturing by reducing the lead times, enabling the fabrication of prototypes to allow rapid design changes and incorporating features such as conformal cooling channels that can improve the tool efficiency by as much as 25%. Steels are the most suitable materials for tooling applications. However, the solid-state phase transformations in steels combined with the residual stresses in AM limits the selection of printable materials. Maraging steels have been shown to have excellent printability as well as the potential for controlling mechanical properties via post fabrication heat treatments. The participant has substantial experience in developing the process parameters for successfully printing maraging steels using fine powders to achieve superior surface finish, especially important for tooling applications.

1.2 TECHNICAL RESULTS

Two distinct builds were deposited using the AddUp LPBF system using a Ti-free Grade 300 maraging steel: an artifact developed by the National Institute of Standards and Technology (NIST) as well as an artifact developed internally at Oak Ridge National laboratory to determine the accuracy of printing using the system compared to the computer aided design (CAD) file. Figure 1 summarizes the findings by comparing the measured dimensions using white light measurements with the CAD dimensions and the printed parts were within 0.5mm of the desired dimensions.

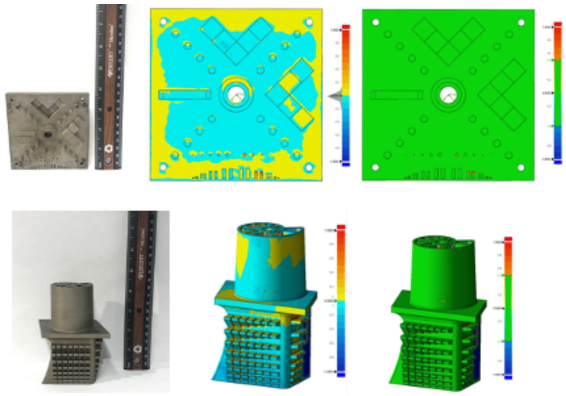

Figure 1. Comparison between the NIST and ORNL artifacts deposited on the AddUp FormUp350 system

The current practice for laser powder bed fusion (LPBF) deposited maraging steels is to stress relieve them followed by a solutionizing and aging heat treatment which can be time and energy intensive. Therefore, ORNL leveraged direct aging treatment to determine if it offers any benefits over the conventional heat treatment [1]. It was demonstrated that a direct aging heat treatment results in simultaneously higher strength and elongation compared to a two-step solutionizing and aging heat treatment as shown in Figure 2. This was attributed to transformation induced plasticity (TRIP) effect [2].

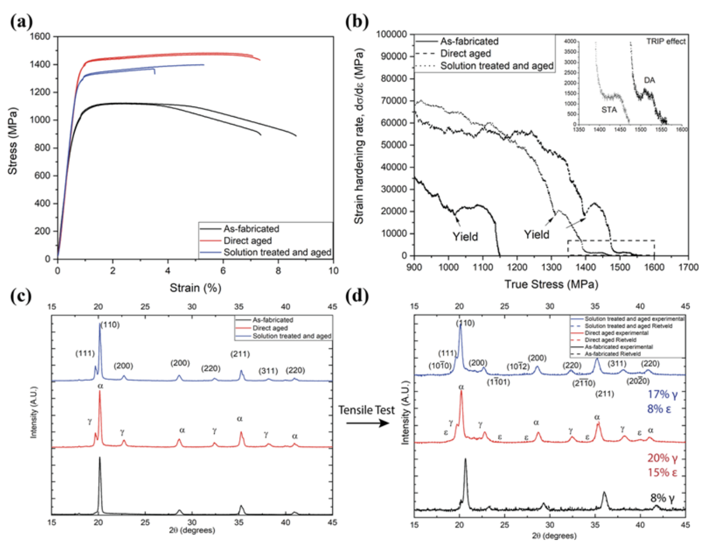

Figure 2. shows higher strength and elongation for direct aged sample compared to a two-step heat treatment as well as higher strain hardening rate during direct aging

The higher strength was attributed to a higher precipitate density in the direct aged condition whereas the TRIP effect was attributed to higher fraction of retained and reverted austenite during direct aging which leads to higher elongation. The direct aging was conducted at 480 ºC based on the peak aging temperature for wrought maraging steel. However, it is well known that the initial microstructure during AM can substantially impact the peak aging temperatures. Therefore, Integrated Computational Materials Engineering (ICME) approach was used to optimize the direct aging temperature a-priori compared to a trial-and-error approach to optimize the aging temperatures. The model was validated based on the calculation and determination of precipitate volume fraction during direct aging based on the characterization of the initial microstructure [3].

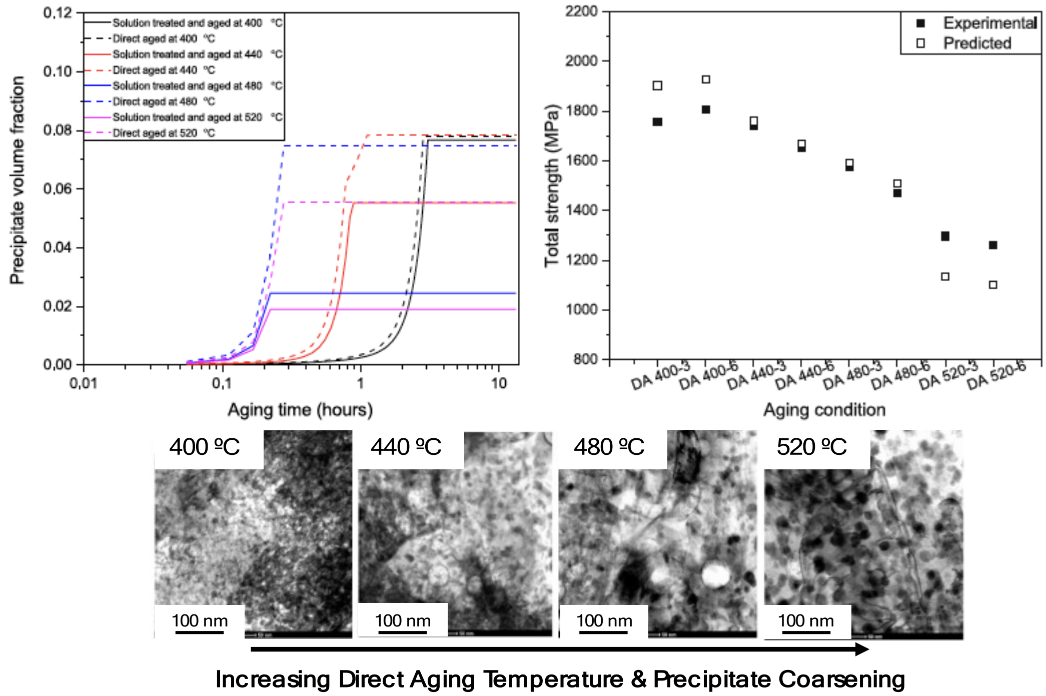

Figure 3 shows the predicted precipitate volume fraction of the strengthening precipitates, and comparison between experimental and calculated strength values, and the transmission electron micrographs showing an increase in precipitate size and volume fraction changes with increasing

Note that the combination of thermo-kinetic models along with strength prediction models agree closely with the experimentally measured values. Based on these models, appropriate heat treatments can be selected for desired strength values. However, these are not sufficient to determine the optimal direct aging treatment. Therefore, further characterization was done to determine the optimal direct aging heat treatment for high fracture toughness as needed for tooling applications, the area under the tensile curve was plotted and the extend of recrystallization of martensite was measured, as summarized in Figure 4.

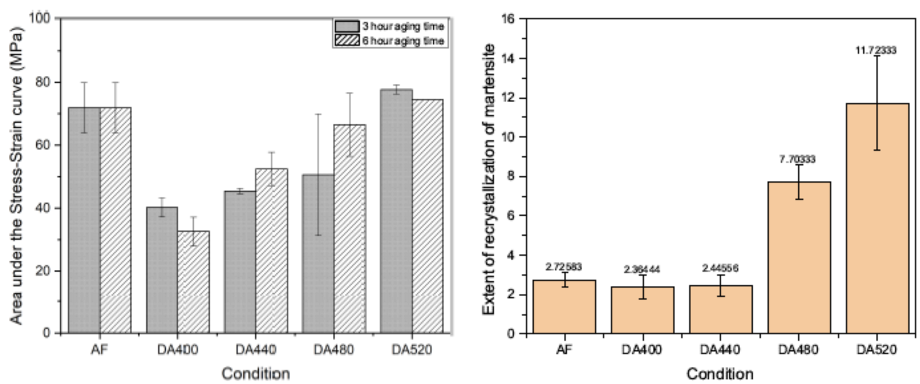

Figure 4 shows the area under the stress-strain curve and the extent of recrystallization of martensite with varying heat treatment conditions

The area under the stress-strain curve is the highest in the as-fabricated condition which also has the lowest strength though. In the case of direct aging, increasing direct aging results in a loss of strength as seen in Figure 3 with an associated increase in the area under the stress-strain curve, as expected.

However, it is interesting to note that, the recrystallization of martensite remains steady until direct aging at 440 ºC and is comparable to the as-fabricated condition, above which it increases significantly. Therefore, based on the extent of recrystallization of martensite and the area under the stress-strain curve, 440 ºC was determined to be the optimal direct aging heat treatment temperature [4]. We further studied the texture evolution during processing and post-process heat treatments of this maraging steel, the results of which are not presented for brevity [5].

The Ti-free Grade 300 powders were used to deposit a large-scale injection mold tool to demonstrate the use of the AddUp FormUp 350 system for tooling applications and the process flow is summarized in Figure 5. The tool was made as two faces with conformal cooling channels, following which the plates were machined to required tolerances. The internal features were left unmachined to determine the effect of AM surface roughness on resulting injection molded composite properties as shown in Figure 5. Tensile bars were also injection molded (not shown) along with the coins. The injection molded tensile bars had similar modulus and strength compared to the tensile samples obtained via a conventionally manufactured injection mold, indicating that the relatively rough AM surface finish does not have negative impact on strength and modulus.

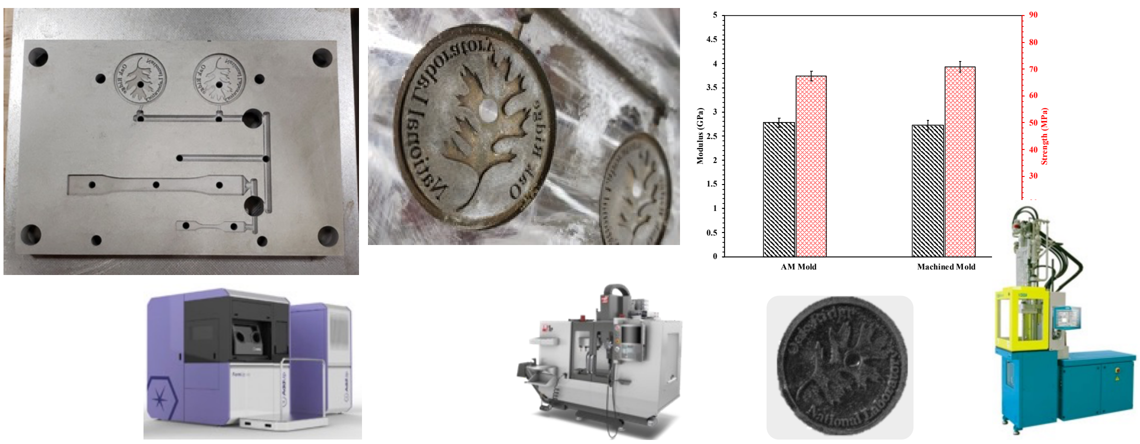

Figure 5 shows one face of the conformally cooled injection molding tool, machined surface, and properties of injection molded material from the AM tool compared to a conventionally machined tool

Finally, the in-situ monitoring capabilities on the FormUp350 system were also evaluated using the Peregrine tool developed at ORNL. The AddUp FormUp 350 is enabled by LayerQam, a 5MP 8-bit grayscale optical camera, which captures two images per layer: one post-laser fusion and one post-powder spreading. There is also a 0.3MP microbolometer which captures a thermal image of the same print area immediately after laser fusion. Figure 6 shows a post-fusion image and Peregrine's pixel classifications overlaid as determined by the convolutional neural network (CNN) which is trained by subject experts who have labeled images with example cases of user-defined pixel classifications. The AddUp FormUp 350 features a bidirectional recoating mechanism commonly referred to as "the carriage" which rolls powder both left-to-right and right-to-left. As a result, lighting artifacts maybe created on even and odd layers which the CNN was trained to distinguish.

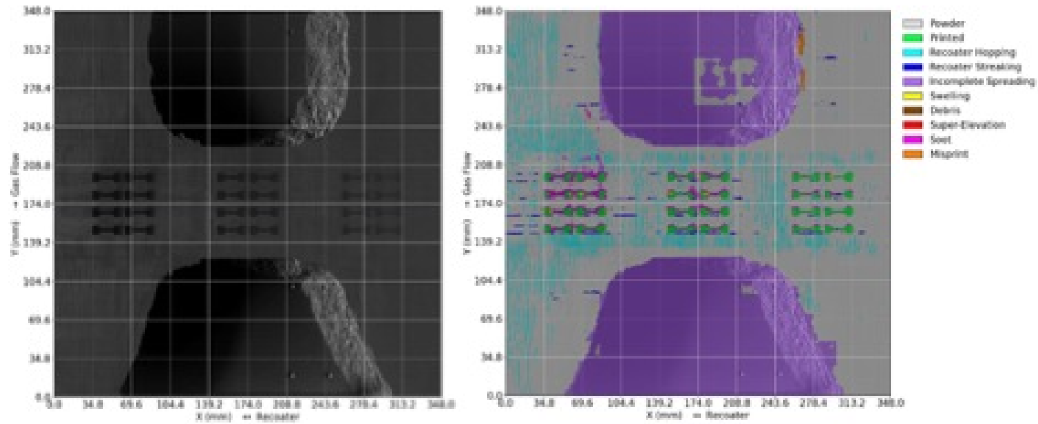

Figure 6 (left) shows a post-fusion optical layer image taken on the AddUp FormUp 350 and (right) Peregrine's pixel classification overlay determined via convolutional neural network trained via user-input ground truths.

Figure 7 shows the use of the in-situ monitoring system coupled with the trained CNN using Peregrine highlighting printed parts, soot and swollen regions on a set of tensile builds. This capability has been useful in rapid development and exploration of process parameter space, especially with changing geometries. The ability to capture swelling events can enable the operator to either turn off the build or change the process parameters on the fly to reduce swelling and avoid build failure.

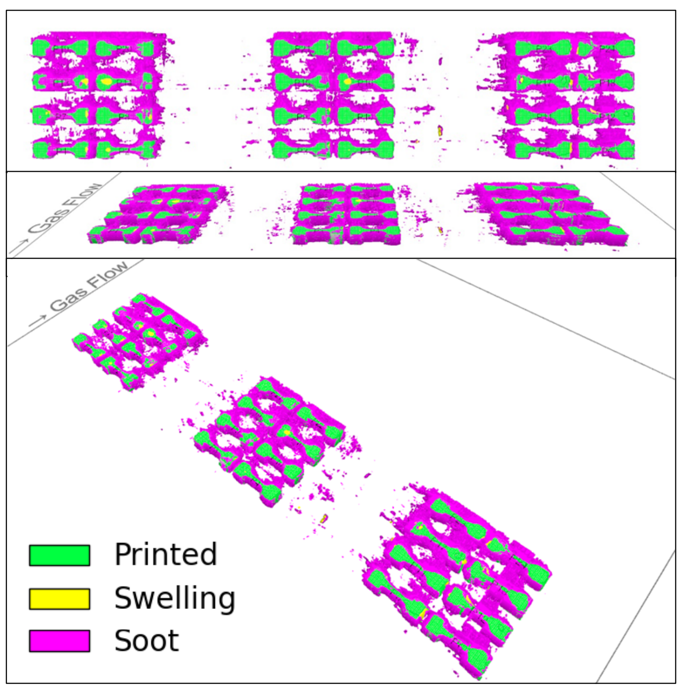

Figure 7 shows 3D reconstructions of Printed, Swelling, and Soot pixel classifications of (top) a top-down view, (middle) a front-on perspective view, and (bottom) an isometric view.

Figure 8 shows an example log file data for various fields of interest like build time, layer times, enclosure oxygen levels, average start plate temperature, etc. that can be correlated on a layer-by-layer basis. Visualizing such data can be critical especially for geometries with varying cross section thickness since a change in print cross-section can reduce the overall layer time and hence the thermal history in specific regions of a component that can also impact the microstructure and properties on a local level. This data can enable site specific characterization efforts that can allow for developing a workflow for part qualification.

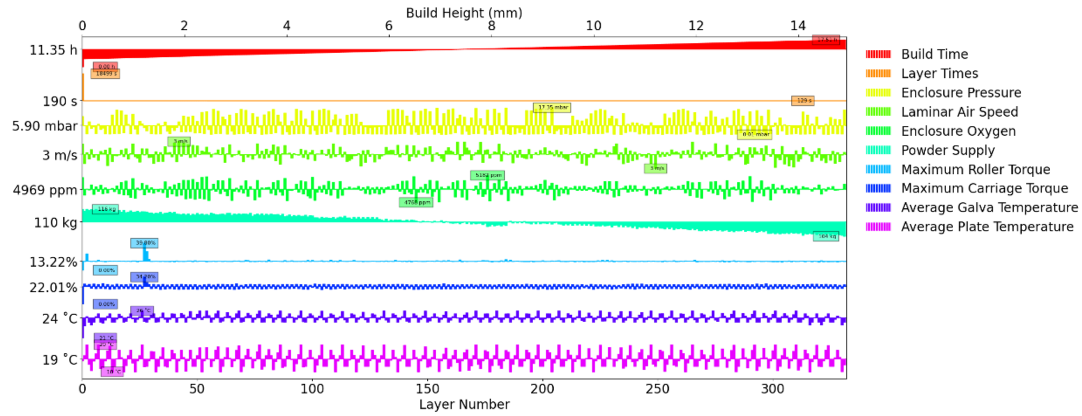

Figure 8 shows an example log file plot generated by Peregrine for the default variables logged by the AddUp FormUp 350.

In the future, a newer system with an in-situ meltpool monitoring system will be evaluated that can provide critical data to calibrate and fine tune thermal and melt pool models for the fabrication of grade 300 maraging steel and other alloys for structural applications.

1.3 CONCLUSIONS

In summary, this CRADA between AddUp and ORNL demonstrated that Grade 300 maraging steel can be used for tooling applications. Laser powder bed fusion of this steel results in unique microstructures that make it amenable to direct aging instead of time and energy intensive two-step heat treatments needed for conventionally fabricated material. Further, we developed thermo-kinetic models to enable apriori determination of appropriate heat treatments which can help bypass the empirical approach to conduct heat treatments.

PUBLICATIONS

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4. Kannan and Nandwana, Effect of phase transformations on mechanical properties of Ti free grade 300 maraging steel manufactured by laser powder bedfusion (LPBF), AWS Fabtech 2020.
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