Post-Processing of Direct Metal Laser Melting of IN-738

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Due to the sensitive nature of the projects described here, critical details have been left out in order to protect GE’s Intellectual Property.
1. Introduction

Greenville, South Carolina is home to the largest industrial gas turbine facility in the world. In order to create these titanic engines, multiple kinds of components and processes need to be developed and maintained. That is part of the reason the advanced manufacturing works (AMW) at GE Greenville was created. Over the summer of 2019, process development and studies on current processes were carried out in the additive manufacturing team. These included standing up a new fluorescent penetrant inspection (FPI) booth, studying the effect of roughness of additive parts on the efficacy of FPI, study of the heat treatment process on IN-738, and the development of an estimator for the time it will take to additively manufacture parts out of metal.

Through this internship, there were multiple goals having to do with the post-processing of additively manufactured components. Improving the post-processing capabilities of the AMW at GE allows for a shorter time to market, improved yield on production of additively manufactured (AM) parts, and a clearer picture with which to make effective decisions. One of the first post-processing techniques improved was fluorescent penetrant inspection (FPI) capability at the AMW. While working at the AMW, I helped set up an FPI system and started calibration and qualification on it.

Another of the projects I worked on was developing an additively manufactured quality indicator for FPI and testing the efficacy of FPI on AM parts regarding the roughness of the surface. This involved using Siemens NX to generate a model. I also interfaced significantly with other engineers on what the design should look like.

Parts built with additive manufacturing need to undergo a heat treatment process in order to reach a microstructure that appropriate for an engineering application. Studying this heat treatment process is integral to creating a heat treatment that has the maximum yield possible. Finally, a couple other projects done over the summer were to build a build time estimation model as well as making the powder capsule into a part file in Siemens NX.

2. Fluorescent Penetrant Inspection Booth Setup

Setting up a fluorescent penetrant inspection booth in the AMW was one of the first tasks I was assigned. This involved mostly making sure the improvements to the FPI Booth was signed off on by EHS. The first task was to determine what needed to be completed. Modifications made to the original installation were a splash guard and a GFCI outlet on the back. As the booth uses water, there is danger of electrocution should the water conduct electricity through a user. The system was brought up to specification and a work instruction document was written so that operators and engineers could easily perform FPI on parts.
3. Roughness studies of as printed parts

The purpose of this project was to understand cost/cycle to surface treatment parts to enable FPI. The point was also to attempt to validate or disprove minimum detectable crack limits based on the roughness of the surface. This was done by creating coupons using siemens NX to imitate discontinuities in additively manufactured parts. This was followed by performing surface roughness with the profilometer in figure 3 and testing the parts with FPI. Then, the coupons were treated using
different surface treatments to decrease the surface roughness. The values of surface roughness were once again determined, and the panels underwent FPI.

**Figure 3:** Surface profilometer used to determine the roughness of the AM coupons.

Values of 325 Ra were normal for as built panels, whereas the panels after full surface treatment have a roughness around 200 Ra.

Panels after FPI can be seen in figure 4. As is apparent in the picture, the smallest indication can be seen in the top right corner. However, the smaller indications did not show up because they welded to themselves as they printed. Note that the as built sample has much more residual penetrant on the surface than the sample that went thru surface treatment.
4. Heat Treatment Process

After parts are build using direct metal laser melting, they need to be post-processed to be useful in an engineering function. Much of this post-processing is cleaning, machining, and inspecting the parts so that they are within the tolerances of the function they need to perform. However, one of the major parts of a metal AM part post-processing is a heat treatment process. In this study, the heat treatment process of IN-738 was studied to determine the point at which parts built out of this material will undergo stresses/strains that reach a critical level and could result in cracking.

For this task, one of the intended goals was to create a model that would predict the precipitation of $\gamma'$ in these alloys as they went through heat treatment. One of the methods used to do this was by using cellular automata to discretely model diffusion in the part during heat treatment. An example of a cellular automaton can be seen in figure 5. Simulations were also run in Thermo-Calc to determine the expected phases. Finally, simulations were tested against reality in experiments run on as-built and heat-treated samples. Differential scanning calorimetry was used to determine where transformations were taking place and which samples (as built or heat treated) were being affected by transformations.

Thermo-Calc was used as a major part of this project. It works by taking data collected by a multitude of papers and collects it into a database. Then it uses this data to inform an equilibrium
calculation as to what phases should be expected at a certain temperature, pressure and composition, as well as other thermodynamic parameters. This can be used for both equilibrium and solidification. By doing both calculations, the solidification microstructure expected can be compared to the equilibrium microstructure expected.

Figure 5. An example of a 1D cellular automaton.

A cellular automaton is a series of cells that have rules denoting their state relative to the cells adjacent to them. By doing an analysis of each cell at a certain time point, then comparing cells to each other, one can simulate time passing and each cell moves on to a new “generation”. This can be used to simulate microstructure on a macro scale.

By using equations found in Karunaratne et. al. [1], it was attempted to go from solidified microstructure to equilibrium microstructure by diffusion. This was done by creating a cellular automaton using volume pixels, or “voxels” as cells, with rules denoting their states. Each voxel would be assigned composition, temperature, and a diffusion coefficient at that temperature. These values could be stored and retrieved from a database. Then the voxels would change according to their adjacent cells. This was the idea, but unfortunately, the equations used ended up providing a negative aluminum content. Thus, other trials should be run, giving the equations and model more scrutiny.

Experiments were also carried out to attempt to understand the transformations occurring during heat treatment. The DSC curves generated show a large peak at 575°C in the as built sample (Figure 6), but no such peak in a sample heat treated to 1000°C for two hours (figure 7).
Figure 6: The DSC curve of an as built IN-738 sample.

Figure 7: The DSC curve of an IN-738 sample heat treated at 1000°C for 2 hours.

Scanning electron microscopy was performed on a sample heat treated to 575°C for two hours (Figure 8) as the DSC curve shows a transformation there. However, the results are inconclusive as to what transformation occurred. Studies must be performed on the as-built microstructure to determine if any significant changes are apparent. However, a large number of carbides are apparent at the grain boundaries, but no $\gamma'$ could be precisely determined.
Figure 8: SEM micrographs of a sample of AM IN-738 heat treated to 575°C.

Thermo-Calc phase diagrams were created for both all phases and only select phases. In the all phases calculation (figure 9), $\gamma'$ is the largest constituent at low temperatures below 1000°C, followed by sigma phase. However, no sigma is seen in as built or even heat treated IN-738.

Figure 9: A phase diagram of IN-738 from Thermo-Calc. This one accepts all phases as possible.

In figure 10, one can see the phase diagram made from running Thermo-Calc of IN-738 with rejecting all phases but $\gamma$, $\gamma'$, and liquid phase. Extra phases can be seen, but for the most part, $\gamma'$ makes up the majority of the phase diagram again.
Figure 10: A phase diagram of IN-738 from Thermo-Calc. This one rejects all phases except \( \gamma, \gamma', \) and liquid.

In figure 11, a scheil solidification curve of IN-738 can be seen. It is apparent in this curve that the first phases expected are \( \gamma \), as well as a BCC phase, likely from the high amount of Co and Cr. Finally, at around 1100°C, \( \gamma' \) shows up. This implies that there is an extremely small amount of \( \gamma' \) expected in the as solidified microstructure.
5. Build Time Estimation

A build time estimator was programmed in python using sci-kit learn’s multiple linear regression function. The input parameters were that the machine, material, and parameter set were constant, and the values of the build volume, build surface area, and build z-height were known. Then the model was fed build times for their corresponding input parameters. This allowed it to build a prediction of how long builds would take given the parameters provided. A summary of the software developed can be seen in Figure 12. Results can be seen compared to reality in Figure 13. Note that sample 5 has no value (nan), but the model was able to predict it to be 33 hours long.
Figure 12: A software diagram of the model built.

![Diagram](image)

**Figure 13:** The actual time vs. the model prediction in hours. One potential improvement would be to truncate the prediction times to be only 2 decimals.

The \( R^2 \) value of this model ended up being around 0.99. This shows that the model fits very closely to the real results. It was able to predict values on the order of magnitude of the real results, which is better than had been done before.

6. Powder Capsule Design

This project was one that needed to be done to improve the builds that the team was performing. The powder capsule is used to document what the state of the powder was for a build, so that analysis does not need to be performed every time. This is done by building a 3D wall around the powder, such that the powder has no egress from the structure. This allows the history of the powder used to build the part to be easily saved and catalogued for later analysis.
7. Conclusions

There were multiple conclusions from this variety of projects. One from the FPI roughness study is that 3D printing very small features is difficult. From the heat treatment process study, we understand that there are a few different events taking place during the heat treatment that bear more scrutiny. Transformations at 575°C and 1065°C may be of interest for heat treatment – perhaps bounds for the heat treatment process. From Thermo-Calc, a large amount of γ' and other TCP phases are expected to appear at equilibrium. However, this is often hard to determine as kinetics of these phases are very slow.

References


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