

Article

Application of mathematical search algorithms for unknown material properties in Additive Manufacturing simulations

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Abstract: Additive manufacturing (AM) simulations have risen as a way to better understand the effect of processing parameters on builds. They are effective for materials which are well characterized and published, however for newer or proprietary materials, they cannot provide accurate results due to the lack of knowledge of material properties. This work demonstrates the process of the application of mathematical search algorithms to develop an optimized material dataset which results in accurate simulations. This was done with 7000 series aluminum and the laser directed energy deposition (DED) process. The Nelder-Mead search algorithm was able to develop an optimized dataset which had a combined width and depth error of just 9.1%. This optimization started from a generic aluminum material properties dataset found in the literature which had an initial error of 600%.

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1. Introduction

Additive manufacturing (AM) is an emerging manufacturing technique which has the potential to revolutionize manufacturing. To realize this revolution, it is necessary to be able to produce components reliably and to understand the process well enough to ensure that builds are consistent enough that the performance of the completed build can

¹ Updated the abstract

² Updated the keywords

be guaranteed. To do this, researchers and manufacturers have turned to mathematical modeling to understand the process [1]. This body of work focuses solely on increasing the accuracy of thermal modeling of the process however the thermal cycling that a build experiences has an effect on the resulting microstructure [2–4], residual stress and distortion [3,5,6], and porosity of the build [7–9]. If the underlying thermal modeling prediction can be improved then the subsequent properties can be more accurately modeled as well.³

The differences in simulation techniques can vary based on the desired response from the simulation and the underlying assumptions which were made during the development of the models. One example of this can be seen when comparing the mathematical models developed by Wang and Chen presented in [10], Roy and Wodo [11], and Moges et al. [12]. They all attempt to model roughly the same aspect of the build but take very different approaches. Wang and Chen [10] take a purely physics-based approach to the solution and works from first principle of the physical process being modeled this is done for Ti-64 and was able to get an accuracy of between 3.6% and 9.0%. On the contrary, Roy and Wodo [11] is a data driven model which used a breadth of data to develop a mathematical model which properly predicts the material behavior this model is applied to the plastic fused filament fabrication (FFF) process due to the volume of data required. It would be possible to develop for a metal process, though could become cost prohibitive quickly. In between these models exists Moges et al. [12] which attempts to marry the two approaches and develop a physics-based model that uses data to improve accuracy for Inconel 625 it was able to produce results with an average relative error of 7.58%.

The one unifying characteristic of these, and all, mathematical models, is the need for the inclusion of a dataset which defines the behavior of the material being investigated, this is colloquially referred to as the material properties. These material properties can vary in literature and this variance in values can lead to a discrepancy in simulation results [13]. This need for input material properties extends to surrogate models which have been developed such as machine learning (ML) models, will require the inclusion of these material properties in order to properly predict the outcome [14–17].⁴

Though variation exists in the literature, values can be found and used when the material is well characterized and published. An example of a well published material is Ti-64 where it is easy to find literature which reports the material properties such as Welsch et al. in [18], Boivineau et al. [19], and Fan and Liou [20]. However, for materials

³ Added justification for need for more accurate thermal modeling

⁴ Added notes of the material modeled and its accuracy,

which are not well characterized understood and published, such as specific aluminum alloys, it can be very challenging though possible to find some properties such as reported by Lindberg [21] and Leitner et al. [22]. There is a need to determine a complete dataset of the material properties, or at a minimum, develop the dataset which produces the most accurate simulation results. This can be accomplished by expending the necessary resources to measure the needed properties using advanced equipment. This process can be expensive and time-consuming which has led to the development of material simulations which attempt to predict the material properties, such as JMatPro[23]. Though faster and cheaper than experimental results, they, like all simulations, have an error that is associated with them, this is reported by Liu et al. [24], Chen et al. [25] and Geng et al. [26]. Using these values alone can lead to unknown errors stacking up in the AM models. This problem also applies to materials where the tolerances for alloying elements is so wide that specimen of the same alloy can have different material properties.

In order to develop a dataset which produces accurate AM simulation results, an multi-objective optimization routine scheme can be used as a search algorithm to determine the dataset which produces the most realistic results. This can be used to develop a dataset for a new alloy along with for a specific batch of stock which has been procured from a supplier.

This work will aim to address one of the current desires in metal AM which is to be able to produce parts out of aluminum. The desire is evident by the volume of effort being applied to aluminum AM ([27], [28], [29]). The challenge associated with this stems from the wide range of alloys which have wildly varying material properties and are not well published. One of the weldable high-strength alloys which has been targeted for metal AM is 7050 [30]. Though the material is widely available, temperature-dependent material properties are not readily available. This work will perform an optimization routine on the material dataset for 7050 aluminum alloy to enable more accurate simulation results. This will be done by validating the model on the well characterized Ti-64 material showing the model's effectiveness. Then utilizing sister alloys, a generic material property dataset will be found from literature. The search algorithm will then be applied to generate an optimal input properties dataset. These optimized material properties will then be used with a range of laser parameters and compared experimentally to show their effectiveness over a processing window. Therefore, this work will find material properties in literature which are an approximation of the 7050 aluminum, namely sister alloys with similar compositions, as a starting point for the search algorithm. From that

starting database, a search algorithm will be applied to develop a material dataset which produces more accurate AM simulation results.⁵

2. Materials and Methods

This body of work begins by describing the thermal model which was developed to simulate the metal AM deposition process for any metal where the material properties could be determined. This model is then validated using a well characterized material, Ti-64. Upon validation of the thermal model, it is applied to a generic aluminum alloy *Representation*⁹¹ and experimentation is used to determine if the results are a good characterization of the physical process. When found to be inaccurate, a mathematical search algorithm was applied to the input parameters in order to increase the accuracy of the models results. Lastly, the optimal input dataset was validated by comparing the simulated results to experimental results with a range of laser scan speeds and power levels.⁶ *for the target Al alloy*⁹⁵

2.1. Simulation description

The model used in this study was developed at Missouri University of Science and Technology. This simulation has the express goal of being efficient while still holding true to physics models. In order to accomplish this, it heavily leverages GPU processing by utilizing image processing techniques. The simulation was developed with the laser DED processes in mind, however, it was developed in a modular manner such that it can be applied to most AM processes.

The model is a voxel-based simulation, which forgoes the calculation of the fluid flow and focuses on heat transfer and material insertion. This decision was based on past simulation development experience, where it was determined that the calculation of the fluid flow was the most computationally expensive part of the simulation.

The governing equations of the model developed can be seen in Equations 1, 2, and 3 which describe the flow of heat from conduction, convection and radiation, and laser absorption respectively [31].

$$\rho c_p \frac{\partial T}{\partial t} = k \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) \quad (1)$$

$$k \frac{\partial T}{\partial n} = -h(T_s - T_a) - \varepsilon\sigma(T_s^4 - T_a^4) + \phi(x, y, z) + \rho c \frac{\partial T}{\partial t} \quad (2)$$

⁵ Added explanation of plan for this body of work

⁶ This section was added to provide a sketch of the methods used in this work

$$\phi(x, y, z) = H(z)\alpha\phi_0 \sqrt{1 - \frac{x^2}{r_0^2} - \frac{y^2}{r_0^2}} \quad (3)$$

In these equations, ρ is density, c_p is specific heat, k is thermal conductivity, h is convection coefficient, ε is emissivity, σ is Stefan-Boltzmann constant, n is the unit (outward) normal vector of a point at location (x, y, z) that is located on the outer surface of the component, r_0 is the radius of the laser beam, α is the absorption of the material with respect to the laser radiation, T_s is the surface temperature, T_a is the ambient temperature, ϕ_0 is the laser power, and $H(z)$ is a step function which is 1 for the node with the largest z value in every (x, y) location and 0 elsewhere.

The main attributes of the model are its ability to predict the thermal history of a part, Figure 1a, the phase map of the part at any given time, Figure 1b, and a cooling rate for any section of the part, Figure 1c. This helps to give a predictor of the microstructure within the deposition which is the driving force behind the final mechanical properties. Additionally, the laser in the simulation is modeled in 3-D to be able to take into account

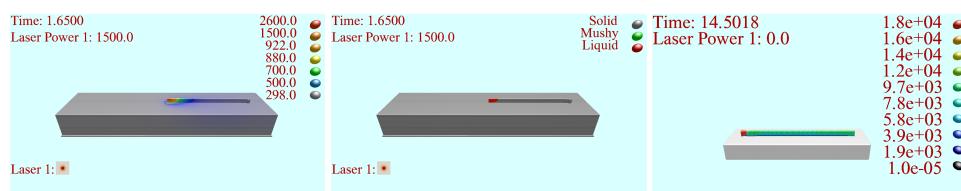


Figure 1. Examples of data maps which can be expected from the simulation.

the beam quality using the beam parameter product (BPP) reported by the manufacturer and shown in Equation 4, where θ and w_0 are the divergence angle and the beam waist respectively.

$$BPP = 0.5\theta w_0 \quad (4)$$

Lastly, the model includes true ray tracing enabling shadowing of the laser, the ability to define a mass which represents the machine acting as a heat sink during the build process, and the inclusion of temperature-dependent material properties.

The main objective of the model is to accurately predict the thermal history of the build. In order to initially validate the models, the well-characterized and published material of Ti-64 was used. The validation was done by scanning a laser on the surface of a substrate at three energy densities with the experimental parameters found in Table 1 and the material properties used in the simulations can be seen in Table 2.⁷

⁷ Updated table to include the property values for Ti-64

Table 1. Simulation parameters used in Ti-64 validation

| Parameter | Value |
|-----------------------------|--|
| Resolution | 60 μm |
| Laser diameter | 2.0 mm |
| Laser Profile | TEM00 |
| Laser power | 1000 W |
| Energy density (Equation 5) | 13, 18, 24 $\frac{\text{W}}{\text{mm}^3/\text{sec}}$ |
| Scan Length | 45 mm |
| Substrate dimensions | 55 mm x 12.7 mm x 6.35 mm |

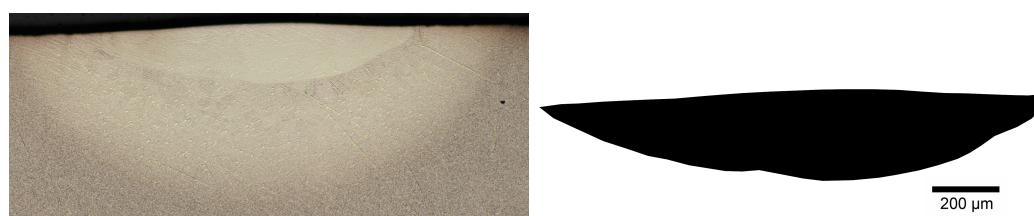
Table 2. Ti-64 material properties used in validation

| Material Property | Value | Reference |
|----------------------|---|-----------|
| Solidus temperature | 1603°C | [18] |
| Liquidus temperature | 1650°C | [32] |
| Solid density | 4420.0 $\frac{\text{kg}}{\text{m}^3}$ | [32] |
| Fluid density | 3920.0 $\frac{\text{kg}}{\text{m}^3}$ | [32] |
| Specific heat | 0.4 - 1.15 $\frac{\text{J}}{\text{gK}}$ | [19] |
| Thermal conductivity | 5.0 - 43.0 $\frac{\text{W}}{\text{mK}}$ | [19] |
| Absorptivity | 0.4 | [20] |

There are several representations of the energy density of a laser beam in AM but the most appropriate method of calculating the energy for the DED process is to use a surface energy density, Equation 5, where P is laser power, A is the laser spot area, and v is the scan speed [33].

$$\text{SED}_{\text{area}} = \frac{P}{Av} \quad (5)$$

In order to analyze the results, the samples from the three parameter sets were sectioned using a wire electrical discharge machine (EDM), polished using an automated polisher to a mirror finish, and etched using Kroll's reagent⁸ to make the melt track visible with an optical microscope as can be seen in Figure 2a, this was done at three points along the melt length. The experiment and simulation were compared and the resulting error



(a) Sample image of the etched slice

Figure 2. Analysis of sliced sample in Ti-64 validation

for the width can be seen in Figure 3a and the depth can be seen in Figure 3b. The average values which are reported on the graph have an associated standard deviation of the 0.62

⁸ Detailed Ti64 etching routine

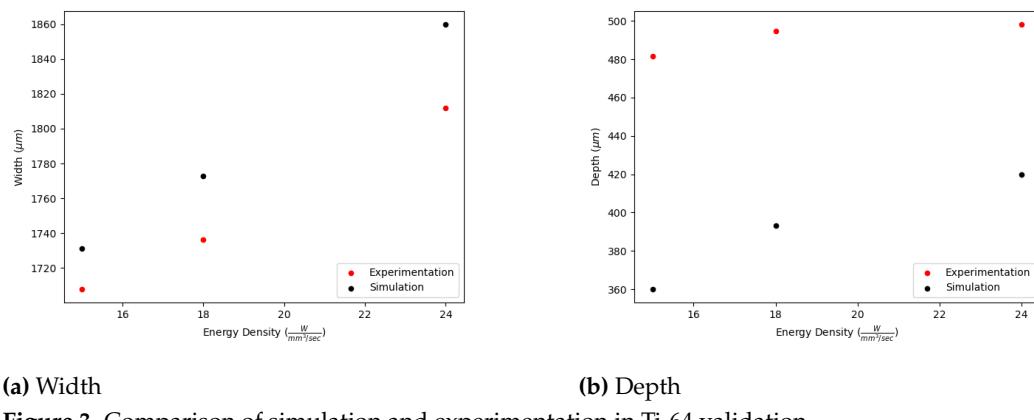


Figure 3. Comparison of simulation and experimentation in Ti-64 validation.

μm , $13.7 \mu m$, and $7.74 \mu m$ for the width measurements for the energy densities of $15 \frac{W}{mm^3/sec}$, $18 \frac{W}{mm^3/sec}$, and $24 \frac{W}{mm^3/sec}$ respectively. For the track depth the standard deviations are $70.2 \mu m$, $113.7 \mu m$, and $13.7 \mu m$ for the energy densities of $15 \frac{W}{mm^3/sec}$, $18 \frac{W}{mm^3/sec}$, and $24 \frac{W}{mm^3/sec}$ respectively.

From the plots, it can be seen that the simulation is capable of predicting the width within 3% error and the depth error is between 15% and 25%. The error in the width is very acceptable at less than 3%. However, the error in the depth is larger due to the resolution (voxel size) of the simulation chosen and its relative size to the depth. This error, of approximately 20%, for the depths which range from $450-500 \mu m$ is 1.3-1.7 times the resolution, $60 \mu m$, of the simulation. Since the trends of the simulation and experimentation match and the error is within two resolution distances the 20% error in the depth is considered acceptable as well. This shows that the mathematical models developed are accurate and if the material property is well characterized, the simulation will produce accurate results.

2.2. *Search Tuning* algorithm description

The search algorithm chosen was the Nelder-Mead search algorithm [34]. This method was selected because it is one of the most popular direct search methods for the minimization of functions. The Nelder-Mead approach is a local optimization search which does not rely on knowledge of the gradient to select the next search point. This is critical for the application to simulation results because the gradient is unknown and finding it would involve running a large number of simulations. With simulation times that can reach into days long, this is a critical consideration. Instead of knowing the actual function, it relies on $n+1$ vertices. This results in a smaller number of simulation runs being needed to perform the minimization [35]. The flow chart in Figure 4 is the flow which is used to determine the next search point.

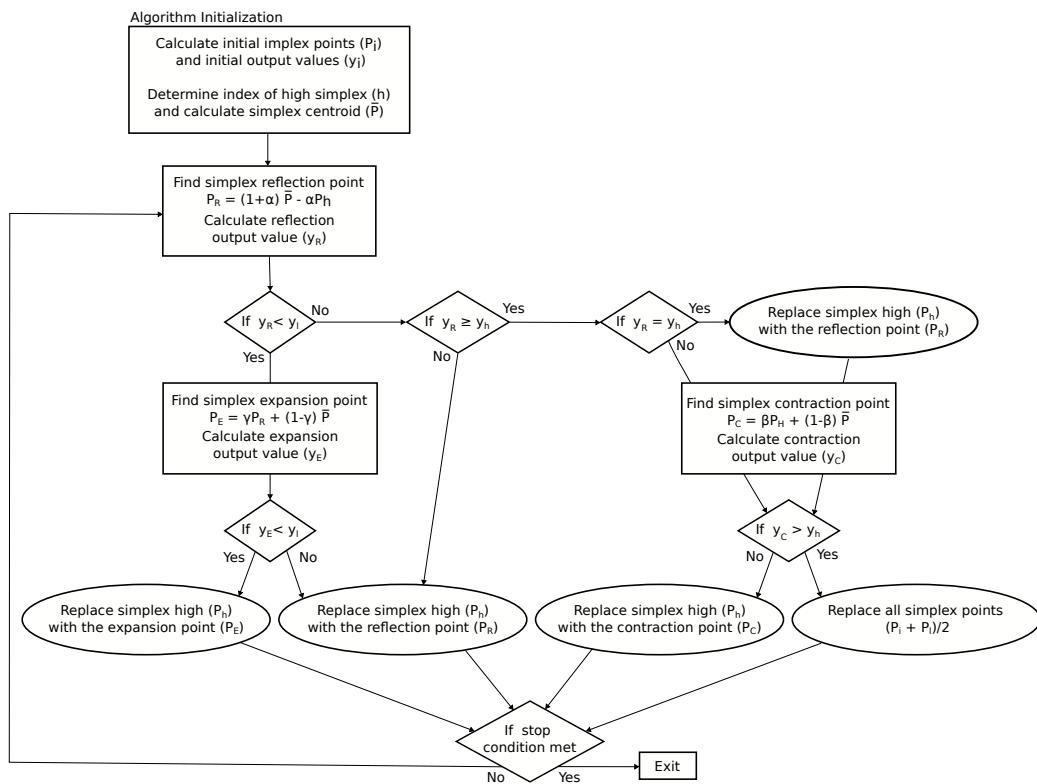


Figure 4. Flow chart for the Nelder-Mead search algorithm

The search begins by calculating the reflection point using Equation 6 where α is the reflection coefficient. 172

$$P_{refl} = (1 + \alpha)P_{cent} - \alpha P_{high} \quad (6)$$

If this reflection point is smaller than the smallest current simplex value, then the expansion 174 is calculated using Equation 7, where γ is the expansion coefficient. 175

$$P_{exp} = \gamma P_{refl} - (1 - \gamma)P_{center} \quad (7)$$

If the expansion point is smaller than the reflection point, then the expansion point is used to replace the largest simplex member. Otherwise, if the reflection point is larger than the expansion point, the reflection point is used to replace the largest member of the simplex, and the algorithm is restarted. If the reflection point is larger than the smallest simplex point and smaller than the second largest point, then the highest point of the simplex is replaced with the reflection and the algorithm is restarted. If the reflection point is between the simplex highest value and second highest value, a contraction is calculated, 180 using Equation 6, with the highest values being replaced with the reflection. Otherwise 181

the contraction is calculated with the original simplex still using Equation 6, where β is the contraction coefficient.

$$P_{cont} = \beta P_{high} - (1 - \beta) P_{cent} \quad (8)$$

If the contraction point is smaller than the largest point of the simplex, then the contraction replaces the largest point and the algorithm is continued. However, if the contraction point is larger than the highest point, a shrink step is performed, detailed in Equation 9, where δ is the shrink coefficient and the algorithm is restarted.

$$P_i = \delta P_i + (1 - \delta) P_{low} \quad (9)$$

2.3. Selection of Properties

One of the attractive characteristics of the Nelder-Mead search algorithm is its ability to scale to an unlimited number of unknowns. The main adverse effects of the scaling are the increased number of runs and the combination of the errors. As the number of unknowns increases the complexity of the search space increases, which in turn increases the number of iterations needed to find a minimum. This can result in drastically longer wait times for the search results. Additionally, with the increased number of unknowns, the stop condition of the search algorithm will be met at a different interval since the stop condition is based on the variance in the simplex. This may result in modifications to the stop conditions being necessary as a larger number of unknowns are included. If the response variable is properly defined, it will not affect the model's results if more unknowns are included [35].

In order to reduce the complexity of the search algorithm, a sensitivity analysis was performed. This work began by finding the material properties which were needed in the models as summarized in Table 3.

Table 3. Key material properties in thermal modeling of AM

| Material Property | Reference |
|----------------------|------------------------|
| Solidus temperature | [36], [21], [37], [38] |
| Liquidus temperature | [36], [21], [37], [38] |
| Solid density | [38], [39] |
| Fluid density | [38], [40], [22] |
| Specific heat | [21], [22] |
| Thermal conductivity | [21], [22] |
| Absorptivity | [41], [42], [43] |

These properties were varied according to a Plackett-Burman design of experiment in order to determine the properties which, when changed, had a statically significant effect

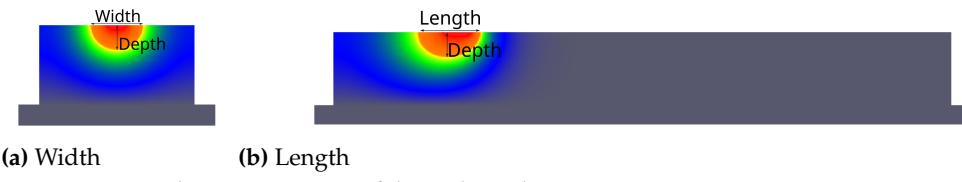


Figure 5. Example measurements of the melt pool

on the resulting melt pool width, depth, and volume, as measured in Figure 5. Analyzing these results with Pareto charts of the standardized effects of the variables and partial regression plots of the residuals it was determined that the variables in Table 4 had a statically significant effect on the resulting melt track when modified. This work included

Table 4. Critical material properties

| |
|--------------------------------|
| Laser absorption at 880°C |
| Laser absorption at 922°C |
| Thermal conductivity at 922°C |
| Thermal conductivity at 1491°C |
| Specific heat at 733°C |

the laser diameter in the search algorithms dataset due to the difficulty associated with accurately measuring the diameter, [this process is detailed in \[44\]](#).

2.4. *Parameter Search Tuning and Simulation setup*

For this study, the Nelder-Mead search algorithm parameters which were used can be seen in Table 5. These parameters were chosen because they fell within the guidelines from

Table 5. Nelder-Mead algorithm parameters

| Parameter | Value |
|-----------|-------|
| α | 5.0 |
| γ | 10.0 |
| β | 0.5 |
| σ | 0.5 |

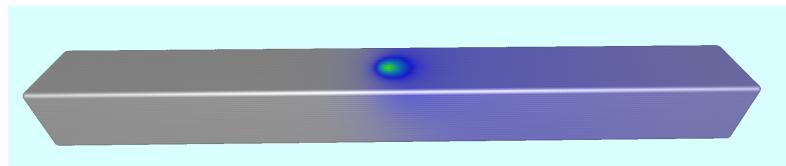
the algorithm description and after trial and error produced the most efficient [searching tuning](#) [34].

The starting values which were used as the starting point for the search algorithm can be seen in Table 6. These values were chosen based on the values which were found in the literature for similar aluminum alloys. The laser diameter was chosen based on the measuring of a melt track width on a substrate. To ensure the search algorithm did not waste time searching in unacceptable regions the constraint was included that none of the material properties were allowed to become negative. This was the only constraint which was needed in addition to the inherent constraints of the Nelder-Mead algorithm.

Table 6. Generic Aluminum materials properties found in the literature

| Property | Material Temp. | Value | Ref. |
|----------------------|----------------|------------------------|------|
| Laser absorption | 880°C | 15.0% | [42] |
| Laser absorption | 922°C | 30.0% | [42] |
| Thermal conductivity | 922°C | 88.8 $\frac{W}{mK}$ | [22] |
| Thermal conductivity | 1491°C | 104.9 $\frac{W}{mK}$ | [22] |
| Specific heat | 733°C | 1108.0 $\frac{J}{kgK}$ | [22] |
| Laser diameter | | 1.6 mm | |

The experimental setup which was used was a simple laser scanning of the surface of a substrate, as shown in Figure 6, with the parameters shown in Table 7. This was chosen in order to simplify the experiment. This setup removes the complexity associated with adding material which includes the rate of material addition, molten metal flow parameters, and acceleration effect associated with turning during deposits.

**Figure 6.** Example of simulation setup used to determine melt track size**Table 7.** Experimental constants used in search algorithm tuning experiments

| Parameter | Value |
|-------------------------|---------------------|
| Resolution (voxel size) | 100 μm |
| Laser Power | 1,750 W |
| Laser Scan Speed | 1143 mm/min |
| Laser Profile | Top Hat |
| Scan Length | 77 mm |
| Substrate dimensions | 82 mm x 8 mm x 8 mm |

2.5. Simulation analysis

Upon completion of each simulation run, the saved data files were analyzed to determine the regions of the simulation which had melted. This was done by developing a map which marked the locations of the domain that had ever been in the fluid phase. This map was then used to determine the width and depth of the melt track along the scan length, excluding the beginning and end where effects from starting and stopping motion would affect the results. These width and depth measurements along the scan length were averaged to develop a single measurement which could be compared to experimentation.

The experimental results were similarly determined, however instead of a continuous set of measurements, there were 4 discrete measurements. These were obtained by slicing the substrate at the prescribed locations using a wire EDM. These slices were polished

using an automatic polishing machine up to a mirror finish and etched using Keller's reagent⁹ in order to make the microstructural differences visible by an optical microscope, an example of this can be seen in Figure 7, where the dark region had been melted during the experimentation.

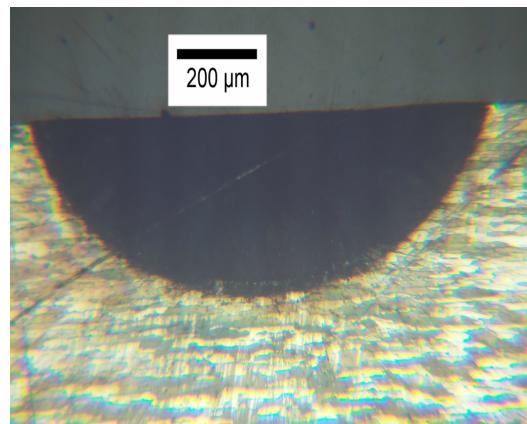


Figure 7. Example of sliced, polished, and etched slice from Aluminum experimentation

In order for the Nelder-Mead search to function properly, a response variable needed to be defined. This function needed to characterize the accuracy of the simulation into a single parameter which could be minimized and upon minimization would result in the most accurate simulation. To accomplish this goal, Equation 10 was developed. This equation takes into account the error in the width of the simulation along with the error in the depth. This equation results in a non-negative number where 0 represents a simulation which perfectly matched experimentation.

$$\text{Response} = \left(\frac{| \text{Sim. Width} - \text{Exp. Width} |}{\text{Exp. Width}} + \frac{| \text{Sim. Depth} - \text{Exp. Depth} |}{\text{Exp. Depth}} \right) * 100 \quad (10)$$

3. Results

3.1. Search algorithm results

The search algorithm was allowed to search the space to determine the best material properties. The resulting response variables can be found in Figure 8. Where the blue circular markers indicate material datasets which developed a melt track and the red diamond markers did not have the energy density to produce a melt track. Due to the vast difference in scales of the initial responses and the final response variables, a new plot

⁹ Detailed Al etching routine

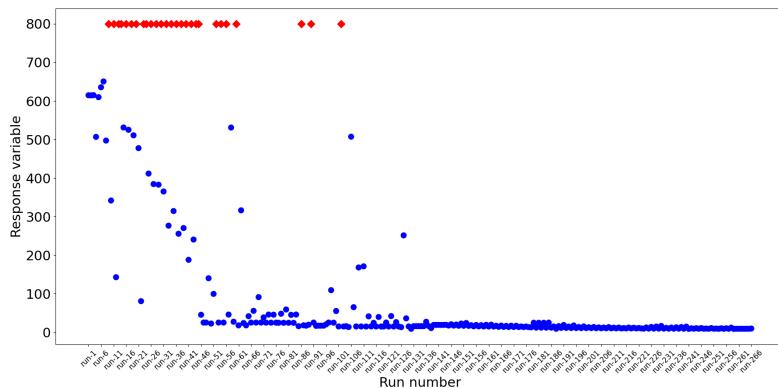


Figure 8. Response variable of the search algorithm for material properties and laser diameter where the blue circle marks developed a melt track and red diamonds did not.

was created which has a max Y value of just over 30. In this plot the blue circular markers are ones which have a response variable less than 30, the green triangle markers are those which completed with a melt track but had response variables greater than 30, and the red diamond markers are those which did not produce a melt track. In addition to these plots,

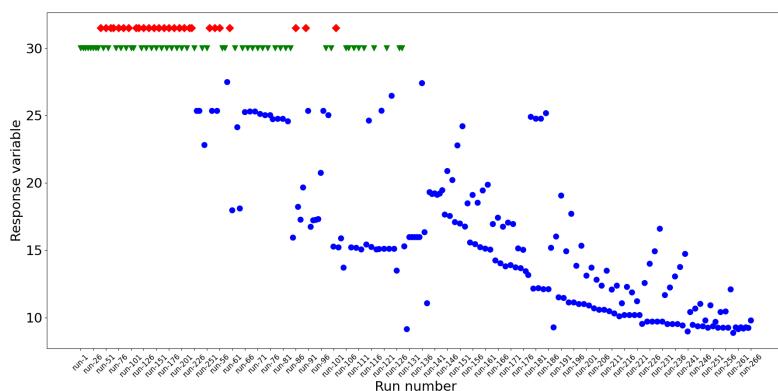


Figure 9. Response variable of the search algorithm for material properties and laser diameter with max y axis value of 30 where the blue circle marks developed a melt track, green triangles developed a melt pool but had a response greater than 30, and red diamonds did not develop a melt pool.

the error in the width and depth were plotted and can be seen in Figure 10. In these plots, it can be seen that the error in the width is 8.83% and the error in the depth is 0.03%. It is not fully understood why all the error is coming from the width, however, it is theorized that this is a product of the difference in the size of the width vs the depth since the width is nearly triple that of the depth.¹⁰

The search algorithm completed and reduced the combined error from over 600% when starting from the material properties found in the literature for the generic aluminum material properties, found in Table 6, to 9.1% when using the values found in Table 8.

¹⁰ Updated figure captions to include marker explanations

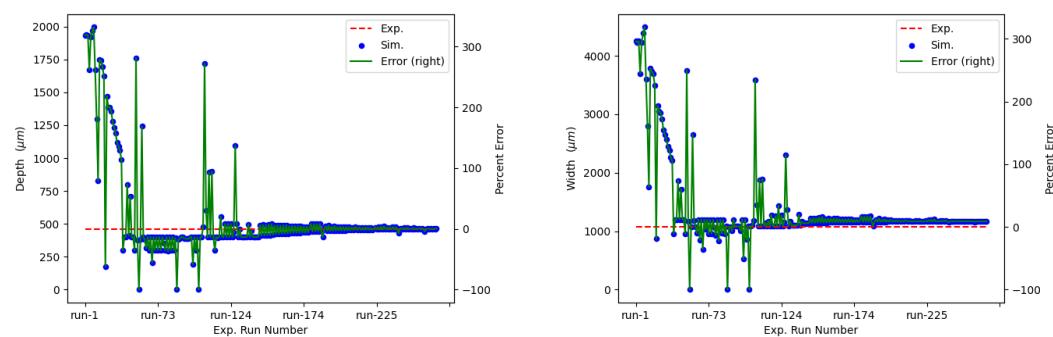


Figure 10. Error in the individual runs of the simulations during the **searchtuning** algorithm

Table 8. Optimized **Aluminum** material properties and laser diameter dataset for the developed simulation

| Property | Material Temp. | Value |
|----------------------|----------------|------------------------|
| Laser absorption | 880°C | 16.8% |
| Laser absorption | 922°C | 10.0% |
| Thermal conductivity | 922°C | 32.2 $\frac{W}{mK}$ |
| Thermal conductivity | 1491°C | 152.3 $\frac{W}{mK}$ |
| Specific heat | 733°C | 2957.6 $\frac{J}{kgK}$ |
| Laser diameter | | 0.864 mm |

3.2. Search results validation

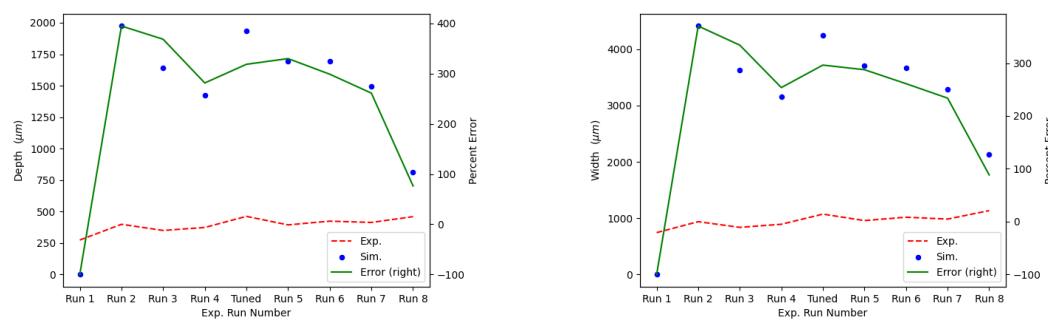
In order to ensure that the search algorithm results were valid across laser travel speeds and power levels, a range of 8 other parameters were compared with experimental results. These experiments and simulations were the setup and analyzed as was used for the **search algorithmtuning** experimental setup. The base experimental parameters can be seen in Table 7 with the scan speed and laser power being varied as seen in Table 9 and the simulation material properties were used from Table 8. The exermental result were

Table 9. **Laser processing parameters validation** Validation processing parameters

| Exp. Id. | Scan speed (mm/min) | Laser Power (W) |
|----------|---------------------|-----------------|
| 1 | 762 | 1000 |
| 2 | 762 | 1500 |
| 3 | 762 | 1250 |
| 4 | 1143 | 1250 |
| 5 | 1143 | 1500 |
| 6 | 1524 | 1750 |
| 7 | 1524 | 1500 |
| 8 | 1524 | 2000 |

collected and graphed in Figure 12 and 11 as the red dashed line and were used as the ground truth with which the models were compared.

These speeds and powers were first completed with the literature determined values from Table 6 and the results can be seen in Figure 11. Where the red dashed line is the



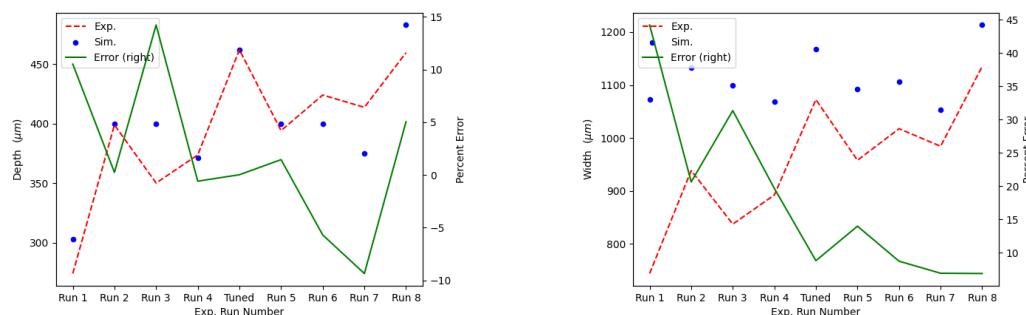
(a) Melt track depth

(b) Melt track width

Figure 11. Comparison of experimental and simulated results for validation points with generic literature values for **aluminum** material dataset

experimental results, the blue dots are the simulation predictions, and the green line is the error when comparing the simulated results to the experimental results. These results show that over the 9 initial parameter sets, when a melt track was developed, the average absolute value of the error in the depth was approximately 290% and the average error in the width was approximately 265%. To put this into terms of the response variable of the search algorithm, the sum of the width and depth error, would be 555% combined error. Additionally, run 1 was unable to develop a melt pool, which is contrary to the experiments where all the parameter sets had a stable melt track. These results corroborate the results from Figure 8 which showed that the parameter set used for **the search algorithm tuning** initial dataset of material properties found in the literature is wholly inadequate for simulating the process at hand.

In contrast to these results, the material dataset which was found in Table 8 was used to simulate each parameter set, and the results can be seen in Figure 12. Where the



(a) Melt track depth

(b) Melt track width

Figure 12. Comparison of experimental and simulated results for **laser processing parameters** validation points with optimized values for **Aluminum** material dataset

red dashed line is the experimental results, the blue dots are the simulation predictions, and the green line is the error when comparing the simulated results to the experimental

results. These results show the average error in the width was approximately 17% and the
297 average error in the depth was approximately 5%, which creates a combined error of only
298 22%. These results show that the optimized dataset is better at predicting the combined
299 error of the simulation by over 500%. This results in a simulation which can be leveraged
300 more intensely during the process development and build qualification process. These
301 results are from a wide parameter set which encompasses most of the usable parameter
302 space for deposition found experimentally. This improvement in accuracy will allow for a
303 greater application in the model in the determination of an optimized parameter set for
304 a given build. In addition, the model is seen to be more accurate at parameters above
305 the parameter used during the optimization. This leads to the conclusion that if a more
306 accurate simulation is needed, the optimization should be done at a parameter set near the
307 desired parameter set.
308

4. Discussion

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310
After the simulation developed was shown to properly model the laser DED process
311 for a material where the material properties were known, Ti-64, it was understood that the
312 model held true to the fundamental physics equations which the model was developed
313 upon and any assumptions in the model were accurate enough to produce accurate results.
314 This was detailed in Section 2.1. If the material properties did not have a drastic effect on
315 the results of the model, then a generic set of aluminum material properties could have
316 been collected and been sufficient for the targeted alloy¹¹, 7050. This proved not to be the
317 case, as was expected due to the range of alloying elements in aluminum alloys and their
318 dramatic effect on the material properties. This resulted in effort needing to be exerted in
319 order to get an accurate model for the desired 7050 alloy.
320

The Nelder-Mead algorithm proved to be an efficient method for finding the material
321 properties¹¹ dataset which produced accurate results. Though more efficient than traditional
322 FEA! (FEA!), the model still is slow taking several hours to produce the needed results.
323 This means that search algorithm selected needed to be efficient and not required numerous
324 queries in order to achieve a minimum error. The process of finding the derivative of the
325 error function in this search would be possible if several new data points were selected
326 around the point of interest resulting in the ability to find the first and second derivatives.
327 This would greatly increase the number of simulation runs required, exponentially increas-

¹¹ Added a discussion section to bridge the gap between the results and conclusions

ing the time required to converge. This ruled the common multidimensional algorithms of the conjugate gradient method, full Newton method, Davidon-Fletcher-Powell, and Broyden-Fletcher-Goldfarb-Shanno method. Whereas, other methods which do not require knowledge of the gradient are the Powell's method and Line searches typically require many more iterations to reach a minimum. Therefore, if the derivatives are not known, or the derivatives are not continuous¹² then the Nelder-Mead algorithm should be attempted first [45]. And upon efficient convergence of the Nelder-Mead, no other algorithms there was no need to investigate other optimization algorithms.¹²

Upon minimization of the error, the results shown in Table 8 can be compared to Table 6 to see the difference between the properties which were found for a generic alloy and that of the optimized properties. Two main observations can be made when comparing the results.

The first is that the laser diameter is approximately half that of the starting value. This derives from the difficulty of measuring the diameter of the laser without the appropriate dedicated equipment. In this experiment, the starting laser diameter was selected based on experimentation where the laser was used to irradiate a piece of paper at the focal point for a very short period of time. The holes which were burned into the paper were measured, and the average size was used as the laser diameter. This rudimentary method was a way to cheaply and quickly get an approximation of the laser diameter, but as was expected this overestimated the laser diameter. This is due to the combustion of the paper going beyond the edges of the laser beam. Specialized equipment could have eliminated this variable, however that is expensive and did not significantly affect the convergence rate of the Nelder-Mead algorithm.

Secondly, it is critical to review the difference between the alloys where the generic material properties were taken from and the experimentally used material. The generic material properties' dataset came from combining the data from pure aluminum [22,42]. When adding alloying elements this can have a drastic effect on the material properties. In this experiment, the alloy of 7050 was used which contains alloying elements of Copper (2.3 %), Magnesium (2.3 %), Zinc (6.2%) and Zirconium (0.12%). This addition of alloying elements had an effect on the material properties in the following ways. Firstly, the laser absorption at the liquidus temperature for the optimized dataset was triple that of the generic dataset. Secondly, the specific heat at 733°C of the optimized data set was also nearly triple the generic dataset that of the generic dataset. Conversely, at 922°C, the generic

¹² Addressed application of other search algorithms

dataset was triple that of the optimized dataset values. And lastly, the thermal conductivity of the optimized dataset was about double of that of the generic dataset at 1491°C. These difference most likely arise from the alloying elements changing the lattice structure of the aluminum altering its material properties.

This model was developed in response to a need from those developing processing parameters and path plans for the metal AM process. They were needing a model which was capable of quickly simulating the heat flow and buildup for a range of path plans and processing parameters. This will allow for researchers to more test a wider range of parameters and path plans in order to better find a global optimal as opposed to the local optimization which might be obtained with a smaller scale set of parameters or path plans, both experimental and simulated. With the current target of an efficient predictor of the thermal history completed, and an optimized input dataset for the high strength aluminum, it is possible to expand this model to predict more components of the build and increase its usefulness.

The next target for the model is to add prediction of microstructure of the material. This is particularly important for the aluminum alloy investigated in this paper because it is the main driving factor as to the expected performance of the final part[46]. In order to predict the microstructural makeup of an AM build, it is necessary to first find the thermal history due to the tight linking between the thermal history, cooling rates, and microstructure which is developed. After this a range of models, both determination and probabilistic, can be used to predict the final microstructural makeup of a completed AM build[47]. These results can then be used to predict the final part performance. Moving forward, various methods of predicting the microstructure of the completed build will be investigated as an intermediate step to estimating the ultimate performance of the component.¹³

5. ConclusionsDiscussion

This work shows that the Nelder-Mead search algorithm is an appropriate multidimensional search algorithm for the determination of the optimal dataset for improved simulation accuracy. It was capable of reducing the error¹⁴ simulated melt track depth and width of a set of processing parameters as measured by the sum of the error in the width and depth measurements (Equation 10) from over 600% for a generic aluminum alloy

¹³ Added discussion about microstructure

¹⁴ The discussion section was more properly renamed to the Conclusions

to 9.1%. by over 500%. This was verified using a range of laser processing parameters to verify the effectiveness over a processing window. This verified the results, using the same error measurement, the average error was improved by over 500% as shown in Figures 11 and Figure 12, which used datasets from literature (Table 6) and the optimized dataset (Table 8) respectively. This was done by defining the response variable (Equation 10) for the search algorithm to be the sum of the error in the width and the depth, which facilitated an efficient search. It was found that for the values of the laser absorption at the liquidus temperature and the specific heat at 733°C, for the optimized dataset was triple that of the generic dataset. Conversely, at 922°C, the generic dataset was triple that of the optimized dataset values. And the thermal conductivity of the optimized dataset was about double of that of the generic dataset at 1491°C. Lastly the laser diameter crudely estimated was nearly double that of the optimized input dataset. This methodology can be used to develop accurate simulations for any material which is not well published or to increase the accuracy of a simulation which utilizes approximations of first principles in order to increase its efficiency. ¹⁵

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¹⁵ Updated conclusion to include more analytical results

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