VALIDATION OF DIRECT METAL LASER SINTERING IN COMPRESSION MOLD MANUFACTURING

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To my mom and dad, thank you for your love and patience.
ABSTRACT

Compression mold tooling fabrication has been traditionally conducted via machining processes—for example, computerized numerical control machining, mill, or lathe operations. While subtractive manufacturing operations provide high-precision tooling, they have an extended lead time and generate material waste, which increases manufacturing costs. This paper analyzes Direct Metal Laser Sintering (DMLS) as a viable alternative to traditional compression mold manufacturing. DMLS is an additive manufacturing process that uses high-powered lasers to fuse metal powders in a layered approach to create high-precision metal components. Through layering materials, DMLS can produce complex geometry, which can have features impossible to machine from current manufacturing methods. Additionally, DMLS uses less material for parts, reducing material costs and lead times. In this paper, DMLS manufactured mold was computationally studied against a traditional compression mold’s thermal and pressure requirement. The DMLS mold was designed with a honeycomb structure to reduce material while maintaining structural integrity. Computational Analysis showed that the production requirement, “maximum deflection of 0.001 inches”, was achieved with the DMLS when pressures and temperatures were similar to those required for the tooling. In addition, DMLS-produced mold utilized 74% less material than a traditionally manufactured mold.
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1. INTRODUCTION

Compression molding is a manufacturing process that utilizes heat and pressure to shape and cure rubber materials into usable components. The aerospace industry uses this method to manufacture products that require the strength-to-weight ratios and flexibility properties rubber composites can provide. This method of molding applies heat and pressure to form “charges” within a mold cavity. The charge is subjected to these temperatures and pressures for a set time to allow the rubber within to cure. Any excess material is purged into flash channels within the mold, allowing parts to maintain consistent weight and density properties between operations. Figure 1 demonstrates a simplified representation of this process, showcasing a simplified mold cavity and exaggerated flash channels.

The procedure of creating compression mold tooling involves forming a relief of a desired part within a cavity via machining. Compression mold tooling fabrication has traditionally been conducted via machining processes like computerized numerical control (CNC) machining or mill and lathe operations. While these machining methods provide high-precision tooling, they also have limitations in their capabilities. Two significant drawbacks of these subtractive manufacturing operations are material waste and high cost (Kara et al., 2016; Nguyen et al., 2019). These machining operations require a high amount
of material investment to produce tooling. This leads to a high scrap yield and a significant amount of waste from the metal and cooling fluids used within the process. From a cost-based perspective, the subtractive manufacturing methods require a high financial investment in machinery and personnel training. Both CNC and mill and lathe operations require skilled workers to operate the machinery. CNC machining requires software training to program the various G-codes needed per operation in addition to support fixtures and machining tools. Direct metal laser sintering is to be considered as an option for compression mold tooling to determine if there are any underlying benefits to an alternative manufacturing method.

Direct Metal Laser Sintering (DMLS) is an additive manufacturing method that uses laser fusion on metal powders to create intricate and complex structures (DebRoy et al., 2018; Kruth et al., 2005). Powders are selectively layered throughout the fusion process, following a desired computer model and utilizing only the required materials to create a part. This layering approach makes it possible for DMLS-based structures to have internal structures like honeycombs, foams, and other forms of pockets. Requiring only necessary materials is an efficient and cost-reducing approach to manufacturing only possible with DMLS. Traditional machining methods would require additional materials and operations to perform similar operations. Additionally, the localized material fusion results in a high degree of density through builds, maintaining the properties of the printed material at similar levels to traditionally machined structures (DebRoy et al., 2018).

Whereas traditional manufacturing methods are restricted by resource and cost expenditure, DMLS manufacturing benefits from minimalized material usage and lower cost thresholds. Direct metal laser sintering’s additive nature eliminates the need for timely
and extensive setups, tool fixturing, and multiple machining operations common to CNC machining (Ding et al., 2015; Gibson et al., 2015). In opposition to these time-consuming requirements, DMLS builds can be sent from computer-aided design (CAD) software like SolidWorks or Catia directly to a printer to start the process. While the reduction of material usage already increases the cost benefits of DMLS, the lead time to print is another contributing factor to the operation’s positive attributes. The variables that define a DMLS operation’s speed include scan speed, layer and powder thickness, and laser power. This typically results in a DMLS process having a max print speed of several tens of cubic centimeters per hour (DebRoy et al., 2018), in contrast to an equivalent CNC cut which may have a speed measured in millimeters.

This application of DMLS aims to expand upon the low-costs and existing benefits compression molding already maintains. Aside from the simplicity of setting up this manufacturing operation, compression molding offers multiple benefits to aerospace production lines, such as high-yield repeatability and tooling geometries supporting complex part shapes. Compression molds may use internal structures such as wedges or mandrels to support rubber curing, but very few advanced software or technical skills are required to work with tooling. These properties allow the aerospace industry to generate consistent rubber products with minimal barriers to learning the process. DMLS seems to have potential within this niche of manufacturing. Since molds are typically produced with high-strength metals like steel or aluminum, the additive process should require minimal adjustment to produce components from these metals (Zong et al., 2015). With successful systems only requiring pressure, heat, and a mold, the low amount of input materials

3
required to begin operations allows compression molding to be low-cost manufacturing welcoming to 3D-printed tooling.

Therefore, the main contribution of this paper is to expand on the capabilities of DMLS structures into tooling and investigate the structural integrity, material usage and cost against CNC machined molds. Subsequent sections of this paper will explain and evaluate computational and experimental methods of study, culminating in a summary of findings and avenues for continuing research.

1.1 References to Literature Review

The introduction made mention of the principle variables associated with compression molding – pressure and temperature. Tooling molds produced from additive manufacturing operations must maintain the structural and thermal requirements existing compression molds undergo during traditional production processes. The DMLS process has an existing presence in aerospace manufacturing, used as recently as March 2023 to manufacture rockets for the aerospace company Relativity Space (Matter, 2023). Additionally, DMLS has precedent in compressive and tensile analyses to determine part performance.

Tooling made from subtractive manufacturing methods often uses a single piece of metal to make each part. This creates consistent grain and surface finish, resulting in uniform mechanical properties like ductility and fatigue resistance. Whereas the strength of a CNC machined tool is constant, a tool manufactured using DMLS can experience different levels of compressive or tensile strength due to fabrication orientation (Alkindi et al., 2021).
The strength of a DMLS part is directly correlated to the orientation in which it is printed. Figure 2 above shows the angles at which samples were printed prior to tensile testing. As noted in Figure 2, a study conducted tensile testing on 11 samples printed at the specified angle orientations. The study concluded that samples printed at 0º and 10º had $\sigma_{\text{max}}$ values of 947.26 and 949.87 MPa, respectively (Alkindi et al., 2021). These two samples had the highest elongation-at-break, with values of 2.98% and 2.2%, respectively. Both tensile stress and elongation-at-break decreased as the angle of the build print increased. The build print with a 90º had a $\sigma_{\text{max}}$ of 440.15 MPa, which is less than half the 0º and 10º builds. This decrease continued within the elongation-at-break, as the 90º build had a value of 0.83% (Alkindi et al., 2021).

In the context of this paper, this implies that build orientation is an important factor in a mold’s resistance to compressive forces. Although the literature references tensile evaluation, the results can be applied inversely to compressive applications. The 90º sample was weak to the tensile testing due to the buildup of stresses at the print layers. However, applying compression to a 90º oriented sample replaces the tensile stress with compressive stress normal to the layering. This would reinforce the layers against each other and provide higher resistance against compressive stress. During the design of experiments section of
this paper, proposed models for a DMLS-produced mold will be printed in a 90° orientation to provide the mold with the best compressive properties.

One of the aforementioned benefits of DMLS is the ability to create complex geometries such as honeycombs or foams. These cavitation types are highly desired within aerospace applications, as honeycomb-based structures are utilized in aircraft for their high strength-to-weight ratios (Karami et al., 2016). Applying these benefits to compression molding requires an evaluation of the compressive properties of porous structures. While beneficial to aircraft, honeycombs and other hollow-support structures may not be suitable for the localized pressurization required of compression molding. An evaluation of 3D-printed foams was conducted to determine the load-bearing properties of these hollow structures.

![Figure 3. 3D-printed Foam Samples of Varying Pore Diameters (Ramesh et al., 2020)](image)

Figure 3 shows a set of cubes with varying pore diameters built and subjected to compression. It was determined through analysis that compressive strength varies directly with part density and inversely with specimen porosity (Ramesh et al., 2020). For the purposes of this paper, the compression mold DMLS created will maintain a high material density and low level of porosity. As referenced in this paper, making honeycomb or foam shapes small while providing a high amount of layers during the build process will give the DMLS mold the best probability of withstanding the pressure parameters.
A similar observation regarding print density was noted in a paper published on the load-bearing properties of 3D-printed metals. Brittleness testing observed the propagation of fractures within test samples. Analysis under a microscope revealed that crack propagation occurred in areas where the fusion of materials did not occur (Kogo B et al., 2022).

![Figure 4. Porosity caused by lack of fusion (Kogo B et al., 2022)](image)

This study was improperly concluded, as the undesired porosity within the samples was determined to be outside the scope of desired experimentation. Figure 4 shows several instances of crack propagation within the samples. The extensive cracks and layer delamination caused quick and inaccurate printing, leading to a high lack of fusion from either low laser power, high scan speed, or improper scan strategy (Kogo B et al., 2022).

Moving into computational studies and a design of experiments, this literature review will allow this paper to present a mold proposal that builds on the benefits and shortcomings of each reference.

### 2. COMPUTATIONAL STUDY

#### 2.1 The Compression Mold Process

For this study, the compression molding operation was conducted within the standard operating environment used to make rubber derivative composite components at a partner company. This approach was used to simulate the typical environment that a CNC mold
process is used and determine if a DMLS compression mold can operate within a production setting. The parameters under which this study was conducted were derived from the work instructions for compression molding rubber parts at an aforementioned partner company. A typical compression mold machine used on the production shop floor has a large rectangular compression bed that is computer controlled. Hydraulic cylinders raise and lower the upper platen of the device to fit molds of various heights while the lower platen stays at a constant height. To help operators load molds into the machine, the lower platen is seated on a short track system that allows for a quick ejection and intake to secure the mold. Due to the limitations of the platen dimensions, additional machinery options are required for molds that do not fit within their surface area. This study will examine a 9” x 9” CNC compression mold and a 6.5” x 5” DMLS compression mold. Additionally, the molds used during this study will not have ejector pins due to not being connectable components to the overall compression machine. Any excess materials generated from compression will be collected in overflow grooves and trimmed as a flash. This is an open-air system where convective heat is transferred from thermal conductors within the platen into molds. The operating parameters are proprietary to the industry partner but shall not exceed 500 °F or 1000 PSI. Each mold utilized during this study will require 25 minutes of time under temperature and pressure to allow the rubber material to cure. Simulated molds will be made from the same type of aluminum, 6061 Aluminum Alloy. Since the proposed DMLS mold utilizes less material than the CNC mold, one of the challenges presented for testing will be the effectiveness of heat transfer within the new mold. Heat transfer is directly correlated with surface area (Kuczmarski et al., 2007), and
a smaller surface area affects the effectivity of the temperature parameters set within the work instructions.

The temperature of the platens is presented on the compression machine interface alongside pressure and time under load readouts. Since heat is applied to the mold from two opposing sources (the opposite platens), the dissemination of the heat can be tracked linearly from start to endpoints. The platens are also the sole points of pressure. Due to the molding operation being exposed to atmospheric temperatures and pressures from the sides of the molds, no significant additional sources outside these parameters must be considered. During the simulation section of this paper, the time it takes for both molds to reach equal thermal temperatures will be measured based on surface area. Per work instructions and general production operations, the overall process to create parts with the typical CNC mold is approximately 30 minutes (Kirkhill, Inc et al., 2023). Therefore, the smaller DMLS mold’s heat transfer will be a vital component in determining if less material within the mold provides any benefit besides financial. The purpose of these parameters is overall to validate the DMLS process as a basis for potential manufacturing methods for compressive tooling. Due to the versatility of the sintering process, any shortcomings found during experimentation can have alternatives discussed in future sections of this report.

2.2 Computational Modeling

In this study, the simulation of heat transfer and application of pressure was modeled using Ansys programming to create the circumstances the CNC and DMLS molds experience in the compressive machine as described in section 2.1. This replication allows for the testing of multiple variations of compression molds while controlling for temperature and pressure parameters. These scenarios were generated by ANSYS 2021 R1 software, Mechanical
Workbench. This specific version of the ANSYS program allows for test structures to be simulated by manufacturing methods. As such, the scenarios presented account for the unique orientation of layers within a DMLS mold versus a solid block of metal machined down to a desired shape alongside the aforementioned production parameters. The models within the simulation will attempt to best represent their real-life counterparts in regard to heat transfer and pressure resistance. This simulation will provide pressure from one source and heat from two sources. Since the temperature to cure the rubber component may not be equivalent to thermal equilibrium throughout the molds, one of the outputs of the simulations will be the time a mold takes to reach the curing temperature. For pressure evaluation, maximum deformation, principle shear, and principle strain will be determined. Per industry process parameters, the total pressure exerted during molding may not exceed 1000 PSI for this specific mold type. However, a general pressure limit will be evaluated in consideration of other parts requiring higher pressurization levels. Heat transfer will be generated from hot plate simulations of the platens. The introduction of atmospheric temperature along the exposed mold sides will be the focus of future works on this subject but is currently outside the scope of this project. This is due to the prioritization of heat and pressure applied to the mold rather than effects from non-applied sources. As a result, this will focus any thermal changes and heat transfer onto the predetermined areas of interest to provide the most accurate results.

2.2.1 Manufacturing Conditions

Within each simulated scenario, the variables evaluated will be CNC versus DMLS mold and time under temperature and pressure within the compression machine. Regarding orientation, the DMLS mold will be presented within the simulation as normal to the
direction of applied force (90°). This orientation, based on the study by Alkindi et al. (2021), will prevent the fracturing of the part at layering sites. Identification of orientations that can produce weak molds will be useful for future fabrication studies. The simulated environment each scenario will be tested within will match the exact circumstances of a traditional production operation. As previously mentioned in prior sections, the process parameters tested will remain proprietary, so upper limit pressures and temperatures will be utilized within this study. Justification for this decision lies in approaching these upper limits as within tolerance of an acceptable range, wherein if the simulated models can withstand these parameters, they should find similar success at nominal values. Any exposed parts of the models will be set to atmospheric pressure and temperature at sea level. Pressure ranges for the molds will be from 14.7 PSI (atmospheric seal level, loading pressure) to 1000 PSI (machine load, maximum pressure). Temperature ranges will be from room temperature 71.6 °F to 500 °F operating temperature. Time under pressure will be set to 30 minutes, with a measurement of internal temperature at the end of the time period.
2.2.2 Simulation Parameters

The figures below are a demonstration of the models utilized for the simulation. Figure 5 represents the existing compression mold, which was made via CNC manufacturing methods.

![Figure 5. Mold A, Currently Existing Mold, CNC Manufactured](image)

Figure 5. Mold A, Currently Existing Mold, CNC Manufactured

Figure 6 represents the hypothetical DMLS-produced mold. These will be the two different mold configurations utilized during this simulation – Mold A and Mold B. Mold A is the CNC machined mold model that is currently in use while Mold B is the DMLS proposed mold.

![Figure 6. Mold B, Proposed DMLS Mold](image)

Figure 6. Mold B, Proposed DMLS Mold

This DMLS mold was designed with 76% less material than the traditional mold. This was accomplished by developing a honeycomb structure in place of the solid metal body. Both
models will utilize Aluminum 6061 T6 material properties for testing. Due to proprietary reasons, no dimensions can be provided for the molds. However, overall volumes for Molds A and B are 117.22 in$^3$ and 31.2 in$^3$, respectively. Specifications regarding the internal structures for both molds have also been omitted from this report due to proprietary reasons. Molds A and B weigh 11.43 and 3.08 lbs, respectively.

The transient model created simulated heat flow within the system as the production operation is a time-dependent function. During each scenario conducted for this project, the mesh was applied at the highest resolution to provide precise readouts throughout the part models for temperature and pressure. For boundaries, the bottom platen was fixed, and the force applied was solely from the upper side of the mold. Heat was applied to both ends of the mold through each platen to provide uniform diffusion rates for thermal energy to permeate the systems. At the start of each scenario cycle, the mold will be fixed in its fully closed position on the bottom platen. Both platens will start at a temperature of 71.6°F before increasing to the desired test temperature. There will be no ramp rate applied to the models due to the evaluation for a uniform thermal application for 30 minutes. There will be a small, 5-minute period to allow for the platens to “heat up”, but this should not be considered a specified ramp rate. The mold will be set to a room temperature of 71.6°F prior to contacting the platen. At this point, the upper platen will compress downward on the mold until reaching the designated testing pressure. Once fully compressed, the system will stay in this position for a period of 30 minutes. At the point of time completion, the internal temperature of the mold will be taken to evaluate for effective and consistent heat transfer. A heat map will be provided to display any variations within the inner cavity. Additionally, the mesh throughout the models will provide data on the structural integrity
of the DMLS mold variants. At any point a fracture is detected within the molds, the operation will indicate this through color gradients. The operation will continue regardless of damages to the molds unless manually stopped. If fracturing occurs in a non-critical area of the mold, the mold model will be reinforced to promote structural integrity. Any fractures found within critical mold areas will cause a mold variant to fail testing.

### 2.2.3 Simulation Scenarios

Each scenario will test desired manufacturing methods, pressures, and heat transfer and compare the performances between the existing mold and proposed alternative.

#### 2.2.3.1 Scenario Matrix

There will be a total of 9 different scenarios conducted for this study. Both the original mold and proposed mold will be subjected to each of these scenarios. The scenarios will test different combinations of temperature and pressure on each of the molds. For each scenario, each mold will be run three times, for a total of 27 simulations per mold and 54 overall simulations. Table 1 is the scenario matrix for design of experiments.

There are three different pressure and temperature parameters that will be used for this project. Atmospheric pressure (14.7 psi) and room temperature (71.6°F) are the lowest parameters for both sections and are intended to evaluate the molds under neither structural nor thermal loads. In regards to Mold B, this is to ensure the design would be able to withstand its own weight before load application. Nominal temperature (275°F) and pressure (500 psi) are representative of values similar to operation parameters for the industry partner. The two final values of high temperature (500°F) and maximum pressure (1000 psi) are to evaluate the existing mold designs to determine performance under
conditions exceeding typical parameters. The 54 scenarios will combine these values to provide insight into mold deformation and stress variables given different pressure and temperature combinations.

**Table 1. Scenario Matrix for Design of Experiments**

<table>
<thead>
<tr>
<th>Pressure Scenarios</th>
<th>Temperature Scenarios</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Room Temperature (71.6°F)</td>
</tr>
<tr>
<td>Atmospheric Pressure (14.7 PSI)</td>
<td>T: 71.6 °F</td>
</tr>
<tr>
<td>Nominal Pressure (500 PSI)</td>
<td>P: 14.7 PSI</td>
</tr>
<tr>
<td>Maximum Pressure (1000 PSI)</td>
<td>T: 71.6 °F</td>
</tr>
<tr>
<td></td>
<td>P: 1000 PSI</td>
</tr>
</tbody>
</table>

**2.2.4 Analytical Results**

A critical variable for evaluation throughout the testing of scenarios was the internal cavity temperature when the model was placed under the temperature and pressure requirements of the processing operation. As such, one of the desired data outputs will be not just the final internal cavity temperature but the rate at which the temperature within the mold changes over time and heat up. There will be a two-step application of heat on the molds. Step one will take 300 seconds (5 minutes) and raise the temperature of the mold from room temp (71.6°F) to the desired value during this time. Once this period is completed, the temperature will remain at the desired value for an additional 1800 seconds (30 minutes), fully simulating the production process. Final results will provide graphs displaying the internal temperature of each scenario at any given second.
In terms of pressure analysis, the parameter that will be tested will be deformation, which is critical to determine whether or not the mold is viable.

3. RELEVANCE TO INDUSTRY APPLICATION

The purpose of evaluating DMLS as a viable tooling fabrication method arises from the desire for lower cost alternatives for traditional tool machining for this project’s industry partner. Current methods utilized by the industry partner to acquire tooling involve purchasing equipment from third party vendors who specialize in machining. While this produces the necessary tooling for production operations, it also creates two downsides – costs and lead times. As such, DMLS is required to perform as well financially as it will mechanically. Significant deviation of DMLS’s internal benchmarking and financial analysis from traditional vendor methods will be used as evidence within this paper for its viability.

The industry partner utilizes third party vendors to make their current tooling inventory. These vendors use traditional manufacturing methods like CNC machining to produce the molds and other tooling accessories needed to compress rubber parts. For this project, the utilized mold was fabricated by one of these outside vendors. This is a compression mold with 4 wedges that weighs 11.43 lbs. with an overall volume of 117.22 in³. The material used for this mold was 6061 T6 Aluminum, which is consistent between the mold and four wedges. Per the vendor purchase order (PO), the cost of this tool was approximately $7500 and required a lead time of 10 weeks. Pricing and lead times from Vendor X is consistent with several other tools vendors that the industry partner uses. It is not uncommon to have a 6–12-week lead time, with pricing starting at around $5000 or based on the size of the mold. Due to proprietary reasons, the actual amount of funds the company allocates
towards annual mold tooling cannot be disclosed. However, an approximation of the true value that can be used for financial analysis is about $1,800,000, with about $75,000 being spent within the next six weeks alone.

For CNC machining, the cost-basis analysis for aluminum tooling can be approached from two perspectives – cost of material and fabrication costs. With the assumption that the aluminum is sourced from United States metal, the cost for a raw stock plate of 6061 Aluminum required to machine Mold A is $220.86 (6061 Aluminum Plate | Midwest Steel & Aluminum, n.d.). In California, the average salary of a CNC machinist is $44,000 annually (CNC Machinist Salary in California – $44,000 | Mint, n.d.), which equates to about $21.15 per hour. Due to the internal geometries of the tooling, plus the need to machine wedges and other fine details, the labor price per hour for this mold can be estimated to be closer to $50 rather than the state average. Setting up and reserving a machine is an additional cost, along with any post processing operations that are required by the industry partner. Refer to the table below for a hypothetical breakdown of costs and lead times for CNC molding Mold A.
Table 2. Cost Breakdown for Mold A, CNC Machined

<table>
<thead>
<tr>
<th>LINE ITEM</th>
<th>LEAD TIME (DAYS)</th>
<th>COST ($)</th>
<th>COST UNIT</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOLD DESIGN</td>
<td>10</td>
<td>35</td>
<td>per design hour</td>
</tr>
<tr>
<td>MATERIAL ACQUISITION</td>
<td>10</td>
<td>220.86</td>
<td>per AL plate</td>
</tr>
<tr>
<td>MACHINE SETUP</td>
<td>2</td>
<td>50</td>
<td>per hour of setup</td>
</tr>
<tr>
<td>MACHINING</td>
<td>20</td>
<td>50</td>
<td>per labor hour</td>
</tr>
<tr>
<td>POST-PROCESS</td>
<td>2</td>
<td>50</td>
<td>per labor hour</td>
</tr>
<tr>
<td>EXPEDITE FEES</td>
<td>1</td>
<td>300</td>
<td>per expedited mold</td>
</tr>
<tr>
<td>TRANSPORT FEES</td>
<td>5</td>
<td>120</td>
<td>per tool mold</td>
</tr>
<tr>
<td>TOTAL COSTS ($)</td>
<td><strong>6040.86</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Lead Time (Weeks)</td>
<td><strong>7.143</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2 represents a close estimation to the partner company’s expectations when ordering tools. Line items represent the workflow between tool conception and delivery of parts. The time between each workflow step is considered a “lead time” which is shown in the second column. Each step of this process requires financial investment along with time, resulting in the final two columns providing financial costs per unit. One important thing to note is that this setup was done without any delays to lead time or fabrication, which can heavily increase the overall price and wait for parts.

Unlike CNC machining, DMLS cost-basis analysis for materials can be calculated by the price per pound of aluminum. As referenced in Mold B, there is less material used to make the mold due to the honeycomb support structure possible through DMLS. 3D metal printing uses powders to produce parts and as such, does not need raw stock to begin a process. A generic bag of AlSi10Mg (the powder needed for Aluminum 3D printing) costs $175.00 per kilogram or $79.38 per pound (AlSi10Mg Aluminum Based Metal Powder for Additive Manufacturing (3D Printing), n.d.). In contrast to the dimensions presented by Mold A, Mold B has a volume of 31.2 in$^3$ and weighs 3.08 lbs. Therefore, the raw material
costs of Mold B would be $244.49. While this exceeds the price of raw stock for a part with 76% more material (Mold A), the downstream costs of DMLS can offset this initial purchase. Whereas Mold A will require additional costs for machining and vendor outsourcing, Mold B’s “operation costs” can be calculated by the power required to print it in a machine.

The industry partner has expressed interest in GE Additive as a vendor for purchasing machinery to conduct in-house DMLS operations.

![Figure 7. GE Additive Concept Laser M2 Series 5](image)

This subsect of the larger GE corporation has 3D printing machines which are qualified for aerospace fabrication by the FAA and can print multiple metal types beyond Aluminum. For calculative purposes, the Concept Laser M2 Series 5 will be used for power consumption and build speed. Figure 7 is a visual representation of this printer as displayed on the GE Additive website. This machine has a productivity optimized build rate of 23.8 cm³/hr. or 1.45 in³/hr. (Concept Laser_M2 Series 5_Machine | G.E. Additive, n.d.).
With no complications, Mold B would be fully printed, wedges and detailing included, in 21.52 hours. Since the operation would be conducted within an automated machine, this print would be completed in this timeframe rather than over 3 8-hour workdays. Therefore, this omits all labor hours required for setup and machining the mold and adds in the new variable of power consumption costs. This machine comes in two power variants – 400 W and 1000 W. The price per kWh in Los Angeles is 25¢/kWh. Running the power consumption cost calculation with both variants gives us the following calculations:

Build at 400W:

\[
400\text{W}/1\text{kW} = 0.4\text{kW} \rightarrow 0.4\text{kW} \times 21.52\text{hrs} \times 25\text{¢/kWh} \times 1\$/100\text{¢} = 2.15
\]

Build at 1000W:

\[
1000\text{W}/1\text{kW} = 1\text{kW} \rightarrow 1\text{kW} \times 21.52\text{hrs} \times 25\text{¢/kWh} \times 1\$/100\text{¢} = 5.38
\]

Generating a cost breakdown table for Mold B similar to the one created for Mold A continues the demonstration of the stark contrast between traditional compression mold machining and the capabilities of DMLS.

<table>
<thead>
<tr>
<th>Table 3. Cost Breakdown for Mold B, DMLS Printed</th>
</tr>
</thead>
<tbody>
<tr>
<td>LINE ITEM</td>
</tr>
<tr>
<td>MOLD DESIGN</td>
</tr>
<tr>
<td>MATERIAL ACQUISITION</td>
</tr>
<tr>
<td>PRINT TIME</td>
</tr>
<tr>
<td>TOTAL COSTS ($)</td>
</tr>
</tbody>
</table>

Table 3 is a duplicate of Table 2’s cost breakdown but for the DMLS produced mold. Each column remains the same as in Table 2 but with adjustments made to the calculations for
the overall pricing of the mold. For this cost breakdown, the Mold Design lead time and
costs were reduced because while the tooling still requires modeling prior to printing, the
operation can be done in house rather than with a vendor. This cost can also be absorbed
by the industry partner into an engineer’s responsibilities, meaning that the hourly labor
rate can range from a senior engineer to an intern and is no longer fixed to a machinist’s
salary. This cost breakdown also omits the price of the machine, as the assumption is that
the machine has already been purchased and in operation.

This hypothetical has reduced the costs and lead times by 72.41% and 72%, respectively.
If this reduction was consistent with actual trends in build speed and cost, then the $75,000
tooling order with a 6-week lead time can hypothetically be reduced to a price of
$20,692.50 with a lead time of 1.68 weeks.

While the two cost scenarios provide hypothetical positives for DMLS tooling, practical
applications can be easier visualized in the lead times to make parts. In regard to lead-time
reduction, this can be further reduced in both fabrication and production with the
introduction of multi-cavity molds. The introduction of this paper presented one of the
benefits of DMLS as the ability to make internal structures. Application of multicavity
mold tooling is typically associated with injection molding, which injects polymers under
high pressure into a mold cavity. DMLS has the potential to take this concept and print
multiple cavities into a volume similar to that of Mold A. Computational analysis would
be required to determine stress concentrations and fracture points, but the printing
capabilities would allow more cavitation per square inch than a CNC operation could
provide.
From a production standpoint, this is the next level of cost-saving benefits. Per the work instructions for this particular mold, time under pressure and temperature takes approximately 30 minutes. Speaking with manufacturing engineers at the industry partner, a typical shop order for the parts made by this mold will have an average of 100 EA per order. Since the only available mold for this part is a single cavity, the production rate would equate to roughly 45 minutes per part (15 minutes for layup and part removal from mold) and a shop order lead time of 75 hours or approximately 2 weeks of non-stop production. Assuming a pay rate of $20 per hour for a production team member operating this mold, labor costs for this operation would amount to $1500. Additionally, this part is ordered several times throughout the fiscal year, at an average of about 1 order per month, increasing the labor cost to $18,000 annually. Accounting for weight, Mold B is 3.77x smaller than Mold A. DMLS can utilize this reduction of weight and build a 4-cavity mold that is slightly heavier than the existing Mold A. Since there’s extra material within the mold, the layup and part removal time can be increased to an hour for proper handling. However, this reduces the cure time per part from 45 minutes to 15 minutes, reducing the operation lead time from 75 hours to 25. Labor costs would be reduced to $500 for an annual labor cost being $6000. While this of course is hypothetical, the financial savings of $12,000 and 50 hours from labor operations brings in more potential for DMLS molds to integrate into existing operations. Should the mechanical aspects of this project be successful, the financial benefits gained would further generate more success. Practical models would need to be developed to test in a true production environment, but the evidence for material, cost, and labor reduction provides enough incentive for DMLS to establish itself as a tooling manufacturing method.
3.1 Significant Shareholders and Users

The development of a DMLS-based compression mold manufacturing system will require a re-evaluation of the industry partner’s current relationships with existing tool vendors and on-site manufacturing engineers. If the GE Additive printer is brought in-house, this shifts the responsibilities of internal and external shareholders within the industry partner. Existing internal and external users can be grouped based on their interaction with the partner. As the industry partner is itself a vendor, external users can be defined as the upstream and downstream vendors and customers the partner interacts with. Internal users would include the partner’s management and employees, both of which are vital to sustaining functions within the business. Refer to Table 4 for a visual representation of internal and external users.

Table 4. Industry Partner Internal and External Users

<table>
<thead>
<tr>
<th>Internal Users</th>
<th>External Users</th>
</tr>
</thead>
<tbody>
<tr>
<td>Executive Management</td>
<td>Vendors</td>
</tr>
<tr>
<td>Company Employees</td>
<td>Customers</td>
</tr>
<tr>
<td>Trade Compliance Teams</td>
<td>Government Agencies</td>
</tr>
<tr>
<td>Auditor Teams</td>
<td>Shareholders</td>
</tr>
</tbody>
</table>

Table 4 represents the internal and external connections the industry partner maintains between itself and its users. While this may seem like generalized connections, the workflow to process raw materials with molds is slightly more refined. The industry partner works with the vendor to produce and acquire the tooling needed to produce and sell parts for customers to buy. Additionally, due to working in the aerospace industry, more
prominent users for both sides includes Trade Compliance Teams and Government Agencies. Parts manufactured for aircraft must abide by rules enforced by the FAA to maintain quality standards to prevent hazardous incidents from occurring (AC 20-62E - Eligibility, Quality, & Identification of Aeronautical Replacement Parts – Document Information, n.d.). Internal trade compliance and audit teams help ensure that internal employees and management produce parts per these standards. In regards to the DMLS process, parts made from printed molds must meet the same standards for parts made using traditional processes. There cannot be much deviation between parts made on printed or machined molds. If deviation exists, external users like government agencies may fine the industry partner for violation of guidelines and shareholders might pull funding in fear of company struggles and image.

The inclusion of DMLS within the production operation will have a mild impact on mold operators but will most significantly affect the CNC operating teams. Production team members working with the compression mold operations will continue expected processes as normal. While the molds will be different than existing variants, they will still be subject to the same pressure and temperature requirements of CNC tools. Financial investments would instead be put towards the machinists and technicians on the production team. DMLS printers, while not requiring dedicated operators, will still need machinists with knowledge of the machines to observe and maintain. This will incur financial costs in the form of maintenance trainings, which may cost approximately $1000 per operator to learn how the machine works. Additionally, another significant cost would be the requirement of a dedicated tooling engineer to design tools and interact with the machine. The industry partner would need to invest in an annual salary of approximately $90,000 for an engineer
to develop tools that meet production requirements while requiring less material and time input. Although the price may seem high, the cost saving benefits from DMLS molds can offset the money needed for this salary. As previously discussed, DMLS printers do not need a dedicated operator. Should CNC machinery be phased out of the manufacturing process, operator roles can either be transferred to other types of machinery positions or the role can be eliminated altogether, further saving the industry partner costs. As mentioned in previous sections, the cost savings benefits from adjustments to the tool molds will bring large changes to the production operation equipment. However, from this hypothetical example, the overall changes to production teams and stakeholder involvement will be moderate, with a new engineer joining the process being the most significant event.

Despite the risk, proper application of DMLS could produce parts indistinguishable from existing inventory after consulting with manufacturing engineering as well as trade compliance teams. Should this occur, workflows and connections can potentially omit tool vendor users as a whole. Table 5 is a representative visualization of how in-house DMLS restructures the user connections. Each user is defined (such as vendor, customer or the partner themselves) alone with their user type and action within the workflow.
As referenced in the table, the Vendor is no longer a major external user within a DMLS-integrated system. This new system allows the industry partner’s manufacturing teams to absorb responsibilities for tool design, fabrication costs, and lead times. While this may seem to present issues with resource allocation, turning this process into an operation within the business offers many benefits to management and executive leadership.

The two most critical benefits for internal stakeholders within business leadership would be increased financial resources and process control. As mentioned in the former section, the in-house tooling creation process would significantly reduce the financial and time
investment needed per mold. This would allow the industry partner to produce a higher volume of parts and mold tooling in a shorter period of time. Such a shift in lead times and ease of tooling acquisition would allow management to reframe their own lead times to meet customer demand faster. Employees, specifically production line workers, would be able to maintain their workload by using existing tooling while being supplemented with DMLS-based equipment. Aside from creating whole tools, small sections of existing tooling can also be printed to prevent lines from shutting down from waiting for new vendor pieces.

This leads into the other critical benefit to internal stakeholders – process control. By omitting the need to rely on vendors to machine tooling, the industry partner has more flexibility and freedom to produce tools on their own timetable and for less funding. Like any vendor, the tool supplier can become inundated with orders or charge extra fees for expedited work. This forces the industry partner to abide by the vendor’s order queue or pay additional costs for faster delivery. Using DMLS, management teams remove themselves from this limitation and can schedule tool builds on an as-needed basis. Instead of budgeting for costs such as tool fabrication, material selection, and priority, management can shift vendor costs towards powder purchasing and delivery fees. Outside of the main production process, manufacturing engineers can use the DMLS process to rapid prototype new tooling to form new product lines or improve existing ones.

It is important to note that while tooling vendors would have lower involvement as an external user, their connection to the industry partner will not entirely fade away. Non-mold related tooling or pieces too large to fit into a print bed will still need machining vendors available to work them. Additionally, while the FAA was briefly mentioned within
this section, critical stakeholders for DMLS produced tooling remain internal to the business. Molds are not the pieces that will be attached to planes, so it will be the responsibility of the internal quality and compliance teams to ensure the parts made with these molds are acceptable. Production managers with larger budgets and lighter workloads can expand production lines using DMLS molds in ways that would potentially attract more business as the company can reliably produce parts on a quicker timescale than competitors.

In reference to competitors, process control would allow the partner to provide forecasts for orders that do not rely on third parties as variables. These forecasts could be more accurate than competitors as the estimates would incorporate the print time for a part as a known variable. This in turn would provide customers with feedback and estimates with shorter lead times that competitors utilizing existing mold manufacturing methods can not keep up with. Rapid prototyping would compound this benent as the industry partner’s DMLS printers could turn concepts into physical items within as little as a week, further establishing themselves as a fast and reliable company. Consistent, high-volume shop orders that are fulfilled in shorter lead times can ultimately allow the partner to receive prioritization for contracts, bids, and other new developments from aerospace firms and government organizations. While this potential is speculative, the speed and accuracy DMLS provides allows for possibilities like this to become reality if utilized effectively and efficiently.
3.2 Environmental Impact and Sustainability

Economic benefits for DMLS produced molds extend beyond financial metrics. Aside from the key benefits that arise from additive processes, DMLS also excels in the reduction of waste production. As mentioned in the introduction section, DMLS operations use laser spot welding to fuse powders together to form structures. While this reduces the material required to build a part, it also significantly reduces any waste produced during the building operation. In contrast, subtractive manufacturing processes like CNC typically produces two waste by-products – metal shavings and cooling fluid (Zhao, et al., 2015). Cooling fluid is used to prevent machining bits like mills from overheating and damaging the part or machine. When combined with the metal shavings, this fluid produces a slurry-like substance that is harmful to the environment if not properly disposed of. Figure 8 is a visual representation of a waste production comparison between additive and subtractive manufacturing methods.

Existing subtractive manufacturing methods within the industry partner’s machine shops require support infrastructure to prevent any accidental leakage of slurry into water systems. This includes systems like buckets, troughs, and spillways within the floor of the machine shop. Additionally, the partner’s machine shops have an isolated drainage system.
that leads to a drainable septic tank to ensure minimal risk to the environment. While the industry partner is maintaining responsible environmental standards, these methods of sustainability within the business’s production floor would need new infrastructure to support the addition of another subtractive manufacturing machine. However, a GE printer does not require the same equipment for waste production management. The build area is an enclosed cube sealed from the atmosphere to prevent oxygen from entering the work area. Additionally, since the only material input into the system (aside from the power needed for the laser) is the metal powder, the only by-product would be residual powders. No liquids are involved in the manufacturing process, so collecting powder via vacuum allows it to be recycled for reuse.

Aside from material efficiency, the DMLS printing operation is also power efficient. The hypothetical power consumption calculations used to estimate the cost of a build above included power requirements common with low energy systems like desk computers. This puts lower strain on the business’s power supply as well as electric bill. Expanding upon the calculations above, a 400W printer running non-stop for 30 days would add approximately $74.00 to the electric bill. This is in stark contrast to CNC machines which consider 1.6kW an energy efficient level of power consumption (Mammone, 2022). From an environmental standpoint, less power consumption produces less emissions. DMLS printers’ lower power needs help reduce the company’s carbon footprint while still maintaining the material output needed to keep production processes from stalling.

The environmental benefits allow the additive process to maintain sustainability unparalleled by subtractive counterparts. This sustainability is most noteable in two areas – machine maintenance and reduced support requirements. GE printers are similar to paper printers in
the sense that they can be serviced and repaired by a technician with relative ease. Internal parts like nozzles or motherboards are quick to replace should any issues arise during production. CNC machines are much larger structures that may require more intensive servicing by technicians or even replacement should critical components fail. Older CNC machines have large gears or forged components that would make the machine unusable should they be damaged. DMLS printer components can almost be described as modular, allowing them to maintain sustainability through repair.

Sustainability is also maintained through less support requirements for operation, with the most significant factor being machine operators. DMLS printers do not require an operator to run. Instead, an engineer can send a file to be built in the same manner a paper report would be printed. This omits the training and salary requirements needed for an on-site machinist while still providing quality molds. The monetary gain saved from this operation can then be invested in a tool engineer role which would further increase the benefits of DMLS by designing better molds. Sustainability can be seen in lower requirements for support tooling. CNC machining requires supplementary components like chucks, mills, and braces that can break and require replacement. Not only do standard DMLS build not require this support equipment, it would be able to print these parts should a CNC needs it. This also extends to the specific mill types. Larger or diameter mills may be required on CNC machines to achieve desired shapes, requiring significantly sized tool libraries to perform these operations. As DMLS is a layering process, no additional tooling would be required to make complex geometries.

When looking at sustainability and environmental responsibility through the lifetime of a GE Printer, the aforementioned repairs and waste production should be consistent despite
the printer’s age. At the end of its useful life, the printer can be recycled similar to other electronics. With no significant waste production or investments aside from powder, the DMLS process should be an environmentally friendly and sustainable alternative to subtractive manufacturing methods.

4. TESTING RESULTS AND DESIGN OF EXPERIMENTS

Fifty four total scenarios were run between the two mold types, with each of the 9 scenarios ran 3 times per mold. Each mold utilized the temperature and pressure parameters listed in Table 1.

Figure 9. Ansys Project Tree for Simulations
The models and simulation data was provided by Ansys R1 Mechanical, utilizing the analysis systems “Static Structural” and “Transient Thermal”. Figure 9 shows the Ansys project tree that was used to develop the scenarios for this project.

Tables 2 and 3 show the results of the simulation in terms of Maximum Deformation. We used a linear mixed model to assess if Mold is a significant factor in the response variable. In this model, the significance of the random effects associated with Mold can be evaluated by looking at the random intercept variance and standard deviation estimates for the Mold grouping factor. If the estimated variance for the Mold intercept is close to zero or the standard deviation is very small, it suggests a slight variation between the different molds. In that case, the Mold factor may not have a significant impact on the response variable.

Table 6. The results of simulation for 27 Experiments in Mold A

<table>
<thead>
<tr>
<th>Pressure [psi]</th>
<th>Temperature [*°]</th>
<th>Mold</th>
<th>Maximum Deformation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>Low</td>
<td>A</td>
<td>1.10023*10^-05</td>
</tr>
<tr>
<td>Low</td>
<td>Low</td>
<td>A</td>
<td>1.08886*10^-05</td>
</tr>
<tr>
<td>Low</td>
<td>Low</td>
<td>A</td>
<td>1.10930*10^-05</td>
</tr>
<tr>
<td>Low</td>
<td>Medium</td>
<td>A</td>
<td>0.000011226</td>
</tr>
<tr>
<td>Low</td>
<td>Medium</td>
<td>A</td>
<td>1.13113*10^-05</td>
</tr>
<tr>
<td>Low</td>
<td>Medium</td>
<td>A</td>
<td>1.12105*10^-05</td>
</tr>
<tr>
<td>Low</td>
<td>High</td>
<td>A</td>
<td>1.13473*10^-05</td>
</tr>
<tr>
<td>Low</td>
<td>High</td>
<td>A</td>
<td>1.13531*10^-05</td>
</tr>
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<td>High</td>
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</tr>
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<td>Medium</td>
<td>Medium</td>
<td>A</td>
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<td>Medium</td>
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</tr>
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<td>Low</td>
<td>A</td>
<td>0.002226684</td>
</tr>
<tr>
<td>High</td>
<td>Low</td>
<td>A</td>
<td>0.00230581</td>
</tr>
<tr>
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<td>Low</td>
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</tr>
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<td>0.002415613</td>
</tr>
<tr>
<td>High</td>
<td>High</td>
<td>A</td>
<td>0.00283359</td>
</tr>
</tbody>
</table>
The fixed effects estimates provide information about how each mold level contributes to the "Maximum Deformation" compared to the reference level (the first level). The output from the linear mixed model concerning the "Mold" factor indicates some variation in the intercept between different molds, as shown by the random effects estimates. The estimated variance of the random intercept for the "Mold" grouping factor is $4.538 \times 10^{-8}$, and the corresponding standard deviation is 0.0002130. This suggests that the molds may have different "Maximum Deformation" baseline levels.

Table 7. The results of simulation for 27 Experiments in Mold B

<table>
<thead>
<tr>
<th>Pressure (PSI)</th>
<th>Temperature (°F)</th>
<th>Mold</th>
<th>Maximum Deformation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>Low</td>
<td>B</td>
<td>1.8636E-05</td>
</tr>
<tr>
<td>Low</td>
<td>Low</td>
<td>B</td>
<td>1.8559E-05</td>
</tr>
<tr>
<td>Low</td>
<td>Low</td>
<td>B</td>
<td>1.8653E-05</td>
</tr>
<tr>
<td>Low</td>
<td>Medium</td>
<td>B</td>
<td>1.8943E-05</td>
</tr>
<tr>
<td>Low</td>
<td>Medium</td>
<td>B</td>
<td>1.8911E-05</td>
</tr>
<tr>
<td>Low</td>
<td>Medium</td>
<td>B</td>
<td>1.8824E-05</td>
</tr>
<tr>
<td>Low</td>
<td>High</td>
<td>B</td>
<td>1.9053E-05</td>
</tr>
<tr>
<td>Low</td>
<td>High</td>
<td>B</td>
<td>1.8950E-05</td>
</tr>
<tr>
<td>Low</td>
<td>High</td>
<td>B</td>
<td>1.9221E-05</td>
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<td>Low</td>
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<td>B</td>
<td>0.00057477</td>
</tr>
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<td>Medium</td>
<td>Low</td>
<td>B</td>
<td>0.000566498</td>
</tr>
<tr>
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<td>Medium</td>
<td>B</td>
<td>0.0005717</td>
</tr>
<tr>
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<td>Low</td>
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<td>Low</td>
<td>B</td>
<td>0.001042796</td>
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<td>Low</td>
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<td>B</td>
<td>0.001259333</td>
</tr>
<tr>
<td>High</td>
<td>High</td>
<td>B</td>
<td>0.001117386</td>
</tr>
</tbody>
</table>
The intercept estimate of $1.728 \times 10^{-3}$ with a t-value of 9.641 indicates a significant difference between Mold B and Mold A regarding their baseline level of the "Maximum Deformation." Mold B is estimated to have a higher baseline level, approximately 0.001728 inches higher than Mold A when all other predictors are at their reference levels. Although this increase in the baseline deformation of Mold A is statistically significant, no fracturing was detected within the DMLS mold. The overall Maximum Deformation for Mold B remains below the required maximum level for production, which is 0.001, and thus the mold meets the production specification.

Figure 10 represents the average maximum deformation between each mold at nominal parameters. While there is a slight increase in deformation within Mold B, it should be noted that both molds experienced similar rates of deformation increase pressure increases. This behavior could indicate that deformation in model B could be related more to the lack of material supporting the mold and the supplemental hollow support structure flexing more to maintain structural stability.
Figure 11 shows the deformation heatmap in molds A and B when subjected to nominal pressure and temperature. The average Maximum Deformation for Mold A and B at production parameters were $3.837 \times 10^{-4}$ and $5.896 \times 10^{-4}$ inches, respectively.

The “X” shape seen in Mold B is due to the internal support structure to which the honeycomb geometries are grafted. This geometry allowed for reinforcement within the mold and extra support for the detailing required for the rubber part. Deformation in Mold A was localized to pry slots as indicated on the heat map.

A critical variable for evaluation throughout the testing of scenarios was the internal cavity temperature when the model was placed under the temperature and pressure requirements of the processing operation. As such, one of the desired data outputs will be not just the final internal cavity temperature but the rate at which the temperature within the mold changes over time and heat up. There will be a two-step application of heat on the molds. Step one will take 300 seconds (5 minutes) and raise the mold temperature from room temp (71.6°F) to the desired value during this time. Once this period is completed, the temperature will remain at the desired value for an additional 1800 seconds (30 minutes), fully simulating the production process. Final results provided graphs displaying the internal temperature of each scenario at any given second. As previously mentioned, the
applied heat had minimal effect on the process parameters, so the variation between values is nearly non-existent. There was a close similarity between the temperature graphs of Mold A and B, with an average variation between values of 0.1832°F. Figures 15 and 16 show that both molds had similar heat graphs.

**Figure 12. Internal Temperature (°F) vs. Time (s) Mold A**

Figure 12 shows the internal temperature over time in Mold A. Figure 13 shows a similar rate of temperature increase for Mold B. As depicted, both molds have a linear increase in temperature until the required temperature is reached, wherein the mold maintains this thermal value. This can be interpreted in several ways.

**Figure 13. Internal Temperature (°F) vs. Time (s) Mold B**

Firstly, the heat transfer coefficient of both materials is equal since, regardless of the manufacturing method, both molds were made of Aluminum. Second, due to the desired parameters of the production process, the heating of the molds was already expected to be brief to provide as much time as possible for the rubber to cure. A final potential variable
that had an impact on the temperature readouts was the setup of the simulation. Pressure simulations required fewer inputs to provide usable data, whereas thermal analysis required insight into the convective energy and heat transfer coefficients needed per mold. Future simulations should be more cognizant of this issue when setting up test materials.

5. CONCLUSION AND RECOMMENDATIONS

This proposed study utilized computational models to investigate the validity of DMLS as a potential manufacturing method for compression mold tooling. The determining metrics for validation included pressure resistance, heat transfer rate, and material usage. Proposed simulated DMLS mold used in this exercise was printed at 90° angle orientation and had honeycomb internal structures. During testing, it was discovered that the DMLS mold experienced a maximum deformation of under .001” under the nominal pressure scenario with no fracture, indicating the honeycomb structure was able to support the necessary production pressure parameters. The changes to the internal structure however increased the overall stress and strain, but did not exceed levels that would be damaging to the mold. Temperature analysis was consistent between both molds, with temperature graphs having similar outputs due to the production parameter circumstances.

After concluding the design of experiments, the DMLS mold proposal was found to be able to successfully withstand the pressure and temperature requirements to cure rubber components within a production setting. This opens up the potential to minimize the size of molds using DMLS to reduce lead times and costs on future tooling. While the heat transfer was slightly lower than a traditional mold, the time the production process takes to cure the material allows the mold to provide adequate heating to the rubber. While an individual cavity may have a lower heat transfer, replication of the cavity with the abilities
of DMLS allows for multiple components to be printed on the same part with less material required per part.

The data provided by this project also provides critical information for the industry partner for the future of mold tooling manufacturing. As mentioned within the industry relevance section, and briefly above, the success of the analytical model expands the potential for future testing and financial benefits. Upon successful implementation of the DMLS operation into new tooling, the industry partner can remove mold machinist vendors as significant company stakeholders. CNC-derived tooling will still be required for different circumstances (like machining existing scrap metals or other tool types) but compression mold tooling can be converted into an in-house process. From a financial standpoint, the model data posits a hypothetical cost savings of up to 72%. Practical models and prototypes may require more investment than calculated. However, practical models are likely able to maintain significantly lower operating costs than current methods, potentially reducing the $2.5 million annual cost to an estimated $1 million. Internal stakeholders at the partner, such as management and production teams, can utilize the reallocation of funds for additional workers, repairs, or investments into new production lines. External stakeholders, such as the industry partner’s customers, can also benefit from the reduction in lead time typically associated with traditional mold making. A traditional mold will take roughly 6 weeks to produce depending on the size and complexity, extending the time a customer needs to wait for their order. However, with the reduction in lead time DMLS provides, customers can receive their orders faster. This in turn allows for more orders to be fulfilled per year when utilizing a compression mold, providing a two-fold financial
benefit to the partner’s internal stakeholders who will be saving money from tool costs and earning money from less lead times.

The cascading effects from bringing the DMLS process in-house include benefits for company sustainability and reduced environmental impact. An in-house transition towards the DMLS compression mold manufacturing process is a more sustainable operation than purchasing tools from vendors. To sustain the vendor operation, the partner must abide by the pricing and lead times set by the vendor. Additionally, tool costs can vary if the vendor has multiple customers requesting parts at the same time or if an expedited order is required. If the vendor was to go under, the partner has to find a new source for tooling, further increasing lead times and costs. In-house operations circumvent this by printing the molds on an as-needed basis. This process reigns in the costs of purchase orders, freight, and lead times from a vendor and transitions them into raw material acquisitions for part printing. To sustain the DMLS process, the partner must provide the powder materials to build with and power to the printer, lowering the partner’s reliance on outside sources while maintaining the sustainability of the operation.

The most significant benefit for the environment by transitioning to DMLS manufacturing involves the reduction of scrap metal and cooling fluids. Infrastructure within the industry partner’s vendor facilities is designed to collect said metal and fluid waste. These by-products of the traditional manufacturing process are harmful to the environment and require investments into proper collection and disposal. Inversely, the application of DMLS produces only gaseous by-products. Since the operation spot-welds materials, an inert gas like argon is used to shield the welding area from more reactive gases like oxygen. Small amounts of this gas may seep from the printer but not enough to cause any harmful damage.
to the environment. Additionally, the utilization of the powders to produce parts minimizes the scrap metal to near zero, as the operation only uses the powder needed to build the part. Therefore, 100g of powder can produce approximately 95g of part, while 100g of metal would produce significantly less part from a subtractive manufacturing method. Due to this, the industry partner’s implementation of DMLS would not require additional investment into waste disposal infrastructure. Waste produced by the operation would be in the form of leftover powders and inert gases, which can be cleaned up with a vacuum, further demonstrating the benefits from DMLS.

Future works on this paper’s study would include further validation of DMLS molds for other manufacturing applications. As previously mentioned, a patterned mold with similar surface areas to the original CNC machined mold could provide sufficient heat transfer to the rubber composites within while increasing the part creation per cycle. It is predicted that this will further reduce material and financial investments while also introducing a reduction in lead time costs. While this paper produced benefits and caveats of using Direct Metal Laser Sintering as a manufacturing method, this paper recommends that DMLS be considered as a viable option for mold manufacturing.
6. REFERENCES


Byrne, Brendan, et al. “A 3D-Printed Rocket Launched Successfully but Failed to Reach Orbit.” NPR, NPR, 23 Mar. 2023


https://mint.intuit.com/salary/cnc-machinist/ca#:~:text=machinist%20in%20California%3F-


https://journals.iau.ir/article_587854_0fb72e603e6fdd2db3dd29501d52309b.pdf


https://www.datron.com/resources/blog/consider-energy-efficient-cnc-machining


6061 Aluminum Plate | Midwest Steel & Aluminum. (n.d.).


https://www.midweststeelsupply.com/store/6061aluminumplate
7. APPENDIX A – DATASHEET FOR ANSYS CALCULATIONS
### Regression Data, Model A (CNC)

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### Model A Statistical Analysis

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### ANOVA

#### Summary

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8. APPENDIX B – CONCEPT LASER M2 SERIES 5
Concept Laser M2 Series 5
Enabling repeatability at scale

Designed for high-quality builds at scale
The M2 Series 5 can unlock your company’s manufacturing potential. The new system provides an elevated level of productivity and repeatability by minimizing the effects of process variations. The result: fast builds that help lower your company’s cost.

The powerful dual-laser system—available in both 400 W and 1 kW—combined with 3D optics enables 100% coverage per laser, meaning that both optical systems have full build-field overlap. A dedicated thermal control of the optics further contributes to improved thermal and optical stability, accuracy, and best-in-class stitching. Due to the small but variable spot size, the system provides the user with more flexibility that enables both fine features and enhanced productivity.

The flow-optimized build chamber of the M2 Series 5 now allows for a more constant gas flow. Additionally, the new optimized gas flow design eliminates recirculation and reduces variation by 25% over the entire build field.

New part vectorization allows for additional flexibility to part parameter design, enabling new geometries and ensuring part quality, especially with increased part complexity. The pre-calculation helps to save time and boost productivity. In combination with multiple internal sensors, this ensures a more tightly controlled build environment, resulting in significantly better part quality and consistency. These are the key drivers for success in safety-relevant industries like aerospace and medical and other industries looking at scaled production.

Machine highlights
- Bigger build volume: 245 x 245 x 350 mm
- 400W or 1 kW dual-laser system with full overlap
- Improved gas flow system
- 3D optics with 70 – 500 µm spot size
- Inert sieving and powder exchange
- Maximized machine uptime
- Pre-calculation software, saving time when building complex parts
- Designed for usability and maintainability
- QuickStart functionality

Offering maximum usability, maintainability and safety
The M2 Series 5 features a unique safety system that promotes safety and efficient handling of reactive materials. This is made possible by the physical separation of the process chamber and a material handling side, connected with a movable build module. Additionally, all powder handling processes are performed under inert gas to prevent oxidation and safety hazards. The integrated glovebox system enables safe, non-contact handling of reactive or harmful materials and enables the dust-protected removal of parts. Together with the newly optimized water-flushable filter modules, the M2 Series 5 offers maximum protection for the machine operators, while extending the filter life and reducing operating costs.

The system is designed to maximize usability and maintainability. All functionalities of the machine have been optimized for easy access and handling. The new software of the M2 Series 5 helps you save time before, during and after the build process.
Software suites

PROCESS MANAGEMENT
Amp™, GE’s software platform

Results matter, so the process matters. Developed exclusively for GE machines, Amp™ integrates the tools engineers need to manage, process and manufacture metal additive parts on one integrated platform—built on GE’s expertise and experience. From development to print production, Amp offers a flexible, streamlined workflow so manufacturers can improve part production and significantly reduce trial and error needed to develop print-ready parts. LEARN MORE

Print Model
Print model is designed to enhance additive manufacturing effectiveness of the M3 Series 3 through a secure, integral tool that reduces design iterations and speeds up the time to print a good part, according to the design intent.
- Automate manual tasks
  - Based on real-world best practices
  - Simplified process to print parts
- Track pedigree
  - Relationships captured between various inputs
  - Audit history of printed parts
- Leverage CAD model
  - Clean data, no need for STL, no healing
- Experience a single data-centric process
  - No saving out to other software tools
  - No learning separate interfaces
  - Everything in one place
- Conduct quality checks
  - Identify build risks before sending to print

Simulation & Compensation
Simulation & Compensation adds predictive capability to the M3 Series 3 builds by anticipating distortions, residual stresses, Secoura Interference and defects before manufacturing and applying corrections before launching production, reducing build trials.
- Add Simulation to your additive process
  - Easy-to-use tools for design/manufacturing engineers
  - Reduced barrier for non-simulation experts
- A unified user experience
  - Seamless flow from build preparation to simcomp
  - All interactions saved for future use
- Save time
  - Digital iterations until your design intent is achieved
  - Reduce manual processes and wasted resources from trial builds
- Save money
  - Reduce costs associated with material and manpower
  - More opportunities to add additive on new parts
  - Get more parts through development and into production
  - Maximize number of possible applications to print

DECREASE time and cost of part development

IMPROVE part yield

MAXIMIZE number of possible applications to print

ENHANCE accessibility and collaboration
MACHINE MANAGEMENT

Software features like pre-calculation enable on-off machine scan path generation. This eliminates calculation delays between layers for complex parts. A new dose profile also helps to further reduce powder consumption for builds with changing geometries.

The additional optical sensors help to monitor the optics temperature to ensure a more stable process and better part quality.

Furthermore, part segmentation and vector tool path support optimized exposure strategies, while the thin walled segmentation enables ultra-fine feature resolution within the part.

CL WRX Parameter 2.x

CL WRX Parameter 2.x is a software application which allows users to create and optimize parameters for their materials. The software enables users to access the full parameter definition (open parameter). The starting point is typically a GE Additive parameter that can be tailored to meet the needs of the application requirements. Additionally, this software can be used to create parameter sets for user-developed materials.

CL WRX Control 2.x

The CL WRX Control 2.x software is supplied with all our DMLS machines. It is installed on the machine industrial PC to provide control of the machine axes and tool path. WRX Control allows for complete calculation of the exposure vectors.

MONITORING AND ANALYTICS

Build Explorer

Build Explorer is a process-monitoring software from GE Additive that enables a user to understand the layer-by-layer performance of a build as the build is happening. It is a machine health and process-monitoring software solution that provides a common user experience. It offers operators and process engineers layer-wise machine sensor and quality information for use real-time during the printing process and for post-build analysis.

Build Explorer gives users the ability to detect real-time machine health trends that can affect build part quality before the quality of a part is affected. Users will then have information that will allow them to take immediate action to minimize cost of poor quality.

QM Meltpool 3D

QM Meltpool 3D is an optional quality management system which is integrated into the optical path of the M2 system. It provides tracking of the ongoing build process via two optical sensors per scanner unit. These sensors are directed at the local emissions of the melt pool to provide high frequency raw intensity and area meltpool data. The system allows analysis of relevant data of the melting path, including full documentation and high resolution mapping (35 µm/Point) the melting pool data. GE Additive is taking active steps to develop future real time fault detection and control, reducing downstream testing procedures and qualification of part parameters.
Concept Laser M2 Series 5

Technical Data

- **Build envelope**: 245 x 245 x max 405° mm (x, y, z)
- **Layer thickness**: 25 - 120 μm
- **Production speed**: Productivity rates and material portfolio available on [website](#)
- **Laser system options**: Fibre Laser 2x3kW (cw), Fibre Laser 2 x 400 W (cw), optional 1 x 400 W (cw)
- **Scanning speed**: Max 4.5 m/s with variable focus adjustment
- **Focus diameter**: 70-500 μm
- **Spot Size range**: 63 - 12 μm
- **Heating System**: Available
- **Reference clamping system (optional)**: EROWA, others on request
- **Connected loads**: Approx. power consumption 25A
  Power supply 3+N/PE AC 400V 32A connector, compressed air & 10bar 2 gas connections provided
  N2 generator external (optional)
- **Inert gas supply**: 51 / min < 1 m³/h
- **Inert gas consumption**: Integrated, with a 20 m² filter surface
- **Filtering system**: Approx. 2,500 kg
- **Dimensions**: 2,719 x 2,050 x 2,781 mm (W x D x H)
- **Weight**: 18 - 25°C

Materials available**

- Stainless Steel 316L
- Stainless Steel 17-4PH
- Maraging Steel M300
- Tool Steel H13
- Aluminium AlSi10Mg
- Aluminium A205
- Aluminium AlSi7Mg
- Nickel 718
- Nickel 625
- Nickel X
- Titanium Ti6Al4V ELI Grade 23
- Titanium cp-Ti
- Titanium Ti6242
- Cobalt CoCrMo
- Cobalt CoCrW

*Build height dependent on build plate configuration and platform thickness (actual range is 405-313 mm)
**Most parameters, data sheets and productivity rates can be found on the [M2 Series 5 website](#)
# Capability Packages

The Concept Laser M2 Series S was designed to meet the most critical requirements by the highly regulated aerospace industry. But we believe that everyone, regardless of industry, region or where you are on your additive journey, should have access to these capabilities. As such, we now offer four capability packages to meet the needs of more customers and help more users adopt additive technology.

- **Standard**: Ideal for entry-level users, standalone prototyping or low volume production
- **Production**: Ideal for full production applications (available in 400W or 1kW)
- **Regulated**: Ideal for high-quality output, regulated industries, and stringent qualification requirements

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### Coming Soon:

- Powder Handling Productivity
- Filter Life
- Thermal Management Package
- Optical Capability

**Amp™ Software Subscription**
M2 Series 5 Aluminum Al-Si10-Mg

Parameter for GE Additive's Concept Laser M2 Series 5

Data in this material datasheet represents material built with a 40 μm layer thickness and is a nitrogen atmosphere on a Concept Laser M2 Series 5 single-laser or dual-laser machine. Values listed are typical.

Aluminum Al-Si10-Mg

Al-Si10-Mg has a chemical composition according to ASTM F3318 and is an essential Aluminum alloy in the world of additive manufacturing. As a good casting alloy for complex geometries, it combines light weight and excellent thermal conductivity. The alloy is ideally suited for part designs with thin walls such as ductwork or heat exchangers. Once post-processed, parts offer good strength and hardness superior to traditionally cast material, as well as good dynamic properties for industries in the aerospace, automotive, automation and cooling sectors. In summary, this aluminum alloy holds great promises to bring additive manufacturing to high volume consumer applications.

M2 Series 5 Al-Si10-Mg

The Al-Si10-Mg parameter for the Concept Laser M2 Series 5 are developed leveraging the performance of the previous M2 generations. The parameter was developed using plasma atomized Al-Si10-Mg powder from APS®. The balanced parameter is a 40 μm parameter that produces surface roughness less than 16 μm without bead blast or shot peening, while delivering good productivity with dual lasers. In particular the down- and upscan areas were further improved to ensure consistent high surface quality across different angles. Moreover, the mechanical properties succeed the limits specified in ASTM F3318 for additive manufactured parts in the as-built and stress relieved (SB1) state.
M2 Series 5 Aluminum Al-Si10-Mg

With appropriate approval* Al-Si10-Mg can be used for lightweight components in aerospace and industrial applications. Data in this material datasheet represents material built 40 μm layer thickness and in a nitrogen atmosphere on a Concept Laser M2 Series 5 single-laser or dual-laser machine. Values listed are typical.

POWDER CHEMISTRY
Aluminum Al-Si10-Mg powder chemical composition according to ASTM F1318.
For additional information on Al-Si10-Mg powder, visit https://www.advancedpowders.com/powders/aluminum/al-si10-mg.

MACHINE CONFIGURATION
- Concept Laser M2 Series 5 (single-laser or dual-laser)
- Nitrogen gas
- Rubber

AVAILABLE PARAMETER
- Base Parameter 268 / 281** 40 μm layer thickness, rubber recoater
**Productivity optimized version (productivity bundle required)

THERMAL STATES
1. As-Built
2. Stress relief (SR1)
   Stress relief 260°C 3 hours, cooled in air

THERMAL TREATMENT COMPARISON

☐ Base Parameter As-Built  ☐ Base Parameter SR1

Spider plot is generated by normalizing typical material data containing both horizontal and vertical data against a range specified for each material family. For Aluminum Alloys, the ranges are as follows: UTS: 6-500 MPa, 0.2% Yield: 0-300 MPa, Elongation: 0-20%, Density: 99.100%, Productivity: 0-30 cm³/hr, Surface Quality (U): 46-55 μm.
<table>
<thead>
<tr>
<th>TYPICAL BUILD RATE</th>
<th>Base Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical build rate w/coating</td>
<td>19.1</td>
</tr>
<tr>
<td>Theoretical melting rate per laser</td>
<td>28.1</td>
</tr>
</tbody>
</table>

*Using standard factory acceptance test layout and 2 lasers
*Calculated (layer thickness x scan velocity x hatch distance)

<table>
<thead>
<tr>
<th>PHYSICAL DATA AT ROOM TEMPERATURE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface Roughness Rz** - Overhang (µm)</td>
</tr>
<tr>
<td>45°</td>
</tr>
<tr>
<td>Uphill</td>
</tr>
<tr>
<td>Downhill</td>
</tr>
<tr>
<td>Surface Roughness Ra** (µm)</td>
</tr>
<tr>
<td>Uphill</td>
</tr>
<tr>
<td>Downhill</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Relative Density (%)</th>
<th>Hardness (HV5)</th>
<th>Poisson’s Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>As-Built</td>
<td>90.7</td>
<td>90.7</td>
</tr>
<tr>
<td>SR1</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TENSILE DATA</th>
<th>Tensile testing done in accordance with ASTM E8 and ASTM E21</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test Temperature:</td>
<td>Modulus of Elasticity (GPa)</td>
</tr>
<tr>
<td>RT</td>
<td>H</td>
</tr>
<tr>
<td>As-Built</td>
<td>70</td>
</tr>
<tr>
<td>SR1</td>
<td>56</td>
</tr>
</tbody>
</table>

H: HORIZONTAL (X) orientation
V: VERTICAL (Z) orientation

* All of the figures contained herein are approximate only. The figures provided are dependent on a number of factors, including but not limited to, process and machine parameters, and the approach is brand specific and/or application specific. The information provided on this material data sheet is illustrative only and cannot be relied on as testing.

** Roughness measurements have been performed according to DIN EN ISO 4287 and DIN EN ISO 4288. In general analysis of the surface quality is strongly dependent on the methodology used and therefore deviations might be observed depending on methodology used. Vertical and horizontal surfaces have been characterized using a tactile system measuring using an optical system.

MD Series 5 Aluminum AlSi10Mg
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SEM IMAGES (low magnification)

As-Built

SR1

SEM IMAGES (high magnification)

As-Built

SR1

H: HORIZONTAL (XY) orientation
V: VERTICAL (Z) orientation

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The platform stability build evaluates porosity, roughness, and tensile properties across different positions and orientations. To illustrate the position dependency of the M2 Series, the samples were homogeneously distributed across the platform on 16 different positions. Regarding surface quality all sides of the specimen, so all orientations with respect to gas flow and optical system, are included in the analysis. Data shown below are dependent on part A print layout as well as batch chemistry variations and thus might deviate from “typical values” given on previous pages.

**BUILD JOB DESIGN AND SUMMARIZED DATA (AS-BUILT)**

<table>
<thead>
<tr>
<th>Sample Size</th>
<th>Mean</th>
<th>Std.Dev.</th>
<th>Sample Size</th>
<th>Mean</th>
<th>Std.Dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rel. Density in %</td>
<td>12</td>
<td>99.83</td>
<td>0.03</td>
<td>YM in GPa (H/V)</td>
<td>16/15</td>
</tr>
<tr>
<td>Sidewall Roughness</td>
<td>64</td>
<td>8</td>
<td>1</td>
<td>YS in MPa (U/V)</td>
<td>16/15</td>
</tr>
<tr>
<td>Upside Roughness</td>
<td>64</td>
<td>6</td>
<td>1</td>
<td>UTS in MPa (I/V)</td>
<td>16/15</td>
</tr>
<tr>
<td>Downside Roughness</td>
<td>64</td>
<td>10</td>
<td>1</td>
<td>Elongation in % (I/H)</td>
<td>16/15</td>
</tr>
</tbody>
</table>

**RESULTS - RELATIVE DENSITY AND SURFACE QUALITY**

**RESULTS - MECHANICAL PROPERTIES IN AS-BUILT CONDITION**

Data points represent the mean value, intervals the 95% confidence level. H: HORIZONTAL (Y) orientation, V: VERTICAL (Z) orientation.

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