Development of a New Method to Fabricate Titanium Metal Matrix Composites via LENS with Improved Material Properties

A Thesis in Materials Science and Engineering

By

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ABSTRACT

A new fabrication method was developed utilizing laser near-net shaping (LENS) additive manufacturing technology to produce novel bulk metal matrix composites (MMC) with dual continuous immersed phases (DCIP) in order to improve material properties. The nature of using LENS to create DCIP samples has several advantages over alternative MMC fabrication methods which allow the creation of bulk parts with material property combinations not found in existing engineered or natural materials.

DCIP samples were produced using near-β and α/β titanium alloys as the constituent phases. The sample’s microstructure is explored via optical microscopy and Vickers hardness testing. A methodology is presented to select processing parameters to avoid defects.

The fabrication method and process development was found to be successful in creating a bulk samples free from processing defects. Vickers hardness testing revealed considerable variability in hardness values across the sample and within individual deposits suspected to be a result of substantial intermixing between adjacent hatches and layers. Further refinement of process parameters is expected to decrease intermixing and hardness variability. Epitaxial grain growth was attenuated by the DCIP morphology as compared to bulk laser deposited Ti-6Al-4V samples.

Additional geometrical considerations are considered. The practicality, potential, and impact of scaling this process to an industrial scale is explored and discussed. Present and future possible uses of this technology are given.

Keywords: laser, additive, manufacturing, LENS, near-net, shaping, rapid, prototyping, processing, parameter, development, defects, MMC, metal, matrix, composite, DCIP, dual, continuous, immersed, phase, hatch spacing, layer height, Z-step, meltpool, bead, shape, profile, contact angle, mass flow rate
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<th>Abbreviation</th>
<th>Full Form</th>
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<tr>
<td>ARL-Penn State</td>
<td>Applied Research Laboratory at The Pennsylvania State University</td>
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<tr>
<td>LENS</td>
<td>Laser Engineered Near-net Shaping</td>
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<td>MMC</td>
<td>Metal Matrix Composite</td>
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<td>DCIP</td>
<td>Dual Continuous Immersed Phase</td>
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<td>DMC</td>
<td>Direct Machine Code</td>
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<td>FGM</td>
<td>Functionally Graded Materials</td>
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<tr>
<td>HIP</td>
<td>Hot Isostatic Pressing</td>
</tr>
<tr>
<td>PF</td>
<td>Powder Feeder</td>
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<tr>
<td>HAZ</td>
<td>Heat Affected Zone</td>
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LENS NOMENCLATURE

**Bead** – Material deposited by a single pass of the deposition head along a line.

**Hatch Spacing** – The distance between line deposits.

**Traverse speed** – The speed at which the process stage moves relative to the deposition head.

**Traverse direction** – The direction which the process stage moves relative to the deposition head during processing.

**Layer** – A number of adjacent deposits made at the sample height.

**Z-Step** – The distance the process head moves between layers.

**Laser Power** – The nominal amount of energy given off by the laser measured in watts.

**Substrate** – The base material to be deposited onto.

**Meltpool** – The instantaneous volume of the liquid material created by the laser at the point of deposition.

**Mass flow rate** or \( \dot{m} \) - The nominal amount of powder feed to the part while building measured in grams per minute.

**Powder capture efficiency** - The fraction of power captured by the meltpool to create the build from the total powder available.

**Powder spot size** – The cross-sectional area of the incoming powder.

**Bead profile** – The cross-sectional area of a single bead of material deposited above the substrate.

**Contact angle** – The angle between the substrate and a line tangent to a circular segment fitted to a bead profile where it meets the substrate.
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Chapter 1

Introduction

1.1 Introduction to Metal Additive Manufacturing Technologies

There are several competing commercially available metal additive manufacturing technologies on the market. Each of them builds up a three dimensional part by depositing a series of stacked two dimensional layers composited of parallel deposits using heat from an electron beam, laser, or electric arc. Metallic powder(s) or wire is delivered to the workspace to be melted or sintered. The correct combination of processing parameters can produce fully dense materials with mechanical properties superior to cast parts and even approaching or exceeding wrought parts[1].

In recent years, additive manufacturing has moved from simply a rapid-prototyping method to producing real parts to be put into service; although there are some technological and economic constraints that determine when metal additive manufacturing is best suited to create a part. Some part geometries are difficult to produce via additive manufacturing techniques, other part geometries are impossible to produce without. Typically some amount of mechanical finishing or machining or thermal post-processing is required before putting additive manufactured parts into service.

Each different additive manufacturing technique has its own advantages and disadvantages. Powder bed technologies are less constrained by geometry, but are typically limited to producing parts from only one metal or alloy at a time. Some systems use servo motors to move the substrate under a deposit head, while other systems use optics to quickly scan a laser or electron beam over the substrate. Servo based systems are limited in their scan speed due to inertia, however fast scan speeds may result in higher levels of residual stress perpendicular to the deposition axis[2]. Additive manufacturing systems have been scaled to build up parts at deposition rates ranging three orders of magnitude from grams per hour to kilograms per hour, though deposition rate typically scales inversely to feature size.
1.2 Overview of laser additive manufacturing system used

1.2.1 ARL’s LENS system

The system that Penn State acquired in late 2009 employs Laser Engineered Net Shaping (LENS) technology. The Materials Research (MR-7) model produced by Optomec Design Company of Albuquerque, NM has a continuous 500W Yb-Fiber laser capable of 500W of continuous energy output at 1075nm wavelength and dual powder feeders. The laser is directed at the surface of a substrate creating an area of molten metal referred to as the meltpool. Powdered material from dual powder hoppers is fluidized by an inert gas stream and delivered coaxially through four 1.1 mm inner diameter nozzles into the meltpool forming a deposited bead of material. Adjacent beads build up a layer and stacked layers build up a part.

Figure 1: Schematic of LENS machine
The work envelope is within an atmosphere controlled glovebox kept at positive pressure with industrial grade argon (99.995%). Oxygen levels in the glovebox are held under 10 ppm by an oxygen getter/scrubber while processing, and under 500ppb is achievable. A substrate material is attached to a stage that moves freely in the positive and negative X and Y direction and the deposition head moves up and down in the Z. A cooling plate is mounted between the substrate and process stage. A schematic is shown in Figure 1.

The dual powder feeders allow for the selective and graded inclusion of ceramics, secondary metals or alloys. This enables the production of large scale functionally graded materials (FGM) and metal matrix composites (MMC) including the geometrically advanced MMC described herein. Further information on the workings of the LENS system is available in open literature [3-5].

1.2.1 Idealized LENS part creation process

To create a simple rectangular deposit, a bead of material would be deposited onto a substrate of similar composition. A second bead is then deposited alongside of the first at a specific distance. Figure 2 details the process at this step. Figure 3 shows how repeating this process will build up a layer. When deposited in this manner, individual deposits are referred to as hatches. The selection of the actual processing parameters is further discussed in section 2.1.

![Figure 2: Schematic of adjacent deposited hatches of similar material. The numbers represent the hatch deposition order. The arrows indicate the direction of deposition. The dashed line represents the profile that the second bead would have if the first were not there.]

* It is understood that the 3D projection shown here is not truly orthogonal.
Figure 3: Schematic of depositing 5 adjacent hatches to build up a single layer. The arrows indicate the direction of deposition.

After creating a single layer, the deposition head is raised and the process is repeated on top of the previous layer. If there is no change in hatch orientation or no hatch offset, a four layer thick deposit will resemble the schematic shown in Figure 4. If the hatch orientation is changed 90° between layers, the deposit will resemble Figure 5. Note that edge effects are not shown in Figure 5 for simplicity.

Figure 4: A four layer thick deposit five hatches wide.

Figure 5: 3D cross-section from a part built with hatch orientation changed 90° between layers. Edge effects are not shown for simplicity.
1.2.2 Programming LENS Direct Machine Code build files

The typical process for creating part files is to draw the part in 3D drafting software. The file is exported as a stereolithography (.STL) file and imported to proprietary LENS software which slices the 3D file into a series of finite 2D cross-sections and saves as a slice file (.SLI). The distance between layers is set as the Z-step, i.e. the distance the deposit head will advance upward after completing a layer. A toolpath within individual layers is generated by spacing parallel deposit paths a specific distance apart. This distance is known as the hatch spacing. The deposit orientation within the layer is known as the hatch angle. The hatch angle may be changed between layers if desired as shown in Figure 4-5. The file at this point sets the Z-step, hatch spacing, and hatch orientation between layers.

The output file is then fed into another program. The user then sets the traverse speed of the XY stage, the powder feeder(s) to be used, and other LENS specific variables. The final format is called a direct machine code file, or .DMC. Additional commands can then be manually entered into the file to automatically control powder feeder speed (which is related to the mass flow rate), laser power, and other commands, or is controlled manually in realtime as the file is being run. Alternatively, .DMC files can be directly programmed, as was necessary to create the complex structures fabricated herein. Manual coding of .DMC files allows direct control of machine commands and conditional programming.

1.2.3 Programming limitations

The processing variables coded by the file cannot be changed while processing except for a scaling factor on traverse speed. No advanced feedback mechanism exists that corrects processing parameters “on-the-fly.” (While a rudimentary system does exist to adjust laser power, the LENS closed loop melting control was not useful for this experiment.) Incorrect selection of processing parameters can and will result in defects to the build such as porosity, lack of fusion between deposits, or a complete failure to build at all. The problems surrounding proper parameter selection or optimization is explored later in this thesis.
1.3 Background on metal matrix composites

A metal matrix composite is composed of at least two distinct phases, one of which must be a metal. These can be arranged in an orderly manner or random fashion. This broad definition includes many possible geometrical orientations and encompasses many naturally forming structures such as those found in carbon steels. Typically the majority constituent is referred to as the matrix and is usually a metal in an MMC. The secondary reinforcing phase can be any number of things such as a ceramic, another metallic phase, metal, or alloy, and even a polymer is possible if the metallic phase has a low enough melting temperature.

Figure 6 shows a micrograph of pearlite in steel. Pearlite is a layered structure of alternating bands of $\alpha$-ferrite (a metal) and Fe$_3$C (a ceramic called cementite). The combination is harder than the pure Fe, yet tougher than cementite alone. The dark bands in Figure 2 are the cementite, the white sections are ferrite. This structure naturally forms via a eutectoid reaction as carbon steel cools below 727°C. By controlling the cooling rate, the structure of the pearlite can be controlled to some degree. The larger the temperature drop below 727°C, the faster nucleation occurs. The slower the cooling rate, the more time atoms have to diffuse and create thicker bands. The thicker the pearlite features, the softer the steel.

Figure 6: Pearlite in carbon steel, a naturally occurring MMC.[6]
Modern engineered MMC are have properties exceeding naturally occurring structures and are typically used in high performance applications in aerospace, military, medicine, and industry. Metal matrix composites are often enabling technologies – not just improving reliability or performance over conventional materials, but creating new applications not possible with existing alternatives.

The conventions shown in Figure 7 are typically used when discussing MMC. In the LENS machine workspace, the transverse, longitudinal, and thickness directions correspond to the X, Y, and Z axes respectively. The black dots would be the reinforcing phase and the white bulk is the matrix phase.

![Figure 7: MMC Conventions](image)

**1.4 Literature Review of Titanium Metal Matrix Composite Fabrication Methods**

The potential of LENS technology to create wear-resistant surfaces has been recognized. Titanium in particular does not wear well[8], so several different surface treatments have been employed to harden the surface. H.C. Man, et al, created *in situ* a surface layer of a TiC/Ti MMC by laser cladding mixtures of Ti and Cr3C2 powder on a Ti6Al4V substrate. Upon irradiance, the ceramic Cr3C2 particles and Ti powder melted. The carbon formed fine TiC particles and the Cr stabilized the β phase of the bulk Ti upon cooling. This formed a hard β surface layer on the Ti6Al4V substrate dispersion strengthened by submicron TiC ceramic particles[9].

Other researchers have created bulk samples by premixing powders before deposition. S. Gopagoni, et al, fabricated an *in situ* Ni-10Ti-10C MMC. The powders were premixed and deposited using a LENS 750
machine. Tribological measurements determined the deposits have low friction yet high hardness; ideal for contact surfaces of moving mechanical parts[8].

Liu, et al, fabricated defect free carbide reinforced Titanium-Aluminide MMC using LENS. Twenty percent TiC by volume was premixed with Ti-48Al-2Cr-2Nb powder and deposited as bulk samples. Vickers hardness testing of the MMC were found to be on average twice as hard as control samples of pure Ti-48Al-2Cr-2Nb[10].

Samples of bulk nickel-carbon nanotube (CNT) nanocomposites were created with a LENS 750 machine by A. R. P. Singh, et al. The Ni and CNT powders were premixed and ball-milled for 24 hours before deposition. A clean interface between the matrix and reinforcement was noted and the CNT’s were well dispersed throughout the deposit[11].

These efforts produce MMC with discontinuous randomly dispersed reinforcement phases. Other MMC fabrication methods can produce sandwich composites with thin Ti foils and a continuous reinforcement phase, but are limited to producing thin parts[12].

The goal of this thesis was to develop a method via LENS to produce a continuously reinforced MMC that could easily be extended to produce 3D components.

**1.5 Introduction to dual continuous immersed phase-metal matrix composites**

**1.5.1 Unexplored manufacturing capability of LENS to create DCIP materials**

No work has been found by the author in the open literature on creating a dual continuous immersed phase-metal matrix composite (DCIP-MMC) via LENS or other manufacturing techniques. A DCIP is defined as a MMC that has two immersed bulk phases that are continuous in at least one direction. When the ratio of constituent materials approaches 50:50, neither phase is truly the matrix or reinforcement phase.
A similar process to typical LENS manufacturing is used to build up a DCIP material, except that the feedstock material is alternated between deposits in a regular manner. This preserves the geometric flexibility of the LENS process in creating a bulk MMC. This is especially important since joining continuously reinforced MMC using conventional fabrication methods is difficult [7] and typically disrupts their structure. Since the properties of an MMC are structurally dependant, joints can be a source of failure, a “weak link.” Since LENS can eliminate the need for joining, it is ideal for fabricating parts with a DCIP morphology.

### 1.5.2 Technical justification for creating DCIP materials

The DCIP morphology offers several advantages over conventional materials by allowing direct compositional control at the sub millimeter scale. Combinations of materials with asymmetric mechanical, electrical, or other materials properties can be combined in one material. Grain growth and distribution can be modified by chemistry control or modifying the deposition process.

The effect is distinct from merely alloying the constituent materials. While some mixing of adjacent materials is required to form a metallurgical bond, each material retains their own inherent composition and material properties within the centers of deposition to some degree. The fast cooling rates inherit to the LENS microdeposition process retain the composition at the sub millimeter scale.

For example, a ductile, highly conductive material may be combined with a harder material, yielding a material with improved properties than existing MMC fabrication methods would allow. Alternatively, if a material with an average alloying composition was desired, materials could be combined that have lower and higher percentages of the alloying elements. Post processing heat treatments may be able to normalize the compositional difference through diffusion depending on the thermodynamic stability and the system equilibrium; yet the grain morphology would be dependent on the deposition geometry.
1.5.3 Selected DCIP deposition geometry

Many different deposition geometries and material ratios are possible; each has their own benefits and drawbacks. Several possible deposition plans are presented in Appendix A. The deposition scheme used to produce the bulk DCIP samples is shown in Figure 8.

![Figure 8: Deposition plan of the produced Dual Continuous Immersed Phase MMC. Orange and brown areas represent distance materials. The numbers represent the individual bead deposition order.](image)

1.6 Statement of Work

The objective of this thesis is to develop the framework for producing defect free DCIP structures with feature sizes less than 1mm. A logical and straightforward methodology for selecting LENS processing parameters which minimize defects is presented. Parameters will be developed for a near-β Ti and an α/β Ti powder which result in similar bead profiles. A novel DCIP specimen will be produced with a “checkerboard” cross sectional schematic using these parameters as shown in Figure 8. The success of the parameter selection process is to be determined using optical microscopy and checking for processing defects in the final specimens. Vickers hardness measurements will be taken in a grid over the cross-section of the final specimen(s) to determine the hardness of each phase within the bulk deposit.
1.7 Additional Engineering Considerations

There are many factors that decide whether to utilize a technology or a particular process on an industrial scale that determine whether the process meets the requirements of the project. Cost, obviously is a primary concern. Additive manufacturing processes are best suited to building items that are difficult or impossible to build using conventional methods due to geometric or chemical constraints, or for creating parts in small lot sizes. Typically, the smaller the fraction is of finished material left in a part versus the solid block it would have to be made out of using conventional methods, the more economical it is to utilize additive manufacturing techniques[13]. The geometrically complicated in Figure 9A would be very difficult and thus time and labor intensive and correspondingly expensive to create using typical subtractive processes, while relatively straightforward to make on the appropriate additive manufacturing system. The monolithic cylinder in Figure 9B is trivial to create using conventional methods but would be unnecessarily expensive to make using additive manufacturing unless in very small lots sizes or if it required material properties unachievable using conventional methods. For example, Figure 9C illustrates a compositionally graded cylinder, which would be ideal to make using additive manufacturing processes like LENS that can incorporate multiple materials into one build.
Society is now more aware of the external environmental effects of a technology. Conventional methods of machining produce scrap metal that is in many cases discarded or not readily recyclable, especially when machining titanium. For example, to create shape in Figure 9A from a solid cylinder would result in about 85% scrap. Also, metal chips are often contaminated with cutting fluids, tooling metals, or oxidized. To effectively recycle the scrap, it typically has to be transported long distances, cleaned, remelted, reduced, cast, and worked. Also, high reliability parts such as rotating aircraft components often require virgin material be used for quality control and safety.

In powder based additive manufacturing performed in inert atmosphere, unused powder has the potential to be reused with little more than screening for large particles[14]. Thus, the majority of the metal used actually goes into the part being built. This cuts down dramatically on waste and reduces the need to mine and process virgin titanium, reducing the environmental impact of the process.
Titanium is known for its high strength and also unfortunately its high cost. Although it is the 9th most common[15] element in earth’s crust, titanium strongly bonds to other elements and is never found in it’s pure form. Subsequently, reducing titanium ores is an energy intensive and costly process. The most commonly used industrial method of reducing titanium is the Kroll process, which uses toxic chlorine gas and produces highly reactive metal halides like titanium tetrachloride gas (TiCl₄) as intermediaries. There have been many casualties and deaths at titanium plants and the surrounding communities in recent years and titanium plants are facing social pressures to close or stay closed[16-18]. In one tragic incident, hundreds of Chinese children were hospitalized after a titanium tetrachloride gas leak from a titanium plant[19].

These tragic cases are not sufficient to deter industry and the military use of titanium. Titanium has such useful mechanical and physical properties that use of it will only continue to rise in the future. As such, in order to minimize incidents like the ones mentioned, the amount of titanium waste must be minimized. Fortunately, due to its ability to reduce waste, laser deposition powder processing can greatly improve the environmental and economic sustainability of creating parts from titanium, improve the manufacturability of parts with complex chemistries and geometries, and reduce the ethical, health, and safety impact of using titanium.

Titanium is considered a strategic material for national security. Due to its superior strength, heat resistance, and lightweight properties, it finds many uses in high end military applications. Reducing the amount of titanium waste and increasing the manufacturability of key defense components will reduce the reliance on foreign titanium suppliers. This in turn can reduce political pressure to engage with undesirable suppliers of titanium that may not follow standard health and safety precautions or might use their titanium supply as leverage in geopolitical negotiations.
Chapter 2

Background

2.1 DCIP Material Selection

2.1.1 Introduction to Material Selection

A great number of factors must be taken into consideration when choosing possible metals or alloys to combine for a DCIP. The nature of joining dissimilar metals can be quite complicated. More obvious dissimilarities such as large difference in melting points can disqualify certain combinations. For example, it may be challenging to deposit refractory metals next to metals like tin or lead. Large differences in heat capacity, thermal conductivity, or the formation of intermetallics could also pose a problem. Internal stresses can build up during manufacturing to the point where they cause cracking when the part is put in service or even while processing. Some amount of post-processing such as Hot Isostatic Pressing (HIPping) or other stress relief methods like annealing could lessen some of these problems, if at the cost of some diffusion, grain growth, or other measure of material property degradation.

2.1.2 Selection of Titanium alloys

Titanium alloys were of particular interest due to their extensive use in high performance applications where the added complexity and cost of this fabrication method is already justified. Titanium alloys are already commonly used in laser additive manufacturing, yet the process is far from optimized. The work completed for this thesis seeks to address some of the challenges that remain in laser deposition of titanium and the production of titanium based DCIP-MMC.
2.1.3 Titanium Crystal Structures and Classifications

Pure unalloyed titanium has a HCP crystal structure called the alpha phase, (α). Above ~888°C Ti transforms into a BCC crystal structure called the beta phase (β). A very fine undesirable omega (Ω) phase can form if held below 480°C during aging heat treatments in moderate to highly beta stabilized alloys.

Titanium alloys are usually broken up into five categories: Alpha (α), Near-alpha (Near-α), Alpha-Beta (α+β), Near-Beta (Near-β), and Beta (β). These reflect the relative volume fractions of α and β that would be present upon equilibrium cooling. Beta is considered to be the stronger phase, and the strength of a titanium alloy generally scales with the percent β phase retained upon cooling.

2.1.4 Effects of Alloying Elements

Similar to the stabilization of austenite in steels by the addition of nickel, the addition of β-stabilizing elements decreases the β-transition temperature (β-transus). Sufficient levels of β-stabilizing elements will stabilize the β phase to 100% at room temperature. There also exist classes of alloying elements that stabilize the α phase. Typical α+β alloys contain a mixture of both. Figure 10 shows some of the common Ti alloys in use, their designation, and how the β-transus lowers with the addition of β-stabilizers.
If alloying elements are in sufficient proportions, the titanium alloy may be considered an intermetallic. These typically have properties resembling a ceramic more than a metal. Titanium diboride (TiB₂) and titanium carbide (TiC) are two commercially significant titanium intermetallics.

2.1.3 Composition of alloys

An α/β Ti alloy and a near-β Ti alloy were chosen for this study to minimize the potential problems outlined in section 2.1.1 yet demonstrate combining two distinct materials. The α/β alloy was nominally Ti-6Al-4V and the near-β alloy was nominally Ti-10V-2Fe-3Al. Both of these alloys are shown in Figure 10. Their compositions are found in Section 3.1.1 Powder specifications. These two alloys are sufficiently distinguishable by their microstructures to demonstrate the DCIP process, yet similar enough
to avoid problems. Further studies with increasingly dissimilar materials are required to fully utilize the potential of this fabrication technology in combining dissimilar material properties into one bulk MMC.

2.2 Introduction to parameter selection

2.2.1 The fundamental processing parameters

The most fundamental processing parameters in laser additive manufacturing are laser power, powder mass flow ($\dot{m}_p$), and traverse speed. These are the primary variables that determine the size and shape of the meltpool – the instantaneous volume of the liquid material created by the laser at the point of deposition. Understanding the factors which control the shape of the meltpool during deposition, how these factors can change as a function of time, and the relation of the meltpool shape to the processing parameters, is crucial to avoid defects while building and achieve desired material properties.

To create a bulk part using LENS requires the user to select the distance between deposits within a layer (hatch spacing) the amount that the deposition head moves between layers (Zstep) and the traverse speed. The machine then creates a toolpath and a set of directions to execute. It falls to the user to determine the proper laser power and $\dot{m}_p$ for the parameters selected - no formal mechanism exists for selecting the five primary processing variables (laser power, $\dot{m}_p$, hatch spacing, Zstep, and traverse speed) for any material on the LENS system. The current standard practice is to start with a “Rule of thumb” selection of processing parameters and then attempt to fix them iteratively. This has proved to be time consuming, costly, and virtually intractable if one wishes to deviate from standard materials produced by the equipment manufacturer. One of the primary goals of this thesis is to present a logical and straightforward framework to select processing parameters.
2.2.2 Process Drift

Process drift is the phenomena of how the shape of the meltpool created with the same laser power, $m_l$, and traverse speed can change during a build. Process drift typically occurs due to a change in heat flow conditions during the build. For example, the first bead of a large build deposited on a cold substrate will be significantly smaller than a bead deposited on top of a thin wall using the same laser power, $m_l$, and traverse speed due to the increased conduction of heat from the meltpool at the substrate[21].

The physics that determine the shape of the meltpool is a function of the energy transfer in and out of the meltpool, which is dependent on the incident laser power, incoming powder mass flow rate, the traverse speed, as well as the residual temperature, heat capacity, heat conduction, heat convection, and surface geometry of the underlying material(s), and beam energy distribution, and coupling efficiency of the laser, and powder spot size, and powder distribution, among other variables. Much further study and advanced feedback mechanisms are required to completely understand and overcome the problem of process drift.

Preventing the excess buildup of heat during the build can lessen process drift. Preliminary work done at ARL suggests that this can be accomplished by adjusting the time between adjacent deposits. The heat buildup can be reduced by intelligent process path planning based on fractal geometric principles. Instead of building adjacent hatches right after one another as shown in Figure 2; the deposition head would skip around the work piece depositing sections at a time to homogenize heat conditions.

Processing parameter drift was accounted for the work completed for this thesis by building in sufficient wait periods between deposits to allow the heat to dissipate to a lower steady state temperature. Conversely, when the processing parameters were developed and when building the part, the substrate was preheated with passes of the laser without powder flow to model the residual heat of a previous still-warm layer. The idea is to model the steady state temperature that the deposit will reach when actually building. By raising the residual temperature of the substrate before depositing the first layer and
allowing the limited cooling of previous layers before depositing additional layers, the actual build conditions can be made to more closely resemble the conditions under which the processing parameters are developed. Build as you develop, develop as you build. Building in wait statements may be at the cost of a decrease in deposition rate, but this is not a concern for since deposition rate is not being optimized.

2.2.3 Bead geometry as it relates to meltpool shape

Laser power and traverse speed can be combined into a secondary variable of energy input per unit distance according to . Here the $f$ term refers to the absorptivity of the incident laser energy from the total power supplied.

$$\frac{f \times \text{laser power (W)}}{\text{traverse speed (unit distance)}}$$

energy input per unit distance $\left(\frac{J}{\text{unit distance}}\right)$

The energy input creates a meltpool from the incident powder and some amount of the underlying and/or adjacent material which is necessary to create a metallurgical bond. The energy input is quickly dissipated through the adjacent material and substrate depending on the constituent material properties, a time variable inversely proportional to the traverse speed, and additional variables as explained in Section 2.2.2. The interactions discussed in this paper are captured in Equation 2, where $S_1$ represents the summation of the effects of the additional variables as explained in section 2.2.2 and $T_m$ is the melting temperature of the underlying material or substrate. The relevant relationships in Equation 2 are as traverse speed decreases, or mass flow increases, energy dissipation increases. As the preheat of the

---

† It is understood that this equation does not distinguish between processing parameters combinations such as 500W and 15mm/s, and 100W and 3mm/s, assuming absorptivity does not change within this range of laser power and traverse speed. Both combinations would supply $(33 f / 1) J/mm$ into the underlying material. The difference between these two combinations is accounted for by the time variable in the energy dissipation equation, Eq [2].

‡ This time variable is very important to understand in situ thermal cycling and residual stress buildup during builds, and further study is needed.
substrate increases, the energy dissipation decreases. Much future work remains in developing a higher fidelity model than the one presented here.

\[
\text{energy dissipation per unit distance} \left( \frac{J}{\text{unit distance}} \right)
\]

\[
= f\left( \frac{1}{\text{traverse speed}}, \left( T_{m,\text{substrate}} - T_{\text{substrate prior to deposition}} \right), \hat{m}, S_1 \right)
\]  

[2]

The overall relationship to be established is that the net energy of the meltpool per unit distance is the difference between the energy input and energy dissipation into the surrounding substrate, and that the energy dissipation decreases as the temperature of the underlying material or substrate increases. The size of the meltpool is directly determined by the net energy available at any moment. Equation 3 captures this overall energy flow that determines the size of the meltpool.

\[
\text{net energy of the meltpool per unit distance} \left( \frac{J}{\text{unit distance}} \right)
\]

\[
= \text{energy input per unit distance} \left( \frac{J}{\text{unit distance}} \right)
- \text{energy dissipation per unit distance} \left( \frac{J}{\text{unit distance}} \right)
\]  

[3]

When the meltpool solidifies the shape of the bead geometry is set. If the powder mass flow into the meltpool is relatively high compared to the net energy of the meltpool, most of the energy will go into melting the incident powder and the bead profile will resemble the shape in Figure 11A. If the mass flow into the meltpool is very low compared to the net energy of the meltpool, most of the energy will go into melting the substrate and adjacent material and the bead profile will resemble the shape in Figure 11B. The deposition shape in Figure 11C is formed by a balance between these two extremes.

Each of these bead geometries has benefits and drawbacks. All else constant, the profile in Figure 11A has the highest deposition rate since most of the energy is used to melt incoming powder and not remelt the substrate. It may however be advantageous to create a bead profile similar to Figure 11B for certain
materials or material combinations. To be explained in the following sections, the processing parameters for the work performed for this thesis were designed to create a bead profile similar to Figure 11C.

### 2.2.4 Bead contact angle

Directly related to the bead geometry is the bead contact angle. It is defined as the angle between the flat plane of the substrate and a line tangent to the point of contact of the bead. Figure 11A, Figure 11B, and Figure 11C, have contact angles of about 70°, 170°, and 120°, as shown; respectively.

Investigations performed at ARL over the past year have found correlation between bead contact angle and the formation of lack of fusion defects. When attempting to deposit another bead next to an existing bead, an acute angle as shown in Figure 11A can block incoming powder from reaching immediately next to the deposit or lower laser absorptivity. Regular lack of fusion defects were observed at spacing intervals equal to the hatch spacing when the contact angle was less than around 120°[14]. Generally, the higher the contact angle, the greater the amount of the intermixing with previous hatches and layers. Since the materials alternative between layers and hatches in a DCIP material, the contact angle should be as close to 120° as possible without creating defects to minimize intermixing. While not optimized, the bead contact angle was targeted to be around 140° for the deposits created for this thesis to ensure defect
free builds. The targeted bead contact angle constrains the possible processing parameter combinations for producing bulk samples§.

### 2.2.5 Additional considerations of processing conditions

It should be understood that all three bead profiles in Figure 10 could have been created by keeping any two variables of traverse speed, laser power, and mass flow constant, and varying the third**. There is an important difference between a bead produced with a slower traverse speed and mass flow rate as compared to a bead produced with a higher traverse speed and mass flow rate, even if the laser power is kept constant for both and the resultant bead profiles are similar. The parameter space mapped out by the three fundamental processing parameters has multiple combinations that can produce a given bead geometry, yet each combination has unique thermal conditions.

For example, the material deposited at a slower traverse speed would have a slower cooling rate, all else constant. If the cooling rate is slower then the grain morphology will be different, and the in situ heat treating of previous layers will also change as well. Other material properties such as hardness or ductility may be impacted as well. This may or may not be desirable for a given application. Optimization of processing parameters requires a full understanding of the tradeoffs between given possible processing parameter combinations.

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§ The bead profile as shown in Figure 11A could be useful for making thin single bead width deposits since bead overlap is not a concern.

** Varying laser power may change the bead width if the optics are not adjusted.
2.3 Primary parameter selection

2.3.1 Laser power and traverse speed

To move from theory to practice requires introducing the real world machine constraints into the parameter space equations. The process stage in LENS can only reliability travel at an upper limit of 15mm/s when processing – one of the limitations of the system as compared to scanned electron or laser beam systems as mentioned in section 1.1. The baseline laser can only supply between 50 to 500W of power, although it is possible to attach a more powerful laser, or introduce energy attenuating optics, if required.

As described in section 2.2.1, 2.2.3, and 2.2.4, the fundamental variables of laser power and traverse determine the energy input into the meltpool, and the $\dot{m}$ determines the shape of the deposited bead. It should be noted that for any travel speed, the energy input into the meltpool could always be increased by increasing laser power. Thus the capacity of the physical laser attached to the LENS system provides the first real constraint. Since the purpose of this experiment was to demonstrate the capability, 400 watts was chosen as the initial target laser power for this experiment. If it is desired to maximize or minimize feature size in future experiments, the laser power can be adjusted accordingly.

Once the laser power is selected, the $\dot{m}$ and traverse speed can be changed to produce the desired size and shape of the meltpool and thus the resulting bead geometry. Because the physical XY stage of the LENS system operates best around 10mm/s, that traverse speed was selected. Once this is set, the only variable that remains to change the shape of the bead is $\dot{m}$.

Further work remains to minimize the feature size possible on the LENS machine. By decreasing laser power near 50W, the smallest possible beads could be developed. Eventually the goal would be to the point where it would be possible to “print” DCIP materials with features on the scale of ten’s of microns. For this experiment, to demonstrate the principle of creating DCIP materials, the feature sizes have not been minimized.
2.3.2 Mass flow determination

To determine the optimum $\dot{m}$, several deposits are made on a piece of laser preheated substrate keeping the laser power and traverse speed constant. The beads are cross-sectioned, polished, and optically imaged. The bead width and height are measured. Using the bead width and height, a circular segment is fit to the bead profile, which has been determined to be a good approximation for the bead profile above the substrate\cite{14}. The mass flow is selected that produces beads with the desired contact angle. The formal procedure is found in Appendix A – LENS Procedure 2011.01.03.

One of the complexities of the LENS machine is that powder mass flow cannot be directly programmed. The powder is fed from hoppers that rotate at a specific rate. It falls to the user to determine the actual $\dot{m}$ as a function of powder feeder rotation speed. In addition to powder feeder rotation speed, the $\dot{m}$ depends on several factors including powder density, gradation, and morphology, carrier gas flow rate, and powder feeder design. Powder mass flow can be fit to a linear curve of powder feeder speed in rotations/min within a limited range. The formal procedure to correlate powder feeder speed with $\dot{m}$ is found in Appendix A – LENS Procedure 2011.01.03.

2.4 Machine parameter selection

The nature of additive manufacturing requires the user select a hatch width and layer thickness. As explained in Section 1.2.3, it is up to the user to ensure that the selected processing parameters of laser power, $\dot{m}$, and traverse speed actually build a part successfully and defect free. The “standard practice” according to the manufacturer of the LENS system was to choose a Zstep around 0.20 – 0.40 mm, make the hatch spacing 50% larger, and use some other “Rule of Thumb” guesses to select the laser power, $\dot{m}$, and traverse speed.
The process has been reversed here. The laser power, traverse speed, and $\dot{m}$ have already been set to create the desired bead geometry. From this geometry the machine parameters of hatch spacing and Z-step are derived.

### 2.4.1 Hatch Spacing

The bead profile above the substrate is the total volume of material added by the deposition process. Circular segments have been used to successfully model deposit cross-sections[14]. Once the width and height of the deposit are measured, it is relatively straightforward to determine the radius of the fitted circle, and the cross-sectional area of the circular segment and hence the cross-section area of the deposit[23].

\[
\begin{align*}
  w &= \text{width, } \mu m \\
  h &= \text{height, } \mu m \\
  r &= \frac{h}{2} + \frac{w^2}{8h} \\
  d &= r - h \\
  \theta &= 2 \times \cos^{-1}\left(\frac{d}{r}\right) \\
  A_{\text{circle}} &= \pi r^2 \\
  A_{\text{sector}} &= \frac{\theta}{360} \times A_{\text{circle}} \\
  A_{\text{triangle}} &= \frac{w \times d}{2} \\
  A_{\text{circular segment}} &= A_{\text{sector}} - A_{\text{triangle}} \\
  \text{Ideal Hatch Spacing} &= \frac{A_{\text{circular segment}}}{h} \\
  \text{Contact Angle} &= 180 - \frac{\theta}{2}
\end{align*}
\]
Basic geometric relationships dictate that the contact angle is 180° less half the θ angle. Figure 12 details the geometry and Eq [4] details the trigonometry. As a note, the cross sectional area multiplied by the traverse speed equals the deposition rate. Also of interest in Figure 12 is that there is significant mixing with the underlying substrate due to convection within the melt pool for the reasons explained in Section 2.2.5.

Adjacent hatches have an area of overlap as shown in Figure 13. The area of overlap is A2, and the negative space bounded by a flat line tangent to both curves and the edges of the curves is A1 in Figure 13, Figure 14, and Figure 15. The hatch spacing determines these areas.
The *ideal hatch spacing* is the condition when the area of overlap is equal to the negative space, that is when $A_2 = A_1$. The reasoning is that in reality you cannot have overlapping area, the excess material has to go somewhere, and that somewhere is into the negative space $A_1$.

Compare Figure 13 with Figure 14 and Figure 15, where the hatch spacing deviates from the ideal condition.
Logically, the deposition process must supply the volume of material required by the hatch spacing and Z-step. Conversely, the cross-sectional area of a single bead should be the same as the hatch spacing multiplied by the Z-step. Due to the way the ideal hatch spacing is calculated, the “ideal” Z-step should be equal to the bead height. The assumption is checked by the following process.

2.4.2 Ideal hatch spacing and layer height verification

The actual hatch spacing or layer height may need to be slightly different than the height or ideal spacing of a single deposited bead due to process drift and overlap interactions. Depositing next to an adjacent bead(s) is not the same as depositing on a flat substrate. The meltpool may grow for several possible reasons.

To correct for this, a single layer is deposited and the average height measured at regular intervals along the deposit. Any adjustments to the hatch spacing and Z-step are then made. Thus, all five processing parameters can be selected in a logically and straightforward manner with a minimum of heuristics.
2.5 Assumptions and simplifications made

Without additional instrumentation it is difficult to model the effective steady state temperature achieved during a build. It was assumed that the laser preheating steps and time delays built into the deposition files was sufficient to model the steady state temperature condition of underlying layers in a build. Related research at ARL has provided a framework upon which to make these assumptions[14].
3.1 Powder characteristics

3.1.1 Powder specifications

The α/β and near-β Ti powders used for these experiments and their specifications were graciously provided by ATI Powder Metals of Pittsburg, PA. Table 1, Table 2, and Table 3 detail their classification, gradation, and elemental composition, respectively.

<table>
<thead>
<tr>
<th>Material</th>
<th>Titanium Classification</th>
<th>Heat</th>
<th>Nominal Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti-6-4</td>
<td>α/β</td>
<td>3807</td>
<td>-100/+325</td>
</tr>
<tr>
<td>Ti-10-2-3</td>
<td>near-β</td>
<td>1627</td>
<td>-60/+200</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Material</th>
<th>-35</th>
<th>-45</th>
<th>-60</th>
<th>-80</th>
<th>-100</th>
<th>-140</th>
<th>-200</th>
<th>-230</th>
<th>-270</th>
<th>-325</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti-6-4</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>95.9</td>
<td>54.9</td>
<td>22.8</td>
<td>13.9</td>
<td>12.8</td>
<td>2</td>
</tr>
<tr>
<td>Ti-10-2-3</td>
<td>100</td>
<td>100</td>
<td>96.3</td>
<td>67</td>
<td>48.3</td>
<td>20.4</td>
<td>2.5</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Material</th>
<th>Ti</th>
<th>Al</th>
<th>V</th>
<th>Fe</th>
<th>C</th>
<th>O</th>
<th>N</th>
<th>H</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti-6-4</td>
<td>Bal.</td>
<td>6.24</td>
<td>3.96</td>
<td>0.04</td>
<td>0.071</td>
<td>0.15</td>
<td>0.012</td>
<td>-</td>
</tr>
<tr>
<td>Ti-10-2-3</td>
<td>Bal.</td>
<td>2.68</td>
<td>9.17</td>
<td>1.85</td>
<td>0.079</td>
<td>0.136</td>
<td>0.012</td>
<td>0.005</td>
</tr>
</tbody>
</table>

The Ti-6-4 had a tap density of 2.86 g/cc and a fall flow of 22 secs, the Ti-10-2-3 had a tap density of 2.62 and a fall flow of 27 secs.
3.1.2 Correlating powder feeder rotation speed with powder mass flow

Powder feeder 1 was filled by the α/β Ti powder, and powder feeder 2 was filled by the near-β Ti powder. Mass flow rate measurements were taken by collecting the mass of powder delivered over the course of a minute and weighing it at several different powder feeder rotation speeds estimated to be close to the desired $\dot{m}$. The $\dot{m}$ as a function of rotation speed was fit to a linear curve, and the values for the required rotations speeds to achieve the desired $\dot{m}$ were interpolated. The full procedure is found in Appendix A – LENS Procedure 2011.01.03. The targeted range of $\dot{m}$ ranged from 2.0 to 4.5 g/min in 0.5 g increments.

3.2 Process development steps

3.2.1 Single bead tracks made at various mass flow rates and laser powers

Single bead tracks were deposited in positive and negative X axis traverse directions using the near-β and α/β Ti on an α/β Ti substrate at mass flow rates of 2.0, 2.5, and 3.0 g/min and 300 watts, and mass flow rates of 2.0 to 4.5 g/min in 0.5 g increments at 400 watts. LENS Procedure 2011.02.01 was followed as shown in Appendix B – LENS Procedure 2011.02.01. A sample .DMC code for LENS Procedure 2011.02.01 is referenced in Appendix E – Sample DMC file used for LENS Procedure 2011.02.01. Two passes of the laser at 300 watts were made prior to deposition, and a sixty second wait period is built in between beads to allow the substrate to cool, such that all beads are produced as similar substrate conditions.

All samples including subsequent builds were cross sectioned, mounted, and polished according to the polishing schedule found in Table 4: Sample polishing schedule on a Struers Planpol-3 polishing machine outfitted with a Pedemax-2 specimen holder.
Samples were etched for 15 seconds using a 18% HCl 11% HF β-etchant. The samples were imaged using optical microscopy on a Nikon microscope at 100X. The width and height of individual beads were measured and a circular segment was fitted to the bead profile as shown in Figure 12. The contact angle and deposit area were computed for each bead in each direction. The width and height between each direction for each combination of $\dot{m}$ and laser power was averaged.

### 3.2.3 Selection of processing parameters to match bead profiles between materials

The average width and height for each combination of $\dot{m}$ and laser power was fed into the equation that fits a circular segment to determines the area and contact area. Three combinations of processing parameters between the two materials were found with similar deposit areas and contact angles. The combination with the closest matching contact angles and deposition height was chosen from the three. The height and width between these two combinations were averaged again to determine the average deposition area between each material.

### 3.3.3 Selection of Ideal Hatch Spacing

The average deposition area of the beads made with both materials at the selected processing parameters was divided by the average deposition height to generate the ideal hatch spacing.
3.3.4 Z-Step verification process

A single layer was produced using the deposition plan as seen in Figure 16. The sample was etched and polished the same as in Section 3.2.1. The deposit profile was measured from the middle of the first deposit to the middle of the last deposit. The .DMC code for LENS Procedure 2011.03.01 is referenced in Appendix F – DMC file used for LENS Procedure 2011.03.01.

![Figure 16: Schematic of single layer built for Z-step verification](image)

3.4 Fabrication of the bulk DCIP sample

A sample was produced using the ideal hatch spacing calculated in Section 3.3.3 and the Z-step calculated in Section 3.3.4. Additional samples were produced at various combinations of hatch spacing and Z-step. The samples were prepared and imaged according to the procedure in Section 3.2.1.

3.5 Hardness Testing

Vickers hardness measurements were taken on a Leco model M-400-61 hardness tester according to ASTM E384 with a 500 g load. Measurements were taken on virgin substrate below the HAZ, within individual beads of the $\alpha/\beta$ Ti and the near-$\beta$ Ti, and in a grid pattern on a bulk specimen.
Chapter 4

Results and Discussion

4.1 Correlating powder feeder rotation speed with powder mass flow

Powder mass flow rates were taken at various powder flow rates for each material. The data showed excellent correlation ($R \approx 0.999$) and is plotted in Figure 1.

![Graph showing powder mass flow rates at various powder feeder speeds](image)

The linear constants were extrapolated to determine the actual powder feeder rotation speeds used to produce the samples shown in Table 5.

<table>
<thead>
<tr>
<th>Material</th>
<th>Linear constants</th>
<th>Powder feeder rotation speeds</th>
<th>g/min</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>α/β Ti</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PF</td>
<td>M 0.708 B 0.055</td>
<td>2 2.75 2.5 3.46 3.5 4.16</td>
<td></td>
</tr>
<tr>
<td></td>
<td>near-β Ti</td>
<td>2 0.730 -0.082 2.85 3.54</td>
<td></td>
</tr>
</tbody>
</table>

Table 5: Powder feeder rotation speeds used to produce samples
4.2 Process development steps

4.2.1 Single bead tracks made at various mass flow rates and laser powers

Table 6 lists all the height and width data measured from the single bead deposits as well as the calculated area and contact angle of a fitted circular segment according to LENS Procedure 2011.02.01.

Unfortunately, the traverse speed was incorrectly left at the previous speed of 10.6mm/s instead of the targeted 10 mm/s, and this error was not noticed until much later in the parameter development process. The traverse speed error does not impact the validity of these data points, provided that subsequent processing parameter steps are made with the same traverse speed of 10.6mm/s. If the speed was left at 10.6mm/s throughout the entire deposition process it would not have mattered, however the traverse speed for the subsequent processing parameter development steps was set to the targeted valued of 10 mm/s. The full impact of this error is discussed herein.

<table>
<thead>
<tr>
<th>Direction</th>
<th>Mass flow rate, g/min</th>
<th>Power, W</th>
<th>Traversal Speed, mms</th>
<th>Width, µm</th>
<th>Height, µm</th>
<th>Area, µm²</th>
<th>Contact Angle</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pos X</td>
<td>4.5</td>
<td>400</td>
<td>10.6</td>
<td>1270</td>
<td>347</td>
<td>3.110E+05</td>
<td>123</td>
<td>α/β Ti</td>
</tr>
<tr>
<td>Neg X</td>
<td>4.5</td>
<td>400</td>
<td>10.6</td>
<td>1236</td>
<td>278</td>
<td>2.384E+05</td>
<td>132</td>
<td>α/β Ti</td>
</tr>
<tr>
<td>Pos X</td>
<td>4</td>
<td>400</td>
<td>10.6</td>
<td>1283</td>
<td>289</td>
<td>2.566E+05</td>
<td>132</td>
<td>α/β Ti</td>
</tr>
<tr>
<td>Neg X</td>
<td>4</td>
<td>400</td>
<td>10.6</td>
<td>1286</td>
<td>314</td>
<td>2.821E+05</td>
<td>128</td>
<td>α/β Ti</td>
</tr>
<tr>
<td>Pos X</td>
<td>3.5</td>
<td>400</td>
<td>10.6</td>
<td>1283</td>
<td>236</td>
<td>2.073E+05</td>
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<td>α/β Ti</td>
</tr>
<tr>
<td>Neg X</td>
<td>3.5</td>
<td>400</td>
<td>10.6</td>
<td>1283</td>
<td>236</td>
<td>2.073E+05</td>
<td>140</td>
<td>α/β Ti</td>
</tr>
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<td>400</td>
<td>10.6</td>
<td>1282</td>
<td>206</td>
<td>1.798E+05</td>
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<td>α/β Ti</td>
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</tr>
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</tr>
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<td>400</td>
<td>10.6</td>
<td>1267</td>
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<td>α/β Ti</td>
</tr>
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<td>400</td>
<td>10.6</td>
<td>1222</td>
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</tr>
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<td>10.6</td>
<td>1235</td>
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<td>α/β Ti</td>
</tr>
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<td>10.6</td>
<td>1027</td>
<td>164</td>
<td>1.144E+05</td>
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<td>α/β Ti</td>
</tr>
<tr>
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<td>10.6</td>
<td>1002</td>
<td>124</td>
<td>8.362E+04</td>
<td>152</td>
<td>α/β Ti</td>
</tr>
<tr>
<td>Pos X</td>
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<td>300</td>
<td>10.6</td>
<td>1027</td>
<td>131</td>
<td>9.075E+04</td>
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<td>α/β Ti</td>
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<td>Neg X</td>
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<td>10.6</td>
<td>909</td>
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<td>α/β Ti</td>
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<td>10.6</td>
<td>1000</td>
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<td>8.559E+04</td>
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<td>α/β Ti</td>
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<td>142</td>
<td>9.816E+04</td>
<td>149</td>
<td>α/β Ti</td>
</tr>
</tbody>
</table>
4.2.1.1 Direction variability

A visual inspection reveals significant variability in data values made at the same conditions except opposite direction. Some values are highlighted in red in Table 6 and Table 7. Misalignment of the powder spot from the laser beam focus or distortion of the powder spot from a powder nozzle clogging could cause variability in beads deposited in one direction or another. To determine whether deposit direction influenced the bead profile, the ratios of the data values found from moving in the positive X direction over the data values found from moving in the negative X direction were computed and listed in Table 7.
Table 7: Ratio of data points from positive X direction over negative X direction

<table>
<thead>
<tr>
<th>Width Ratio</th>
<th>Height Ratio</th>
<th>Area Ratio</th>
<th>Contact Angle Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>3%</td>
<td>25%</td>
<td>30%</td>
<td>-7%</td>
</tr>
<tr>
<td>0%</td>
<td>-8%</td>
<td>-9%</td>
<td>3%</td>
</tr>
<tr>
<td>4%</td>
<td>10%</td>
<td>15%</td>
<td>-1%</td>
</tr>
<tr>
<td>10%</td>
<td>10%</td>
<td>22%</td>
<td>0%</td>
</tr>
<tr>
<td>-3%</td>
<td>-18%</td>
<td>-21%</td>
<td>4%</td>
</tr>
<tr>
<td>-1%</td>
<td>1%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>2%</td>
<td>33%</td>
<td>37%</td>
<td>-5%</td>
</tr>
<tr>
<td>13%</td>
<td>2%</td>
<td>15%</td>
<td>2%</td>
</tr>
<tr>
<td>-2%</td>
<td>-11%</td>
<td>-13%</td>
<td>2%</td>
</tr>
<tr>
<td>-3%</td>
<td>-5%</td>
<td>-8%</td>
<td>1%</td>
</tr>
<tr>
<td>-3%</td>
<td>-11%</td>
<td>-14%</td>
<td>3%</td>
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<tr>
<td>1%</td>
<td>-6%</td>
<td>-6%</td>
<td>2%</td>
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<tr>
<td>3%</td>
<td>10%</td>
<td>13%</td>
<td>-1%</td>
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<tr>
<td>0%</td>
<td>-7%</td>
<td>-7%</td>
<td>2%</td>
</tr>
<tr>
<td>-2%</td>
<td>14%</td>
<td>12%</td>
<td>-2%</td>
</tr>
<tr>
<td>-1%</td>
<td>-14%</td>
<td>-15%</td>
<td>3%</td>
</tr>
<tr>
<td>0%</td>
<td>-23%</td>
<td>-24%</td>
<td>5%</td>
</tr>
<tr>
<td>4%</td>
<td>14%</td>
<td>19%</td>
<td>-2%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Average</th>
<th>1%</th>
<th>1%</th>
<th>3%</th>
<th>0%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stdev</td>
<td>4%</td>
<td>15%</td>
<td>18%</td>
<td>3%</td>
</tr>
</tbody>
</table>

Since the standard deviations are at least four times greater than the average difference there does not appear to be a significant difference in processing in one particular direction. Still, subsequent deposits were made only in the positive X direction. For future experiments, it is recommended that multiple beads be deposited in each direction instead of just one.
4.2.1.2 The effect of changing laser power and mass flow rates on bead width

The bead width appears to be largely independent of mass flow rate but highly dependent on laser power as shown in Figure 18. Previous work done at ARL on characterizing the LENS laser beam has determined that laser spot size decreases with decreasing laser power\cite{14}, all else constant. Adaptive optics may be able to change the laser spot size without changing power and influencing the bead width.

Since the laser beam width constrains the bead width at a set traverse speed, any changes in mass flow rate should increase the bead height and subsequently the area and contact angle of the bead. As the mass flow increases the powder capture efficiency will increase and the melt pool will rise out of the substrate moving from a bead profile as seen in Figure 11B closer to a bead profile as seen in Figure 11C and eventually resembling Figure 11A if the mass flow is high enough.

![Figure 18: The effect of changing laser power and mass flow rates on bead width](image-url)
4.2.1.3 The effect of changing laser power and mass flow rates on bead height

The bead height correlates well with increasing mass flow rate and laser power as shown in Figure 19 as expected.

4.2.1.4 The effect of changing laser power and mass flow rates on bead area

The bead area appears to be largely dependent on both mass flow rates and laser power as shown in Figure 20. This was expected as bead area is a function of the bead width and height, and both increase with higher laser power, and bead height increases with increasing mass flow rates.
Figure 20: The effect of changing laser power and mass flow rates on bead area

The effect of changing laser power and mass flow rates on bead area is shown in the graph. The equation and $R^2$ value for each condition are as follows:

- **400 watts**
  - Equation: $y = 6.045E+04x - 5.68E+03$
  - $R^2 = 0.8436$

- **300 watts**
  - Equation: $y = 2.820E+04x + 1.84E+4$
  - $R^2 = 0.513$
4.2.1.4 The effect of changing laser power and mass flow rates on bead contact angle

The bead contact angle appears to be independent of laser power but highly dependent on mass flow rates for beads deposited at 400W, and loosely dependent for beads deposited at 300W as shown in Figure 21. The correlation with mass flow rates was explained further in Section 4.2.1.2 and Section 2.2.4 Bead contact angle. The lack of correlation between changing laser power and contact angle at a constant mass flow may be due to the smaller meltpool width associated with the lower power. If adaptive optics were used to keep the laser beam width constant throughout changing laser powers, it is expected that a higher laser power will result in a lower contact angle as the bead height increases.

Figure 21: The effect of changing laser power and mass flow rates on bead contact angle
4.2.2 Selected micrographs of single bead deposits

Figure 22 and Figure 23 show two of the polished cross sections of tracks made at the processing parameter combinations selected to compute the ideal hatch spacing as further explained in Section 4.2.3 Selection of processing parameters to match bead profiles between materials. A circular segment has been fitted to each bead to demonstrate how successfully the circular segment can model the additional material above the substrate deposited by a single bead.

![Figure 22: Cross section of made with $\alpha/\beta$ Ti powder at 300W and 2.5 g/min (100X)](image)

Note the epitaxial grain growth of the $\alpha/\beta$ Ti from the $\alpha/\beta$ Ti substrate in Figure 22: Cross section of made with $\alpha/\beta$ Ti powder at 300W and 2.5 g/min and also the definitive interface between the bead and substrate as seen in Figure 23. The sharp interface in Figure 23 is a result of the abruptly chemistry change between the near-$\beta$ Ti and the $\alpha/\beta$ Ti substrate. The abrupt transition is desired for this experiment for each material to retain its inherent material properties. Also note that the interface line in Figure 23 is almost a mirror image of the bead profile above the substrate. A volume of substrate almost equal to the
deposition area is being intermixed with the near-β Ti. While some degree of intermixing is desired to ensure a sound metallurgical bond, the high degree of intermixing here is suboptimal for creating a DCIP material. As explained further in Section 2.2.4 Bead contact angle and Section 2.2.5 Additional considerations of processing conditions, lowering the contact angle should decrease the degree of intermixing. It is recommended that future work target contact angles as close to 120° as possible without creating defects.

4.2.3 Selection of processing parameters to match bead profiles between materials

The thirty-six data points for bead height and width in Table 6 were averaged together between deposit directions and reduced to the eighteen values in Table 8. Bead area and contact angles were determined using these averages. The parameters were organized by area smallest to largest. The top three combinations are highlighted in Table 8 that have the smallest difference in bead area yet include each material. The green area in Table 8 is overlap between the blue and yellow sections.

Table 8: Sorting average processing parameters by difference in deposit area

<table>
<thead>
<tr>
<th>Difference, µm²</th>
<th>Area, µm²</th>
<th>Mass flow rate, g/min</th>
<th>Power, W</th>
<th>Width, µm</th>
<th>Height, µm</th>
<th>Contact Angle</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>77806</td>
<td></td>
<td>2.0</td>
<td>300</td>
<td>996</td>
<td>116</td>
<td>154</td>
<td>near-β Ti</td>
</tr>
<tr>
<td>6847</td>
<td>84653</td>
<td>2.5</td>
<td>300</td>
<td>968</td>
<td>129</td>
<td>150</td>
<td>α/β Ti</td>
</tr>
<tr>
<td>2875</td>
<td>87528</td>
<td>2.5</td>
<td>300</td>
<td>1010</td>
<td>128</td>
<td>151</td>
<td>near-β Ti</td>
</tr>
<tr>
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<td>91814</td>
<td>2.0</td>
<td>300</td>
<td>1010</td>
<td>135</td>
<td>150</td>
<td>α/β Ti</td>
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<tr>
<td>6962</td>
<td>98776</td>
<td>3.0</td>
<td>300</td>
<td>1014</td>
<td>144</td>
<td>148</td>
<td>α/β Ti</td>
</tr>
<tr>
<td>335</td>
<td>99111</td>
<td>2.0</td>
<td>400</td>
<td>1229</td>
<td>120</td>
<td>158</td>
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<tr>
<td>10615</td>
<td>109726</td>
<td>3.0</td>
<td>300</td>
<td>1014</td>
<td>159</td>
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<tr>
<td>10349</td>
<td>120075</td>
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<td>3.0</td>
<td>400</td>
<td>1223</td>
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<td>144</td>
<td>α/β Ti</td>
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<tr>
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<td>163483</td>
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<td>1282</td>
<td>188</td>
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<td>near-β Ti</td>
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<td>135</td>
<td>near-β Ti</td>
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</table>
The three combinations from Table 8 are relisted in Table 9 along with some additional calculations. In Table 9 the same process used to average the bead width and height together in Table 8 was repeated to determine the average bead height and width for each combination. For each combination, the ideal hatch spacing was determined via the procedure outline in Section 3.3.3 Selection of Ideal Hatch Spacing. Note that while for this experiment the ratio of materials was targeted to be 50:50 and thus combinations were chosen that have similar bead areas, this averaging process should be valid for a range of material and area ratios.

<table>
<thead>
<tr>
<th>Parameter pairing</th>
<th>Material</th>
<th>Mass flow rate, g/min</th>
<th>Power, W</th>
<th>Traverse speed, mm/s</th>
<th>Area, µm²</th>
<th>Contact angle</th>
<th>Height, µm</th>
<th>Width, µm</th>
<th>Ideal hatch spacing, µm</th>
</tr>
</thead>
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<td>1</td>
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<td>400</td>
<td>10.6</td>
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<td>191</td>
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<tr>
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<td>10.6</td>
<td>15386</td>
<td>8</td>
<td>147</td>
<td>183</td>
<td>1244</td>
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<tr>
<td></td>
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<td>120</td>
<td>3</td>
<td>8</td>
<td>57</td>
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<td></td>
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<td>4.29%</td>
<td>4.69%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Average bead parameters</td>
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<td></td>
<td>15380</td>
<td>9</td>
<td>146</td>
<td>187</td>
<td>1215</td>
</tr>
<tr>
<td>2</td>
<td>α/β Ti</td>
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<td>300</td>
<td>10.6</td>
<td>84653</td>
<td>150</td>
<td>129</td>
<td>968</td>
<td></td>
</tr>
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<td></td>
<td>near-β Ti</td>
<td>2.5</td>
<td>300</td>
<td>10.6</td>
<td>87528</td>
<td>151</td>
<td>128</td>
<td>1010</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Absolute Difference</td>
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<td>2875</td>
<td>1</td>
<td>1</td>
<td>42</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Percent Difference</td>
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<td></td>
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<td>3.34%</td>
<td>0.94%</td>
<td>0.80%</td>
<td>4.27%</td>
<td></td>
</tr>
</tbody>
</table>

†† Note that while the nominal mass flows of the two Ti powders for the first and third combination are not the same; the deposited area is still similar. The powder capture efficiency is higher for the near-β Ti powder in the first combination, yet lower for the near-β Ti powder for the third combination.
Since no perfect match exists, the selection of any one of these three combinations could be valid depending on what weighting factors were used. Without any formal procedure, since the 50:50 ratio condition was satisfied within 5% for all three combinations, it was reasoned that matching the build height was the next most important factor so that the resulting layer height would be consistent. The middle set of conditions was then selected on this basis.

### 3.3.4 Z-Step verification process

A single layer was deposited using the parameters calculated by the process detailed in Table 9 and is shown in Figure 24. The height of the layer profile was measured at regular intervals along the sample between the middle of the first and last deposit as shown in the schematic in Figure 16. Extra measurements were taken if the features abruptly changed. The measures and weighted average height are shown in Figure 25.

![Figure 24: Single layer built for Z-step verification (100X)](image)
When the DMC code for this file was written, the original targeted speed of 10mm/s was used. Unfortunately the error mentioned in Section 4.2.1 was not known at the time. Due to the unintended traverse speed discrepancy the deposited area of each bead was significantly larger than planned. As a result, the 668 µm hatch spacing was effectively too close, and the too narrow condition listed in Figure 14 happened. The extra material had nowhere to go but up, which is how the average height grew to be 191µm from conditions that were supposed to create beads with an average height of 129µm as shown in Table 9. The beads of near-β Ti were effectively “spilling over” the area allotted to them between the beads of the α/β Ti previously deposited. A close up of this effect is shown in Figure 26.
4.4 Fabrication of bulk DCIP sample #1

At the time the traverse speed discrepancy was not yet discovered and the height difference was attributed to process drift. Processing parameter development continued and a sample was produced with the parameters found in Table 10 and the deposition plan shown in Figure 8.

Table 10: Summary of processing parameters used to create bulk DCIP sample #1‡‡

<table>
<thead>
<tr>
<th>Material</th>
<th>Mass flow rate, g/min</th>
<th>Power, W</th>
<th>Traverse speed, mm/s</th>
<th>Hatch spacing, µm</th>
<th>Z-step, µm</th>
<th>Single bead width, µm</th>
<th>Single bead height, µm</th>
<th>Single bead area, µm²</th>
<th>Contact angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>α/β Ti</td>
<td>2.5</td>
<td>300</td>
<td>10</td>
<td>668</td>
<td>191</td>
<td>1002</td>
<td>165</td>
<td>1.13E+05</td>
<td>144</td>
</tr>
<tr>
<td>near-β Ti</td>
<td>2.5</td>
<td>300</td>
<td>10</td>
<td></td>
<td></td>
<td>1356</td>
<td>185</td>
<td>1.70E+05</td>
<td>149</td>
</tr>
</tbody>
</table>

In DCIP Sample #1 shown in Figure 28 the dark areas are the near-β Ti and the lighter areas are the α/β Ti. The “lumpy” shape is due to the traverse speed error being propagated through the rest of the processing parameter development steps. Despite the error, the sample built with only a few pores. The observed pores are likely due to the Ti powder manufacturing process. Gas atomized powder is known for creating these defects and there is little that can be done to prevent it. No processing defects such as lack of fusion were observed.

4.5 Epitaxial grain growth disruption

The long “fingerlike” shapes in Figure 28 and Figure 29 are long columnar grains. These are especially problematic in laser deposited Ti-6-4[24]. When building with Ti-6Al-4V on a Ti-6Al-4V substrate, epitaxial grain growth is almost immediately observed as seen in Figure 22. When depositing solely Ti-6-4, the columnar grains typically extend from the substrate all the way to the top of the build with few breaks. These columnar grains result in undesirable mechanical property anisotropies between along the deposition direction and perpendicular to the build.

‡‡The single bead characteristics listed here do not match the values in Section 4.2.3 but rather those in Section 4.6.2
Figure 29 provides a closer examination of the outlined area in DCIP Sample #1 shown in Figure 27. Micrographs with at an increased magnification were taken at the locations shown in Figure 29 and are shown in Figure 32 and Figure 33.
Figure 27: Bulk DCIP Sample #1 (100X)

Figure 28: Bulk DCIP sample #2 (100X)
Figure 29: Columnar grain growth disruption attributed to DCIP morphology (200X)

It is hypothesized that the columnar grain growth normally seen in laser deposited Ti-6-4 is disrupted by the abrupt change in chemistry in the DCIP samples. The concentration of alloying elements in titanium changes the solidification behavior significantly. The two titanium alloys used in this thesis work have different concentrations of vanadium, aluminum, and iron. To normalize the effects of all of the α-stabilizing and β-stabilizing elements, Rosenberg, et al, have devised a “aluminum equivalency” and “molybdenum equivalency” ratio based off of how much of each element is required to stabilize the β phase.[25] The calculations for the specific chemistries of the Ti alloys used for this work are shown in Table 11.
Table 11: Mo and Al equivalencies of Ti alloys used

<table>
<thead>
<tr>
<th>Alpha Stabilizers</th>
<th>Al Equiv. Factor</th>
<th>wt%</th>
<th>Calculations</th>
<th>Calculations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>1</td>
<td>6.24</td>
<td>6.24</td>
<td>2.68</td>
</tr>
<tr>
<td>Zr</td>
<td>0.17</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sn</td>
<td>0.33</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>O</td>
<td>10</td>
<td>0.15</td>
<td>1.50</td>
<td>0.136</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.36</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Beta Stabilizers</th>
<th>Mo Equiv. Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mo</td>
<td>1</td>
</tr>
<tr>
<td>Ta</td>
<td>0.2</td>
</tr>
<tr>
<td>Nb</td>
<td>0.28</td>
</tr>
<tr>
<td>W</td>
<td>0.4</td>
</tr>
<tr>
<td>V</td>
<td>0.67</td>
</tr>
<tr>
<td>Cr</td>
<td>1.25</td>
</tr>
<tr>
<td>Ni</td>
<td>1.25</td>
</tr>
<tr>
<td>Mn</td>
<td>1.7</td>
</tr>
<tr>
<td>Co</td>
<td>1.7</td>
</tr>
<tr>
<td>Fe</td>
<td>2.5</td>
</tr>
<tr>
<td>Volume fraction</td>
<td></td>
</tr>
<tr>
<td>Al Equiv.</td>
<td>7.74</td>
</tr>
<tr>
<td>Mo Equiv.</td>
<td>2.75</td>
</tr>
</tbody>
</table>

In Ti-6-4 the α-stabilizers dominate and in the Ti-10-2-3 the β-stabilizers dominate. The solidification behavior of the two alloys is significantly different. The Ti-Al and Ti-Mo phase diagrams are shown in Figure 30 and Figure 31, respectively. Note the distance between the liquidus and solidus lines at 90% and 95% Ti on both phase diagrams.
Figure 30: Titanium-Aluminum Phase Diagram[26]

Figure 31: Titanium-Molybdenum phase diagram[27]
The gap between the liquidus and solidus lines grows in the Ti-Mo phase diagram, but is very small in the Ti-Al phase diagram. This indicates that the temperature difference over which Ti-6-4 solidifies, the “mushy zone,” is much smaller than for Ti-10-2-3. The small mushy zone is thought to be a major contributor to the epitaxial columnar grain growth typically seen when laser depositing Ti-6-4, especially given the fast cooling rates inherent to the process. Since the Ti-10-2-3 solidifies over a larger temperature range, there is more time for new grains to nucleate from the liquid before it solidifies, disrupting the epitaxial columnar grain growth.
Figure 32: Selected Micrographs of A series (Left 500X, Right 1000X)
Figure 33: Selected Micrographs of B series (Left 500X, Right 1000X)
4.6 Additional deposits made

4.6.1 Bead profile variability and sensitivity to traverse speed changes

A series of five beads deposited with each material at the correct speed of 10mm/s were made and measured. The results shown in Table 12 indicate that there is significant different in bead height and area made with the same parameters but little difference in width or contact angle. The low variability in bead width agrees with the strong correlation of bead width to laser power as discussed in Section 4.2.1. Since all these deposits were made at the same power there should not be much difference. The scatter in the data in Section 4.2.1 for the height and area of beads made at the same mass flow rates is repeated here. The scatter may be due to fluctuations in the real time mass flow rates. The current method of measuring mass flow rates over a minute does not have the resolution necessary to determine whether this is the case. Further research into the stability of mass flow rates is needed.

<table>
<thead>
<tr>
<th>Direction</th>
<th>Mass flow rate, g/min</th>
<th>Power, W</th>
<th>Traverse Speed, mms</th>
<th>Width, µm</th>
<th>Height, µm</th>
<th>Area, µm²</th>
<th>Contact Angle</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pos X</td>
<td>2.5</td>
<td>300</td>
<td>10</td>
<td>1034</td>
<td>157</td>
<td>1.102E+05</td>
<td>146</td>
<td>α/β Ti</td>
</tr>
<tr>
<td>Pos X</td>
<td>2.5</td>
<td>300</td>
<td>10</td>
<td>952</td>
<td>132</td>
<td>8.505E+04</td>
<td>149</td>
<td>α/β Ti</td>
</tr>
<tr>
<td>Pos X</td>
<td>2.5</td>
<td>300</td>
<td>10</td>
<td>1048</td>
<td>167</td>
<td>1.190E+05</td>
<td>145</td>
<td>α/β Ti</td>
</tr>
<tr>
<td>Pos X</td>
<td>2.5</td>
<td>300</td>
<td>10</td>
<td>977</td>
<td>195</td>
<td>1.310E+05</td>
<td>136</td>
<td>α/β Ti</td>
</tr>
<tr>
<td>Pos X</td>
<td>2.5</td>
<td>300</td>
<td>10</td>
<td>999</td>
<td>175</td>
<td>1.194E+05</td>
<td>141</td>
<td>α/β Ti</td>
</tr>
</tbody>
</table>

Average     1002  165  1.129E+05  144
Stdev       40    23  1.724E+04  5
Percent     4%    14%  15%    3%

| Pos X     | 2.5                   | 300      | 10                  | 1340     | 165       | 1.492E+05 | 152          | near-β Ti |
| Pos X     | 2.5                   | 300      | 10                  | 1403     | 176       | 1.667E+05 | 152          | near-β Ti |
| Pos X     | 2.5                   | 300      | 10                  | 1319     | 172       | 1.533E+05 | 151          | near-β Ti |
| Pos X     | 2.5                   | 300      | 10                  | 1359     | 191       | 1.758E+05 | 149          | near-β Ti |
| Pos X     | 2.5                   | 300      | 10                  | 1360     | 222       | 2.055E+05 | 144          | near-β Ti |

Average     1356  185  1.701E+05  149
Stdev       31    23  2.246E+04  3
Percent     2%    12%  13%    2%
There is significant difference between the average bead profiles made at 10.6mm/s and 10mm/s. As shown in Table 13, the beads made at 10mm/s have areas that are a third to nearly double the size. The average bead width for the near-β Ti is also a third wider. This indicates a high sensitivity of bead profile to traverse speed that should investigated further. The differences are such that if the process development step 2011.02.01 was performed at the correct speed, these two combinations of processing parameters would likely not be chosen.

### Table 13: Comparison of bead profiles made at 10.6mm/s and 10mm/s

<table>
<thead>
<tr>
<th>Direction</th>
<th>Mass flow rate, g/min</th>
<th>Power, W</th>
<th>Traverse Speed, mms</th>
<th>Width, µm</th>
<th>Height, µm</th>
<th>Area, µm²</th>
<th>Contact Angle</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ave</td>
<td>2.5</td>
<td>300</td>
<td>10.6</td>
<td>968</td>
<td>129</td>
<td>84716</td>
<td>150</td>
<td>α/β Ti</td>
</tr>
<tr>
<td>Pos X</td>
<td>2.5</td>
<td>300</td>
<td>10</td>
<td>1002</td>
<td>165</td>
<td>112919</td>
<td>144</td>
<td>α/β Ti</td>
</tr>
<tr>
<td>Ratio</td>
<td></td>
<td></td>
<td></td>
<td>104%</td>
<td>128%</td>
<td>133%</td>
<td>96%</td>
<td></td>
</tr>
</tbody>
</table>

| Ave       | 2.5                    | 300      | 10.6                | 1010    | 128       | 87597    | 152           | near-β Ti      |
| Pos X     | 2.5                    | 300      | 10                  | 1356    | 185       | 170077   | 149           | near-β Ti      |
| Ratio     |                        |          |                     | 134%    | 144%      | 194%     | 99%           |                |

### 4.6.2 Correct hatch spacing for given processing parameters

Averaging the bead profiles for deposits made at 10mm/s in Table 13 results in the following hatch spacing shown in Table 14. The hatch spacing should have been 800 µm, a full 20% larger than it truly was. This is the reason that the single layer height was so much larger than the 129 µm predicted.

### Table 14: Correct hatch spacing for the processing parameters used

<table>
<thead>
<tr>
<th>Traverse Speed, mm/s</th>
<th>Width, µm</th>
<th>Height, µm</th>
<th>Area, µm²</th>
<th>Contact angle</th>
<th>Ideal hatch spacing, µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>1179</td>
<td>175</td>
<td>1.401E+05</td>
<td>147</td>
<td>800</td>
</tr>
<tr>
<td>10.6</td>
<td>989</td>
<td>129</td>
<td>8.609E+04</td>
<td>151</td>
<td>668</td>
</tr>
<tr>
<td>94%</td>
<td>119%</td>
<td>136%</td>
<td>163%</td>
<td>97%</td>
<td>120%</td>
</tr>
</tbody>
</table>
4.6.3 DCIP Sample #2

Before the correct bead size and hatch spacing was known several different deposits were made at various hatch spacings and Z-steps since it was evident that the selected hatch spacing was too narrow in the Z-step verification process. One of these samples is shown in Figure 28. DCIP Sample #2 was produced with the parameters found in Table 15 and the deposition plan shown in Figure 8. Note that the

Table 15: Summary of processing parameters used to create bulk DCIP sample #2

<table>
<thead>
<tr>
<th>Material</th>
<th>Mass flow rate, g/min</th>
<th>Power, W</th>
<th>Traverse speed, mm/s</th>
<th>Hatch spacing, µm</th>
<th>Z-step, µm</th>
<th>Single bead width, µm</th>
<th>Single bead height, µm</th>
<th>Single bead area, µm²</th>
<th>Contact angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>α/β Ti</td>
<td>2.5</td>
<td>300</td>
<td>10</td>
<td>735</td>
<td>142</td>
<td>1002</td>
<td>165</td>
<td>1.13E+05</td>
<td>144</td>
</tr>
<tr>
<td>near-β Ti</td>
<td>2.5</td>
<td>300</td>
<td>10</td>
<td></td>
<td></td>
<td>1356</td>
<td>185</td>
<td>1.70E+05</td>
<td>149</td>
</tr>
</tbody>
</table>

4.7 Hardness Testing

Vickers hardness measurements were made in the virgin α/β Ti substrate below the HAZ; in single bead deposits of the α/β Ti deposits; and in single bead deposits of the near-β Ti deposits. The data is presented in Table 16.
Table 16: Hardness data from single bead deposits and DCIP Sample #1

<table>
<thead>
<tr>
<th>Substrate</th>
<th>D1</th>
<th>D2</th>
<th>α/β</th>
<th>D1</th>
<th>D2</th>
<th>near-β</th>
</tr>
</thead>
<tbody>
<tr>
<td>near-β</td>
<td>54.8</td>
<td>53.9</td>
<td>314</td>
<td>48.4</td>
<td>48.1</td>
<td>398</td>
</tr>
<tr>
<td>53.2</td>
<td>52.4</td>
<td>333</td>
<td>48</td>
<td>47.2</td>
<td>409</td>
<td>46.4</td>
</tr>
<tr>
<td>53.2</td>
<td>53.2</td>
<td>328</td>
<td>48.4</td>
<td>48.4</td>
<td>396</td>
<td>46.9</td>
</tr>
<tr>
<td>52.5</td>
<td>52.8</td>
<td>334</td>
<td>48.1</td>
<td>48.3</td>
<td>399</td>
<td>47.2</td>
</tr>
<tr>
<td>52.1</td>
<td>53.5</td>
<td>333</td>
<td>47.9</td>
<td>47.9</td>
<td>404</td>
<td>48.6</td>
</tr>
<tr>
<td>52.2</td>
<td>53.8</td>
<td>330</td>
<td>48.3</td>
<td>48.2</td>
<td>398</td>
<td>47.9</td>
</tr>
<tr>
<td>52.7</td>
<td>55.4</td>
<td>317</td>
<td>48.4</td>
<td>47</td>
<td>407</td>
<td>48.9</td>
</tr>
<tr>
<td>Average</td>
<td>327</td>
<td></td>
<td></td>
<td>48.1</td>
<td>47.4</td>
<td>407</td>
</tr>
<tr>
<td>Stdev</td>
<td>8.16</td>
<td></td>
<td></td>
<td>48.2</td>
<td>47.2</td>
<td>401</td>
</tr>
<tr>
<td>Max</td>
<td>334</td>
<td></td>
<td></td>
<td>47.7</td>
<td>47.5</td>
<td>409</td>
</tr>
<tr>
<td>Min</td>
<td>314</td>
<td></td>
<td></td>
<td>47</td>
<td>47.3</td>
<td>417</td>
</tr>
<tr>
<td>Range</td>
<td>20</td>
<td></td>
<td></td>
<td>47.8</td>
<td>47.9</td>
<td>405</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>47.9</td>
<td>48.1</td>
<td>402</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>47.9</td>
<td>47.6</td>
<td>407</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>48.3</td>
<td>48.1</td>
<td>399</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Substrate</th>
<th>D1</th>
<th>D2</th>
<th>α/β</th>
<th>D1</th>
<th>D2</th>
<th>near-β</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>404</td>
<td></td>
<td></td>
<td>44.9</td>
<td>43.5</td>
<td>474</td>
</tr>
<tr>
<td>Stdev</td>
<td>5.64</td>
<td></td>
<td></td>
<td>47.6</td>
<td>47.4</td>
<td>411</td>
</tr>
<tr>
<td>Max</td>
<td>417</td>
<td></td>
<td></td>
<td>47.7</td>
<td>47.5</td>
<td>409</td>
</tr>
<tr>
<td>Min</td>
<td>396</td>
<td></td>
<td></td>
<td>47</td>
<td>47.3</td>
<td>417</td>
</tr>
<tr>
<td>Range</td>
<td>21</td>
<td></td>
<td></td>
<td>47.8</td>
<td>47.9</td>
<td>405</td>
</tr>
</tbody>
</table>

All hardness measurements made in the single bead deposits were higher than the virgin substrate, which is expected. The hardness values for the α/β Ti were very consistent while the hardness values for the near - β Ti were scattered. The spread in the hardness measurements for the near - β Ti is thought to be a result of the high level of intermixing with the underlying substrate. Convention currents mix the molten material in the melt pool, and the β stabilizing alloying elements are dispersed to some degree in varying concentrations. Despite this intermixing, which effectively dilutes the β stabilizing alloys, on average the near - β Ti have a higher hardness.

For the bead made with α/β Ti powder, the average composition is already very close to the α/β Ti substrate, so there is essentially no diluting of alloying elements. Because there is no abrupt change in
chemistry they is no clear interface between the beads and substrates, and subsequently epitaxial columnar grains form immediately.

Hardness measurements were taken in a grid over the face of DCIP sample #2, shown in Table 17 and Figure 34. The results were highly variable and no direct correlation between the phase and hardness value was found except that the hardness decreased below the deposit and HAZ.

Table 17: Vickers hardness measurements taken on face of DCIP Sample #2

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>378</td>
<td>413</td>
<td>383</td>
<td>472</td>
<td>399</td>
</tr>
<tr>
<td>2</td>
<td>446</td>
<td>433</td>
<td>470</td>
<td>351</td>
<td>388</td>
</tr>
<tr>
<td>3</td>
<td>365</td>
<td>392</td>
<td>458</td>
<td>462</td>
<td>442</td>
</tr>
<tr>
<td>4</td>
<td>390</td>
<td>397</td>
<td>379</td>
<td>400</td>
<td>413</td>
</tr>
<tr>
<td>5</td>
<td>398</td>
<td>392</td>
<td>396</td>
<td>405</td>
<td>404</td>
</tr>
<tr>
<td>6</td>
<td>413</td>
<td>415</td>
<td>381</td>
<td>392</td>
<td>398</td>
</tr>
<tr>
<td>7</td>
<td>358</td>
<td>343</td>
<td>316</td>
<td>363</td>
<td>367</td>
</tr>
<tr>
<td>8</td>
<td>329</td>
<td>327</td>
<td>323</td>
<td>331</td>
<td>304</td>
</tr>
</tbody>
</table>
Figure 34: Vickers hardness measurements taken on face of DCIP Sample #2 (100X)
Chapter 5

Conclusions

5.1 Conclusions

Despite the unintended discrepancy in traverse speed between process parameter development steps, following the process development method still successfully created a bulk DCIP sample free from processing defects. To decrease the degree of intermixing the contact angle should be as close to 120° as possible when creating future DCIP materials.

There does not appear to be a significant difference in bead profiles when processing in one particular direction; however it is recommended for future experiments that multiple beads be deposited in each direction instead of just one for LENS Procedure 2011.01.03. There is a standard deviation of over 10% for both bead height and area for deposits made with the same processing parameters. The scatter may be due to fluctuations in the real time mass flow rates. Further research into the stability of mass flow rates is needed to determine the cause of the scatter.

The bead width appears to be largely independent of mass flow rate but highly dependent on laser power, while the bead contact angle appears to be independent of laser power but highly dependent on mass flow rates. The area and height correlate well with increasing both mass flow rate and laser power.

Scientific papers discussing additive manufacturing should report more than the mass flow rate, laser power, traverse speed, hatch spacing, and Z-step used to create a build or part. Many machine specific variables can heavily influence the beam size and energy distribution, and powder spot size and distribution, which will heavily influence the shape of the meltpool. Thus at least the width and height of a single bead made on the specific machine with the conditions as close to the actual processing conditions should also be included as standard reporting processing parameters. From these the single
bead cross-sectional area and contact angle could be determined and should be report as well. Table 15 shows an example.

The high degree of intermixing was thought to be the cause of the considerable variability in hardness values across the sample and within individual deposits due to dilution of alloying elements. Epitaxial grain growth was attenuated by the DCIP morphology as compared to typical bulk laser deposited Ti-6Al-4V samples. The cause of the epitaxial grain growth disruption is thought to be a result of the larger temperature range over which Ti-10-2-3 solidifies, which increases the time for new grains to nucleate from the meltpool. Further refinement of processing parameters is expected to decrease intermixing and hardness variability and improve column grain disruption.

The laser power constrains the width of individual deposits at a given traverse speed on the LENS system across a range of mass flow rates. To minimize feature sizes, the lowest possible laser power (50W) should be used with the highest traverse speed possible. High variability in bead geometry is observed between beads created with identical processing parameters so more than two beads should be made with each combination of laser power and mass flow for LENS Procedure 2011.01.03.

### 5.2 Future Work

- The processing parameter selection should be done again from the start with a consistent traverse speed and targeting a contact angle near 120°.
- DCIP’s should be created with CP Ti and β Ti with the smallest possible feature sizes so that the average composition is an α/β Ti. Perhaps the β Ti could have a composition near Ti-12-8 so that when averaged with CP-Ti the average would be Ti-6-4.
- The hatch orientation should be changed between layers.
- Instead of using two distinct materials, selectively introduce a second phase like a ceramic or reactive gas. Similar to the operation of powder feeders, have the ability to switch on a reactive gas when desired or in a certain concentration.
• Magnetically polled materials when processing. Lay down magnetic material with a strong magnetic field applied, switch field when going a different direction. Create materials with custom tailored magnetic properties.

• Instead of alternating materials regularly, build in specific paths with a second material to build specific electrically conductive or thermally conductive paths through the bulk object.

• Explore the effect of different hatch geometries as shown in Appendix D – Alternative deposition geometries.

• A DCIP material could hypothetically be created from just one alloy or metal if the cooling rates of distinct beads were different enough to quench in a martensitic phase for one combination of processing parameters, and a near-equilibrium cooling phase for another combination. In practice, the subsequent *in situ* heat treating from adjacent layers and hatches may make this difficult to achieve.
REFERENCES


<http://www.weirondailytimes.com/page/content.detail/id/559261.html>.


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Appendix A

LENS Procedure 2011.01.03

Procedure for Measuring Powder Mass Flow Rate in LENS MR-7

Version

01: 25 April 2011: Original Procedure

02: 26 April 2011: Modified Z-axis

03: 02 May 2011: Changed wording on pressure, changed flow stabilization measurement.

Requirements:

1) Chamber atmosphere at nominal processing conditions. For example, if processing Ti-6Al-4V, O₂ level should be less than 10 ppm.
   a. Center purge does not have to be on.
   b. I have also been turning off the flow to the unused powder feeder.
   c. Check the seal of the o-ring in the powder hopper for leaks.

2) Pressure in chamber should be kept as low as possible. For consistency use a pressure of less than 0.5 inch of water, and this pressure should be steady (the solenoid should not be opening). This can be obtained by adjusting the exhaust valve. For reference 1 inch of water is 0.0361 psi.

3) The gas-inlet valve that supplies argon to the center purge and powder feeders should be wide open to minimize fluctuations in the gas flow. Adjustments are then made by the flow meters.

4) The balance must be placed on a flat surface, with all four feet on this surface. Check with level. Note if the water cooled plate is in place, it will have to be removed in order to place the scale and flask.

5) The glass flask shall be used.

6) The metal pan on the scale shall be used.

7) The scale display shall be facing forward, and brushed clear of powder.

8) The Z axis should be adjusted to place the nozzle tips just at the lip of the flask.

9) During measurement, gloves shall be in the chamber and covers closed

10) The pressure of gas at the manifold shall be 50 psi.

11) Use repeating countdown timer of 1 minute. This timer will countdown a desired time and once 0 is reached will automatically begin counting down again.

Procedure:

1. Mass Flow Rate Determination
   1.1. Check Calibration. If the mass of the calibration weights are less than or greater than 0.05 g of the sum of the weights, recalibrate. Calibrate the scale using the calibration weights.
   1.2. Ensure that the above requirements are met (gas should be flowing through the powder nozzles, pressure between 0 and 0.5 inches of water and steady, and O₂ less than 10 ppm).
   1.3. Place empty glass flask on scale, zero. Set the Powder Feed (PF) RPM to desired setting.
1.4. Start powder flow and timer simultaneously.
1.5. Allow powder to flow for 1 minute. During the last 5 seconds of the period, view the scale display and listen for the timer. Note the scale display when the timer expires. Record value in spreadsheet.
1.6. During the 1 minute period, record chamber pressure, O₂ level, flow settings for center purge and powder hoppers.
1.7. During the last 5 seconds of the period, view the scale display and listen for the timer. Note the mass of powder when the timer expires. At the same time, increase the PF setting to the next level (this can be done by typing the RPM value ahead of time, but not pressing enter until the timer goes off). Record the mass value in the spreadsheet.
1.8. Repeat procedure from step 1.5.
1.9. Complete at least 4 different PF settings. \{2,4,6,8\}.
1.10. Stop powder flow
1.11. Empty the glass flask
1.12. Repeat measurement procedure Steps: 1-11 but Reverse the order of PF settings \{8,6,4,2\}
1.13. Repeat measurement procedure Steps: 1-11 but use the original PF settings \{2,4,6,8\}.

2.1. Check Calibration. If the mass of the calibration weights are less than or greater than 0.05 g of the sum of the weights, recalibrate. Calibrate the scale using the calibration weights.
2.2. Ensure that the above requirements are met (gas should be flowing through the powder nozzles, pressure between 0 and 0.5 inches of water and steady, and O₂ less than 10 ppm).
2.3. Set the countdown timer to 10 second intervals.
2.4. Place empty glass flask on scale, zero. Set the Powder Feed (PF) RPM to the low powder feed rate setting (e.g. 2 for a range of \{2,8\}).

\[\text{§§ Recommend only looking at the scale for the last 5 seconds so as to not tire the eyes.}\]
Appendix B

LENS Procedure 2011.02.01


Version

01: Date: 02 May 2011: Original Procedure

Objective:

This procedure serves to standardize the method by which processes are developed in the LENS system. This procedure will vary the powder feed rate, and hold travel speed and power constant. This procedure should be used when a new powder is being processed for the first time.

Summary:

The first step in process development is to determine the appropriate hatch spacing. This is determined from individual tracks. Several tracks will be deposited at different powder RPM settings to determine the contact angle and appropriate spacing.

Requirements:

12) The conditions under which processes are developed shall be as close as possible to the anticipated final deposit.
13) Chamber atmosphere at nominal processing conditions. For example, if processing Ti-6Al-4V, O₂ level should be less than 10 ppm.
14) Pressure in chamber should be kept as low as possible. For consistency use a pressure of less than 0.5 inch of water, and this pressure should be steady (the solenoid should not be opening) This can be obtained by adjusting the exhaust valve. For reference 1 inch of water is 0.0361 psi.
15) The gas-inlet valve that supplies argon to the center purge and powder feeders should be wide open to minimize fluctuations in the gas flow. Adjustments are then made by the flow meters.
16) The pressure of gas at the manifold shall be 50 psi.
17) The most recent powder flow calibration should have been conducted within 24 hours of process development.
18) The substrate thickness and material should be representative of the final part.
19) Clean the tray of old powder (even if it is the same you are depositing) prior to deposition
20) If to be used, the cold plate should be installed (after the tray has been cleaned

Path Planning:

- A program can be written to produce a complete set of process development samples, or a more manual approach where a single track is made.
• Use 1 inch long tracks.
• Spacing between tracks should not be less than 0.080 inch.
• Sufficient time should be allowed between tracks to allow heat to dissipate and for powder to change. A minimum of 30 seconds shall be required. This should be increased to the time to attain steady state powder flow as described by LP-2011.01.03, Part 2. This time should be maintained for all tracks.
• Make all positive directions first, and then repeat with negative directions.

Procedure:

1. Produce Deposits
   1.1. Verify the number of turns of the brass ring.
   1.2. Inspect cover glass.
   1.3. Verify power output to the workpiece (SKIP for now)
   1.4. Verify powder laser alignment (SKIP for now)
   1.5. Verify standoff is 0.375 inches.
   1.6. Verify PF gas flow rate. It must be the same as that used to determine the powder flow rates.
   1.7. Verify center purge is set at 30 L/min.
   1.8. Locate sample starting position on substrate. The sample shall be 0.1 inches from any edge.
   1.9. Set power level.
   1.10. A range of at least three powder feed settings should be used. For example \{5,6,7\}
   1.11. 
   1.12. Produce at least 1 deposit, in each of the anticipated build directions (e.g. ±x and or ±y) for each powder feed setting. A total of at least 6 deposits should be made.
   1.13. Remove sample from chamber.

2. Analyze deposits.
   2.1. Slice the substrate into halves using the cut-off saw and appropriate blade. The deposits shall be facing the blade to minimize dross on the surfaces which will be measured.
   2.2. Engrave a sample number on a surface of each piece with an engraver. Sample number convention: YYYYMMDD. Identify the first and last sample, by number corresponding to the process development record.
   2.3. Manually grind flat both surfaces, maintaining perpendicularity as best as possible.
   2.4. Grind through the finest grit paper (e.g. 320, 400, 600, 1000) if only the deposit profile is to be examined. If fusion zone information is required, polish to higher levels and etch
   2.5. Obtain macrographs using the stereoscope and lighting to obtain high edge contrast. The macrographs shall contain one track and sufficient substrate to yield a contact angle measurement.
   2.6. All macrographs shall be made at the same magnification.
   2.7. Obtain a macrograph of each track. File naming convention: YYYYMMDD-SampleNumber
   2.8. Include a macrograph of a steel scale, in 64ths of an inch. Any change in focus requires a new scale image. File naming convention: YYYYMMDD-SCALE-SampleNumbers. If samples 1 through 10 were made using this macrograph, SampleNumbers=10.
   2.9. Provide images.
3. Measure in Image J. (Not Complete)
   3.1. Straighten image so substrate is horizontal.
   3.2. Measure the width of the track at the substrate, the height of the track at the center, and fit a
circle to the track using three points.
   3.3. Analyze in Excel
   3.4. Determine ideal offset.
Appendix C

LENS Procedure 2011.03.01


Version

01: Date: 02 May 2011: Original Procedure

Objective:

This procedure serves to standardize the method by which processes are developed in the LENS system. This procedure will vary the powder feed rate, and hold travel speed and power constant. This procedure should be used when a new powder is being processed for the first time.

Summary:

The second step in process development is to determine the appropriate layer thickness, given a power, travel speed, and mass flow rate and associated hatch spacing determined during step 1. At this point in process development a single set of process conditions may be chosen.

Requirements:

21) The conditions under which processes are developed shall be as close as possible to the anticipated final deposit.
22) Chamber atmosphere at nominal processing conditions. For example, if processing Ti-6Al-4V, O₂ level should be less than 10 ppm.
23) Pressure in chamber should be kept as low as possible. For consistency use a pressure of less than 0.5 inch of water, and this pressure should be steady (the solenoid should not be opening) This can be obtained by adjusting the exhaust valve. For reference 1 inch of water is 0.0361 psi.
24) The gas-inlet valve that supplies argon to the center purge and powder feeders should be wide open to minimize fluctuations in the gas flow. Adjustments are then made by the flow meters.
25) The pressure of gas at the manifold shall be 50 psi.
26) The most recent powder flow calibration should have been conducted within 24 hours of process development. If more than 24 hours have passed, verify powder flow at a minimum of one data point, closest to which processing will occur.
27) The substrate thickness and material should be representative of the final part.
28) Clean the tray of old powder (even if it is the same you are depositing) prior to deposition
29) If to be used, the cold plate should be installed (after the tray has been cleaned

Path Planning:

• A program should be used for each sample (set of power, travel speed, mass flow rate, and hatch spacing)
• Use the lesser of a) 1 inch long tracks or b) the actual part dimensions.
• The time between tracks shall be that of the actual part. (Need equation)
• Use the lesser of a) the number of tracks to complete the width of the part or b) a minimum of 6 tracks shall be used.
• The path directions should be that of the first layer of the final part (e.g. ±x and or ±y).

Procedure:

4. Produce Deposits
   4.1. Verify the number of turns of the brass ring (Skip if confident no changes were made to system, as zeroing may affect powder–laser alignment).
   4.2. Inspect cover glass.
   4.3. Verify power output to the workpiece (SKIP for now)
   4.4. Verify powder laser alignment (SKIP for now)
   4.5. Verify standoff is 0.375 inches.
   4.6. Verify PF gas flow rate. It must be the same as that used to determine the powder flow rates.
   4.7. Verify center purge is set at 30 L/min.
   4.8. Locate sample starting position on substrate. The sample shall be 0.1 inches from any edge.
   4.9. Set power level.
   4.10. Produce at least two deposits of each condition. The time between each deposit shall be the number of tracks times 30 seconds.
   4.11. Remove sample from chamber.
   4.12. DO NOT Remove Powder From the Surface.

5. Analyze deposits.
   5.1. Slice the substrate into halves using the cut-off saw and appropriate blade. The deposits shall be facing the blade to minimize dross on the surfaces which will be measured.
   5.2. Engrave a sample number on a surface of each piece with an engraver. Sample number convention: YYYYMMDD. Identify the first and last sample, by number corresponding to the process development record.
   5.3. Manually grind flat one surface, maintaining perpendicularity as best as possible.
   5.4. Grind through the finest grit paper (e.g. 320, 400, 600, 1000) if only the deposit profile is to be examined. If fusion zone information is required, polish to higher levels and etch
   5.5. Obtain macrographs using the stereoscope and lighting to obtain high edge contrast. The macrographs shall contain all tracks and sufficient substrate to yield a contact angle
measurement. Note it is has been difficult to stitch images on the stereoscope (this could be due
to uneven lighting … the ring light may help this)
5.6. All macrographs shall be made at the same magnification.
5.7. Obtain a macrograph of each track. File naming convention: YYYYMMDD-SampleNumber
5.8. Include a macrograph of a steel scale, in 64ths of an inch. Any change in focus requires a new
scale image. File naming convention: YYYYMMDD-SCALE-SampleNumbers. If samples 1
through 10 were made using this macrograph, SampleNumbers=10.
5.9. Obtain a macrograph and scale of the surface of the layer surface (x-y plane) to show the
coverage with powder particles. File naming convention: YYYYMMDD-SampleNumber-XY
5.10. Provide images.

6. Measure in Image J. (Not Complete)
   6.1. Straighten image so substrate is horizontal.
   6.2. Measure, using rectangles, the maximum peak, the minimum peak, the maximum valley and the
        minimum valley. Or alternatively, each peak and valley starting with the first layer.
   6.3. Analyze in Excel
   6.4. Determine ideal hatch layer thickness.
Appendix D – Alternative deposition geometries

Each of these geometries is shown with and without the imaginary lines between the individual layers. There will be some degree of intermixing below each bead with the underlying or adjacent materials. Each unique deposition geometry may have its own advantages and disadvantages.

The hatch orientation is changed 90° between layers, reducing anisotropy between the X and Y axes.

Here the material deposition order is alternated every third layer and the hatch orientation changed 90° between layers. The deposition order is important; this deposition scheme further reduces anisotropy.
This scheme would decrease the degree of intermixing between materials since only half the time would a bead of Material A be deposited directly on top of Material B, compared to the scheme used to create the DCIP materials in this thesis where it alternated every time. The size of individual features would double.
It may be desirable to create a layered structure as shown for certain materials.
It may be desirable to create a layered structure as shown for certain materials.
It may be desirable to create a layered structure as shown for certain materials.
Appendix E – Sample DMC file used for LENS Procedure 2011.02.01

REM Determine Hatch Spacing 2011.02.01
REM *****************************************
REM Resolution = 5000
REM Contour Feedrate = 25
REM X Axis Resolution = 200000
REM Y Axis Resolution = 200000
REM Z Axis Resolution = 200000
REM Laser On Feedrate = 25
REM Laser On Accel = 40000
REM Laser On Decel = 40000
REM Laser On Shutter Delay = 20
REM Laser Off Feedrate = 40
REM Laser Off Accel = 40000
REM Laser Off Decel = 40000
REM Laser Off Shutter Delay = 20
REM *****************************************

SHW
DP 0,0,0
REM -------------------- LASER OFF SET SPEED
AC 2222222,2222222,2222222
DC 2222222,2222222,2222222
SP 133333,133333,133333
REM -------------------- TURN POWDER ON
REM PF 1&2 to 0 g/min
REM PF 0.00,0.00
UI 5
REM PF 0.00,0.00
WT 35000
REM -------------------- BEGIN 3.5.0
REM -------------------- LASER POWER TO 300 NOMINAL WATTS
OFW=6.0
REM -------------------- 3.5.0 PH 1
PA 200000,4000
BG XY
AM XY
VM XY
VA 2222222
VD 2222222
VS 78740
VP -200000,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM -------------------- 3.5.0 PH 2
PA 0,-4000
BG XY
AM XY
VM XY
VA 2222222
VD 2222222
VS 78740
VP 200000,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM -------------------- TURN POWDER ON
REM PF 2 to 3.5 g/min
REM PF 0.00,4.91
UI 5
REM PF 0.00,4.91
REM ------------------- MOVE UP SO GAS DOESN'T COOL PART
PR 0.0,600000
BG Z
AM Z
REM ------------------- WAIT FOR POWDER FLOW TO STABILIZE
WT 7000
REM ------------------- MOVE DOWN TO DEPOSITION HEIGHT
PR 0.0,-600000
BG Z
AM Z
REM ------------------- LASER POWER TO 400 NOMINAL WATTS
OFW=8.0
REM ------------------- DEPOSIT SINGLE BEAD
REM Hatch 3.5.0
PA 200000,0
BG XY
AM XY
VM XY
VA 2222222
VD 2222222
VS 78740
VP -200000,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM ------------------- TURN PF OFF
REM PF 1&2 to 0 g/min
REM PF 0.00,0.00
UI 5
REM PF 0.00,0.00
REM ------------------- MOVE TO CENTER OF DEPOSIT
PA 0.0
BG XY
AM XY
VM XY
VA 2222222
VD 2222222
VS 78740
VP 100000,0
VE
REM SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM ------------------- COOL DOWN FOR 60 Secs
WT 60000
REM ------------------- END OF LINE
REM ------------------- BEGIN 3.5+
REM ------------------- LASER POWER TO 300 NOMINAL WATTS
OFW=6.0
REM ------------------- 3.5+ PH 1
PA 0.28000
BG XY
AM XY
VM XY
VA 2222222
VD 2222222
VS 78740
VP 200000,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM ------------------ 3.5+ PH 2
PA 200000,20000
BG XY
AM XY
VM XY
VA 22222222
VD 22222222
VS 78740
VP -200000,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM ------------------ TURN POWDER ON
REM PF 2 to 3.5 g/min
REM PF 0.00,4.91
UI 5
REM PF 0.00,4.91
REM MOVE UP SO GAS DOESN'T COOL PART
PR 0,0,600000
BG Z
AM Z
REM ------------------ WAIT FOR POWDER FLOW TO STABLIZE
WT 7000
REM ------------------ MOVE DOWN TO DEPOSITION HEIGHT
PR 0,0,-600000
BG Z
AM Z
REM ------------------ LASER POWER TO 400 NOMINAL WATTS
OFW=8.0
REM ------------------ DEPOSIT SINGLE BEAD
REM Hatch 3.5+
PA 0,24000
BG XY
AM XY
VM XY
VA 22222222
VD 22222222
VS 78740
VP 200000,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM ------------------ TURN PF OFF
REM PF 1&2 to 0 g/min
REM PF 0.00,0.00
UI 5
REM PF 0.00,0.00
REM ------------------ MOVE TO CENTER OF DEPOSIT
PA 200000,24000
BG XY
AM XY
VM XY
VA 22222222
VD 22222222
VS 78740
VP -100000,0
VE
REM SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM ------------------ COOL DOWN FOR 60 Secs
WT 60000
REM ------------------ END OF LINE
REM -------------------- BEGIN 3.5-
REM ------------------ LASER POWER TO 300 NOMINAL WATTS
OFW=6.0
REM ------------------ 3.5- PH 1
PA 200000,52000
BG XY
AM XY
VM XY
VA 2222222
VD 2222222
VS 78740
VP -200000,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM ------------------ 3.5- PH 2
PA 0,44000
BG XY
AM XY
VM XY
VA 2222222
VD 2222222
VS 78740
VP 200000,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM ------------------ TURN POWDER ON
REM PF 2 to 3.5 g/min
REM PF 0.00,4.91
UI 5
REM PF 0.00,4.91
REM MOVE UP SO GAS DOESN'T COOL PART
PR 0,0,600000
BG Z
AM Z
REM ------------------ WAIT FOR POWDER FLOW TO STABILIZE
WT 7000
REM ------------------ MOVE DOWN TO DEPOSITION HEIGHT
PR 0,0,-600000
BG Z
AM Z
REM -------------------- LASER POWER TO 400 NOMINAL WATTS
OFW=8.0
REM -------------------- DEPOSIT SINGLE BEAD
REM Hatch 3.5-
PA 200000,48000
BG XY
AM XY
VM XY
VA 2222222
VD 2222222
VS 78740
VP -200000,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM ------------------ TURN PF OFF
REM PF 1 & 2 to 0 g/min
REM PF 0.00,0.00
UI 5
REM PF 0.00,0.00
REM ------------------ MOVE TO CENTER OF DEPOSIT
PA 0.48000
BG XY
AM XY
VM XY
VA 2222222
VD 2222222
VS 78740
VP 100000,0
VE
REM SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM ------------------ COOL DOWN FOR 60 Secs
WT 60000
REM ------------------ END OF LINE
REM ------------------ BEGIN 4+
REM ------------------ LASER POWER TO 300 NOMINAL WATTS
OFW=6.0
REM ------------------ 4+ PH 1
PA 0.76000
BG XY
AM XY
VM XY
VA 2222222
VD 2222222
VS 78740
VP 200000,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM ------------------ 4+ PH 2
PA 200000,68000
BG XY
AM XY
VM XY
VA 2222222
VD 2222222
VS 78740
VP -200000,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM ------------------ TURN POWDER ON
REM PF 2 to 4 g/min
REM PF 0.00,5.59
UI 5
REM PF 0.00,5.59
REM MOVE UP SO GAS DOESN'T COOL PART
PR 0,0,600000
BG Z
AM Z
REM ------------------ WAIT FOR POWDER FLOW TO STABILIZE
WT 7000
REM ------------------ MOVE DOWN TO DEPOSITION HEIGHT
PR 0,0,-600000
BG Z
AM Z
REM ------------------ LASER POWER TO 400 NOMINAL WATTS
OFW=8.0
REM ------------------ DEPOSIT SINGLE BEAD
REM Hatch 4+
PA 0,72000
BG XY
AM XY
VM XY
VA 2222222
VD 2222222
VS 78740
VP 200000,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM ------------------ TURN PF OFF
REM PF 1 & 2 to 0 g/min
REM PF 0.00,0.00
UI 5
REM PF 0.00,0.00
REM ------------------ MOVE TO CENTER OF DEPOSIT
PA 200000,72000
BG XY
AM XY
VM XY
VA 2222222
VD 2222222
VS 78740
VP -100000,0
VE
REM SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM ------------------ COOL DOWN FOR 60 Secs
WT 60000
REM ------------------ END OF LINE
REM ------------------ BEGIN 4-
REM ------------------ LASER POWER TO 300 NOMINAL WATTS
OFW=6.0
REM ------------------ 4- PH 1
PA 200000,100000
BG XY
AM XY
VM XY
VA 2222222
VD 2222222
VS 78740
VP 200000,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM ------------------ 4- PH 2
PA 0,92000
BG XY
AM XY
VM XY
VA 2222222
VD 2222222
VS 78740
VP 200000,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM ------------------ TURN POWDER ON
REM PF 2 to 4 g/min
REM PF 0,00,5,59
UI 5
REM PF 0,00,5,59
REM MOVE UP SO GAS DOESN'T COOL PART
PR 0,0,600000
BG Z
AM Z
REM ------------------ WAIT FOR POWDER FLOW TO STABILIZE
WT 7000
REM ------------------ MOVE DOWN TO DEPOSITION HEIGHT
PR 0,0,-600000
BG Z
AM Z
REM ------------------ LASER POWER TO 400 NOMINAL WATTS
OFW=8,0
REM ------------------ DEPOSIT SINGLE BEAD
REM Hatch 4-
PA 200000,96000
BG XY
AM XY
VM XY
VA 2222222
VD 2222222
VS 78740
VP -200000,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM ------------------ TURN PF OFF
REM PF 1&2 to 0 g/min
REM PF 0,00,0,00
UI 5
REM PF 0,00,0,00
REM ------------------ MOVE TO CENTER OF DEPOSIT
PA 0,96000
BG XY
AM XY
VM XY
VA 2222222
VD 2222222
VS 78740
VP -200000,0
VE
REM SB 1
WT 20
BGS
AMS  
CB 1  
WT 20  
REM --------------- COOL DOWN FOR 60 Secs  
WT 60000  
REM --------------- END OF LINE  
REM --------------- BEGIN 4.5+  
REM --------------- LASER POWER TO 300 NOMINAL WATTS  
OFW=6.0  
REM --------------- 4.5+ PH 1  
PA 0,124000  
BG XY  
AM XY  
VM XY  
VA 2222222  
VD 2222222  
VS 78740  
VP 200000,0  
VE  
SB 1  
WT 20  
BGS  
AMS  
CB 1  
WT 20  
REM --------------- 4.5+ PH 2  
PA 200000,116000  
BG XY  
AM XY  
VM XY  
VA 2222222  
VD 2222222  
VS 78740  
VP -200000,0  
VE  
SB 1  
WT 20  
BGS  
AMS  
CB 1  
WT 20  
REM --------------- TURN POWDER ON  
REM PF 2 to 4.5 g/min  
REM PF 0.00,6.28  
UI 5  
REM PF 0.00,6.28  
REM MOVE UP SO GAS DOESN'T COOL PART  
PR 0,0,600000  
BG Z  
AM Z  
REM --------------- WAIT FOR POWDER FLOW TO STABILIZE  
WT 7000  
REM --------------- MOVE DOWN TO DEPOSITION HEIGHT  
PR 0,0,-600000  
BG Z  
AM Z  
REM --------------- LASER POWER TO 400 NOMINAL WATTS  
OFW=8.0  
REM --------------- DEPOSIT SINGLE BEAD  
REM Hatch 4.5+  
PA 0,120000  
BG XY  
AM XY  
VM XY  
VA 2222222  
VD 2222222  
VS 78740  
VP 200000,0  
VE  
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM ------------------ TURN PF OFF
REM PF 1&2 to 0 g/min
REM PF 0.00,0.00
UI 5
REM PF 0.00,0.00
REM ------------------ MOVE TO CENTER OF DEPOSIT
PA 200000,120000
BG XY
AM XY
VM XY
VA 2222222
VD 2222222
VS 78740
VP -100000,0
VE
REM SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM ------------------ COOL DOWN FOR 60 Secs
WT 60000
REM ------------------ END OF LINE
REM ------------------ BEGIN 4.5-
REM ------------------ LASER POWER TO 300 NOMINAL WATTS
OFW=6.0
REM ------------------ 4.5- PH 1
PA 200000,148000
BG XY
AM XY
VM XY
VA 2222222
VD 2222222
VS 78740
VP -200000,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM ------------------ 4.5- PH 2
PA 0,140000
BG XY
AM XY
VM XY
VA 2222222
VD 2222222
VS 78740
VP 200000,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM ------------------ TURN POWDER ON
REM PF 2 to 4.5 g/min
REM PF 0.00,6.28
UI 5
REM PF 0.00,6.28
REM MOVE UP SO GAS DOESN'T COOL PART
PR 0,0,600000
BG Z
AM Z
REM --------------------- WAIT FOR POWDER FLOW TO STABILIZE
WT 7000
REM --------------------- MOVE DOWN TO DEPOSITION HEIGHT
PR 0,0,-600000
BG Z
AM Z
REM --------------------- LASER POWER TO 400 NOMINAL WATTS
OFW=8.0
REM --------------------- DEPOSIT SINGLE BEAD
REM Hatch 4.5-
PA 200000,144000
BG XY
AM XY
VM XY
VA 22222222
VD 22222222
VS 78740
VP -200000,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM --------------------- TURN PF OFF
REM PF 1&2 to 0 g/min
REM PF 0.00,0.00
UI 5
REM PF 0.00,0.00
REM --------------------- MOVE TO CENTER OF DEPOSIT
PA 0,144000
BG XY
AM XY
VM XY
VA 22222222
VD 22222222
VS 78740
VP 100000,0
VE
REM SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM --------------------- COOL DOWN FOR 60 Secs
WT 60000
REM --------------------- END OF LINE
REM -----------------------------------------------
REM --------------------- TURN OFF PROCEDURE
WT 20
UI 3
WT 20
Appendix F – DMC file used for LENS Procedure 2011.03.01

REM Determine single layer thickness 2011.03.01
REM ***********************************************************
REM Resolution = 5000
REM Contour Feedrate = 15mm/s
REM X Axis Resolution = 200000
REM Y Axis Resolution = 200000
REM Z Axis Resolution = 200000
REM Laser On Feedrate = 10mm/s
REM Laser On Accel = 40000
REM Laser On Decel = 40000
REM Laser On Shutter Delay = 20
REM Laser Off Feedrate = 40
REM Laser Off Accel = 40000
REM Laser Off Decel = 40000
REM Laser Off Shutter Delay = 20
REM ***********************************************************
SHW
REM Hatch Spacing (648um)
varH=5102
REM Hatch Length
varL=196850
REM ******************************************************
REM ----------------LASER OFF SET SPEED -10mm/s & 15mm/s
AC 2624671,2624671,2624671
DC 2624671,2624671,2624671
SP 118110,118110,118110
REM ----------------- DEFINE POSITION
DP 0,0,0
REM ----------------- LASER POWER TO 300 NOMINAL WATTS
OFW=6.0
REM ----------------- TURN POWDER ON TO ZERO
REM PF 1&2 to 0 g/min
REM PF 0.00,0.00
UI 5
REM PF 0.00,0.00
WT 15000
REM ------------------------------- BEGIN Preheat pass 1
REM ------------------------------- +0
PA 0,0
BG XY
AM XY
VM XY
VA 2624671
VD 2624671
VS 78740
VP varL,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM ------------------------------- +2
PA 0,varH*2
BG XY
AM XY
VM XY
VA 2624671
VD 2624671
VS 78740
VP varL,0
VE
SB 1
WT 20
BGS
AMS
VM XY
VA 2624671
VD 2624671
VS 78740
VP varL,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM ------------------- +5
PA 0, varH*5
BG XY
AM XY
VM XY
VA 2624671
VD 2624671
VS 78740
VP varL,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM ------------------- +7
PA 0, varH*7
BG XY
AM XY
VM XY
VA 2624671
VD 2624671
VS 78740
VP varL,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM ------------------- +9
PA 0, varH*9
BG XY
AM XY
VM XY
VA 2624671
VD 2624671
VS 78740
VP varL,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM ------------------- END OF LINE
REM
REM ------------------- BEGIN Preheat pass 2
REM ------------------- +0
PA 0,0
BG XY
AM XY
VM XY
VA 2624671
VD 2624671

94
VS 78740
VP varL,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM ------------------ +2
PA 0, varH*2
BG XY
AM XY
VM XY
VA 2624671
VD 2624671
VS 78740
VP varL,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM ------------------ +4
PA 0, varH*4
BG XY
AM XY
VM XY
VA 2624671
VD 2624671
VS 78740
VP varL,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM ------------------ +6
PA 0, varH*6
BG XY
AM XY
VM XY
VA 2624671
VD 2624671
VS 78740
VP varL,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM ------------------ +8
PA 0, varH*8
BG XY
AM XY
VM XY
VA 2624671
VD 2624671
VS 78740
VP varL,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM --------------- +1
PA 0,varH*1
BG XY
AM XY
VM XY
VA 2624671
VD 2624671
VS 78740
VP varL,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM --------------- +3
PA 0,varH*3
BG XY
AM XY
VM XY
VA 2624671
VD 2624671
VS 78740
VP varL,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM --------------- +5
PA 0,varH*5
BG XY
AM XY
VM XY
VA 2624671
VD 2624671
VS 78740
VP varL,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM --------------- +7
PA 0,varH*7
BG XY
AM XY
VM XY
VA 2624671
VD 2624671
VS 78740
VP varL,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM --------------- +9
PA 0,varH*9
BG XY
REM -------------------- END OF LINE
REM
REM --------------------- DEPOSIT LAYER 1
REM
REM --------------------- TURN POWDER ON
REM
REM PF 1 to 2.5 g/min
REM
REM PF 3.45,0.00
REM
UI 5
REM PF 3.45,0.00
REM
REM --------------------- MOVE UP SO GAS DOESN'T COOL PART
REM
REM PR 0,0,600000
REM
BG Z
AM Z
REM
REM --------------------- WAlT FOR POWDER FLOW TO STABILIZE
REM
WT 7000
REM
REM --------------------- MOVE DOWN TO DEPOSITION HEIGHT
REM
REM PR 0,0,-600000
REM
BG Z
AM Z
REM
REM --------------------- +0
REM
PA 0,0
REM
BG XY
AM XY
VM XY
REM
VA 2624671
VD 2624671
VS 78740
VP varL,0
REM
VE
REM
SB 1
REM
WT 20
REM
BG S
REM
AM S
REM
CB 1
REM
WT 20
REM
REM --------------------- +2
REM
PA 0, varH*2
REM
BG XY
AM XY
VM XY
REM
VA 2624671
VD 2624671
VS 78740
VP varL,0
REM
VE
REM
SB 1
REM
WT 20
REM
BG S
REM
AM S
REM
CB 1
REM
WT 20
REM
REM --------------------- +4
REM
PA 0, varH*4
REM
BG XY
AM XY
VM XY
REM
VA 2624671
VD 2624671
VS 78740
VP varL,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM -------------------- +6
PA 0, varH*6
BG XY
AM XY
VM XY
VA 2624671
VD 2624671
VS 78740
VP varL,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM -------------------- +8
PA 0, varH*8
BG XY
AM XY
VM XY
VA 2624671
VD 2624671
VS 78740
VP varL,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM -------------------- SWITCH POWDER
REM PF 2 to 2.5 g/min
REM PF 0.00,3.54
UI 5
REM PF 0.00,3.54
REM -------------------- MOVE UP SO GAS DOESN'T COOL PART
PR 0,0,600000
BG Z
AM Z
REM -------------------- WAIT FOR POWDER FLOW TO STABILIZE
WT 7000
REM -------------------- MOVE DOWN TO DEPOSITION HEIGHT
PR 0,0,-600000
BG Z
AM Z
REM -------------------- +1
PA 0, varH*1
BG XY
AM XY
VM XY
VA 2624671
VD 2624671
VS 78740
VP varL,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM ------------------- +3
PA 0, varH*3
BG XY
AM XY
VM XY
VA 2624671
VD 2624671
VS 78740
VP varL,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM ------------------- +5
PA 0, varH*5
BG XY
AM XY
VM XY
VA 2624671
VD 2624671
VS 78740
VP varL,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM ------------------- +7
PA 0, varH*7
BG XY
AM XY
VM XY
VA 2624671
VD 2624671
VS 78740
VP varL,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM ------------------- +9
PA 0, varH*9
BG XY
AM XY
VM XY
VA 2624671
VD 2624671
VS 78740
VP varL,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM ------------------- END OF LINE
REM=""'
REM ------------------- TURN PF OFF
REM PF 1&2 to 0 g/min
REM PF 0.00,0.00
UI 5
REM PF 0.00,0.00
REM ------------------------- MOVE TO CENTER OF DEPOSIT
PA 0.5*varL,5*varH
BG XY
AM XY
VM XY
VA 2222222
VD 2222222
VS 83333
VP 0,0.5*varH
VE
REM SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM ------------------------- MOVE UP
PR 0,0,600000
BG Z
AM Z
REM ------------------------- WAIT
WT 7000
REM ------------------------- MOVE DOWN TO DEPOSITION HEIGHT
PR 0,0,-600000
BG Z
AM Z
REM ------------------------- END OF LINE
REM -----------------------------------------------
REM ------------------------- TURN OFF PROCEDURE
WT 20
CB 1
WT 20
UI 3
Appendix G – DMC file used to create DCIP sample #1

REM Determine single layer thickness 2011.03.01
REM *****************************************************
REM Resolution = 5000
REM Contour Feedrate = 15mm/s
REM X Axis Resolution = 7874/mm
REM Y Axis Resolution = 7874/mm
REM Z Axis Resolution = 7874/mm
REM Laser On Feedrate = 10mm/s
REM Laser On Accel = 10mm/s/s
REM Laser On Decel = 10mm/s/s
REM Laser On Shutter Delay = 20ms
REM Laser Off Feedrate = 40ms
REM Laser Off Accel = 10mm/s/s
REM Laser Off Decel = 10mm/s/s
REM Laser Off Shutter Delay = 20ms
REM Number of preheats = 1
REM *****************************************************
SHW
REM Hatch Spacing (668um)-nom
varH=5262
REM Hatch Length (25mm)
varL=196850
REM Zstep (191mm)
varZ=-600000+1504
REM *****************************************************
REM -------------------- LASER OFF SET SPEED - 10mm/s/s & 15mm/s
AC 2624671,2624671,2624671
DC 2624671,2624671,2624671
SP 118110,118110,118110
REM -------------------- DEFINE POSITION
DP 0,0,0
REM -------------------- LASER POWER TO 300 NOMINAL WATS
OZW=6.0
REM -------------------- TURN POWDER ON TO ZERO
REM PF 1&2 to 0 g/min
REM PF 0.00,0.00
UI 5
REM PF 0.00,0.00
WT 20000
REM *****************************************************
REM -------------------- BEGIN Preheat pass 1
REM -------------------- +0
PA 0,0
BG XY
AM XY
VM XY
VA 2624671
VD 2624671
VS 78740
VP varL,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM -------------------- +2
PA 0, varH*2
BG XY
AM XY
VM XY
VA 2624671
VD 2624671
VS 78740
VP varL,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM ------------------ +4
PA 0, varH*4
BG XY
AM XY
VM XY
VA 2624671
VD 2624671
VS 78740
VP varL,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM ------------------ +6
PA 0, varH*6
BG XY
AM XY
VM XY
VA 2624671
VD 2624671
VS 78740
VP varL,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM ------------------ +8
PA 0, varH*8
BG XY
AM XY
VM XY
VA 2624671
VD 2624671
VS 78740
VP varL,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM ------------------ +1
PA 0, varH*1
BG XY
AM XY
VM XY
VA 2624671
VD 2624671
VS 78740
VP varL,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM ------------------ +3
PA 0, varH*3
BG XY
AM XY
VM XY
VA 2624671
VD 2624671
VS 78740
VP varL,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM ------------------ +5
PA 0, varH*5
BG XY
AM XY
VM XY
VA 2624671
VD 2624671
VS 78740
VP varL,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM ------------------ +7
PA 0, varH*7
BG XY
AM XY
VM XY
VA 2624671
VD 2624671
VS 78740
VP varL,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM ------------------ +9
PA 0, varH*9
BG XY
AM XY
VM XY
VA 2624671
VD 2624671
VS 78740
VP varL,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM -------------- END OF LINE
UI 5
REM PF 3.36,0.00
REM --------------------- MOVE UP
PR 0,0,600000
BG Z
AM Z
REM --------------------- WAIT FOR POWDER FLOW TO STABILIZE
WT 11000
REM --------------------- MOVE DOWN TO DEPOSITION HEIGHT
PR 0,0,-600000
BG Z
AM Z
REM --------------------- +0
PA 0,0
BG XY
AM XY
VM XY
VA 2624671
VD 2624671
VS 78740
VP varL,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM --------------------- +2
PA 0,varH*2
BG XY
AM XY
VM XY
VA 2624671
VD 2624671
VS 78740
VP varL,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM --------------------- +4
PA 0,varH*4
BG XY
AM XY
VM XY
VA 2624671
VD 2624671
VS 78740
VP varL,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM --------------------- +6
PA 0,varH*6
BG XY
AM XY
VM XY
VA 2624671
VD 2624671
VS 78740
VP varL,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM ------------------ +8
PA 0, varH*8
BG XY
AM XY
VM XY
VA 2624671
VD 2624671
VS 78740
VP varL,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM ------------------ TURN PF OFF
REM PF 1&2 to 0 g/min
REM PF 0.00,0.00
UI 5
REM PF 0.00,0.00
REM ------------------ MOVE TO CENTER OF DEPOSIT
PA 0.5*varL, 5*varH
BG XY
AM XY
VM XY
VA 2222222
VD 2222222
VS 83333
VP 0, 0.5*varH
VE
REM SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM ------------------ MOVE UP
PR 0,0,600000
BG Z
AM Z
REM ------------------ WAIT
WT 36000
REM ------------------ SWITCH POWDER
REM PF 2 to 2.5 g/min
REM PF 0.00,3.47
UI 5
REM PF 0.00,3.47
REM ------------------ WAIT FOR POWDER FLOW TO STABLIZE
WT 16000
REM ------------------ MOVE DOWN TO DEPOSITION HEIGHT
PR 0, 0,-600000
BG Z
AM Z
REM ------------------ +1
PA 0, varH*1
BG XY
AM XY
VM XY
VA 2624671
VD 2624671
VS 78740
VP varL,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM --------------- +3
PA 0, varH*3
BG XY
AM XY
VM XY
VA 2624671
VD 2624671
VS 78740
VP varL,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM --------------- +5
PA 0, varH*5
BG XY
AM XY
VM XY
VA 2624671
VD 2624671
VS 78740
VP varL,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM --------------- +7
PA 0, varH*7
BG XY
AM XY
VM XY
VA 2624671
VD 2624671
VS 78740
VP varL,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM --------------- +9
PA 0, varH*9
BG XY
AM XY
VM XY
VA 2624671
VD 2624671
VS 78740
VP varL,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM ------------------ END OF LINE
REM --------------------------
REM ------------------ BETWEEN LAYER SEQUENCE
REM ------------------ TURN PF OFF
REM PF 1&2 to 0 g/min
REM PF 0.00,0.00
UI 5
REM PF 0.00,0.00
REM ------------------ MOVE TO CENTER OF DEPOSIT
PA 0.5*varL,5*varH
BG XY
AM XY
VM XY
VA 2222222
VD 2222222
VS 83333
VP 0,0.5*varH
VE
REM SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM ------------------ MOVE UP
PR 0,0,600000
BG Z
AM Z
REM ------------------ WAIT
WT 52000
REM ------------------ MOVE DOWN TO DEPOSITION HEIGHT
PR 0,0,varZ
BG Z
AM Z
REM ------------------ END OF LINE
REM --------------------------
REM ------------------ DEPOSIT LAYER 2
REM ------------------ TURN POWDER ON
REM PF 1 to 2.5 g/min
REM PF 3.36,0.00
UI 5
REM PF 3.36,0.00
REM ------------------ MOVE UP
PR 0,0,600000
BG Z
AM Z
REM ------------------ WAIT FOR POWDER FLOW TO STABILIZE
WT 11000
REM ------------------ MOVE DOWN TO DEPOSITION HEIGHT
PR 0,0,-600000
BG Z
AM Z
REM ------------------ +1
PA 0,varH*1
BG XY
AM XY
VM XY
VA 2624671
VD 2624671
VS 78740
VP varL,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM ------------------ +3
PA 0,varH*3
REM -------------------- +5
PA 0, varH*5
BG XY
AM XY
VM XY
VA 2624671
VD 2624671
VS 78740
VP varL,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM -------------------- +7
PA 0, varH*7
BG XY
AM XY
VM XY
VA 2624671
VD 2624671
VS 78740
VP varL,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM -------------------- +9
PA 0, varH*9
BG XY
AM XY
VM XY
VA 2624671
VD 2624671
VS 78740
VP varL,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM -------------------- TURN PF OFF
REM PF 1&2 to 0 g/min
REM PF 0.00,0.00
UI 5
REM PF 0.00,0.00
REM -------------------- MOVE TO CENTER OF DEPOSIT
PA 0.5*varL,5*varH
BG XY

108
AM XY
VM XY
VA 222222
VD 222222
VS 83333
VP 0,0.5*varH
VE
REM SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM --------------- MOVE UP
PR 0,0,600000
BG Z
AM Z
REM --------------- WAIT
WT 36000
REM ------------------ SWITCH POWDER
REM PF 2 to 2.5 g/min
REM PF 0.00,3.47
UI 5
REM PF 0.00,3.47
REM --------------- WAIT FOR POWDER FLOW TO STABLIZE
WT 16000
REM ------------------ MOVE DOWN TO DEPOSITION HEIGHT
PR 0,0,-600000
BG Z
AM Z
REM --------------- +0
PA 0,0
BG XY
AM XY
VM XY
VA 2624671
VD 2624671
VS 78740
VP varL,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM --------------- +2
PA 0, varH*2
BG XY
AM XY
VM XY
VA 2624671
VD 2624671
VS 78740
VP varL,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM --------------- +4
PA 0, varH*4
BG XY
AM XY
VM XY
VA 2624671
VD 2624671
VS 78740
VP varL,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM ------------------ +6
PA 0, varH*6
BG XY
AM XY
VM XY
VA 2624671
VD 2624671
VS 78740
VP varL,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM ------------------ +8
PA 0, varH*8
BG XY
AM XY
VM XY
VA 2624671
VD 2624671
VS 78740
VP varL,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM --------------- END OF LINE
REM ====================================================
REM ------------------- BETWEEN LAYER SEQUENCE
REM --------------- TURN PF OFF
REM PF 1&2 to 0 g/min
REM PF 0.00,0.00
UI 5
REM PF 0.00,0.00
REM ------------------- MOVE TO CENTER OF DEPOSIT
PA 0.5*varL,5*varH
BG XY
AM XY
VM XY
VA 2222222
VD 2222222
VS 83333
VP 0,0.5*varH
VE
REM SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM ------------------- MOVE UP
PR 0,0,600000
BG Z
AM Z
REM --------------- WAIT
WT 52000
REM -------------------- MOVE DOWN TO DEPOSITION HEIGHT
PR 0,0,VARZ
BG Z
AM Z
REM -------------------- END OF LINE
REM

REM -------------------- DEPOSIT LAYER 3
REM -------------------- TURN POWDER ON
REM PF 1 to 2.5 g/min
REM PF 3.36,0.00
UI 5
REM PF 3.36,0.00
REM -------------------- MOVE UP
PR 0,0,0
BG Z
AM Z
REM -------------------- WAIT FOR POWDER FLOW TO STABILIZE
WT 11000
REM -------------------- MOVE DOWN TO DEPOSITION HEIGHT
PR 0,0,-600000
BG Z
AM Z
REM -------------------- +0
PA 0,0
BG XY
AM XY
VM XY
VA 2624671
VD 2624671
VS 78740
VP VARL,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM -------------------- +2
PA 0,VARH*2
BG XY
AM XY
VM XY
VA 2624671
VD 2624671
VS 78740
VP VARL,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM -------------------- +4
PA 0,VARH*4
BG XY
AM XY
VM XY
VA 2624671
VD 2624671
BG Z
VS 78740
VP VARL,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM -------------------- +6
PA 0, varH*6
BG XY
AM XY
VM XY
VA 2624671
VD 2624671
VS 78740
VP varL, 0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM -------------------- +8
PA 0, varH*8
BG XY
AM XY
VM XY
VA 2624671
VD 2624671
VS 78740
VP varL, 0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM -------------------- TURN PF OFF
REM PF 1&2 to 0 g/min
REM PF 0.00, 0.00
UI 5
REM PF 0.00, 0.00
REM -------------------- MOVE TO CENTER OF DEPOSIT
PA 0.5 * varL, 5 * varH
BG XY
AM XY
VM XY
VA 2222222
VD 2222222
VS 83333
VP 0, 0.5 * varH
VE
REM SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM -------------------- MOVE UP
PR 0, 0.600000
BG Z
AM Z
REM -------------------- WAIT
WT 360000
REM -------------------- SWITCH POWDER
REM PF 2 to 2.5 g/min
REM PF 0.00, 3.47
UI 5
REM PF 0.00, 3.47
REM -------------------- WAIT FOR POWDER FLOW TO STABILIZE
WT 160000
REM -------------------- MOVE DOWN TO DEPOSITION HEIGHT
PR 0.0, -600000
BG Z
AM Z
REM ------------------- +1
PA 0, varH*1
BG XY
AM XY
VM XY
VA 2624671
VD 2624671
VS 78740
VP varL,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM ------------------- +3
PA 0, varH*3
BG XY
AM XY
VM XY
VA 2624671
VD 2624671
VS 78740
VP varL,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM ------------------- +5
PA 0, varH*5
BG XY
AM XY
VM XY
VA 2624671
VD 2624671
VS 78740
VP varL,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM ------------------- +7
PA 0, varH*7
BG XY
AM XY
VM XY
VA 2624671
VD 2624671
VS 78740
VP varL,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM ------------------- +9
PA 0, varH*9
BG XY
AM XY
VM XY
VA 2624671
VD 2624671
VS 78740
VP varL,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM -------------- END OF LINE
REM =---------------------------------------------------------------------
REM -------------- BETWEEN LAYER SEQUENCE
REM -------------- TURN PF OFF
REM PF 1&2 to 0 g/min
REM PF 0.00,0.00
UL 5
REM PF 0.00,0.00
REM -------------- MOVE TO CENTER OF DEPOSIT
PA 0.5*varL,5*varH
BG XY
AM XY
VM XY
VA 2222222
VD 2222222
VS 83333
VP 0.0,5*varH
VE
REM SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM -------------- MOVE UP
PR 0.0,600000
BG Z
AM Z
REM -------------- WAIT
WT 52000
REM -------------- MOVE DOWN TO DEPOSITION HEIGHT
PR 0.0, varZ
BG Z
AM Z
REM -------------- END OF LINE
REM =---------------------------------------------------------------------
REM -------------- DEPOSIT LAYER 4
REM -------------- TURN POWDER ON
REM PF 1 to 2.5 g/min
REM PF 3.36,0.00
UL 5
REM PF 3.36,0.00
REM -------------- MOVE UP
PR 0.0,600000
BG Z
AM Z
REM -------------- WAIT FOR POWDER FLOW TO STABLIZE
WT 11000
REM -------------- MOVE DOWN TO DEPOSITION HEIGHT
PR 0.0,-600000
BG Z
AM Z
REM -------------- +1
PA 0, varH*1
BG XY
AM XY
VM XY
VA 2624671
VD 2624671
VS 78740
VP varL,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM ----------------------- +3
PA 0,varH*3
BG XY
AM XY
VM XY
VA 2624671
VD 2624671
VS 78740
VP varL,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM ----------------------- +5
PA 0,varH*5
BG XY
AM XY
VM XY
VA 2624671
VD 2624671
VS 78740
VP varL,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM ----------------------- +7
PA 0,varH*7
BG XY
AM XY
VM XY
VA 2624671
VD 2624671
VS 78740
VP varL,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM ----------------------- +9
PA 0,varH*9
BG XY
AM XY
VM XY
VA 2624671
VD 2624671
VS 78740
VP varL,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM ------------------ TURN PF OFF
REM PF 1&2 to 0 g/min
REM PF 0.00,0.00
UI 5
REM PF 0.00,0.00
REM ------------------ MOVE TO CENTER OF DEPOSIT
PA 0.5*varL,5*varH
BG XY
AM XY
VM XY
VA 2222222
VD 2222222
VS 83333
VP 0.0,5*varH
VE
REM SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM ------------------ MOVE UP
PR 0,0,600000
BG Z
AM Z
REM ------------------ WAIT
WT 36000
REM ------------------ SWITCH POWDER
REM PF 2 to 2.5 g/min
REM PF 0.00,3.47
UI 5
REM PF 0.00,3.47
REM ------------------ WAIT FOR POWDER FLOW TO STABILIZE
WT 16000
REM ------------------ MOVE DOWN TO DEPOSITION HEIGHT
PR 0,0,-600000
BG Z
AM Z
REM ------------------ +0
PA 0,0
BG XY
AM XY
VM XY
VA 2624671
VD 2624671
VS 78740
VP varL,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM ------------------ +2
PA 0, varH*2
BG XY
AM XY
VM XY
VA 2624671
VD 2624671
VS 78740
VP varL,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM ------------------ +4
PA 0, varH*4
BG XY
AM XY
VM XY
VA 2624671
VD 2624671
VS 78740
VP varL,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM ------------------ +6
PA 0, varH*6
BG XY
AM XY
VM XY
VA 2624671
VD 2624671
VS 78740
VP varL,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM ------------------ +8
PA 0, varH*8
BG XY
AM XY
VM XY
VA 2624671
VD 2624671
VS 78740
VP varL,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM ------------------ END OF LINE
REM --------------------------------------------------------------
REM ------------------- BETWEEN LAYER SEQUENCE
REM ------------------- TURN PF OFF
REM PF 1&2 to 0 g/min
REM PF 0.00,0.00
UI 5
REM PF 0.00,0.00
REM ------------------- MOVE TO CENTER OF DEPOSIT
PA 0.5*varL, 5*varH
BG XY
AM XY
VM XY
VA 2222222
VD 2222222
VS 83333
VP 0.0.5*varH
VE
REM SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM --------------- MOVE UP
PR 0,0,600000
BG Z
AM Z
REM --------------- WAIT
WT 52000
REM --------------- MOVE DOWN TO DEPOSITION HEIGHT
PR 0,0,varZ
BG Z
AM Z
REM --------------- END OF LINE
REM
REM --------------- DEPOSIT LAYER 5
REM --------------- TURN POWDER ON
REM PF 1 to 2.5 g/min
REM PF 3.36,0.00
UI 5
REM PF 3.36,0.00
REM --------------- MOVE UP
PR 0,0,600000
BG Z
AM Z
REM --------------- WAIT FOR POWDER FLOW TO STABILIZE
WT 11000
REM --------------- MOVE DOWN TO DEPOSITION HEIGHT
PR 0,0,-600000
BG Z
AM Z
REM --------------- +0
PA 0,0
BG XY
AM XY
VM XY
VA 2624671
VD 2624671
VS 78740
VP varL,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM --------------- +2
PA 0,varH*2
BG XY
AM XY
VM XY
VA 2624671
VD 2624671
VS 78740
VP varL,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM --------------- +4
PA 0,varH*4
BG XY
AM XY
VM XY
VA 2624671
REM -------------------- +6
PA 0, varH*6
BG XY
AM XY
VM XY
VA 2624671
VD 2624671
VS 78740
VP varL,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM ------------------ +8
PA 0, varH*8
BG XY
AM XY
VM XY
VA 2624671
VD 2624671
VS 78740
VP varL,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM ------------------ TURN PF OFF
REM PF 1 & 2 to 0 g/min
REM PF 0.00,0.00
UI 5
REM PF 0.00,0.00
REM ------------------ MOVE TO CENTER OF DEPOSIT
PA 0.5* varL,5* varH
BG XY
AM XY
VM XY
VA 2222222
VD 2222222
VS 83333
VP 0,0.5* varH
VE
REM SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM ------------------ MOVE UP
PR 0,0,600000
BG Z
AM Z
REM ------------------ WAIT
WT 36000
REM ------------------ SWITCH POWDER
REM PF 2 to 2.5 g/min
REM PF 0.00,3.47
UI 5
REM PF 0.00,3.47
REM ----------------- WAIT FOR POWDER FLOW TO STABILIZE
WT 16000
REM ----------------- MOVE DOWN TO DEPOSITION HEIGHT
PR 0.0,-600000
BG Z
AM Z
REM ----------------- +1
PA 0, varH*1
BG XY
AM XY
VM XY
VA 2624671
VD 2624671
VS 78740
VP varL,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM ----------------- +3
PA 0, varH*3
BG XY
AM XY
VM XY
VA 2624671
VD 2624671
VS 78740
VP varL,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM ----------------- +5
PA 0, varH*5
BG XY
AM XY
VM XY
VA 2624671
VD 2624671
VS 78740
VP varL,0
VE
SB 1
WT 20
BGS
AMS
CB 1
WT 20
REM ----------------- +7
PA 0, varH*7
BG XY
AM XY
VM XY
VA 2624671
VD 2624671
VS 78740
VP varL,0
VE
SB 1
WT 20