Understanding Ti-6Al-4V Microstructure Control in Additive Manufacturing via Process Maps

Joy Gockel and Jack Beuth

Department of Mechanical Engineering, Carnegie Mellon University, Pittsburgh, PA 15213

Abstract

In direct metal additive manufacturing, the ability to predict and control as-deposited microstructure can reduce the need for post-processing and speed up the qualification process. In this work, a microstructure process map is presented for deposition of single beads of Ti-6Al-4V using an electron beam wire feed process. Further, comparison with a previously developed process map for melt pool geometry control demonstrates that indirect control of Ti-6Al-4V solidification microstructure (prior beta grain size and morphology) is possible through direct, real time melt pool dimension control. These approaches for microstructure prediction and control can be extended to additional additive processes such as electron beam powder bed processes.

Introduction

Additive manufacturing (AM) is an attractive process for aerospace applications [1]. For small batch production, AM incurs minimal initial cost compared to traditional manufacturing processes such as casting. AM can also be used to decrease initial costs for large components with detailed features. Significant machining of large components requires additional time, and creates large amounts of material waste. By using AM, a simple forging can be manufactured with subsequent detailing done by adding material. Additive manufacturing can also be used for repair of cracks or worn components [2].

The ability to obtain a consistent and desirable microstructure is critical to the successful application of AM processes [3]. While AM offers the promise of increased efficiency and flexibility compared to conventional manufacturing [4,1], widespread commercialization of these processes requires the ability to predict and control process characteristics such as melt pool dimensions and solidification microstructure in terms of process variables [5]. Various forms of process maps have been developed for control of residual stress and melt pool dimensions through a wide range of processing variables [6,7,8,9,10]. However, the ability to correctly deposit a part is not sufficient if the mechanical properties of the completed part are not suitable for the desired application. The mechanical properties of the deposited material are dependent on the solidification microstructure (grain size and morphology), which is controlled by the thermal conditions at the onset of solidification [11].

Many different materials can be used in AM processes. Ti-6Al-4V is an attractive material for the aerospace industry because of its lightweight, high strength properties and excellent behavior at high temperatures [12]. Ti-6Al-4V is a two phase, alpha beta alloy. The cooling rate from the melting temperature (1893 K) determines the beta grain size and cooling rate and thermal gradient determine grain morphology. The alpha grain size can be determined by cooling rates at the beta transus temperature (1270 K) and below [13]. Many material properties are governed by the alpha grain size, but they can be modified by post process heat treatment. It has been suggested that the beta grain structure is the dominating factor for other mechanical properties, such as fatigue behavior and the beta grain structure typically remains unchanged through traditional heat treatments [13,14]. Therefore it is crucial to obtain suitable, as deposited beta grain size and morphology. In this work, solidification microstructure refers to the beta grain size and morphology.

Background

Many in the material science and manufacturing communities have explored the solidification microstructure produced by additive manufacturing. Brandl et al. characterized the as-deposited microstructure of blocks built using a laser wire feed process, comparing the results to a powder bed process [15]. Antonysamy et al. deposited walls of different thickness and determined that thicker walls have different patterns of grain growth possibly due to the cross hatching required to fill the walls [16]. Though significant insights have been gained through these types of characterizations, the lack of structure in approach limits results to specific cases.

Developing trends through post process characterization of material requires much iteration for insight into the control of microstructure. The microstructure must be determined in terms of process variables. Bontha et al. developed thermal process maps for predicting trends in solidification microstructure in terms of process variables [17,18,19]. Kobryn et al. investigated the role of process variables on microstructure and mechanical properties through experimentation and observation of solidification behavior [11,20]. Recently, Puebla et al. have concluded that increasing the melt scan speed decreased the alpha phase grain width [21]. In this case, even though the microstructure is being predicted in terms of process variables, the presentation of results is not concise, limiting their usability. Each process variable is investigated individually, which makes process control more difficult.

In this work, a patent-pending process mapping approach [22,23] applicable to the building of 3-D shapes across all direct metal AM processes is used to predict solidification microstructure in terms of two primary process variables (beam power and velocity). The process map for solidification microstructure is created for single bead deposits by an electron beam wire feed AM process (e.g. the EBF3 process developed at NASA Langley or the commercially developed Direct Manufacturing process by Sciaky). Solidification microstructure is predicted using the solidification map for Ti-6Al-4V and the cooling rates and thermal gradients from finite element material added models. The solidification data is used to plot curves of constant cooling rate and the grain morphology boundaries in power versus velocity space, creating a P-V process map for microstructure control. Solidification microstructure predictions are then related to a process map for controlling melt pool dimensions [6], exploring the ability for real time indirect microstructure control through melt pool dimension control.

Methods

Process Mapping:

Process mapping is an approach that maps process characteristics as a function of identified primary process variables. This approach allows for understanding of and expansion of processing space. Absorbed beam power and velocity have been identified as primary process variables. Absorbed power is a function of the type of process and includes an experimentally determined parameter that accounts for power losses between the source and the material. In this work, the process characteristic of interest is the microstructure (beta grain size and morphology).

Figure 1 shows the previously developed process map for melt pool dimension control. Curves of constant melt pool cross sectional area (a melt pool size metric) as well as curves of constant melt pool length to depth ratio (a melt pool shape metric) are plotted [6]. Melt pool cross sectional area is the largest area perpendicular to the travel velocity. The length is the distance between the maximum depth and end of the melt pool parallel to the direction of travel velocity. The depth is the effective depth, which is determined from the cross sectional area making the assumption that the area is a semi circle. The P-V process map for melt pool dimension control allows for decreased deposition time (high deposition rates) and for the deposition of detailed features (low deposition rates) while keeping melt pool size or shape constant.

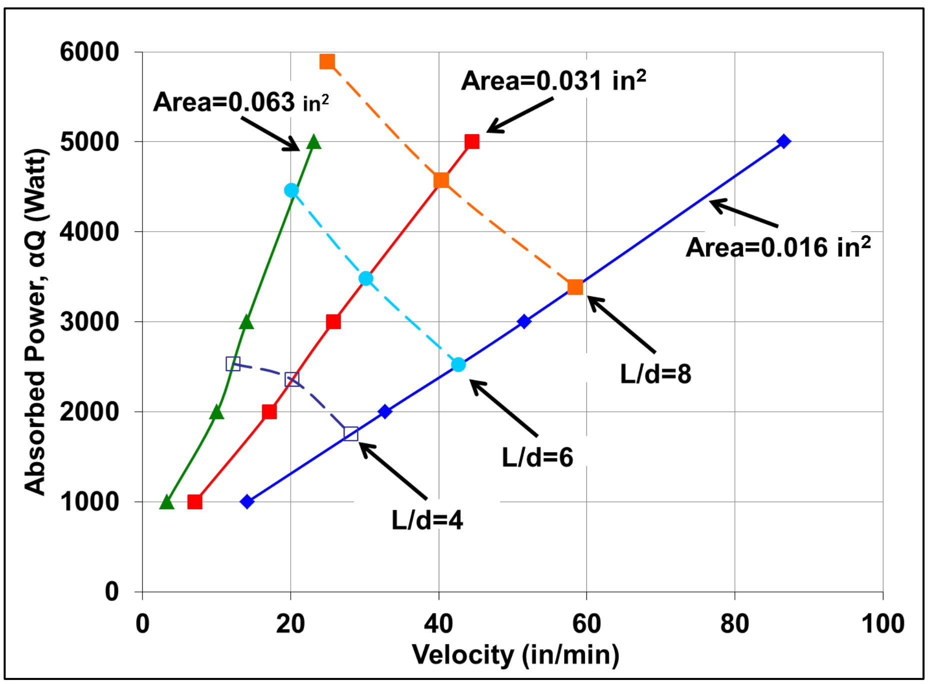


Figure 1: Process map for controlling melt pool dimensions

Solidification Map for Ti-6Al-4V:

Solidification maps are used to predict the solidification microstructure based on thermal conditions. The solidification map for Ti-6Al-4V is seen in Figure 2. The y-axis is the variable G, which is the magnitude of the thermal gradient vector. R is the solidification rate, which is on the x-axis. The solidification rate is defined as the cooling rate divided by G, $R = \frac{1}{G}\frac{\partial T}{\partial t}$. The regions defined on the solidification map correspond to the grain morphology: fully equiaxed, mixed or fully columnar. Columnar grains are elongated in one direction, while equiaxed grains are the roughly the same dimension in all directions. Grain morphology regions have been determined through experimental calibration by Kobryn et al. [11]. In this research, thermal conditions used to predict the solidification microstructure are obtained using material added finite element models. This follows methods for process mapping of microstructure developed by Klingbeil and co-authors [17,18,19].

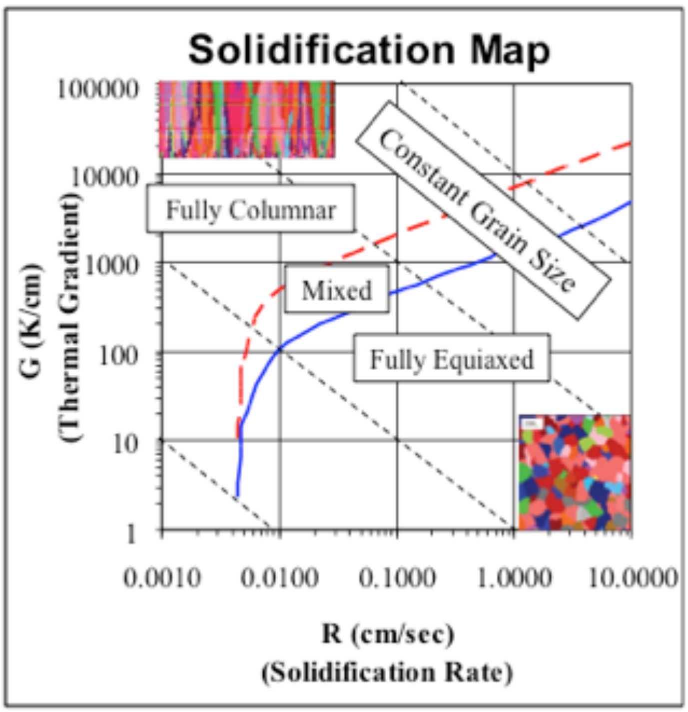


Figure 2: Solidification map for Ti-6Al-4V

Material Added Finite Element Models:

Finite element simulations in ABAQUS are used to model single bead deposition and the addition of material by the wire feeder. Material is added ahead of the heat source at each step as the simulation progresses as seen in Figure 3. Because the deposition takes place in a vacuum, the 3-D models do not include convective heat transfer on their vertical and top surfaces. The models have an initial temperature of 373 K and a constant temperature of 373 K specified at the base. Eight-noded, linear brick elements are used throughout the model. The model is biased to the top where the material is added, in order to reduce computation time as seen in Figure 4. A distributed heat flux is applied along the top of the added bead to simulate rapid beam oscillation across the melt pool, which reduces the concentration of heat on the surface. Temperature-dependent properties and latent heat are used. The thermal gradient and cooling rate are obtained as the temperature changes from the liquid to the solid range along the trailing edge of the melt pool as seen in Figure 5.

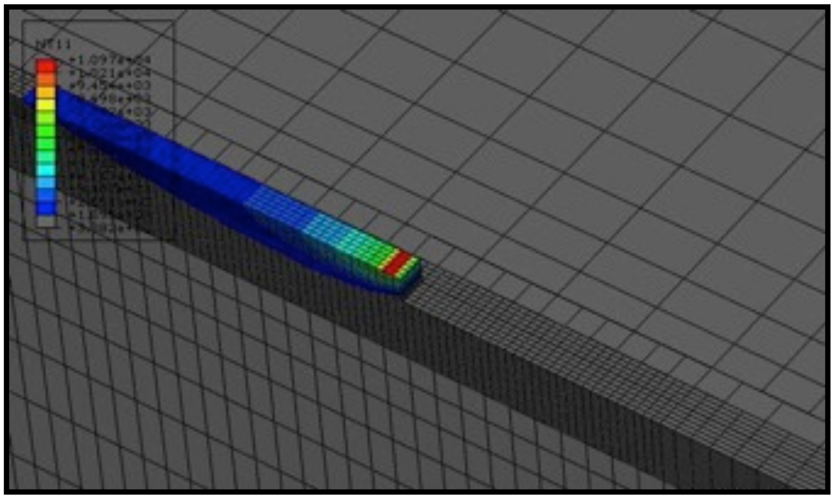


Figure 3: Material being added to the model

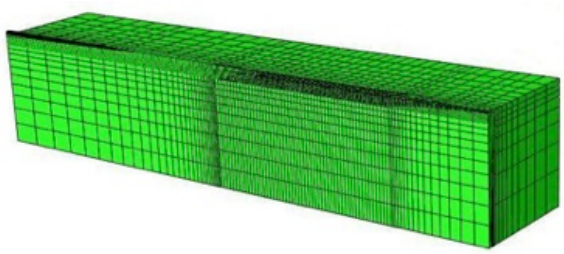


Figure 4: Finite element mesh

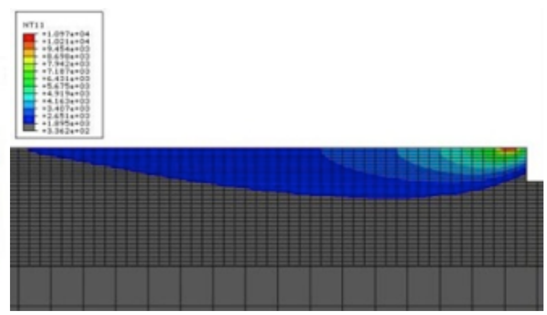


Figure 5: Melt pool contour

Results

P-V Process Map for Microstructure Control:

Solidification maps predict microstructure in terms of thermal gradient and solidification rate, but are difficult to use by process developers. Monitoring the cooling rates and thermal gradients in situ is difficult and can only be observed on the surface, so it is rarely done. Therefore, operators want to know solidification microstructure in terms of key input process variables, beam power and velocity. A P-V process map for solidification microstructure is created in order to identify paths or regions of processing space with constant grain size and different grain morphologies.

The grain size and morphology data from the G vs. R plot in Figure 1 is translated onto a plot of power versus velocity in Figure 6 using finite element material added simulations. The thermal gradients along the solidification front span a large range. The data presented here is for the top of the melt pool, where the lowest gradients are present and the morphology region transitions will first take place. The result is the P-V process map for controlling solidification microstructure for single bead deposits of Ti-6Al-4V in an electron beam wire fed process.

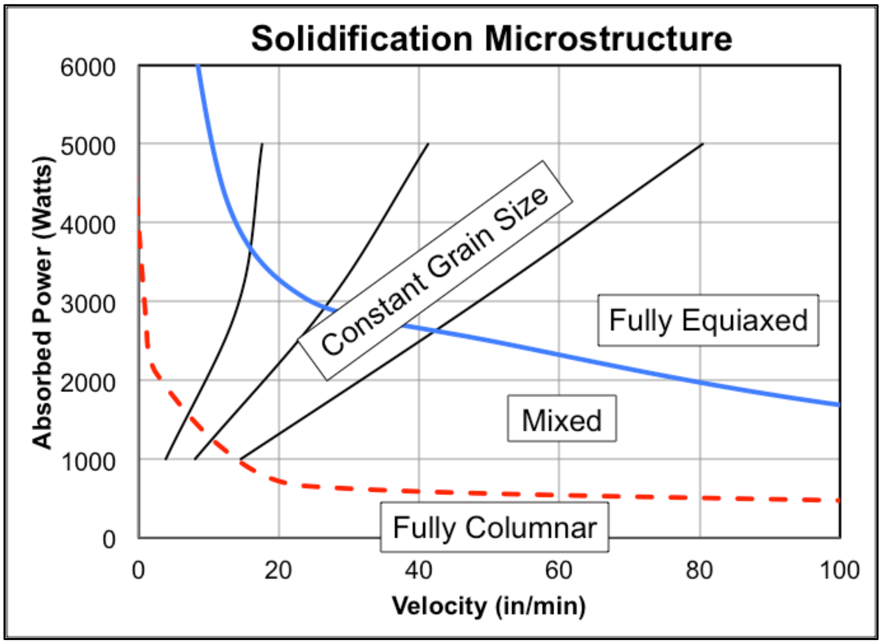
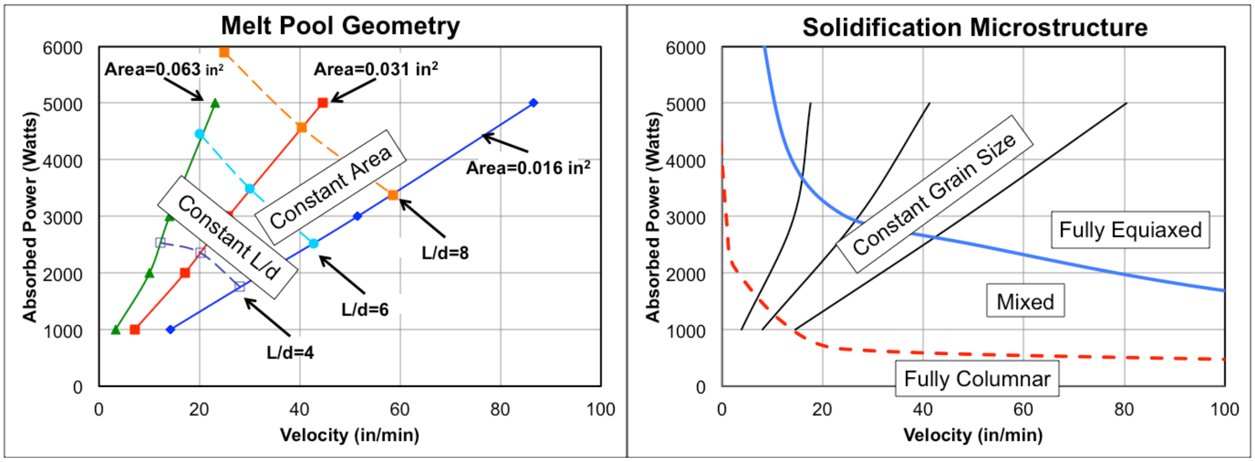


Figure 6: Microstructure process map for Ti-6Al-4V

The solid black lines in Fig. 6 are curves of constant cooling rate. It is shown that it is possible to maintain a constant grain size while moving from low powers and low velocities, to high powers and high velocities if the identified path is followed. The dashed line represents the boundary between fully columnar and mixed grain morphology. The boundary between mixed and fully equiaxed grain morphology is the curved solid line. These curves define the boundaries of three regions where columnar, mixed and equiaxed grain morphologies exist.

Integrated Control of Microstructure and Melt Pool Dimensions:

Currently, post processing and microscopy is required to observe the solidification microstructure. Using recent results [6], the solidification microstructure can be related to melt pool dimensions. When comparing the process map for solidification microstructure in Figure 6 to the process map for melt pool dimensions in Figure 1, connections can be drawn between the two process maps. As seen in Figure 7, the curves of constant grain size are similar to the curves of constant melt pool area. This result shows that by controlling melt pool area, a constant grain size is also maintained. The grain morphology region boundaries are similar to a line of constant length to depth ratio. The boundary represents the point where the morphology transition will first take place. As a result, an operator can observe how long and skinny a melt pool becomes, and can maintain fully columnar microstructures by not allowing the length to depth ratio to become too large.



a) Melt pool geometry process map b) Solidification microstructure process map

Figure 7: Integrated microstructure and melt pool dimension control

Melt pool size and shape cannot be independently controlled, with corresponding consequences for microstructure control. While keeping the melt pool area constant and increasing the deposition rate, the grain size will remain constant, but the length to depth ratio will become larger and more equiaxed grains will be present. The connections drawn from the comparison of the two process maps exposes the potential to control melt pool size and shape in real time, which results in the indirect control of solidification microstructure.

Conclusions

Part and process qualification has been identified as an important area of research for the AM field. This paper gives insight into regions of processing space that can produce desired solidification microstructure. A P-V process map has been created for single bead deposition of Ti-6Al-4V, which predicts solidification microstructure in terms of process variables. Curves of constant beta grain size and regions of grain morphology are identified in beam power versus velocity space.

Comparing the microstructure process map to the process map for controlling melt poll dimensions exposes relationships that can be used to indirectly control solidification microstructure through melt pool dimension control. Results have demonstrated that a constant melt pool area results in a constant grain size while moving through processing space. Similarly, monitoring the length to depth ratio can be used to control grain morphology. The added benefit of in-situ microstructure control is that it provides the ability to predict the microstructure based on the observed real time melt pool behavior.

Acknowledgements

The authors wish to acknowledge collaborations with Karen Taminger of NASA Langley for experiments related to this research. This research was supported by a National Defense Science and Engineering Graduate (NDSEG) Fellowship and by the National Science Foundation under grant CMMI-1131579.

References

[1] K M Taminger and R A Hafley, "Electron Beam Freeform Fabrication for Cost Effective Near-Net Shape Manufacturing," NATO/RTOAVT-139 Specialist' Meeting on Cost Effective Manufacture via Net Shape Processing, Amsterdam, Netherlands, 2006.

[2] R Grylls, "Laser Engineered Net Shapes," *Advanced Materials and Processes*, p. 45, 2003.

[3] F Arcella and F Froes, "Producing Titanium Aerospace Components from Powder Using Laser Forming," *JOM*, vol. 52, pp. 28-30, 2000.

[4] J W Sears, "Direct Laser Powder Deposition- "State of the Art," Knolls Atomic Power Laboratory, Schenectady, New York, Tech. Rep. 1999.

[5] J Beuth and N Klingbeil, "The Role of Process Variables in Laser-Based Direct Metal Solid Freeform Fabrication," *JOM*, pp. 36-39, September 2001.

[6] E Soylemez, J Beuth, and K Taminger, "Controlling Melt Pool Dimensions Over a Wide Range of Material Deposition Rates in Electron Beam Additive Manufacturing," in *Solid Freeform Fabrication Proceedings*, Austin, TX, 2010.

[7] A Vasinonta, J Beuth, and M Griffith, "A Process Map for Consistent Build Conditions in the Solid Freeform Fabrication of Thin-Walled Structures," *ASME Journal of Manufacturing Science and Engineering*, vol. 123, pp. 615-622, 2001.

[8] A Vasinonta, J Beuth, and M Griffith, "Process Map for Controlling Residual Stress and Melt Pool Size in Laser-Based SFF Processes," in *Solid Freeform Fabrication Proceedings*, Austin, TX, 2000, pp. 200-208.

[9] A Vasinonta, J Beuth, and M Griffith, "Process Maps for Laser Deposition of Thin-Walled Structures," in *Solid Freeform Fabrication Proceedings*, Austin, TX, 1999, pp. 383-391.

[10] A Vasinonta, J Beuth, and M Griffith, "Process maps for predicting residual stress and melt pool size in the laser-based fabrication of thin-walled structures," *Journal of Manufacturing Science and Engineering*, vol. 129, no. 1, pp. 101-109, 2007.

[11] P Kobryn and S Semiatin, "Microstructure and Texture Evolution During Solidification Processing of Ti-6Al-4V," *Journal of Materials Processing Technology* , vol. 13, pp. 330-339, 2003.

[12] D Eylon, J R Newman, and J K Thorne, *Metals Handbook*, 10th ed. Materials Park, OH: ASM Int, 1990, vol. 2.

[13] G Lutjering and J C Williams, *Titanium, Second Edition*.: Springer, 2007.

[14] M Donachie, *Titanium: A Technical Guide*.: ASM, 2007.

[15] E Brandl, A Schoberth, and C Leyens, "Morphology, microstructure, and hardness of titanium (Ti-6Al-4V) blocks deposited by wire-feed additive layer manufacturing (ALM),"

Materials Science and Engineering A, vol. 532, pp. 295-307, 2012.

[16] A Antonysamy, P Prangnell, and J Meyer, "Effect of Wall Thickeness Transitions on Texture and Grain Structure in Additive Layer Manufacture (ALM) of Ti-6Al-4V," *Materials Science Forum*, pp. 205-210, 2012.

[17] S Bontha and N Klingbeil, "Thermal Process Maps for Controlling Microstructure in Laser-Based Solid Freeform Fabrication," *Solid Freeform Fabrication Proceedings*, pp. 219-226, 2003.

[18] S Bontha, N Klingbeil, P Kobryn, and H L Fraser, "Effects of Process Variables and Size Scale on Solidification Microstructure in Beam-Based Fabrication of Bulky 3D Structures," *Materials Science and Engienering A*, vol. 513-514, pp. 311-318, 2009.

[19] S Bontha, N Klingbeil, P Kobryn, and H Fraser, "Thermal Process Maps for Predicting Solidification Microstructure in Laser Fabrication of Thin Wall Structures," *Journal of Materials Processing Technology*, vol. 178, pp. 135-142, 2006.

[20] P Kobryn, E Moore, and S Semiatin, "The Effect of Laser Power and Traverse Speed on Microstructure, Porosity and Build Heightin Laser Deposited Ti-6Al-4V," *Scripta Materialia*, vol. 43, pp. 299-305, 2000.

[21] K Puebla et al., "Effect of Melt Scan Rate on Microstructure and Macrostructure for Electron Beam Melting of Ti-6Al-4V," *Materials Science and Applications*, vol. 3, pp. 259-264, 2012.

[22] J Beuth, N Klingbeil, and J Gockel, "Process Mapping of Cooling Rates and Thermal Gradients," Provisional Patent 61/742,734, August 17, 2012.

[23] J Beuth, N Klingbeil, and J Gockel, "Process Mapping of Cooling Rates and Thermal Gradient," PCT/US2013/055422, August 16, 2013.