CHARACTERIZATION OF THIN WALLED Ti-6Al-4V COMPONENTS PRODUCED VIA ELECTRON BEAM MELTING

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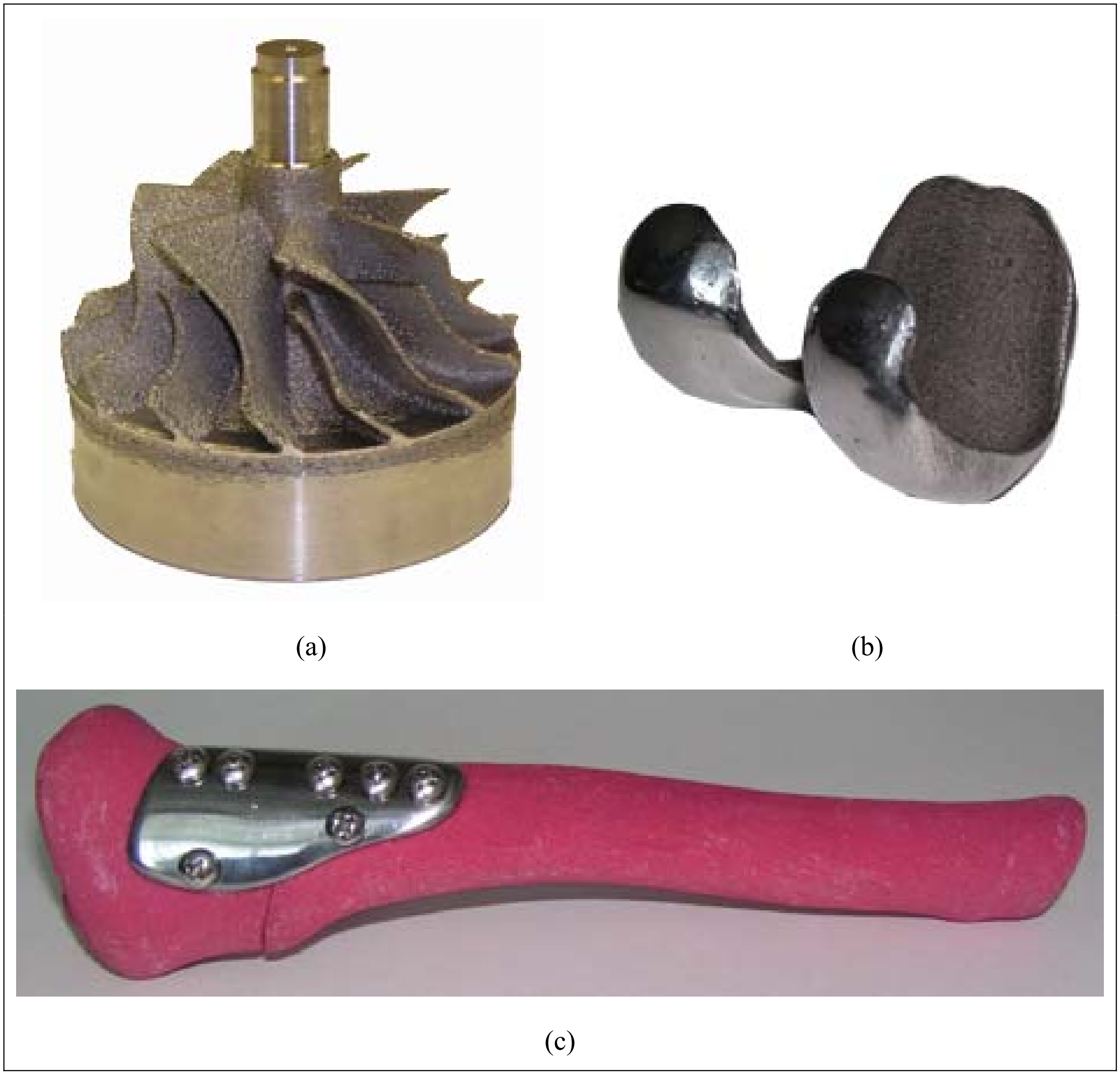
Abstract

Direct-metal energy beam SFF processes typically produce layers by scanning the contours and then filling in the area within the contour. Process parameters used to solidify contours are often different from those for fill areas. It is to be expected, therefore, that the contour and fill area regions will have different microstructures. This can have important ramifications for thin walled components such as biomedical implants whose slices have very little fill area. This paper characterizes the metallurgical differences in contour and fill areas in titanium components produced via Electron Beam Melting. The implications of these properties for thin walled components are described.

Introduction

Arcam's Electron Beam Melting (EBM) process (www.arcam.com) is a direct-metal freeform fabrication process that uses a 4.8 kW electron beam to selectively scan and melt layers of metal powder one on top of the next. Details of the process can be found in reference [1]. Titanium (Ti-6Al-4V) is an alloy that is receiving considerable interest for use with this process from industry. The EBM process was originally developed with the tool and die making industry in mind. Whereas the H13 tool steel components originally targeted with this process are typically large bulky parts, the titanium components built with the process tend to be thin walled in nature. For purposes of this paper, a thin walled part is a part with a thickness of approximately 14 mm. Representative thin-walled Ti-6Al-4V components built with this process include the turbocharger compressor wheel shown in Figure 1(a), the knee implant shown in Figure 1(b), and the bone plate shown in Figure 1(c). The vanes on the turbocharger wheel are approximately 1.2 mm thick, and the knee implant and bone plate each has an average thickness between 3-4 mm.

Most beam-based freeform fabrication processes melt or otherwise solidify a raw material by scanning the contour of a given slice and then scanning the fill area inside of the contours. In the case of direct-metal freeform fabrication processes, it is not uncommon for different process settings to be used when solidifying contours versus fill area. This is done primarily for reasons of improving surface finish and appearance. As the solidification rate of the metal powder can be influenced by differences in process settings (e.g. beam power and scan speed), it is possible for the contours and fill area to have substantially different microstructure and mechanical properties.


(a) (b)

(c)

Figure 1 – (a) Ti-6Al-4V Turbocharger Wheel; (b) Knee Implant; (c) Bone Plate

Figure 2 shows the slice data for a relatively bulky part on the left and a thin walled part on the right. A typical melting cycle for the layer illustrated in Figure 2(a) would start by melting the inner and outer contours. For purposes of improving surface finish, it is not uncommon to melt two contours, with the second contour being offset inward from the first contour by a user-specified amount. After the contour is melted, the area shown by dashed lines is melted. Although the system control software varies the beam current and scan speed to achieve the necessary heat input, the contours are often melted at approximately 100-200 mm/sec with a beam power of 300-600W. In contrast to the relatively low melting speed for contours, the fill region is typically melted with a scan speed in the 400-700 mm/sec range and a beam power in the 1,200-1,800W range. Although different melting speeds are used, the beam power is adjusted so that the overall power density during melting is approximately the same for both contours and fill area.

Figure 2(b) shows the slice data for a thin-walled part. Note that the entire melting cycle consists solely of melting a single contour since it is not possible to offset a second contour. Likewise, there is no fill area to be melted. Since contours are melted more slowly in order to improve the surface finish and appearance of the part, lower melting speeds could potentially result in lower solidification rates. On the other hand, the speed with which a part looses heat following processing is largely determined by conduction between the part and the surrounding powder bed. The higher surface area-to volume ratio of thin-walled parts versus bulky parts would logically imply that thin-walled parts cool down more quickly than bulky parts.

As Arcam's EBM process was originally targeted towards the fabrication of relatively bulky parts, there are no "build styles" specifically developed for the fabrication of thin-walled titanium parts whose slices consist primarily of contours. The aim of this paper, therefore, is to examine and characterize the metallurgical differences between thin-walled and bulky components built via the EBM process using Arcam's default settings.

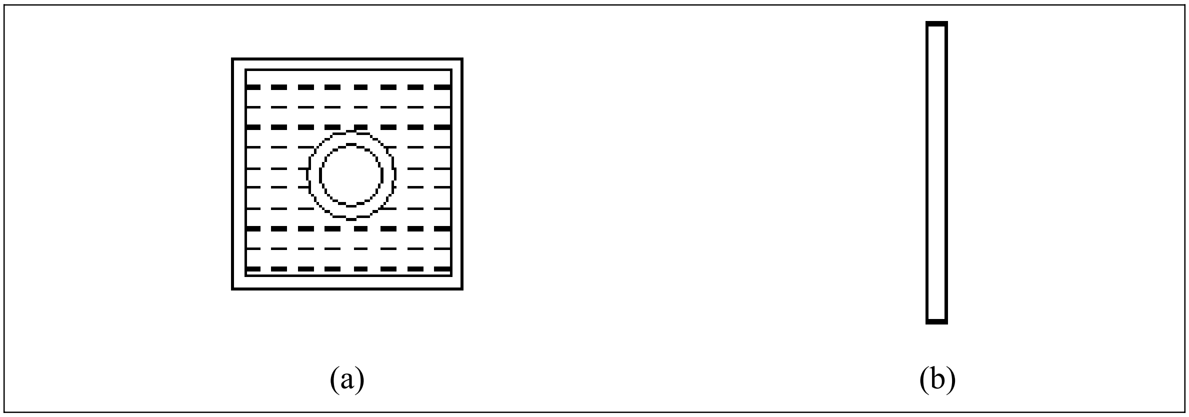


Figure 2 - Bulk Versus Thin-Walled Melt Geometry

Experimental Procedure

Two Ti-6Al-4V components were fabricated using an Arcam EBM machine – one "bulky" part and one "thin-walled" part as shown in Figure 3. For microstructural examination, each part was sectioned perpendicular to the build direction using a water-cooled silicon carbide cut-off saw. Each specimen was then mounted in a room-temperature curing resin. After grinding with successively finer grits of emery paper, the samples were polished using 6 µm diamond paste, 1 µm alumina, and 0.3 µm alumina. Prior to metallographic examination, the polished surfaces were etched with Kroll’s reagent.

Figure 3 - Bulky (L) and Thin Walled (R) Parts

Results and Discussion

When heated, titanium undergoes an allotropic phase transformation at 882°C, changing from close packed hexagonal α-Ti to body centered cubic β-Ti. Therefore, the as-cast microstructure of Ti-6Al-4V primarily consists of acicular α-Ti that has transformed from the grains of β-Ti that solidified initially. In addition, α-Ti is also present at the prior grain boundaries of the β-Ti [2]. This same microstructure is observed in the parts produced via the EBM process, as shown in Figures 4 and 5. Of particular significance from these micrographs is the fact that the α-Ti needles produced in the thin wall specimen are approximately one third the size of those produced in the bulk part. Microhardness measurements taken on both samples were within the range of HV 285-300 (HRC 28-30).

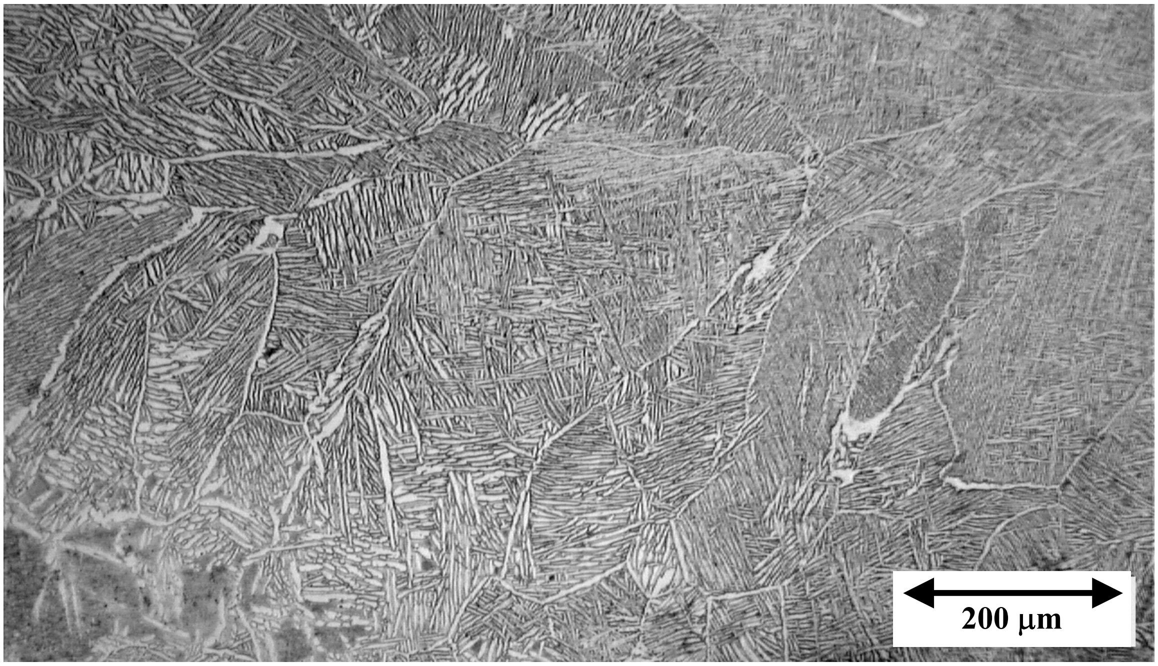


Figure 4 - Thin-Walled Microstructure at 100X Magnification

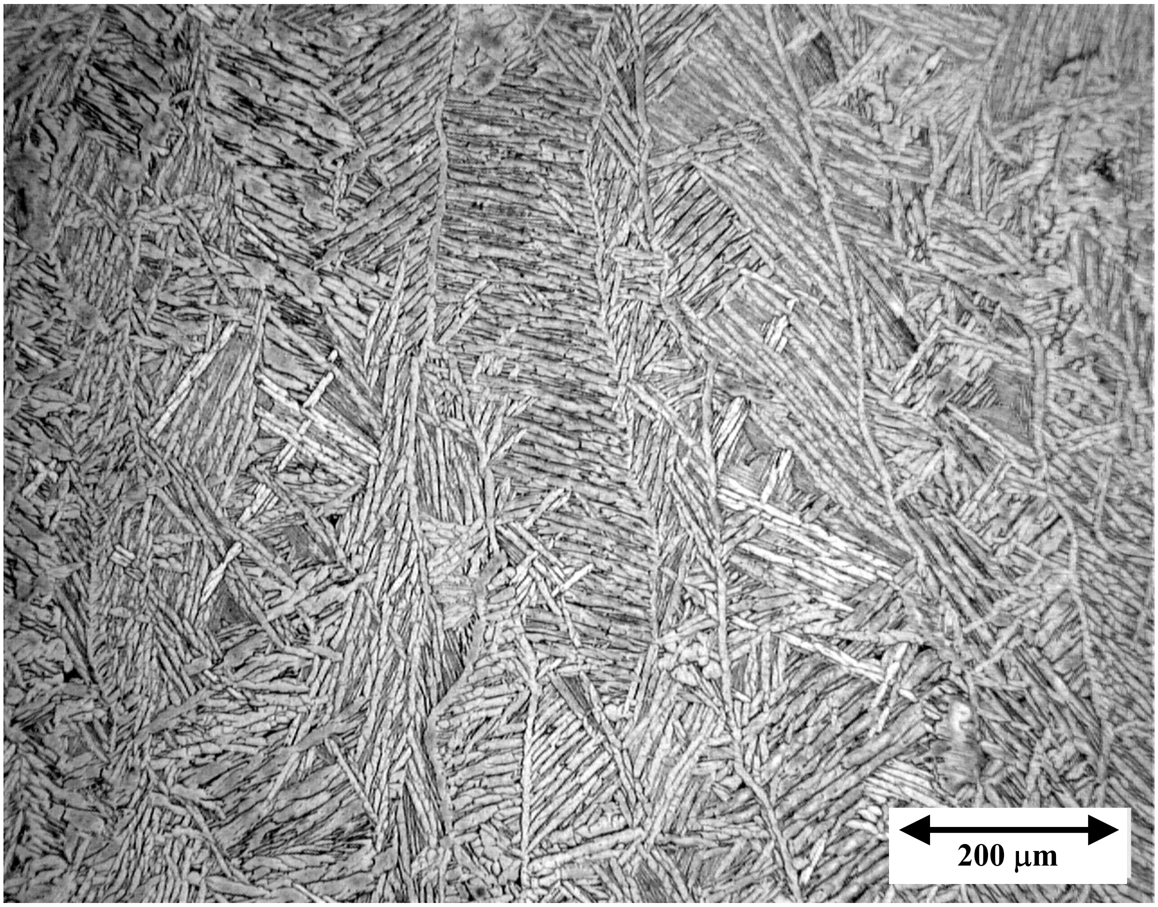


Figure 5 - Bulk Part Microstructure at 100X Magnification

Examination of the prior β-Ti grain boundaries revealed that epitaxial growth occurred between layers. In Figures 4-6, the build direction is from the bottom to the top of the micrograph. Given that each build layer is nominally 150 μm thick, each micrograph spans multiple horizontal layers, with Figure 6 displaying 10-11 horizontal layers. Note that there is no observable delineation between successive layers in either the bulk or thin-walled parts and that the prior β-Ti grain boundaries are continuous through the layers. The growth of β-Ti grains is particularly evident in Figure 6. This implies that the part temperature is maintained above the β transus, and that solidification of the melted powder occurs by growth of β-Ti directly onto the "seed" grains of the previous layer. Control and characterization of this mode of solidification will be the subject of further investigations.

During processing, the EBM process control algorithm is designed to keep the part being fabricated at an elevated temperature in order to reduce thermal stresses. While thermal imaging techniques may be used to measure surface temperatures at the top of a part during the build [3], it is quite difficult to measure temperature within the body of a part during a build due to the nature of the process. However, each part with this process is built up from a steel base plate, and a thermocouple is attached to the underside of the base plate. A base plate temperature of 850°C was maintained during the builds that produced all parts shown in this paper. There is obviously an increasing temperature gradient from the underside of the start plate to the very top surface of the part that extends above the melting temperature of the alloy. With a start plate temperature of 850°C, the bulk of the part is above the β transus for the duration of the build. The α-Ti needles therefore do not form until the entire part is cooled below the β transus following the completion of electron beam melting. The process parameters (e.g. beam current and scan speed) had relatively little influence on the size of the α-Ti needles. Instead, the cooling rate and resulting microstructure was largely dominated by the part geometry in these cases. In a vacuum environment, heat loss through conduction with the surrounding powder bed is the primary cooling mechanism, and thin walled parts will cool down more rapidly than bulky parts for a given input power density. The thin walled part represented in Figure 4 was melted at a much slower speed than the bulky part shown in Figure 5, yet it has a much more refined microstructure. Within the range of values recommended by the process control algorithm, it was clear that part geometry had more to do with microstructure than processing parameters.

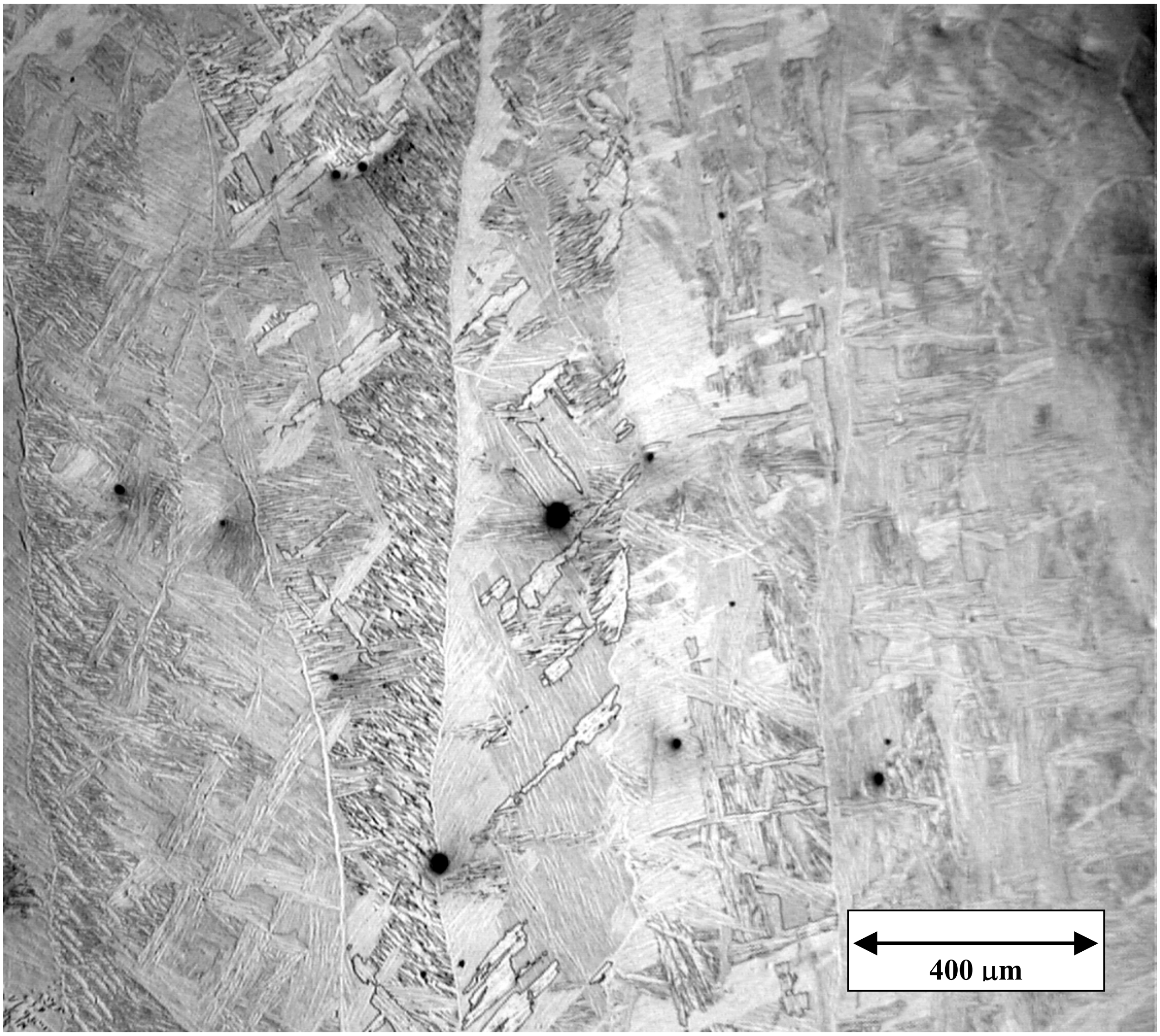


Figure 6 - Micrograph of Bulk Part at 50X Magnification

Conclusions and Future Directions

Each layer that is melted in the EBM process involves both contours and fill area. Contours are melted at roughly 25% of the speed of fill area in order to improve surface finish. Because each layer of a thin wall part consists primarily of contours rather than fill area, thin walled parts are built primarily using the slower scan speeds associated with contours. Conversely, bulky parts whose layers are primarily fill area are built using much higher scanning speeds. For the thin wall components such as those shown in Figure 1, all surfaces will be subject to light finish machining. Any improvement in surface finish resulting from slower scan speeds of the contours is largely for cosmetic purposes and will not affect the final form of the part following finish machining. It is therefore worth investigating whether or not a special build style can be used to optimize the microstructure and properties of thin wall parts.

Using the generic recommended processing parameters, experiments determined that the refined microstructure of the thin wall part was due primarily to the effect of geometry on cooling rate. While there was no significant difference in microhardness, the finer microstructure of the thin wall part is preferred in fatigue applications where fracture toughness is important [4] [5]. The turbocharger and bone implant applications shown in Figure 1 certainly fall into this category.

The growth of columnar grains demonstrated in these experiments could give rise to EBM parts with tailored anisotropic microstructures. Titanium Aluminide (TiAl) is an alloy of particular interest as a lighter weight substitution for nickel-based superalloys in elevated temperature applications. If the same columnar growth behavior can be induced with TiAl, then the result would be similar to directional solidification. In that case, components could be oriented within the build chamber to maximize benefits of the columnar grain structure.

The presence of columnar grain growth spanning multiple layers suggests that the temperature of the parts were held above the β transus throughout the build. During processing, the control algorithm uses the electron beam to deliver extra heat to both the part and the surrounding powder bed in order to reduce thermal stresses. It is not strictly necessary to maintain the elevated temperature above the β transus. Future experiments will therefore investigate the effects of maintaining a body temperature that is below the β transus to see if a more rapid transition from β-Ti to α-Ti will take place during processing. Since the size of the β-Ti grains impose an upper limit on the size of the α-Ti needles, it is conceivable that increasing the scanning speed and beam current to those levels currently used for fill melting will produce a even finer α-Ti grain structure. For components such as those shown in Figure 1 that undergo cyclic stresses, this further refinement of microstructure could prove to be quite beneficial in terms of fatigue performance. It is recognized that by lowering the target body temperature, the potential for increased residual stresses and warping exists. The tradeoffs between microstructural refinement and residual stresses will be considered as part of the studies.

References

[1] Cormier, D., Harrysson, O., and West, H. (2004) "Characterization of H13 steel produced via electron beam melting" Rapid Prototyping Journal, V10N1, pp. 35-41.

[2] Metals Handbook 9th Edition, Volume 9: Metallography and Microstructures, American Society for Metals, 1985.

[3] Hofmeister, W., Wert, M., Smugeresky, J., Philliber, J., Griffith, M., and Ensz, M. (1999) "Investigating Solidification with the Laser-Engineering Net Shaping (LENS) Process," JOM, Vol. 51, No. 7, available from JOM-e online at:
http://www.tms.org/pubs/journals/JOM/9907/Hofmeister/Hofmeister-9907.html.

[4] Broek, D. (1983) Elementary Engineering Fracture Mechanics, Martinus Jijhoff Publishers, The Hague.

[5] Smith, M. (1956) Principles of Physical Metallurgy, Harper & Brothers Publishers, NY.