Effects of internal porosity and crystallographic texture on Charpy absorbed energy of Electron Beam Melting titanium alloy (Ti-6Al-4V)*

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ABSTRACT

The effects of internal porosity and crystallographic texture on miniaturized Charpy absorbed energy behavior of electron beam melting (EBM) titanium alloy (Ti-6Al-4V) are shown through investigation of material in two heat treatment conditions (As-Built and Hot Isostatically Pressed (HIPed)) and two specimen orientations (Vertical and Horizontal). Internal porosity was assessed by use of x-ray micro-computed tomography (CT) and fractography. Electron backscatter diffraction (EBSD) was used to characterize crystallographic texture. Charpy absorbed energy was measured over a range of temperatures (-196 °C to 600 °C). Results suggested internal porosity has a deleterious effect on Charpy absorbed energy. Internal porosity was observed in the As-Built condition (99.8 % dense) but not in the HIPed condition, and the HIPed material had a higher Charpy absorbed energy. An observed increase in α lath thickness due to HIPing also contributed to this trend in Charpy absorbed energy. Crystallographic texture and anisotropic grain morphology (*i.e.*, prior- β grains elongated in the build direction) influenced the measured Charpy absorbed energy. It was observed that for similar texture, crack pathways that crossed more prior- β grain boundaries resulted in higher Charpy absorbed energy. However, differing textures were found to negate the prior- β grain boundary strengthening effect, emphasizing the influence of texture and variations in texture on Charpy absorbed energy. Mixed textures were measured for all heat treatment conditions and specimen orientations, ranging from predominantly $\langle 001 \rangle_{\beta}$ to predominantly $\langle 110 \rangle_{\beta}$ (both in the build direction), but none matched the most commonly reported texture for this material (*i.e.*, exclusive $(001)_{\beta}$ -fiber in the build direction). Hypothesized processing parameters leading to these textures are discussed.

KEYWORDS Additive Manufacturing; Electron backscatter diffraction (EBSD); Crystallographic texture; Charpy impact test; Porosity; Titanium

1 INTRODUCTION

The sale of additive manufacturing (AM) products and related services is projected to exceed US\$6.5 billion worldwide by 2019 [1]. Despite this success, there are very few instances of metal AM products being used in fatigue and fracture critical applications [2]. To enable use of metal AM products in these types of applications, findings from a recent workshop [3, 4] identified the need for deeper understanding of fatigue and fracture behavior of these materials through detailed investigations of processing-structure-property-performance relationships. The limited number of previous investigations on metal AM fatigue and fracture behavior have been reviewed recently [5-10].

The current work has determined the effect of internal porosity and crystallographic texture on the Charpy absorbed energy properties of a titanium alloy (Ti-6Al-4V) fabricated by electron

beam melting (EBM), which is in the powder bed fusion (PBF) class of AM techniques [11]. The effect of internal porosity was determined by investigating material in two heat treatment conditions (*i.e.*, As-Built and after Hot Isostatic Pressing (HIP) heat treatment). The as-built condition was expected to have internal porosity, and the high temperature and high pressure of the HIP heat treatment was expected to reduce internal porosity, based on previous results [12, 13]. The effect of crystallographic texture was determined by testing miniaturized Charpy specimens built in different orientations with respect to the build direction: Vertical and Horizontal. These different specimen orientations have fracture planes with differing orientations compared to the microstructural anisotropy expected for this material.

EBM Ti-6Al-4V is known to be a two-phase material with acicular α laths in a matrix of β . Prior- β grains, which are remnants of a high-temperature single-phase region and much larger than the α laths, are most often elongated in the build direction [12, 13]. β texture in AM Ti-6Al-4V is dictated by the strongest thermal gradient, and a strong $\langle 001 \rangle_{\beta}$ -fiber texture in the build direction is almost universally reported in the literature for electron beam-based [14-17] and laser beam-based [18-20] AM Ti-6Al-4V of both PBF and directed energy deposition (DED) classes. α texture is dictated by β texture according to the well-known Burgers orientation relationship (BOR) [21]: $(0001)_{\alpha} || \{110\}_{\beta}$ and $\langle 11\overline{2}0 \rangle_{\alpha} || \langle 111 \rangle_{\beta}$

However, Chaput, *et al.* [22] have recently reported the achievement of a predominantly $\langle 110 \rangle_{\beta}$ texture for EBM Ti-6Al-4V leading to a 10 % increase in yield strength over the more commonly reported $\langle 001 \rangle_{\beta}$ -fiber texture. These different textures were hypothesized to occur due to differences in energy density arising from different melt parameters and arrangement of parts on the build plate. A lower energy density resulted in the predominantly $\langle 110 \rangle_{\beta}$ texture, and a higher energy density resulted in the $\langle 001 \rangle_{\beta}$ -fiber texture. This previous observation is pertinent to the current work and will be discussed in greater detail later in this paper. This previous work also demonstrates that texture cannot be assumed for this material, and differences in texture can have significant effects on mechanical properties.

There has been one previous study measuring Charpy absorbed energy of EBM Ti-6Al-4V [23], but the investigation focused on chemistry effects. The major finding was an inverse relationship between oxygen content and absorbed energy. They did endeavor to determine the effects of internal pores and texture, but they did not measure either quantity directly. They also performed Charpy testing at room temperature only. The current work conducted Charpy testing over a range of temperatures and directly measured pore characteristics (number, size, location) using x-ray micro-computed tomography (CT) and texture via electron backscatter diffraction (EBSD). This allowed more conclusive determination of the effects of these microstructural features on Charpy absorbed energy.

It is important to note that bulk chemistry was also measured in the current work to determine if it was an uncontrolled variable. Residual stress can also have significant effects on AM metals in general, but we can be reasonably certain that it was not an unintended variable in this work as previous neutron scattering and high-cycle fatigue measurements of EBM Ti-6AL-4V [24] have shown negligible residual stress in both the as-built and HIPed conditions. This was assumed to result from the layer preheating in EBM leading to high enough background temperatures to relieve any residual stresses during the build.

2 EXPERIMENTAL

Ti-6Al-4V (wt %) material was fabricated using an Arcam¹ A1 EBM machine. The standard Arcam A1 build theme for Ti-6Al-4V (accelerating voltage 60 kV, layer thickness 50 µm, speed

factor 35, software version 3.2.132) and the standard Arcam Ti-6Al-4V gas atomized powder (particle size range approximately 40-100 μ m, average approximately 70 μ m) were used. Figure 1 (a, c) shows the build layout highlighting horizontal (blue) and vertical (green) Charpy build volumes. Charpy build volumes were built 5 mm above the build plate and connected to the build plate using standard thin wafer supports (Figure 1d, e). It is important to note that Chaput, *et al.* [22] did not use supports and instead built parts directly attached to the build plate. The implications of this will be discussed later in this paper.

Figure 1b shows all build volumes, not just the ones used for the current work. The purpose of this is to enable quantification of a manufacturer-specific parameter called "scan length", which determines energy density and is hypothesized to affect texture [22]. Scan length is the distance the electron beam travels on a single track before turning around to begin the next track. Arcam uses control algorithms in their melt scan strategies that purposely vary electron beam scan speed and electron beam current to reduce porosity formation and achieve microstructurally consistent material. The scan length control algorithm increases scan speed and beam current as scan length increases. Scan length can be longer than the dimensions of a single build volume because Arcam allows users to group multiple build volumes into the same "melt model". All the build volumes in a melt model are melted together, and the scan length is the linear distance across all build volumes in that melt model. Also, the electron beam scan direction rotates 90 degrees after each layer, so there are two scan lengths that must be considered (*i.e.*, X and Y). Chaput, et al. [22] observed two scan lengths: approximately 90 mm (lower energy density, $(110)_{\beta}$ texture) and approximately 20 mm (higher energy density, $(001)_{\beta}$ -fiber texture). Figure 1b is color coded to show the melt models (*i.e.*, groupings of build volumes) used in the current study. Scan lengths ranged from 18 mm to 58 mm and were not consistent across types of specimens (Horizontal, Vertical) or directions (X, Y). Additionally, scan length variation often occurred within one build volume.



Figure 1. Build layout schematics showing a) top view highlighting horizontal (blue) and vertical (green) Charpy build volumes, b) top view with part groupings (i.e., "melt models") identified by color for purposes of measuring scan length, c) iso view highlighting horizontal (blue) and vertical (green) Charpy build volumes, d) iso and e) bottom view of single horizontal Charpy specimen showing support structure used (pink). The Z-direction is the build direction. Layers are deposited in the X-Y plane.

Of the 20 build volumes for each specimen orientation (Horizontal, Vertical), half were randomly assigned for HIPing, and the other half remained As-Built, leading to four testing conditions (As-Built/Horizontal, As-Built/Vertical, HIPed/Horizontal, and HIPed/Vertical). The standard Ti-6Al-4V HIP cycle was used (2 hours at 900 °C and 100 MPa in argon, with 12 °C/min heating and cooling rates). Charpy build volumes were created to have 4 mm extra material in each dimension.

After AM building and HIPing, build volumes were machined to the final dimensions (Figure 2a), corresponding to the reduced half-size (RHS) miniaturized Charpy specimen type included in ASTM E2248 [25]. Figure 2b shows the notch orientation of horizontal and vertical Charpy specimens with respect to the previously defined AM coordinate system (Figure 1). Charpy tests were performed on a small-scale Charpy machine equipped with an instrumented striker. The machine has a capacity (potential energy) of 50.8 J and an impact velocity of 3.5 m/s. In accordance with ASTM E2248 [25], the radius of the striking edge is 3.86 mm (nominal 4-mm striker). Charpy tests were performed at temperatures ranging from -196 °C to 600 °C. One specimen for a given testing condition was tested per temperature. Temperature was measured using thermocouples for tests below room temperature and a noncontact infrared temperature sensor for tests above room temperature. The estimated test temperature precision was ± 3 °C. Absorbed energy (KV) was normalized by the factor Bd^2 , where B is specimen thickness and d is the ligament size, *i.e.*, $KV_{norm} = KV/Bd^2$ [26-28] to facilitate comparison of these miniature (i.e., RHS) Charpy results to other literature values that may use different specimen sizes. Values of normalized absorbed energy (KV_{norm}) were plotted and fitted as a function of test temperature by means of the commonly used hyperbolic tangent model [29]. Lateral expansion and instrumented Charpy curves were also analyzed [30, 31] but are omitted from this paper as they did not provide any additional enlightenment of microstructural mechanisms.



Figure 2. Schematics of Charpy RHS specimens showing a) final machined dimensions and b) orientation of notches for horizontal and vertical specimens with respect to the previously defined AM coordinate system

Wrought Ti-6Al-4V (mill-annealed condition) was also Charpy tested to provide a non-AM comparison for Charpy properties. The mill-annealed Ti-6Al-4V microstructure is different than that of EBM Ti-6Al-4V, and this should be considered when comparing Charpy absorbed energies.

Chemistry was measured for wrought Ti-6Al-4V, As-Built EBM Ti-6Al-4V, and HIPed EBM Ti-6Al-4V. These chemistry results were compared to ASTM F2924 (Standard Specification for Additive Manufacturing Titanium-6 Aluminum-4 Vanadium with Powder Bed Fusion [11]). Aluminum, vanadium, and iron were measured by optical emission spectroscopy (OES). Oxygen, nitrogen, and hydrogen were measured by inert gas fusion. Carbon was measured by the combustion method. Approximate relative uncertainties for each measurement were as follows: oxygen (3 %), nitrogen (14 %), hydrogen (6 %), and carbon (6 %). Uncertainties for aluminum, vanadium, and iron were not available.

Internal porosity was non-destructively evaluated for As-Built and HIPed material using a laboratory x-ray micro-computed tomography (CT) instrument (Zeiss Xradia¹ 500). A 1.0 μ m voxel size (edge length) was achieved, and Image J [32] was used for segmentation and analysis. Equivalent spherical pore diameter was calculated for each pore, and pores with less than three voxels (3 μ m) diameter were not considered.

Texture was measured using electron backscatter diffraction (EBSD) on a scanning electron microscope (SEM) operated at 20 keV. Samples were mounted and polished with diamond slurry to 1 μ m and then vibratory polished with 0.05 μ m colloidal silica for up to 8 hours. Both β and α texture were measured directly at 30 nm step size for 13 fields of view per testing condition. It is important to note that in all other cases in the literature [14-20], α texture was measured directly, but β texture was calculated from α texture using the BOR [21]. All β and α texture measurements were made near the notch on X-Y plane cross-sections of Charpy specimens. Larger area texture maps were measured at 500 nm step size to qualitatively investigate texture variation, and both X-Y and X-Z planes were measured.

 α lath thickness was measured using SEM in backscatter mode to achieve atomic number contrast between β and α . Samples were prepared similarly to those for EBSD, and α lath thickness was measured as a function of distance from the build plate (Z-direction), as that is the direction of expected anisotropy [12, 13, 24]. For each data point, the thickness of 20 α laths were randomly chosen and measured in each of three fields of view. SEM was also used to perform fractography on all fractured Charpy specimens.

3 RESULTS

Chemistry results are shown in Table I, showing no appreciable difference between As-Built and HIPed conditions. This eliminates chemistry as an unintended variable in the comparison of these two conditions. Wrought material does have different chemistry compared to As-Built and HIPed material. The difference in oxygen content, where Wrought is higher (0.18 wt %) compared to As-Built and HIPed (0.14 wt %), requires specific mention as previous work has shown similarly small changes in oxygen content to have significant deleterious effect on Charpy absorbed energy [23].

Table I. Chemistry for As-Built EBM Ti-6Al-4V, HIPed EBM Ti-6Al-4V, Wrought (mill annealed) Ti-6Al-4V, and comparison to ASTM F2924 Standard Specification for Additive Manufacturing Titanium-6 Aluminum-4 Vanadium with Powder Bed Fusion [11]. All values are listed in wt %. Uncertainties are given where available.

	Ν	С	Η	Fe	0	Al	V
ASTM F2924	0.05 max	0.10 max	0.015 max	0.30 max	0.20 max	5.5-6.75	3.5-4.5
As-Built	0.020 ± 0.002	0.010 ± 0.001	0.0010 ± 0.0001	0.16	0.140 ± 0.004	5.89	4.4
HIPed	0.020 ± 0.002	0.010 ± 0.001	0.0010 ± 0.0001	0.17	0.140 ± 0.004	5.82	4.3
Wrought	0.010 ± 0.001	0.020 ± 0.001	0.0030 ± 0.0002	0.25	0.180 ± 0.005	6.58	4.3

X-ray CT results are shown visually in Figure 3 and the size distribution of pores is shown in Figure 4 for the As-Built condition. No pores were observed (1 μ m voxel size) in the HIPed condition. The pore size distribution for the As-Built condition (Figure 4) agrees well with previous work on the same material [33]. However, the same previous work found pores up to 10 μ m diameter in HIPed material. Despite the gross appearance of the porosity in Figure 3, the relative density was calculated as 99.8 % dense. All observed porosity was approximately spherical, indicating it is of the gas porosity, and not the lack of fusion, variety [12, 13, 24]. Multiple formation mechanisms have been investigated for gas porosity, including keyhole collapse [34] and entrainment of porosity from hollow powder [35].



Figure 3. Visual representation of internal porosity (red) observed in As-Built conditions using x-ray CT (1 μ m voxel size). Spherical gas porosity is observed, but no lack of fusion porosity is observed. Relative density of this material is 99.8 % dense.



Figure 4. Size distribution of internal pores observed in As-Built conditions using x-ray CT (1 μm voxel size).

Representative fracture surfaces for all conditions are shown in Figure 5, and there are two main features of interest: internal pores and ridges. Internal porosity (Figure 5f) was observed on all As-Built fracture surfaces but not on HIPed fracture surfaces. Ridges (Figure 5e) were observed on all Horizontal fracture surfaces but not on Vertical fracture surfaces. These ridges ran perpendicular to the layers (X-Y plane) and parallel to the build direction (Z). They were elongated in the build direction and had approximate dimensions of a couple hundred μm in width and a couple mm in length.



Figure 5. SEM images of fracture surfaces for the four testing conditions investigated: a) As-Built/Horizontal, b) As-Built/Vertical, c) HIPed/Horizontal, and d) HIPed/Vertical. Internal pores (black arrows and f) were observed for all As-Built samples but none for HIPed samples. Ridges (white arrows and e) were observed for all Horizontal samples but not on Vertical samples.

 α lath thicknesses as a function of distance from bottom of build volume are shown in Figure 6. Significant coarsening was observed due to HIPing, but within each condition, α lath thicknesses did not change appreciably as a function of distance from the bottom of the build volume.



Figure 6. α lath thickness measurements as a function of distance from the bottom of the build volume. 2 mm was added to each surface of the build volume. Therefore, measurements at 2.5 mm are approximately 0.5 mm from the bottom of the machine specimen. Measurements at 12 mm are indicative of α lath thickness at the Vertical specimen fracture plane. The fracture plane of Horizontal specimens ranges from 2 mm to 7 mm.

Figure 7 shows representative examples of the direct measurements of β phase content, and α lath coarsening due to HIPing is observed, as quantified in Figure 6. From measurements of β texture orientation for the four conditions (Table II), it is clear that this material does not have the exclusive $\langle 001 \rangle_{\beta}$ -fiber texture most commonly reported for this material [14-20]. For all testing conditions there was a mix of orientations, and for three of the four testing conditions, a predominantly $\langle 110 \rangle_{\beta}$ texture is observed, which is similar to the longer scan length and lower energy density condition from Chaput, et al. [22]. The As-Built/Vertical testing condition had a majority of $\langle 001 \rangle_{\beta}$ orientation, but it was far from an exclusive $\langle 001 \rangle_{\beta}$ -fiber texture. The Burgers relationship was found to hold for α orientations with respect to β (Figure 8). It should be noted that while the Burgers relationship indicates $\langle 11\overline{2}0 \rangle_{\alpha}$ is parallel to $\langle 111 \rangle_{\beta}$, $\langle 001 \rangle_{\beta}$ is within a few degrees of $\langle 11\overline{2}0 \rangle_{\alpha}$ and may be considered an alternate orientation relationship,

though it does not fit exactly within the Burgers relationship. Larger area texture maps were compared for two different planes (X-Y and X-Z) each for two testing conditions (HIPed/Horizontal and HIPed/Vertical) in Figure 9. No appreciable differences were observed between the two testing conditions, but considerable differences were observed between the two planes (X-Y and X-Z) due to the anisotropic morphology of the prior- β grains (*i.e.*, elongated in the build direction (Z-direction)).



Figure 7. EBSD images showing representative direct β texture measurements (bright green) using 30 nm step size for a) As-Built and b) HIPed conditions.

Table II. Distribution of prior- β grain orientations for all four testing conditions. 13 prior- β grains were measured for each testing condition.

Testing Condition	Distribution of prior-β Grain Orientations (%)					
	<001>	<110>	<111>			
As-Built/Horizontal	15	69	16			
As-Built/Vertical	54	31	15			
HIPed/Horizontal	8	69	23			
HIPed/Vertical	8	84	8			



Figure 8. Representative examples of indexing of β and α texture. It is clear that α texture is determined by β texture according to the Burgers relationship. The most appropriate indexing of both $\langle 001 \rangle_{\beta}$ and $\langle 111 \rangle_{\beta}$ is $\langle 11\overline{2}0 \rangle_{\alpha}$.



Figure 9. EBSD larger area α texture maps for a) HIPed/Horizontal X-Y plane, b) HIPed/Vertical X-Y plane, c) HIPed/Horizontal X-Z plane, and d) HIPed/Vertical X-Z plane. Elongated prior- β grains in the z-direction are clearly visible, but there are no discernable differences between the larger area texture variation between HIPed/Horizontal (a, c) and HIPed/Vertical (b, d) conditions.

Charpy results (Figure 10) suggest that HIPed conditions have higher absorbed energy than As-Built conditions. For the HIPed condition, the Vertical orientation appear to have higher absorbed energy than the Horizontal orientation. However, this apparent trend does not seem to exist for the As-Built condition. All of these observed differences appear to be larger at higher temperatures. HIPed EBM Ti-6Al-4V compares well with Wrought Ti-6Al-4V, despite differences in microstructure (mill annealed) and chemistry (e.g. oxygen content).



Figure 10. Charpy absorbed energy for all four EBM Ti-6Al-4V test conditions as well as Wrought Ti-6Al-4V (mill annealed). Data are fitted by means of the commonly used hyperbolic tangent model [29]. Solid lines correspond to closed symbols. Dashed lines correspond to open symbols.

4 DISCUSSION

The results suggest internal porosity has a deleterious effect on Charpy absorbed energy. Xray CT measurements showed internal porosity in the As-Built condition, but not in the HIPed condition (Figure 3 and Figure 4), and fractography (Figure 5) supported these results through evidence of pores on the fracture surfaces of As-Built but not of HIPed Charpy specimens. In Charpy results (Figure 10), HIPed conditions had higher absorbed energy compared to As-Built conditions, and this result was attributed to the effect of internal porosity. This deleterious effect of porosity on Charpy absorbed energy has been shown previously for other material systems [36]. The observed coarsening of α laths due to HIPing (Figure 6, Figure 7) also likely contributed to this trend as it is known that coarser Ti-6Al-4V microstructures have higher Charpy absorbed energy [37]. Unfortunately, the respective contributions of these two effects (i.e. porosity and coarsening) cannot be quantified from the results of this work.

The results also suggest crystallographic texture has an effect on Charpy absorbed energy. For the HIPed condition, the Vertical orientation exhibited higher absorbed energy compared to the Horizontal orientation (Figure 10). However, for the As-Built condition, there appears to be no difference in Charpy absorbed energy between Vertical and Horizontal orientations. Also, it

is apparent from Figure 9 that prior- β grains are elongated in the build (Z) direction. It has recently been shown that prior- β grain boundaries impede dislocation motion as long as the two adjacent prior- β grains are of different texture orientation [38]. Since the crack pathway for the Vertical orientation crosses more prior- β grain boundaries than the crack pathway for the Horizontal orientation, and because the texture orientation distributions observed in all four test conditions were mixed (Table II), the Vertical specimens were expected to have higher Charpy absorbed energy. This was the case for the HIPed condition where the predominant texture orientation (*i.e.*, $(110)_{\beta}$) was the same for Vertical and Horizontal specimens (Table II). However, the Vertical orientation was not tougher than the Horizontal orientation for the As-Built conditions, and it is hypothesized this is because of the differing texture (*i.e.*, predominantly $\langle 110 \rangle_{\beta}$ for Horizontal and predominantly $\langle 001 \rangle_{\beta}$ for Vertical). In this case, the advantage for the Vertical orientation (*i.e.*, crack pathways crossing more dissimilar prior-β grain boundaries) is balanced by the disadvantage of the predominantly $\langle 001 \rangle_{\beta}$ texture having lower toughness compared to the predominantly $(110)_{\beta}$ texture (qualitatively ascertained from tensile properties in the literature for the two types of texture [22]), leading to negligible difference in Charpy absorbed energy for As-Built/Horizontal and As-Built/Vertical test conditions (Figure 10).

It is possible that the ridges observed on fracture surfaces of Horizontal orientation specimens (Figure 5a, c, and e) indicate influence of dissimilar prior- β grain boundaries on crack pathway, as they are of the same size and morphology (elongated in Z-direction) as prior- β grains. It is unlikely that any Hall-Petch-like grain size effects played a role in the comparison of Vertical and Horizontal orientation specimens, as the change in α lath thickness as a function of distance from the bottom of the build volumes was found to be relatively small (Figure 6). We can be reasonably certain that any martensite (α ') formed upon rapid cooling would be fully transformed to α due to the high background temperatures of EBM (550 °C - 750 °C [39]). Tempering of Ti-6Al-4V α ' has been found to completely transform to α within 30 minutes at temperatures between 600 °C - 800 °C [40], which is much shorter than the duration of this build (16.5 hours, not including heat-up and cool-down times). Also, chemistry was found not to vary significantly when comparing the two AM heat treatment conditions (Table I).

The main differences between test conditions observed in the Charpy absorbed energy results (i.e. HIPed higher than As-Built, HIPed/Vertical higher than HIPed/Horizontal) appear to become greater with increasing temperature. All test conditions, including wrought data, seem to converge at the lower test temperatures. This convergence at lower shelf temperatures is common for many metallic materials and makes observation of differences between material test conditions easier at higher temperatures where behavior tends to be more divergent.

It is important to note that the texture measured in this work deviated largely from the commonly reported texture for EBM Ti-6Al-4V (*i.e.*, $\langle 001 \rangle_{\beta}$ -fiber) [14-20]. This motivates future work to further understand the influences of processing parameters on texture in this material. In general for Ti-6Al-4V, $\langle 001 \rangle_{\beta}$ texture forms in the direction of dominant thermal gradient. Chaput, *et al.* [22] have hypothesized that scan length affects energy density, which in turn affects the dominant thermal gradient and texture. However, only extreme scan lengths were studied, with no ability to interpolate behavior at intermediate scan lengths. Also, there are most likely additional AM processing factors that influence dominant thermal gradient and must therefore be considered. One such factor is part supports, which were used in this study (Figure 1d, e). Chaput, *et al.* [22] studied parts that were directly attached to the build plate, which acts as a large thermal mass during the AM process and favors the dominant thermal gradient in the

build direction, so heat flows down through the part to the build plate. However, supports thermally isolate the part from the build plate, as parts are built above the plate and attached only via thin wafer-like support material. This practice is utilized often in industry, and understanding the influence of the thermal isolation of supports on dominant thermal gradient and texture is of practical and scientific importance. Unfortunately, this cannot be accomplished in the current study, as scan length and support design were not systematically investigated, so it will be the goal of future work to achieve this deeper understanding of the influences of various EBM processing variables on texture and mechanical properties of EBM Ti-6Al-4V. This information will provide important inputs to AM process and material models (e.g. cellular automata [41]), as well as continuing to optimize this exciting class of materials (e.g. texture control through melt parameter optimization [42]).

5 CONCLUSIONS

Results suggest that internal porosity has a deleterious effect on the Charpy absorbed energy of EBM Ti-6Al-4V. This was evident as HIPed material displayed higher Charpy absorbed energy over a range of temperatures (-196 °C to 600 °C) compared to As-Built material, and spherical internal porosity was found (x-ray CT, fractography) in the As-Built condition (99.8 % dense) but not after HIPing. An observed increase in α lath thickness due to HIPing also contributed to this trend in Charpy absorbed energy. Texture (measured by EBSD) was also found to influence Charpy absorbed energy along with the anisotropic grain morphology (*i.e.*, prior- β grains elongated in the build (Z) direction). It was observed that for similar texture, crack pathways that cross more prior- β grain boundaries lead to higher Charpy absorbed energy. However, differing textures were found to negate the prior- β grain boundary strengthening effect in some cases, emphasizing the influence of texture and variations in texture on Charpy absorbed energy. For the four testing conditions investigated in this work (As-Built/Vertical, As-Built/Horizontal, HIPed/Vertical, and HIPed/Horizontal), types of texture varied from predominantly $\langle 001 \rangle_{\beta}$ to predominantly $\langle 110 \rangle_{\beta}$, but none matched the most commonly reported texture for this material (*i.e.*, $\langle 001 \rangle_{\beta}$ -fiber). A deeper understanding of the influences of processing on texture is necessary and will be addressed in future work.

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7 FOOTNOTES

¹Commercial names are identified in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the NIST nor does it imply that they are necessarily the best available for the purpose.

8 DATA AVAILABILITY

The raw/processed data required to reproduce these findings cannot be shared at this time due to technical or time limitations.

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