Microstructural Modification of Ti-6Al-4V by Using an In-Situ Printed Heat Sink in Electron Beam Melting® (EBM)

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Abstract

Unidirectional heat transfer during additive manufacturing (AM) processes results in anisotropy of microstructure and mechanical properties in fabricated components. In the present study, the influence of in-situ printed heat sinks on the microstructure of Ti-6Al-4V was investigated. Different numbers of heat sinks were designed and produced by the Electron Beam Melting® (EBM) process. The coupons were characterized by an optical microscope, scanning electron microscope, tensile and hardness tests, and fracture analysis. An increase in the number of heat sinks was accompanied by a reduction in grain thickness. While elongated grains still formed in all coupons, due to the dominant heat transfer along the buildup direction. The refinement of microstructure was confirmed by a reduction in the average thickness of α -lath from 1.73 μm in the coupon with no heat sink to 1.01 μm in the coupon with the highest number of the heat sinks. The ultimate tensile strength and hardness were increased by increasing the number of heat sinks. The results of fractography suggested that coupons with the maximum number of heat sinks (5-HS) showed a more ductile fracture. Also, digital reconstruction of the fracture surface showed that the unmelted powder particles had an influence on the crack initiation.

Keywords: Additive Manufacturing; Electron Beam Melting® (EBM); Ti-6Al-4V; Anisotropy; Fractography; Mechanical Properties.

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1. Introduction

The ability of additive manufacturing (AM) processes to produce complex geometries causes their rapid growth in a number of related industries.^[1] Energy saving, less material waste, faster design-to-final fabrication period, design optimization, and product customization are the most important advantages of powder-bed AM over traditional manufacturing methods.^[1,2] However, surface finish, dimensional tolerance, processing speed, and elongated microstructure and mechanical properties are some of the challenges that need to be tackled for improving the quality of final products.^[2] Each of the issues could be influenced by the thermal history of a three dimensional (3-D) printed component during the layer-by-layer manufacturing. Therefore, understanding the thermal history during AM processes is essential to overcome the challenges. Numerical modeling has been widely used as a suitable tool to investigate the effect of the process parameters and material properties on heat distribution during the Electron Beam Melting® (EBM) process.^[3-5] Additional experimental studies are needed to modify the microstructure and properties of EBM® products.

During the layer-by-layer manufacturing of a part by EBM®, the substrate and pre-deposited layers could act as a heat sink, while loose powder around the part could have a very low thermal conductivity and provide an almost thermally-isolated area around the component. Hence, the building direction might be the only dominant direction of the heat transfer.^[6] As the preferred growth direction of grains is in the opposite direction of the heat transfer, the formation of a columnar microstructure in the components is expected. Therefore, a part can show different mechanical properties along the building direction and normal to it.^[7] M. Yamaguchi et al.^[8] showed that in a directionally solidified part with a lamellar microstructure, the tensile properties strongly depend on the angle between the loading axis and lamellar boundaries (ϕ).

Some studies were performed on minimizing the microstructural elongation in AM processes. S. Mitzner et al.^[1] studied the effect of beam and arc modulation on microstructure in the electron beam freeform fabrication (EBF³) and gas tungsten arc (GTA) deposition. The decrease in the size of molten pool and a more competitive grain growth resulted in the formation of a finer microstructure with an improved isotropy. According to the results, α -lath width was decreased, while the β -phase volume fraction was increased.^[1] Colegrove et al.^[9] used the interpass rolling between the layers of Ti-6Al-4V deposited by tungsten arc welding. Even though the study aimed to reduce the residual stress, at the same time a refinement in

microstructure was observed. As a result, anisotropy was decreased in both strength and elongation. Y. Ning et al.^[10] demonstrated that a change in the length and orientation of hatch during selective laser melting (SLM) can alter the heat distribution and sintering time of the material. It was shown that by using a shorter hatch line, a homogenous microstructure was achieved. Thijs et al.^[11] studied the effect of scan strategy on the microstructure of AlSi10Mg produced by SLM. A 90-degree rotation in scanning direction between the layers resulted in the formation of a more homogenous microstructure with a weak cubic texture. Niendorf et al.^[12] developed two-laser SLM equipment with two separate laser heads at 400 W and 1000 W. Different areas of a coupon made of stainless steel AISI 316 L were scanned by either the 400 W or 1000 W laser. Due to manipulation of the heat transfer mechanism in the scanned areas, clear local differences in microstructure and mechanical properties were observed.

In the present work, the influence of an in-situ fabricated heat sink on the microstructure and mechanical properties of Ti-6Al-4V was investigated. Four sets of coupons were produced by the EBM® process, three of which were designed with a different number of heat sinks. The fourth set of coupons was built without heat sink for the sake of comparison. The influence of the heat sinks on the microstructure, mechanical properties, and fracture of components was investigated by the use of characterization techniques.

2. Material and Methods

2.1. Material (Ti-6Al-4V)

Ti-6Al-4V alloy is classified as a combination of α and β -phases in its microstructure. The microstructure of Ti-6Al-4V produced by EBM® consists of columnar prior β grains.^[13] However, there is an allotropic transformation in the titanium alloy during its cooling from the melting point. The transformation results in changing the crystallographic structure from a body-centered cubic (BCC) structure or β -phase to a hexagonal close-packed (HCP) structure or α -phase. The β -phase can transform to both colony and basket-weave $\alpha+\beta$ microstructure at room temperature.^[14] In thin walls with a low thermal mass, the thermal situation is suitable for the formation of α' -phase with a martensitic microstructure.^[14] However, it was reported that at a temperature of 700°C, full decomposition of α' microstructure into a Widmanstätten $\alpha+\beta$ microstructure can be achieved.^[6, 15] Fig. 1 shows the schematic of the pseudo-binary equilibrium phase diagram for titanium alloys.^[16] The vertical dashed line is representative of

Fig. 1. Schematic of the pseudo-binary equilibrium phase diagram for titanium alloys (modified version of [16]).

the Ti-6Al-4V alloy. The exact transformation temperature (β -transus) is influenced by the type and amount of alloying elements.^[13] The β -transus in Ti-6Al-4V is approximately equal to 1000°C.^[17]

2.2. EBM® Process Parameters

In this study, the EBM® refers to the AM process invented by the Swedish ARCAM Company. A tungsten filament (cathode) is heated up and produces the electrons. Then, a high voltage potential applied between the anode and cathode accelerates electrons. In the next step, electrons pass through a vertical column that is surrounded by three electromagnetic coils, responsible for increasing the beam intensity and controlling the stirring of the beam. Finally, the high-speed focused electrons strike the stainless steel substrate. The kinetic energy of electrons is transformed into heat upon striking the target and preheat the substrate to a specific temperature. By reaching the desired temperature, the horizontal translation of a rake applies the first layer of powder on the substrate. According to the 3-D design, the electron beam fully melts the powder where a solid is needed, while the rest of the powder bed surface is partially melted to provide the required volume support. The description of the coupons' preparation steps by the EBM® process was explained elsewhere.^[3, 18]

All of the coupons were produced by using an identical set of process parameters including the electron beam current, voltage, and scanning speeds of 14 mA, 60 kV, and 1000 mm/s, respectively. The Ti-6Al-4V alloy was in powder form of with a particle size between 45 and 100 micrometers. Powder layer thickness and initial preheating temperature were set at 100 micrometers and 730°C, respectively.

2.3. Design of the Heat Sinks

The design of the coupons was based on a design of tensile test samples to simplify mechanical testing after the EBM® process. The tensile test coupons were produced by using four different numbers of heat sinks (see Fig. 2). Heat sinks were designed as rings with a 0.5-in. (12.7-mm) outer diameter and 0.1-in. (2.54 mm) thickness, around the gauge area. The produced coupons were numbered based on the number of heat sinks, where 0-HS had no heat-sink, and 5-HS had five heat sinks. Also, a series of cubic lattice structures of 0.5 in. (12.7 mm) in height were placed at the bottom of each coupon. The lattice structure was used to lower heat transfer from the tensile coupons to the substrate. Therefore, the possible influence of the designed heat

Fig. 2. Schematic of the in-situ printed heat sinks on mini-tensile test coupons produced by EBM® (HS: Heat Sink).

Fig. 3. Schematic of the design of the mini-tensile test coupons **per ASTM E8 standard** (the arrows show the location of heat sinks).

sinks on the heat transfer could be maximized. All four coupons were produced in the same batch. Fig. 3 shows the dimension of the mini-tensile test coupon with a 0.2-in. (5.08 mm) thickness, **prepared per ASTM E8 standard**.

2.4. Preparation of Coupons for Experimental Tests

To minimize the influence of surface roughness on the mechanical response of the coupons during tensile testing, their side surfaces were slightly grinded. Fig. 4(a) shows the schematic of the designed fixture and the assembly of the tensile test coupon in the fixture. For the microstructural analysis, the tensile test coupons were cut according to Fig. 4 (b). All of the

Fig. 4. (a) Schematic of designed fixture and assembly of the tensile test coupon; and, (b) schematic of the cutting method for coupon preparation for the microstructural analysis. The black dot shows the location of the hardness measurement.

coupons were grinded using a rotary disc and sand paper from 200 to 1000 grid. Diamond suspension with a particle size of 9 to 0.05 μm was used to polish the coupons on a rotary cotton cloth. After polishing, the coupon surfaces were rinsed off with water then dried out. Kroll's reagent (2 ml HF, 10 ml nitric acid, and 88 ml water) was used to etch the coupons. The etching time was set at 15 seconds for the through-cut coupons. The Keyence VHX-1000 digital microscope was used to observe the microstructure. All of the images were prepared by assembling several images captured by a Keyence polarizing filter that minimized the glare. For the observation of the fracture surfaces, a SEM, LEO 1450VPSE, was used.

An Instron machine was used for the tensile test. Five coupons were produced for each design of heat sinks. The coupons broken beyond the gauge area (in 0-HS and 5-HS) were removed from averaging the mechanical strength. However, the mentioned coupons were used for microstructural analysis. Fractography was performed on the coupons that fractured in the gauge area. The ultimate tensile strength (UTS) at the failure point was recorded. The strain rate used for the tensile test was set equal to 0.1 mm/sec. Fracture surfaces of the tensile test coupons were scanned by using a 2-axis optical profilometer. The Nanovea PS50 optical profilometer was equipped with a 3.5-mm optical pen and 8- μm spot diameter, providing a 4- μm lateral resolution and a vertical accuracy of 400 nm. The hardness test was performed using a Clark CM-700AT micro-hardness tester on the through-cut surfaces with a normal force and dwelling time of 500 grams and 15 seconds, respectively. The indentation spots were located at the center of through-cut surface (Fig. 4 (b)).

3. Results and Discussion

3.1. Microstructural Analysis

Figure 5 compares the macrostructure of coupons with different numbers of heat sinks. The bright and dark areas observed on the through-cut surfaces are representative of the grains with different growth directions. According to Fig. 5, elongated grains were formed along the buildup direction in all coupons. This observation could be explained by the effect of the thick steel substrate underneath the coupons. The presence of this considerable mass of material resulted in the establishment of a vertical heat transfer toward the substrate that lasted during the whole buildup process. While the coupons could be distinguished by comparing grain sizes normal to the buildup direction. In Coupon 0-HS, the whole width of gauge area was covered by thick

Fig. 5. Comparison of the macrostructure on through-cut surfaces of coupons with different number of heat sinks; Images were prepared by assembling several images captured by a Keyence polarizing filter.

grain(s), while much narrower grains were formed in Coupon 5-HS. The introduction of a heat sink in the gauge area (in coupon 1-HS) resulted in the formation of a local heat transfer regime normal to the buildup direction. Additional heat sinks encouraged lateral heat transfer and resulted in the formation of narrower grains. Therefore, the influence of the heat sink design was more pronounced in producing thinner grains, while all coupons still had elongated grains.

Heat transfer caused by the design of heat sinks was effective for a short distance from the surface, while in core of the coupons, the major heat transfer occurred along the buildup direction. Therefore, for grains formed close to the external walls, the outcome of the two

directional heat transfers was effective. As a result, an inclination in the growth direction of the sub-surface grains was observed (Fig. 5). Both the refinement in microstructure and change in the direction of the grain growth could be observed at the center of the coupons, especially in Coupon 5-HS.

In order to confirm the possible influence of heat sinks on the microstructure, the coupons were compared at a higher magnification by using a SEM (see Fig. 6). In Fig. 6, the white lines are representative of the β -phase, and the parallel gray bands are the α -laths grown in the β -matrix. The narrow white lines inserted in the images were used to measure the thickness of α -laths.

Grain refinement during AM processes could occur during solidification from the melting point as well as in-situ heat treatment of previously solidified layers. During the solidification step, the size of a grain is a function of the product of thermal gradient (G) and growth rate (R).^[19] An increase in $G \cdot R$ or cooling rate results in the formation of a finer microstructure. Also, the in-situ heat treatment after solidification can alter microstructure. During AM

Fig. 6. Comparison of the microstructure of coupons at a higher magnification; the white lines are representative of the β -phase, and the parallel gray bands are the α -laths grown in the β -matrix.

processes, the layer-by-layer addition of material is accompanied by multiple thermal cycling which acts as an in-situ heat treatment for the previously solidified layers. The influence of the multiple thermal cycling on the microstructure was proved by the formation of layer-bands.^[20]

The influence of the heat sink design on the grain refinement is better explained in Fig. 7. A schematic of the EBM® process is presented in Fig. 7(a). A thin wall was built, layer by layer, for a total number of n layers. As shown, the top layer (n th) was still in the melting state. The wall was surrounded by the thermally-isolated powder particles, while on the bottom side, the thin wall was attached to the substrate. Any layer along the thin wall experienced several thermal cycles during the fabrication. The layers along the buildup direction could have different cooling rates, depending on the distance from the top (melting) layer. The layers close to the top surface experienced a temperature above the β -transus, where a slight homogenization (H) could occur. The index i was used to specify the order of layers for the H stage, and nH represents the number of layers that experience the homogenization. Fig. 7(b) compares the maximum temperatures and the cooling rates for Coupons 0-HS and 5-HS. It is evident that a higher number of heat sinks

Fig. 7. Schematic of the influence of thermal cycles on microstructural development in the EBM® process. (a) powder-bed process to build a thin wall; (b) comparison of the effect of heat sink design on the cooling rate during the homogenization; and (c) effect of the cooling rates on the development of microstructure during the homogenization process [plotted according to 21, 22 and 23].

will result in a higher cooling rate.

Fig. 7-c schematically illustrates the influence of the cooling rate on the grain size. At a temperature above T_β , an increase in the cooling rate leads to the formation of finer prior β grains. The microstructural observation in Fig. 5 confirmed the refinement in macrostructure caused by the higher cooling rate. By reduction of temperature below T_β , the primary α was deposited on the grain boundaries of prior β .^[21] The primary α is shown by the gray thick lines along the grain boundaries in Fig. 7(c). The prior β grain boundaries and primary α were indicated by β_{PGB} and α_{PGB} , respectively. Because the thickness of the primary α -phase has an inverse relationship with the cooling rate, an increase in the cooling rate was accompanied by the formation of a thinner primary α -phase.^[21]

The third possible change in microstructure caused by a higher cooling rate could be observed in the size of α -colonies. At a lower temperature and after the formation of the primary α , the side plates of α -phase (platelet α) started to grow epitaxially from the grain boundaries of the prior β .^[24] Because the formation of alpha colonies are controlled by diffusion, a smaller colony is formed in response to the higher cooling rate related at Coupon 5-HS. The boundaries of α -colony are indicated by the solid lines in Fig. 7(c).

Figure 8 compares the thicknesses of α -laths in the fabricated coupons. The measurement was performed at the center of the gauge areas. According to Fig. 8, an increase in the number of heat sinks was accompanied by a decrease in α -lath thickness. However, the decrease in thickness was more pronounced from 0-HS to 1-HS. Therefore, addition of the first heat sink in

Fig. 8. Comparison of the average thickness of α -lath in the coupons different number of heat sinks. The measurement was performed at the center of the gauge areas.

1-HS resulted in the establishment of heat transfer normal to the buildup direction. Whereas, the increase in the number of heat sinks in 3-HS and 5-HS strengthened lateral heat transfer. These results are in accordance with the macrostructural observations presented in Fig. 5. The average thickness of the α -lath decreased from 1.73 μm for Coupon 0-HS to 1.01- μm for Coupon 5-HS. Therefore, as was expected, a higher cooling rate related to the increased number of heat sinks resulting in the formation of a finer microstructure. The similar influence of the cooling rate on the α -lath width was reported in other studies as well.^[22]

In addition, in the case of a high cooling rate (5-HS), the basket-weave α could form at an appropriate distance from the grain boundaries of the prior β .^[23] Figure 9 shows the formation of basket-weave structure in Coupon 5-HS, where the black-solid line indicates the prior β grain boundary. The dotted-black lines were added to the image to provide a better presentation of basket-weave structure. The platelet α and basket-weave α -phases were indicated by α_{Pl} and α_{BW} in Fig. 7, respectively.

Other than the design of heat sinks, other parameters could also alter heat transfer regime. Packing density of the powder bed is among those parameters, where an increase in packing

Fig. 9. The formation of a basket weave microstructure in Coupon 5-HS caused by a high cooling rate; the black solid line indicates the prior β grain boundary. The dotted-black lines were added to the image to better present the basket-weave structure.

density results in a faster heat dissipation and a higher cooling rate.^[3] Likewise, arrangement of components in the EBM® build up chamber can considerably change the amount of heat accumulated between components. Jamshidinia and Kovacevic^[4] studied the influence of heat accumulation on surface roughness of thin walls produced by EBM®. In this study, the same batches of Ti-6Al-4V powder with identical powder size distribution were used to minimize variation in powder bed packing density. Also, all of the coupons were produced at the same distance from each other to minimize differences in cooling rate caused by heat accumulation.

3.2. Analysis of Mechanical Properties

The influence of microstructural refinement on mechanical properties of Ti-6Al-4V was investigated in several studies. Sen et al.^[25] showed that a 38 percent reduction in α -lath width resulted in an 8-10 percent increase in mechanical strength. Although there are some differences in refinement mechanisms and sizes of α -lath width, a similar trend could be expected to occur in this study. The experimental results of mechanical testing are plotted in Fig. 10. As can be seen, an increase in the number of heat sinks was accompanied by an increase in the strength and hardness of the coupons.

The increase in strength due to microstructural refinement can be explained by the Hall-Petch equation:^[26]

$$\sigma = \sigma_0 + kd^{-\frac{1}{2}} \quad (1)$$

where σ is the stress, σ_0 is the friction stress, k is the stress intensity for transferring the

Fig. 10. The influence of heat sink design on the mechanical properties of Ti-6Al-4V produced by EBM®: (a) Ultimate tensile strength; and (b) Microhardness results.

dislocation strains at the grain boundaries, and d is the size of the grain.^[26, 27] According to this theory, in a smaller grain, dislocation pile-up behind the grain boundaries can develop a lower level of stress concentration.^[27] Therefore, a higher level of stress would be needed to initiate a plastic deformation in the neighboring grains.^[26] As a result, in a structure with the finer grain size, failure could occur at a higher level of stress. Therefore, the higher strength in Coupon 5-HS could be related to its finer microstructure compared to Coupon 0-HS. Likewise, the effect of grain size on the hardness can be explained by the Hall-Petch theory also.^[26] The finest microstructure observed in Coupon 5-HS resulted in the highest level of microhardness, as well (see Fig. 10). These results are in accordance with the effect of microstructural refinement on mechanical strength.^[25]

3.3. Fracture Analysis

The fracture surface analysis could provide useful data regarding the type and cause of the fracture. Figure 11 compares the fracture surfaces of the coupons at a higher magnification. Based on the fracture theories, the entire fracture process could consist of three steps including nucleation, growth, and coalescence of voids in the material.^[26] The first two steps occur in response to the initial loading, while the last step is caused by a far-field loading. In the ductile fracture, the last step is accompanied by the formation of a cup-cone feature.^[26] Tensile testing resulted in the formation of cup-cone features on the fracture surfaces of all 5-HS coupons. While, tensile specimens with no heat sinks (0-HS) had a sharp and flat surface, without a noticeable indication of cup-cone feature. Coupons 1-HS and 3-HS showed a mixture of the two fracture modes. Therefore, the experimental results of fractography suggested that coupons with the maximum number of heat sinks (5-HS) showed a more ductile fracture.

A Nanovea PS50 profilometer was used to more precisely investigate the fracture surfaces. Figure 12(a) illustrate a digital reconstruction of the fracture surface in coupon 5-HS. A cup-cone feature, indicated by the black arrows, can be clearly observed on the fracture surface of this coupon. The topography data was edited by applying appropriate filters and a limited range of thresholds in the Nanovea PS50-profilometer software. As a result, the crack propagation path was revealed on the fracture surface (Fig. 12-b). The areas with a dark-blue color were of minimal height and represented the locations of dimples formed on the fracture surface. The areas with brown color were on the opposite side of the dimples formed at the other side of the

Fig. 11 Comparison of fracture surface of the coupons with different designs of heat sinks.

Fig. 12. Digital reconstruction of the fracture surface by using a light profilometer; (a) fracture surface of coupon 5-HS, where cup-cone feature formed on the fracture surface are indicated by black arrows. (b) the modified topographical results of fracture surface of Coupon 5-HS.

fracture surface. The black dashed lines were drawn along the estimated crack propagation paths (Fig. 11-b). As shown, the cracks were approximately initiated from the top-center of the fracture surface, indicated by a red star. This area was exactly at the same location that some unmelted powder particles were observed. It could be concluded that the unmelted powder particles had an influence on the crack initiation, and eventually, the failure of the coupon. Additional study will be needed to investigate the possible relationship between the heat sink design and the formation of unmelted powders.

4. Future Study

The authors studied the possible relationship between population of unmelted powders on fracture surfaces and the number of heat sinks. According to the results, a strong correlation could not be established between the number of unmelted powders and the design of the heat sinks. In the future study, the possible influence of local heat transfer on the formation of systematic defects such as lack of fusion (LOF) and porosity will be investigated.

The results of this preliminary study proved that in-situ printed heat sinks with a proper design could be used to modify the microstructure in the powder-bed AM of metals. In the future study, the authors will investigate the influence of the heat sink design on the anisotropy in microstructure and mechanical properties. In addition, an optimized design of the heat sinks will be developed. Inappropriate design of support structure could result in the application of excessive heat, accompanied by grain coarsening or even the formation of porosity. The shape and thickness of supports, their connection to the substrate and distance from a coupon will be among the variables to be studied. Results of this study could be used by AM systems' manufacturers. Optimization of support structures will enable manufacturers to customize the microstructure of metals during AM processes.

5. Conclusions

The influence of in-situ printed heat sinks on the microstructure of Ti-6Al-4V was investigated. Four sets of coupons with a different number of heat sinks were designed and produced by EBM®. According to the performed analysis, the following could be concluded:

- (1) An increase in the number of heat sinks resulted in the formation of a finer microstructure, caused by a higher cooling rate. The refinement of microstructure was confirmed by comparison of macro and microstructure of the coupons. In addition, measurement of α -laths thickness showed an inverse relationship between the number of heat sinks and α -laths thickness. The average thickness of α -laths decreased from 1.73 μm in coupon 0-HS to 1.01 μm in coupon 5-HS.
- (2) An increase in the number of heat sinks resulted in an increase in the ultimate tensile strength and hardness. The increase in strength and micro-hardness was explained by the Hall-Petch equation.
- (3) The results of fractography suggested that coupons with the maximum number of heat sinks (5-HS) showed a more ductile fracture. An increase in the number of heat sinks resulted in the formation of cup-cone feature on the fracture surfaces.
- (4) Digital reconstruction of the fracture surface showed that the unmelted powder particles had an influence on the crack initiation, Additional study will be needed to investigate the possible relationship between the heat sink design and the formation of unmelted powders.

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7. References

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Figure Captions

Fig. 1. Schematic of the pseudo-binary equilibrium phase diagram for titanium alloys (modified version of [16]).

Fig. 2. Schematic of the in-situ printed heat sinks on mini-tensile test coupons produced by EBM® (HS: Heat Sink).

Fig. 3. Schematic of the design of the mini-tensile test coupons per ASTM E8 standard (the arrows show the location of heat sinks).

Fig. 4. (a) Schematic of designed fixture and assembly of the tensile test coupon; and, (b) schematic of the cutting method for coupon preparation for the microstructural analysis. The black dot shows the location of the hardness measurement.

Fig. 5. Comparison of the macrostructure on through-cut surfaces of coupons with different number of heat sinks; Images were prepared by assembling several images captured by a Keyence polarizing filter.

Fig. 6. Comparison of the microstructure of coupons at a higher magnification; the white lines are representative of the β -phase, and the parallel gray bands are the α -laths grown in the β -matrix.

Fig. 7. Schematic of the influence of thermal cycles on microstructural development in the EBM® process. (a) powder-bed process to build a thin wall; (b) comparison of the effect of heat sink design on the cooling rate during the homogenization; and (c) effect of the cooling rates on the development of microstructure during the homogenization process [plotted according to 21, 22 and 23].

Fig. 8. Comparison of the average thickness of α -lath in the coupons different number of heat sinks. The measurement was performed at the center of the gauge areas.

Fig. 9. The formation of a basket weave microstructure in Coupon 5-HS caused by a high cooling rate; the black solid line indicates the prior β grain boundary. The dotted-black lines were added to the image to better present the basket-weave structure.

Fig. 10. The influence of heat sink design on the mechanical properties of Ti-6Al-4V produced by EBM®: (a) Ultimate tensile strength; and (b) Microhardness results.

Fig. 11 Comparison of fracture surface of the coupons with different designs of heat sinks.

Fig. 12. Digital reconstruction of the fracture surface by using a light profilometer; (a) fracture surface of coupon 5-HS, where cup-cone feature formed on the fracture surface are indicated by black arrows. (b) the modified topographical results of fracture surface of Coupon 5-HS.