Microstructural evolution along the build height of laser melting deposited TA15 alloy

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Abstract- This study emphasizes the TA15 alloy microstructural distribution fabricated by the laser melting deposition (LMD) technique. The motivation of the study is to analyze the microstructural features, such as grain or laths thickness, phase fraction, and porosity occurrence in the different regions along the build height, due to the complex thermal-solidification history during the laser melting deposition. During laser deposition of titanium alloy, the laser beam forms a melt pool, where the near-α and α+β alloys transform into a single β-phase, followed by rapid solidification. This process is repeated when a successive layer is deposited, where the previously deposited layers are re-melted. These thermal cycles can affect the parent microstructure in the previously deposited layers. It was identified from the results that the width of α-laths was larger in the regions near the top of the build component. In comparison, the bottom region near to substrate contained fine laths due to a steep thermal gradient and repeated thermal effect. The volume fraction of β-phase was higher in the bottom region, which could be regarded as the transformed β matrix due to the successive thermal effect in the α+β field. The results also showed shallow porosity existence in the top and near to top regions. According to the morphology and size, the formation of these pores can be attributed to the gas entrapment during the deposition process.

1. Introduction
TA15 near-α titanium alloy has been widely used in aerospace large-scale structural and engine components due to its remarkable characteristics of high corrosion resistance, good durability, high strength-to-weight ratio, and extended workability at high temperatures [1, 2]. However, titanium alloys have some intrinsic limitations, such as high reactive to oxygen and low heat-conductivity. Consequently, it limits the large-scale use of titanium alloys due to their high cost, which raises the buy-to-fly ratio (up to 40:1) during production by traditional manufacturing techniques [3]. The long series of machining is predominantly found in complex-shaped structural components in the forging and cast-based production. Recently, rapid production with a high-cost saving of titanium alloys has become possible by laser melting deposition (LMD) technique. LMD is a prototype method to fabricate three-dimensional intricate shaped components with high design accuracy and low production cost. The technique works on the principle of layer-by-layer deposition of feedstock material (powder/wire) melted by laser as a heat source [4]. The technique has been applied to produce various titanium alloys having remarkable mechanical strength [5-7].

TA15 alloy exhibits dual-phase crystal structures, such as hcp (α-phase) and bcc (β-phase). The alloy contains a single β-phase above β-transus (990±5), which is transformed to α- or α+β phases during the solidification process. The solidification rate of LMD is higher than 10⁵ K/sec, which is much higher
than the cooling rate of the forging-based technique [8]. During layer over layers deposition, the rapid solidification and thermal repetition constitute columnar β grains structures prolonged over several deposited layers. These columnar grains formed by the thermal gradient grow in a preferred <100> direction opposite to heat-flow (downward to the substrate) [9]. During transformation, the rapid cooling result in a complex microstructure, including martensite α’ or basketweave α and some retained β. The α-laths distribution and amount of retained β is dependent on the cooling rate experienced in the α+β phase field and alloying composition [6, 8]. It is identified that initially, a continuous or discontinuous grain boundary α precipitates at the prior β grain boundary, which further act as nuclei for the parallel α-plates growing in the β grain interior. The high nucleation driving force constitutes randomly oriented α-plates in the grain interior [10]. The length and width of the α-plates are limited by the neighboring grains or prior parent β grain. These microstructural features are found high influential on the deformation behavior of titanium alloys [11].

The continuous layer of GB-α has been found detrimental to the ductility of the titanium alloy because it can favorably accumulate the strain [12, 13]. The GB-α can be found in nearly all the titanium alloys manufactured by LMD technique. Significant work has been done on the formation of GB-α and its effect on the mechanical strength in various titanium alloy [6, 13, 14]. However, not enough work has been carried out to explore the thermal gradient influence on the structure variance in the build height in laser melting deposited TA15 alloy. It is essential to analyze due to probable precipitation of the second phase in the prior solidified matrix due to thermal repetition in the sliced deposition. This present study will provide the necessary information about as-built alloy that can help to improve the manufacturing of LMD with more optimized microstructural and mechanical performance.

2. Experimental
The feedstock pre-alloyed powder having a compositional ratio of Ti-6Al-2Zr-1Mo-1V was utilized to fabricate the solid three-dimensional TA15 alloy component by laser melting deposition. The mesh powder size ranged from 75-145µm and the dimension of the fabricated TA15 bulk component was 180×42×130 mm³, as shown in Figure 2a. A high-power IPG laser was used as a heat source to melt the feedstock mesh powder by coaxial nozzle supply on the same alloy cast-based substrate. An alternate scan strategy was adopted during the sliced deposition to deposit the new layer on the existing layer. The processing parameters were finalized based on the built and check method to obtain a high-density solid component. The final chosen manufacturing parameters are given in our previously published article [15].

For microstructural analysis, the test specimens were extracted using wire-electric discharge machine from the five different spots along the build height. The specimens were further grinded with abrasive papers and mechanically polished using 0.5µm Alumina, followed by OPS. An electrochemical polishing was carried out to minimize the stress layers on the specimens during mechanical polishing. For phase volume fraction identification, X-ray diffraction (Bruker D8 XRD Detector) was used. For the metallographic observation, scanning electron microscope (SEM, S8000) and electron backscattered diffraction (EBSD, Oxford instrument) were used in the current analysis.

3. Result and discussion

3.1 Phase volume fraction
The α- and β-phase fraction in the five regions along the build height was identified using XRD, shown in Figure 1. The quantitative volume fraction of β-phases was identified in region 1 to region 5 was 11.2%, 9.4%, 7.8%, 7%, and 3.7%, respectively. From the quantitative analysis, it was observed that the α-phase fraction increased as the build height increased. It can be seen in Figure 1 that the peaks’ intensity decreases both for α- and β-phase as the build height increased. However, in region 1, both the peaks for α- and β-phases are obvious, indicating a clear existence of retained β-phase and fine α-laths. This variance in different regions can be attributed to the number of thermal cycles experienced by
different zone along the build height. The least volume fraction of β-phase in region 5 can be ascribed to the rapid cooling of the melt pool, which curbs an atomic diffusion resulting in bcc β- to hcp α-transformation [16]. The increase in β-phase volume fraction and peaks’ intensity in the bottom layers can be attributed to increased thermal cycles. Indeed, the bottom region will experience more thermal cycles as maximum successive layers are deposited, and the thermal gradient will be down to the substrate. During the successive layers, the peak temperature in the previously deposited layers is below the β-transus, which would ultimately transform the initial microstructure to retained αp phase and fine laths of transformed β matrix [17].

3.2. Microstructural characterization

The microstructural evolution of the LMD TA15 alloy was examined in the specimens extracted from the five regions along the built height. The gap interval between these specimens sectioning was 15 mm. These regions are labeled by R1-R5, as shown in Figure 2. Most commonly, the broad microstructure distribution is relatively identical in all these regions, composed of grain boundary α (prior β grain boundary) and intergranular randomly oriented α-laths. The precipitation of GB α takes place primarily when the columnar prior β grains undergo the phase transformation. Continuous GB α is commonly found in laser deposited α+β alloys, irrespective of their elemental compositions [7, 18]. Further, parallel laths can be seen along with GB α in all regions. The arrayed arrangement of these parallel laths is explained in detail by Zhao et al. [10]. However, a substantial morphological difference can be found in the microstructure from bottom region 1 to top region 5, revealed in Figure 2. It can be seen visibly from Figure 2(R1), the parallel α-laths along both sides of the GB-α are regularly arranged with the nearly same width and fine structure. A very slight difference was identified in the parallel α-laths along the GB-α. However, the surface roughness was increased in the region, attributed to the shallow porosity appearance. The appearance of porosity was more prominent and increased in regions 4 and 5, which will be explained in the next section. The width ratio of the parallel α-laths nucleated from GB-α has remarkably increased in region 4 and region 5, shown in Figure 2(R4,R5). The comparison of these laths’ width was further revealed by the EBSD IPF map, shown in Figure 3. These microstructural variations along the build height can be attributed to the variance in the cooling-heating effect and residual stresses experienced by different zones during the deposition process. It is identified that the region near the substrate is faced with a high cooling rate due to the maximum heat dissipation [19]. The faster cooling rate thus provides high driving nucleation force to the fine α-laths precipitation. In contrast, by increasing the build height, the cooling rate decreases due to low heat dissipation, which ultimately results in low nucleation driving force [10]. Consequently, the region closer to the top surface experiences high-temperature phase transformation. Thus, the relatively slower nucleation rate increases the laths width in the top region compared to the region near the substrate. The growth mechanism of α-
laths might also be influenced by the residual stresses, which is also observed as influential in the laser deposited titanium alloys. Nevertheless, the detailed analysis of these interactions is relatively intricate, which is not focused in the current investigation.

Figure 2. Microstructural distribution along the build height

Figure 3. The width comparison of parallel α-laths in the bottom and top regions

3.3. Porosity
The presence of porosity is a critical issue commonly found in the laser deposited metal alloys due to the inappropriate processing parameters and manufacturing disturbances. The presence of pores is one of the critical defects found influential on the mechanical performance of fabricated material [20]. The orientation of pores to the applied stress and shape of pores are also influential factors in mechanical performance [21]. Figure 4 compares the surface view of specimens extracted from regions 1 (bottom) and 5 (top). The defects can also be seen in Figure 2 (R4, R5); hence, to identify porosity distribution over a wide range, different sites from the intergranular basketweave structure were chosen from regions 1 and 5 shown in Figure 4. Figure 4(a) (region 1) exhibit lack of porosity over a wide range of area. In contrast, Figure 4b (region 5) contain randomly distributed pores on the surface. The morphologies of the pores are nearly identical, shallow, nearly round-shaped and vary from 0.5µm-1µm in diameter. Several mechanisms regarding porosity formation were identified, such as un-melted or partly melted feedstock particles, lack-of-fusion, delamination between sequential layers, or gas entrapment during
the deposition process [22]. These mechanisms are all associated with the process parameters and laser power that provides energy to the melt pool. The insufficient energy provided by laser to the melt pool cause balling and partial wetting effect that eventually leads to porosity formation [23]. In the present case, the porosity appearance was only identified in the region (4, 5) closer to top. The lack of porosity in the middle and bottom regions can be attributed to thermal cycles experienced by each layer during the deposition of successive layers. Thus, the feedstock metal is exposed to sufficient wetting energy to melt and solidify by the following cooling effect. While the region closer to the top surface of the build component experiences relatively less thermal repetition, that might be a reason to leave the feedstock unmelt. In addition, the presence of sparse pores with a very small size could also be caused by gas entrapping during the deposition process. The entrapped gases are mainly caused where the energy density is higher than the optimum energy density [24]. In both of these cases, the deposition of successive layers and thermal repetition is an important factor to reduce the porosity in the built material.

4. Conclusion
This paper examined the microstructural features of near α TA15 alloy fabricated by laser melting deposition along the build height. Five regions with a gap of 15 mm were chosen from the bottom (near substrate) to the top region of built component. The laths thickness, phase fraction, and porosity existence were examined. Based on the above results, the conclusions are drawn as below.

1. The microstructure of the laser melting deposited TA15 alloy was mainly composed of GB-α (prior β GB) and intergranular basketweave structure. The thickness of the lath was larger in the top regions compared to the region near the substrate.
2. The volume fraction of β was lower in the top region and was linearly increased in the region closer to the substrate, which can be regarded as the transformed β matrix by thermal repetition.

3. The existence of sparse porosity was only identified in the upper regions of the built component, while the lower and middle regions were found free of porosity due to the repeated thermal and solidification cycles.

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