Materials Research Proceedings **10** (2019) 114-120 doi: http://dx.doi.org/10.21741/9781644900031-16

The Effect of HIP Treatment on the Mechanical Properties of Titanium Aluminide Additive Manufactured by EBM

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Keywords: HIP, Electron Beam Melting (EBM), Additive Manufacturing, Titanium Aluminide

Abstract. Titanium aluminide, one of the important next generation high temperature materials, attracts intense R&D interests, and the application for the aeronautics and space fields is being intensely investigated. TiAl components additively manufactured by us possesses more than 99% density and good mechanical properties, however residual voids are problematic in the area where cyclic properties are important, therefore hot isostatic pressing (HIP) treatment is necessary. In this study, the effect of HIP treatment on the lamellar structure of TiAl alloy which showed excellent tensile ductility is investigated.

1. Introduction

Recently, in the transport industry, especially in the aeronautic section, high efficiency becomes vitally important in regards to reducing the environmental burden, fuel cost and decreasing the amount of exhaust gases. For example, the Boeing 787 successfully reduced 20% of its fuel cost, mainly due to this increased efficiency of its engine. This increased efficiency of jet engine stems from reducing the total engine weight. One way this is achieved is through the employment of TiAl alloy with its high strength to weight ratio and high elevated temperature strength which is the reason its application has widely spread [1]. Currently, TiAl alloy is employed in low pressure turbine blades, however if higher reliability is achieved, wider use of this alloy is possible, and thus even higher efficiency will be attainable.

Conventionally, TiAl parts are manufactured by precision casting, such as the lost wax method [2]. However, TiAl alloy has inherently low fluidity when casting, which sometimes results in casting defects. Usually, turbine blades design incorporates complicated cooling channels, requiring a sophisticated manufacturing process employing various cores. Since TiAl alloys are very reactive, it has a tendency to react with the casting mold as well as forming imperfections of surface oxide. Therefore, after casting, surface machining is essential and results in considerable material loss.

This has led us to focus on an additive manufacturing method as a more efficient process, especially through using an electron beam melting 3D printing (3D EBM), because it operates in a high vacuum, thus enabling little surface contamination and a negligible amount of material loss. Furthermore, it has been reported for Co-Cr-Mo and Ti-6Al-4V alloys [3-5], that by carefully choosing operational parameters, it is possible to control not only the shape but also the microstructure and mechanical properties of parts manufactured by 3D EBM. We have started our development work on low pressure turbine blades for aeronautic jet engines, focusing on shape and microstructural control. By using the 3D EBM and applying optimum parameters, it was possible to manufacture TiAl parts with a microstructure consisting of layered microstructure of soft and ductile equiaxed γ grain layers (γ bands) and a hard duplex-like region as shown in Fig. 1. Fig. 2 shows that EBM-TiAl exhibits yield strength of 550 MPa or higher at room temperature regardless of orientation with respect to its aligned structure [6]. However, ductility at room temperature is strongly dependent on the layered microstructure, and when the test direction is 45 degrees to the layered microstructure, the maximum elongation of more than 2.5% is obtained, as shown in Fig. 3 [6]. The high hardness and elongation obtained in this study are the deformation concentration effect on soft γ band compared to duplex-like region and the physical properties obtained from layered structure of different properties with high strength of microstructure duplex-like region. This high room temperature elongation is derived from the existence of γ bands which play a key role in the shear deformation to the maximum shear direction. Even though the 3D EBM results in a high density of 99% or higher, it is still prone to defects or porosities [7].

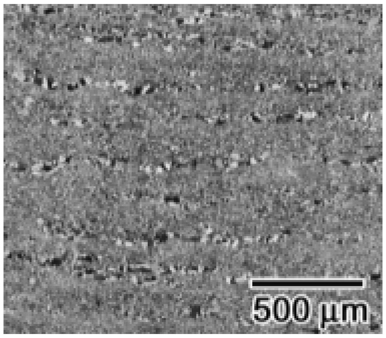

Fig. 1 Microstructure of EBM-TiAl [6]

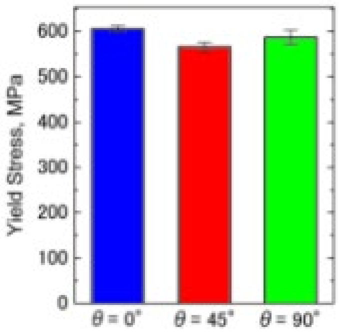

Fig. 2 Yield stress of EBM-TiAl (room temperature) [6]

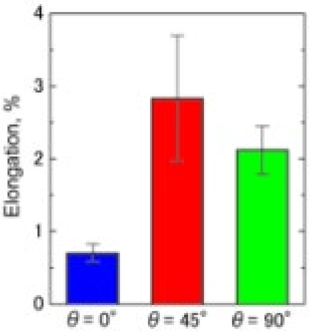

Fig. 3 Elongation of EBM-TiAl (room

Our previous study on a 3D EBM manufactured Ti6Al4V alloy revealed the existence of porosities in the as-build condition, and by applying hot isostatic pressing (HIP) treatment, fatigue properties of the alloy can be drastically improved as a result of pore elimination [8]. Since the low pressure turbine blades are used in a harsh environment, it is regarded as important to have a high reliability for EBM-TiAl through HIP treatment.

In this study, we sought to reduce the defects and porosities found in EBM-TiAl while maintaining the characteristic layered microstructure, and investigated the optimum HIP conditions whilst focusing on the microstructure. In addition we also investigated the influence of the HIP conditions on the mechanical properties of the EBM-TiAl.

2. Experimental Procedure

The powder of the Ti-48Al-2Cr-2Nb (at %) alloy, used in the present study, consists of spherical particles of which average diameter is approximately 100µm. TiAl cylindrical rods of 10 mm diameter and 90 mm length were built using an Arcam A2X^{TM} using Ti-48Al-2Cr-2Nb powder; the composition is shown in Table 1. Details of manufacturing conditions are made in previous reports. [6].

Table 1 Chemical composition of TiAl alloy powder (at.%)

	Al	Cr	Nb	C	O	N	Ti
Powder	48.6	1.74	1.95	0.032	0.198	0.008	Bal.

In this study, direction is defined as 0 degrees when the building direction is parallel to the bar axis. HIP treatments at 1100 °C and 1250 °C for 3 hours were performed on the as-built material. The microstructures of the alloy were examined with an optical and scanning electron microscope before and after HIP treatment. The specimens for the observation were electrically polished in a $HClO_4$: butanol : methanol (6 : 35 : 59 vol%) solution.

Defects were observed by optical microscopy over 550 mm^2 area, while pores were investigated by scanning electron microscopy over 0.05 mm^2 area. The number of samples for each defect and pore observations is not enough for determining appropriate standard deviation.

The volume fraction of α_2 phase in duplex-like region was determined by counting area percent of α_2 phase under scanning electron microscope over 0.2mm^2 area. The resultant area percent was used for the volume fraction.

Mechanical properties of the sample were determined with tensile and fatigue tests conducted at RT. Specimen shapes for both the tensile test and fatigue tests are shown in Fig. 4 and both the tensile and fatigue specimens were polished with colloidal SiO_2 suspension. For the tensile test, an Instron-type testing machine was used, and strain rate was chosen at 1.7×10^{-4} s^{-1}. The fatigue test was performed on an electro-servo-hydraulic testing machine under stress ratio (R) of –1 (tension-compression mode) and frequency (f) of 10 Hz. The fatigue test was stopped after 1×10^6 cycles.

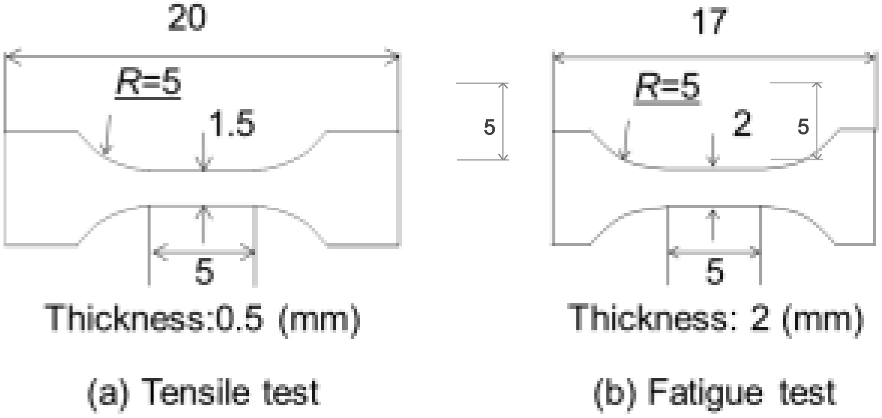

Fig. 4 Schematic drawing of tensile (a) and fatigue (b)

3. Results and discussion

3.1 Effect of HIP treatment on microstructure of the EBM-TiAl

Observation results of defects and pores before and after HIP treatment are shown in Figs. 5 and 6.

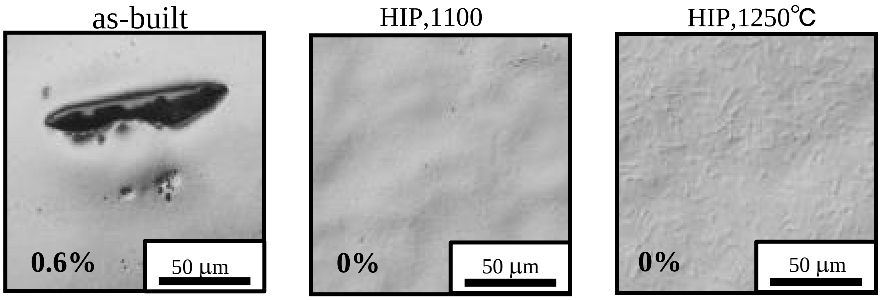

Fig. 5 Volume fraction of defect change by HIP treatments

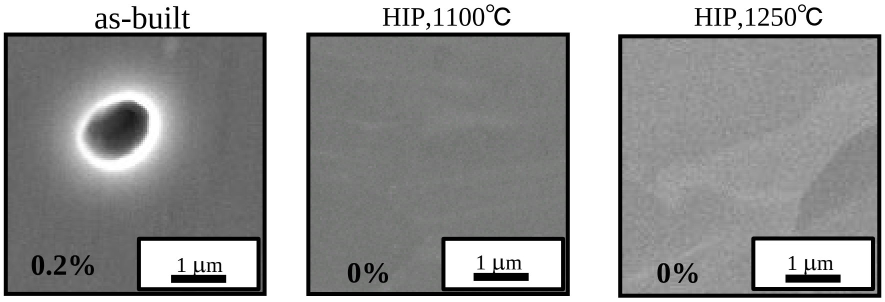

Fig. 6 Volume fraction of pores change by HIP treatments

As-build material contains 0.6% of defects and 0.2% of pores. It can be clearly seen that these defects and pores can be drastically eliminated by HIP treatments at 1100 and 1250 °C, indicating the beneficial effect of HIP on the densification of EBM-TiAl. Fig. 7 compares the microstructural change by HIP treatments. γ bands were completely deleted by the HIP treatment at 1250 °C, which is conventional HIP temperature for cast TiAl alloys. In this case, volume fraction of α_2 phase in duplex-like region increased from 17% to 36%. On the other hand, when HIP treatment was performed at 1100 °C, γ band width increased compared with as-built material, and layered microstructure remained. Volume fraction of α_2 phase in duplex-like region decreased to 12%.

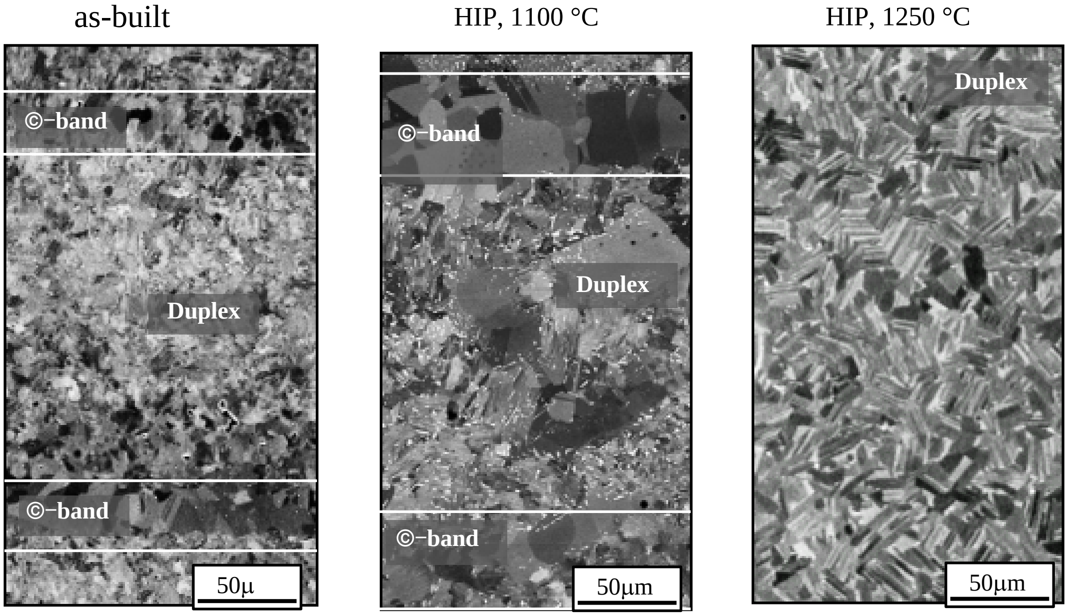

Fig. 7 Microstructural change in EBM-TiAl by HIP treatment at several

Table 2 Change of microstructures

	1100 °C	**1250** °C
γ-band	**Increased**	**Decreased strongly**
α_2 phase in duplex	**Decreased**	**Increased strongly**
Layered microstructure	**No change**	**All Duplex**

These microstructural changes can be explained by the phase diagram of Ti-Al system [9], which is shown in Fig. 8. Comparing the HIP treatments at 1100 °C and 1250 °C, it is clear that in case of 1100 °C, volume fraction of γ phase increases and also that of α_2 phase decreases. For this reason, it is obvious that by choosing the optimum HIP temperature, defects and pores can be effectively eliminated while maintaining the layered microstructure of γ bands and duplex-like region.

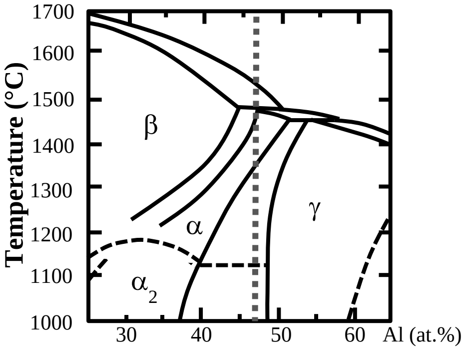

Fig. 8 Ti-Al binary phase

3.2 Effect of HIP treatment on mechanical properties of the EBM-TiAl

Room temperature tensile properties of as built and HIP treated material are shown in Fig. 9.

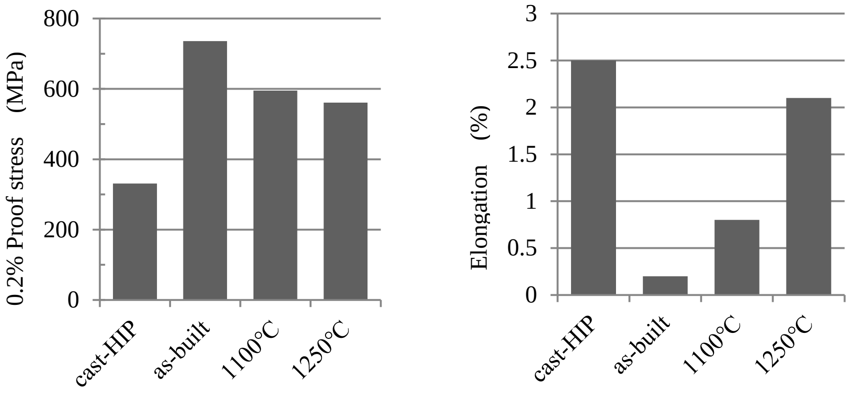

Fig. 9 RT tensile properties of EBM-TiAl before and after HIP treatment at several temperatures compared to that of cast material after HIP treatment

HIP treatment at 1100 °C has resulted in the yield strength of 550 MPa or higher, and elongation improved from 0.2% to approximately 1.0%. This improvement in ductility is derived from the increase in γ bands which contributes to the shear deformation. Compared with cast material [10], material HIP treated at 1250 °C shows the equivalent ductility, while maintaining higher yield strength. This high strength is derived from the finer grain size of EBM-TiAl than that of cast material.

Fig. 10 compares the room temperature fatigue properties of as-built and HIP treated material. An improvement is obvious in fatigue life particularly at smaller stress ampli[illegible]ely at a high-cycle fatigue life region. It is regarded that drastic reduction of defects and pores by HIP treatment suppresses the initiation of crack nucleus as well as the propagation rate of fatigue cracks. Also material HIP treated at 1100 °C exhibits higher fatigue strength of more than 400 MPa, compared with the one HIP treated at 1250 °C of 300 MPa. This indicates the beneficial presence of γ bands which effectively reduces the crack initiation by promoting strain reduction.

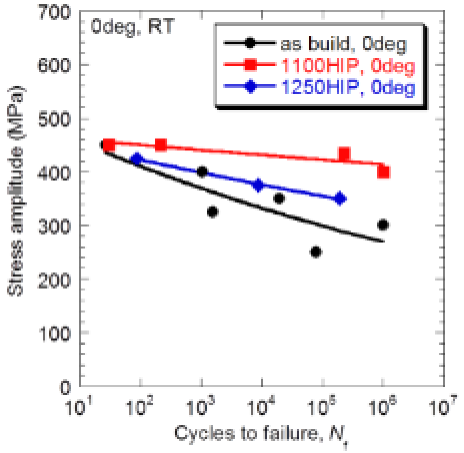

Fig. 10 Fatigue properties of EBM-TiAl before and after HIP treatment

From the results of this study, it is obvious that HIP treatment at optimum conditions can improve the mechanical properties of EBM-TiAl significantly. Since the as-build material manufactured in a 45 degree direction exhibits a high elongation of 2.5% or higher, it is expected that further improvements in tensile ductility as well as fatigue properties are possible with the adoption of HIP treatments.

4. Conclusions

Cylindrical rods of Ti-48Al-2Cr-2Nb alloy were additively manufactured by EBM method, and microstructural and mechanical properties of HIP treated materials were investigated. The main findings are briefly summarized below.

1. With HIP treatments at 1100 and 1250 °C, defects and pores found in as-build samples can be effectively eliminated.
2. It is possible to maintain the layered microstructure of γ bands and duplex-like region by performing HIP at 1100 °C, where γ band width increases while volume fraction of α_2 phase in duplex-like region decreases. On the other hand, HIP treatment at 1250 °C could not maintain the layered microstructure.
3. Mechanical properties of EBM-TiAl can be significantly increased through HIP treatments at 1100 or 1250 °C. Especially, HIP treatment at 1100 °C brings yield strength of more

than 550 MPa and at the same time tensile elongation superior to as built material. Fatigue properties are also improved.

HIP treatment is therefore a key manufacturing step for additively manufactured parts not only for TiAl but for other alloys to achieve high reliability and full density of fine microstructure at the same time.

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