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Effects of Heat Treatment on Unique Layered Microstructure and Tensile Properties of Tial Fabricated by Electron Beam Melting

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Abstract. In the present study, effects of heat treatment on microstructures and tensile properties of the cylindrical bars of Ti-48Al-2Cr-2Nb (at.%) alloy with unique layered microstructure consisting of equiaxed γ grains region (γ band) and duplex-like region fabricated by electron beam melting (EBM) were investigated. We found that it is possible to control width of the γ bands (W_γ) by heat treatments at 1100°C and 1190°C. The W_γ increases with decreasing heat treatment temperature. The bars heat-treated at 1190°C exhibit high elongation of 2.9% at room temperature (RT) with maintaining high strength. The RT elongation increases with increasing the W_γ because of increasing deformable regions. In contrast, the RT elongation of the bars decreases with increasing the W_γ when W_γ is very large. This is because the large γ band leads intergranular fracture. These results indicate that there is appropriate width for the γ band to obtain excellent tensile properties at RT.

Introduction

Titanium aluminide (TiAl) alloys are candidate materials for aerospace applications because of their excellent high temperature strength, low density (approximately 3.8 g/cm^3) and good corrosion resistance [1, 2]. Therefore, TiAl alloys have started to be used for low pressure turbine blades in an aircraft jet engine (e.g. GEnx engine) [3]. TiAl alloys have mainly been manufactured by precision investment casting today [4]. However, reactivity of TiAl alloys leads to oxidation and contamination by impurities from the casting mold [4]. Moreover, their poor room temperature (RT) ductility makes them difficult to process. To resolve these problems, a new manufacturing process for TiAl alloys is required for one of the solutions.

Recently, electron beam melting (EBM), one of additive manufacturing (AM) processes to fabricate metal parts, have been developed [5-7]. In EBM process, metal parts are easily fabricated by adding layer-on-layer of materials using an electron beam [5]. Moreover, it is possible to prevent from oxidation and contamination of the parts because that is vacuum and near-net process [6].

Therefore, EBM is one of the suitable manufacturing processes for TiAl alloys. Microstructures and mechanical properties of TiAl alloys fabricated by EBM and appropriate process parameters to fabricate TiAl alloys have been investigated [8-10].

Various microstructures of TiAl alloys such as fully lamellar consisting of Ti_3Al (α_2) phase and TiAl (γ) phase, duplex consisting of lamellar and γ grains, and near γ consisting of coarse γ grains can be obtained by heat treatment at different temperatures [1]. Moreover, mechanical properties of the alloys depend strongly on their microstructures [1].

In previous study, we found that the cylindrical bars of Ti-48Al-2Cr-2Nb (at.%, 48-2-2, hereafter) alloy fabricated by EBM with appropriate process parameters exhibit a unique layered microstructure consisting of equiaxed γ grains region (γ band) and duplex-like region perpendicular to building direction [11, 12]. This layered microstructure is closely related to the temperature distribution around the melt pool during the EBM process [11]. We also found that RT elongation of the bars is larger than that of conventional cast-TiAl alloys [11]. Moreover, the RT elongation of the bars fabricated at an angle θ between building and cylinder (loading) direction of 45° (θ = 45°) is higher than 2.5%. This is due to the localized shear deformation in the soft γ bands [11]. However, suitable morphology of the unique layered microstructure for improving RT ductility has not been investigated yet.

In the present study, microstructures of the 48-2-2 alloy bars fabricated by EBM at θ = 45° were controlled by heat treatments at various temperatures to improve RT ductility of the bars. Moreover, the relationship between microstructures and the tensile properties of the bars was clarified.

Experimental

48-2-2 alloy raw powder used in the present study was fabricated by Ar gas atomization. The average particle diameter of the raw powder is around 100 μm. The cylindrical bars of the alloy, 10 mm in diameter and 70 mm long, were fabricated using an Arcam A2X EBM system (Arcam AB, Sweden) at θ = 45°. These as-built bars were subjected to the heat treatment at 1100°C or 1190°C, followed by water quenching or furnace cooling, respectively. Hereafter, the bars annealed at 1100°C and 1190°C are referred to as HT1100 and HT1190, respectively.

The microstructures of the bars were observed using a scanning electron microscope (SEM) (JEOL, JEM-6500F). The specimens for SEM observation were cut by an electro-discharge machining from the center of the cylindrical bars and polished using waterproof emery papers up to 2000 grit and electrically polished in a perchloric acid: butanol: methanol (6: 35: 59 vol%) solution at 20 V for 5 min.

Tensile tests were conducted at RT at strain rate of 1.67×10^{-4} s^{-1} in vacuum using a universal testing instrument. The tensile test specimens of which gauge dimension is 1.5 × 0.7 × 5 mm were cut by an electro-discharge machining from the center of the bars. The surface of the tensile test specimens was polished using waterproof emery papers up to 2000 grit and a colloidal SiO_2 suspension. The fracture surfaces of the tensile deformed specimens were observed using a SEM.

Results and Discussion

Microstructures. Fig. 1 shows microstructures of 48-2-2 alloy bars fabricated by EBM before and after the heat treatments. The unique layered microstructure consisting of γ band and duplex-like region perpendicular to building direction can be found in the as-built bars. This layered microstructure is formed by repeated local heat treatment in the vicinity of the melt pool during EBM process [11]. It is noted that the average grain diameter in duplex-like region (lamellar grains and γ grains) is approximately 15 μm. These grains are much finer than that of the cast alloys (50–500 μm) [13]. It is also noted,

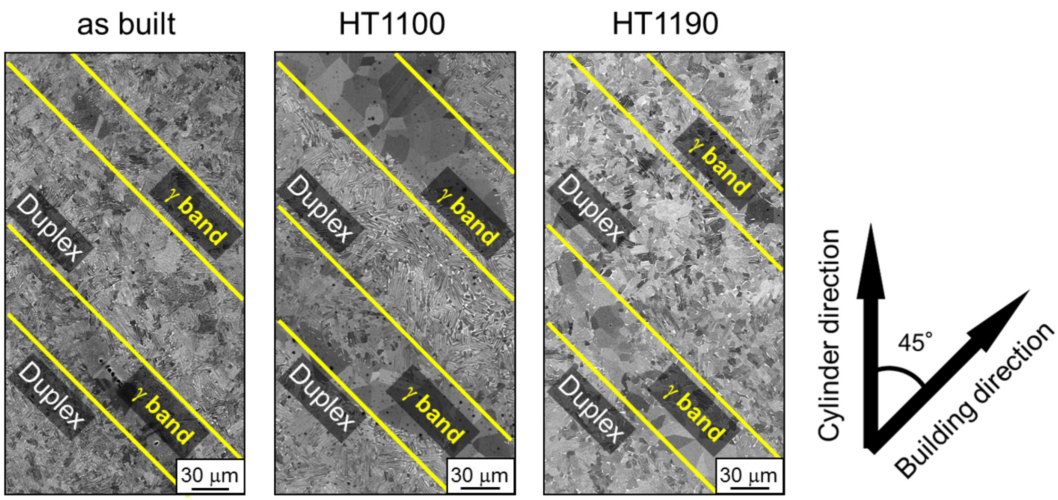

Fig. 1. SEM images of the alloy bars fabricated by EBM before and after heat treatments at 1100°C and 1190°C.

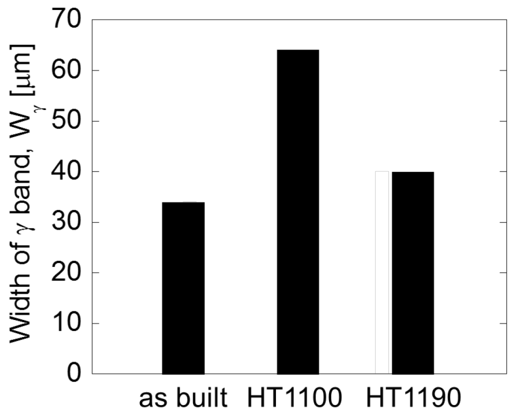

Fig. 2. Wγ of the alloy bars fabricated by EBM before and after heat treatments at 1100°C and 1190°C.

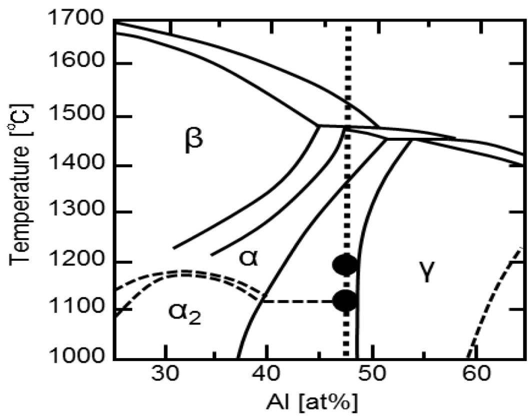

Fig. 3. Ti-Al binary phase diagram.

that the heat-treated bars also exhibit the layered microstructure. Fig. 2 shows the width of γ band (W_γ) for the studied bars evaluated from the SEM images. The W_γ of as-built bars is approximately 34 μm. On the other hand, the W_γ of HT1100 and HT1190 are 64 μm and 40 μm, respectively. The increase in W_γ after the heat treatments can be understood according to the Ti-Al binary phase diagram [1]. As shown in Fig. 3, at 1100°C, the fraction of the γ phase is larger than that of the α_2 phase, according to the lever rule. On the other hand, the fraction of the γ phase and the α_2 phase decreases and increases, respectively, at 1190°C compare to at 1100°C. Thus, the morphology of the γ bands reflects the fraction of the constituent phases; higher fraction of γ phase at 1100°C results in higher W_γ.

Tensile properties. Fig. 4 (a) shows 0.2% proof stress ($\sigma_{0.2}$) of the bars fabricated by EBM before and after the heat treatments. The $\sigma_{0.2}$ of the as-built bars, HT1100 and HT1190 are 529 MPa, 698 MPa and 478 MPa, respectively. Thus, the $\sigma_{0.2}$ of these bars are higher than that of the cast alloys (more than 350 MPa) [2]. This is because the average grain diameter in the duplex-like region is smaller than that of the cast alloys.

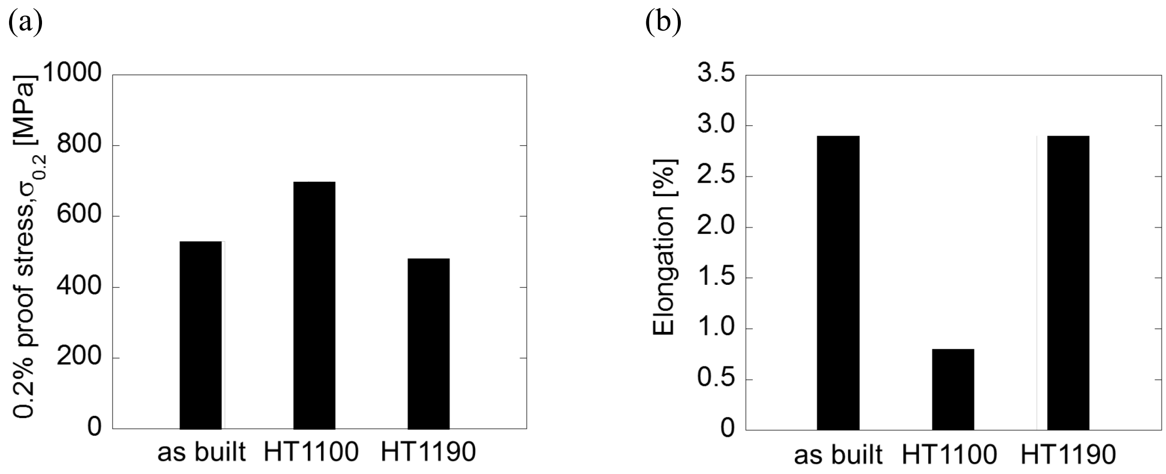

Fig. 4. 0.2% proof stress (a) and room temperature elongation (b) of the alloy bars fabricated by EBM before and after heat treatments at 1100°C and 1190°C.

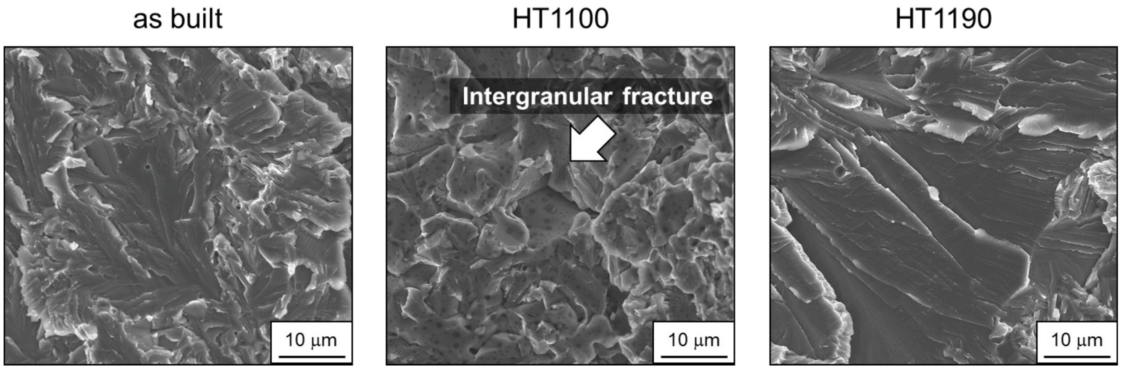

Fig. 5. SEM fractographs after tensile test at RT of the alloy bars fabricated by EBM before and after heat treatments at 1100°C and 1190°C.

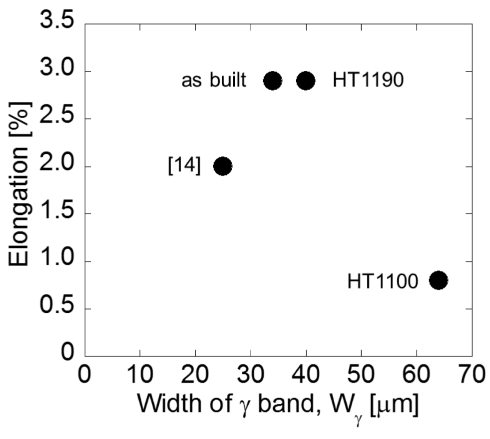

Fig. 6. Room temperature elongation of alloy bars as a function of the W_γ.

The RT elongations of the alloy bars fabricated by EBM before and after the heat treatments are shown in Fig. 4 (b). After the heat treatment at 1100°C, the elongation drastically decreases to 0.8%. On the other hand, the alloy bars annealed at 1190°C keep the elongation above 2.5%. In order to investigate the fracture mechanism of the alloy bars, the fracture surfaces of the tensile deformed specimens were observed by SEM (Fig. 5). It is noted that the intergranular fracture in the γ bands can be observed on the fracture surfaces of HT1100, whereas the as-built bars and HT1190 show transgranular fracture in the γ bands. This means that the decrease in the RT elongation at HT1100 is due to the intergranular fracture in the γ bands.

Fig. 6 shows RT elongation of the alloy bars as a function of the W_γ, along with that of the alloy bars [14] with small W_γ. The elongation increases with increasing W_γ up to 40 μm since the γ bands are soft and deformable. However, further increase in W_γ results in a decrease in elongation due to the intergranular fracture in the γ bands. In fact, the intergranular fracture takes place in HT1100 with high W_γ, as shown in Fig. 5. This result indicates that an optimum W_γ to obtain high ductility at RT is in the range of approximately 30-40 μm.

Summary

Effects of heat treatments on microstructures and tensile properties of 48-2-2 alloy bars fabricated by EBM were examined focusing on the unique layered microstructure. The following conclusions can be drawn from the present study:

1. The grains in the duplex-like region of the bars are much finer than that of the cast alloys. The width of the γ band, W_γ of the bars heat-treated at 1100°C (HT1100) is greatly larger than that of the as-built before heat treatment. On the other hand, the width of the γ band in the bars heat-treated at 1190°C (HT1190) is slightly larger than that of the as-built before the heat treatment.

2. The $\sigma_{0.2}$ of the alloy bars are higher than that of the cast alloys. After the heat treatment at 1100°C, the elongation of the bars drastically decreases to 0.8% due to the intergranular fracture in the γ bands. On the other hand, the alloy bars annealed at 1190°C, which show the transgranular fracture in the γ bands, keep the elongation larger than 2.5%. In contrast, HT1100 shows the intergranular fracture in the γ bands.

3. The RT elongation increases with increasing W_γ up to 40 μm because of large deformability of the γ bands and shows a maximum above 2.5%. However, the elongation decreases by further increase in W_γ due to the intergranular fracture in the γ bands. The appropriate W_γ to obtain large ductility at RT is in the range of approximately 30-40 μm.

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