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Additive Manufacturing of Titanium Aluminides for Aircraft Engine Applications

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Titanium aluminide (TiAl) alloys have been widely used for low pressure turbine blades of aircraft engine due to their excellent strength-to-weight ratio and good oxidation resistance. However, contamination from crucible and oxidation during precision investment casting are hard to avoid. Recently, electron beam powder bed fusion (EB-PBF), one of the additive manufacturing processes, has attracted much attention to fabricate TiAl low pressure turbine blades since the process can build 3D objects with arbitrary shape while suppressing contamination and oxidation. It is also noted that microstructure and mechanical properties of TiAl alloys can also be controlled by EB-PBF process. For instance, Ti-48Al-2Cr-2Nb (at.%) alloys mainly consist of the α_2 and γ phases with the $D0_{19}$ and $L1_0$ structures, respectively. The microstructure depends strongly on an input energy density depending on the process parameters such as beam current, scanning speed and scanning pitch. At appropriate energy densities, peculiar banded structure composed of fine duplex structure and a chain of equiaxed γ grains (γ band) is formed, which results from the temperature distribution around a melt pool and repeated powder feed/fusion cycles during the EB-PBF process. The mechanical properties of TiAl alloys fabricated by EB-PBF are closely related to the microstructure. If the angle between a tensile axis and the γ bands is 45°, large elongation can be obtained at room temperature, which is favorable for the practical applications. This is because the soft γ phase is parallel to maximum shear stress plane. High temperature strength, fatigue and creep properties of the alloys also depend on the microstructure. However, since the banded structure is so sensitive to the energy densities, microstructure of the large product varies from area to area. In the present study, a new scan strategy of EB-PBF is proposed to obtain TiAl alloys with homogenous banded structure throughout the product.

NOMENCLATURE

E = input energy density during EB-PBF process
θ = angle between building direction and longitudinal direction of the cylinder specimen fabricated by EB-PBF
U = beam voltage
I = beam current
v = scanning speed
p = scanning pitch
d = powder layer thickness at each cycle

1. Introduction

Titanium aluminide (TiAl) is an intermetallic compounds with the $L1_0$ structure. In the last three decades, extensive efforts have been made in developing TiAl alloys as high temperature structural materials because of its excellent strength-to-weight ratio and good oxidation resistance[1-3]. Recently, TiAl alloys have been used as low pressure turbine blades of an aircraft jet engine. In general, TiAl turbine blades are fabricated by precision investment casting. However, contamination from a crucible and oxidation during casting are hard to avoid. So, huge amount of the surface layer is removed by grinding.

Additive manufacturing (AM) has attracted much attention since the process can build 3D object with arbitrary shape. In particular, electron beam powder bed fusion (EB-PBF), one of the AM processes, is effective in fabricating TiAl turbine blades, since the process can minimize the contamination and oxidation[4,5]. Ti-48Al-2Cr-2Nb (at.%, 48-2-2, hereafter) low pressure turbine blades fabricated by EB-PBF will be installed in GE9X engine. It is also interesting to note that peculiar banded structure is created in 48-2-2 alloys after EB-PBF process and the structure strongly influences the mechanical properties[6,7]. In this paper, we report on the microstructure and mechanical properties of 48-2-2 alloys fabricated by EB-PBF, focusing on the process parameter.

2. Microstructure and Mechanical Properties of EB-PBFed 48-2-2 Alloys

2.1 Microstructure of EB-PBFed TiAl Alloys

Cylindrical rods of 48-2-2 alloys, 10 mm in diameter, were fabricated by EB-PBF at different angles θ between the cylinder and building directions, as schematically illustrated in Fig. 1 (a). The microstructure depends strongly on an input energy density E during EB-PBF, given by,

$$E = UI/vpd \qquad (1)$$

where U is the beam voltage, I is the beam current, v is the scanning speed, p is the scanning pitch and d is the powder layer thickness at each cycle (Fig. 1 (b)). The microstructure of 48-2-2 alloys consists of the γ phase with the $L1_0$ structure and small amount of the α_2 phase with the $D0_{19}$ structure and can be classified into four structures: “full-lamellar”, “near-lamellar”, “duplex” and “near-γ”[1). (i) full-lamellar: lamellar grains with the α_2 and γ phases, (ii) near-lamellar: lamellar grains with small γ grains, (iii) duplex: a mixed structure of fine lamellar and γ grains, (iv) near-γ: equiaxed γ grains with small amount of the α_2 grains. At higher E, the lamellar structure or the duplex structure is preferentially formed while the near-γ structure can be seen at lower E. It is well known that the microstructure of TiAl alloys changes with decreasing annealing temperature in the following order: full-lamellar, near-lamellar, duplex and near-γ structures. For instance, higher E results in higher temperatures during the EB-PBF process. Thus, higher E is favorable for the formation of the lamellar and the duplex structure while near-γ structure is formed at lower E. It is also interesting to note that peculiar banded structure composed of the duplex structure and a chain of equiaxed γ grains (γ band) is formed at middle E (Fig. 2). Moreover, the γ band is always perpendicular to the building direction, regardless of θ. The formation of the banded structure is closely related to the temperature distribution around the melt pool during the EB-PBF process. When an electron beam is irradiated on the powder bed, temperature decreases with increasing distance from the top surface. Therefore, microstructure varies in the following manner from the top surface: full-lamellar, near-lamellar, duplex and near-γ structures. The near-γ structure corresponds to the γ band. Thus, a pair of the duplex structure and the γ band is formed at the bottom of the heat-affected zone. Next, the sample stage goes down and new powder layer is fed and then melted. As a result, new γ band is created and the distance between the γ bands is equal to d. In this way, the peculiar banded-structure is formed. Therefore, layer-on-layer process during the EB-PBF process is responsible for the formation of the banded structure.

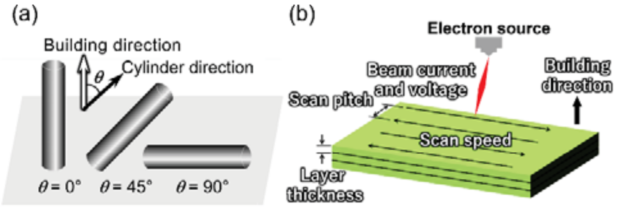

Fig.1 (a) A schematic illustration of cylindrical rods built at ,
(b) process parameters of EB-PBF process.

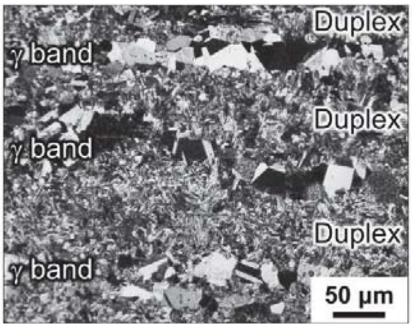

Fig. 2 Peculiar banded structure formed in EB-PBFed 48-2-2 alloys.

2.2 Mechanical properties of EB-PBFed 48-2-2 Alloys

Fig. 3 shows the yield stress and elongation of 48-2-2 alloys fabricated at different θ and then tensile-deformed at room temperature. The banded structure is found to strongly influence the mechanical properties of the alloys. The yield stress at $\theta = 45°$ is slightly lower than that at $\theta = 0°$ or 90°. On the other hand, the specimens built at $\theta = 45°$ exhibit a large elongation more than 2% even at room temperature. It is well known that low ductility at room temperature is a disadvantage of TiAl alloys. In TiAl alloys, the α_2 and γ phases act as strengthening and ductile phases, respectively. If the specimens are built at $\theta = 45°$, soft γ bands are parallel to a maximum shear stress plane, resulting in high ductility at room temperature. Below 800°C, the yield stress and elongation show small anisotropy depending on θ, while they are independent of θ at 800°C. Fatigue properties at room temperature are also dependent on θ. At room temperature, fatigue strength at θ=45° is higher than that of $\theta = 0°$ due to high fracture toughness. On the other hand, fatigue strength is nearly independent of θ at 750°C. At 760°C, minimum creep rate at $\theta = 45°$ is slightly higher than that at $\theta = 0°$ and 90°. However, creep properties of EB-PBFed 48-2-2 alloys at 760°C is comparable to that of cast TiAl alloys.

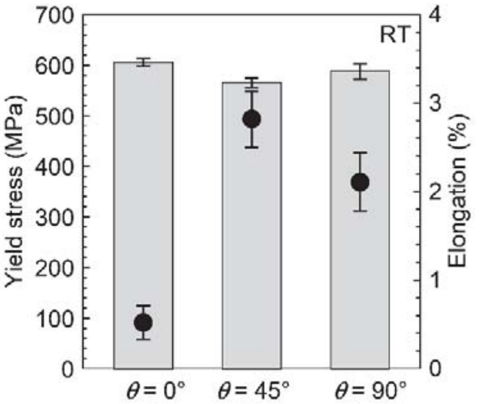

Fig. 3 Yield stress and elongation of 48-2-2 alloys fabricated at different and then tensile-deformed at room temperature.

2.3 Fabrication of TiAl Large Product by EB-PBF

If we build a large product of 48-2-2 alloys with complicated shape such as turbine blade, temperature distribution around melt pool becomes inhomogenous, resulting in the formation of inhomogeneous microstructure. Thus, in order to get homogenous microstructure throughout the product after EB-PBF, process parameter is changed for each location. As a result, TiAl turbine blades with homogenous banded-structure inclined at 45° from the longitudinal direction can be fabricated. The turbine blades show a large tensile elongation (>2%) at room temperature, similar to the cylindrical rods. Hot isostatic pressing (HIP) and grinding process after the EB-PBF process are also successful (Fig. 4).

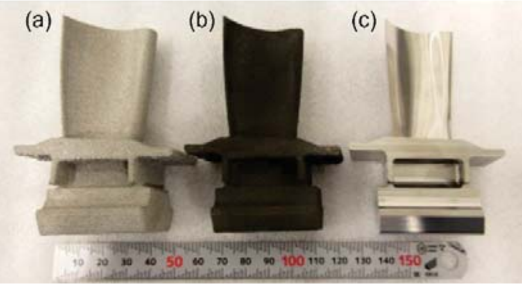

Fig.4 48-2-2 turbine blades fabricated by EB-PBF process. (a) as built, (b) HIPed and then (c) grinded.

3. Conclusions

Microstructure and mechanical properties of 48-2-2 alloys are found to depend strongly on input energy density during the EB-PBF process. In particular, peculiar banded structure is formed at an appropriate process parameter. If the cylindrical rods are fabricated at $\theta = 45°$, large elongation above 2% is obtained at room temperature, since γ bands are aligned parallel to a maximum shear stress plane. Homogeneous banded structure can be formed in the turbine blade by changing the process parameter at each location.

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