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Effect of process parameters on microstructure of TiAl alloy produced by electron beam selective melting

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Abstract

Pre-alloyed Ti-47Al-2Cr-2Nb powder was utilized to fabricate samples via electron beam selective melting. The microstructures of as-built components were characterized by optical microscopy, scanning microscopy and X-ray diffraction, while an electronic dispersive spectrometer was employed to study the chemical compositions. It is worth noting that the atomic percentage of aluminium decreased along with the increase of energy input. There appeared to be an element loss of aluminium up to 15% at the highest energy input. The microstructures consisted of lamellar α_2-Ti3Al)/γ-TiAl, basket-weave α_2 (Ti_3Al) and B2 phase. With varied melting beam currents, different phase transformations resulted from different thermal cycles and varied element losses of aluminium. γ-TiAl was the main phase of Sample-1 with the lowest energy input, while α_2-Ti_3Al was the main phase of Sample-4 with the highest energy input. The thickness of lamellar α_2 decreased as the cooling rate increased due to the increasing energy input.

Keywords: TiAl; Electron beam selective melting; Chemistry analysis; Microstructure

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1. Introductions

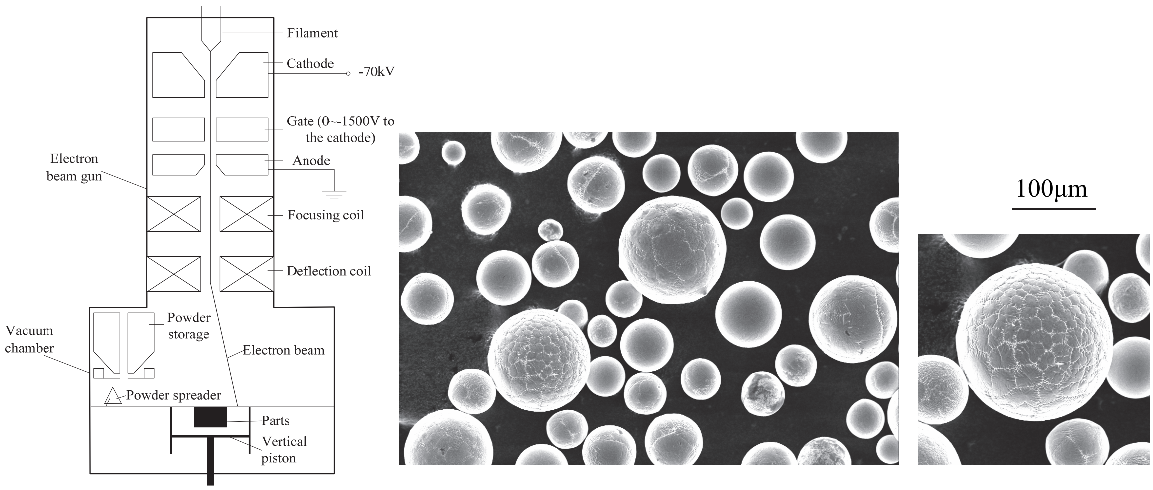
Gamma titanium aluminize alloys are gaining more and more attention as novel and practical candidates for automotive engines, aviation turbines and common industrial products. Two-phase gamma titanium aluminize alloys have a good combination of properties, such as a high melting point, low density and strength and stiffness retention with temperatures up to ~700 °C [1]. The properties of TiAl alloys strongly depend on the microstructures, especially the morphology of γ-TiAl and α2-Ti3Al phases. There are four types of microstructures in TiAl alloys, fully lamellar, nearly lamellar, duplex and equiaxial near-γ. Fully lamellar microstructures are most attractive for their good fatigue resistance, fracture toughness and creep resistance. The conventional fabrication methods of titanium aluminize alloys are casting, forging and powder metallurgy. However, these alloys have low ductility and toughness at ambient temperature and are difficult to process via conventional processing routes. Rapid prototyping is a promising technology to fabricate high-performance TiAl alloys. Srivastava, et al investigated the effect of fabrication parameters on the microstructures of direct laser fabricated Ti-48Al-2Mn-2Nb alloys [2]. Kalinyuk, et al fabricated Ti-6Al-4V samples using electron-beam melting [3]. Murr et al. fabricated solid and foam TiAl components using electron beam melting [4]. They also studied the microstructures and mechanical behaviour of as-fabricated and processed INCONEL alloy 625 components [5].

During the electron beam selective melting (EBSM) process, complex microstructures may form as the process contains continuous cooling and repeated heating. Fabrication parameters in the EBSM process, such as electron beam current and scanning velocity, will have a significant effect on as-built quality and microstructures. Thus it is important to understand the effect of fabrication parameters on the microstructures of TiAl alloys.

2. Experimental procedures

In order to investigate the effect of fabrication parameters on the microstructures, a series of fabrication experiments were conducted using the EBSM-250 system. Fig. 1a shows the schematic diagram of the EBSM-250 system designed by the Bio-manufacturing and Rapid Forming Technology Laboratory at Tsinghua University. The EBSM-250 system can mix two different kinds of powder and fabricate functionally gradient materials. In the system, an electron beam is generated in the electron gun and accelerated at a voltage of 60 KV. The electron beam is focused by a focusing coil and scanned by a deflection coil to preheat and selectively melt powders layer by layer.

Gas-atomized Ti-47Al-2Cr-2Nb powders were utilized as the raw material as shown in Fig. 1b. The 316L stainless steel plate used as the substrate was 10.mm thick and 80 × 80 mm in area. Before the forming process, the substrate was pre-heated to about 600 °C. Each powder layer was also pre-heated to be slightly sintered by employing a scanning beam current of 10mA and scanning velocity of 5 m/s. Then, specific areas of powder layer were melted with a higher energy input. The energy input depends on the scanning velocity, beam current and the size of the beam focus, which also decide the depth of the molten pool. In order to investigate the effect of energy input on the chemical compositions and microstructures, components measuring 2 × 2 ×5 mm were fabricated employing various melting beam currents, 4 mA for Sample-1, 6mA for Sample-2, 8 mA for Sample-3 and 10 mA for Sample-4. After the forming process was finished, the specimens remained in the vacuum chamber for approximately 4-5 hours to cool down to room temperature.



(a) (b)

Fig. 1. (a) EBSM-250 system schematic diagram. (b) SEM view of precursor Ti47Al2Cr2Nb powder.

The fabricated specimens were cut, mechanically ground, polished and then rinsed in ethanol. They were then etched utilizing Kroll's reagent (2% HF, 5% HNO_3 and 93% H_2O). The microstructures of the specimens were observed via a JSM-7001F field emission scanning electron microscope and the elemental analysis and phase analysis was conducted employing energy disperse spectroscopy and X-ray diffraction, respectively.

3. Results and discussion

3.1. Chemical composition

The chemical composition of build-up was tested by energy dispersive spectroscopy in FESEM. The results of the elemental analysis of the as-built specimens are listed in Table 1. From the results shown in Table 1, it can be seen that aluminum content can be lost dramatically at high beam energy. Compared with the raw powders, Sample-1 had no obvious change in chemical composition while Sample-2 and Sample-3 had Al loss of about 8% and 10%, respectively. Sample-4 showed a significant loss of approximately 15%, which turned out to be Ti3Al-based alloy. Chemical composition change will result in different phase composition and transition. As a result, the mechanical properties will be affected. The EBSM process has characteristics of rapid cooling and heat cycling which affect the microstructures of the as-built samples. The vacuum environment provided by the EBSM system can limit the pickup of impurities such as oxygen and carbon but induce the evaporation of lightweight element Al[6]. High beam current indicates high energy input. Element Al loss in Sample-4 was relatively high compared to Sample-2 and Sample-3.

Table 1. Chemical composition of as-built samples (atomic percentage).

	Melting beam current (mA)	Ti	Al	Cr	Nb
Sample-1	4	45.25	50.48	2.17	2.10
Sample-2	6	55.63	39.71	2.08	2.58
Sample-3	8	58.13	37.43	1.62	2.82
Sample-4	10	61.85	33.50	1.47	3.19

3.2. Microstructure characteristics

The microstructure of Sample-1 showed a typical continuous cooling transformation microstructure of TiAl alloy as the chemical composition had no change. Fig. 2a shows the typical lamellar α_2+γ, with lamellar colony sizing ~20μm. During the thermal cycles in the EBSM process, fine lamellar structure (Fig. 2b) formed in the different orientations of lamellar grain boundary. The XRD analysis of Sample-1 confirmed the presence of α_2-Ti3Al and γ-TiAl, and revealed the γ-TiAl as the main phase (Fig. 3).

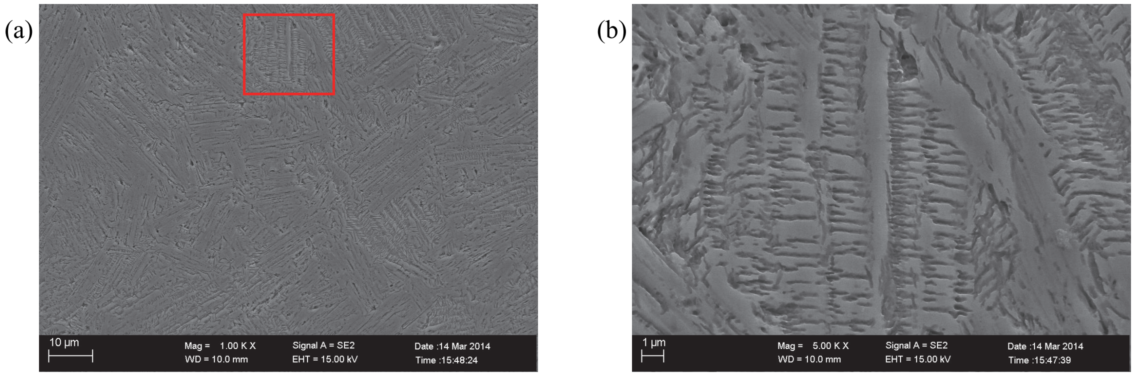


Fig. 2. Optical microscopy of Sample-2, Sample-3 and Sample-4 in the top region (a) and (b).

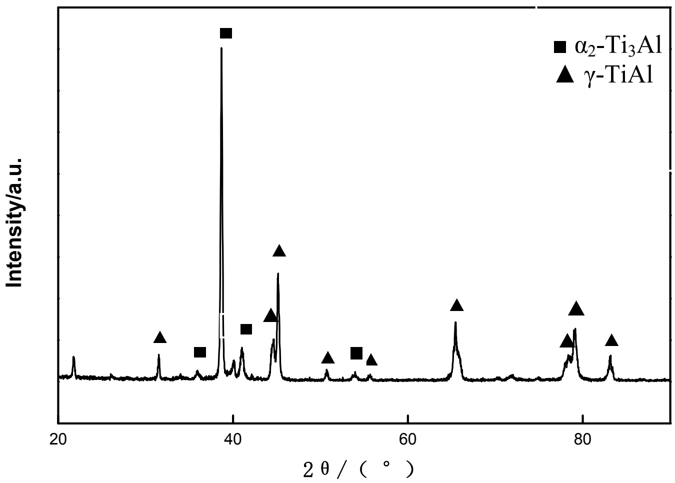


Fig. 3. XRD pattern of Sample-1.

The phase transformation in Sample-2, Sample-3 and Sample-4 was different from Sample-1 as a result of aluminum loss during the forming process. The microstructures of Sample-2, Sample-3 and Sample-4 contain columnar grains of β phase growing along the building direction with $\alpha_{2+}\gamma$ laths in β grains (Fig. 4). The XRD analysis of Sample-2 confirmed the presence of β phase and revealed α_2-Ti_3Al as the main phase (Fig. 6). Columnar grain sizes in Sample-2, Sample-3 and Sample-4 were approximately 150 μm in width, with needle-like

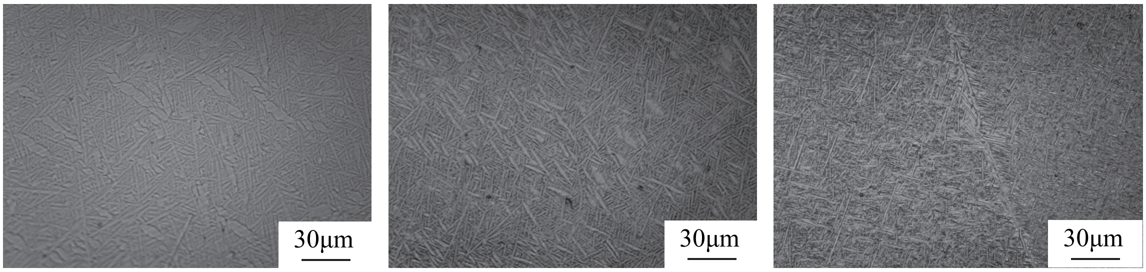
α_2 phase irregular arrangement in the beta matrix. In addition, the morphologies varied in the build-up sample parallel to the building direction. In the top region were fine needle-like laths and a small amount of irregular mass α_2 phase, while in the bottom region α_2 demonstrated lath and rod-like morphologies. Needle-like α_2-Ti_3Al becomes fine and short under different electron beam currents with a thickness of 1.5, 0.8 and 0.5 μm, respectively in Sample-2, Sample-3 and Sample-4. Heat dissipation is conducted through thermal radiation and heat conduction to the base plate and powder bed. The temperature of the base plate is approximately 600 °C. Solidification rate of each layer when cooling from melting temperature to 600 °C is very high. Lamellar α_2-Ti_3Al thickness decreases as the cooling rate increases and the relation between lamellar thickness and cooling rate is as follows:

$$\lambda = C\,(dT\,/\,d\tau)^{-1/2}\,, \tag{1}$$

where λ is the thickness of lamellar α_2-Ti_3Al, C the revision factor, T the temperature and τ the time.

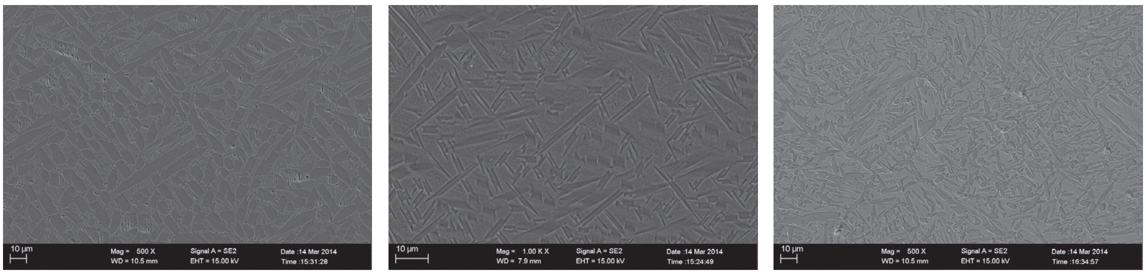
The as-formed layers experienced a continuous thermal cycle during the forming process. The thermal cycle resulted in changes in microstructures. Fig. 5 shows the microstructure in the bottom region of Sample-2, Sample-3 and Sample-4, where α2-Ti3Al was about 5 times coarser than that of the bottom region. Fine lamellar α2 phase decomposed and coarsened under the thermal cycle. Stefansson, et al found that there are two stages in the static heat treatment of Ti-6Al-4V [7]. The initial stage is the segmentation of the lamellar via boundary splitting and the latter stage is the microstructural coarsening. They also found that the segmentation stage is dependent on the formation and evolution of dislocation substructure and the driven force provided by the reduction in interface energy.

Li et al. pointed out that lamellar structure will coarsen in two ways in the process of heat treatment [8]. Continuous coarsening is governed by the body diffusion and discontinuous coarsening is governed by the interface. Coarsening of lamellar α2 phase depends on the migration of interface defects. During the coarsening process, α2 phase spheroidization occurs as a result of the Raleigh's breakdown. As shown in Fig. 2, the α_2 phase boundary is not straight, which provides the condition for instability of decomposition.



(a) (b) (c)

Fig. 4. Optical microscopy in top region (a) Sample-2, (b) Sample-3 and (c) Sample-4.



(a) (b) (c)

Fig. 5. SEM microscopy of coarsening α_2 in top region(a) Sample-2, (b) Sample-3 and (c) Sample-4.

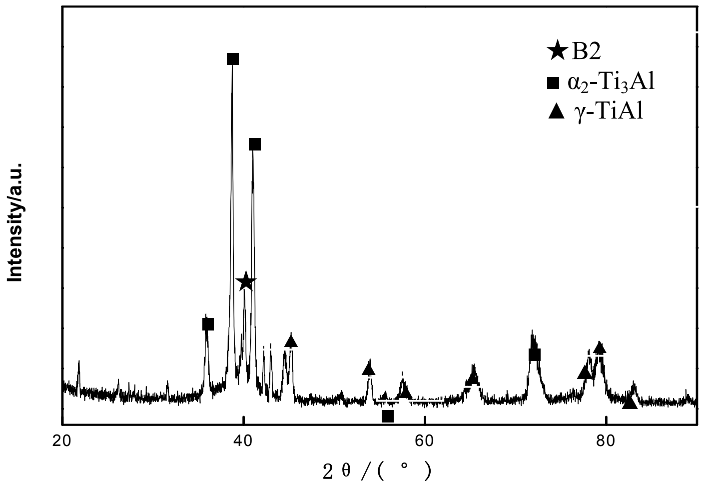


Fig. 6. XRD pattern of Sample-2.

4. Conclusions

In this study, Ti-47Al-2Cr-2Nb components were directly fabricated by electron beam selective melting. The chemical composition and microstructure showed a tight relationship with energy input. Aluminum had no loss in Sample-1 with a beam current of 4mA, while in Sample-2, Sample-3 and Sample-4 there was a loss of 8%, 12% and 15%, respectively. The microstructure exhibits lamellar structure in the top region and coarsening and spheroidization in the bottom. Laths α_2 phase sizes changed with energy input variation, and averaged ~1 μm in the top region and 5 μm in the bottom.

Acknowledgements

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