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ARTICLE

Microstructure and Mechanical Properties of Ti-6Al-4V by Electron Beam Rapid Manufacturing

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Abstract: Electron beam rapid manufacturing (EBRM) is a novel layer-additive manufacturing process which was developed to directly fabricate metal parts from computer aided design (CAD) data. The present study was conducted to evaluate the microstructure and the mechanical properties of Ti-6Al-4V by EBRM. Results show that typical microstructures exhibit large columnar β grains nucleated at the substrate and grew epitaxially along the height direction of deposits through many deposition layers, and alternately light and dark banded textures at layer-layer and bead-bead interfaces have been also found due to complex thermal history during deposition process. As a result, the tensile properties of the as-deposited and the as-annealed deposits exhibit distinct anisotropy. The strength in X and Y directions are similar and markedly higher than that in Z. No significant impact of annealing treatment has been found on room temperature tensile properties. Hot isostatic pressing (HIP) treatment obviously decreases the dispersion of the high cycle fatigue data and improves both ductility and toughness, while at the expense of the tensile strength. The tensile properties of the as-deposited and as-annealed Ti-6Al-4V by EBRM can meet the mechanical property requirements of AMS4999 standard, but can not fully meet the requirements of HB5432 standard.

Key words: electron beam rapid manufacturing; Ti-6Al-4V; microstructure; mechanical property

Electron beam rapid manufacturing (EBRM) is a novel layer-additive manufacturing process which was developed over the past decade to directly fabricate complex metal components from computer aided design (CAD) data. In a vacuum environment, a molten pool is created by electron beam on a substrate and moves along the paths designed by computer program. The metal wire is fed into the molten pool and deposited layer by layer to form a near net shape metal part. Compared to other direct metal deposition technology, the EBRM process has such superiorities as high deposition rate, for instance, in excess of 3500 cm^3/h for titanium or aluminum alloys[1], and excellent mechanical properties can be obtained which is comparable to those of wrought plate at some circumstances[2]. This process has wide-spread potential applications for fabrication of large aircraft and spacecraft structures with the benefits of lower cost and shorter depositing time than conventional casting, or forging[3-5].

Ti-6Al-4V produced by EBRM has been investigated by researchers from NASA Langley Research Center, Boeing Phantom Works, Lockheed Martin company and Sciaky company to evaluate this technology[6-8]. AMS4999 revised in 2011 by Boeing is a specification for as-annealed Ti-6Al-4V fabricated by direct deposition. It has been demonstrated that the properties of EBRM materials are influenced by such factors as the raw materials, forming process, heat treatment, shape of the structure, etc[9]. In this study, Ti-6Al-4V was produced by EBRM. After the annealing and HIP treatment, microstructure, tensile properties, impact toughness and high cycle fatigue in different directions were investigated to give a better understanding of the microstructure-property relation-

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ship for this kind of alloy.

1 Experiment

This study was performed on a EBRM machine of Science and Technology on Power Beam Processes Laboratory, Beijing Aeronautical Manufacturing Technology Research Institute (BAMTRI). The machine consists of a 10 kW/60 kV gun, a vacuum chamber of 1.2 m long, 0.6 m wide and 1.0 m high, wire-feeding assembly and 3-axis positioning worktable (*X, Y, Z*).

In the present experiment, Ti-6Al-4V wire with a diameter of 2.0 mm was used with nominal composition in accordance with GB/T 3623. Depositing parameters included a beam current with power setting of 35 mA at 60 kV, the wire feeding rate of 90 cm/min (0.75 kg/h), and the path travel speed of 30 cm/min. The gun-to-work distance was 30 cm, and the beam focus was above the part. The substrate was a Ti-6Al-4V rolled plate (2 cm thick, 17 cm long and 12 cm wide), and clamped to the worktable by bolts after cleaning. The deposition paths were parallel lines parallel to *X* direction. The layer was added along the height direction of the deposit，and each single layer was about 1.2 mm thick.

The sample built in this experiment is shown in Fig.1, and its size is about 150 mm long, 100 mm wide and 100 mm high. This sample was sliced into many plates of 20 mm-thickness. Then these plates were divided into three groups: the first

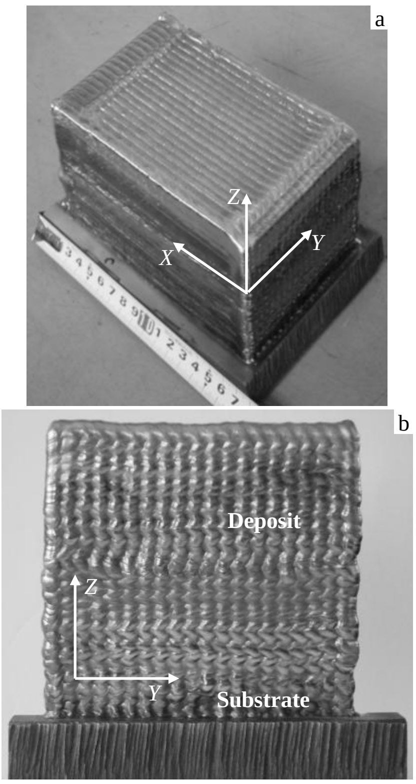

Fig.1 Ti-6Al-4V sample built by EBRM (150 mm× 100 mm × 100 mm)

Table 1 Tests scheme and the orientation of specimens

Tests content (room temperature)	Heat treatment and orientation of specimens		
	As-deposited	As-annealed	As-HIPed
Tensile	*X, Y, Z*	*X, Y, Z*	*X, Y, Z*
Impact	—	—	*X, Y, Z*
High cycle fatigue	*X*	—	*Z*

group was as-deposited, the second was soaked to a stress relief annealing (vacuum, 650 °C, 2 h, furnace cooling), and the third was subjected to a HIP treatment of 920 °C/110 MPa/2 h. The specimens for tension, impact and fatigue tests along *X*, *Y* and *Z* directions were prepared. The testing scheme and orientation of the specimens are shown in Table 1.

There were more than 5 tensile specimens for each heat treatment condition and orientation, not less than 10 for the impact toughness, and not less than 30 for fatigue.

2 Results and Discussion

2.1 Characteristics of microstructure

Fig.2 shows the macrograph of the Ti-6Al-4V bulk built by EBRM. In EBRM process, columnar β grains grow epitaxially along the contrary direction of thermal flux with the largest thermal gradient. And the columnar grains are capable of growing through many depositing layers from the substrate along the height direction of the deposit. The moving speed and the direction of heat source have a significant impact on the thermal gradient. Axes of the prior β grains will incline toward the beginning of the paths if the heat source moving along single direction in a layer. However, in the present experiment, the heat source moving paths are to-and-fro; therefore, the axes of the prior β grains are perpendicular to the faceplate of the substrate.

The prior β grain size is varying in a deposition and the average width grows from 0.5~2 mm to 10~15 mm, and the average length increases from 2~5 mm to 20~30 mm from the substrate to the top of the part during depositing. With the cumulation of heat in the part, the thermal gradient decreases and the temperature rises, which may accounts for the β grain growth along the height of the EBRM part. Even at the same height in a complex component, the β grain size may be distinctly different due to the different heat dispersing conditions. It is necessary to optimize the deposition process or carry out subsequent heat treatments to minimize the unfavorable influence resulting from the microstructure heterogeneity of β grains.

Alternately light and dark banded textures exist around the layer-to-layer and bead-to-bead boundaries all over the section of the deposit, exhibiting parallel stripes in *XZ* section (Fig2.b) and meshy network in *YZ* section perpendicular to the depositing paths (Fig.2c). The origin of the banded textures are similar to the heat affect zone (HAZ) occurring in welding. The deposition consists of many beads formed by moving

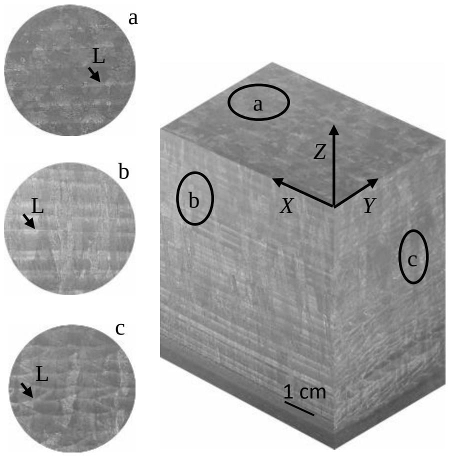

Fig.2 Macrograph of the Ti-6Al-4V bulk built by EBRM: (a) *XY* section, (b) *XZ* section, and (c) *YZ* section

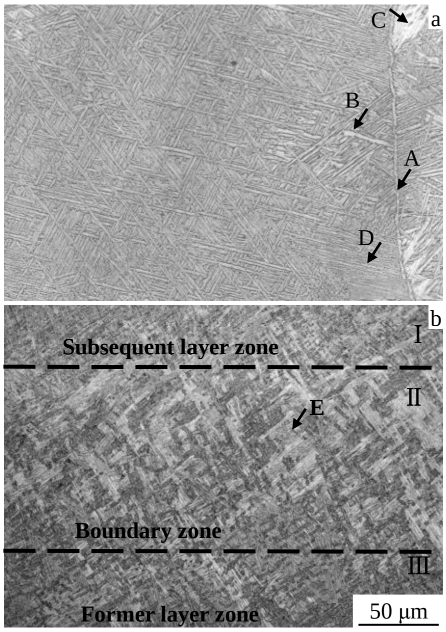

Fig.3 Microstructure of the EBRM Ti-6Al-4V: (a) weaved fine acicular α laths, α bunches and continuous grain boundary α; (b) microstructure around interlayer boundaries

molten pool with feeding wire along the paths. Therefore, the prior solidified metal close to the fusion boundary is reheated by subsequent depositing of beads, and the $\alpha\rightarrow\beta\rightarrow\alpha'$ or $\alpha+\beta$ phase transformation will happen during this transient heating and cooling process. The resulting microstructure is exhibited in Fig.3b. The banded textures reflect the actually gradient microstructure caused by thermal gradient resulting from the complex thermal history during deposition. Therefore, it may be not so apparent or even disappear when the temperature is very high and the thermal gradient is small in the part; on the contrary, if the temperature of the deposition is comparatively lower and the thermal gradient is large, the banded textures will be obvious.

The microstructures of the as-deposited Ti-6Al-4V are shown in Fig.3. Basketweave microstructure can be found within a layer which composed of fine acicular α laths, and fine continuous α phase is found along former β grain boundaries, as indicated by A arrow in Fig.3. In some local areas, coarsened α laths can be found, as shown by arrow B in Fig.3 and α colony composed of parallel α laths is found on both sides of the former β grain boundaries, as shown by C and D arrows in Fig.3.

The shape and the size of α laths are found to vary with the position. Fig.3b shows the microstructure near the interlay region. For the sake of description, this region is divided into three parts as illustrated in Fig.3b. It is found that the horizontal lines between the light and dark zone in Fig.2 (labeled as L) consist of α colonies with parallel α plates (see E area in Fig.3b). The microstructures change from coarsened strip α laths at the top of the former layer zone to fine needle-like α laths at the bottom of the subsequent zone. And Widmänsttten consisting of α bunches are within the boundary zone. It is believed that the temperature is above the β transus temperature, and $\beta\rightarrow\alpha'$ occurs upon cooling which leads to formation of fine needle-like α' laths. However, in the former layer zone, region III in Fig.3b, temperature is just high enough to trigger $\alpha'\rightarrow\alpha+\beta$ phase transformation, and α laths grow to the size close to that of the grain boundary α.

2.2 Characteristics of mechanical property

2.2.1 Room temperature tensile property

Fig.4 shows the tensile properties of EBRM Ti-6Al-4V in as-deposited, annealed and as-HIPed conditions, and each datum in Fig.4 is an average of five tensile data. Table 2 exhibits the required minimum tensile properties of annealed Ti-6Al-4V produced by direct deposition in AMS4999 revised by Boeing in 2011, and that of wrought plates in HB5432 of China revised in 1989. Differences can be found by comparing the data in Fig.4 and Table 2.

(1) Anisotropy of tensile properties

The tensile properties in deposited, annealed and HIP conditions all exhibit an anisotropy and this phenomenon is specially distinct in the former two conditions. Among the *X*, *Y* and *Z* directions, the highest ultimate strength and yield strength are found in *X* direction while the lowest is found in *Z* direction in deposited and annealed conditions. The difference of ultimate strength between *X* and *Y* directions is less pronounced (22 MPa) than that between *X* and *Z* directions (61 MPa). After annealing treatment, the anisotropy becomes more distinct, and the difference of ultimate strength between *X* and *Y* directions increases to 38 MPa and that between *X* and *Z* directions increases to 73 MPa. On the contrary, HIP treatment decreases the anisotropy, and the strengths in different directions are close while the ductility still exhibits anisotropy.

(2) Heat treatment impact on tensile properties

Fig.4 indicates that a relief stress annealing treatment at 650 °C has no significant impact on the tensile properties. In as-HIPed conditions, the anisotropy of strength is reduced, accompanied with distinct decrease of both ultimate and yield strength in all the three directions, and the decrease in *X* and *Y* directions is more pronounced than that in *Z*. For instance, the ultimate strength of the as-deposited Ti-6Al-4V is 907 MPa in *X* direction, which is corresponding 809 MPa in the as-HIP conditions, and the difference is 98 MPa. However, in *Z* direction, the decrease is only 30 MPa, i.e., from 846 MPa in the as-deposited condition to 816 MPa in the as-HIPed condition. Meanwhile, HIP treatment increases the ductility in all three directions.

(3) The difference of the present tensile properties with that in the specifications

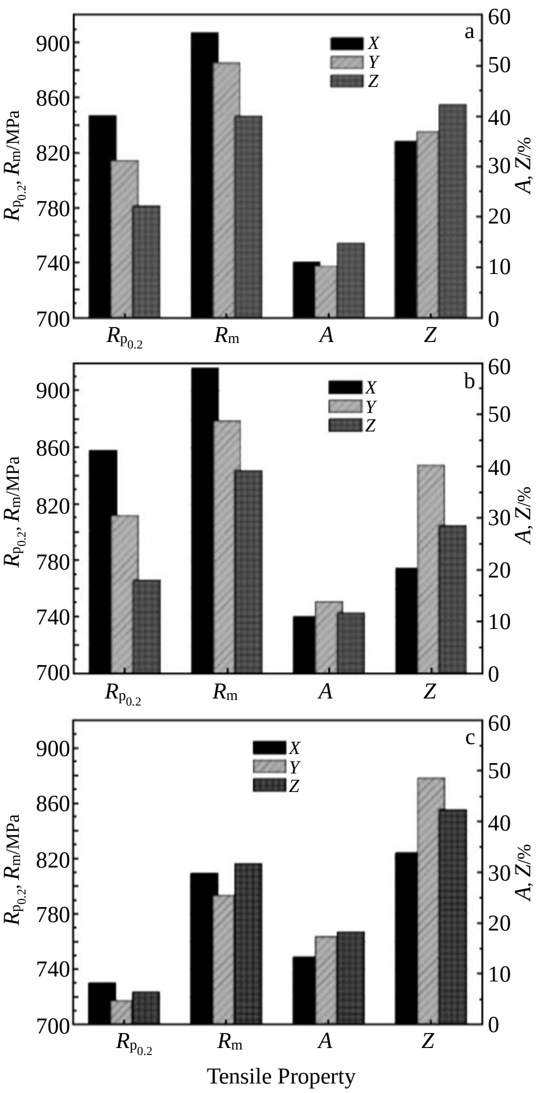

Fig.4 Tensile properties in three directions (*X*, *Y*, *Z*) of EBRM Ti-6Al-4V alloy under as-deposited (a), as-annealed (b), and as-HIPed (c) conditions

Table 2 Tensile specifications of Ti-6Al-4V in AMS4999 and HB5432

Specifications	Ultimate strength/MPa	Yield strength/MPa	Elongation/ %
HB5432 (China) Wrought plates (δ≤150 mm)	≥895 (*X*, *Y*, *Z*)	≥825 (*X*, *Y*, *Z*)	≥10 (*X*, *Y*, *Z*) ≥8 (Z)
AMS4999 (USA) Direct deposited products (annealed)	≥889 (*X*, *Y*) ≥855 (*Z*)	≥799 (*X*, *Y*) ≥765 (*Z*)	≥6 (*X*, *Y*) ≥5 (*Z*)

The ductilities in the as-deposited, as-annealed and as-HIPed conditions are all comparable to that of wrought plate (δ≤150 mm) in HB5432, which is a specification used in Chinese aerospace industry. It is clear that the mean values of ultimate and yield strength of the as-deposited and as-annealed EBRM TC4 in *X* direction are slightly above and those in *Y* direction are slightly below the minimum requirement, and those in *Z* direction are significantly below the requirement and the gap is about 50 MPa. The strengths of the as-HIPed are distinctly below the requirement by 79~100 MPa. AMS4999 is an aerospace material specification of the USA, which defines the acceptance criteria of annealed Ti-6Al-4V produced by direct deposited process. In the present experiment, both the mean values of strength and ductility are comparable to the AMS4999 requirements.

(4) The effect of microstructure on tensile properties

In reviewing the tensile test data and the macrograph of the EBRM Ti-6Al-4V, it can be believed that the large β grains along the height direction may be the main cause for the anisotropy of tensile properties. Since the annealing temperature is 650 °C, and the microstructure can not change remarkably, in turn which leads to little change of the tensile properties for this kind of titanium alloy. In the HIP condition, the material is subjected to a temperature high in the $\alpha+\beta$ phase field for a long time then followed by a low cooling rate comparable to furnace cooling, which leads to coarsening of both primary α laths and secondary α in transformed β phase. As a result, the strength decreases and ductility increases.

2.2.2 Room temperature impact energy

Room temperature impact tests were carried out and the results are shown in Fig.5. The specimens were in the as HIPed condition, and the impact energy in three directions (*X*, *Y*, *Z*) were studied. “U” grooves were machined on the *XY* surfaces for the specimens in *X* and *Y* directions and for specimens in *Z* direction, grooves were on the *ZY* plane. The results show that the impact toughness of the as HIPed EBRM Ti-6Al-4V also exhibits an anisotropy like tensile properties, and the impact energies are higher in *X* and *Y* directions (the mean value is about 101 J/cm^2) than in *Z* direction (the mean value is about 80 J/cm^2). All the data are above the minimum requirement in HB5432 (≥35 J/cm^2).

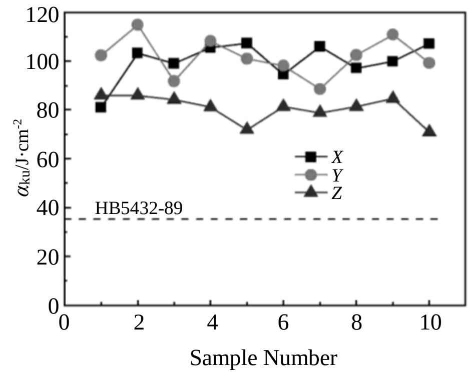

Fig.5 Room temperature Impact toughness α_{ku} of Ti-6Al-4V as-HIPed in three directions (*X*, *Y*, *Z*); selected 10 samples on *X*, *Y*, *Z* directions, respectively (as Fig.2 show)

2.2.3 High cycle fatigue property

It is illustrated in the present experiment that the tensile strength in *X* direction obviously is higher than that in *Z* for as-deposited EBRM Ti-6Al-4V. High cycle fatigue tests (K_t=1, R=0.1) were performed on the specimens in *X* direction under as-deposited condition and in *Z* direction under as-HIPed condition in order to estimate the difference of fatigue properties between the two directions.

The results are given in Fig.6. It can be seen that the fatigue limits are similar, 565 MPa in *X* direction and 545 MPa in *Z* direction. However, the curves are clearly different. At high stress level above 660 MPa and low stress level near the fatigue limit, the *S-N* curve in *X* direction is above that in *Z* direction. The data of the as-HIPed material exhibit less scatter than those of the as-deposited in *X* direction. As high cycle fatigue is sensitive to defects existing in the fatigue specimens, the present tests indicate that the HIP treatment may efficiently help to eliminate the defects produced in the deposition process. As a result, the reliability and the security of the parts subjected to fatigue loading may be increased by HIP treatment.

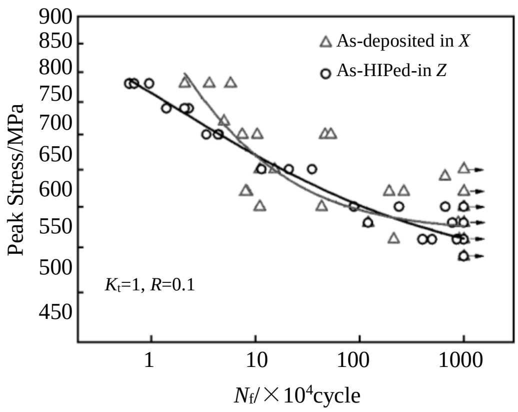

Fig.6 High cycle fatigue *S-N* curves of EBRM Ti-6Al-4V in *X* and *Z* directions

2.2.4 Discussion on methods to improve property

The materials, the deposition process and the subsequent heat treatment have significant impacts on the mechanical properties of direct deposited Ti-6Al-4V. The following ways are believed to be capable of improving the properties.

(1) As the EBRM is carried out in vacuum environment, aluminum in the alloy tends to volatilize which results in decreasing of the strength. The proper control of the contents of aluminum and oxygen can increase the strength of the material.

(2) HIP treatment can decrease the scatter of fatigue data and improve the reliability at the expense of strength reduction. The strength can be improved by performing solution plus aging treatment after HIP.

(3) The optimizing of the deposition process by increasing the thermal gradient can refine the microstructure and improve the strength.

3 Conclusions

1) A typical microstructure is characterized by large columnar β grains throughout many deposition layers and alternately light and dark banded textures at interlayers and inter-beads boundaries due to complex thermal history during deposition.

2) The tensile properties in the as-deposited and as-annealed conditions exhibit distinct anisotropy.

3) The strength in *X* and *Y* direction are similar and distinctly higher than that in *Z* direction.

4) Annealing treatment has a insignificant impact on room temperature tensile properties. HIP treatment obviously decreases the dispersion of high cycle fatigue data, and improves the ductility and the toughness at the expense of tensile strength. The tensile properties of as-deposited and as-annealed EBRM Ti-6Al-4V can meet the requirements in AMS4999 but fail to meet all the requirements in HB5432.

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电子束快速成形 Ti-6Al-4V 合金的组织与性能

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摘　要：电子束快速成形是一种利用金属丝材沉积直接制造金属零件的新型增材制造技术。用电子束快速成形方法制备了 Ti-6Al-4V 合金，对其显微组织和快速成形态、退火态、热等静压态下的力学性能进行了研究。电子束快速成形 Ti-6Al-4V 合金的低倍组织典型特征为沿堆积高度方向生长的贯穿多层沉积层的粗大柱状晶以及分布于层间及堆积路径间的明暗相间的带状条纹。各种状态下室温拉伸性能均有明显的方向性，其中 *X* 向、*Y* 向强度较高，*Z* 向强度低但塑性较好；消应力退火处理对室温拉伸性能没有明显影响；热等静压处理后材料的抗拉伸强度显著降低，但具有良好的塑性与韧性，同时能够明显降低高周疲劳性能数据的分散性。快速成形态及退火态室温拉伸性能均可满足 AMS4999 标准的要求，但与锻件标准 HB5432 相比仍有差距。

关键词：电子束快速制造；Ti-6Al-4V；显微组织；力学性能

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