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ARTICLE

Effects of Deflection Scanning of Electron Beam on Microstructure, Hardness and Treated Depth of TC18 Titanium Alloy

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Abstract: The high frequency deflection scanning of vacuum electron beam technology (DSEB) with line by line scanning mode and no overlap was employed to treat the surface of TC18 titanium alloy, for obtaining a homogeneous hardened surface layer. The purpose of the present work was to investigate the effects of critical process parameters, including beam current, focus current and treatment times, on the microstructure, hardness and treated depth of the treatment area. The treated specimens were characterized by SEM, optical microscope, and Vickers hardness tester. After treated by DSEB, the hardened surface layer is formed, which is mainly consisted of the acicular martensite, and the surface hardness of the treatment area is improved. Moreover, the microstructure of the hardened zone is homogeneous and has no obvious transition at the contact parts of two adjacent electron beams scanning. The depth of the hardened zone can be more than 200 μm and basically constant. These results show that DSEB is a very promising technological solution for the surface heat treatment of titanium alloy of large area and complex components.

Key words: deflection scanning of electron beam; surface hardening; acicular martensite; hardness

In recent years, more and more surface modification technologies such as ion implantation, magnetron sputtering, plasma spraying, and laser beam have been employed to improve the titanium alloy surface properties (e.g., surface hardness, wearable property and corrosion resistance). In general, the films of ion implantation and magnetron sputtering are very thin, only about a few microns or less[1-4]. Compared with ion implantation and magnetron sputtering, the coating thickness of plasma spraying can reach dozens or hundreds of micrometers, but the adhesive strength of the coating is low, which usually is only a dozen or dozens of MPa[5,6]. To improve the adhesive strength of the coating, laser technology, such as laser cladding, laser surface hardening, laser surface alloying and laser plasma hybrid spraying technology, are employed to achieve the metallurgical bonding between the coatings and substrate[7-12]. In the above mentioned laser surface modification methods, laser surface hardening is the most popular research, with the fastest development, and makes it possible to achieve hundreds of micrometers hardened surface layer with no quenching medium, which can improve the hardness, wear resistance and increase the fatigue strength of the component[12-15]. However, laser surface hardening is seldom used to treat the large area components due to temper softening phenomena occurring at the overlapping zone of laser beam repeatedly scanning[16-20].

Compared with the laser beam, the vacuum electron beam (EB) has the advantages of higher energy density and conversion efficiency (usually above 90%), perfect protection in a vacuum environment and faster scanning speed. Recently an increasing attention for surface modification is high current pulsed electron beam (HCPEB), which has been proved to be a powerful tool to treat the surface of many materials such as steel, copper alloy and thermal sprayed coating, and a significant enhancement of

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mechanical properties of surface characteristics can be obtained[21-26]. However, the special equipment is required for HCPEB surface treatment, characterized by high voltage (~270 kV), short pulse duration (~1 μs) and high current density (~10^4 A/cm^2)[26], which is cost-intensive and difficult to meet the need of another EB processing technology. As is known, continuous EB is usually used to welding, but if a deflection scanning system is equipped on an EBW machine, it can not only realize EBW with multi-beam[27-30], but also carry out the material surface treatment. Bataev et al used EB with deflection scanning to perform the mild steel alloying and cladding, subsequent surface quenching and tempering of the cladding layer[31]. Chen et al studied the microstructures and wear properties of Ti-36Nb-2Ta-3Zr-0.35O alloy treated by electron beam melting[32]. Grumbt et al employed electron beam hardening to improve load-supporting capacity for Ti1-*x*Al*x*N coatings[33]. All of the above studies found that EB surface treatment can significantly improve wear, fatigue resistance, hardness and friction coefficient of material surface. However, detailed investigations on the influences of EB surface treatment process parameters on the surface properties of materials have not been carried out to date, especially for TC18 titanium alloy.

In the present study, the deflection scanning of electron beam technology (DSEB) with line by line scanning mode and no overlap was employed to treat the surface of TC18 titanium alloy, which is a high strength $\alpha+\beta$ titanium alloy and widely applied as structural material in fuselage and undercarriages, to improve the surface hardness. Compared with existing EB surface treatment methods, DSEB employed smaller Gaussian beam diameter of 0.1 mm (usually more than 10 mm in the above studies), which could obtain more uniform heat distribution because electron beam heat source usually assumes Gaussian heat distribution in radial direction, and when the beam diameter is larger, the heat distribution is more nonuniform. Moreover, smaller beam diameter is more suitable for the surface hardening of complex components. The effect of the crucial process parameters, including beam current, focus current and scanning times, on the microstructure, hardness and treated depth of the treatment area of TC18 was investigated by SEM, optical microscope, and Vickers hardness tester. It is anticipated that the results of this study would provide a novel electron beam surface hardening technology for titanium alloy.

1 Experiment

TC18 titanium alloy plates with dimensions 100 mm×100 mm×4 mm were employed in the present study. TC18 is a high strength $\alpha+\beta$ titanium alloy with nominal composition Ti-5Al-5Mo-5V-1Cr-1Fe (mass fraction, %), which is widely applied as structural material in fuselage and undercarriages due to its high strength, high toughness, and excellent hardenability.

Fig.1 presents the fundamental principle of DSEB. As shown in Fig.1, the driving current in *X* direction coil changes fast and periodically, while that of *Y* direction coil rises slowly, which causes that the deflection electromagnetic field changes fast and periodically in *X* direction and rises slowly in *Y* direction. Therefore, when electron beam goes through the deflection electromagnetic field, DSEB with line by line scanning mode can be achieved, such as scanning from O point to X1 point, then back to O1 point immediately. When the beam spot diameter is 0.1 mm, n is equal to 200, and $nT1=T2$ ($T1$ is the cycle time of the current wave in X direction coil, and $T2$ is the cycle time of the current wave in Y direction coil), the scanning area of 20 mm×20 mm can be obtained.

DSEB was executed in a high voltage vacuum EBW machine ZD150-15MH CV3M. The basic parameters of DSEB are listed in Table 1.

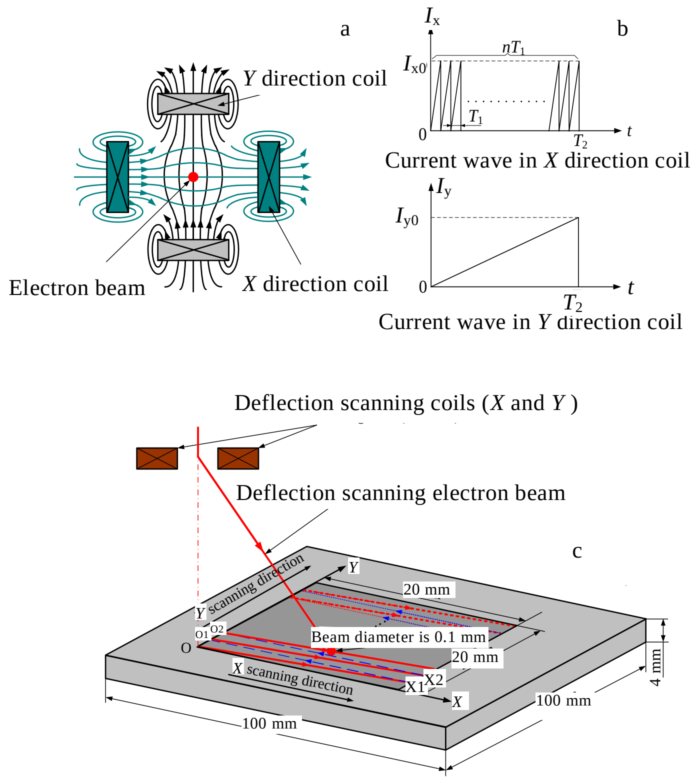

Fig.1 Illustration of DSEB: (a) deflection scanning coils and magnetic field, (b) driving current waves in *X* and *Y* coils, and (c) the deflection scanning mode and sizes

Table 1 Basic parameters of the DSEB

Beam voltage, U_b/kV	Working distance, d/mm	Scanning frequency, f/Hz	Beam current, I_b/mA	Focus current, I_f/mA	Scanning times, N
150	400	9648	10	2502	10

The DSEB process parameters correlate with each other and produce a large parameter matrix for the experimental investigations. To reduce the number of the experiments, some parameters including beam voltage, working distance and scanning frequency were decided on base of the past experience, and kept unchanged. With the respective change of beam current, focus current and scanning times, which are crucial process parameters in the experiments, effects of DSEB on the microstructure, hardness and treated depth of TC18 titanium alloy was discussed. In order to gain more homogeneous EB energy distribution, over focus was usually employed to treat the surface of TC18 when focus current was 2502 mA[34].

Hardness of the treatment area by DSEB was measured by HAZ-1000 Vikers tester with 10 N load and 10 s dwelling time at room temperature. First measurement point was at the center of treatment area, and the remaining points symmetrically distributed on both sides, as shown in Fig.2.

Specimens used for metallographic examination were cut from the treatment area of TC18 titanium alloy plates. The cross-sections of specimens were prepared by mounting, standard mechanical grinding and polishing procedures, and were etched with a mixture solution of HF, HNO_3 and H_2O (1:1:50). The optical photographs of the surface of treatment area were observed on a Leica DM4000 Optical microscope and the microstructures of cross-sections were investigated on a CamScan 3400 scanning electron microscope (SEM).

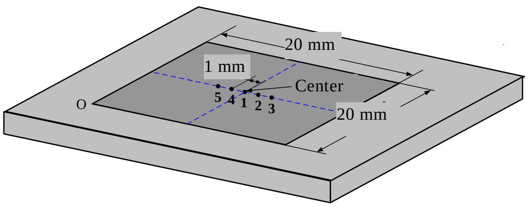

Fig.2 Schematic illustration of hardness measurement points

2 Results and Discussion

2.1 Microstructure

2.1.1 Surface grains

The optical photographs of the surface of treatment area by DSEB with different beam currents are presented in Fig.3, which were observed directly with no polishing and etching. It can be seen that the surface grain size of treatment area has almost no change when beam current is 10 and 15 mA, but when exceeding 15 mA, the grains grow up quickly. The dimension of the grain is about 90 μm at 15 mA beam current, while the dimension of the grain increases up to about 400 μm at 20 mA beam current.

The optical photographs of the surface of treatment area by DSEB with different treatment times are given in Fig.4. With the increasing of treatment times of DSEB, the surface grains of treatment area grow up gradually. particularly exceeding 30 times, the dimension of the grain grows up about 5 times.

The increase of beam current and treatment times of DSEB means that the heating input energy is enhanced, which could increase the surface temperature of treatment area and decrease the cooling rate, and then the surface grains grow up quickly (shown in Fig.3 and Fig.4). Therefore, in order to obtain the fine grains on the surface of treatment area, beam current and treatment times must be optimized.

2.1.2 Microstructure of cross-sections

The microstructure of the typical cross-section of the specimen treated by DSEB is shown in Fig.5. It can be seen that the treatment area is composed of the base metal, the transition zone, hardened zone, and the surface of treatment area. The microstructure of base metal is made up of α phase and β phase. The transition zone consists of short and small acicular martensite structure, α phase and β phase. Fig.5b shows that the hardened zone is mainly made up acicular martensite structure.

As a high power density beam heating method, the DSEB has the characteristics of high peak temperature, extremely fast heating and cooling rates. In particular, due to high scanning frequency (9648 Hz), small scanning area (20 mm ×20 mm) and big substrate (100 mm×100 mm×4 mm,

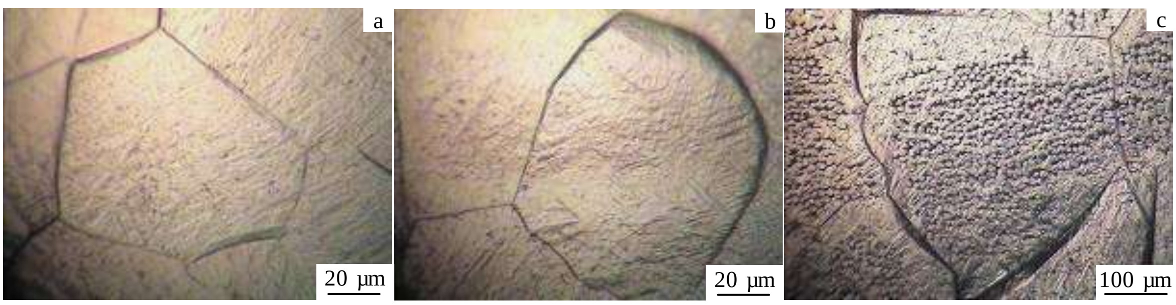

Fig.3 Optical photographs of surface treatment area by DSEB with different beam currents: (a) 10 mA, (b) 15 mA, and (c) 20 mA

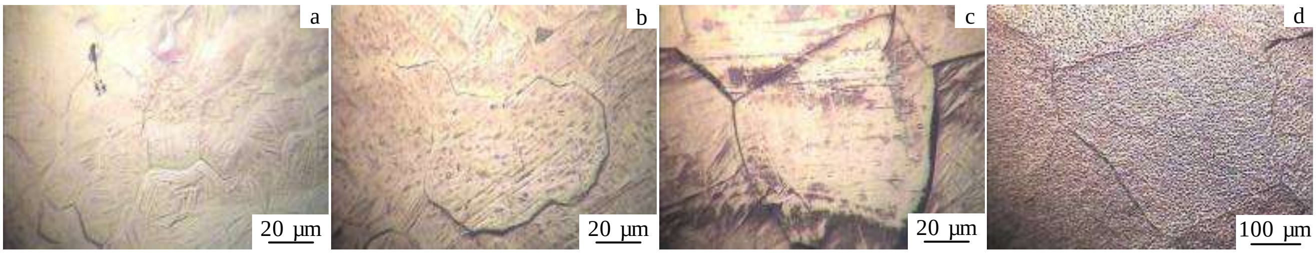

Fig.4 Optical photographs of surface treatment area by DSEB with different treatment times: (a) 10 times, (b) 20 times, (c) 30 times, and (d) 40 times

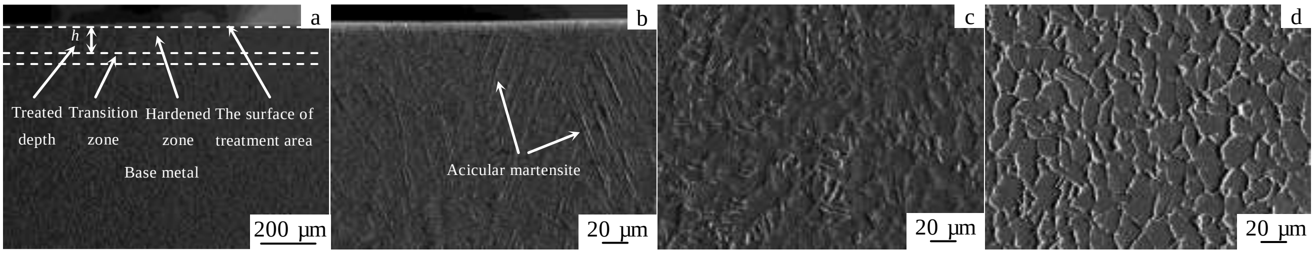

Fig.5 Microstructures of the typical cross-section of the specimen treated by DSEB: (a) cross-section of the specimen, (b) treatment zone, (c) transition zone, and (d) base metal

shown in Fig.1) as an efficient heat sink, faster cooling rate could be achieved compared with vacuum EBW process. The α phase of the surface metal of treatment area completely transfers to β phase because the peak temperature during the DESB process is higher than the β transus temperature of TC18 titanium alloy. Then, because of the sharply fast cooling rate, there is no enough time to exceed the transformation from β phase to α phase through atom diffusion, and acicular martensite is formed in the treatment area[35,36], shown in Fig.5b. In general, the hardness of the acicular martensite is higher than that of α phase, and the results of microstructure observation and hardness measurement below are consistent with each other.

In the laser surface hardening process, the hardened surface layer distribution by a single laser beam scanning is usually not uniform, like a crescent[18,20]. Therefore, in order to gain more uniform hardened layer distribution, when the areas of the component to be treated are larger than that of the laser spot, multiple laser beam scanning are needed with overlap. However, the overlapping zone usually leads to a tempering softening effect of the hardened zone because martensite formed in the first pass might be decomposed[16-20].

Compared with the laser surface hardening and the stationary defocused electron beam exposure, DSEB in this study employed a smaller beam diameter (0.1 mm) to obtain more uniform energy distribution of beam spot and precise position control, which make it easier to gain uniform hardened layer distribution without the overlap of electron beam scanning. From Fig.5a and 5b, it can be seen that the microstructure of the hardened zone is homogeneous and has no obvious transition at the contact parts of two adjacent electron beams scanning. Meanwhile, the depth of the whole hardened zone is basically constant.

2.2 Hardness

2.2.1 Beam current

Hardness distributions on the surface of the treatment area by DSEB with 5, 10, 15 and 20 mA beam current are presented in Fig.6. As shown in Fig.6, the hardness of treatment area fluctuates with the increase of beam current, which increases firstly and then decreases. The average hardness (HV) of the original TC18 titanium alloy is approximately 3510 MPa. The peak of hardness distribution appears when scanning beam current is 10 mA, and the maximum of the hardness is 3955 MPa which increases by 12.7% compared with that of the original TC18 titanium alloy. This might be caused by alterations in the microstructure of treatment area. Due to the sharply fast heating and cooling rates, large amounts of acicular martensite (shown in Fig.5b), which can enhance the hardness of materials, is formed in the treatment area by DSEB.

When beam current is 5 mA, the temperature of treatment area is lower than phase-transition temperature and the microstructure has no change. While beam current exceeds 10 mA (e.g. 15 and 20 mA), heat input of the treatment area increases and then cooling rate decreases, thus the formed

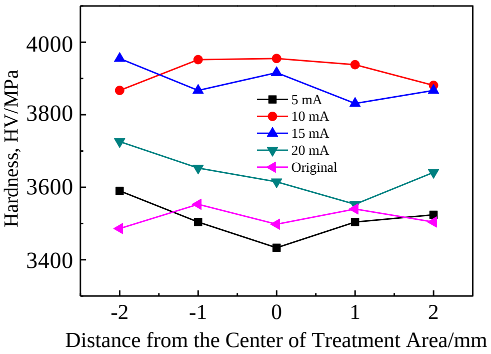

Fig.6 Hardness distributions on the surface of the treatment area by DSEB with different beam currents (focus current I_f = 2502 mA, scanning times N=10)

acicular martensite decreases and grains grow up quickly (shown in Fig.3) to cause the decrease of hardness (shown in Fig.6).

2.2.2 Focus current

There are three kinds of beam focuses in the electron beam, including surface focus, over focus and under focus, as shown in Fig.7, in which surface focus has minimum beam diameter and maximum energy density. In the present study, 2455, 2485, 2515 and 2545 mA focus currents were employed. When focus current is 2485 mA, surface focus could be obtained.

The hardness distributions on the surface of the treatment area by DSEB with different focus currents are given in Fig.8. It can be seen that with the comparison of the original TC18 titanium alloy, the maximum of the hardness of the treatment area by DSEB with surface focus is 4222 MPa which increases by 20.3%. It can be suggested that DSEB with surface focus is helpful to improve the hardness of the treatment area because of higher energy density input.

2.2.3 Scanning times

Specimens were treated by DSEB with 10, 20, 30 and 40 scanning times and hardness distributions on the surface of the treatment area are shown in Fig.9. It can be seen that hardness distributions are decreased with the increase of scanning times, even lower than that of the original TC18 titanium alloy. Increasing scanning times mean to increase heat input of the treatment area and cause the decrease of the cooling rate. Hence, it is also hard to form acicular martensite, meanwhile the grains grow up (shown in Fig.4), and cause the hardness to decrease.

2.3 Treated depth

The treated depths (shown in Fig.5a, h value, not including the transition zone) of specimens by DSEB with different beam currents, focus currents, and scanning times

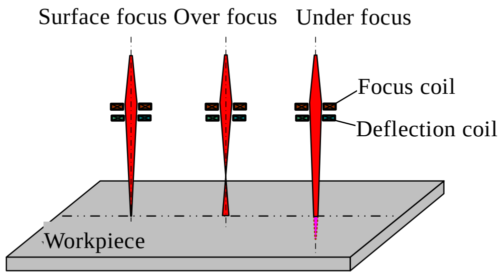

Fig.7 Schematic diagram of three kinds of beam focuses

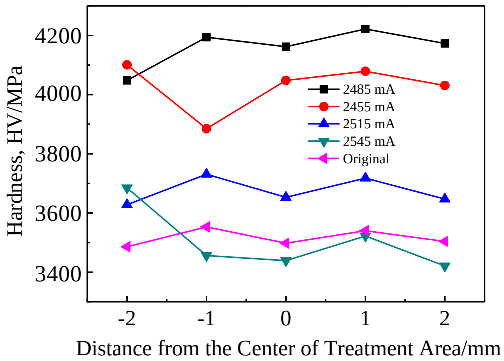

Fig.8 Hardness distributions on the surface of the treatment area by DSEB with different focus currents (beam current I_b = 10 mA, scanning times N=10)

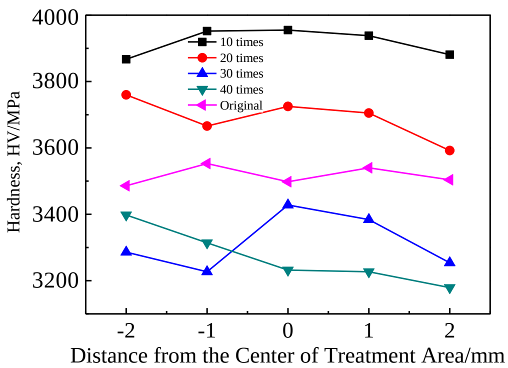

Fig.9 Hardness distributions on the surface of the treatment area by DSEB with different scanning times (beam current I_b = 10 mA, focus current I_f = 2502 mA)

are presented in Fig.10. It is obvious that with the increase of beam current and scanning times, the treated depths of specimens increase gradually, and maximum depth is 254.2 μm when scanning times are 40. Moreover, compared with the over focus and under focus, treated depth with

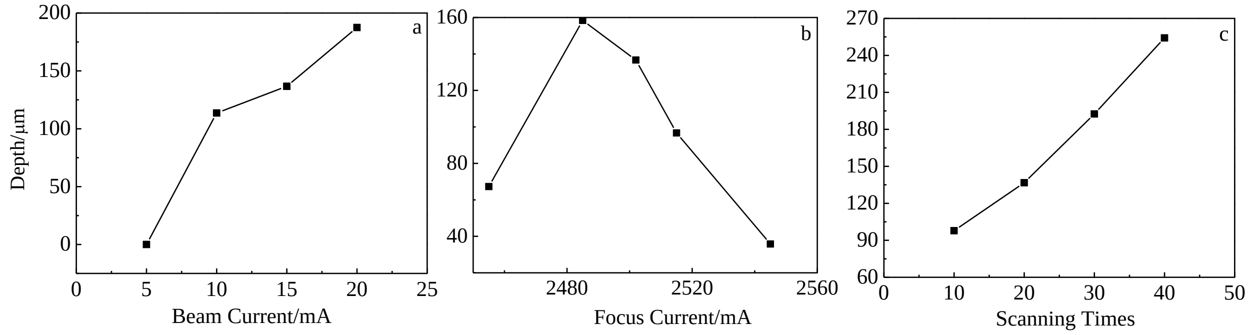

Fig.10 Treatment depths (basic process parameters are listed in Table 1 with different beam currents (a), focus currents (b) and scanning times (c)

surface focus is maximum, which is 158.4 μm when focus current is 2485 mA, shown in Fig.10b. It is obvious that increasing the input energy or energy density of treatment area can increase the treatment depths of specimens.

To sum up, with the increase of beam current and scanning times, the treated depth increases, grains grow up quickly and the hardness decreases. In order to obtain better combination of the hardness and depth of the hardened layer, the optimized process parameters of the DSEB for TC18 titanium alloy are 15 mA beam current, surface focus and 10 times scanning times. The hardened surface layer formed by DSEB with the above optimized process parameters, can achieve about 20% improvement of the hardness and more than 200 μm depth of hardened zone, which is comparable with that of laser beam hardening[37]. However, the energy conversion efficiency of the laser beam interaction with material is very low, usually less than 30%[19]. Moreover, this process not only needs complex optics system and moving control system to realize laser beam scanning[19,20], but also requires perfect protection of the component during processing because of operation in the air. Therefore, DSEB is a promising technology for the surface hardening of TC18 titanium alloy to improve the surface hardness, the wear resistance and the corrosion resistance.

3 Conclusions

1) The optimized process parameters of the DSEB for TC18 titanium alloy are 15 mA beam current, surface focus and 10 scanning times. Due to extremely fast heating and cooling rates during the DSEB process, the hardened surface layer is formed, which is mainly consisted of acicular martensite structure.

2) The hardness on the surface of hardened layer by DSEB increases by about 20%, and the depth of the hardened zone is more than 200 μm. Moreover, the microstructure of the hardened zone is homogeneous and has no obvious transition at the contact parts of two adjacent electron beams scanning, and the depth of the whole hardened layer is also constant. Therefore, DSEB is a very promising technological solution for the surface heat treatment of large area and complex components.

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电子束偏转扫描对 TC18 钛合金组织、硬度和作用深度的影响

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摘 要：为了形成均匀的表面硬化层，采用逐行、无搭接的电子束高频偏转扫描技术（DSEB）对 TC18 钛合金的表面进行处理。重点研究了电子束束流、聚焦电流和处理次数等关键参数对TC18组织、表面硬度和处理深度的影响。处理的试样通过扫描电镜（SEM）、光镜和维氏硬度计进行检测。经 DSEB 处理后，TC18 钛合金表面形成了主要由针状马氏体组成的表面硬化层，表面硬度得到提高；硬化区的金相组织均匀，在扫描束斑相邻区域没有明显的过渡；硬化层深度均匀，可达200 μm以上。试验结果表明 DSEB 有望成为大面积、复杂形状的钛合金构件的表面处理新方法。

关键词：电子束偏转扫描；表面硬化；针状马氏体；硬度

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