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Microstructures and fatigue properties of electron beam welds with beam oscillation for heavy section TC4-DT alloy

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Abstract With the development of the manufacturing technology, electron beam welding (EBW) is capable of producing titanium alloy large parts in aero fields. To increase the applications and improve the properties, EBW with beam oscillation was investigated on TC4-DT alloy with 50 mm thickness. We detected the welding samples by X-ray NDT, observed the microstructures of the welds, and tested the fatigue properties of the joints. The results showed that EBW with beam oscillation improved the weld morphology as well as welding quality, and the microstructure homogeneity of the welds and HAZ along the weld penetration were also improved. The fatigue properties of the joints with beam oscillation were more excellent than those of conventional EBW, even equal to those of the base metal under high stresses. The influences of the processing and the microstructure on the properties with beam oscillation were discussed.

1. Introduction

TC4-DT alloy is an alpha–beta damage-tolerance titanium alloy with medium strength and high fracture toughness, properties of which is equal to those of Ti6Al4V ELI alloy. Forgings and heat treatments were investigated on TC4-DT alloy in China,[1–6] and fatigue properties and fracture tenacity were studied,[7–9] which showed that this material was suitable for aero fuselage parts. To achieve weight cut, cost saving, and excellent properties for aircraft, large parts of TC4-DT alloy have been manufactured by welding.

Because of high-power density, high efficiency, low deformation, and great depth-to-width ratio, EBW is capable of manufacturing large titanium alloy parts, especially full penetration welds of complex geometry with heavy thickness by a single pass.[10,11] Companies in USA employed EBW to weld the fwd and aft booms of F-22 raptor, and made the wing

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box for F-14 TOMCAT, with the thickness of the joints being 6.4–57.2 mm.[12,13] Engineers in Russia and European countries welded satellites' tanks of titanium alloy by EBW,[14,15] and the welding thickness was 2–30 mm.

The processing and mechanical properties of EBW have been studied for Ti6Al4V titanium alloy in India, USA, and European countries. Barreda et al.[16] studied the behaviors of a 17 mm Ti6Al4V weld with a filler titanium alloy of similar and different compositions by EBW. Saresh et al.[17] studied the microstructures and mechanical properties of single-pass and two-pass double-side weld joints of Ti6Al4V alloy with 21 mm thickness, and qualified all the test requirements of aerospace applications. Huez et al.[18] welded Ti6Al4V alloy plates with 10 mm thickness in different processes by EBW, and the configurations of α martensite in the weld were different after post-welded heat treatment, which resulted in the difference of mechanical properties. The research of heavy-thickness titanium alloy with EBW was few in USA and European countries, but the processes were studied on heavy-thickness steels and superalloy with EBW.[19–22] Reisgen et al.[19–21] employed the EB deflection technology to improve weld penetration, and Börner et al.[22] brought out the multi-focus technology to weld heavy-thickness steels. Engineers in China welded heavy-thickness titanium alloy by EBW, and observed and studied the microstructures of the joints in different conditions.[23–27] Tang et al.[26,27] studied the strain fatigue properties and fatigue crack growth behaviors of the joints with EBW. Jin et al.[28] observed fatigue course and studied the fracture morphology by an in situ tensile method. However, the methods to improve weld microstructures and fatigue properties of EBW have not been reported in detail for heavy section titanium alloy, and the influences of the processing and the microstructure on fatigue properties have not been investigated.

With the development of advanced airplane, EBW is confronted with the challenge of welding above 50 mm thickness of titanium alloy, and the properties are requested to be more excellent than before. The microstructures and geometric characteristics of the welds have a crucial influence on mechanical properties, which are attributed to the processing. EBW was investigated on TC4-DT alloy with a thickness of 50 mm in this paper. We employed beam oscillation during welding, and studied the morphogenetic characteristics, microstructures, and fatigue properties of the joints.

2. Experimental procedures

The materials used were TC4-DT alloy with forging and dual-annealing, chemical compositions of which comprised Al 6.0% (weight percent), V 4.2%, C 0.028%, O 0.039%, N 0.003%, H 0.0011%, and Ti balance. Samples of 200 m m × 200 mm × 50 mm were grinded on the oxidation surface and cleaned by ethanol before welding. We adjusted welding velocity and beam current, and accomplished the penetrated welds by a single pass using a ZD30CCV65M EB welder. Beam oscillation was applied to improve welding quality with 50 mm heavy thickness (as shown in Fig. 1(a) and (b), which employed electromagnetic fields to alter freely the direction of the electron beam.

Oscillating the electron beam is an effective method to improve welding fusion and solidification, and increases the diameter of the keyhole. Beam oscillation prevents the molten envelopes from collapsing, and reduces the root spiking of the welds. Furthermore, beam oscillation increases the width of the fusion zone, and allows gas porosity to rise and escape from the weld pool.[10]

The amplitude of beam oscillation was less than 1 mm, and the oscillating frequency was more than 200 Hz, which were optimum to weld heavy section TC4-DT alloy by EBW. The functions of beam oscillation were circle, triangle, and rectangle (as shown in Fig. 1(c)).

The parameters were listed in Table 1 for TC4-DT alloy with 50 mm thickness. Where f_p and B were respectively the frequency and amplitude of beam oscillation, and B_x was the amplitude of beam oscillation along X direction. The processing of number 1 was conventional EBW (without beam oscillation), while number 2 with beam oscillation. The beam current with beam oscillation was 28 mA higher than that

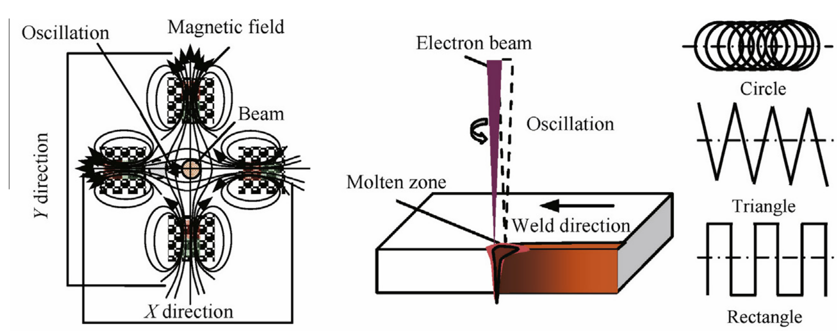
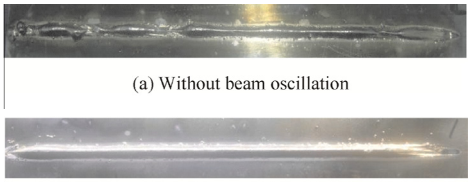


Fig. 1 Sketch of EBW with beam oscillation.

Table 1 Parameters of EBW.

Processing	Voltage	Beam current	Focusing current	Velocity	Oscillation		
No.	U_a (kV)	I_b (mA)	I_f (mA)	v (mm/s)	Shape	f_p (Hz)	B (mm)
1	150	102	2195	13.3			
2	150	130	2195	13.3	Circle	500	B_x = 0.6



(a) Without beam oscillation

(b) With beam oscillation

Fig. 2 Welds' photos with a velocity of 10 mm/s.

without oscillation, which showed that EBW with beam oscillation consumed more energy.

The welds' photos are shown in Fig. 2. The appearances of the welds with beam oscillation were smoother, flatter, and steadier than those without beam oscillation. The undercuts of the welds with beam oscillation were also reduced, and the reinforcements were narrow and high. The width of the front weld with beam oscillation was 9 mm, which was wider than that without beam oscillation (7.3 mm). The welds with beam oscillation were optimum.

After welding, we annealed the samples at 700 °C for 2 h in a vacuum furnace to reduce welding residual stresses. The annealing temperature was lower than that of recrystallization, which would not influence the microstructures and mechanical properties.

3. Results and discussion

3.1. NDTs for the welds

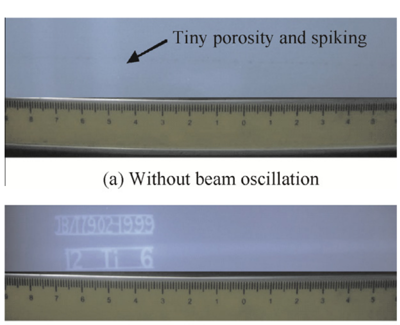
We detected the welds by X-ray NDT (as shown in Fig. 3). Because of the characteristics of EBW and welding metallurgy, conventional EBW of heavy-thickness titanium alloy easily caused tiny porosity and spiking, as shown in Fig. 3(a), which apparently initiated rupture tips of fatigue tests. The tiny pores and the root spiking were not detected in the weld with beam oscillation, as shown in Fig. 3(b). Compared with the welds without beam oscillation, the welding quality with beam oscillation was better.

3.2. Microstructure of welds

The welding samples were fixed with backing plates on the bottoms before welding. The welds penetrated the samples with 50 mm thickness, but incompletely penetrated the backing plates. The investigations were on the welds with 50 mm thickness, not including the backing parts. The weld morphologies with and without beam oscillation are shown in Fig. 4, and the welds with beam oscillation were parallel, similar to a bell pattern according to references.[29–31] The weld width (at the half thickness) with beam oscillation was 5 mm, which was wider than that without oscillation. The figuration of the weld toe with beam oscillation was smooth, not like a nail tip. The depth–width ratios of the welds with and without beam oscillation were 10:1 and 14:1, respectively. Because of the super-cooling in the liquid boundary with high input, epitaxial solidification resulted in directional grains from the molten boundary, and dendrites formed from the base metal to the weld center, The grains of the base metal near the weld avoided superheating and grew into crassitude with high welding velocity.

The microstructures of the base metal were lamellar α–β and a few equiaxed α (as shown in Fig. 5), which contributed to improving the fracture toughness and tenacity of the material.[32] We assigned observation locations (see Fig. 6) on the cross section of the welds, and observed the microstructures along the penetration depth, including the weld, HAZ (heat affected zone) and base metal.

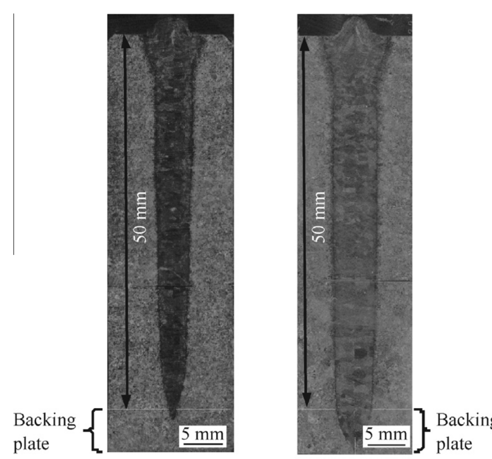
After conventional EBW (number 1), the microstructures of the welds were acicular α′ martensite and acicular α–β, while a mixture of acicular α′, acicular (α–β), and equiaxed α coexisted in HAZ (as shown in Fig. 7). The microstructure of the base metal near the weld was the same as that before welding. With the increase of the weld penetration, acicular α′ martensite did not change in the welds, but the α–β structure in the welds gradually grew and coarsened from the top to the bottom. The



(a) Without beam oscillation

(b) With beam oscillation

Fig. 3 X-ray NDT photo without and with oscillation.



(a) Without oscillation (b) With oscillation

Fig. 4 Cross-section of welds.

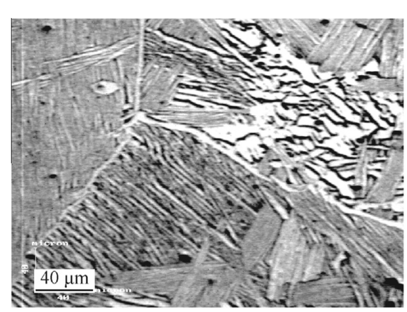


Fig. 5 Microstructure of base metal.

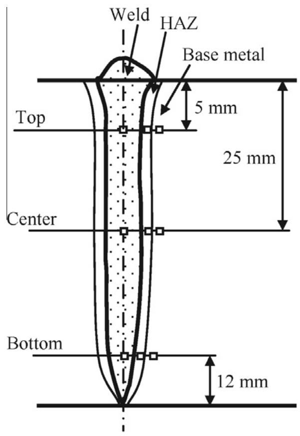


Fig. 6 Microstructure observation locations.

acicular α′ martensite in HAZ gradually became thinner from the top to the bottom with the increase of the weld penetration, and the α–β structure also gradually coarsened and grew.

The microstructures of the welds with beam oscillation were α′ martensite with a few α–β, and lathy α′ martensite and lamellar α–β structure co-existed in HAZ, as shown in Fig. 8. The martensite in the weld gradually grew up into the lathy structure with the increase of the weld penetration, even became coarse and lathy α′ in the weld toe. With the increase of the weld penetration, lathy α′ and lamellar α–β structure in HAZ gradually became thin and tiny, and lamellar α–β structure in the welds also became thin. The microstructure of the base metal near the welds also did not change.

Compared with EBW without oscillation, the microstructures of the weld and HAZ with beam oscillation were coarser and more homogeneous from the top to the bottom. From Ref.[10] the homogeneous platelet microstructure contributed to the excellent properties of the joints with beam oscillation. However, the inhomogeneity of the weld microstructure with or without beam oscillation still existed along the penetration depth, which would affect mechanical properties.

3.3. Fatigue properties of joints

The stress fatigue tests of the joints were investigated, which were under room temperature at atmosphere. The fatigue specimens were made from the middle thickness of the samples.

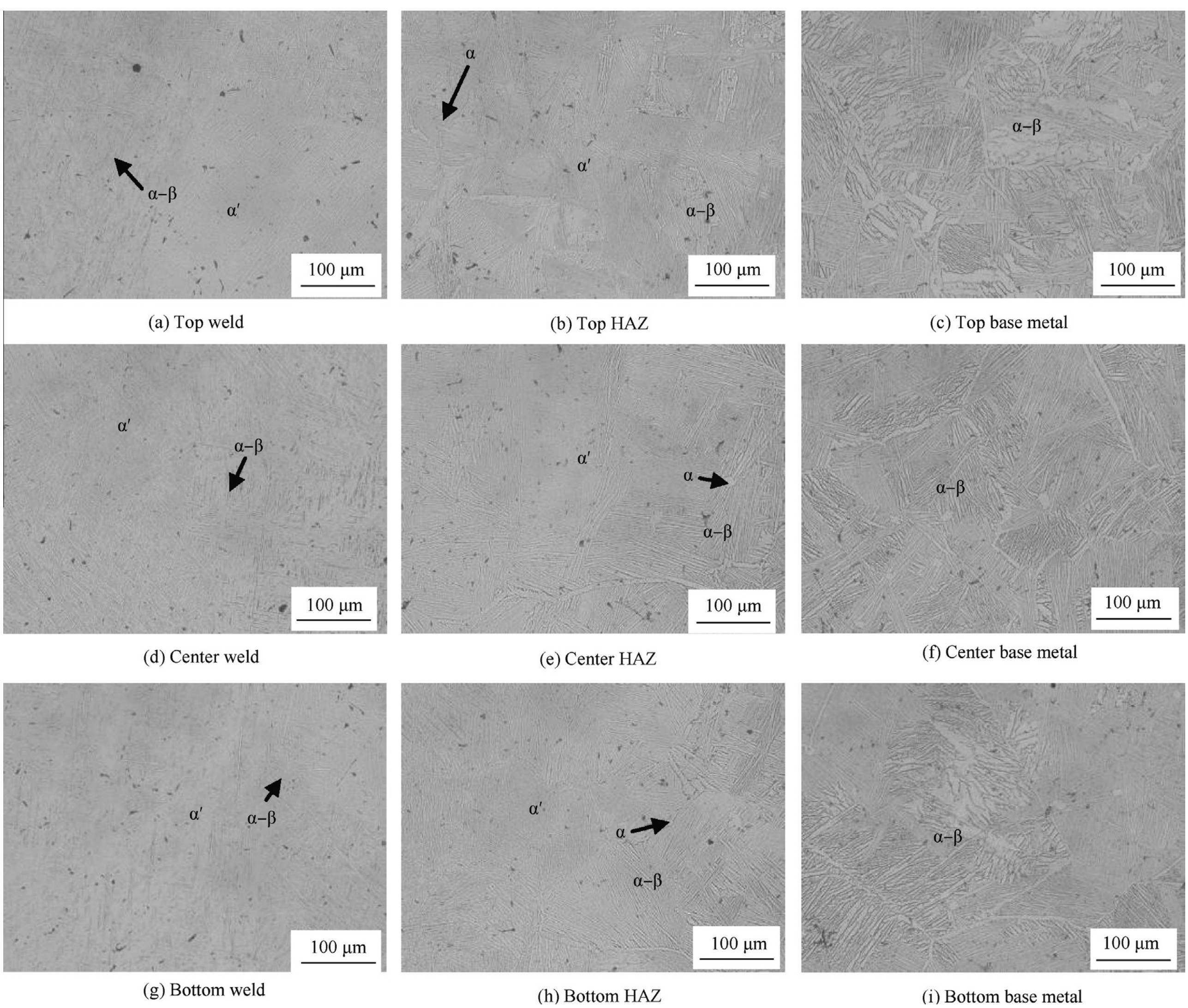


Fig. 7 Microstructures of welds without beam oscillation.

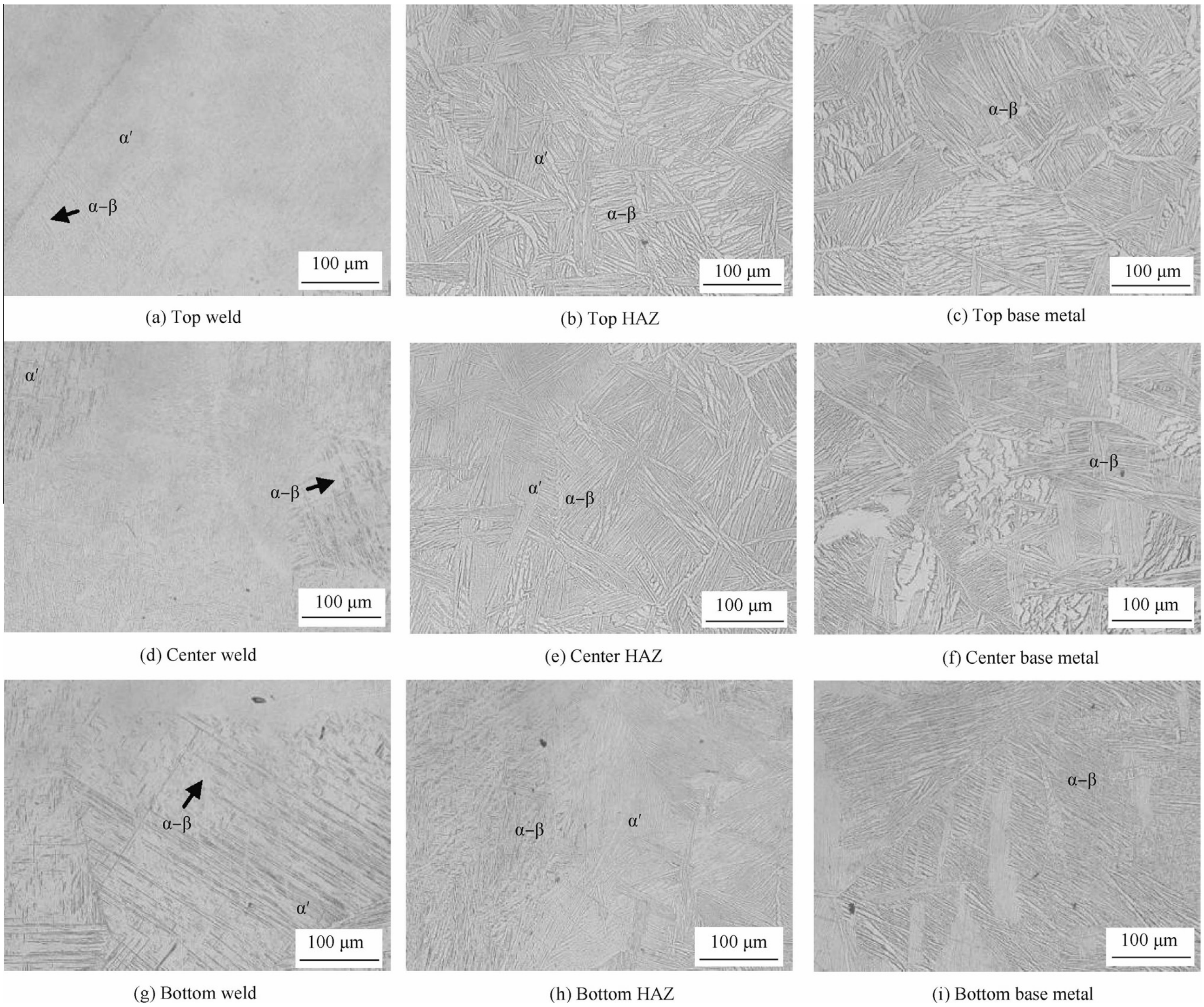


Fig. 8 Microstructures of joints with beam oscillation.

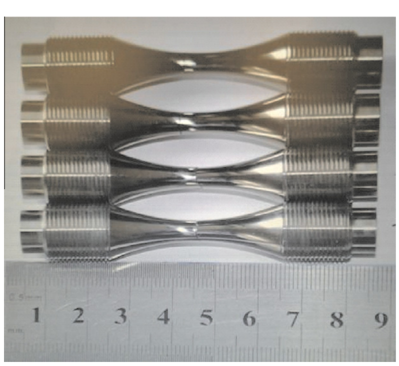


Fig. 9 Fatigue specimens.

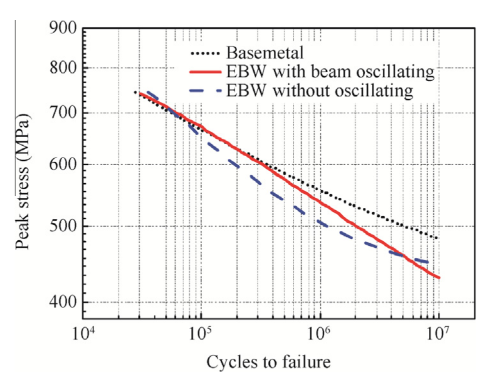


Fig. 10 Fatigue curve of *S*–*N*.

The fatigue specimens were funneled, and the thinnest diameter was 5 mm in the welds (as shown in Fig. 9). The fatigue tests were carried out using the settings of GPS-100, in which the stress ratio was loaded by 0.1 and the wave frequency was 100–130 Hz.

The fatigue results are shown in Fig. 10. The fatigue strength (σ_D) of the joints with beam oscillation was approximately equal to that of the joints without oscillation, which was lower than that of the base metal. The fatigue life values of the base metal were longer than those of both joints. Under peak stresses of 460–700 MPa, the joint values of fatigue life with beam oscillation were longer than those without beam oscillation, even equal to those of the base metal under stresses of above 620 MPa. The fatigue properties of the joints with beam oscillation were more excellent than those without beam oscillation, which were influenced by the homogeneity of weld morphologies and weld microstructures.

Because of strength overmatching of titanium alloy with EBW, the fatigue fracture of the joints mainly ruptured in the base metal near HAZ. The fracture sections comprised of a crack initiation region (I), a crack propagation region (II), and a final rupture region (III), as shown in Fig. 11. The crack sources in the crack initiation region (I) were from the surface

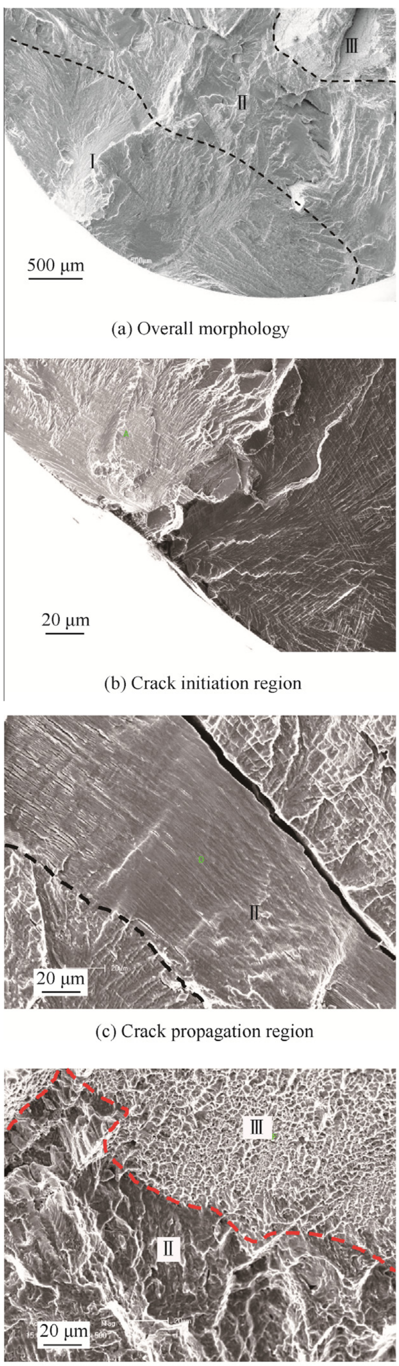


Fig. 11 Fatigue fracture sections: crack initiation region (I), crack propagation region (II), final rupture region (III).

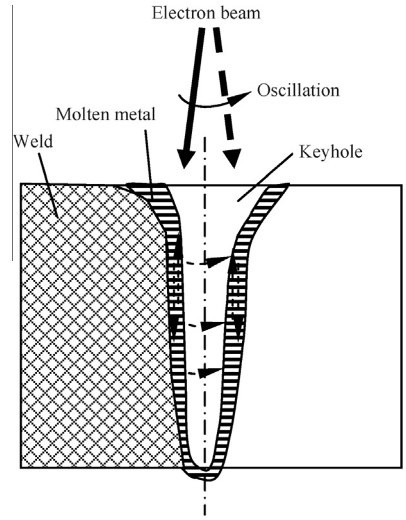


Fig. 12 Sketch of molten metal with beam oscillation.

of the samples, and the secondary cracks and tiny fatigue strips existed near the crack sources. The arris lines grew in the crack propagation region (II), and the brittle slips existed. The turn-up morphology arose in the transcrystalline of the final rupture region (III), and the tenacious nests were tiny and tense.

3.4. Discussion

The macro morphology and microstructure of the weld have an effect on fatigue properties of the joints, which are determined by the technological characteristic and the welding processing method.

EBW with beam oscillation improves weld morphologies, welding qualities, and weld microstructures, which ensure the excellent properties of the joints. Beam oscillation has an influence on the fluidity and solidification of the molten metal (as shown in Fig. 12). The oscillation of the electron beam with a high frequency, which has an intense stir function, enhances the whirlpool of the molten metal along the wall of the hole, and generates an apparent keyhole effect. Furthermore, beam oscillation decreases the blocking of metal gas to the keyhole, and prolongs the opening time of the key hole, which contributes to escaping the gas and eliminating welding defects. The energy distribution along the weld penetration is homogeneous for EBW with beam oscillation, and the absorbed energy of the weld toe is more than that without oscillation, which would result in parallel welds. Beam oscillation ultimately improves the temperature gradient and cooling velocity during EBW, and the morphology and microstructure of the weld are homogeneous, which would improve the mechanical properties of the joints.

4. Conclusions

(1) EBW with beam oscillation improved the weld morphology and welding quality of TC4-DT alloy with 50 mm thickness, and broadened the width of the welds.
(2) Because of improving the fluidity and solidification of molten metal with beam oscillation, the microstructures of the welds were homogeneous along the weld penetration.

(3) The parallel morphologies and homogeneous microstructures of the welds contributed to enhancing the mechanical properties. The fatigue properties of the joints with beam oscillation were more excellent than those without oscillation, even equal to those of the base metal.

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