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Short communication

Effect of treatment in weld surface on fatigue and fracture behavior of titanium alloys welded joints by vacuum electron beam welding

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ABSTRACT

The effect of treatment in weld surface on four-point bend fatigue properties and fracture characteristic of Ti–6.5Al–2Zr–1Mo–1V alloy by vacuum electron beam welding were tested and analyzed. When the excess weld metal and excess penetration are removed, the high fatigue strength of joints can be obtained. When the excess weld metal and excess penetration were not removed, the fatigue strength of joints is about 40% of yield strength of base metal. Two kinds of fatigue crack initiations can be observed under the upper surface of joint, which show the obvious local tearing fracture morphology and bulk inclusions or compounds morphology.

Titanium alloys are used in aerospace and a wide variety of other industries because of their high specific strength, good ductility, and excellent fatigue properties [1]. Ti–6.5Al–2Zr–1Mo–1V (wt.%) is an important type alloys of the most important titanium alloys used in aircraft engine components, which are subjected to high cycle fatigue loading induced by high frequency vibrations [2]. Some components were used in the form of important welding structures [3]. Therefore, compared with titanium alloys that were used as components directly, the high cycle fatigue loading of welding structures subjected has more influence on service life.

Titanium alloys as important components were joined by a variety of welding methods [4–7], among which vacuum electron beam welding (VEBW) is the use of directional high-speed motion of the electron beam impinging on the workpiece so that the kinetic energy into heat and the workpiece to melt, forming a weld. VEBW has drawn particular attention due to its high energy density, a deep and narrow joint, a minimal heat-affected zone (HAZ), low residual stress and small distortion of welded materials [8]. Previous studies concerning the welded joints of titanium alloys were mainly focused on microstructure, phase morphology, hardness, and tensile and S–N curve properties [9]. However, these studies were performed via a method of pulsed tensile fatigue of welded joints. The existing methods about the fatigue analysis for welded joints are not enough to analyze and evaluate the effect of microstructural evolution on the fatigue behavior of welded joints. The self-adapting low-cycle four-point bend test using the optimum testing geometry in the four-point bend is a novel technology to minimize some factors which affected the exact fatigue test [10]. In our previous researches [11], microstructural properties and four-point bend fatigue behavior of Ti-6.5Al–2Zr–1Mo–1V welded joint by VEBW was drawn. In fact, since the structure of welded joints is quite heterogeneous, using other methods to analyze the fatigue characteristics is likely to cause a larger error. Moreover, the effect of treatment in weld surface on four-point bend fatigue properties and fracture characteristic is still not clear.

In this letter, we used the four-point-bend apparatus to obtain fatigue data for VEBW joints of Ti–6.5Al–2Zr–1Mo–1V alloy and described the experimental investigations performed to study the micro-crack initiation, propagation and fracture behavior of joints. The effect of the excess weld metal and excess penetration on the fatigue strength including no excess weld metal and excess penetration are all tested and analyzed by four-point bend fatigue testing. This study will be helpful to evaluate the fatigue performance of VEBW joints of titanium alloy, and provide a novel and effective method to know the fatigue performance of welded joint by other fusion welding technology. The present results had been used in the life evaluation of the EBW joint of sheet titanium plate used in military aircraft.

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The nominal chemical composition in weight percentage of Ti–6.5Al–2Zr–1Mo–1V alloys used for this work is 6.72 Al, 2.32 V, 1.77 Mo, 2.19 Zr, 0.08 Fe, 0.14 Si and balance Ti. The tensile yield strength of the alloy was 740 MPa. The dimensions of the test plate are 200 mm × 100 mm × 5 mm. Titanium alloys sheets were joined by means of VEBW. The welding parameters are the working voltage 150 kV, the focus current 2443 mA, the beam current 48 mA, the welding speed 30 mm/s and the vacuum degree 5.5×10^{-4}. After welding, these welded joints were annealed (650 °C × 2 h) by vacuum heat treatment equipment, and the vacuum degree is 4×10^{-3}. The main aim is to relieve residual stress by annealing.

The four-point-bend test was used to gauge the fatigue properties of the titanium alloy. The test was performed in the equipment of MTS 810 Materials Test System. Samples for the tests were cut from the VEBW joints. The geometry and the loading of four-point bend specimens were shown in Fig. 1. Before fatigue tests the polishing process was carried out on the surfaces of the samples that were loaded in tension during the test using waterproof SiC polishing papers followed by mechanically polished using a silica colloidal liquid. The fatigue tests with a stress radio (R, $R = \sigma_{min}/\sigma_{max}$) of 0.1 were conducted at a frequency of 20 Hz, with a waveform and at room temperature in laboratory air of which the humidity was maintained at about RH 15 pct. Fatigue tests were periodically interrupted for observation and measurement of cracks. After failure, the fracture and fatigue behavior were analyzed by scanning electron microscope (SEM) of Hitachi S-4800.

According to Fig. 1, the four-point bend fatigue test of VEBW joints for titanium alloys and base metal was preformed. The standard specimens were prepared by lining cutting machine, including base metal (non-annealing) and welded joints (annealing 650 °C × 2 h). Moreover, the yield strength of base metal, 740 MPa, was used. A range of loading stress level is from 150% to 40%. With the increase of cycle times, the flexibility of specimens would be gradually increased. When the cycles reach to 5500000 times and the specimen has not been destroyed, the loading stress is as the fatigue strength or fatigue limitation of materials tested. The curve of four-point bend fatigue test of TA15 titanium alloys is shown in Fig. 2. The curve of four-point bend fatigue test of welded joints is shown in Fig. 3.

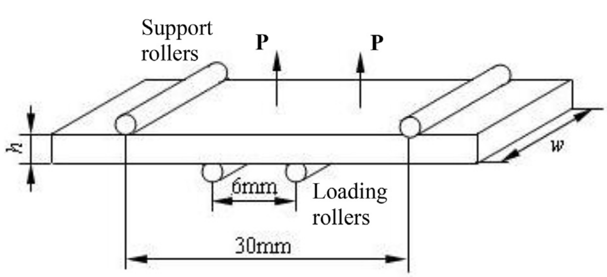

Fig. 1. The geometry of four-point bend specimens and the loading.

With the decrease of loading stress level the fatigue strength of base metal and welded joints increases gradually (see Fig. 2a and a). There is an adjacent linear relationship between the stress level (*S*) and logarithmic transformation of cycles (*LogN*). It can be seen in Fig. 2b and b. The fatigue strength of base metal, 888 MPa, is about 120% of yield strength. When the excess weld metal and excess penetration were removed, the fatigue strength of joints is 814 MPa. It is about 110% of yield strength of base metal. The test results indicated that the welding joint of titanium alloy experienced the VEBW has a higher fatigue strength compared with base metal.

For further the effect of the excess weld metal and excess penetration on the fatigue strength are also tested and analyzed The test results are shown in Fig. 3c, d, 3e and 3f. When only the excess weld metal was removed, the fatigue strength of joints is 444 MPa (see Fig. 3c and d). It is about 60% of yield strength of base metal. While when the excess weld metal and excess penetration both were not removed, the fatigue strength of joints is 298 MPa (see Fig. 3e and f). It is about 40% of yield strength of base metal. Fig. 4 shows the effect of the excess weld metal and excess penetration on the fatigue strength. It is obvious that the weld face treated effectively could play an important role to improve the performance of joints. When the weld face of joints (the excess weld metal and excess penetration) was completely treated by machining flush and polishing treatment, the joints showed the higher fatigue strength. That is to say, the excess weld metal and excess penetration are the main source of stress concentration to decrease the fatigue strength of joint. Therefore, when the load stress is relatively small, the stress concentration location will provide energy to accelerate the fatigue crack propagation rate.

Fig. 4a shows the macro-fracture morphology of fatigue failure under the 120% stress level for VEBW joints. The fracture shows three typical regions: (1) the I region—fatigue crack initiation; (2)

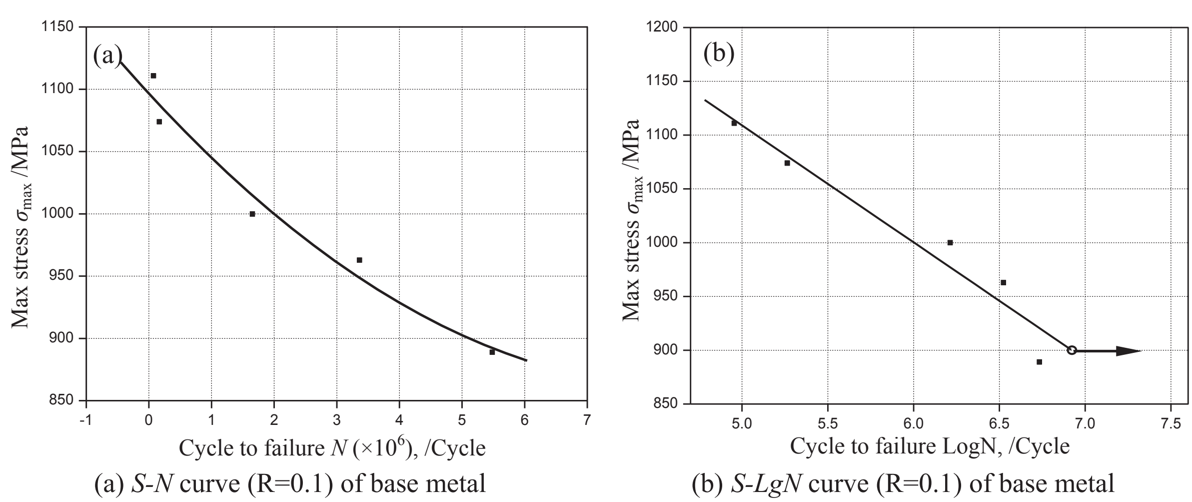

Fig. 2. *S-N* and *S-LgN* curves (R = 0.1) of four-point bend test of TA15 titanium alloys: (a) *S-N* curve (R = 0.1) of base metal; (b) *S-LgN* curve (R = 0.1) of base metal.