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Effect of laser beam welding on fracture toughness of a Ti-6.5Al-2Zr-1Mo-1V alloy sheet

Yaowu Shi · Fei Zhong · Xiaoyan Li · Shuili Gong · Li Chen

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Abstract Investigation of fracture toughness on Ti-6.5Al-2Zr-1Mo-1V alloy thin sheet and its laser-welded joints has been carried out. In the test compact tension (CT) specimens and single specimen technology were used. In addition, hardness distribution and microstructure of the welded joints were examined. Fracture test indicates that brittle unstable fracture occurs after slow crack propagation for all the specimens, except that one heat affected zone (HAZ) specimen is brittle crack initiation. It is found that rolling directions have no obvious effect on fracture toughness of base metal. Moreover, fracture toughness of weld metal is obviously decreased in comparison with base metal whatever in as-welded condition or in stress relief condition. Post-weld heat treatment (PWHT) leads to fracture toughness of the welds further decreasing. Fractography observation shows that the fracture mode is predominantly dimpled in base metal. However, there exists intergranular fracture in the weld metal. Thus, the transition of fracture mode from both base metal and HAZ to weld metal may lead to dramatic decrease in fracture toughness. Microstructure examination reveals that the microstructure of weld metal consists of large grains with fine acicular structure. The formation of fine α acicular structure is due to rapid cooling during laser welding. After PWHT, the acicular structure is coarsened.

Y. Shi (✉) · F. Zhong · X. Li
School of Materials Science and Engineering, Beijing University of Technology, 100 Ping Le Yuan, Chaoyang District, Beijing 100022, P.R. China
e-mail: shiyw@bjut.edu.cn

S. Gong · L. Chen
State Defence Key Laboratory For High Energy Density Beam Processing Technology, Beijing Aeronautical Manufacturing Technology Research Institute, Beijing 100024, P.R. China

Introduction

Titanium and its alloys have been considered as important structure materials in industries. This is because of their excellent combination of properties such as elevated strength-to-weight ration, toughness, excellent resistance to corrosion and good fatigue properties, which make them attractive for many chemical, marine, and aeronautical applications.

Ti-6.5Al-2Zr-1Mo-1V alloy is a Russian titanium alloy named VT 20. The corresponding titanium alloy is TA 15 in Chinese. The Ti-6.5Al-2Zr-1Mo-1V alloy is in catalog of near-α type of titanium alloy. The α-titanium alloy containing a small amount of β-stabilizing elements are widely used in aviation industry. Solid solution strengthening of the alloy is mainly through adding α-stabilizing element, Al. Moreover, the processing ability can be improved through adding small amount of the neutral element Zr and β-stabilizing elements, Mo and V. Thus, the alloy exhibits good creep strength, thermal stability and weldability as α-titanium alloys, and better formability as α-β alloys.

Titanium at temperatures above 350 °C, and particularly in a molten state, is known to be very reactive towards most atmospheric gases such as oxygen, nitrogen and hydrogen. Generally, titanium may rapidly absorb hydrogen at temperature above 300 °C, oxygen at temperature above 600 °C, and nitrogen at temperature above 700 °C. These gas elements reduce ductility and toughness, while increasing strength and hardness. Thus, reliable shielding of weld zone is essential during welding. Nowadays, the titanium alloys are joined by a wide variety of conventional fusion welding processes and solid-state processes. Fusion welding of titanium is performed principally in inert gas-shielded arc welding and high-energy beam welding process. Vacuum or inert gas protection is required to avoid contamination of the fusion and heat affected zone (HAZ) both on the face and root sides until cooling at temperature below 300 °C. Laser beam welding is suitable for joining titanium alloy thin sheet, as the expansion of the beam is small in comparison with the electron beam welding, but inert gas protection is still needed both on the face and root sides.

Till now researches on welding of Ti-6.5Al-2Zr-1Mo-1V alloy have mainly been focused on welding technology, which includes welding defects, microstructure evolution, and conventional mechanical property of welded joints [1–6]. Many results on fracture of welded joints reported for titanium alloys are concentrated to Ti-6Al-4V alloy. In the work by Keshava et al. [7], the effect of microstructure change on the fracture toughness J_{1c} of fusion zone was investigated for the Ti6Al4V alloy welds. Gas tungsten arc and electron beam welds were produced in sheet material. It was found that fracture toughness of the fusion zone in the as-welded condition was greater than for the base metal, and postweld heat treatment at 700 °C reduced the fracture toughness considerably. Similar result was given by the work of Thomas et al. [8]. Electron beam welds were conducted in a Ti6Al4V alloy sheet. It was found that low temperature stress relieving or aging carried out subsequent to the welding operation improved the tensile properties but decreased the toughness at the fusion zone. Barreda et al. [9] measured the crack tip opening displacement (CTOD) of plasma arc welded joints of a Ti-6Al-4V alloy and observed that the maximum fracture toughness was achieved in the weld metal. They attributed the high fracture toughness was related to the acicular microstructure. HAZ of the welds shows a toughness reduction that was related to the presence of martensite. Zhou et al. [10] reported that Charpy impact toughness of the weld was found to be more than 50% higher than that of the base metal and HAZ for a Ti-6Al-4V alloy, even the weld metal has the coarsest grains compared with the HAZ and base metal. The increase in fracture toughness was shown to be due to the much-reduced amount of primary α grains in the weld metal, and boundaries of primary α grains were observed to be preferential sites for microcrack nucleation and provide relatively easy path for crack propagation. Kweietniewski et al. [11] investigated the effect of plastic deformation on the fracture toughness of radial friction welds in Ti-6Al-4V-0.1Ru alloy. The results indicated that the fracture toughness was practically independent of the deformation level imposed.

Recently, there is an increasing interest on the laser beam welding of titanium alloys to expand their fields of application. Laser beam welding has become an attractive alternative to the well-established gas tungsten arc welding process. The major advantages over gas tungsten arc welding are attributed to the low energy input, thus, lower distortion and residual stress level [12]. Moreover, the high welding speed of laser joining is also essential in structure production. However, few works has been reported for the fracture toughness of welded joints of Ti-6.5Al-2Zr-1Mo-1V alloy. Especially, few results have been done with the fracture toughness of VT 20 titanium alloy welded sheet under condition of laser welding. In order to evaluate the life safety for the critical components and structures, one has to know the effect of welding on fracture toughness for the Ti-6.5Al-2Zr-1Mo-1V alloy.

In the present work, fracture toughness of the Ti-6.5Al-2Zr-1Mo-1V alloy thin sheet welded by laser beam welding process was investigated. At the same time effect of laser welding on microstructure of welded joints are examined. Based on the results investigated, the reasons for the change in fracture toughness of welds are discussed.

Materials and experimental procedure

Materials and processing

The material used in this investigation was Ti-6.5Al-2Zr-1Mo-1V (VT 20) titanium alloy. Nominal thickness of the thin sheet was 2.5 mm, but the practical thickness for the tested sheet was 2.64 mm. The chemical composition (wt.%) of the alloy was: 6.82Al; 2.16Zr; 1.47Mo; 1.8V; 0.046Fe; 0.046Si; 0.011C; 0.0069N; 0.0024H; 0.054O; balance Ti.

The size of the welded sheet was 100 mm × 200 mm for preparing welded specimens. The alloy sheets were welded along the edges normal to the rolling direction, using laser-welding process. The welding equipment is PRC4000 CO_2 laser with power of 4 kW manufactured by United State. The power output adopted was 2,680 W, and welding speed was 2.0 m/min. High purity argon was used as shielding gas during welding and as trailing gas right after welding to prevent absorption of oxygen, nitrogen from the atmosphere both on the face and root sides. Some of the welded sheets were subjected to post-weld heat treatment (PWHT) for stress relieving, in which vacuum annealing was selected at 650 °C for 2 h.

Tensile testing

The specimen used for tensile testing was machined along the rolling direction from base alloy sheet according to the geometry and dimensions defined by the China National standard GB 3076-82 for small size flat tensile specimens

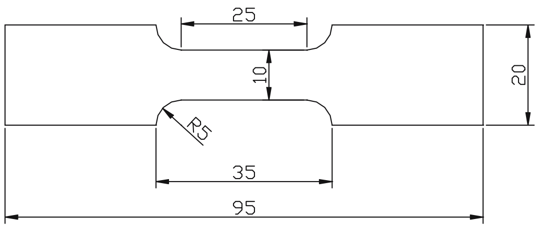


Fig. 1 Geometry of tensile specimen (mm)

[13]. Geometry of the specimen is shown in Fig. 1. Surface of the specimen was rolling surface without any machining. Side edges of the specimen were finished by milling machining. Uniaxial tensile tests were conducted at a loading rate of 1 mm/min at 19 °C in an effort to determine the quasi-static mechanical properties of the base alloy.

Fracture toughness testing

For evaluating fracture toughness, the elastic-plastic parameter J_c was used. The determination of J_c was conducted in accordance with British Standard Draft BS7448-1997 [14]. In the testing the single-specimen technique was used to measure the toughness parameter. The geometry of the compact tension (CT) specimen employed is illustrated in Fig 2.

For base metal the test specimens were machined in the L-T and T-L orientation, in which the first letter designates the direction of loading, while the second letter designates the direction of crack propagation. L represents the longitudinal rolling direction of the sheet, and T represents the long transverse direction. For the welded sheet the weld seam was parallel to the L direction of base sheet. The notch roots were located in weld metal center, and in the fusion zone between weld metal and HAZ, respectively shown in Fig 2b and c. The thickness of the specimens was full thickness of the rolling sheet.

The notch was spark-machined first, then fatigue precracking was done to develop an initial crack length a_0 including the notch length. The ratio of initial crack length

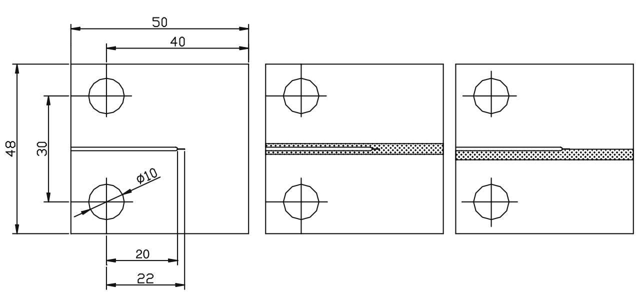


Fig. 2 Geometry of fracture specimen (mm). (**a**) base metal specimen; (**b**) weld metal specimen; (**c**) HAZ specimen

to specimen width, a_0/W, was approximately equal to 0.55. The maximum load used for fatigue precracking was 1.5 kN and the minimum load was 0.2 kN. Frequency was 5 Hz.

The fracture toughness tests were carried out in a MTS 810 materials testing system with loading rate of 1 mm/min. Test temperature was 20 °C. During testing load versus load-line displacement was recorded continuously, then the data was processing through a software Origin.

Metallographic observation

Microstructural observation of welded joints was performed by an OLYMPUS PMG3 optical microscopy. All sectioning of the welded specimens was carried out using spark machine. The sectioned samples were cold mounted, ground on SiC papers, polished, and chemically etched for observation. Etching was carried out in a solution of 5% HF, 5% HNO_3, and 90% H_2O. Moreover, Vickers microhardness measurement was taken under a 100 g load using a HXD-1000 Microhardness Tester. After fracture toughness test, fracture surfaces of the tested specimens were examined carefully under a FEI QUANTA200 scanning electron microscope (SEM).

Results and discussion

Tensile test

The mechanical properties of the tensile specimen were: yield stress of 872.6 MPa, ultimate tensile strength of 1,030.5 MPa, and elongation of 17%. Figure 3 shows a tensile stress/strain curve for the Ti-6.5Al-2Zr-1Mo-1V alloy specimen along the rolling direction.

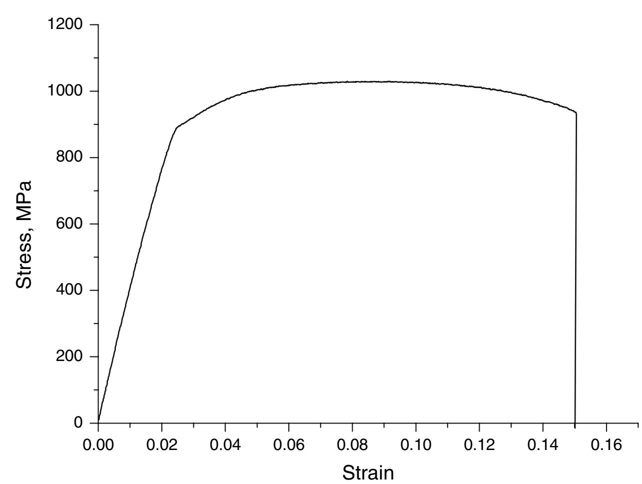


Fig. 3 Tensile curve of Ti-6.5Al-2Zr-1Mo-1V alloy sheet

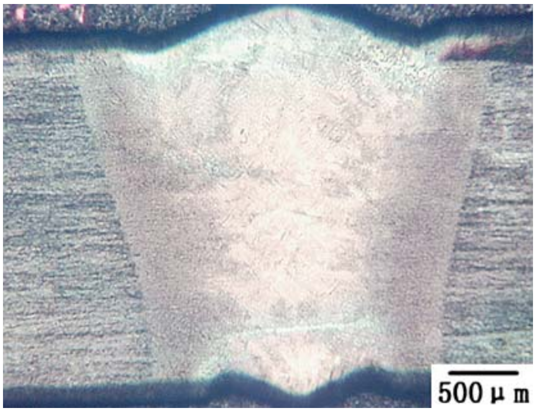
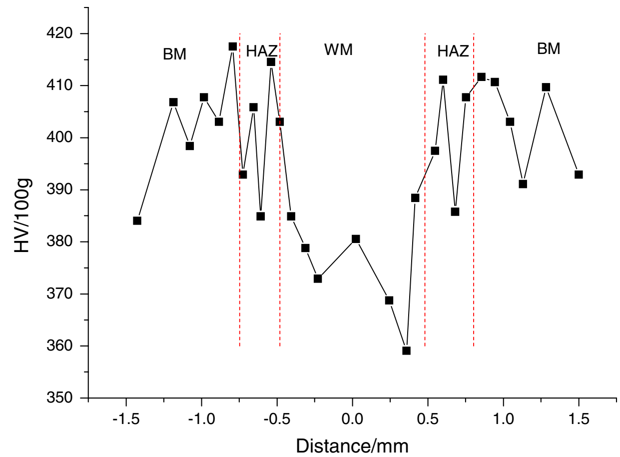
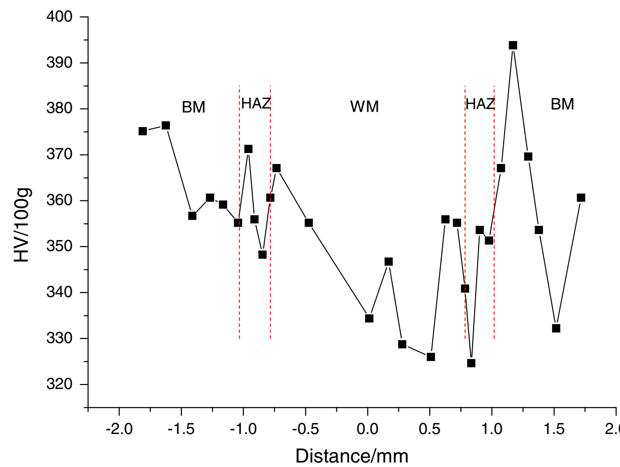


Fig. 4 Configuration of cross-section of typical welds



(a) as-weld



(b) PWHT

Fig. 5 Hardness distribution of welded joint for Ti-6.5Al-2Zr-1Mo-1V alloy

Hardness measurement

Vickers hardness was measured in a transverse section of welded joints. Typical cross-section of the laser welds is shown in Fig 4.

The hardness distribution across weld metal are shown in Fig 5. The Fig 5a and b are as-weld (AW) condition and PWHT condition, respectively. The origin in the abscissa is the center of the welds. Hardness distribution is basically in symmetry to the center of the welds. Before heat treatment the averages of the hardness HV are 403, 400, and 376 separately for base metal, HAZ and weld metal. After heat treatment the averages of the hardness Hv are 363, 351, and 346 separately for base metal, HAZ and weld metal.

It is clear that heat treatment makes hardness of the welds decreasing. Here, the average of hardness HV is decreased by 40, 49, and 30, respectively for base metal, HAZ, and weld metal after heat treatment. Anyway, the welded joint is under the condition of the weld strength undermatching for both the AW condition and PWHT condition.

Fracture toughness test

In the test all the characteristic values of J-integral were J_u, except that one result was J_c. J_c represents a measure of fracture toughness at instability without significant stable tearing crack extension. J_u represents fracture instability after the onset of significant stable tearing crack extension. Even the value of J_u is size-dependent and a function of test specimen geometry, it may be useful to serve as a basis for material comparison and technological selection. The test results are given in Table 1, in which each result is an average of two specimens.

It may be seen from Table 1 that the fracture toughness of base metal with L-T orientation is only slightly higher than that with T-L orientation. In fact, for practical purposes this small dependence is not significant. Moreover, the fracture toughness of weld metal is obviously decreased in comparison with base metal whatever in as-welded condition or in PWHT condition. The reason may be related with the formation of coarsened cast structure in weld metal. Furthermore, the fracture toughness of HAZ is located between the base metal and weld

Table 1 Test results of characteristic fracture toughness

	J(kJ/m^2)	Property
T-L base metal	151.7	J_u
L-T base metal	166.8	J_u
Weld metal(AW)	75.0	J_u
HAZ(AW)	102.8	J_u
Weld metal(PWHT)	53.5	J_u
HAZ(PWHT)	36.1	J_u and J_c

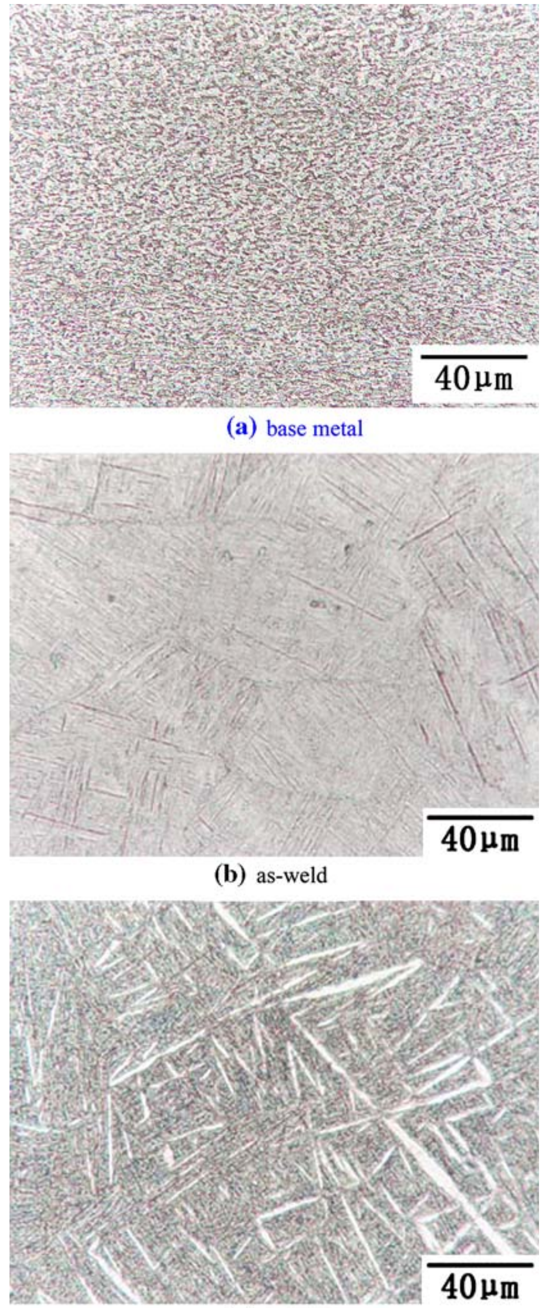
metal for the as-weld condition. Actually the PWHT leads to fracture toughness of the welds further decreasing. It should be mentioned that it is not possible to obtain a reliable evaluation of the fracture toughness of the HAZ, due to the very thin HAZ of the laser beam joints. The precrack front sometimes includes two parts of HAZ and base metal. In addition in the test it is found that the length of slow crack extension is very short before fracture instability. As shown in Table 1, the characteristic parameter is J_u. Actually the slow crack growth is only about 0.5 mm for the HAZ test specimen. Before brittle instability the short crack is not easy to develop further into base metal or weld metal. Actually, the fracture toughness measured for the HAZ may be a mixture which consist of HAZ and base metal.

Metallographic examination

Figure 6 shows the microstructure of base metal and weld metal for the Ti-6.5Al-2Zr-1Mo-1V alloy. It is found that there fine α phases exists for the base metal. Moreover, it is clear that the microstructure of weld metal consists of large grains with fine acicular structure, as shown in Fig 6b. The formation of fine α acicular structure is due to rapid cooling during laser welding. After PWHT, the acicular structure is remained, but the acicular structure is coarsened. Till now it is hard to explain the reason for the coarsening of the acicular structure. Similar results occurred in welding repair of the same Ti alloy plate. It is found that the grain size grows and the α acicular structure is coarsened in the first-pass weld metal due to the subsequent heat effect of welding repair [6]. In addition, it seems that the large grain boundaries may be further deteriorated, because entrapped gases or impurity is further concentrated to grain boundaries during the heat treatment process. This may be a reason of decrease in toughness of welds after PWHT also.

Figure 7 shows the fractography of tested specimens. Fig 7a and b show clearly that the fracture surface of the tested specimen notched in base metal has a starting with the formation of a small flat triangular zone. The triangular zone and followed slanted zone grow together, as shown in Fig 7b. The formation of slant or lip zone represents the increase in fracture toughness of base metal with L-T orientation.

The tested specimens notched in the base metal reveal dimpled fracture surfaces as shown in Fig 7c–d. It is verified that the fracture mode is predominantly ductile in base metal. It seems that the size and shape of dimples observed are similar on the fracture surfaces of L-T and T-L orientation. This may be another witness indicating that the fracture toughness of the titanium alloy sheet is about the same regardless of the rolling direction.



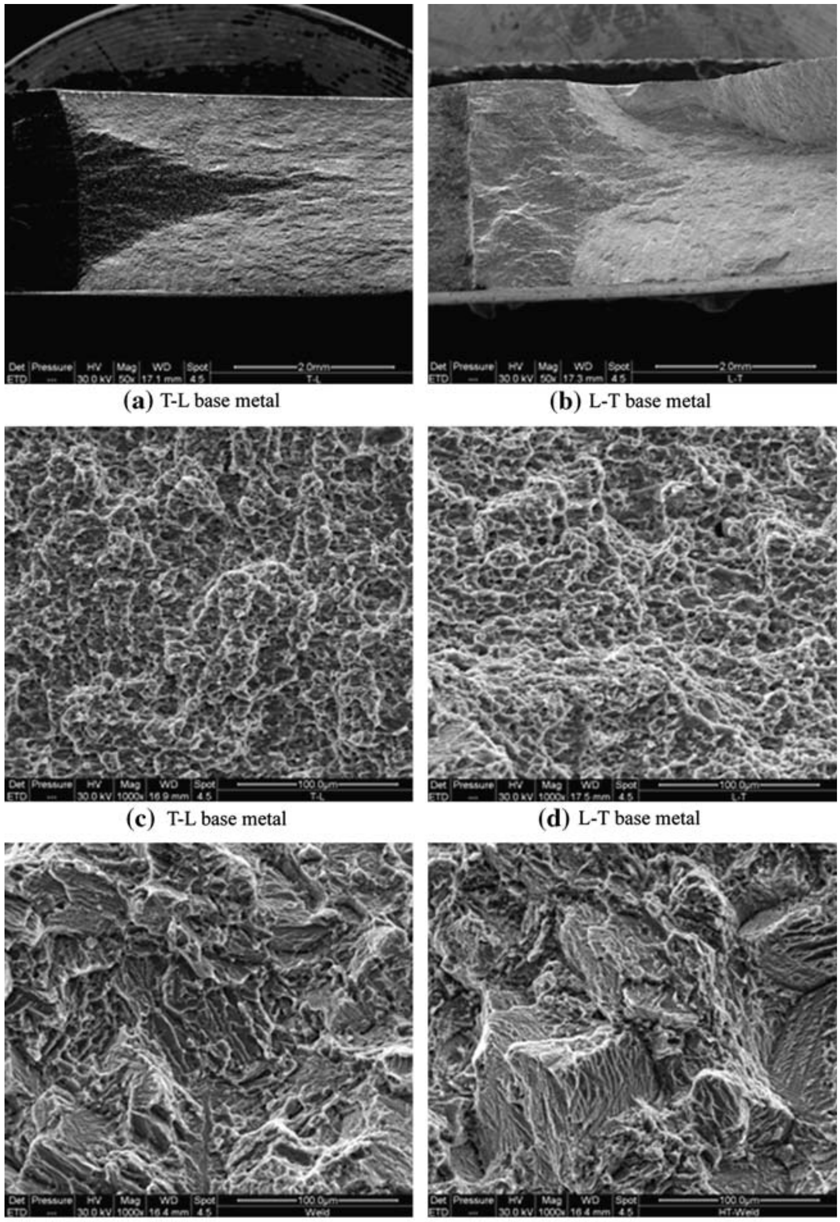
(a) base metal

(b) as-weld

(c) PWHT

Fig. 6 Microstructure of Ti-6.5Al-2Zr-1Mo-1V alloy and its weld metal

Examination of the tested specimen notched in weld metal reveals the existence of intergranular fracture along the crack surface, as shown in Fig 7e and f. The fracture surface is with obvious rock-like pattern. The intergranular fracture leads to dramatic decrease in fracture toughness of weld metal. Moreover, it is worth to note that there exist many striations on the surface of intergranular fracture, which may be relevant to the acicular α structure.



(a) T-L base metal (b) L-T base metal

(c) T-L base metal (d) L-T base metal

(e) weld metal (as-weld) (f) weld metal (PWHT)

Fig. 7 SEM fractography of Ti-6.5Al-2Zr-1Mo-1V alloy and its welds

Conclusion

(1) Results of fracture toughness test using the CT specimens indicate that fracture instability occurs after the onset of significant stable tearing crack extension for all the CT specimens of base metal and welded joints, except that one result of HAZ specimen was fracture at instability without significant obvious stable tearing crack extension.

(2) The fracture toughness of base metal with L-T orientation is only slightly higher than that with T-L orientation. Thus, the effect of rolling direction on fracture toughness is not significant.

(3) Fracture toughness of weld metal is obviously decreased in comparison with base metal whatever in as-welded condition or in PWHT condition. PWHT leads to fracture toughness of the welds further decreasing.

(4) Fracture mode is predominantly ductile in base metal. However, there exists intergranular fracture in the weld metal. The transition of fracture mode from base metal to weld metal may lead to dramatic decrease in fracture toughness.

(5) Microstructure of weld metal consists of large grains with fine acicular structure. The formation of fine α acicular structure is due to rapid cooling during laser

welding. After PWHT, the acicular structure is coarsened.

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