Materials Research Express

PAPER

Effect of welding heat input on microstructure and properties of TC4 titanium alloy ultra-narrow gap welded joint by laser welding with filler wire

Naiwen Fang¹⁻², Erjun Guo¹, Ruisheng Huang¹, Limeng Yin¹⁻⁴, Yongsheng Chen¹, Caiyou Zeng¹, Hao Cao¹, Jipeng Zou² and Kaixin Xu²

¹ Harbin University of Science and Technology, Harbin 150080, People’s Republic of China
² Harbin Welding Institute Limited Company, Harbin 150028, People’s Republic of China
³ Chongqing University Science & Technology, Chongqing 401331, People’s Republic of China
⁴ Guangdong Modern Welding Key Laboratory, China O. Paton Institute of Welding, Guangzhou 510651, People’s Republic of China

E-mail: guoerjun98@126.com

Keywords: heat input, TC4 titanium alloy, laser welding with filler wire, microstructure, mechanical property

Abstract

A 10 mm narrow gap TC4 titanium alloy welded joint by laser welding with filler wire was obtained by different welding heat inputs. The microstructures of the welded joint were analyzed by OM, SEM, XRD and EBSD. The mechanical properties of the welded joint were analyzed by microhardness test and tensile test. The results show that with the increase of laser welding heat input, the average grain size and width of the equiaxed crystal zone in the center of the weld increases, the grain angle in the columnar crystal zone gradually tends to be perpendicular to the center of the weld, and the width of the heat affected zone (HAZ) increases without obvious grain coarsening. The HAZ of the welded joint is softened, and its microhardness value is lower than that of the weld and the base metal. The tensile strength of the welded joint is slightly higher than those of the base metal, but the elongation after fracture is less than that of the base metal, and it decreases with the increase of laser welding heat input.

1. Introduction

As one of the most widely used titanium alloys because of its high specific strength, excellent corrosion resistance and good processing and forming advantages [1], TC4 titanium alloy has been commonly used in the manufacture of nuclear submarines, deep submersibles, aerospace and weaponry [2, 3]. It is a typical α-β two-phase titanium alloy, which contains about 6 wt% α-stable element Al and about 4 wt% β-stable element V [4]. The large-scale application of TC4 titanium alloy is often realized by welding, such as inert gas welding (TIG welding), vacuum electron beam welding and laser welding. However, the groove angle of TIG welding is generally greater than 30° and there are defects such as low welding efficiency, large welding deformation and residual stress, coarse weld structure and tungsten inclusion in the weld [5, 6]; vacuum electron beam welding is often limited by the size of welding components, and the equipment for the welding is expensive and has radiation; laser welding might cause concavity, undercut and insufficient surface after welding [7]. Laser welding with filler wire not only takes into account the small heat input, narrow heat affected zone and precise energy regulation, but also improves the microstructure and properties of the weld, which is of great significance for low deformation, low cost and high-quality welding of titanium alloy components.

At present, TC4 titanium alloy welding is mainly adopted in thin plate laser welding and laser welding with filler wire for square groove TC4 titanium alloy ultra-thin plate. Cui Bing et al [8] used TA2 welding wire as filler metal to weld 10 mm thick TC4 titanium alloy plate by ultra-narrow gap laser welding. Due to the Meshing Effect of ultra-narrow gap, the maximum tensile strength of welded joint reached 893 Mpa, which was close to 84.7% of that of the base metal. The fracture location was in the center of the weld, and the microhardness of the weld seam area and heat affected zone was higher than that of the base metal. There is a study on the underwater laser welding process with filler wire for TC4 titanium alloy. High quality weld was obtained by adjusting the...
welding speed and wire feeding speed \([9]\). With the welding speed and wire feeding speed of 20 mm \(\text{s}^{-1}\) and 60 mm \(\text{s}^{-1}\) respectively, the weld with good forming and continuous stability was obtained. The yield strength was 813.42 MPa, the impact toughness at room temperature reached 39.07 J cm\(^{-2}\), and the fracture surface is cleavage and ductile mixed. Yang Wulin \([10]\) studied the fatigue properties of laser welded joint and base metal of TC4 titanium alloy thin plate, and observed the fatigue fracture surface. The results show that the fatigue life of the joint is higher than that of the base metal at low stress level and lower than that of the base metal at high stress level. The fatigue crack of the base metal initiates on the surface of the sample. In the crack propagation zone, there are parallel bending secondary cracks and finer fatigue striations in between, and small equiaxed dimples are distributed in the instantaneous fracture zone. However, there are few studies on the technology of laser welding with filler wire for TC4 titanium alloy thin plate with groove, and the research on the effect of welding heat input on the microstructure and properties of ultra-narrow gap laser welding joint of TC4 titanium alloy plate is rarely reported. In this paper, TC4 titanium alloy plate with U-shaped groove (10 mm thick) was used for narrow gap laser welding with filler wire, and the effect of different welding heat input on the microstructure and properties of the joint was systematically studied in order to provide reference and guidance for narrow gap laser welding of TC4 titanium alloy for thick plate and ultra-thick plate.

2. Experiment

The size of TC4 titanium alloy plate used in the experiment is 300 mm \(\times\) 150 mm \(\times\) 10 mm. The microstructure of TC4 titanium alloy base metal amplified by 200 times and 500 times is shown in figures 1(a) and (b), respectively. It can be seen that TC4 titanium alloy base metal is composed of \(\alpha + \beta\) biphase, and the average grain size is about 40 \(\mu\text{m}\). TC3 welding wire was used as filler metal with diameter of 1.2 mm. The chemical compositions of base metal and filler wire are shown in table 1. In the process of laser welding with filler wire, the front and back sides of the welding joint were shielded by high-purity Ar gas, and the flow rate was 20 l min\(^{-1}\). the welding test plate was processed into U-shaped groove, with 2 mm root face, and the groove gap was set as 3.2 mm. The size of welding groove is shown in figure 2.

The laser welding system includes KUKA robot, wire feeder of Fronius Austria, and YLS-30000 fiber laser by IPG. The focal length is 460 mm, the output wavelength is 1.06 \(\mu\text{m}\), the minimum spot diameter is 0.69 mm, and the maximum output power is 30 kW. The output mode of continuous laser and front laser is adopted. Figure 3 is the schematic diagram of laser welding with filling wire. Before welding, pickling was carried out on TC4 titanium alloy to remove the surface oxide film and oil stain. The pickling solution was 24%HCl + 38%HNO\(_3\) + 11%HF + H\(_2\)O. After pickling, rinse with clean water and blow dry. In order to reduce welding deformation, TC4 titanium alloy plate was welded after rigid fixation. Welding parameters in
Table 2 were adopted for one pass of back welding, three passes of filling welding, and one pass of cosmetic welding. During the welding process, the back side is protected by filling argon, and the front welding pass is protected by a row of pipes.

After welding, the metallographic samples of the weld cross-section were obtained by wire cutting perpendicular to the welding direction. The microstructure was observed in the metallographic microscope after sandpaper grinding, polishing and etching of the samples. The etchant agent used was HF: HNO₃: H₂O = 1:2:7. Olympus optical microscope was applied for metallographic analysis. The grain boundary characteristics and fracture morphology of welded joints were observed by FEI Quanta-200 field emission scanning electron microscope equipped with electron backscatter diffractometer. X-ray diffraction (XRD) patterns were collected using Empyrean diffractometer. The microhardness was analyzed by HVS-1000z microhardness tester, with a load of 500 g and the loading time of 10 s. The tensile properties at room temperature were tested on INSTRON 5569 electronic universal testing machine, with a tensile rate of 1 mm min⁻¹.

3. Experimental results and analysis

3.1. Microstructure of welded joint

Figure 4 shows the microstructure of the joint under different welding heat input conditions. It can be seen that the weld microstructure is composed of coarse original β-columnar grains and a small amount of equiaxed grains, and a large number of elongated needle like α′ phases are interlaced in the β grains. With heat input of 2.29 kJ cm⁻¹, the microstructure of HAZ I (coarse grain zone) is acicular α′ phase with equiaxed and coarse grains. The peak temperature of coarse grain region is close to the melting point with a longer duration of high temperature. In addition, the diffusion coefficient of β phase atom at the temperature above the phase transition point is large. As a result, the grains grow dramatically. Compared with HAZ I (coarse grain zone), HAZ II (fine grain zone) has shorter duration at the temperature above the phase transition point, so there is no sufficient
Table 2. Welding parameters.

| Sample no. | Laser power $P$/W | Heat input $E$/kJ · cm$^{-1}$ | Wire feed speed $V_1$/cm · s$^{-1}$ | Welding speed $V_2$/cm · s$^{-1}$ | Focal length $f$/mm | Defocus quantity $\Delta f$/mm |
|------------|---------------------|-----------------------------|----------------------------------|---------------------------|------------------|-----------------------------|
| 1          | 2200                | 2.29                        | 6                                | 0.96                      | 428              | +20                         |
| 2          | 2800                | 2.67                        | 1.05                             | 3500                      | 3.02             | 1.16                        |
| 3          | 3500                | 3.02                        | 1.16                             |                           |                  |                             |
time for the grains to grow, resulting in finer grains. The microstructure of the zone is primary intergranular α′ phase + massive α′ phase + intragranular lamellar (α + β), which retains the microstructure of base metal. However, the grain boundaries of some α phase are fuzzy. The total width of HAZ is about 1.2 mm. The microstructure of the base metal consists of intergranular primary α-phase + massive α-phase + intragranular lamellar(α + β). There is no significant difference in the microstructure between the welded joints with heat inputs of 2.67 kJ cm$^{-1}$, 3.02 kJ cm$^{-1}$ and 2.29 kJ cm$^{-1}$. In the process of laser welding with filler wire, the β phase of TC4 titanium alloy weld metal grows rapidly, and coarse columnar crystal is formed in the weld area. Due to the rapid cooling of the weld, the transformation of the weld metal from β phase to α phase by diffusion transformation is too late to be carried out. Instead, it shear transformed into different forms of lath martensite α′ phase, which intersects with a small amount of β between the lamellar phases. The difference of the morphology of α′ martensite is mainly affected by nucleation defects, which is related to the
molten pool stirring. The higher the laser power, the stronger the metal evaporation and plasma spraying in the molten pool, and the welding pool is strengthened at the same time by its stirring effect. In this process, the defects which the martensite nucleation depends on are easy to be produced in the weld, and more nucleation cores are formed. As soon as the martensite nucleates, its growth is completed rapidly, thus forming a more scattered and staggered structure [11]. The grains in the whole HAZ grow slightly, but there is no obvious coarsening occurred. The grain size in the HAZ of welded joint is 3.0 grade under three welding heat inputs. In the conventional arc welding process of titanium alloy, grain in the HAZ is often coarsened seriously, which leads to the reduction of toughness. However, for laser welding with filling wire, the influence on HAZ is greatly reduced due to the concentration of heat and fast welding speed, which effectively inhibits the coarsening of grain in the HAZ.

The area percentage of the columnar crystal zone in the entire weld cross-section varies with welding heat input, as shown in figure 5(a). It decreases with the increase of welding heat input. In the process of laser welding with filler wire, the isotherm of laser heat source is elliptical. The temperature gradient G in front of laser moving direction is larger than that in rear. With the increase of welding heat input, the temperature and the superheat degree of molten pool increase, the heating time of molten pool extends, and the width of high temperature zone in weld center increases. The above factors lead to the decrease of temperature gradient G in the center of molten pool behind heat source during cooling. Grain growth velocity R at the boundary of both sides of the weld pool is small, and the crystallization rate \( R = V \cdot \cos \theta \) (V is the welding speed, and \( \theta \) is the angle between the welding wire and the molten pool). There is little difference of welding speed V, and \( \theta \) remains constant. So the ratio G/R of molten pool decreases, resulting in the increase of undercooling degree of composition in the front of the original \( \beta \)-grain growth interface, which is conducive to the heterogeneous nucleation of \( \beta \)-grains in the weld, and finally leads to the increase of equiaxed crystal quantity and the decrease of columnar crystal percentage.

The relationship between the width of the heat affected zone and the heat input is shown in figure 5(b). It can be found that the width of HAZ(1 coarse grain zone) + HAZII(2 fine grain zone) in welded joint is between 1.5 mm to 1.8 mm under three welding heat inputs. With the increase of heat input, the heat affected zone gradually widens. In the process of laser welding of titanium alloy with filler wire, with the increase of heat input, the energy transferred from laser to molten pool increases, the temperature of metal vapor and plasma increases, the heat radiation and heat transfer of molten pool flow strengthen, and the molten metal increases. In addition, due to the enhancement of keyhole effect in the weld pool, the metal vapor inside the small hole will eject to the lower part of the workpiece, and the reaction will force the liquid metal to flow around the hole. The back side of the weld is enhanced by the laser effect. The shielding gas on the back of the weld pool can prolong the heating time of the lower surface of the weld pool, thus widening the heat affected zone [12].

Figure 6 shows the XRD pattern of weld zone under different welding heat input. It can be seen from the figure that the weld of the laser welding of TC4 titanium alloy with filling wire is mostly composed of \( \alpha' \) phase. There is no obvious diffraction peak of \( \beta \) phase. This may be due to its small content and intergranular distribution, resulting in the difficulty in its detection by XRD. It can also be found from figure 6 that the change of welding heat input has little effect on the phase composition and peak height of each phase, indicating that the change of welding heat input has no significant effect on the relative content of each phase in the weld.
addition, it has been reported that $\omega$ phase will be introduced into TC4 titanium alloy weld under non-equilibrium rapid cooling condition, which results in the increase of weld strength, hardness and elastic modulus, and the decrease of plasticity [13]. However, the formation of $\omega$ phase is not found in this experiment.

Figure 7 shows the EBSD orientation imaging maps of the base metal structure and the weld microstructure with the welding heat input of 2.29 KJ cm$^{-1}$. It can be seen from figure 7(a) that the matrix of TC4 titanium alloy is mainly composed of equiaxed grains with uniform distribution before welding. Compared with figure 7(b), it can be found that the grain boundary of martensite $\alpha'$ phase in the weld zone is slender, and the width of fine martensite lath is about several hundred nanometers, distributing among the coarse original $\beta$ grains. Furthermore, the martensite laths in different original $\beta$-grains have different orientations, while in the same $\beta$-grain, martensite laths tend to have preferred orientation distribution. For Ti-6Al-4V alloy, burgers lattice correspondence must be satisfied when BCC $\beta$ phase transformed into HCP $\alpha'$ martensite phase, namely $\langle 0001 \rangle \alpha' // \langle 110 \rangle \beta$ and $\langle 1120 \rangle \alpha' // \langle 111 \rangle \beta$. In theory, a certain oriented $\beta$ phase can be transformed into 12 $\alpha'$ martensite variants with different orientations. But in the welding process, there is a high temperature gradient between the fusion zone and the base metal zone. Under the condition of high temperature gradient, a certain orientation of $\beta$ phase tends to transform into a preferred orientation of $\alpha'$ martensite to keep the total energy of the system minimum. As a result, the preferred oriented $\alpha'$ martensite in the coarse primary $\beta$ grains was observed [14].

Figure 8 is the statistical results of the local misorientation of the TC4 titanium alloy base metal and the weld structure with a welding heat input of 2.29 KJ cm$^{-1}$. The results show that there are more grain boundaries between $0^\circ \sim 10^\circ$ and $55^\circ \sim 60^\circ$ in the base metal. The statistics show that the grain boundaries with the angle
between $0^\circ \sim 10^\circ$ account for about 6.5%, the grain boundaries with the angle between $55^\circ \sim 65^\circ$ account for 31%, and the remaining 62.5% of the grain boundaries are approximately evenly distributed. The percentage of grain boundary angle between $55^\circ \sim 65^\circ$ is about 41.3%, and that between $0^\circ \sim 10^\circ$ accounts for 4.6%. After laser welding with filler wire, the number of small angle grain boundaries in the weld is obviously less than that in the base metal. It can be concluded that the fine acicular martensite in the weld zone has a high density of large angle grain boundary, which has a good blocking effect on dislocation starting and sliding, and contributes greatly to the strength. However, within the same original $\beta$-grain, the orientation difference of martensite lath is small, and the martensite lath interface is parallel arranged and runs through the whole coarse original $\beta$-grain, which has less effect on crack propagation. Therefore, the elongation of weld zone is low, which can be verified from the following tensile property analysis.

### 3.2. Mechanical properties of welded joint

#### 3.2.1. Microhardness

Figure 9 shows the microhardness distribution in different zones of welded joint under different welding heat input. From left to right are base metal zone, heat affected zone and weld zone. It can be seen that the microhardness in the weld area is significantly higher than that in the base metal and heat affected zone, and the average microhardness of the weld is the highest, which can reach 340 HV.

The peak value generally appears in the fusion zone near the fusion line. After crossing the fusion line, the microhardness decreases suddenly. The values of different zones slightly varies under different heat input, but the distribution trend is basically the same. The hardness of weld area decreases gradually with the increase of welding heat input. According to Hall-Petch formula, the smaller the grain size is at room temperature, the more grain boundaries are contained in unit volume, and the better strengthening effect is [15]. Therefore, the smaller the grain size is, the higher the hardness value is. With the increase of welding heat input, the grain size of equiaxed grain in the center of weld increases gradually, so the hardness value decreases gradually.

It can be seen from figures 4 and 5 that when the welding heat input is 2.29 kJ cm$^{-1}$ and 2.67 kJ cm$^{-1}$, the grain size of the weld is smaller than that of the base metal, and the hardness value of the weld is higher than that of the base metal. When the welding heat input is 3.02 kJ cm$^{-1}$, the grain size in the center of the weld is equivalent to that of the base metal, while the columnar grain at the edge is coarsened obviously. At the same time, the hardness of the weld is higher than that of the base metal due to its high dislocation density. In addition, HAZ of welded joint softens, and its hardness value is lower than that of weld and base metal. This is because dislocation density of grains in HAZ decrease after welding thermal cycle. The growth of the grains results in lower hardness than base metal and weld.

#### 3.2.2. Tensile test

Static load tensile tests were carried out on TC4 titanium alloy base metal and welded joints of laser welding with filling wire at room temperature. The results are shown in table 3. The tensile strength of the base metal is 925 MPa and the elongation is 12.5%. The fracture position of welded joint mainly occurs at the weld with high hardness value. From the crack point of weld fracture (see figure 10), it is found that the fracture mainly occurs at the grain boundary of coarse columnar crystal in the weld structure. Due to the obvious directionality, the columnar grains in the weld grow perpendicular to the fusion line and are almost parallel to the load direction.
during the tensile process. The bearing capacity of the columnar grains is significantly lower than that of the anisotropic equiaxed grains. The narrow width of HAZ formed by laser welding with filler wire might have a certain strain strengthening effect on the HAZ during the tensile process. Therefore, the fracture is more likely to occur in the weld zone with more coarse columnar grains.

In addition, the tensile strength of TC4 titanium alloy welded joint is equivalent to that of the base metal, but the elongation after fracture is about 62 ~ 72% of the base metal, which is obviously lower than that of the base metal. Moreover, with the increase of welding heat input, the elongation after fracture of welded joint decreases gradually. The reason is that with the increase of laser welding heat input, the number of proeutectoid coarse β grains in the weld increases, which obviously increases the brittleness of welded joint. The ability of coordinating

| Sample no. | Heat input/KJ·cm⁻¹ | Tensile strength Rm/MPa | Elongation percentage A/% | Fracture position |
|------------|---------------------|-------------------------|---------------------------|------------------|
| Base metal | —                   | 925                     | 12.5                      | —                |
| 1          | 2.29                | 924                     | 9.0                       | Weld metal       |
| 2          | 2.67                | 915                     | 8.3                       | Weld metal       |
| 3          | 3.02                | 919                     | 7.8                       | Weld metal       |

Figure 9. Microhardness distribution of TC4 joint welded with different heat input.
deformation between grains becomes poor, which leads to the difficulty of plastic deformation and the gradual decrease of elongation.

3.2.3. Fracture surface morphology

The tensile fracture morphology of welded joint under different heat input is shown in figure 10. A large number of dimples are distributed on the tensile fracture surface of welded joints with heat input of 2.29 kJ cm\(^{-1}\). There are small dimples in the large dimples, so it is ductile fracture. The nucleation of micropores is mostly generated due to the separation of the second phase from the matrix when the plastic deformation reaches a certain degree. With the development of plastic deformation, dislocations enter into the micropores, and microcracks are formed along with the necking fracture of micropores. As the tensile force large enough to cause fracture, the fracture features of fiber like macroscopically and dimple state microscopically are formed. When the heat input is 2.67 kJ cm\(^{-1}\), the dimples on the fracture surface become shallower and less. It is still ductile fracture, but the toughness getting poor. When the heat input is 3.02 kJ cm\(^{-1}\), the fracture surface of the weld is composed of a large number of fine dimples and quasi cleavage surfaces, and the fracture mode is ductile brittle mixed.

The strengthening elements in TC4 titanium alloy weld are mainly V and Al. V is \(\beta\) phase stable element. The decrease of V content will lead to the instability of \(\beta\) phase and promote the transformation of \(\beta\) phase to \(\alpha'\) phase. \(\alpha'\) phase is a close packed hexagonal structure, with only 3 slip systems. \(\beta\) phase is body centered cubic structure, including 12 slip systems. Therefore, the plastic deformation ability of \(\beta\) phase is better than that of \(\alpha'\) phase, which results in the decrease of elongation of welded joint with the increase of heat input. The analysis results of tensile test are verified hence.

As a stable element of \(\alpha'\) phase, Al is easy to melt into \(\alpha'\) solid solution and plays a role of solution strengthening. With the increase of welding heat input, the molten base metal of TC4 titanium alloy transits to the weld metal, that is, the dilution ratio increases obviously, which leads to the transition of the base metal with higher Al content to the weld metal. Moreover, with the increase of heat input, the content of Al element in the weld increases, which leads to the improvement of the strength of welded joint. The analysis results also verify the data analysis of tensile test.

Figure 10. Fracture surface morphology and EDS (a)2.29 KJ cm\(^{-1}\), (b)2.67 KJ cm\(^{-1}\), (c)3.02 KJ cm\(^{-1}\).
4. Conclusions

(1) The microstructure of the weld is composed of coarse columnar grains and a small amount of equiaxed grains. The elongated acicular α′ phase of large aspect ratio can be observed in the grain, with adjacent α′ phases parallel to each other. The proportion of columnar grains in the weld decreases with the increase of welding heat input. The width of the HAZ of the three welding heat input ranges from 1.5 mm to 1.8 mm and becomes wider with the increase of heat input.

(2) The hardness of weld zone is higher than that of base metal and heat affected zone. The values of each zone are slightly varied under different heat input, but the distribution trend is basically the same. The hardness of weld zone decreases with the increase of welding heat input.

(3) The fracture location of welded joint mainly occurs at the grain boundary of coarse columnar crystal in the weld structure with higher hardness. The tensile strength of the welded joint is equivalent to that of the base metal. The elongation after fracture of the welded joint is about 62%–72% of the base metal. With the increase of welding heat input, the elongation after fracture of the welded joint decreases gradually, and the tensile strength increase slightly.

Acknowledgments

The authors gratefully acknowledge the financial support of the state key research and Development Program (2016FYB1102103).

ORCID iDs

Naiwen Fang @ https://orcid.org/0000-0002-5622-6899

References

[1] Ning G et al 2019 Research on underwater laser welding with filler wire process of TC4 titanium alloy Journal of Mechanical Engineering 56 118–24
[2] Yongqing Z 2014 The new main titanium alloys used for shipbuilding developed in China and their applications Materials China 33 398–404
[3] Weiping F et al 2019 Stress corrosion crack sensitivity of ultra-thick TC4 titanium alloy electron beam welding joints Transactions of the China Welding Institution 40 121–8
[4] Qingjie S et al 2013 Analysis on welded joint of thick Ti-6Al-4V plate by magnetically controlled narrow-gap TIG welding Transactions of the China Welding Institution 34 9–12
[5] Liu H et al 2012 Microstructural characteristics and mechanical properties in laser beam welds of Ti6Al4V alloy J. Mater. Sci. 47 1460–70
[6] Elmesalamy A, Francis J A and Li L 2014 A comparison of residual stresses in multi pass narrow gap laser welds and gas-tungsten arc welds in AISI 316L stainless steel Int. J. Press. Vessels Pip. 113 49–59
[7] Aiqin D et al 2019 Effect of undercut defect on deformation behavior TC4 titanium alloy laser welded butt joint under static tensile loading Transactions of the China Welding Institution 40 54–60
[8] Bing C et al 2018 Microstructure and mechanical properties of TC4 titanium alloy joint by ultra-narrow gap laser welding Materials Review 32 333–5
[9] Huang K and Loge R E 2018 Microstructure and flow stress evolution during hot deformation of 304L austenitic stainless steel in variable thermomechanical conditions Materials Science & Engineering A 711 600–10
[10] Wu lin Y et al 2012 Analysis on Fatigue Property and Fracture Mechanism of TC4 Titanium Alloy Joint During Laser Welding 33 105–8
[11] Hongning Y et al 2015 Microstructure and mechanical properties of high-strength TC11 titanium alloy joints welded by laser beam The Chinese Journal of Nonferrous Metals 25 1–8
[12] Manikandan M et al 2015 Improvement of microstructure and mechanical behavior of gas tungsten arc weldments of alloy c-276 by current pulsing Acta Metall. Sinica 28 208–15
[13] Donghai C et al 2009 Microstructure and mechanical properties of Ti-6Al-4V joints by laser beam welding Rare Met. Mater. Eng. 38 259–62
[14] Oehring M et al 2013 Microstructural refinement of boron-containing β-solidifying γ-titanium aluminide alloys through heat treatments in the β-phase field Intermetallics 52 12–20
[15] Cui C Y et al 2013 Microstructure and microhardness of fiber laser butt welded joint of stainless steel plates Mater. Des. 49 761–5