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ARTICLE

Study on the Electron Beam Welding Process of ZTC4 Titanium Alloy

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Abstract: The electron beam (EB) welding process of Ti casting plates was investigated. For achieving the welds with an acceptable quality, the cross-sectional shape, the microstructure and the tensile properties of the electron beam joint of casting TC4 (ZTC4) alloy were studied. The results show that the double-side molding in electron beam welding of ZTC4 can be achieved by adjusting the welding speed and welding current, but it is difficult to achieve double-sided weld shape in welding the thick plates, and its internal quality meets the standard requirement. The microstructure of electron beam weldment of casting TC4 alloy in the base metal is composed of α laths and β phase, the weld consists of acicular martensites, and the heat affected zone (HAZ) consists of thin acicular martensites, α laths and β phase. The tensile strength of ZTC4 EB-joints is higher than that of the base metal, so the tensile strength of ZTC4 EB-weld can be improved by optimizing the composition and the microstructure of base metal. Impact test shows that stress concentration factor has a great effect on absorbed energy.

Key words: casting titanium; electron beam welding; process; weld shape

Titanium alloys are widely used in the aeronautical industry and for bio-medical applications. The interest in titanium and its alloys originates from its remarkable properties, such as a good heat resistance, a particular resistance to corrosion, bio-compatibility, and its superplastic capacities and its interesting specific strength compared to other high strength alloys such as steels[1]. Ti6Al4V is the first practical titanium alloy developed successfully by United States in 1954, and now it has become the workhorse materials in titanium industry. In the consumption of all titanium alloys, Ti6Al4V occupies more than 50%[2]. However, the cost of titanium alloy is high, and hard to be processed. The thermomechanical processing and machining cost of titanium occupies 70%~80% of a entire part[3].

Foundry methods permit the production of complex-shape titanium components, and as a result, reduce costs in comparison with machining. Casting titanium alloys have become increasingly popular because large, complex, one-piece shapes can be made to replace the components which were previously assembled by mechanically fastening several pieces together[4,5].

If the size of a component is too large, the component has to be divided to two or three parts to cast. The electron beam welding is an effective join process used to achieve the larger components. The interest in welded structure can be explained by its remarkable properties, such as light weight, high efficiency, fewer parts, less failure and high reliability features, in which areas it can overcome the deficiencies of the mechanical connection by the welded structure. In the aerospace industry, several welding methods, such as TIG welding, diffusion welding, electron beam welding and laser welding are commonly used[6]. The electron beam welding is still the preferred joining technique for a variety of components[7], because of the obvious advantages like a deep and narrow weld zone, reduced heat-affected zone (HAZ), the ability to control gas content and high reliability[8,9]. Compared with conventional arc welding, electron beam welding can also save auxiliary materials and reduce energy consumption, which greatly

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improves the technical and economic indicators of the material welded[10,11].

This paper studied the welding process of EB welding of casting ZTC4Ti plates, the welding quality of EB welds and the optimizing welding process to promote the using of cast titanium alloy and joint of large structures in the aerospace industry, to provide a technical support for the realization of the weight and manufacturing cost reduction, saving the energy consumption and reducing the emission of aerospace engines and aircraft.

1 Experiment

The electron beam joints were produced using a high vacuum electron beam welding equipment with an accelerating voltage of the electron gun of 150 kV and a rated power of 60 kW.

In order to study the weldability of ZTC4 alloy, the test plates with the thickness of 20 mm were selected. The plates were mechanically polished and chemically cleaned on their surfaces, scrubbed with anhydrous ethanol, and then the test of electron beam welding was carried out. In the welding process, the specimens were lain flat on the pad, without external binding. During the weldability test, in order to study the effect of welding parameters on the weld shape, only one parameter, welding current, was changed, and other welding parameters kept the same values, including focus current, welding speed, scan frequency, and the value of such bias. Welding test parameters are shown in Table 1.

From the results we can see that the surfaces of all 20 mm thick penetrated welds (1#, 2#, 3# in Table 1) have excessive penetration, and the surfaces of part-penetrated welds have undercuts, as shown in Fig.1. The plates (4#, 5# in Table 1) have no penetrated welds. At the welding speed of 25 mm/s, the weld cross-section morphology with the parallel boundary can be achieved by the adjustment of welding current. This weld morphology is propitious to control the welding distortion and to calculate the welding shrinkage. The weld width of the part-penetrated weld is significantly greater than that of penetrated weld, and it will lead to a larger welding deformation or contraction.

Based on the weldability test, weld formation tests were performed. The test plates of ZTC4 alloy with the thicknesses of 12, 21 and 45 mm were mechanically polished and chemically cleaned on the surface, and scrubbed with anhydrous ethanol before the electron beam welding. In the welding process, the specimens were lain flat on the pad, without any external binding. In order to study the effects of welding parameters on the weld shapes, only one parameter, welding current, was changed, and other welding parameters kept the same value, including focus current, welding speed, scan frequency, and the value of such bias. Welding test parameters are shown in Table 2.

Table 1 Welding parameters of ZTC4 plate with 20 mm thickness

Specimen No.	Acceleration voltage/kV	Beam current/ mA	Welding speed/ mm·s^{-1}
1#		160	
2#		150	
3#	150	120	25
4#		90	
5#		95	

Fig.1 Appearance of ZTC4 plate weld by electron beam welding (20 mm thickness)

Then, in accordance with the standard "AIPS airbus process AIP01-04-011Specification electron beam welding of hard metals" provided by Airbus, the electron beam weld quality was inspected by X-ray, to determine the existence of internal cracks, weld excessive porosity and other weld defects. Weld quality should meet the assessment of weld quality A-class standard condition. For achieving the welds with acceptable quality, the cross-sectional shapes were observed, and the effect of welding parameters on the weld shapes were studied. And the microstructure and the tensile properties of electron beam joints of casting TC4 alloy were also studied.

2 Results and Discussion

2.1 Weld formation

The weld formation of 12, 21 and 45 mm thick electron beam weld are shown in Fig.2.

Fig.2 shows that the ZTC4 alloys with different thicknesses have different appearances of the electron beam welds. As can be seen, for the 12 and 21 mm thick test plates, the double-side molding in electron beam welding can be achieved by adjusting the welding speed and the welding current. Comparing with the weldability test shown in Fig.1, the forming of

Table 2 Electron beam welding parameters of ZTC4 plates with different thicknesses

Thickness/ mm	Acceleration voltage/kV	Beam current/mA	Welding speed/mm·s^{-1}	Work distance/mm
12		110	25	345
21	150	140	20	334
45		145	15	500

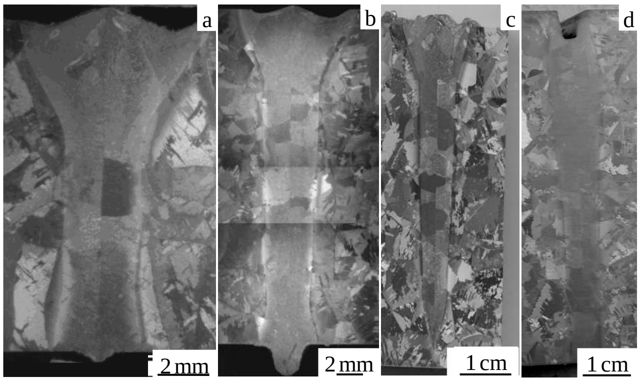

Fig.2 Appearance of ZTC4 plates weld by electron beam welding: (a) 12 mm thickness, (b) 21 mm thickness, and (c, d) 45 mm thickness

the back of the weld is full, and the undercut defect can be avoided. The defect slightly below the plate edges at both sides of the reinforcement on the face weld, can be repaired by defocusing welding method or removed by reserving a machining allowance method in the welding structure. In Fig.2, there are two pictures of weld formation of 45 mm thick test plate, one is a part-penetration weld, and the other is a penetration weld. From these two pictures, it can be seen that the part-penetration weld shape of 45 mm thick test plate is similar with that of the 20 mm thick test plate. And it is obvious that there is an excessive penetration for the penetration weld. It indicates that this welding material has a good liquidity and a smaller surface tension. On the other hand, with the increase of the weld penetration, the part-penetration weld has the “nail tips” effect. Therefore, in welding ZTC4 plate with a middle thickness, an excess material should be set aside in the direction of the weld penetration to ensure the structural quality.

When the weld penetration depth is larger than 20 mm, the weld with the depth/width ratio greater than 10:1 can be achieved by the optimized electron beam welding technology. After welding, the EB weld quality of the ZTC4 alloys was inspected by the X-ray according to the inspection standard provided by Airbus. The results show that there are no cracks and blowhole defects which exceed the inspection standard significantly in the EB weld, and its internal quality can meet the A-class acceptance conditions of the inspection standard" AIPS Airbus Process AIP01-04-011Specification Electron Beam Welding of Hard Metals" provided by Airbus.

Observed from the test, for the penetration welding, because of the lower surface tension of metal melting liquid of casting titanium alloy, the face weld is easy to be depressed and difficult to gain good formation. It needs to increase thickness in the direction of the weld penetration before welding and removing the allowance by machining. In this study, technical difficulties of the weld forming for a thick casting titanium plate have been overcome, and the double-side molding technology has been realized successfully.

2.2 Microstructure analysis

The microstructure of the electron beam weldment of casting TC4 alloy are illustrated in Fig.3, which exhibits columnar β grains in the fusion zone due to the epitaxial solidification mechanism. The sizes of the columnar grains are in relation to the microstructure of base metal. It is observed that the width of the β grains in the fusion zone of casting TC4 alloy is above 2 mm, while it is only 100~300 μm in the fusion zone of electron beam weldment of TC4 plate.

As illustrated in Fig.3, the base metal of casting TC4 alloy shows lamellar structure in the form of α laths and β phases. The HAZ near the base metal is observed to consist of acicular martensites, α laths and β phase because of the relatively low peak temperature during welding. As compared to the BM and HAZ, the microstructure in the fusion zone was considerably different; the initial lamellar structure in BM was transformed to thin acicular martensitic structure. For the alpha-beta titanium alloy TC4, this evolution in the fusion can be reasoned by the rapid cooling rate during welding.

As illustrated in Fig.4, the base metal of TC4 plate consists of equiaxed primary α and β phases. The HAZ near the fusion zone is observed to consist of martensites, undissolved α phase and β phase. It is also observed that the HAZ region far from the fusion zone exhibits fewer equiaxed primary α phase which resulted from lower peak temperature during welding thermal cycle compared with the HAZ region near the fusion zone. As compared to the BM and HAZ, the microstructure in the fusion zone is observed to consist of thin acicular martensitic structure.

2.3 Tensile properties

The tested tensile properties are listed in Table 3. The 0.2% yield stress is in the range of 765~805 MPa and is averaged at 786 MPa. The ultimate tensile stress is in the range of 795~855 MPa and is averaged at 822 MPa. The elongation is about 4.3% within a narrow range of 3%~5.5%. The fracture area reduction is about 17.2% within a large range of 7%~24.8%. It was found

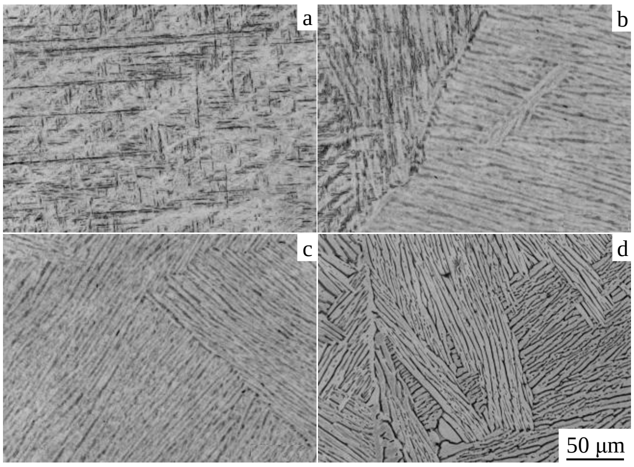

Fig.3 EB joint microstructures of ZTC4 alloys: (a) the center of the weld, (b) the junction of the weld and the HAZ, (c) HAZ, and (d) the base metal

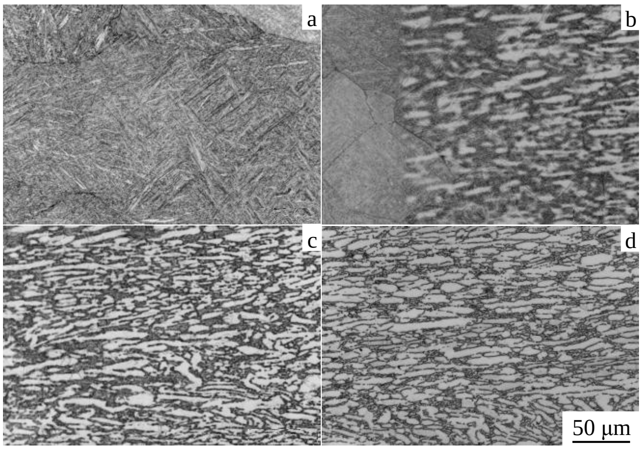

Fig.4 EB joints microstructure of TC4 alloys: (a) the center of the weld, (b) the junction of the weld and the HAZ, (c) HAZ, and (d) the base metal

Table 3 Tensile properties of ZTC4 alloy welded plates

Sample No.	R_m/MPa	$R_{p0.2}$/MPa	A/%	Z/%
1-1	855	805	5.2	14.1
1-2	795	765	4.0	13.1
1-3	835	790	4.4	15.7
1-4	825	785	4.0	20.7
1-5	800	765	4.0	24.8
1-6	800	780	4.8	18.5
2-1	825	795	4.0	19.0
2-2	825	785	5.5	20.0
2-3	830	800	4.0	19.5
2-4	830	790	3.0	7.0
Average value	822	786	4.29	17.24

Table 4 Impact properties of EB joints of ZTC4 alloys

Sample No. (V-shape notch)	K_{V_2}/J	Sample No. (U-shape notch)	K_{U_2}/J
ZTC4-1-1	12	ZTC4-2-1	27
ZTC4-1-2	16	ZTC4-2-2	25
ZTC4-1-3	22	ZTC4-2-3	24
ZTC4-1-4	16	ZTC4-2-4	36
ZTC4-1-5	22	-	-
ZTC4-1-6	21	-	-
Average	18.17	-	28

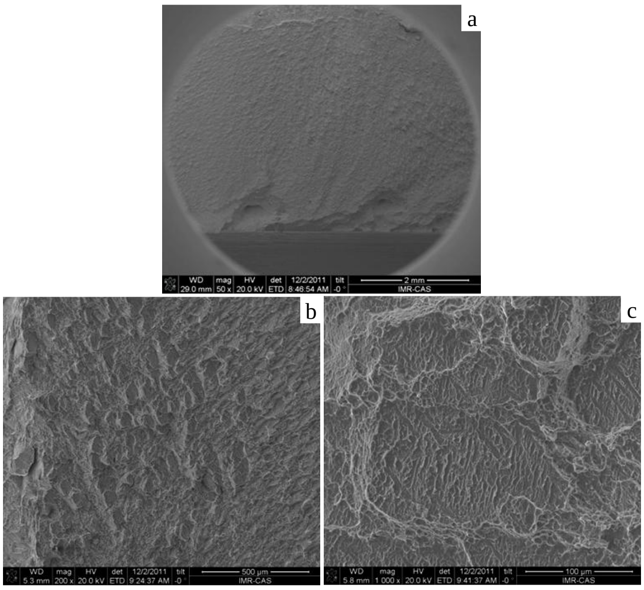

Fig.5 SEM images of fracture surface of the impact tested samples: (a) macrograph, (b) ZTC4-2-3, and (c) ZTC4-2-4

that except ZTC4-2-4 all samples were broken at the base metal rather than welds which indicates that the welds are stronger than the base metal. Sample ZTC4-2-4 was broken around welds and had the lowest ductility. Welding defects may exist in this sample. The large scattering of tensile properties is probably due to the microstructural inhomogeneity in the base metal as expected for castings.

2.4 Impact properties

Charpy impact tests of samples across the weld lines were performed to evaluate its impact property. Test results are listed in Table 4. The absorbed energy during impacting is about 18.2 J for the samples with V-shape notch and 28 J with U-shape notch. This indicates that the sharpness of notch or the stress concentration factor has a significant effect on the impact toughness.

The SEM images of fracture surfaces of samples ZTC4-2-3 and ZTC4-2-4 are shown in Fig.5. The fracture surface of ZTC4-2-3 is flat and shows typical transgranular brittle fracture, which may explains why it has the lowest impact toughness. ZTC4-2-4 has the highest toughness and its fracture surface is relatively rough and shows a quasi-cleavage fracture and small dimples which can be seen under high magnification.

3 Conclusions

1) The double-side molding in electron beam welding of ZTC4 can be achieved by adjusting the welding speed and welding current, and its internal quality meets the A-class acceptance conditions of the inspection standard provided by Airbus.

2) In welding the thick plates, it is difficult to achieve a double-sided weld shape, so an excess material should be set aside in the direction of weld penetration to ensure the structural quality.

3) For the microstructure of electron beam weldment of casting TC4 alloy, the base metal is composed of α laths and β phases, the weld consist of acicular martensite, and HAZ consists of thin acicular martensites, α laths and β phase.

4) The tensile strength of ZTC4 EB-joints is higher than that of the base metal, so the tensile strength of ZTC4 EB-welds can be improved by optimizing the composition and the microstructure of the base metal.

5) Impact test shows stress concentration factor has a great effect on absorbed energy.

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铸造 TC4 合金电子束焊接工艺研究

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摘　要：主要探讨铸造 TC4 合金电子束焊接工艺。为了获得良好的铸造 TC4 合金电子束焊接接头，作者对焊缝形貌，微观组织和接头拉伸性能进行研究。结果表明：通过调节焊接电流和焊接速度可以获得电子束焊双面成型工艺，但是对于厚板却很难获得双面成形的焊缝形状，经 X 射线检测焊缝内部质量，能满足检验标准；铸造钛合金电子束焊接接头微观组织构成的母材由板条状 α 相和 β 相组成，焊缝区域由针状马氏体组成，热影响区由细针状马氏体、板条状 α 相和 β 相组成；铸造 TC4 电子束焊接接头拉伸性能与母材相当，因此可以通过改善母材的组织成分和显微组织来提高其焊接接头的拉伸强度。冲击试验表明应力集中系数对吸收功有很大的影响。

关键词：铸造钛合金；电子束焊接；焊缝形状

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