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Research on ELI Grade Casting Titanium Alloy and Its Precision Forming Technology

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Extra low interstitial (ELI) grade titanium alloy castings are very important in the manufacture of high-end equipment, especially in the areas of aviation and aerospace. In this research, two types of ELI grade casting titanium alloy Ti-5Al-2.5Sn ELI and Ti-6Al-4V ELI are investigated on their chemical compositions, microstructure, mechanical properties and the process of precision forming. Result shows that the optimal chemical composition for Ti-5Al-2.5Sn ELI is Al 4.5-5.5 wt.%, Sn 2.0-3.0 wt.% and for Ti-6Al-4V ELI is Al 5.5-6.5 wt.%, V3.5-4.5 wt.%. The testing results, tensile strength $R_m \geq 780$ MPa, elongation $A \geq 15\%$, impact value $KU_2 \geq 67$ J for Ti-5Al-2.5Sn ELI and $R_m \geq 910$ MPa, $A \geq 10$ %, $KU_2 \geq 62$ J for Ti-6Al-4V ELI, in room temperature indicate favorable mechanical properties. Also, these two ELI alloys show a high fracture toughness and damage resistance. In addition, two methods, ceramic mould investment process and machining graphite mould combined with ceramic core process, are developed for the precision forming process of ELI alloys. With these methods, castings with minimum surface roughness R_a 3.2 μm, highest dimensional tolerance IT14 and surface contamination layer ≥ 6 μm can be achieved.

Keywords: *Extra Low Interstitial (ELI); Casting Titanium Alloy; Ti-5Al-2.5Sn ELI; Ti-6Al-4V ELI; Precision Forming*

1. Introduction

Extra low interstitial (ELI) grade titanium alloy, which contains low-level amount of interstitial elements (C, N, H, O) and impurity elements (Fe, Si etc.) is designed for the requirement of high damage tolerance of parts. Since 1960s, many countries have developed their own designations and standards of ELI grade titanium alloy[1],such as standards AMS4907,AMS4931,ASTM367, ASTM F136 (medical implants) for Ti-6-4 ELI alloy(U.S.), AMS4909, AMS4924 for Ti-5-2.5 ELI alloy(U.S.); IMI318 ELI(Britain), TA6V ELI(France); TAF 6400E(Japan) and TC4-DT (China).Due to the prospective applications of ELI grade titanium alloys in aviation and aerospace, a lot of research have been carried out, such as effects of oxygen content on the thermal deformation of Ti-6Al-4V ELI, effects of surface roughness and notch on the low temperature fatigue property of Ti-5Al-2.5Sn ELI, effects of cooling rate on the microstructure and properties of TA15 ELI[2-5], etc. Most work focused on the aspects of ingredients, structures and properties of ELI grade titanium alloys shaped by forging or powder metallurgy. However, in recent years, as the rapid development in aviation and aerospace, larger amount and higher properties of ELI grade titanium alloys are required for casting applications in rockets, airplanes and missiles. However, related study has rarely been done so far. In this paper, the factors which influence the performance of ELI grade cast titanium alloy and precision forming technology have been studied to provide important technical support for the development and application of casting technology of ELI grade titanium alloys.

2. Experimental procedure

In this paper, samples were melted and poured in vacuum consumable electrode arc skull furnace, with 40-50 V melting voltage, 5000-8000 A electric current and 15 Pa vacuum degree. The mother alloy is cast ingots of Φ200mm Ti-6Al-4V ELI and Ti-5Al-2.5Sn ELI alloy, which are melted twice in vacuum consumable electrode arc furnace. The cast mold is made of graphite block by machining, and used for pouring after vacuum degassed at the temperature of 800 ℃. Samples were poured by centrifugal casting with a speed of 150 r/min. After HIP treatment (920±10 ℃, 2 h, 130 MPa), the chemical component, mechanical properties and metallographic structure of samples are analyzed. For element testing, the sample with a size of Φ3×30 mm is tested by meter TCH-600 for

N, H, O and direct-reading spectrometer QSN750 for other elements. Also, universal material testing machine CSS-1120, impact testing machine JB-300W and electro-hydraulic servo fatigue testing machine Instron8801 are used for the testing of tensile property, impact property, fracture toughness and fatigue crack growth rate at room temperature. The phase analysis was conducted on X-ray diffraction analysis meter D/max 2500pc. For optical testing, the metallographic specimen is etched in a solution with a component ratio of $HF:HNO_3:H_2O=1:3:7$ for 2 min and then observed under optical microscope OLYCIAm3 and transmission electron microscope JEM200CX.

3. Results and discussion

3.1 Chemical composition of cast ELI grade titanium alloy

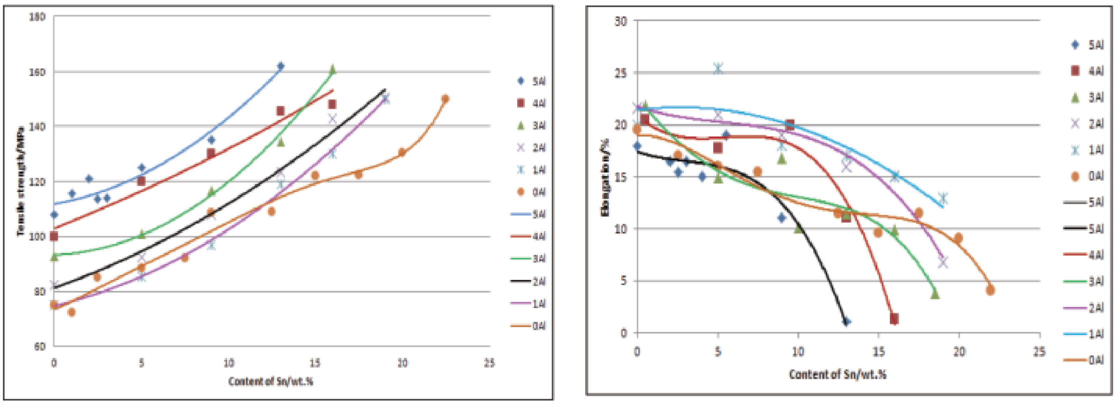
Recently, the standards of ELI grade titanium alloy on element content are different in different countries (Table 1). The current standard of the content range is too wide for ELI grade titanium, which makes it difficult to ensure a steady quality of castings because of the large dispersion of mechanical properties. Basically, Al and Sn can increase the strength of Ti alloy and decrease the plasticity. In Fig. 1, we can see that the content ratio of Al is lower than 7 wt.% for most Ti alloys, except for TiAl, because a brittle-phase Ti_3Al can be easily formed and seriously weaken the plasticity when the weight ratio is higher than this value. This phenomenon also occurs when the content of Sn increases in Ti alloy. In this paper, optimal component ratios Al = (4.5-5.5) wt.%, Sn= (2.0-3.0) wt.% for Ti-5Al-2.5Sn ELI alloy and Al = (5.5-6.5) wt.%, V= (3.5-4.5) wt.% for Ti-6Al-4V ELI casting are proposed for the balance of strength and plasticity. However, the interstitial impurity elements in alloy don't satisfy the requirement of damage tolerance design because it needs strict control of the upper limit (Table 2).

Table 2 Composition of cast ELI grade titanium alloys proposed and their castings (wt.%)

Nominal code	Forming method	Al	Sn	V	C	N	H	O
Ti-5Al-2.5Sn ELI	cast	4.5-5.5	2.0-3.0	-	≤ 0.05	≤ 0.03	≤ 0.0120	≤ 0.12
Ti-6Al-4V ELI	cast	5.5-6.5	-	3.5-4.5	≤ 0.05	≤ 0.03	≤ 0.0120	≤ 0.12
Ti-5Al-2.5Sn ELI	cast	5.1	2.7	-	0.02	0.01	0.009	0.05
Ti-6Al-4V ELI	cast	6.2	-	4.1	0.01	0.02	0.0010	0.09

Table 1 Typical ELI grade titanium alloys and their composition (wt.%)

Country	Shaping method	Standard and grade	Nominal code	Al	Sn	V	C	N	H	O
America	Deformation	ASTM348 (Grade 23)	Ti-6Al-4V ELI	5.5-6.5	-	3.5-4.5	≤ 0.08	≤ 0.03	≤ 0.0125	≤ 0.13
France	Deformation	NF L14 (TA6V ELI)	Ti-6Al-4V ELI	5.5-6.75	-	3.5-4.5	≤ 0.08	≤ 0.05	≤ 0.01	≤ 0.13
England	Deformation	IMI318 ELI	Ti-6Al-4V ELI	5.5-6.75	-	3.5-4.5	≤ 0.08	≤ 0.03	≤ 0.0125	≤ 0.13
Japan	Deformation	JIS H4657 (TAF 6400E)	Ti-6Al-4V ELI	5.5-6.5	-	3.5-4.5	≤ 0.08	≤ 0.03	≤ 0.0125	≤ 0.13
China	Deformation	GB/T 3620.1 (TC4 ELI)	Ti-6Al-4V ELI	5.5-6.5	-	3.5-4.5	≤ 0.08	≤ 0.03	≤ 0.0120	≤ 0.13
China	Deformation	(TC4-DT)	Ti-6Al-4V ELI	5.6-6.3	-	3.6-4.4	≤ 0.05	≤ 0.03	≤ 0.0120	≤ 0.12
America	Deformation	AMS4909 (Ti-5-2.5 ELI)	Ti-5Al-2.5Sn ELI	4.5-5.75	2.0-3.0	-	≤ 0.05	≤ 0.035	≤ 0.0125	≤ 0.12
China	Deformation	GB/T 3620.1 (TA7 ELI)	Ti-5Al-2.5Sn ELI	4.5-5.75	2.0-3.0	-	≤ 0.05	≤ 0.035	≤ 0.0125	≤ 0.12



(a) influence of Sn on strength (b) influence of Sn on plasticity

Fig. 1 Influence of content of Sn on mechanical properties of titanium alloys[6]

The final contents of the poured ELI grade titanium alloy samples are shown in Table 2. It shows that the contents of impurity elements, especially C, N, H, and O, are controlled in a low level.

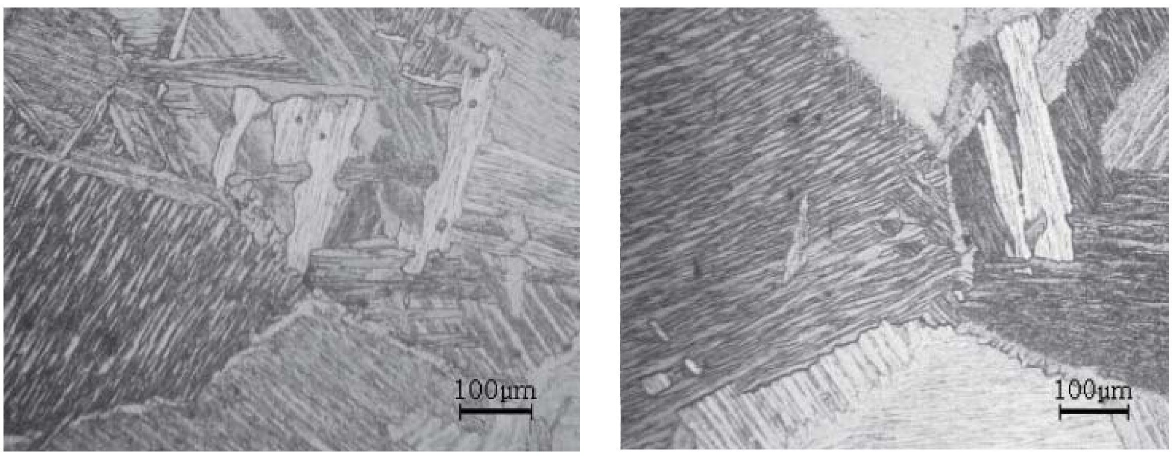
3.2 Structure of cast ELI grade titanium alloy

3.2.1 Microstructure of cast Ti-5Al-2.5Sn ELI alloy

Microstructure of Ti-5Al-2.5Sn ELI alloy in different state are shown in Fig. 2. It shows that some original β phase is kept in the microstructure of Ti-5Al-2.5Sn, which is a typical Widmanstatten structure. Inside the grain, there are lath-shaped colonies arraying in a certain orientation, among which the boundaries are visible clearly. There is also continuous or discontinuous coarse grain boundary phases distributed on the boundaries of the original β phase, which are irregular curves. XRD analysis results of these two kinds of microstructure are shown in Fig. 3, in which, the microstructure of Ti-5Al-2.5Sn ELI alloy is mainly composed of α phase (colonies in Fig. 2a). The grain boundary phase is also shown to be α phase in Fig. 4 TEM analysis. In HIP state, the microstructure of Ti-5Al-2.5Sn is still composed of lath-shaped colonies and grain boundary of original β phase (Fig. 2b), and the major phase is still platelet α phase (Fig. 3b). However, comparing with as-cast structure, the colonies are less but larger in HIP state structure, accompanied with thinner and more straight grain boundaries.

3.2.2 Microstructure of cast Ti-6Al-4V ELI alloy

Fig.5 shows the microstructure of cast Ti-6Al-4V ELI alloy, which is mainly composed of equiaxed grains with lamellar phase (Fig. 5a). In β phase there are very clear grain boundaries around with either continuous or discontinuous intergranular phases. The β grain, which also



(a) as-cast (b) HIP treated

Fig. 2 Microstructure of cast Ti-5Al-2.5Sn ELI alloy

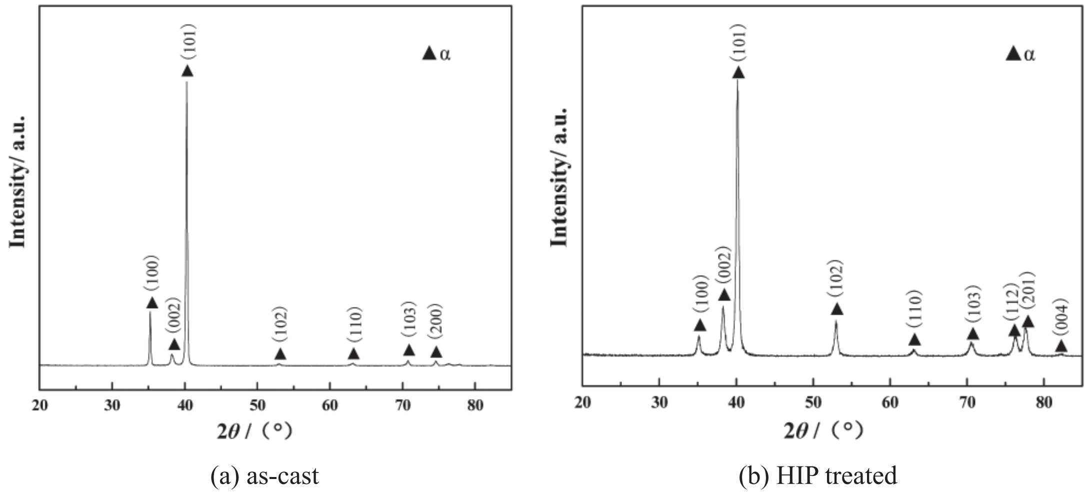


Fig. 3 XRD patterns of cast Ti-5Al-2.5Sn ELI alloy

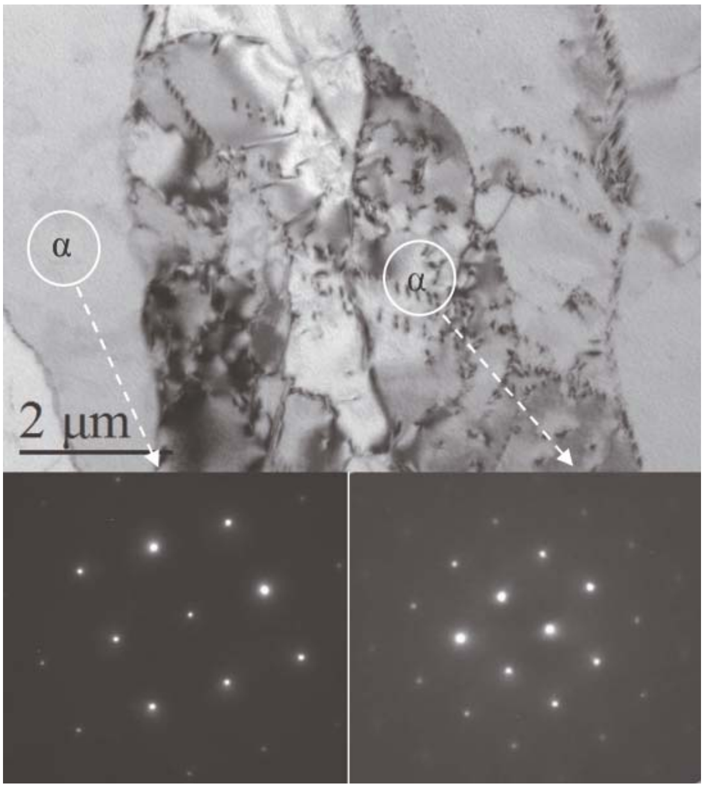
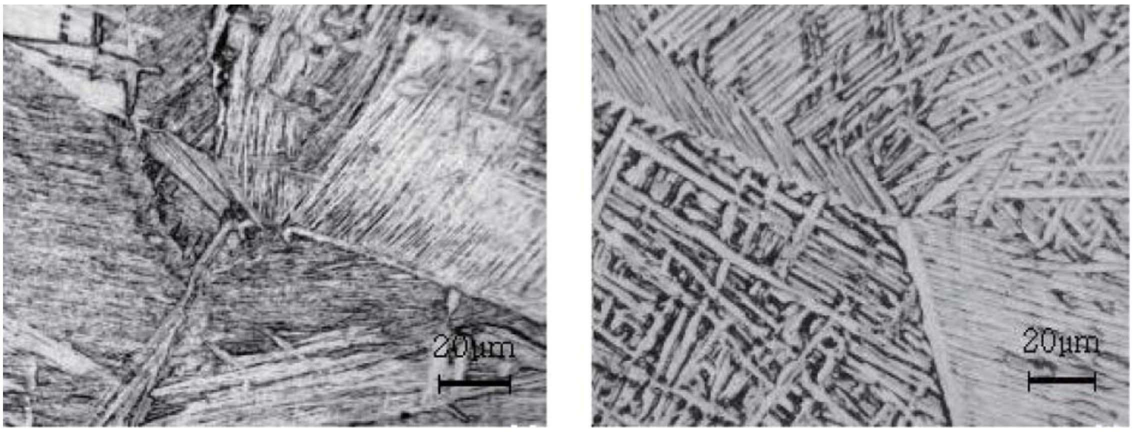


Fig. 4 TEM analysis of Ti-5Al-2.5Sn ELI alloy

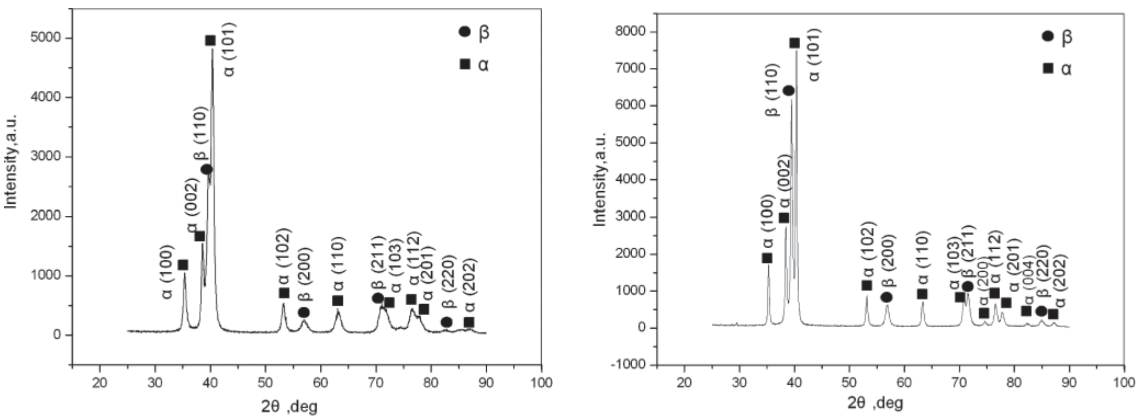
contains some subgrains inside, is relatively large with a size of 200 μm. The XRD analysis (Fig. 6) illustrates that the microstructure is composed of both α and β phase. And the TEM analysis in Fig. 7 shows that the white lamellar phase in Fig. 5a is α phase, while the black phase, which distributes among α phase, is β phase, and the phase on the original β grain boundary is intergranular α phase. Fig. 5b shows the microstructure of Ti-6Al-4V ELI alloy after HIP treatment. It is clear that the lamellar phase after HIP treatment is coarser and thicker, compared with that of casting alloy.

Furthermore, the biggest change is the appearance of basketweave structure within the grain, which is quite different from platelet α phase in lath colonies. The results of XRD and TEM analysis show that the lamellar phases whether in lath or in basketweave structure are α phase. Also, the phases on the grain boundary are α phases, while β phases are actually distributed among α phases. This phenomenon is caused by the change of hole defects. For example, in the HIP treatment, shrinkage of cavity and porosity accompany with creep of alloys occur under high



(a) as-cast (b) HIP treated

Fig. 5 Microstructure of cast Ti-6Al-4V ELI alloy



(a) as-cast (b) HIP treated

Fig. 6 XRD patterns of cast Ti-6Al-4V ELI alloy

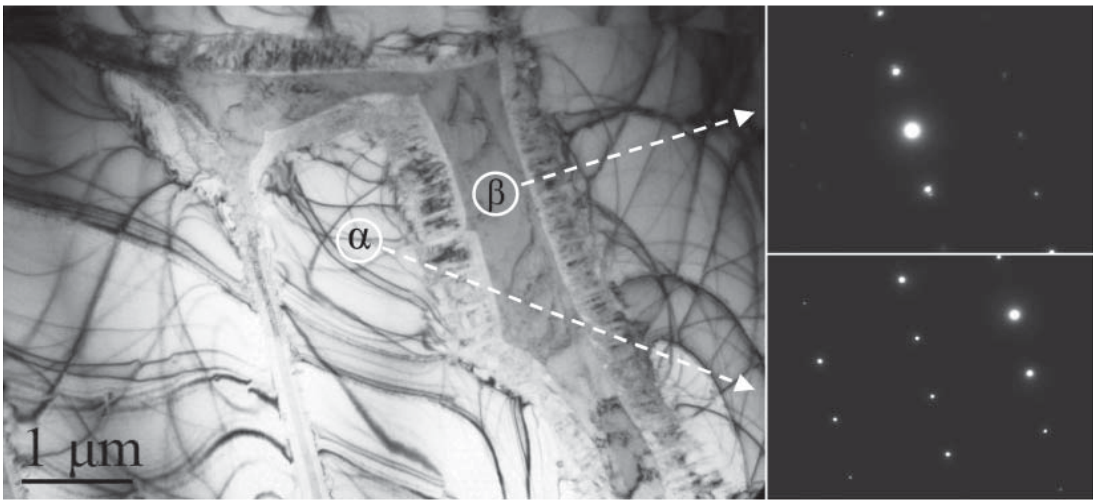


Fig. 7 TEM image of cast Ti-6Al-4V ELI alloy

temperature and high pressure. In these areas, where voids close, recrystallization occurs because of the creep deformation[8-9], and allows part of the lamellar structure to be equiaxed. The lamellar α phases grow under the effect of the second diffusion of element, which can release some stress concentrated on the edge of lamellar α grain and benefit improving the plasticity of alloys.

3.3 Mechanical properties of cast ELI grade titanium alloy

3.3.1 Tensile properties

Tensile properties of cast Ti-5Al-2.5Sn ELI alloy are shown in Table 3. It can be seen that as-cast Ti-5Al-2.5Sn ELI alloy has high tensile strength and good plasticity. After treatment of HIP, its yield strength and elastic modulus have no obvious change while the elongation increases in a certain degree. This change is ascribed to the changes of the microstructure. On one hand, the macro- and micro-void defects such as gas holes, shrinkage and cavity are closed and disappear after HIP treatment, and the crack source caused by defects during the process of tensile test decreases significantly. On the other hand, in the area of defects closed, equiaxed grains cross each other, the lap joints of them are firm, and the crack is difficult to propagate, as illustrated in Reference 10. The tensile fracture morphologies of cast Ti-5Al-2.5Sn ELI alloy in the condition of casting and HIP treatment are shown in Fig. 8. It can be seen that in the condition of casting, most of the dimples are small in size and shallow in depth, the deep one is scare, but after HIP treatment, there are many large and deep dimples, and there are many small dimples in the large dimples. In general, the size, amount, and depth of dimple are directly related with the energy absorbed during fracturing; many large and deep dimples can absorb more energy, which is not easy to fracture. These indicate again that the plasticity of Ti5Al2.5Sn ELI alloy has been improved obviously after HIP treated.

Table 3 Tensile properties of cast Ti-5Al-2.5Sn ELI alloy at room temperature

Condition	Sample	R_m/MPa	$R_{p0.2}$/MPa	A/%	Z/%	E/GPa
Casting	#1-1	785	745	12.0	24.5	121
	#1-2	790	750	11.5	22.0	123
HIP	#2-1	795	760	17.5	29.0	123
	#2-2	790	755	15.5	28.0	122

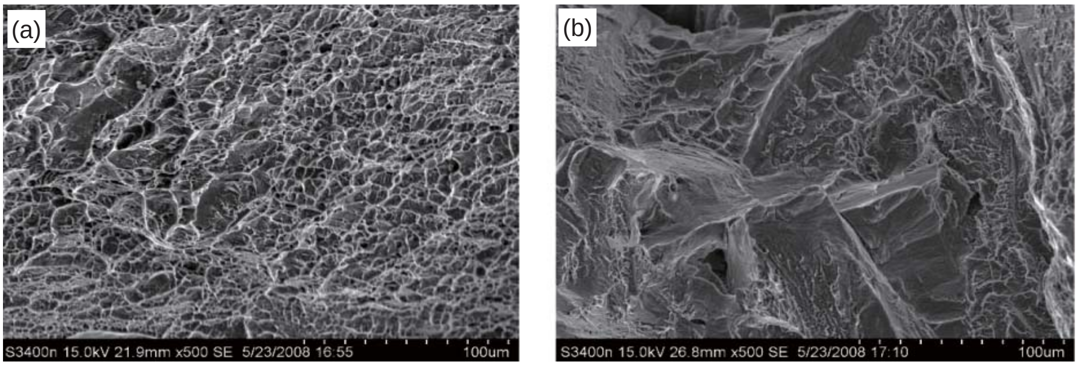


Fig. 8 Tensile fracture morphology of Ti-5Al-2.5Sn ELI alloy after (a) casting and (b) HIP treatmen

Table 4 shows the tensile properties of cast Ti-6Al-4V ELI alloy after casting or HIP treated. It can be seen that cast Ti-6Al-4V ELI alloy has high strength and good plasticity. Both in the conditions of casting and HIP treatment, the tensile strengths of cast Ti-6Al-4V ELI alloy are higher than that of cast Ti-5Al-2.5Sn ELI alloy by about 100 MPa. Both the strength and the elongation of cast Ti-6Al-4V ELI alloy increase after HIP treatment, which is also ascribed to the changes of chemical composition and microstructure. As mentioned above, the defects and the casting stress are both eliminated, and the composition segregation is reduced during HIP treatment. So the homogeneity of composition and microstructure are improved significantly, and the tensile properties are improved.

Table 4 Tensile properties of cast Ti-6Al-4V ELI alloy at room temperature

Condition	Sample	R_m/MPa	$R_{p0.2}$/MPa	A/%	Z/%	E/GPa
Casting	#1-1	890	845	10.5	18.0	110
	#1-2	895	850	12.0	17.0	109
HIP	#2-1	910	855	15.5	22.0	115
	#2-2	920	860	16.5	24.0	118

3.3.2 Impact properties

Table 5 shows the comparison among impact values of cast Ti-6Al-4V alloy, cast Ti-5Al-2.5Sn alloy and their ELI grade alloys. The data shows that the impact property of ELI grade alloy is higher than that of the same alloy in non-ELI grade. For different kinds of alloys with the same level of impurity, the impact value of Ti-5Al-2.5Sn alloy is higher than that of Ti-6Al-4V alloy. Also, for alloys with the same chemical composition and same impurity level, the impact value of HIP-treated one is higher than that of as cast. Generally, the impact value of alloy is related to both the type of microstructures and the contents of interstitial impurities.

Table 5 Impact properties of ELI and non-ELI cast titanium alloys

Alloy	Condition	KU_2/J	Alloy	Condition	KU_2/J
Ti-5Al-2.5Sn ELI	cast	61	Ti-6Al-4V ELI	cast	58
Ti-5Al-2.5Sn ELI	HIP	67	Ti-6Al-4V ELI	HIP	62
Ti-5Al-2.5Sn	cast	54	Ti-6Al-4V	cast	51
Ti-5Al-2.5Sn	HIP	58	Ti-6Al-4V	HIP	54

Previous research[6] shows that impurity elements such as C, N, H, O exist in the lattice gaps of titanium alloys. These impurity elements reduce the amount of slip system and also lead to crack sources caused by the stress concentration. Therefore, the ductility and toughness of ELI grade cast titanium alloys are higher than those of non-ELI grade alloys generally. In addition, the influence of interstitial impurities is different for different types of microstructures of alloys. For α titanium alloys, the crystal lattice is close-packed hexagonal structure, and interstitial elements exist in its tetrahedral interstice and octahedral interstice. But for α+β titanium alloys, the interstitial impurity elements exist in both tetrahedral α phase and octahedral interstice of β phase simultaneously. These two types of crystal have same type and number of lattice interstice, but the largest interstice radius of close-packed hexagonal lattice, which is the radius of octahedral interstice, 0.146*a* (*a* is lattice constant), is larger than that of body-centered cubic lattice, which is the radius of tetrahedral interstice, 0.126*a*. So in the same condition, the number of interstitial impurity element atoms contained in body-centered cubic lattice is smaller than that of close-packed hexagonal lattice. For titanium alloys, comparing with close-packed hexagonal lattice α phase, the distortion of β phase with body-centered cubic lattice is more serious when the content of interstitial elements is the same. And the interstitial elements that can not be accommodated by the structure are easier to precipitate as compound, which leads to a decrease in plasticity and toughness.

3.3.3 Fatigue crack growth rate

Fig. 9 shows how fatigue crack growth rates da/dN of above four kinds of cast alloys, which are HIP treated, change with the stress intensity factor ΔK. The curves indicate that within the range of ΔK value, the growth rates of ELI grade alloys are lower than those of non-ELI grade alloys with the same chemical composition. And Ti-5Al-2.5Sn (ELI) alloy has lower growth rate than Ti-6Al-4V (ELI) alloy at the same level of interstitial impurity. The Ti-6Al-4V alloy is shown to have the highest growth rate, while the Ti-5Al-2.5Sn ELI alloy has the lowest. The growth rate D*a*/d*N* is one of the most important indexes to measure the reliability of materials. Generally, the lower the growth rate, the better the anti-fatigue crack growth ability of material could be. Therefore, in terms of the anti-fatigue crack growth ability, ELI grade titanium alloy is better than non-ELI grade alloy, and Ti-5Al-2.5Sn (ELI) is better than Ti-6Al-4V (ELI) alloy.

Actually, there are many factors that influence the da/dN value of titanium alloy, such as load ratio, microstructure, environment parameter, etc. This paper mainly focuses on the factor of the content of interstitial element C, N, H, O in alloys. As we know, elements C, N, H and O exist in the tetrahedral interstice and octahedral interstice of titanium alloy and form into solid solution with the matrix. They can increase the lattice constant *a* and *c*, even *c/a* for α phase, and lead to lattice distortion, which prevents the dislocation and reduces the slid system of alloy, leading to an enhancement of tensile strength. Furthermore, the lattice distortion decreases the plastic area of

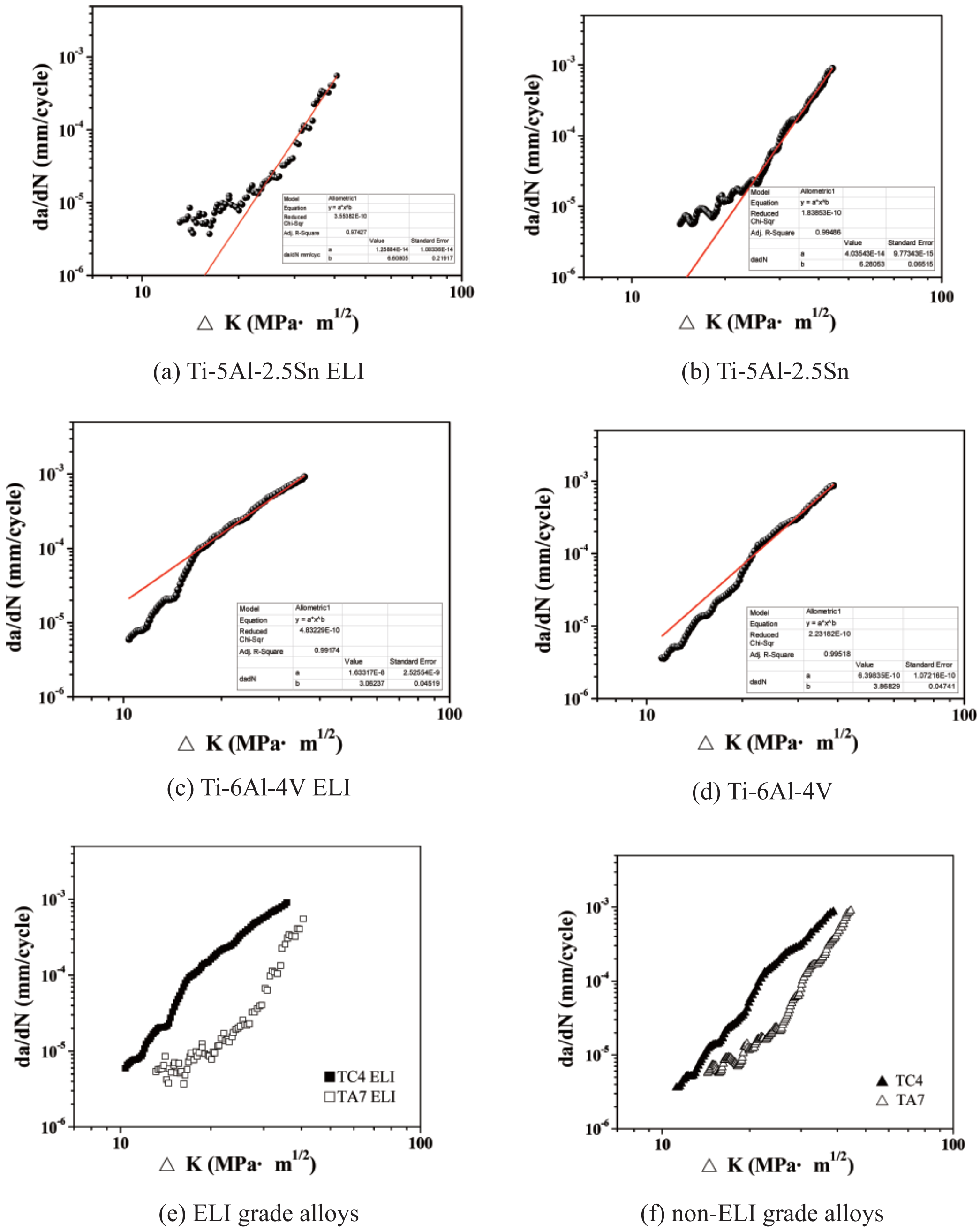


Fig. 9 Fatigue crack growth rate of titanium after HIP treated

crack tip, which results in a stress concentration. It provides a driving force for the propagation of crack on the interface of α/β phase and lamellar α phase, where lattice defects exist. Besides, the HIP treated Ti-5Al-2.5Sn alloy and Ti-6Al-4V alloy are both in lamellar structure, no matter whether they are ELI grade or not. The previous research also shows that for single-phase α titanium alloy, fatigue crack propagates along the interface of α phase lamellas, and for α+β titanium alloy, fatigue crack propagates along the α/β interface of the lamellar structure, but the propagation can either be parallel or perpendicular to the lamellas. Compared with single phase titanium alloy, two phase titanium alloy has larger atomic misfit on the α/β interface, where the fatigue crack is easier to propagate because of the weak binding force. That's why two-phase alloy Ti-6Al-4V (ELI) has higher fatigue crack growth rate than single-phase alloy Ti-5Al-2.5Sn (ELI).

3.3.4 Fracture toughness

Test data of the four alloys' fracture toughness are shown in Table 6. In the field of engineering, K_{Ic}, the plane strain fracture toughness of material, is usually used as the basis for damage tolerance design. In this study, K_q, the conditional value of K_{Ic}, is obtained under the test condition of K_{Ic}. As a valid value of K_{Ic}, K_q needs to meet two requirements of plane strain fracture toughness. First, the specimen sizes should be B, a_0 and (W-a_0) $\geq$ 2.5$(K_q/R_{p0.2})^2$. Second, the load ratio should be $P_{max}/P_q \leq 1.10$ (P_{max} is the maximum load, Pq is the conditional load, a0 is the length of crack). Values of P_{max}/P_q in Table 6 are all greater than 1.1, and B, a_0, (W-a_0) <2.5$(K_q/R_{p0.2})^2$, so the data doesn't meet the requirement and is not able to calculate the criterion of valid K_{IC}. Therefore, K_q is used as the criterion of fracture toughness in this paper. As shown in Table 6, cast Ti-6Al-4V ELI alloy has the maximum fracture toughness. The second and third are cast Ti-6Al-4V alloy and cast Ti-5Al-2.5Sn ELI alloy, respectively. And cast Ti-5Al-2.5Sn alloy has the minimum fracture toughness. In terms of microstructure of alloys, dual-phase Ti-6Al-4V (ELI) has higher fracture toughness than that of single-phase Ti-5Al-2.5Sn (ELI) alloy. Previous research[12] indicates that fracture toughness of material is related to the size of plane strain plastic zone, r_0 ($r_0 = (K_q/R_{p0.2})^2/(4\sqrt{2}\pi)$), and yield strength, $R_{p0.2}$. In general, fracture toughness increases with the raise of r0 and the decline of $R_{p0.2}$. Because as the yield strength decreases, the area of bearing failure load as well as the maximum bearing load of materials will increase. Also, with the expansion of plastic zone, more energy from external work can be absorbed. Therefore, the material can achieve a higher load bearing ability and higher fracture toughness. Table 3 and 4 show that trend of how the fracture toughness K_q of the four types of alloys change is consistent with that of r_0, while it is opposite to that of $R_{p0.2}$ for alloys with same microstructures. This result also consists with the existing research results.

Table 6 Fracture toughness of ELI grade and non-ELI grade cast alloys

Alloy	NO.	B /mm	W /mm	a_0 /mm	(W-a_0) /mm	P_{max} /kN	P_q /kN	P_{max}/P_q	2.5$(K_q/R_{p0.2})^2$/mm	K_q /(MPa.m$^{1/2}$)	r_0 /mm
Ti-5Al-2.5Sn ELI	1	25.47	50.13	27.05	23.08	89.5	50.44	1.77	39.26	97.12	0.88
Ti-5Al-2.5Sn ELI	2	25.45	50.21	26.88	23.33	89.52	51.39	1.74	39.42	97.32	0.89
Ti-5Al-2.5Sn	3	25.3	50.73	24.90	25.83	97.13	56.64	1.71	32.10	87.83	0.72
Ti-5Al-2.5Sn	4	25.45	50.22	26.24	23.98	88.9	47.25	1.88	30.61	85.75	0.69
Ti-6Al-4V ELI	5	25.19	50.89	25.34	25.55	76.77	64.1	1.20	50.71	108.25	1.14
Ti-6Al-4V ELI	6	25.17	50.94	25.62	25.32	75.93	64.39	1.18	52.85	110.50	1.19
Ti-6Al-4V	7	25.3	50.76	25.32	25.44	77.82	61.54	1.26	46.73	103.90	1.05
Ti-6Al-4V	8	25.32	50.85	25.23	25.62	75.2	61.56	1.22	45.83	102.90	1.03

4. Precision forming technology of cast ELI grade titanium alloys

4.1 Melting process

At present, available melting processes for titanium alloys are vacuum consumable electrode arc skull melting, vacuum induction melting (ISM) and electron beam melting, etc[1], among which the first two are usually used for casting. Due to the content of many low melting point elements, narrow range of composition, and low content of impurity, there is high requirement for the melting process of ELI grade titanium alloy in casting. In terms of the element evaporation of Ti-5Al-2.5Sn and Ti-6Al-4V titanium alloy when melting in vacuum, the influence of melting temperature and element evaporation rate Nm has been studied by Guo Jingjie et al[13~15]. And they point out that for the influence on Nm , there is an obvious critical point of vacuum chamber pressure, above which the Nm drops quickly. Also, the higher the melt temperature is, the higher the critical point could be. Since evaporation is actually a thermal dynamic phenomenon, so for metals of the same element, higher melting point means higher evaporation rate, and for metals of different elements, lower melt point facilitates the evaporation. For example, the evaporation rate of Al is tens or hundreds times higher than that of Ti and V in Ti-6Al-4V alloy. But due to the complex mechanism in real evaporation, sometimes the evaporation rate doesn't really decrease with the increase of melt point in the same melting condition. It is shown in Reference 13 that evaporation rate of element Al is greater than that of element Sn at the same temperature.

According to above discussion, the vacuum consumable electrode arc skull melting is considered to be more suitable for melting ELI grade titanium alloy in this paper. On one hand, the arc melting process is faster than ISM process, which shortens the evaporation time; on the other hand, the superheat, which is usually 50-150 ℃ higher than the melting point, of melt alloy is lower, and the alloy has a lower critical point (*Nm*), so the evaporation rate can be reduced. In addition, to satisfy the requirement of ELI grade alloy on the control of gas element, the vacuum condition is necessary in the melting process. Since the evaporation of element Al, Sn and V is inevitable, to control the composition accurately, it is important to improve the original content of mother alloy or to add elements in the process of melting. In this study, to control the composition of ELI grade titanium alloy efficiently, a melting process with low voltage, high current, low pressure and inert ambient is applied. (Specific melting process parameters are shown in Section 2 and the final chemical composition is shown in Table 2.)

4.2 Molding process

Because of the high requirement of impurity controlling for ELI grade titanium, the cavity of mold needs good surface quality and high temperature stability. Currently, there are three kinds of casting molds available for the forming of titanium alloys by casting: block graphite mold, investment shell and metal mold. Among them, the graphite mold made of high-purity graphite block has high strength, high temperature stability but poor withdrawing capability, which results in a poor forming quality. And for the investment shell, sintered refractory oxide is applied as surface layer because it has good stability and forming quality in high temperature and also easy to be made in complex structure. But the process of the preparation is too complicate and too sensitive to the environment parameters. The method of metal mold uses cheap metals such as cast iron and is usually for castings with simple parting surface. The forming quality of this method is between those of graphite mold and investment shell.

In this paper, a new casting process, which applies coated graphite mold and oxide ceramic core, is developed. It can cover the shortage of above molds and realize the casting forming and chemical composition accurate control of ELI grade titanium alloy. In this process, graphite mold is used as the outer shell and refractory oxide coating is sprayed on the surface of cavity to reduce the cooling rate of the graphite mold and prevent carbonaceous dust and particles from getting involved in the melt. Also, oxide ceramic blocks are used as cores of complex cavity to reduce the cooling rate of thin-walled structure, thereby improving its formability and surface quality. This process combines advantages of graphite mold and investment shell, resulting in an ELI grade titanium alloy casting with pure chemical composition, smooth surface and even no cold shut, flow, hole or other defects. Fig. 10 shows graphite mold, oxide ceramic core and their combination. Fig. 11 shows the ELI grade titanium alloy casting made in this process.

Fig. 10 Pattern of mold figure

Fig. 11 ELI grade titanium alloy casting

4.3 Mold filling process

Accounting for the limitation of vacuum consumable electrode arc furnace melting, the superheat of ELI grade titanium alloy melt is low and the fluidity of melt is poor just like conventional titanium alloys. To complete the forming of ELI grade titanium alloy complex casting, its liquidity needs to be increased. At present, there are two technologies to improve titanium alloy liquidity which are centrifugal casting and pressure casting, and each one has its respective advantages and disadvantages. In this study, to improve the liquidity of melt further, vacuum infrared heating centrifugal casting is developed based on the thought of decreasing cooling rate of melt, which is heating mold by infrared heating device inside the vacuum chamber and pouring in centrifuge. Fig. 12 shows the principle diagram of this method. The advantage is that the mold can be heated to 400-600 ℃ real-timely, and heat loss of the melt is little in the process of filling, meanwhile, the melt can fill the mold rapidly under the action of centrifugal force. By applying this technology, the titanium alloy fluidity and forming ability are enhanced obviously. Fig. 13 shows the titanium alloy casting with complex curved surfaces and thin walls formed by the technology, and the minimum thickness of wall is 1 mm.

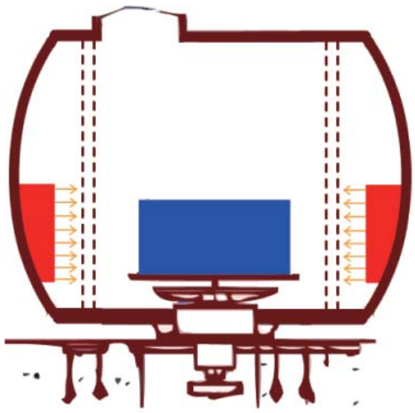


Fig. 12 Principle diagram of mold by infrared heating in vacuum

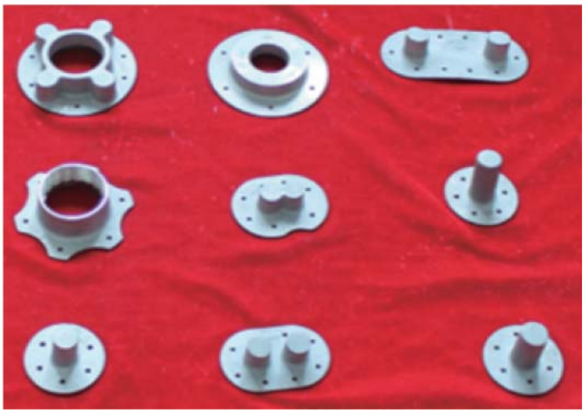
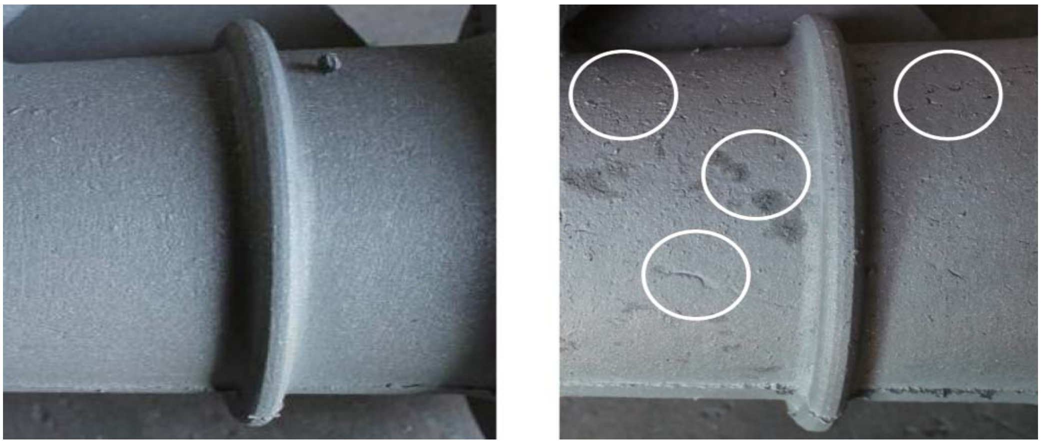


Fig. 13 Thin-wall titanium alloy castings poured

4.4 Quality of forming

Surface defects, roughness, contamination layer, etc. of the ELI grade titanium castings manufactured with above technology have been analyzed. Fig. 14 shows the surface quality of castings with mold coating or without mold coating, and the data in Table 7 is about surface roughness of the casting. The result indicates that most of the cold shuts, flow marks and blowholes are eliminated; meanwhile the surface roughness of casting, which is reduced significantly, can reach a level of R_a 3.2 μm. Fig. 15a shows that the thickness of surface contamination of casting is about 6 μm,

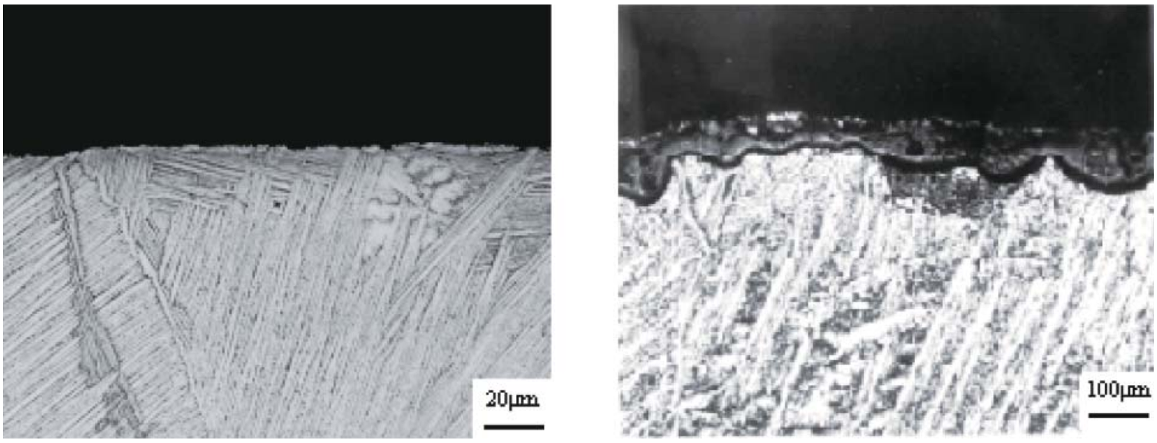


(a) coating (b) no coating

Fig. 14 Surface of ELI grade titanium alloy castings by different technologies

Table 7 Roughness of ELI grade titanium alloy casting by coating mold

Mold	Roughness, Ra /μm				
	1	2	3	4	5
Coating	3.05	3.20	3.28	3.32	3.25
	3.11	3.19	3.35	3.18	3.22
No coating	12.22	12.25	12.10	12.62	11.10
	12.35	11.90	12.40	12.48	11.56



(a) coating (b) no coating

Fig. 15 Surface contamination layer of titanium alloy castings by different technologies

which is also decreased greatly compared with that of general graphite mold casting, 100 μm (Fig. 15b). Moreover, the dimension tolerance of casting is proved to be in level IT14 with the measurement of different wall thickness. As a conclusion, the technology developed in the paper provides an effective way to form high quality cast ELI grade titanium alloys precisely.

5 Conclusions

(1) The optimal composition of cast ELI titanium alloys is Al (4.5-5.5) wt.%, Sn (2.0-3.0) wt.% for cast Ti-5Al-2.5Sn ELI alloy and Al (5.5-6.5) wt.%, V (3.5-4.5) wt.% for cast Ti-6Al-4V ELI alloy. The content of interstitial impurity is C $\leq$ 0.05 wt.%, N $\leq$ 0.03 wt.%, H $\leq$ 0.0120 wt.%, O $\leq$ 0.12 wt.%.

(2) For the Ti-5Al-2.5Sn ELI alloy, microstructures of both as-cast and HIP treated cast actually consist of single α phase. Compared with the as-cast, the structure of the HIP-treated one has coarser α phase, smaller amount of lath colonies, equiaxed parts and in which, the original grain boundary disappears or narrows. However, for Ti-6Al-4V ELI alloy, the as-cast and the HIP treated cast consist of α and β phases. In as-cast condition, α phase is arranged as platelet westergren; while in the condition of HIP treatment, α phase is arranged as basketweave besides platelet westergren.

(3) Tensile strength of cast Ti-6Al-4V alloy is higher than that of cast Ti-5Al-2.5Sn alloy, no matter it is ELI grade or not. ELI grade alloy has higher impact toughness than non-ELI grade alloy, while the fatigue crack propagation rate of ELI alloy is lower than that of non-ELI grade alloy. For alloy with same major composition, fracture toughness of ELI grade alloy is higher than that of non-ELI grade alloy. Therefore, the damage resistance of ELI grade alloy is higher than that of non-ELI grade alloy.

(4) Precision forming of complex thin wall casting of ELI grade titanium alloy can be realized by using following techniques: the process of melting in consumable electrode arc skull furnace with low pressure, molding with combination of graphite shell and ceramic cores, centrifugal casting by infrared heating. With these technologies, an ELI grade titanium alloy casting with a minimum thickness of 1 mm, roughness of Level R_a 3.2 μm, contamination layer thickness of 6 μm and dimension tolerance of Level IT14 can be achieved with good forming quality.

Acknowledgments

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