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ARTICLE

Effects of Centrifugal Forces and Casting Modulus on Structures and Mechanical Properties of Ti-6Al-4V Alloy

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Abstract: The present investigation mainly focuses on effects of centrifugal forces and casting modulus on structures and mechanical properties of Ti-6Al-4V alloy formed under different vertical centrifugal casting conditions in graphite molds. Mold rotating rates of 0, 110 and 210 r/min were adopted in the experiment. Results show that grain size and lamellar thickness decrease with the decreasing of casting modulus or the increasing of centrifugal force, while tensile strengths are considerably enhanced, but the elongation of the casting shows the opposite changing trend. The quantitative relationships among gravity coefficient, casting modulus and structures or mechanical properties of Ti-6Al-4V alloy have been obtained. As the comparison of Ti-6Al-4V alloy cast in graphite mold under gravity field, the structures of stepped casting in metal mold were also investigated. It is found that the grain size or lamellar thickness in the two molds shows the same changing trend with the cooling rate, and the quantitative relationships between structures and cooling rates have been obtained.

Key words: centrifugal force; casting modulus; structure; mechanical property; Ti-6Al-4V alloy

Titanium possesses low density and high strength which make it very attractive in applications for aerospace, military, biomedicine fields and so on[1]. Thereinto, Ti-6Al-4V accounts for 50% of the use of titanium in the world today[2], and it has been widely applied to the above-mentioned fields where special structural components are urgently demanded. However, as the superheat of the alloy melt is generally not very high, it is difficult to fill the mold completely for the castings with complex shapes by conventional methods in gravity field. Therefore, centrifugal casting process is adopted for most titanium alloys to improve their mold-filling capability. For the practical application, it is strict in requirements for microstructure and mechanical property. However, most studies have been done on the solidified structures and the properties of Ti-6Al-4V alloy mainly focus on the conventional gravity field [3-6], and little research has been done on centrifugal field. Microstructures and hardnesses of Ti-6Al-4V centrifugal castings have been investigated in Ref. [7], but it only emphasized the effects of casting modulus on the structures, not including the coaction of the centrifugal force causing the particularity of the microstructure and mechanical property for its gradient distribution. Hence, for practical application of Ti-6Al-4V alloy with thin wall and complex shapes, it is significant to deeply study the influence of both casting modulus and the centrifugal forces on its microstructures and mechanical properties, which are the main aim of the present investigation.

As Ti-6Al-4V alloy that we refer to in this paper, both the nucleation and growth of its grain and lamellar structure together determine the grain size and lamellar thickness. Cooling rate of the casting is the main factor affecting its macro and micro structures while the materials and pouring conditions are definite (including alloy composite, pouring temperature and pouring velocity)[8].

In the present investigation, the influence of cooling rate on Ti-6Al-4V alloy structures cast under gravity force has been investigated. Moreover, the effects of centrifugal force and casting modulus on the structures and the mechanical

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properties in centrifugal casting process have been proposed.

1 Experiment

Experiments were done in a vacuum cold-crucible furnace with a horizontal rotating casting platform. The titanium alloy was remelted in copper crucible in evacuated chamber with the vacuum degree of 0.1 Pa and the melting power of 350 kW. The melt was poured into the metal and graphite molds, separately. Fig.1a shows the casting system with metal mold and the dimensions of stepped casting including three columns with different diameters and the riser. The centrifugal casting system with four stepped and four wedge-shaped castings alternately distributed in a high- strength graphite mold was designed as shown in Fig.1b, and the axis of the jar-shaped sprue was taken as the rotating axis. In Fig.1b, the maximum rotation radius measured by the farthest end of the horizontal runner from the turning axis, was about 500 mm. The two secondary horizontal runners with the length of about 440 mm, were 170 mm apart. The sizes of the four stepped castings were 95 mm long, 56 mm wide, and 20 mm and 40 mm, respectively in thickness. The other four wedge castings had the same length and width as the stepped castings but with a maximum thickness of 20 mm. In order to investigate the influence of cooling rate/modulus and centrifugal force on Ti-6Al-4V alloy, the casting experiments were proceeded in a metal mold under gravity field and in graphite mold with three runs of centrifugal casting operations at rotating rates of n=0, 110 and 210 r/min. Generally, the gravity coefficient G was adopted to represent the centrifugal force, which is expressed as follows:

$$G=\omega^2 r/g \qquad (1)$$

Where ω is the rotating angular velocity of the mold ($\omega=\pi n/30$), r is the rotating radius, g is the gravity acceleration, and n is rotating rate. Therefore, G values will be obtained from 0 to 23.50 for the present experiment with the castings distributed as Fig.1b. According to the definition of casting modulus which was obtained by the ratio of cross-sectional area to circumference, the range of modulus for the different specimens in the present investigation were 0.86 to 11.67.

Thermocouples were placed at the centers of different parts of the stepped casting, marked as M1 to M4, to measure the alloy cooling curves in the metal mold, as shown in Fig.1a. For the graphite mold casting trails while n=0 r/min, thermocouples were placed at different parts of cast parts, marked as G1 to G5, to obtain the cooling rates, as shown in Fig.1b. The mold rotated during the centrifugal casting process, and it was hard to measure the changing of cast parts cooling rate. Therefore, the effect of casting modulus on microstructures and mechanical properties was adopted to substitute the influence of cooling rate.

The observed specimens with the size of 8 mm×8 mm×8 mm were taken near the thermocouples to research the influence of cooling rates on the alloy structures in both the metal and graphite molds. For the centrifugal castings in the graphite mold, 1.2 mm-thick tensile specimens were spark-cut layer-by-layer in the thickness directions of a casting for both microstructure examinations and mechanical property tests at the locations as “ ”-marked in Fig.1b. 11 and 28 tensile specimens could be taken from the thin wall and the thick wall of one stepped casting, respectively, and in total, 22 tensile specimens could be obtained from one wedge casting.

Optical microscope was used to analyze the alloy grain structures, and scanning electron microscopy was used to analyze the lamellar structures. On the basis of the mean grain size and transversal methods, the grain size and α/β lamellar thickness were measured. The shape and dimension of tensile specimens are shown in Fig.2, and the tensile experiment was proceeded with a material testing machine.

Temperature-time (T-t) curves of the titanium alloy during cooling process were measured by Eight-channel Data Acquisition Instrument.

2 Results

2.1 Effect of cooling rate on microstructure of Ti-6Al-4V alloy cast under gravity field

T-t curves of the Ti-6Al-4V alloy cast under the gravitational force field in two different molds are shown in Fig.3. For the

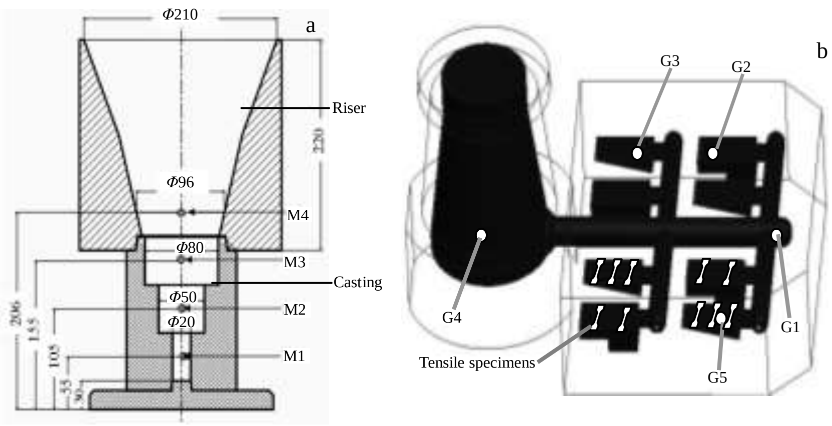

Fig.1 Schematic of gravity and centrifugal casting system: (a) metal mold under gravity force and (b) graphite mold under centrifugal force

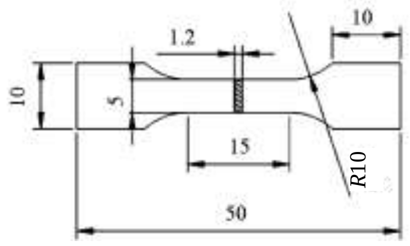

Fig.2 Shape and dimension of a tensile specimen

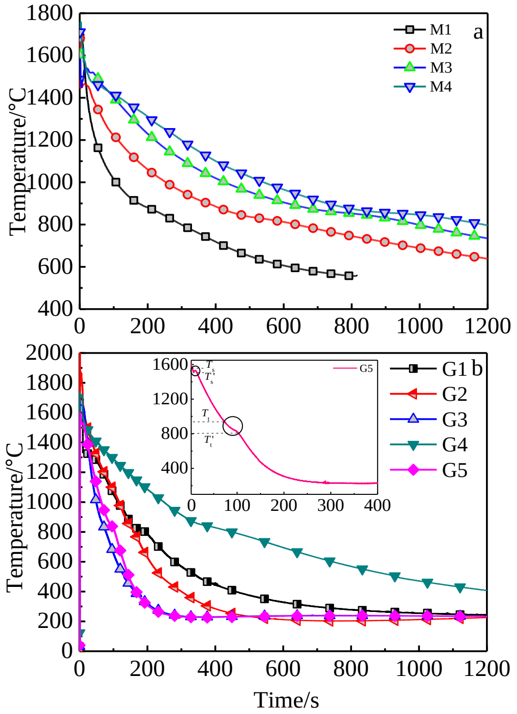

Fig.3 *T-t* curves of Ti-6Al-4V alloy cast under gravitational field in two different molds: (a) metal mold and (b) graphite mold

stepped casting in the metal mold, the column with the diameter of 20 mm has the fastest cooling rate and the part of *Φ*96 mm is the lowest, as shown in Fig.3a.

In Fig.3b, the cooling curve of G5 was taken as an example to analyze the solid and phase-transition characteristics of Ti-6Al-4V alloy, and the magnified part is shown in the top of Fig.3b. Obviously, in the present investigation, the liquidus temperature is 1664 ℃, and solidus temperature is 1565 ℃. It again shows that Ti-6Al-4V alloy has a narrow solidification range (approximate 100 ℃). The phase-transition beginning temperature is 910 ℃, and the ending temperature is 820 ℃ Therefore, the $\beta \rightarrow \alpha$ transformation range is about 90 ℃.

The average cooling rate of the solidification ε_s is expressed as follows:

$$\varepsilon_s = \Delta T / \Delta t \qquad (2)$$

Where, $\Delta t = t_s - t_s'$, t_s is solidification beginning time, and t_s' is the ending time; $\Delta T = T_s - T_s'$, T_s and T_s' are the casting temperatures correspond to t_s and t_s'. The average cooling rate of phase-transition ε_t can be obtained with the same method.

The typical microstructures of specimens near the thermocouples are shown in Fig.4, and the grain size (d_G) was measured by mean grain sizes, and the lamellar thickness of α/β ($d_{\alpha/\beta}$) was measured by the transversal method. The cooling rate and its corresponding grain size/lamellar thickness of the specimens obtained from the data analysis are presented in Fig.5. It is noted that the grain sizes or lamellar thicknesses in the two different molds show the same changing trend with the cooling rate. Therefore, the experiment data in two molds are used together to analyze the relationship between microstructures and cooling rates in the present study.

By curve fitting (as shown in Fig.5), the relationship between cooling rate ε_s and grain size d_G can be expressed as follows:

$$d_G = 2.31\,\varepsilon_s^{-0.25} \qquad (3)$$

And, the relationship between cooling rate ε_t and lamellar thickness $d_{\alpha/\beta}$ can be expressed as follows:

$$d_{\alpha/\beta} = 1.52\,\varepsilon_t^{-0.46} \qquad (4)$$

From Eq.(3) and (4), it can be seen that with the cooling rate increasing, both grain size and lamellar thickness of α/β decrease. When Ti-6Al-4V alloy cast under gravity force, cooling rate is the main factor affecting its microstructures, and the relationships between microstructure and cooling rate for the two molds show the same changing trend.

2.2 Microstructures of Ti-6Al-4V alloy cast under centrifugal forces in the graphite mold

The microstructural observation and analysis results show that when the gravity coefficient is definite, both grain size

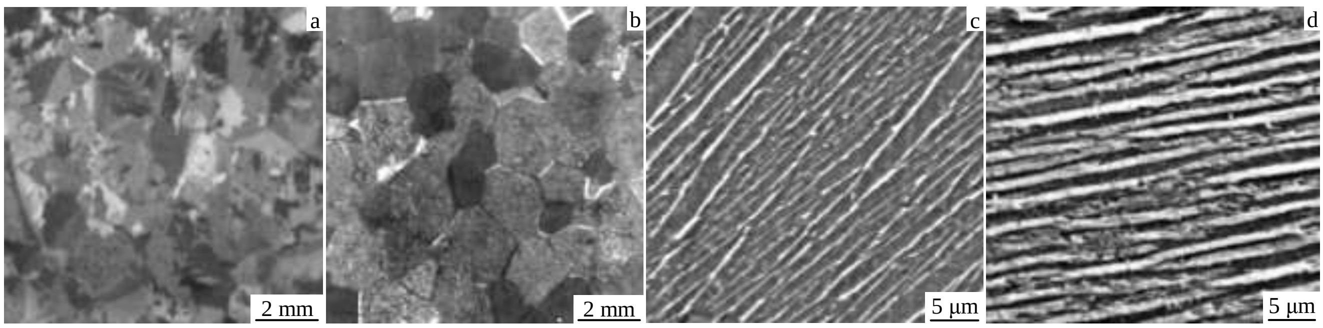

Fig.4 Typical microstructures of Ti-6Al-4V specimens: (a, c) grain/lamellar structures at M3 and (b, d) grain/lamellar structures at G2

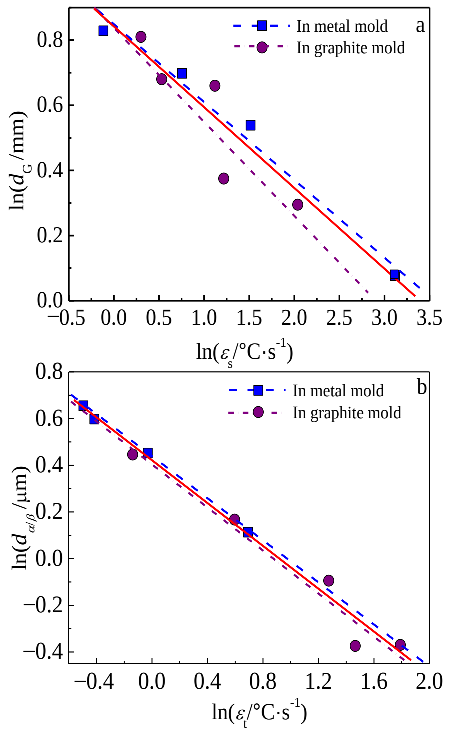

Fig.5 Relationship between microstructures and cooling rates of Ti-6Al-4V alloy cast under gravitational field: (a) grain size-cooling rate and (b) lamellar thickness - α/β-cooling rate

and lamellar thickness increase with the increasing of cast modulus; however, the effect of centrifugal force shows a difference. Fig.6 and Fig.7 show the typical optical micrographs and SEM images of grains and lamellar microstructures of Ti-6Al-4V alloy centrifugal castings at different centrifugal forces and a definite casting modulus of 11.67 mm. It can be seen from the two figures that grain size decreases with the increasing of the centrifugal force, and lamellar thickness shows the same changing trend with grain size.

The effects of casting modulus and centrifugal force on grain size and lamellar thickness are schematically shown in Fig.8. Both the experiment data and its fitting curved faces are shown in the figures. By polynomial fitting, following results have been obtained for the Ti-6Al-4V alloy centrifugal castings in graphite mold, and the relationship among grain size d_G, cast modulus M and gravity coefficient G can be expressed as follows:

$$d_G=1.090+0.052M-0.026G \quad (5)$$

And, the relationship among lamellar thickness $d_{\alpha/\beta}$, M and G can be expressed as:

$$d_{\alpha/\beta}=0.739+0.034M-0.007G \quad (6)$$

2.3 Mechanical properties of Ti-6Al-4V alloy cast under centrifugal forces in the graphite mold

The mechanical properties measured and analyzed in the present paper include tensile strength, yield strength and elongation of Ti-6Al-4V alloy centrifugal castings. Results show that, both the tensile and yield strength decrease with the increasing of cast modulus, and increase with the increasing of centrifugal force; however, elongation decreases gradually with the increasing of centrifugal force at which situation the structure is refined, and for the above results the opposite

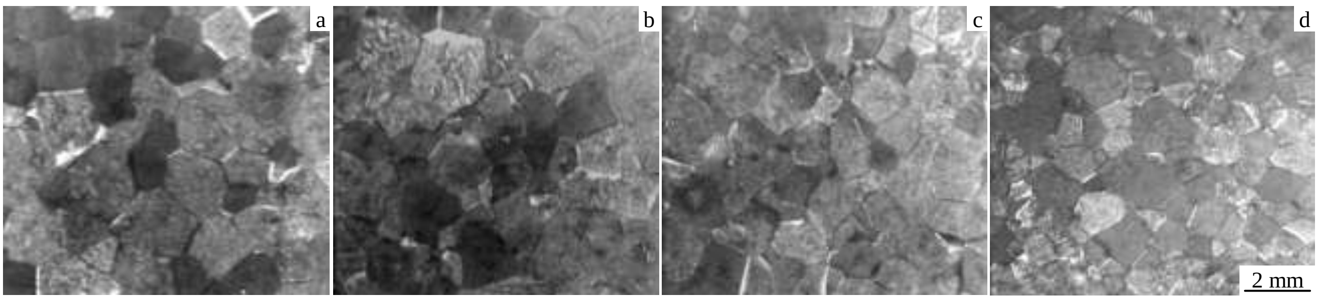

Fig.6 Grain microstructures of Ti-6Al-4V castings at different centrifugal forces and a definite casting modulus of 11.67 mm: (a) G=0, (b) G=4.08, (c) G=5.59, and (d) G=20.36

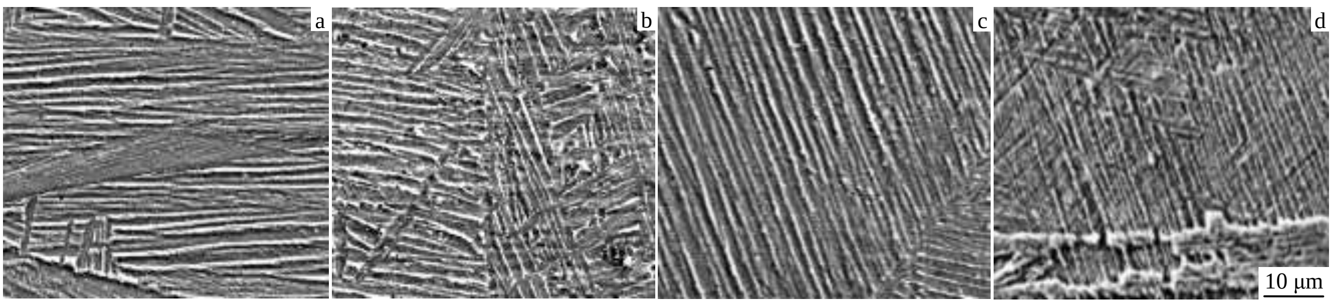

Fig.7 Lamellar microstructures of Ti-6Al-4V alloy castings at different centrifugal forces and a definite casting modulus of 11.67 mm: (a) G=0, (b) G=4.08, (c) G=5.59, and (d) G=20.36

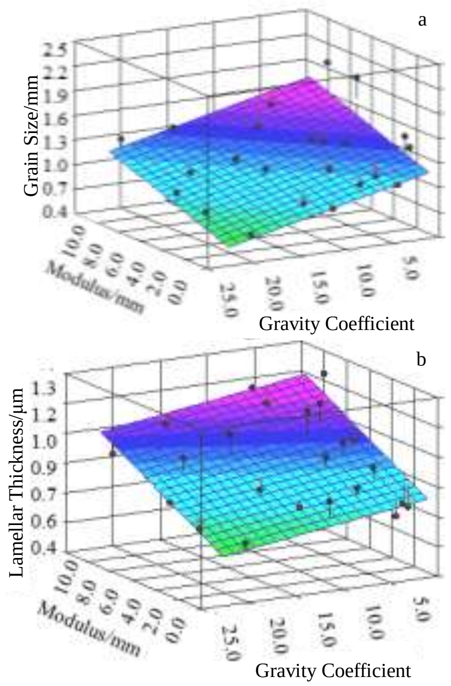

Fig.8 Effects of centrifugal force and cast modulus on microstructures of Ti-6Al-4V alloy: (a) grain size and (b) lamellar thickness

changing trend was shown in previous studies[9]. Typical scanning electron images of the fracture surfaces for Ti-6Al-4V alloy at different centrifugal forces and a definite casting modulus of 11.67 mm are shown in Fig.9. It is seen obviously, as the modulus is definite, the dimple structure is refined when the gravity coefficient increases.

The effects of cast modulus and centrifugal force on strength and elongation are schematically shown in Fig.10. Both the experiment data and its fitting curved faces are shown in the figures. By polynomial fitting, the following results have been obtained for Ti-6Al-4V alloy centrifugal castings in the graphite mold, and the relationship among tensile strength σ_b, cast modulus M and gravity coefficient G can be expressed as follows:

$$\sigma_b=942.004-3.269M+0.946G \qquad (7)$$

And, the relationship among yield strength σ_s, M and G can be expressed as:

$$\sigma_s=792.576-4.536M+2.598G \qquad (8)$$

And, the relationship among elongation δ, M and G can be expressed as follows:

$$\delta=4.989+0.142M-0.054G \qquad (9)$$

3 Discussion

The results obtained in the present study show that for the centrifugal casting of Ti-6Al-4V alloy, the microstructures, including grain size and α/β lamellar thickness can be refined with the decreasing of cast modulus or increasing of centrifugal force. Compared with the two influencing factors, it can be seen that the effect of centrifugal force is not so important as the casting modulus. Mechanical properties, including tensile strength and yield strength are considerably enhanced with the decreasing of modulus or increasing of gravity coefficient; however, elongation presents the opposite changing trend.

The above results can be explained as follows. Smaller casting modulus leads to greater cooling rate of the alloy and shorter growing time for every grain, which will inhibit the growing up of the grain [10]. Centrifugal force increases with the increase of rotation speed or the radius, and this causes the contact area between the melt and the mold to increase. Consequently, the heat transfer and cooling rate of the melt are enhanced. Moreover, centrifugal force may affect the nucleation rate and crystal growth of the alloy. On one hand, nucleation rate increases while the pressure increases within a certain range[11], and the centrifugal pressure of the rotating melt increases with the increasing of gravity coefficient [12], which leads to the increase of nucleation rate with the increase of centrifugal force. On the other hand, greater centrifugal pressure will lead to a smaller crystal growing rate because of its inhibition action on the atomic diffusion[13].

The phase transformation from β phase to α phase belongs to solid-state phase change and the new phase is formed by nucleating and growing [14]. Hence, modulus and centrifugal force have the same effects on phase transformation as they are on crystal growing. Therefore, within a certain range, grain

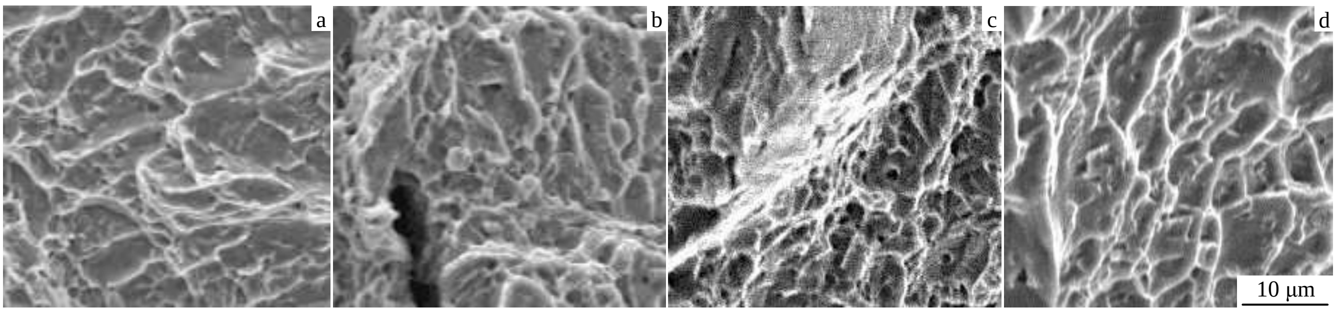

Fig.9 Scanning electron images of fracture surfaces for Ti-6Al-4V alloy at different centrifugal forces and a definite modulus of 11.67 mm: (a) G=0, (b) G=4.08, (c) G=5.59, and (d) G=20.36

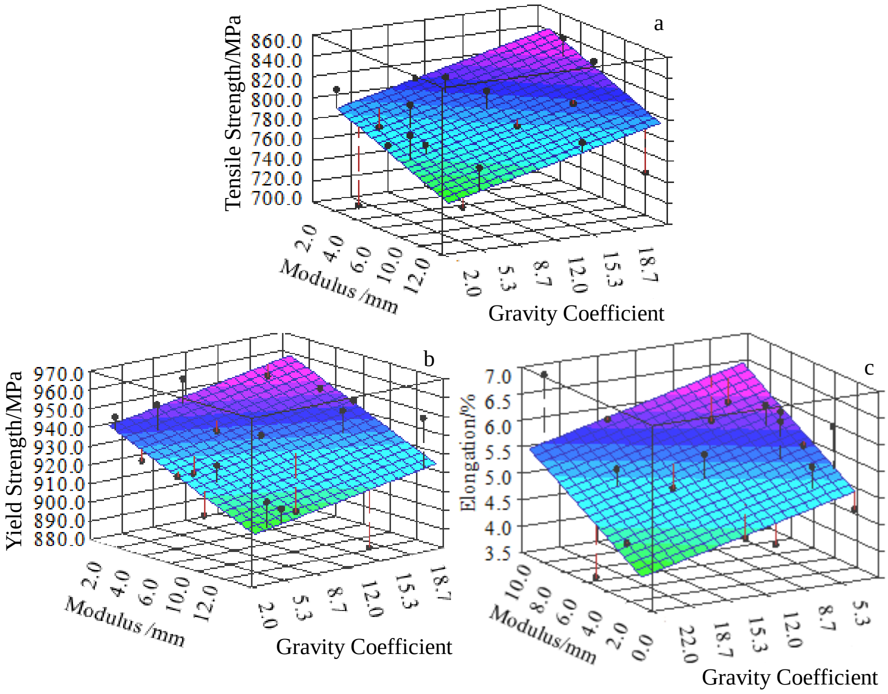

Fig.10 Effects of cast modulus and centrifugal force on mechanical properties of Ti-6Al-4V casting: (a) tensile strength, (b) yield strength, and (c) elongation

size and lamellar thickness are refined with the modulus decreasing or the centrifugal force increasing.

It is proverbial that mechanical properties would be improved while the microstructures are refined for most of the alloys. However, the castings formed under centrifugal forces would contain many inclusions because of the fluid washing out of the sprue or the wall of graphite mold. In one hand, inclusions have little effect on tensile strength or yield strength, but a significant influence on properties which are plasticity-related such as elongation [15]. In the other hand, the inclusions in fluid such as oxygen and carbon will cause solution strengthening, and this leads to the increase of casting strength and decrease of elongation. Therefore, the inclusions in casting increase with the increase of centrifugal forces, and the elongation decrease, even though microstructures would be refined under large centrifugal force.

4 Conclusions

1) Under gravity field, the grain size or the lamellar thickness in both metal and graphite molds show the same changing trend with the cooling rate, and the relationships between microstructures and cooling rates can be obtained.

2) Microstructures, including grain size and lamellar thickness decrease with the decreasing of modulus or increasing of centrifugal force.

3) Mechanical properties, including tensile strength and yield strength are considerably enhanced with the decreasing of modulus or increasing of centrifugal force, but the elongation shows the opposite changing trend.

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离心力及铸件模数对 Ti-6Al-4V 合金组织与力学性能的影响

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摘　要：研究在石墨型中不同立式离心力场下离心力及铸件模数对 Ti-6Al-4V 合金组织及性能的影响。实验过程中铸型的旋转速度主要考虑了 3 种情况：0, 110 及 210 r/min。结果表明：晶粒尺寸及片层厚度随铸件模数的减小和离心力的增加而减小，抗拉强度随铸件模数减小和离心力增加而明显增大，但铸件延伸率呈现相反的变化趋势。同时给出了重力系数、铸件模数与 Ti-6Al-4V 合金组织和力学性能之间的定量关系。作为与重力场下石墨型中 Ti-6Al-4V 合金铸件对比分析，研究了金属型中 Ti-6Al-4V 合金阶梯铸件组织的变化情况。研究发现：2 种铸型中浇铸的合金铸件晶粒尺寸、片层厚度随冷却速度的变化趋势基本一致，结合 2 组实验数据，给出了重力场下 Ti-6Al-4V 合金铸件组织随冷却速度变化的定量关系。

关键词：离心力；铸件模数；组织；力学性能；Ti-6Al-4V 合金

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