The mechanism of hot crack formation in Ti-6Al-4V during cold crucible continuous casting

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Abstract: Hot crack is one of common defects in castings, which often results in failure of castings. This work studies the formation of hot crack during cold crucible continuous casting by means of experiments and theoretical analysis. The results show that hot crack occurs on the surface and in the circumference of ingots, where the solidified shell and the solidification front meet each other. The tendency of hot cracking decreases with the increase of withdrawal velocities in some extent. The hot crack is caused mainly by the friction force between the shell and the crucible inner wall, and it takes place when the stress resulting from friction exceeds the tensile strength of the shell. The factors of μ_m, h_t, h_s and h_m, affecting hot cracks are analyzed and verified. In order to decrease the tendency of hot cracks, technical parameters should be optimized by decreasing μ_m, h_t, h_s and h_m.

Keywords: Ti-6Al-4V alloy; cold crucible continuous casting; hot cracks

1. Introduction

Titanium-based alloys are promising materials, which are widely used in aerospace and shipbuilding industries due to their high specific strength, hot resistance and corrosion resistance. However, there exist some difficulties in controlling chemical elements and temperatures in melting and casting processes of titanium-based alloys because of their high melting point, chemical activity and variation of physical properties at high temperatures. Water-cooled cold crucible technique provides an effective method for melting titanium-based alloys. The cold crucible continuous casting process is a technique that integrates a soft contact between the crucible wall and the alloy melt by electromagnetic force into continuous casting[1, 2]. A cold crucible made of a number of separate segments is surrounded by a water-cooled and spirally wound induction coil. The gaps between the segments is used to prevent shielding the electromagnetic field by the electrically conducting crucible. When an A. C. high frequency current is applied to the coil, materials in the crucible are melted, confined and stirred. This technique includes induction melting, soft contact and continuous casting. Because of its advantages of high speed melting, taintless, and continuous casting for titanium alloy[3, 4], the cold crucible continuous casting process can shorten the melting time and save energy. Therefore, it will arise to be an important metal forming technology in the future.

In fact, water-cooled cold crucibles have been used in preparing in aluminum, steel, titanium alloys[5, 6], photovoltaic multicrystalline and single silicon. More applications are expected in cold crucible continuous casting, such as treatment of radioactive materials, near net shape, production of new materials and so on. However, there are still many problems which need to be resolved. For example, hot crack is a commonly occurs in cold crucible continuous castings, which often results in failure of castings. Although scientists have investigated the problem for many years and obtained some promising results[7~9], the formation process and mechanism of hot crack are not clear up to now. The reasons are diverse and complicated[10, 11]. The tendency of hot cracking are varying from one condition to another even for the same alloy. The cold crucible continuous casting process is different from traditional casting processes, in which alloys are melted and restricted by electromagnetic field in the crucible. Consequently, the hot crack formation in the cold crucible continuous casting process can not be elucidated by the mechanisms established for conventional casting processes. Tanaka[1] and Gilles Dour[12] studied hot crack during continuous casting of titanium alloys and silicon, respectively. They failed to investigate the factors affecting hot cracks in detail. This paper discusses the factors affecting hot cracks based on experiments and theoretical analysis with the testified results. Some suggestions are proposed on cold crucible continuous casting to eliminate hot crack.

2. Experimental method

A multi-function continuous casting and directional solidification apparatus was used in this study, as schematically shown in Fig.1. Titanium alloy ingot is melted in the upper part and a new ingot is continuously cast in the bottom part. This apparatus comprises:

- The furnace chamber made of steel vessel with three monitor windows and a vacuum can be established by an exhaust pump in the chamber;
- A water cooled and segmented copper crucible with eight vertical slits 30 mm in internal diameter and 130 mm in height.
- A four-turn water cooled induction coil surrounding the crucible and supplying a 50 kHz frequency current

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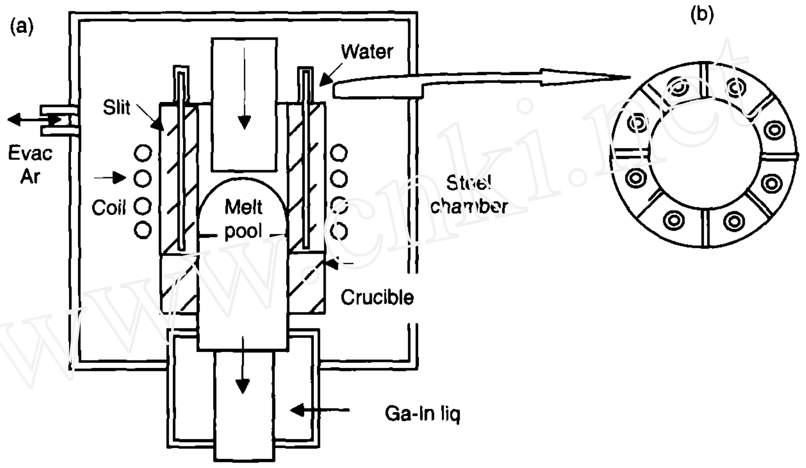
generated by a transistor generator of which the maximum output power is 100 kW.

- A mechanically withdrawing system and a mechanical feeder that both can be controlled at different velocities individually. The raw materials used in the casting are Ti-6Al-4V alloy ingots. The continuous casting procedure is as follows. A Ti-6Al-4V alloy ingot with 27 mm in diameter and 500 mm in height is fixed on feeder and a primer is placed in the crucible where it can be induced. A vacuum of 1 Pa is established, and then Argon gas is introduced to 200 Pa. Power is gradually transmitted to the charge until it reaches 50 kW. The supply of raw materials and the continuous withdrawal of the ingot starts 5 minutes later when a liquid metal dome with a suitable shape formed, and the solidified ingot is cooled by Ga-In liquid alloy in the bottom part. The withdrawal velocities are 0.5 mm/s, 2 mm/s and 4 mm/s. The supplying quantity of the raw material depends on the withdrawal velocity.



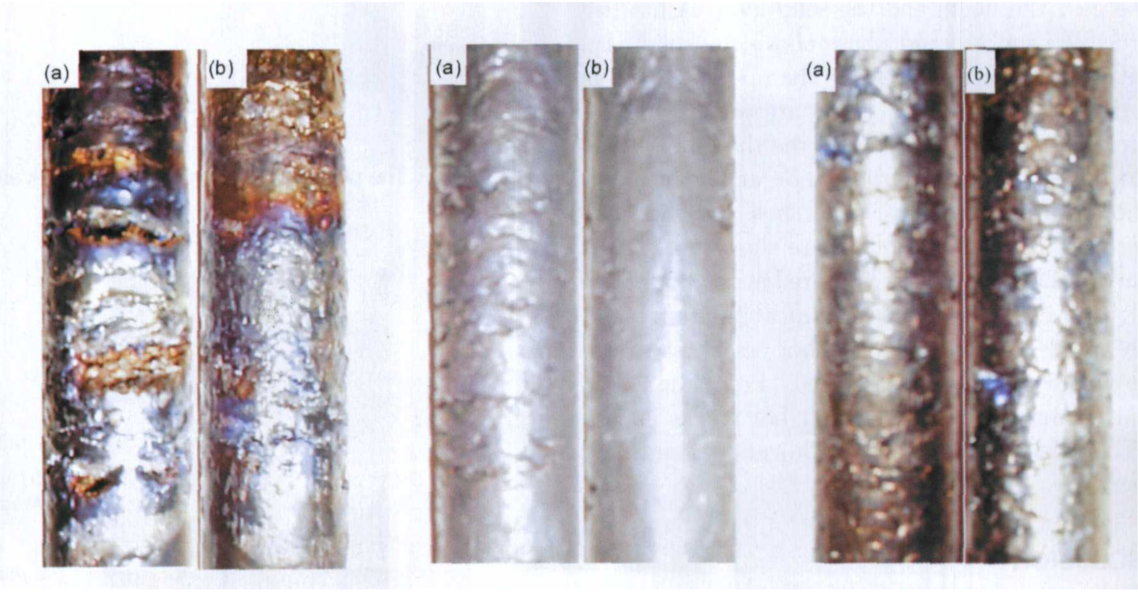
(a) Process and equipment (b) Transverse section of cold crucible

Fig. 1 Scheme of cold crucible continuous casting

3. Results

3.1 Characteristics of hot crack

Three kinds of ingots cast under three different withdrawal velocities are numbered as 1, 2 and 3, as shown in Fig. 2. Two sides of each ingot (the fine surface side and the poor surface side) are labeled as (a) and (b), respectively.



0.5 mm/s 2.0 mm/s 4.0 mm/s

Fig. 2 Ingots under different velocity: (a) coarse side, (b) smooth side

It is observed from Fig.2 that the surface morphology of those ingots are different. In case 1, hot cracks are long and deep, but fewer; in case 2, hot cracks become smaller but more than those in case 1; in case 3, hot cracks are very small but the most. It is noticed that the hot cracks in each ingot are irregular in the circumference direction, and are focused on one side and seldom on the other, even crack free on one side of the second ingot. The ingots have some common characteristics in the withdrawal direction, of which hot cracks appear at intervals and are almost horizontal.

Sections of 50 mm length[12] are section from each ingot. The number of the cracks, the length, the width and the depth of the largest cracks, the distance between two adjacent cracks, the feature of the cracks, the results and the crack ratio (the ratio of crack area and total surface area) are measured, listed in Table 1. It is evident that the crack ratio, namely the tendency of hot crack formation, decreases with an increase in the withdrawal velocities.

Table 1 Measurements of hot cracks in ingots

Sample	Number of cracks	The biggest crack (mm)			Interval (mm)	The features	Crack ratio (%) (Crack area/total area)
		Length	Depth	Width			
1	27	29	10	7	5~7	Fewer but bigger	20.37
2	39	22	6	4	4~6	Medium	8.03
3	43	21	3	3	2~5	More but smaller	5.36

3.2 Initiation position of hot crack

In order to ascertain the initiation position of hot crack, both ingots are obtained in two different casting conditions: in one of them, the heating power and the withdrawal are stopped at the same time, in[13] the other, the ingot is pulled into Ga-In liquid alloy at a high speed during continuous casting. The outersurface and the vertical sections of the two ingots are shown in Fig.3 and Fig.4, in which the vertical sections are polished and etched. From Fig.3, it is worth noting that slot marks are on the top of the ingot, which is the result of the melt infiltrating into the slit between crucible segments because the power is shut down; the solidification front are clear, which is marked by identifying different microstructure. Through the slot marks and solidification front, it can be deduced that there is a liquid meniscus above three-phase line defined as the line where the gas, the liquid and the solid meet each other in the crucible, and a liquid phase above the solidification front before power is cut off. The up-most crack is formed finally, indicated by the arrows in Fig.3. Therefore, hot crack appears below the three-phase line and near the solidification front, not at the position where the solidification starts. The shell and the fractured place of the ingot by pulling are shown in Fig.4. It is observed that the ingot is fractured at the bottom of the shell, above and near the solidification front, and crack free in the shell. Hence, the hot crack appears at the place where the shell is fractured. From the above discussion, it may be concluded that hot cracks appear at the place where the shell and solidification front meet each other.

4. Discussion

4.1 The mechanism of hot crack formation

Hot crack is aroused by stress centralization because solidification contraction is restricted or obstructed. The crack forms when the level of stresses exceeds the tensile strength of a certain part. The characteristics of crystal growth and the solidification contraction influence the formation of hot cracks. There is enormous literature related to the mechanisms of hot crack formation, such as the liquid film theory, the strength theory, dendritic bridging theory, solidification shrinkage repairing theory and so on[13~15].

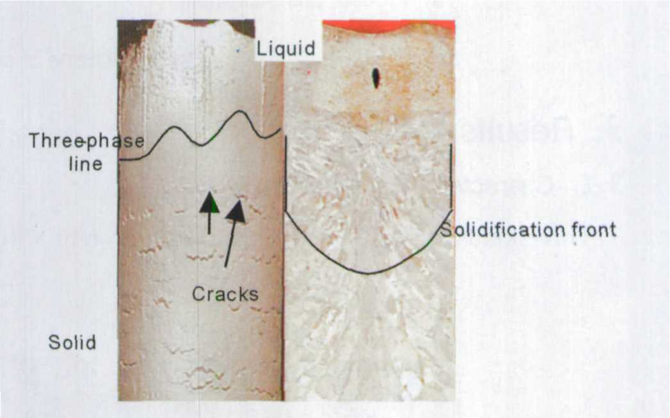


Fig.3 The position of hot cracks and solidification front

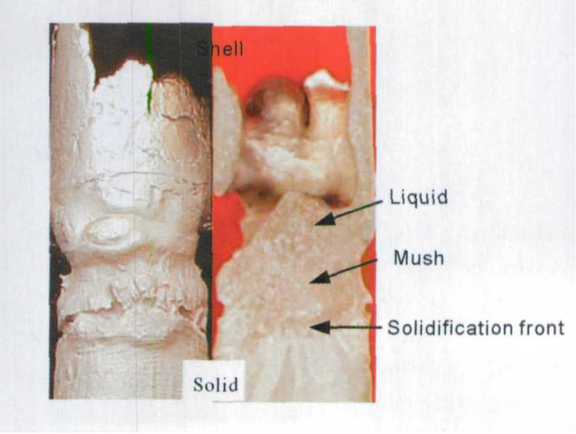


Fig.4 The shell and solidification front

According to the solidification principle of alloys, at the beginning of solidification and before a continuous skeleton is formed in the dendrites, its strength is very low, and its behavior of plasticity is very high. This stage is called quasi-liquid phase. Once the continuous skeleton is formed in the dendrites, the alloy possesses certain strength which increases gradually, and its plasticity decreases. The plasticity lowers continuously as solidification continues on. This stage is called pre-solid phase. When the temperature decreases to some degree, the strength and the plasticity are both increased because of the formation of dendritic bridge and the distortion of the grains. This phase is called dendritic bridge phase. Because the strength and the plasticity are very low, grains tend to be separated when the solidification contraction is restricted in the pre-solid phase. If there are passages for repairing the separation of grains, the hot cracks can not remain. If the passages are blocked, the separation can not be repaired and consequently the hot crack forms[16].

The formation of hot cracks owing to shrinkage obstruction tends to distribute in the circumference and perpendicular directions. However, the hot cracks in the obtained ingots are all present in circumference direction. As such, shrinkage obstruction should not be the main reason for the present studied cases. Fig. 5 schematically illustrates the continuous casting, which is based on this experimental results. When the current is transmitted to the induction coil, the titanium alloy ingot melts and the melt drips on the primer. Then, the melt is shaped meniscus by electromagnetic force. The liquid metal contacts the crucible wall when the hydrostatic pressure exceeds the sum of electromagnetic pressure and the surface tension. The liquid metal solidifies and forms a shell as soon as it contacts the water-cooled wall, and then the shell detaches from the wall because of solidification shrinkage which forms a tiny space between the wall and the shell (Fig. 5b). Friction force between the crucible wall and the shell is produced once the primer begins to withdraw. The hot cracks appear when friction force is higher than the strength of the shell. The electromagnetic field reheats the shell due to forming a gap, which lowers the strength of the shell and increases the hot crack tendency. The hot crack maintain when the liquid metal in the shell is not capable of repairing and/or the reheating is not able to remelt the formed cracks. The liquid near the cracks solidifies quickly because of the strong cooling in the bottom and the withdrawal of the ingot. When the strength of the solidified part is higher than the friction force, the cracks are reserved and no longer extended.

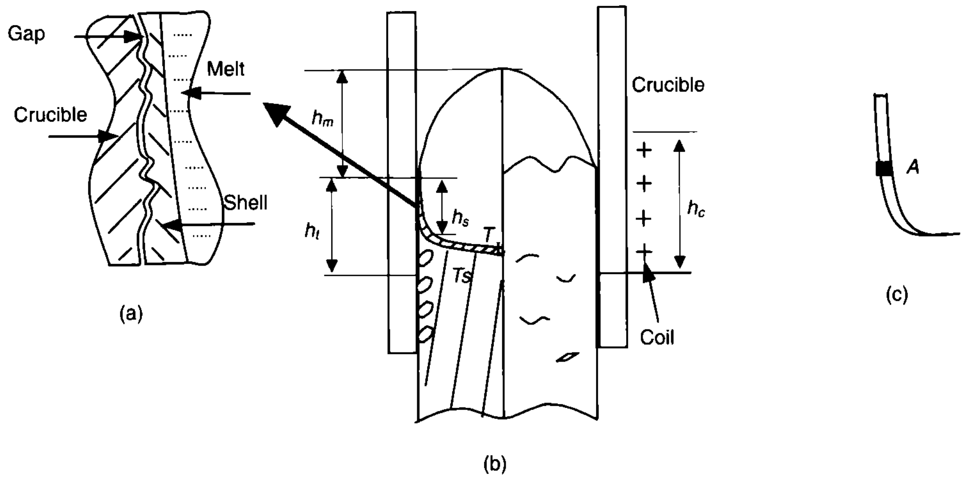


Fig. 5 Scheme of continuous casting: (a) The shell and the wall, (b) Process, (c) The shell

4.2 Analysis of factors affecting hot cracking

4.2.1 Analysis of factors considering a solidified shell

Assuming that the thickness of the shell is uniform and the force between the shell and the crucible wall is equal when the shell is solid. unit A of the shell shown in Fig. 5c is considered. The forces acting on the unit is analyzed, as shown in Fig. 6.

In the horizontal direction,

$$P_s = P_c \tag{1}$$

where P_s is the pressure of the wall to the shell in unit A determined by physical properties of the alloy; P_c is the pressure of the shell to the wall in unit A.

(a) Horizontal direction (b) Perpendicular direction

Fig. 6 Analysis of force acted on unit A

The friction force of unit A is

$$f = P_s \cdot \mu_m \tag{2}$$

where μ_m is friction coefficient between crucible inner wall and the shell's surface.

In the perpendicular direction, if the hot cracks form on unit A, the condition is

$$F_m > F_n \tag{3}$$

F_m and F_n are the total tensile strengths that unit A suffered and maximum strength that unit A can bear, respectively.

$$F_m = f \cdot x \cdot u_m \tag{4}$$

where x is the height from unit A to three-phase line, the maximum x is the height of the shell.

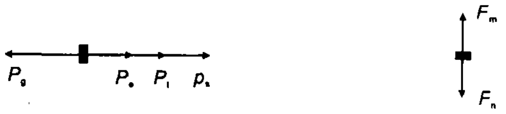
From equation (3), it is evident that F_m is directly proportional to P_s. Therefore, P_s, μ_m and x should be decreased in order to decrease F_m, that is, the crucible inner wall should be kept as smooth as possible and decrease the height of the shell h_s.

$$F_n = \sigma_A \cdot S_A \tag{5}$$

where, σ_A is the surface tension of unit A related to the state of the shell, S_A is the area of unit A. The less of σ_A, the higher temperature of the shell. The electromagnetic field heats the shell. The heating effect is determined by the heating time, the height of the shell in the coil, and the intensity of magnetic field B. As a result, σ_A is related to B, withdrawal velocity v, and h_t (the height of three-phase line, that is the height from the three-phase line to the spot where the crucible has no slit) as well. S_A is decided by b (the thickness of shell) and r (the radius of the shell). In order to increase F_n, we should decrease h_t, or increase v or b.

4.2.2 Analysis of the factors considering a shell reheated to mush phase

If the shell is reheated to mush phase, unit A is analyzed by forces, as shown in Fig.7



(a) Horizontal direction (b) Perpendicular direction

Fig.7 Analysis of unit A by forces

In the horizontal direction:

$$P_t = P_g - P_e - p_s \tag{6}$$

$$\text{with} \quad P_g = \rho g\ (h_m + x), \quad P_e = B^2/2\mu \tag{7}$$

where, P_t is contact force, P_g is metallostatic pressure, P_e is electromagnetic force, h_m is the height of the meniscus, μ is magetic conductivity and p_s is the surface tension which can be neglected in unit A due to its relatively small size.

The friction of unit A is

$$f = P_t \cdot \mu_m = [\rho g\ (h_m + x) - B^2/2\mu] \cdot \mu_m \tag{8}$$

The total tensile force of unit A suffered because of friction:

$$\begin{aligned} F_m &= \int_0^{h_s} \mu_m\ [\rho g\ (h_m + x) - B^2/2\mu] \cdot dx \\ &= \mu_m\ [\rho g h_m h_s + \frac{1}{2}\rho g h_s^2 - \int_0^{h_s} B^2/2\mu \cdot dx] \\ &= \mu_m\ [\rho g h_m h_s + \frac{1}{2}\rho g h_s^2 - k h_s^3] \end{aligned} \tag{9}$$

Where, k is a coefficient. From equation (9), it can be seen that F_m is directly proportional to μ_m, which increases with the increase of h_m. Because there is a non-linear relationship between B and x, the effect of B on F_m becomes complicated. The situation can be divided into two cases: one is that when h_s is smaller than 1, F_m increases with the increase of h_s; the other is that when h_s is larger than 1, F_m decreases with the increase of h_s. Therefore, F_n can be determined by the temperature of unit A which is inversely proportional to the temperature.

From the analysis of the two cases above, it appears that the dominating factors affecting the formation of the hot cracks are the friction coefficient between crucible wall and the shell μ_m, the height of three phase line h_t, the height of the shell h_s, and the height of the meniscus h_m. h_t, h_s, h_m can be determined by the power and the frequency of the induction coil, the cooling rate and the withdrawal velocity. In order to decrease the tendency of hot crack, the reduction of μ_m, h_t, h_s and h_m should be maximized.

4.3 Effect of withdrawal velocity on hot crack

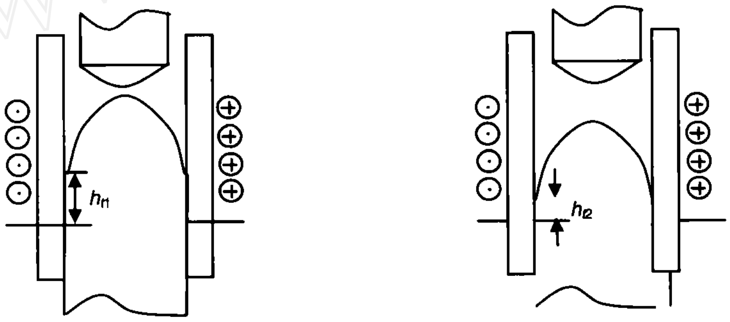
From the outer surface of the ingots, it can be found that the withdrawal velocity has an important effect on hot crack. The tendency of the hot cracks decreases with the increase of the withdraw velocities. The withdrawal velocity affects the formation of the hot crack in two manners: One is that increasing withdraw velocity in some extent can ascend solidification front[1], which decreases h_s; the other is that increasing withdrawal velocity decreases the degree of reheating the shell, which will increase F_n. Both manners results in the low tendency of hot crack.

4.4 Asymmetry of hot cracks in ingots

The distribution of hot cracks in ingots is asymmetry, namely hot cracks occur on one side and seldom on the other. This phenomenon is caused by two reasons: the first is the height of coil is not equal, inducing magnetic field distribution unconformity, and leading to h_t unequal, as shown in Fig.4; the second is the asymmetry of the ingot in the crucible, resulting in the change of P_c asymmetrically

4.5 Optimization of parameters

In order to reduce hot crack, the experimental parameters according to the above analysis were optimized. The inner wall of crucible was polished to decline the friction coefficient, and h_t was decreased by taking a smaller feed velocity than a suitable velocity, so that the meniscus and the three-phase line descends when the supply of the feed alloy is not sufficient, as shown in Fig.8. The surface of the ingot cast under the optimized condition is shown in Fig.9. The outer surface is more smooth than those of the former ingots, and the number of hot cracks is reduced. This proves that the friction coefficient has a significant effect on the formation of hot cracks. The ingot can be divided into three sections in the withdrawal direction: hot crack, crack free and feed shortage sections. At the beginning of the casting, the three-phase line is very high, resulting in hot cracks. Three-phase line descends and hot cracks become fewer as the casting continues. When the three-phase line descends to a low position, crack free section appears because of feed shortage. The feed alloy is short and the three-phase line is very low at the last stage. The meniscus is violently stirred by electromagnetic field. The violently shaken liquid solidifies when it meets the water-cooled wall. This solidification leads to the formation of the coarse feed shortage section.



(a) Three-phase line is high (b) Three-phase line is low

Fig.8 Scheme of three-phase line descend

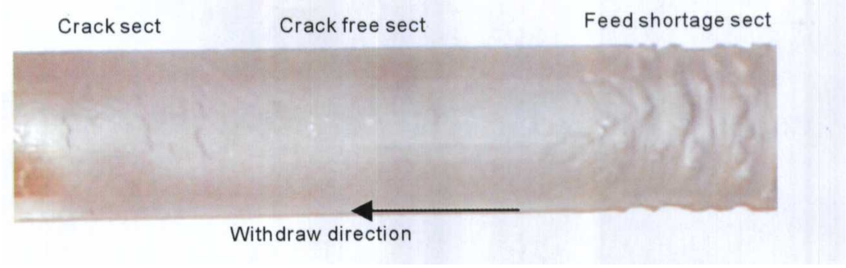


Fig.9 The ingot obtained in a smaller feed velocity than suitable velocity

5. Conclusions

(1) Hot cracks forms in circumference direction, are asymmetry in cold crucible continuous castings of Ti-6Al-4V alloy, and usually appears at the place where the shell and solidification front meet each other.

(2) Withdrawal velocity has a significant effect on the formation of hot crack because it changes the height of solidification front and the degree of reheating the shell. The tendency of hot crack decreases with the increase of withdrawal velocities.

(3) The mechanisms of hot crack formation are different between cold crucible continuous castings and traditional castings. Hot crack is caused by the restriction of solidification shrinkage in traditional castings, but is caused by friction in continuous castings.

(4) The factors affecting hot cracks are μ_m, h_t, h_s and h_m, which are determined by the cold crucible inner wall, electrical parameters and withdrawal velocity. In order to decrease the tendency of hot crack, process parameters should be optimized by decreasing μ_m, h_t, h_s

and h_m.

6. Acknowledgements

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