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ARTICLE

Design of Crucible Size of Electron Beam Cold Hearth Melting for Ultra-long and Ultra-thin TC4 Ingot

Liu Qianli, Jiang Peng, An Feipeng

National Engineering Research Center for Advanced Titanium and Titanium Alloy Material Technology, Luoyang Ship Material Research Institute, Luoyang 471023, China

Abstract: Solid-liquid interface morphology of the titanium ingot has a great influence on the microstructure during the solidification process. The effect of crucible's 3D dimension for the ultra-long and ultra-thin TC4 slab ingot on the solid-liquid interface morphology was investigated. The results show that when the cross-sectional length of TC4 slab ingot exceeds 450 mm, the cooling capacity of the crucible does not increase. When the length exceeds the effective distance, the depth of molten pool and the width of mushy zone will not change with the increase of the crucible length. Moreover, increasing the aspect ratio of the crucible is helpful for improving the production quality. The simulation results show that it is better to choose an aspect ratio between 4:1 and 6:1. When the height of the crucible is higher than 300 mm, the depth of the molten pool and the width of mushy zone will not change. Therefore, a certain range of theoretical basis can be obtained for designing the crucible's three-dimension during electron beam cold hearth melting (EBCHM) for the ultra-long and ultra-thin TC4 slab ingot.

Key words: ultra-long and ultra-thin titanium ingot; continuous casting; solid-liquid interface; crucible dimension

Titanium alloy has excellent properties such as low density, high strength and good corrosion resisting. Hence, it is used as important structural and anti-corrosion materials in the field of aviation, aerospace, shipbuilding, etc[1-4]. In the field of titanium processing, titanium ingot is the basis for all subsequent titanium processing. Only high quality titanium ingot and titanium alloy ingot with uniform internal structure, no composition segregation, and low density inclusions can be processed into high quality titanium and titanium alloy product. Therefore, production of high quality titanium ingot is particularly important.

Electron beam cold hearth melting (EBCHM) in solving the composition segregation, microstructure distribution and reducing large and low density inclusion is much better than vacuum arc remelting (VAR), so the EBCHM has become a widespread melting technique[5,6]. The specific morphology of liquid-solid interface during the solidification is determined by the specific parameters. And the producing of liquid-solid interface and morphology have deep influences on the titanium microstructure. The key to eliminating or reducing macro segregation or other defects of titanium ingot is that we should keep the liquid-solid interface morphology with small curvature and thin mushy zone[7,8]. The high-quality TA1 slab ingot has a batch production by EBCHM with existing crucible and process conditions in the actual production[9,10].

However, it is difficult to produce high-quality TC4 slab ingot, not only because of the volatile elements, but also the liquid-solid interface morphology in the solidification[11-14]. During the process of electron beam cold hearth melting, optimizing the production condition and changing the crucible's three-dimension are the most important methods to get the liquid-solid interface morphology with small curvature and narrow mushy zone. In this study, the effect of crucible's three-dimension on the solid-liquid interface morphology was studied by calculating the temperature distribution during EBCHM for the ultra-long and ultra-thin TC4 slab-ingot solidification. The quantitative relationships

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Corresponding author: Liu Qianli, Ph. D., National Engineering Research Center for Advanced Titanium and Titanium Alloy Material Technology, Luoyang Ship Material Research Institute, Luoyang 471023, P. R. China, Tel: 0086-379-67236526, E-mail: lql725@yeah.net

among the inner length, ratio of inner length to inner width, height and wall thickness of the crucible and the depth of molten pool were obtained, which gives a certain range of theoretical basis for designing the crucible's three-dimension during EBCHM for the ultra-long and ultra-thin TC4 slab ingot.

1 Mathematical Model

In consideration of the TC4 alloy solidification inside the crucible of EBCHM, the continuous process schematic of the titanium is shown in Fig.1. The molten titanium will move downward under the pulling velocity when it solidifies in the crucible. The heat transmission in the ingot follows the Fourier-Kirchhoff equation:

$$\rho(T)\partial H/\partial H = \nabla \cdot \left(\lambda(T)\nabla T\right) \tag{1}$$

where H, ρ and λ are the heat enthalpy, the density and the thermal conductivity of the materials as the function of temperature T, respectively; t is the heat transfer time and $\nabla = \frac{\partial}{\partial x}\vec{i} + \frac{\partial}{\partial y}\vec{j} + \frac{\partial}{\partial z}\vec{k}$ ($\vec{i}, \vec{j}, \vec{k}$ are the unit vector of x, y, z coordinate, respectively).

Besides, the heat transfer in the crystallizer can also be formulated using the partial differential equation of non-steady heat transfer as follows:

$$c_{\rm pm}\rho_{\rm m}\partial T_{\rm m}/\partial t = \nabla \cdot \left(\lambda_{\rm m}\nabla T_{\rm m}\right) \tag{2}$$

where the subscript m corresponds to the crystallizer. $c_{\rm pm}$ is the specific heat capacity of the crystallizer at a constant pressure as a function of temperature.

During the actual producing, the continuous casting process is under the vacuum environment. In order to maintain the temperature of the surface of the liquid titanium, there is an electron gun above the liquid level with a definite move frequency and heating power. It is assumed that temperature on the titanium liquid level is a homogeneous determined value (the electronic gun power corresponds to the liquid level temperature one-to-one). Other boundary conditions of the titanium ingot are set as follows.

1) Water cooling on the crucible's broadside, which is $H_2 - H_1 < y < H_2$, $x=\pm (L_1/2+H)$ or $z=\pm (L_2/2+H)$:

$$-\lambda_{\rm m}\vec{n} \cdot \nabla T_{\rm m} = h_0(T_{\rm m} - T_0) \tag{3}$$

where $\vec{n}$ is the normal unit vector of crucible's broadside, h_0=5000 W·m^{-2}·K^{-1} is the heat transfer coefficient, T_0=15 °C is the water temperature.

2) Heat exchange at the interface of crucible and ingot, which is $H_2 - H_1 \le y \le H_2$, $x=\pm L_1/2$ or $z=\pm L_2/2$:

$$-\vec{n} \cdot \left(\lambda\nabla T - \lambda_{\rm m}\nabla T_{\rm m}\right) = h(T - T_{\rm m}) \tag{4}$$

where h=1000 W·m^{-2}·K^{-1} is the coefficient of heat transfer at the interface of crucible and ingot.

3) Air cooling on the ingot's broadside, which is $y < H_2 - H_1$, $x=\pm L_1/2$ or $z=\pm L_2/2$:

$$-\lambda\vec{n} \cdot \nabla T = h_1(T_{\rm m} - T_1) \tag{5}$$

where h_1=10 W·m^{-2}·K^{-1}, temperature T_1=20 °C.

4) Set adiabatic condition for other surfaces of the ingot and crucible, $\vec{n} \cdot \nabla T = 0$.

What should pay attention to in this study is the continuous casting process of industry pure titanium. This process contains the heat transition control, so diffusing effect of the impurity element is ignored[15,16].

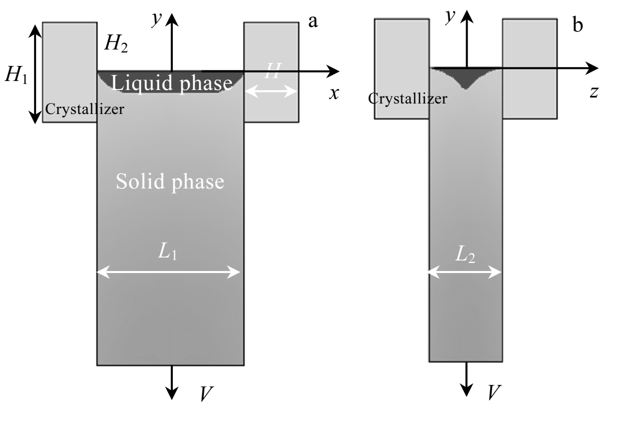

Fig.1 Schematic diagram of TC4 ingot continuous casting process: (a) cross section in width direction and (b) cross section in thickness direction

2 Physical Parameters

From the function, it should use heat enthalpy instead of two physical quantity-latent heat and constant pressure specific heat. The physical parameters of TC4 alloy, including density, heat enthalpy and thermal conductivity varying with temperature, are shown in Fig.2. The thermal conductivity and the specific heat of the copper are shown in Fig.3, which are calculated by ProCAST software.

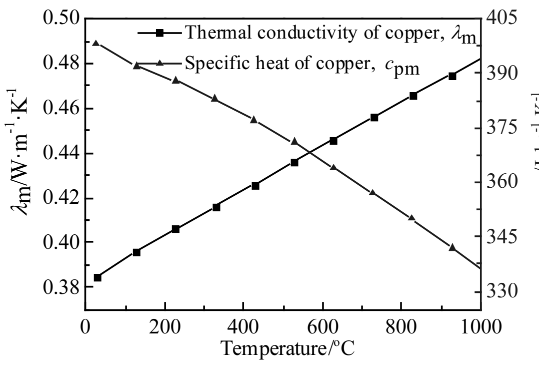

Fig.2 Relationship between thermal physical parameters and temperature of copper

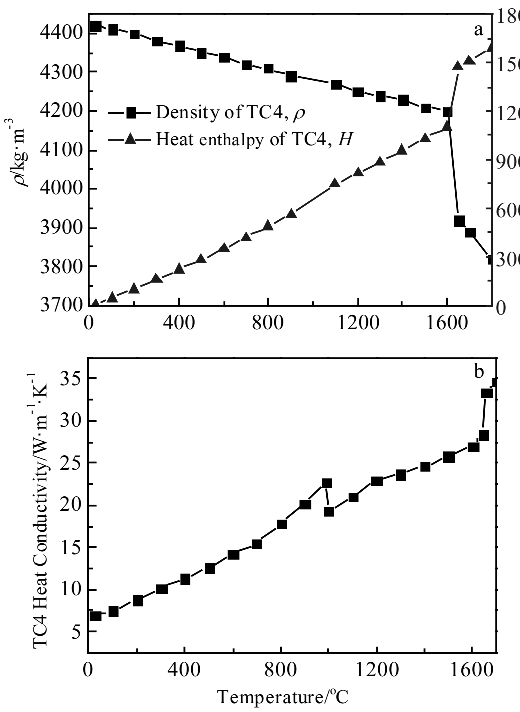

Fig.3 Relationship between thermal physical parameters and temperature of TC4: (a) density and heat enthalpy; (b) heat conductivity

3 Analysis of Results

Fig.4 shows the schematic diagram of the crucible's structure. In the actual production of ultra-long and ultra-thin TA1ingot using EBCHM, the three-dimensional dimensions of the crucible were measured: length (*L*), width (*W*), height (*H*) and wall thickness (*T*) are 1250, 210, 660 and 75 mm, respectively. To optimize the crucible's structure during EBCHM for TC4 alloy ingot solidification, the solid-liquid interface morphology was analyzed by changing the dimensions of crucible's cross-section. Based on the actual three-dimensions of the crucible for the production of ultra-long and ultra-thin TA1 ingot, the temperature field simulation was carried out during EBCHM for TC4 alloy ingot solidification process by changing the length, width, height and wall thickness of the crucible.

(1) Keep the height (660 mm), thickness (75 mm) and the width (210 mm) constant, and the length was set as 300, 400, 450, 650, 850, 1050, 1250 and 1450 mm. The effect of crucible's length on the solidification interface of ultra-long and ultra-thin TC4 slab ingot was analyzed by the temperature distribution.

(2) Keep the area of crucible's cross-section ($L\times W$=1.6×10^5 mm^2) constant, and the effect of the ratio of crucible's length to width on the solidification interface of ultra-long and ultra-thin TC4 slab ingot was analyzed by the temperature distribution. Therefore, $L\times W$ was set as 400 mm×400 mm, 500 mm×320 mm, 640 mm×250 mm, 800 mm×200 mm, 1000 mm×160 mm and 1600 mm×100 mm. The different setting modes are shown in Fig.5. The cross-section area of TC4 slab-ingot is kept constant at 1.6×10^5 mm^2.

(3) Keep the width (210 mm), thickness (75 mm) and length (1250 mm) constant, and the height was set as 150, 175, 200, 300, 400, 600 and 800 mm. The effect of crucible's height on the solidification interface of ultra-long and ultra-thin TC4 slab ingot was analyzed by the temperature distribution.

(4) Keep the width (210 mm), height (660 mm) and length (1250 mm) constant, and the thickness was set as 50, 60, 70, 75, 80 and 90 mm. The effect of crucible's thickness on the solidification interface of ultra-long and ultra-thin TC4 slab ingot was analyzed by the temperature distribution calculation.

3.1 Effect of crucible's length on the solid-liquid interface morphology

In consideration of symmetry, half of the crucible's geometry is represented in Fig.6. H_1 represents the depth of liquidus and H_2 represents the depth of solidus.

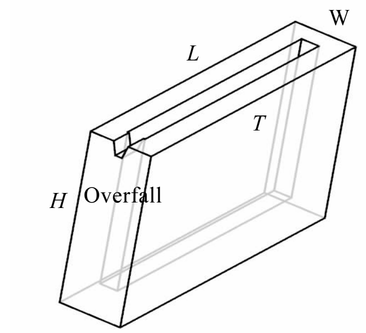

Fig.4 Schematic diagram of structure of crucible

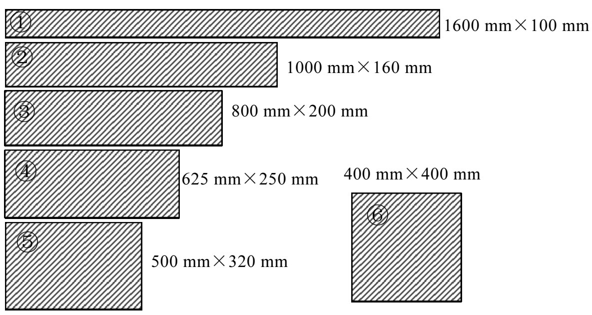

Fig.5 Different setting modes of the internal length and width of crucible with the same area of TC4 slab ingot cross-section

The central sections of TC4 flat ingot with different lengths are compared and shown in Fig.7. It can be seen from Fig.7 that with the increase of the length, the curvature of the solid-liquid interface morphology of the TC4 slab ingot tends to stabilize and the bottom of the molten pool finally reaches a flat and straight face. When the length increases to 450 mm, the shape of the solid-liquid interface morphology of TC4 slab ingot will not change (left part of the dashed line in Fig.7). While the length of the solid-liquid interface morphology only increases in the cross-section with increasing the length. From the qualitative analysis of the macroscopic morphology, the solid-liquid interface morphology of TC4 slab ingot is the same, all of which are funnel-shaped. What's more, the flat surface at the bottom of solid-liquid interface no longer changes when the length exceeds 450 mm. From the quantitative analysis of the measurement results, the relationship between the depth of TC4 liquidus, solidus and the internal length of crucible is shown in Fig.8. When the length increases from 300 mm to 450 mm, the depth of solidus increases from 5.34 cm to 10.41 cm and the depth of liquidus increases from 4.24 cm to 8.17 cm. Besides, no matter how long the length increases, the depth of the molten pool and the width of the mushy zone will not change.

Because the heat dissipation of the TC4 flat ingot depends on the cooling capacity of the crucible, the cooling ability of the water-cooled crucible determines the solid-liquid interface morphology when the molten pool of the TC4 slab ingot reaches the steady state. When the cooling water maintains a certain initial temperature and water flow, the cooling capacity on the unit cross-section of the crucible is certain. Under the constant width, the effective cooling distance of the crucible is determined. For the solidification process of TC4 slab ingot, the effective cooling distance of crucible is 450 mm. When the length of the cross-section of TC4 slab ingot is lower than this distance, the solid-liquid interface morphology of TC4 slab ingot is determined by the width and length of crucible.

When the length of the cross-section of TC4 slab ingot exceeds this distance, the solid-liquid interface morphology of TC4 slab ingot is determined only by the width of mold. With the increase of crucible's length, only the horizontal length at the solid-liquid interface of TC4 slab ingot will be increased. While the depth of the molten pool and the width of the mush zone no longer change. Therefore, the effective cooling distance of the crucible is the key to distinguish whether the cross-section length of the slab ingot affects the morphology of the solid-liquid interface.

Compared to the existing crucible used for producing ultra-long and ultra-thin TA1 slab ingot, the influence of different crucible's lengths on the morphology of the molten pool of ultra-long and ultra-thin TA1 flat ingot was also calculated. Fig.9 shows the comparison of the molten pool morphology of TA1 slab ingot with different internal lengths of crucible. As can be seen from Fig.9, the morphology and depth of molten pool of the TA1 slab ingot do not change obviously when the inner length of crucible increases to 600 mm (Fig.9a, left part of the dashed line). Under the simulated conditions, the effective cooling distance of the crucible is 600 mm for the solidification process of TA1 slab ingot. Therefore, as long as the length of cross-section of slab ingot is larger than 600 mm, the same length of the water-cooling crucible can be used whether it is a TA1 or TC4 titanium alloy slab ingot. Therefore, the length of the crucible can be designed according to the width of the required roll strip and the requirements of the rolling mill specifications in actual production, then changing the length of the cross-section of titanium and titanium alloy slab ingots.

3.2 Effect of aspect ratio of the crucible on the solid-liquid interface morphology

When the cross-section area of titanium and titanium alloy slab ingot increases, the actual production efficiency will improve in the actual production conditions. Therefore, the product of crucible's length and width depends on the

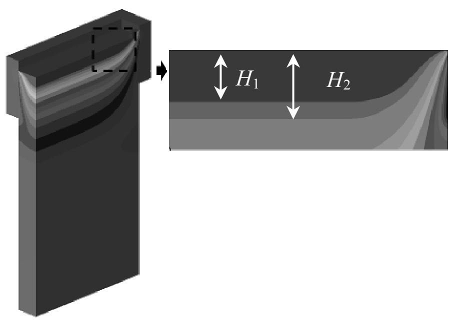

Fig.6 Simulation calculation diagram of crucible

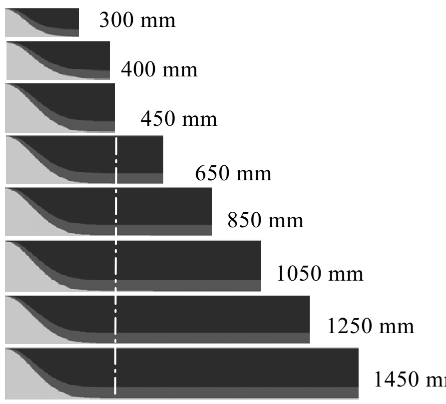

Fig.7 Molten pool morphologies of TC4 slab ingot with different internal lengths of crucible (sliced on the central cross-section along the length direction of slab ingot cross-section)

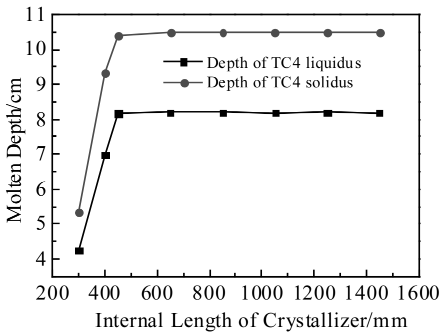

Fig.8 Relationship between depth of TC4 liquidus, solidus and the internal length of crucible

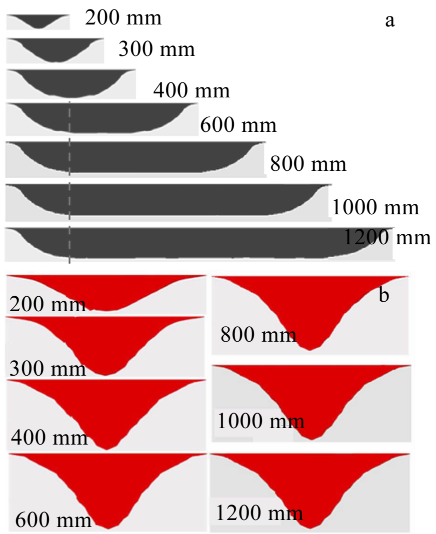

Fig.9 Molten pool morphologies of TA1 slab ingot with different internal lengths of crucible: (a) length direction of TA1 slab ingot cross-section and (b) width direction of TA1 slab ingot cross-section

cross-section area of TC4 slab ingot. Under a certain electron gun power (corresponding to pouring temperature of molten pool surface) and melting speed (corresponding to pulling speed of solidification process), the production efficiency keeps constant, that is to say, the cross-section area of TC4 slab ingot is constant. Based on the same cross-section area, the effect of the ratio of the crucible's length to width on the solid-liquid interface morphology was studied by calculating the temperature during EBCHM for the ultra-length and ultra-thin TC4 slab-ingot solidification.

The temperature field of ultra-long and ultra-thin TC4 slab ingot is calculated by setting six different aspect ratio modes (crucible's length to width). Fig.10 shows the relationship of the depth of TC4 liquidus, solidus and mushy zone under different modes with the identical area of the TC4 slab ingot cross-section. The results show that with decreasing the ratio of the crucible's length to width, the depth of the middle position of molten and the width of mushy zone between the liquidus and the solidus increase gradually. From mode 1 to mode 6, the width of mushy zone increases from 0.81 cm to 2.85 cm. When the ratio is 1:1, the depth of the liquidus is 17.86 cm, and that of the solidus is 20.71 cm. In this case, the depth of the molten pool is nearly half of the height of the crucible (660 mm). In order to prevent the occurrence of unsafety accidents such as leakage and break in the process of drawing the ingot, the proportion of the crucible (1:1) is not selected when designing crucible used for producing the ultra-long and ultra-thin TC4 slab ingot. In addition, when the ratio of the crucible's inner length to inner width is 16:1, the depth of liquidus and solidus is only 2.15 and 2.96 cm, respectively. In order to eliminate or to reduce the metallurgical defects in the casting process, it can be predicted from the calculated results by controlling the small curvature solid-liquid interface and the narrow mushy zone. So the larger the ratio of length to width in the mold, the better the quality of slab ingot. Results show that the quality of slab ingot is better than that of the square ingot, as can be seen from Fig.10.

However, considering the fluidity of the melt, the larger ratio of crucible's length to width is not designed in the actual production. Because when the depth of the molten pool decreases to a certain extent, the viscosity of the fluid increases, which stops the flow of the TC4 titanium alloy melt, reaching the overflow outlet opposite, so more casting defects form. Considering synthetically, it is helpful to improve the production quality of TC4 slab ingot by properly increasing the ratio of crucible's inner length to inner width. In this work, the ratio of crucible's inner length to inner width is generally chosen to be 4~6, when designing the crucible's three-dimension during EBCHM for the ultra-long and ultra-thin TC4 slab ingot.

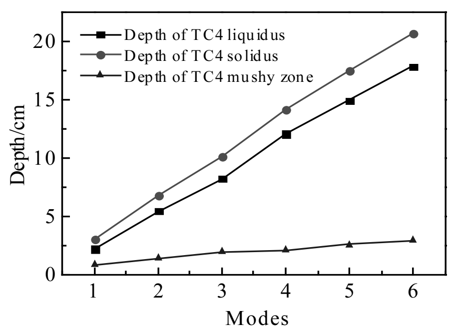

Fig.10 Relationship of the depth of TC4 liquidus, solidus and mushy zone under different modes with identical area of the TC4 slab ingot cross-section

3.3 Effect of the crucible's height on the solid-liquid interface morphology

Keep the width (210 mm), thickness (75 mm) and length (1250 mm) constant, and the height was set as 150, 175, 200, 300, 400, 600 and 800 mm. The effect of crucible's height on the solidification interface of ultra-long and ultra-thin TC4 slab ingot was analyzed by the temperature distribution. Fig.11 shows comparison of the molten pool morphology of TC4 slab ingots with different heights of crucible, which are sliced on the central cross-section along the length direction of TC4 slab ingot cross-section.

Analyzing from the perspective of macro morphology, the solid-liquid interface morphology, the depth of the center molten pool and the width of the mushy zone of the TC4 slab ingot no longer significantly change when the height of the crucible increases to 300 mm. According to the results of the measurement data shown in Fig.12, when the crucible's height increases from 150 mm to 300 mm, the depth of the liquidus of TC4 slab ingot decreases from 11.94 cm to 8.21 cm, and the depth of solidus decreases from 26.73 cm to 10.47 cm. As the height of the crucible increases, the depth of the molten pool and the width of the mushy zone remain unchanged. Therefore, under the simulated conditions, the effective cooling height of the crucible is 300 mm. The solid-liquid interface morphology of TC4 slab ingot molten pool will not be affected by the height of the crucible when the height of crucible designed is higher than 300 mm. Moreover, the depth of molten pool and the width of the mushy zone will not change any more.

3.4 Effect of the crucible's thickness on the solid-liquid interface morphology

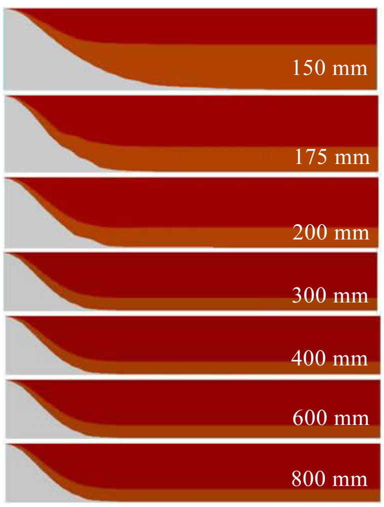

Fig.11 Molten pool morphologies of TC4 slab ingot with different heights of crucible (sliced on the central cross-section along the length direction of TC4 slab ingot cross-section)

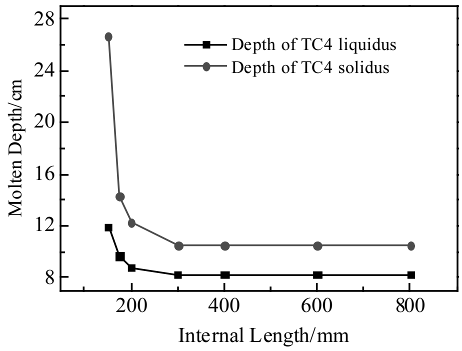

Fig.12 Relationship between the depth of TC4 liquidus, solidus and the height of crucible

In addition to length, width and height in the three-dimensional size of the crucible above, the thickness of the crucible also needs to be defined when designing the crucible. Keep the width (210 mm), height (660 mm) and length (1250 mm) constant, and the thickness was set as 50, 60, 70, 75, 80 and 90 mm, respectively. The effect of crucible's thickness on the solidification interface of ultra-long and ultra-thin TC4 slab ingot was analyzed by the temperature distribution. Fig.13 shows the relationship between the depth of TC4 liquidus, solidus and the thickness of crucible. It can be found that depth of liquidus and solidus does not change significantly with the increase of the crucible's wall thickness, which demonstrates the little effect of crucible's wall thickness on the solid-liquid interface morphology. Therefore, in the actual design of the water-cooling crucible for TC4 slab ingot production, the internal water-cooling pipe design should be given priority consideration.

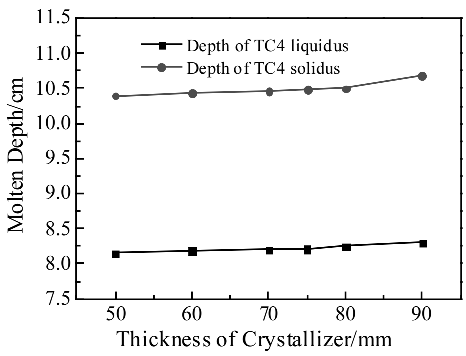

Fig.13 Relationship between the depth of TC4 liquidus, solidus and the thickness of crucible

4 Conclusions

1) The effect of crucible's three-dimensional size on the

solid-liquid interface morphology can be studied by calculating the temperature distribution during EBCHM for the ultra-long and ultra-thin TC4 slab-ingot solidification. The quantitative relationships of the length, ratio of length to width, height and wall thickness of the crucible and the depth of molten pool are obtained.

2) When the length of the cross-section of TC4 slab ingot is lower than 450 mm, the solid-liquid interface morphology of TC4 slab ingot is determined by the width and length of crucible.

3) The quality of slab ingot is better than that of the square ingot.

4) The solid-liquid interface morphology of TC4 slab ingot molten pool cannot be affected by the height of the crucible when the height of crucible designed is higher than 300 mm.

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电子束冷床炉熔炼超长超薄 TC4 铸锭过程中坩埚的尺寸设计

刘千里，蒋　鹏，安飞鹏

（洛阳船舶材料研究所 先进钛及钛合金材料技术国家地方联合工程研究中心，河南 洛阳 471023）

摘　要：钛锭固液界面形貌对其凝固组织有着很大的影响。研究了超长超薄 TC4 扁锭 EB 炉熔炼中结晶器三维尺寸对固液界面形貌的影响。结果表明：当 TC4 扁锭截面长度超过 450 mm 时，结晶器的冷却能力不再增加。当长度超过有效距离时，随着结晶器长度的增加，熔池深度和糊状区宽度不再发生改变。此外，提高结晶器的长宽比有利于提高 TC4 扁锭的表面质量。计算结果表明，结晶器内长和内宽比应在 4:1 和 6:1 之间。当结晶器高度大于 300 mm 时，熔池深度和糊状区宽度不变。本研究可以为电子束冷床炉(EBCHM)熔炼超长超薄 TC4 扁锭的结晶器三维设计提供一定的设计依据。

关键词：超长超薄钛锭；连续凝固；固液界面；结晶器尺寸

作者简介：刘千里，男，1991 年生，博士，洛阳船舶材料研究所，河南 洛阳 471023，电话：0379-67236526, E-mail: lql725@yeah.net