

Preparation and compositional distribution of a TA17 titanium alloy ingot via a novel semi-continuous induction melting process

*Wei-dong Li^{1,2}

1. State Key Laboratory of Materials Processing and Die & Mould Technology and School of Materials Science and Engineering, Huazhong University of Science and Technology, Wuhan 430074, China

2. Luoyang Ship Material Research Institute, Luoyang 471039, Henan, China

Copyright © 2026 Foundry Journal Agency

Abstract: A novel semi-continuous induction melting technology for the production of large-volume titanium alloy ingots was introduced. The effects of the melting power and ingot drawing speed on the production process of TA17 titanium alloy ingots via this technology were systematically investigated. The results show that insufficient melting power or excessive drawing speed leads to failure in alloy melting, whereas excessively high melting power or overly slow drawing speed causes overheating of the cooling circulation system, leading to equipment failure. Optimal conditions are achieved at a melting power of 750 kW and an ingot drawing speed of 4 kg·min⁻¹, resulting in efficient production of titanium alloy ingots with an energy utilization rate of 8.3%. Under these conditions, a 522 kg TA17 titanium alloy ingot with a diameter of 280 mm was successfully produced. The aluminum distribution in the TA17 titanium alloy ingot was analyzed, and the results indicate that the aluminum content does not vary significantly along the axial direction. However, a slight decreasing trend in the aluminum content is observed from the edge to the center in the radial direction, with all variations confined within ±0.1wt.%. Microstructural analysis via optical microscopy reveals a transition from acicular to flaky grain structures from the edge to the center of the ingot in the radial direction. Furthermore, the grain size across the ingot cross-section exhibits a gradient distribution characteristic, decreasing progressively from M-6.5 (approximately 52.5 μm) at the center region to M-6.0 (about 44.2 μm) near the edge. This microstructural heterogeneity primarily originates from the temperature distribution during solidification. The higher temperature and slower cooling rate at the ingot center provide favorable conditions for grain growth, whereas the rapid heat dissipation at the edge due to contact with the crucible significantly enhances nucleation rate and suppresses grain growth, ultimately resulting in refined microstructure.

Keywords: semi-continuous induction melting technology; titanium alloy ingot; multistage vacuum feeding; intermittent drawing ingot

CLC numbers: TG146.23

Document code: A

Article ID: 1672-6421(2026)05-757-11

1 Introduction

Titanium alloys, featuring high specific strength, excellent corrosion and heat resistance, nonmagnetic and nontoxic properties, and good biocompatibility, are important metal materials following steel and aluminum. Widely used in aviation, aerospace,

navigation, military, nuclear power, electronics, medical, chemical, and other fields, these materials are known as the “third metal”, “space metal”, “ocean metal”, and so on^[1-7]. However, the more demanding extreme service environment places higher requirements on the impurity content, composition uniformity, performance, reliability, and cost of titanium alloy ingots. Therefore, how to achieve a low impurity content and high homogeneity of titanium alloy ingots has become a main research direction in this field^[8-10].

The cold crucible for induction melting is an ideal process for preparing high-quality titanium alloy ingots

*Wei-dong Li

Male, born in 1985, Senior Engineer. His research interests mainly focus on investment casting process of advanced titanium alloys.

E-mail: liweidong589@163.com

Received: 2025-03-20; Revised: 2025-08-07; Accepted: 2026-03-05

because of its high degree of superheating, short processing time, low impurity content, and good homogeneity^[11-13]. A cold crucible induction melting alloy mainly generates alternating magnetic flux in the crucible by electrifying the coil, and then generates an induction electromotive force and an induced current in the melted alloy, thus realizing the heating and melting of the alloy. When the coil is electrified, the distributions of the electromagnetic field, energy loss, and heat conduction are complex^[14, 15]. Even under the same conditions of frequency and output power, the induced electromotive force, induced current, permeability, and resistivity of the melting are different at different temperatures, and the energy acting on the melt is also different^[15-17]. At present, no corresponding theory has the ability to effectively reflect the energy and magnetic field distributions in this complex process and cannot effectively guide the establishment of the induction melting process^[13, 16, 18-20]. Moreover, owing to the limitation of the equipment and process, cold crucible induction melting method cannot be used to prepare large (weight>200 kg) titanium alloy ingots.

To address the bottlenecks in traditional large-scale titanium alloy ingot production, namely lengthy processes, high costs, and severe compositional segregation^[9, 11], this study introduces a novel semi-continuous induction melting technology. This method utilizes the electromagnetic stirring effect of induction melting to suppress compositional segregation on the one hand, and employs continuous ingot withdrawal technology to solve the problem of excessively small ingot dimensions on the other hand. The research aims to optimize this new process to achieve the efficient and low-cost production of large ingots with high homogeneity and low impurity content. To achieve the semi-continuous induction melting of titanium alloy ingots, it is necessary to study the power and energy utilization rates of the power supply and the melting efficiency of the alloy, as the energy loss of the cold crucible melting process and melting efficiency are the key factors for the preparation of large titanium alloy ingots. Based on the law of energy conservation, the matching relationship between the power supply, cooling cycle system, and melting speed of the alloy was studied by measuring the energy absorbed (the energy output of the power supply minus the energy loss), and then the semi-continuous induction melting process for $\Phi 280\text{ mm} \times 1,800\text{ mm}$ TA17 titanium alloy ingots was established. During semi-continuous induction melting, pronounced temperature gradients develop within the molten alloy, resulting in preferential aluminum segregation and volatilization, which significantly alters the grain morphology. The homogeneity of ingots can be effectively assessed through aluminum content analysis, given its low melting point and volatile nature which promote elemental segregation during solidification. To characterize the metallurgical properties of the as-cast ingots, the aluminum distribution and grain structure evolution in TA17 titanium alloy were systematically investigated.

2 Method and device for semi-continuous induction melting of titanium alloy ingots

The production of titanium alloy ingots via semi-continuous induction melting was accomplished through a precisely coordinated control system that integrated three key processes: multistage vacuum feeding, induction melting, and intermittent ingot drawing. The system configuration is shown in Fig. 1. The manufacturing process began with the loading of preprocessed titanium alloy raw materials into the first-level feeding chamber; then, the valve between the first-level feeding chamber and the second-level feeding chamber was opened, and the materials were transferred to the second-level feeding chamber. Following this transfer, the valve between the first-level feeding chamber and the second-level feeding chamber was closed, and the second-level feeding chamber undergone vacuum evacuation through an integrated vacuum system, achieving a chamber pressure below 0.9 Pa. The raw materials were subsequently advanced to the third-level feeding chamber through controlled valve operation, where both the third-level feeding chamber and the furnace chamber were evacuated to maintain the specified vacuum level (<0.9 Pa). The raw materials were then pushed into the cold crucible within the melting chamber, and the valve between the second-level feeding chamber and the third-level feeding chamber was closed. Through synchronized control of valve operations within the three-stage feeding system and precise coordination with the vacuum extraction system, continuous material feeding was achieved while maintaining optimal vacuum conditions. Concurrently, the raw materials undergone controlled melting within the cold crucible. The molten titanium alloy was then systematically drawn and solidified through the intermittent pulling mechanism. This cyclic process, characterized by its precisely controlled vacuum maintenance and material handling sequence, enables the production of large titanium alloy ingots with consistent metallurgical properties and structural integrity.

Copper serves as an ideal material for cold crucibles in induction melting systems due to its excellent thermal

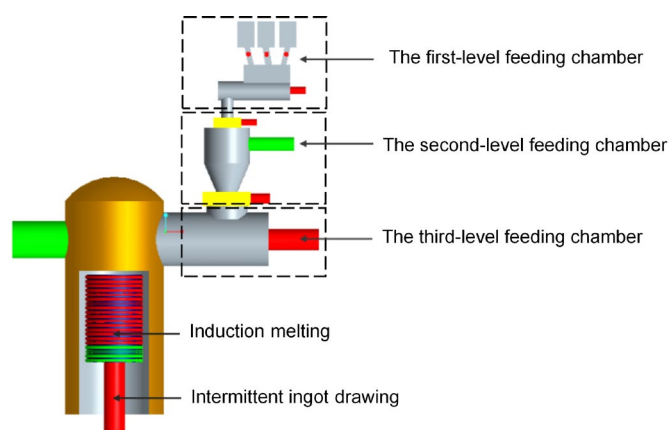


Fig. 1: Schematic diagram of cold crucible semi-continuous induction melting device

conductivity and magnetic shielding effect. The cold crucible, with an inner diameter of 280 mm, a height of 410 mm, and a wall thickness of 30 mm, was equipped with a 8-turn induction coil. To facilitate effective induction melting of titanium alloys, the cold crucible must maintain appropriate magnetic permeability. However, the inherent magnetic shielding properties of copper present a technical challenge. To address this limitation, the crucible was designed with a segmented structure comprising 24 individual lobes separated by 1 mm gaps filled with mica sheets for electrical insulation. Additionally, each lobe incorporated a dedicated cooling water channel (15 mm diameter) to ensure efficient heat dissipation and maintain structural integrity during operation. The detailed configuration of the cold crucible is illustrated in Fig. 2.

Based on the spatial distribution of induction coils and the cooling circulation system within the crucible, three distinct functional areas were established during the semi-continuous induction melting of titanium alloys: the melting area, junction area, and solidification area, as illustrated in Fig. 3.

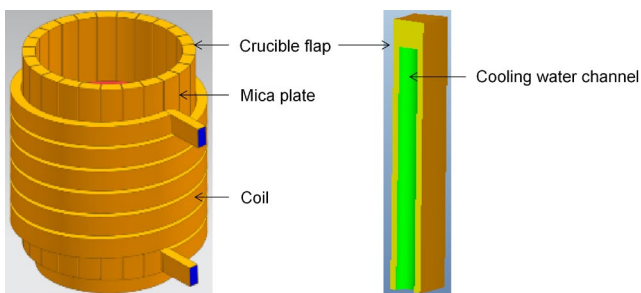


Fig. 2: Schematic diagram of cold crucible structure

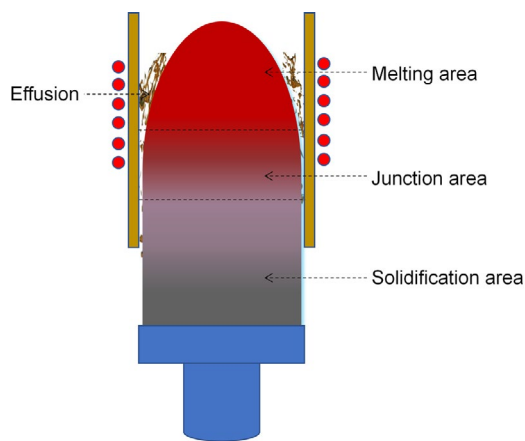


Fig. 3: Functional areas in semi-continuous induction melting

3 Mathematical model

In a semi-continuous vacuum induction melting furnace, thermal energy is generated through electrical power input and is distributed into two primary components during the alloy melting process: heat loss and energy absorption by the alloy. Under conditions of prolonged steady-state continuous melting, the furnace chamber temperature stabilizes at a specific equilibrium value. Based on the principle of energy

conservation, the net heat absorbed by the alloy can be calculated by subtracting the total heat loss (comprising heat dissipated through the cooling circulation system and thermal radiation from the furnace chamber) from the total heat generated by the power input. This energy balance relationship can be mathematically expressed via Eq. (1):

$$Q_E = Q_T - Q_L \quad (1)$$

where Q_E is the effective value of energy (J); Q_T is the output heat of the power (J); and Q_L is the heat loss (J).

$$Q_T = W \cdot T \quad (2)$$

where W is the output power of the power supply (W) and T is the power supply working time (s).

The outer body of the furnace cavity incorporates an integrated cooling circulation water system, which significantly reduces the temperature gradient between the cooled outer surface and the ambient atmosphere. This efficient thermal management results in minimal heat dissipation from the exterior of the furnace cavity to the surrounding environment. To simplify the computational model, this component of heat loss is considered negligible. Under this assumption, the primary heat loss mechanism is attributed to the energy absorbed by the cooling circulation water. Consequently, the effective thermal energy available in the semi-continuous vacuum induction melting system can be determined by subtracting the energy absorption of the cooling water from the total power supply output, as mathematically represented by Eq. (3):

$$Q_E = Q_T - Q_W \quad (3)$$

where Q_W is the heat taken away by the cooling circulating water (J).

Based on the effective heat utilization rate calculated via Eq. (3), thermal analysis was conducted under the assumption that the raw materials, including sponge titanium and aluminum-vanadium alloy, completely transformed into TA17 titanium alloy during the melting process. Starting at all initial temperature of 25 °C, the TA17 titanium alloy reaches a molten state at 1,800 °C, resulting in a total temperature difference of 1,775 °C during the melting process. Under stable melting conditions, the melting rate of TA17 titanium alloy can be determined via Eq. (4):

$$W_T = Q_E / (1775 \cdot C_{Ti}) \quad (4)$$

where W_T is the melting rate of TA17 titanium alloy ($\text{kg} \cdot \text{s}^{-1}$) and C_{Ti} is the specific heat of TA17 titanium alloy [$520 \text{ J} \cdot (\text{kg} \cdot ^\circ\text{C})^{-1}$]^[21].

$$\eta = W_T / \{Q_T / (1775 \cdot C_{Ti})\} \quad (5)$$

where η is the effective utilization rate of energy.

4 Experiment

The research methodology comprised three sequential phases. Initially, the alloy melting-power requirement correlation was examined through controlled ingot heating experiments at varying power levels. Based on these fundamental parameters, a manufacturing process for TA17 titanium alloy ingots was subsequently developed, and corresponding melting experiments were conducted. Finally, comprehensive

evaluation and analysis were performed on the prepared TA17 titanium alloy ingots, with a focus on the aluminum distribution and microstructural characteristics.

4.1 Power supply evaluation for TA17 titanium alloy ingot melting

The experimental procedure was conducted as follows: a $\Phi 278 \text{ mm} \times 300 \text{ mm}$ TA17 titanium alloy ingot was precisely positioned within the cold crucible, followed by sealing the furnace chamber and initiating the vacuum pumping process. Power activation commenced when the chamber pressure reached less than 0.9 Pa concurrently with the activation of the cooling circulation water system, which maintained a constant flow rate of $0.006437 \text{ m}^3 \cdot \text{s}^{-1}$. To ensure optimal equipment performance and prevent thermal shock, the power input was gradually increased at a controlled rate of $100 \text{ kW} \cdot \text{min}^{-1}$ until the predetermined operational parameters were reached. The total duration of power application was maintained within 20 min throughout the melting process.

A systematic experimental investigation was conducted by applying the established methodology to five distinct power supply configurations, as detailed in Table 1. During each test, the inlet and outlet water temperatures of the cooling circulation system were precisely monitored via calibrated thermometers, with measurements recorded at one-minute intervals. Through comprehensive energy analysis, the effective energy utilization was determined by calculating the difference between the total energy generated by the power supply and the energy dissipated through the cooling circulation system. This energy balance approach enabled accurate calculation of the TA17 titanium alloy melting rate under various operational conditions.

Table 1: Test schemes of melting power supply

Schemes	Output power
#1	450 kW
#2	550 kW
#3	650 kW
#4	750 kW
#5	800 kW

4.2 Melting process test of TA17 titanium alloy

The raw materials used in the experiment were sponge titanium and aluminum-vanadium alloy. TA17 titanium alloy was configured according to Al: 4.025wt.%, V: 2.8wt.%. Among them, the aluminum-vanadium alloy was wrapped with aluminum foil. Using the calculated melting parameters, a series of controlled melting process experiments were conducted on TA17 titanium alloy. The experimental procedure was strictly carried out according to the operational protocol specified in Section 4.1. The power was gradually increased

to the preset value until a stable molten pool formed at the upper section of the $\Phi 278 \text{ mm} \times 300 \text{ mm}$ titanium alloy ingot, followed by batch-wise addition of the pre-prepared alloy packets into the crucible for melting. Subsequently, the ingot pulling process was performed, and the closed-loop process of feeding→melting→pulling was repeated cyclically. Through systematic evaluation of the experimental results, the optimal process parameters for cold crucible semi-continuous induction melting of $\Phi 278 \text{ mm} \times 1,800 \text{ mm}$ TA17 titanium alloy ingots were established across various power input conditions.

4.3 Examination and analysis of TA17 titanium alloy ingot

Chemical composition analysis of the TA17 titanium alloy ingot prepared by semi-continuous induction melting was performed via an EXPEC 6500 inductively coupled plasma optical emission spectrometer, with a particular focus on the aluminum distribution. The sampling locations were strategically selected from three distinct regions: the upper section, middle section, and bottom section of the ingot. Microstructural characterization was conducted through combined metallographic microscopy and scanning electron microscopy. The specific sampling locations and corresponding analytical locations are systematically illustrated in Fig. 4.

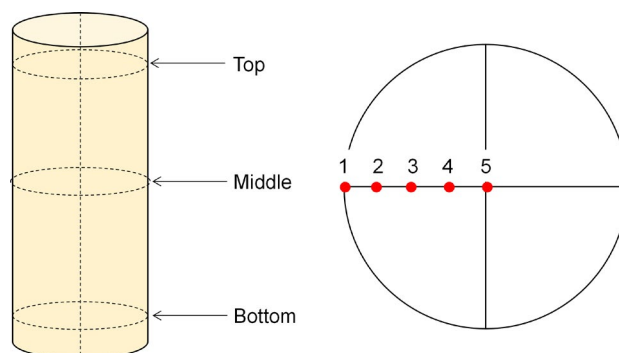


Fig. 4: Sampling position diagram

5 Results and discussion

5.1 Effect of power on melting process

The inlet water temperature (IWT) and outlet water temperature (OWT) of the cooling circulation water system under five different power test schemes are shown in Table 2, where 0 min represents the initial temperature (25°C) of the cooling water.

Figure 5 shows that the temperature difference of inlet and outlet water of Schemes #1 and #2 tends to be stable when the power supply works for 12 min and 10 min, respectively, and the entire melting system achieves a balance between heat absorption and heat dissipation. Schemes #3, #4, and #5 indicate that with increasing power and melting time, the water temperature difference between the inlet and outlet of the cooling circulation system rapidly increases, and the outlet water temperature exceeds the upper limit temperature of

Table 2: Inlet water temperature (IWT) and outlet water temperature (OWT) (°C)

Schemes	#1		#2		#3		#4		#5	
Time	IWT	OWT	IWT	OWT	IWT	OWT	IWT	OWT	IWT	OWT
1 min	25.1	27.1	25.3	27.4	25.1	27.3	25.4	27.3	25.2	27.5
2 min	25.1	29.9	25.5	29.2	25.6	28.6	25.5	28.5	25.4	28.6
3 min	25.6	33.2	25.8	33.9	26.1	32.7	25.8	30.4	26.5	31.6
4 min	26.2	34.7	26.7	35.3	26.8	34.2	27.2	34.5	27.1	34.6
5 min	27.3	39.4	27.5	38.2	27.4	37.7	27.8	37.9	27.4	37.6
6 min	28.1	42.1	28.7	42.3	28.3	42.2	28.3	42.0	28.1	41.0
7 min	28.2	43.9	28.8	45.4	28.5	44.2	28.5	44.6	28.7	44.5
8 min	28.5	44.4	28.7	47.6	28.4	46.2	28.5	46.7	28.7	46.5
9 min	28.7	44.7	28.8	48.8	28.4	48.3	28.6	48.6	28.7	50.9
10 min	28.8	45.2	28.9	49.2	28.3	50.1	28.7	51.1	28.9	54.9
11 min	28.9	45.3	28.8	49.1	28.3	51.2	28.8	55.8	29.3	56.2
12 min	28.8	45.4	28.8	49.1	29.8	52.8	29.2	56.9	29.5	59.5
13 min	28.9	45.5	28.9	49.2	29.8	53.7	29.2	57.4	29.4	63.6
14 min	28.9	45.5	28.9	49.2	29.8	54.5	/	/	/	/
15 min	28.9	45.5	28.9	49.2	29.8	57.2	/	/	/	/
16 min	28.9	45.5	28.9	49.2	/	/	/	/	/	/
17 min	28.9	45.5	28.9	49.2	/	/	/	/	/	/
18 min	28.9	45.5	28.9	49.2	/	/	/	/	/	/
19 min	28.9	45.5	28.9	49.2	/	/	/	/	/	/
20 min	28.9	45.5	28.9	49.2	/	/	/	/	/	/

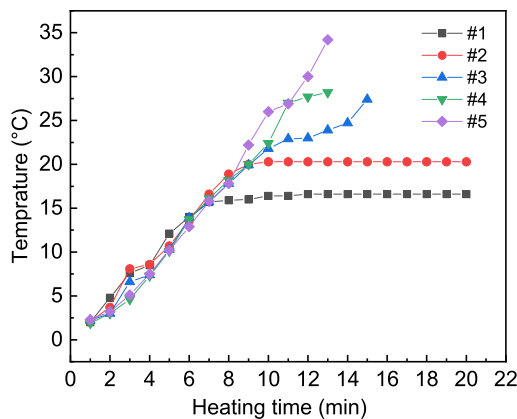


Fig. 5: Temperature difference of inlet and outlet water

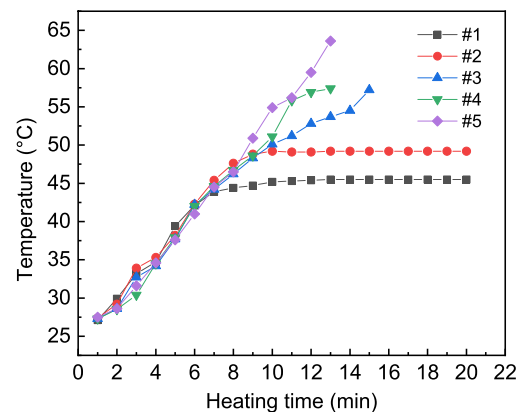


Fig. 6: Outlet water temperature of cooling circulation system

55 °C (operational requirements for equipment), as shown in Table 2 and Fig. 6, which has a negative effect on the crucible.

In Schemes #1 and #2, melting is limited to the edge regions of the TA17 titanium alloy in contact with the crucible gap, as shown in Fig. 7(a). The induced current is generated by alternating magnetic flux, so it attenuates from the surface

to the inside of the workpiece, and its attenuation is roughly exponential^[16]. In engineering, when the conductor current density decays inward from the surface to a value equal to $1/e$ times the surface current density, the distance δ from the surface is called the current penetration depth (e , Euler's number, is approximately 2.71828)^[12]. Therefore, most of

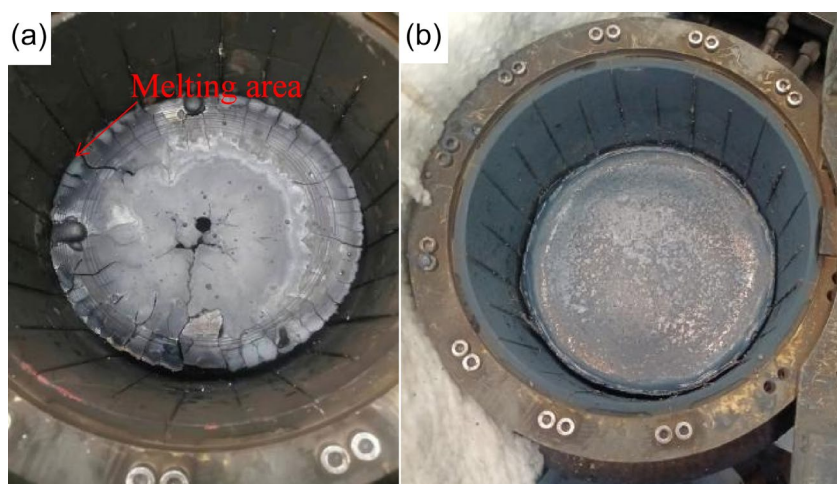


Fig. 7: Unmelted (a) and melted (b) TA17 alloy ingots

the heat generated by the current in the titanium alloy can be assumed to be concentrated at the current penetration depth δ . The penetration depth δ is expressed by Eq. (6)^[12]:

$$\delta = \sqrt{P/(U_r f)} \quad (6)$$

where P is the resistivity of the conductor material ($\Omega \cdot \text{cm}$); U_r is the relative permeability of the conductor material ($\text{H} \cdot \text{m}^{-1}$); and f is the current frequency (Hz).

As shown in Eq. (6), when the alloy material and current frequency remain constant, the greater the power supply, the greater the amount of energy that will be obtained at the same penetration depth of the alloy. Therefore, Schemes #3, #4, and #5 melt the TA17 titanium alloy ingot at 13 min, 10 min, and 9 min, respectively, and melt and solidify the TA17 titanium alloy ingot, as shown in Fig. 7(b). Under these conditions, the temperature of the crucible is relatively high, which leads to the edge of the TA17 titanium alloy ingot being remelted and an increase in the cooling circulation water temperature.

Table 3 and Fig. 8 show the energy obtained from the TA17 titanium alloy ingot and the trend of the energy obtained per minute under the five schemes, respectively. The effective energy values of all five schemes initially increase with working time during the first eight minutes, but exhibit a decreasing trend upon further prolongation of operation time.

The effective energy of Schemes #1 and #2 is basically stable beginning at 12 min and 10 min, respectively, as shown in Fig. 8. These two schemes do not melt the TA17 titanium alloy ingot within 20 min, indicating that the effective energy of the power supply is too low to melt the TA17 alloy. The effective energy is still positive after 12 min and 10 min because the heat dissipation of the furnace body to the atmosphere is assumed to be zero. According to the conservation of energy, this energy is the heat lost from the outer body of the furnace chamber to the atmosphere.

It is observed that the TA17 titanium alloy ingots are completely melted at 13 min, 10 min, and 9 min by Schemes #3, #4, and #5, respectively. The rapid rise in cooling water temperature at this point (Fig. 6) is attributed to the further contact between the fully molten metal and the crucible wall, and this temperature increase confirms complete melting of

the metal. The energy of the alloy absorbed per minute is negative at 14 min, 13 min, and 12 min, respectively, as shown in Table 3. When the TA17 titanium alloy is in the liquid state, with the continuous work of the power supply, the outlet water temperature increases sharply at 15 min, 11 min, 9 min (Table 2), respectively, and the cooling circulating water system dissipates more energy, so the energy absorbed by the alloy becomes negative.

According to the inlet water temperature and outlet water temperature of Schemes #3, #4, and #5, without considering the heat dissipation of the furnace body to the atmosphere, the weight of the TA17 titanium alloy that is melted per unit time of the three schemes can be calculated by Eq. (4). The weights of the TA17 titanium alloy melted per minute for Schemes #3, #4, and #5 under full-power conditions are $3.96 \text{ kg} \cdot \text{min}^{-1}$, $10.9 \text{ kg} \cdot \text{min}^{-1}$, and $14.0 \text{ kg} \cdot \text{min}^{-1}$, respectively.

5.2 Semi-continuous induction melting of TA17 titanium alloy

According to the above calculation results, different feeding weight per minute tests were carried out for Schemes #3 (650 kW), #4 (750 kW), and #5 (800 kW), and the specific test plans are shown in Table 4. Excessive feed rates induce alloy bridging, whereas insufficient rates lead to overheating of the cooling water.

(1) Bridging at high feeding rates [as shown in Fig. 9(a)]: Excessive feeding rates cause solid feedstock accumulation ("bridging") in the crucible, preventing continuous melt flow. This occurs in Scheme #5 ($12 \text{ kg} \cdot \text{min}^{-1}$, $6 \text{ kg} \cdot \text{min}^{-1}$), Scheme #4 ($8 \text{ kg} \cdot \text{min}^{-1}$), and Scheme #3 ($3 \text{ kg} \cdot \text{min}^{-1}$).

(2) Cooling system over-temperature at low feeding rates: Insufficient feeding rates lead to an imbalance in the thermal load, causing the circulating cooling water outlet temperature to exceed the 55°C safety limit (Table 2). This halts operation in Scheme #5 ($3 \text{ kg} \cdot \text{min}^{-1}$), Scheme #4 ($2 \text{ kg} \cdot \text{min}^{-1}$), and Scheme #3 ($1 \text{ kg} \cdot \text{min}^{-1}$).

(3) Successful continuous melting is achieved only within an intermediate feeding rate range, as shown in Fig. 9(b). Scheme #4 successfully produced a 522 kg ingot at $4 \text{ kg} \cdot \text{min}^{-1}$,

Table 3: Obtained energy (J) per minute from TA17 titanium alloy ingot

Schemes	#1	#2	#3	#4	#5
Time	Q_E	Q_E	Q_E	Q_E	Q_E
1 min	2,755,752.0	2,593,539.6	2,431,327.2	2,917,964.4	2,269,114.8
2 min	4,213,804.8	5,998,141.2	7,133,628.0	7,133,628.0	6,809,203.2
3 min	5,671,857.6	4,860,795.6	7,293,981.6	10,538,229.6	9,727,167.6
4 min	10,211,946.0	10,049,733.6	11,996,282.4	12,158,494.8	11,834,070.0
5 min	7,372,299.6	12,643,273.2	13,292,122.8	13,616,547.6	13,454,335.2
6 min	4,290,264	10,939,113.6	13,452,476.4	13,776,901.2	15,074,600.4
7 min	1,532,653.2	6,072,741.6	13,532,653.2	15,883,803.6	16,370,440.8
8 min	1,208,228.4	2,341,856.4	10,126,192.8	15,477,343.2	19,126,192.8
9 min	1,046,016.0	557,520.0	6,719,732.4	12,557,520.0	11,988,847.2
10 min	397,166.4	70,882.8	3,637,696.8	8,664,422.4	5,824,776.0
11 min	397,166.4	70,882.8	1,853,360.4	1,202,652.0	4,364,864.4
12 min	72,741.6	70,882.8	1,691,148	67,165.2	-663,720.0
13 min	72,741.6	70,882.8	231,236.4	-743,896.8	-7,476,640.8
14 min	72,741.6	70,882.8	-1,066,462.8	/	/
15 min	72,741.6	70,882.8	-5,446,197.6	/	/
16 min	72,741.6	70,882.8	/	/	/
17 min	72,741.6	70,882.8	/	/	/
18 min	72,741.6	70,882.8	/	/	/
19 min	72,741.6	70,882.8	/	/	/
20 min	72,741.6	70,882.8	/	/	/

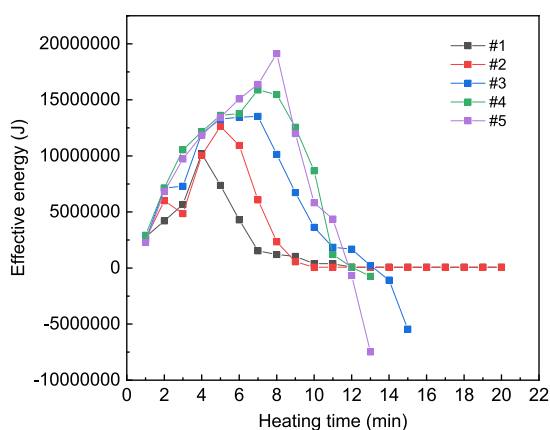


Fig. 8: Available energy under different power and time conditions

Table 4: Melting schemes of different power feeding speeds

Scheme	Power (kW)	Feeding weight ($\text{kg} \cdot \text{min}^{-1}$)		
#3	650	3	2	1
#4	750	8	4	2
#5	800	12	6	3

as shown in Fig. 9(c), achieving an energy utilization rate of approximately 8.3% calculated via Eq. (5).

It is found that an excessively heavy alloy charge combined with insufficient power input during melting can easily cause a “alloy bridge” to form in the crucible. The low-temperature molten TA17 titanium alloy is immersed in the gap of the crucible and solidified, and the temperature is further reduced by excessive feed. Insufficient melting power resulting from a weak electromagnetic force and correspondingly low current intensity prevents the alloy in the crucible gap from melting and suspending. Since the magnetic induction is proportional to the current, the low energy and weak electromagnetic force cause the formation of an alloy bridge during titanium alloy melting, which further prevents the melting process.

5.3 Composition and microstructural analysis of TA17 titanium alloy ingot

Under the process conditions of $750 \text{ kW}/4 \text{ kg} \cdot \text{min}^{-1}$, the radial distribution of Al element in the TA17 ingot at different heights is shown in Fig. 10. At any given height, the aluminum content consistently exhibits a decreasing trend from the surface toward the center. The main reason for this trend is that

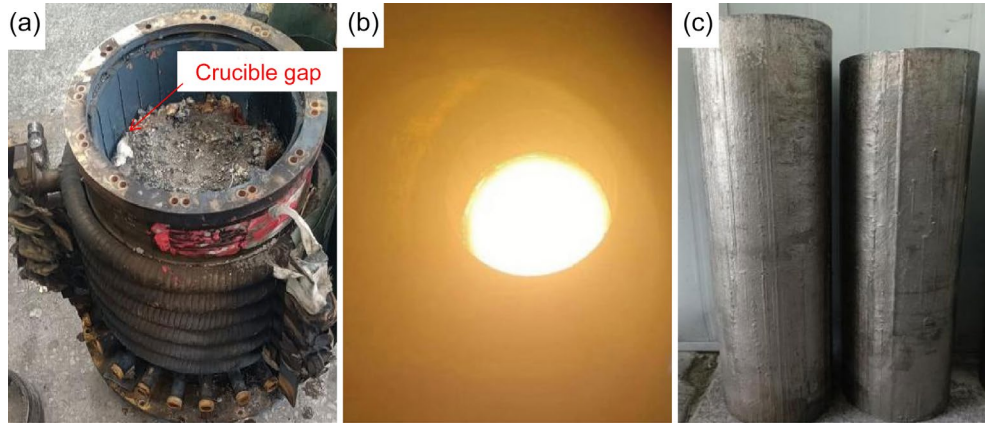


Fig. 9: TA17 titanium alloy ingot melting conditions: (a) alloy bridge; (b) molten pool; (c) TA17 titanium ingot

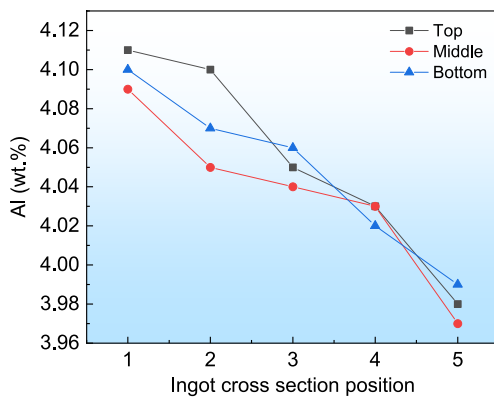


Fig. 10: Radial distribution characteristics of Al element in TA17 ingot at different heights under 750 kW/4 kg·min⁻¹ process parameters

the alloy is heated by electromagnetic induction, and the heat is concentrated mainly within the surface of the melt because of the skin effect of induction heating^[13, 22, 23]. Therefore, the surface temperature of the molten TA17 titanium alloy is higher than that of the core at the melting stage, and the solubility of Al in the high-temperature molten titanium is higher than that in the low-temperature molten titanium. During the ingot pull-down process, the edge of the molten TA17 titanium alloy cools and solidifies rapidly so that the Al remains in the ingot.

The melt temperature field, melting time, and oxygen partial pressure critically govern the aluminum burning loss and its resultant distribution within the ingot. To elucidate and quantify the influence of these three factors, this study developed a mathematical model with the objective of accurately predicting and optimizing the Al distribution during semi-continuous induction melting, thereby providing a theoretical basis and practical guidance for process control.

The surface current density of the molten pool can be calculated using Eq. (7)^[13, 15]:

$$J_0 = \sqrt{\frac{P_{\text{absorbed}} \sigma}{\delta \pi R}} \quad (7)$$

where J_0 is the surface current density (A·m⁻²), R is the inner radius of the crucible (m), P_{absorbed} is the absorbed power by the melt (W).

The electromagnetic heat source power density $q_{\text{Gen}}(r)$ is given by Eq. (8)^[13]:

$$q_{\text{Gen}}(r) = \frac{1}{\sigma} J_0^2 e^{-2(R-r)/\sigma} \quad (8)$$

where $q_{\text{Gen}}(r)$ represents the heat source density (W·m⁻³) at a distance r from the melt center, reaching its maximum value when $r=R$.

The temperature gradient within the molten material $\left(\frac{d_t}{d_r}\right)$, reaches its theoretical maximum value at the periphery, as described by Eq. (9)^[14]:

$$\frac{d_t}{d_r}(\text{max}) = \frac{q_{\text{Gen}}(R)\delta}{K} \quad (9)$$

where $\frac{d_t}{d_r}$ is the temperature gradient within the molten material (K·mm⁻¹); K is the thermal conductivity of molten TA17 titanium alloy.

Assuming the temperature gradient within the skin-effect region maintains its maximum value, the temperature distribution $T(r)$ in the melt during the heating stage can be expressed by Eq. (10)^[24]:

$$T(r) = T_{\text{core}} + \nabla T \times (R - r) \times 10^{-3} \quad (10)$$

where $T(r)$ is the temperature of the melt at a radial distance r from the center; T_{core} is the temperature of the melt at a distance δ from the crucible wall, $\nabla T \approx d_t / d_r(\text{max})$.

The aluminum loss is calculated by the comprehensive Eq. (11)^[16]:

$$\Delta C_{\text{Al}} = C_{\text{Al}}^0 \cdot [1 - \exp(-Q \cdot t \cdot T^{1.5} \cdot P_{\text{O}_2}^{-n})] \quad (11)$$

where ΔC_{Al} is the aluminum loss (wt.%), C_{Al}^0 is the initial aluminum content of the melt (wt.%), $C_{\text{Al}}(t)$ is the instantaneous aluminum content in the melt at melting time t (wt.%), Q is the aluminum depletion rate constant; t is the melting time (s), n is the argon shielding process constant, T is the melt temperature (K), and P_{O_2} is oxygen partial pressure (Pa).

In addition, the cooling rate of the ingot core is slow, and Al easily volatilizes at the melting stage as described by Eq. (11). Therefore, the Al content at the edge of the ingot is higher than that of the core. Moreover, during post-solidification non-equilibrium phase transformation in TA17 alloy, substantial

solute redistribution occurs. Furthermore, the $\beta \rightarrow \alpha$ phase transformation that occurs upon cooling causes Al to migrate preferentially toward the cooler edge of the ingot, making the periphery marginally enriched in Al compared to the core.

Although the aluminum content in the ingot is higher at the periphery and lower at the core, the TA17 titanium alloy ingot shows no significant difference in aluminum content across axial positions such as the top, middle, and bottom, with all variations remaining within $\pm 0.1\text{wt.}\%$. The main reason is that the same axial position is subjected to the same heat and electromagnetic force during the process of melting and drawing, which has the same stirring effect on the melt. Therefore, the axial Al content of the TA17 titanium alloy ingot prepared via semi-continuous induction melting is uniform.

Although electromagnetic stirring effectively promotes solute homogenization during semi-continuous induction melting, the distribution characteristics of the microstructure serve as a critical indicator for assessing the overall quality of the ingot. As can be seen from Fig. 11, the grain structure varies across different regions of the ingot, evolving from acicular (needle-like) at the edges to columnar (lath-like) towards the center. The grain size across the ingot cross-section exhibits a gradient distribution characteristic, with the grain size decreasing

progressively from M-6.5 (approximately $52.5\text{ }\mu\text{m}$) at the core region to M-6.0 (about $44.2\text{ }\mu\text{m}$) near the edge. The main reason for this phenomenon is that during the ingot drawing process after melting, the edge of the molten TA17 titanium alloy moves down to the unheated zone and contacts the wall of the crucible. The molten TA17 titanium alloy cools quickly to form a fine needle-like structure, whereas the molten TA17 titanium alloy in the center of the crucible cools relatively slowly, forming a relatively thick plate and strip structure during solidification.

To further analyze the microstructural differences at different radial positions of the ingot, the distribution characteristics of the β phase were examined. Figure 12 shows that the shape and size of the β phase in different radial parts of the ingot are different. The β phase at the edge of the ingot is relatively small and dispersed, as shown in Fig. 12(b), whereas the β phase at the core of the ingot is relatively thick and concentrated, as shown in Fig. 12(d). The main reason for this phenomenon is that the molten TA17 titanium alloy at edge rapidly cools when in contact with the crucible wall after leaving the melting zone during the drawing process. The fast cooling rate inhibits the growth of the β phase, thus forming a small and relatively dispersed β phase. The center of the molten TA17 titanium alloy is far from the crucible surface,

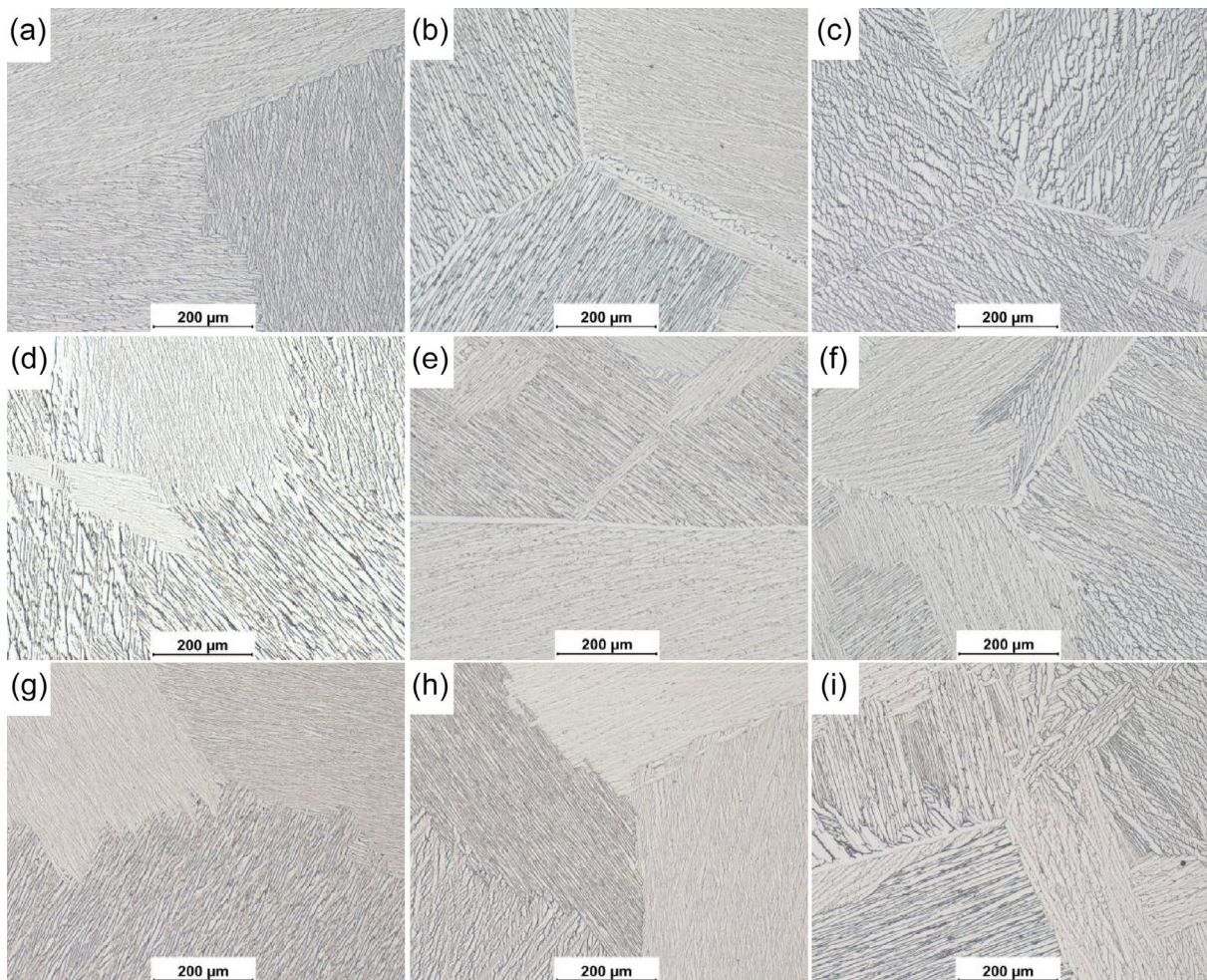


Fig. 11: Metallographic structure of ingots at different positions: (a) Top-1; (b) Top-3; (c) Top-5; (d) Middle-1; (e) Middle-3; (f) Middle-5; (g) Bottom-1; (h) Bottom-3; (i) Bottom-5

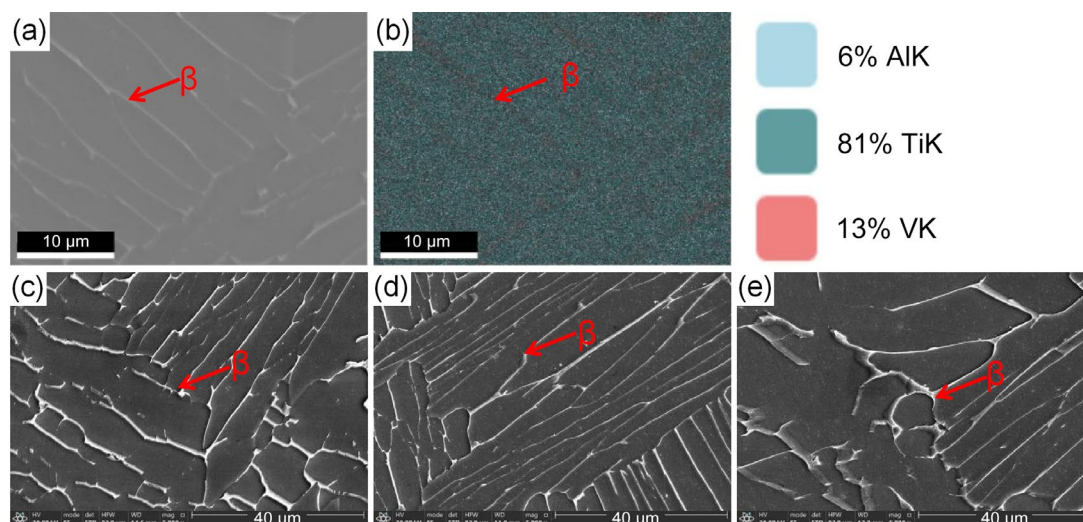


Fig. 12: Microstructures of TA17 titanium alloy ingot: (a) Middle-2; (b) EDS result of Middle-2; (c) Middle-1; (d) Middle-3; (e) Middle-5

and the cooling rate is relatively slow; thus, the β phase is present at high temperatures for a long time, resulting in β phase aggregation and growth.

6 Conclusions

(1) Semi-continuous induction melting for fabrication of large-scale titanium alloy ingots can be realized via the collaborative control of “vacuum feeding-induction melting-intermittent ingot withdrawal”.

(2) Although TA17 titanium alloy ingots ($\Phi 278$ mm) can be melted within the 650–800 kW power range, this work reveals that setting the power at 750 kW with a feed rate of $4 \text{ kg} \cdot \text{min}^{-1}$ simultaneously resolves two key process challenges: alloy bridging and cooling water overheating. Based on this optimized parameter set, a 522 kg TA17 titanium alloy ingot was successfully prepared using the semi-continuous induction method.

(3) The overall Al content of the TA17 titanium alloy ingot is uniform within $\pm 0.1 \text{ wt.}\%$, and the grain morphology and size remain consistent at the same position along the axial orientation. However, from the edge to the center of the ingot, the grains change from fine to coarse, and the β phase also changes from a fine dispersion near the edge to a coarse morphology near the center.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

- [1] Li G Q, Ma F C, Liu P, et al. Review of micro-arc oxidation of titanium alloys: Mechanism, properties and applications. *Journal of Alloys and Compounds*, 2023, 948: 169773. <https://doi.org/10.1016/j.jallcom.2023.169773>.
- [2] Singh P, Pungotra H, Kalsi N S. On the characteristics of titanium alloys for the aircraft applications. *Materials Today: Proceedings*, 2017, 4(8): 8971–8982. <https://doi.org/10.1016/j.matpr.2017.07.249>.
- [3] Zhao Q Y, Sun Q Y, Xin S W, et al. High-strength titanium alloys for aerospace engineering applications: A review on melting-forging process. *Materials Science and Engineering: A*, 2022, 845: 143260. <https://doi.org/10.1016/j.msea.2022.143260>.
- [4] Wu Z H, Kou H C, Chen N N, et al. Recent developments in cold dwell fatigue of titanium alloys for aero-engine applications: A review. *Journal of Materials Research and Technology*, 2022, 20: 469–484. <https://doi.org/10.1016/j.jmrt.2022.07.094>.
- [5] Guo Z J, Huang Y Z, Sun C C, et al. Preparation and characterization of metastable β -type titanium alloys with favorable properties for orthopedic applications. *Journal of Alloys and Compounds*, 2023, 949: 169839. <https://doi.org/10.1016/j.jallcom.2023.169839>.
- [6] Nichul U, Hiwarkar V. Carbon dot complimentary green corrosion inhibitor for crystallographically textured Beta C titanium alloy for marine application: A state of art. *Journal of Alloys and Compounds*, 2023, 962: 171116. <https://doi.org/10.1016/j.jallcom.2023.171116>.
- [7] Freitag L, Schmidt G, Hubáľková J, et al. Functionally graded calcium zirconate molds with alginate-based spray coating for titanium investment casting. *Journal of the European Ceramic Society*, 2022, 2(42): 682–692. <https://doi.org/10.1016/j.jeurceramsoc.2021.10.024>.
- [8] Song Q Z, Liang T, Qian K, et al. Corrosion resistance of calcium zirconate crucible to titanium-copper melts. *Journal of the European Ceramic Society*, 2022, 7(42): 3321–3331. <https://doi.org/10.1016/j.jeurceramsoc.2022.02.011>.
- [9] Wang Y Z, Li W, Yuan H, et al. Microstructure refinement and improvement of mechanical properties of Ti46Al8Nb0.9B alloys by electromagnetic cold crucible continuous solidification. *Intermetallics*, 2022, 140: 107391. <https://doi.org/10.1016/j.intermet.2021.107391>.
- [10] Bao C L, Zhang S Q, Ren Y Y, et al. Research progress on refractory composition and deformability of shell molds for TiAl alloy castings. *China Foundry*, 2018, 15(1): 1–10. <https://doi.org/10.1007/s41230-018-7022-9>.
- [11] Fashu S, Lototsky M, Davids M W, et al. A review on crucibles for induction melting of titanium alloys. *Materials & Design*, 2020, 186: 10829. <https://doi.org/10.1016/j.matdes.2019.108295>.

- [12] Chen R R, Yang J R, Ding H S, et al. Magnetic field in a near-rectangular cold crucible designed for continuously melting and directionally solidifying TiAl alloys. *Journal of Materials Processing Technology*, 2012, 9(212): 1934–1940. <https://doi.org/10.1016/j.jmatprotec.2012.04.018>.
- [13] Yu K, Zheng Q, Li L F, et al. Numerical and experimental investigation of electromagnetic cold crucible used for emissivity measurement of molten material. *International Journal of Thermal Sciences*, 2023, 192: 10841. <https://doi.org/10.1016/j.ijthermalsci.2023.108417>.
- [14] Moon B Y, Seo J H, Lee H J, et al. Method of recycling titanium scraps via the electromagnetic cold crucible technique coupled with calcium treatment. *Journal of Alloys and Compounds*, 2017, 727: 931–939. <https://doi.org/10.1016/j.jallcom.2017.08.129>.
- [15] Shi J, Huang Z X, Zu X D, et al. Experimental and numerical investigation of jet performance based on Johnson-Cook model of liner material. *International Journal of Impact Engineering*, 2022, 170: 104343. <https://doi.org/10.1016/j.ijimpeng.2022.104343>.
- [16] Wang S, Wang Q, Chen R R, et al. Numerical analysis for solid-liquid interface shape at various temperature gradient in electromagnetic cold crucible directional solidification. *International Journal of Heat and Mass Transfer*, 2022, 199: 123443. <https://doi.org/10.1016/j.ijheatmasstransfer.2022.123443>.
- [17] Zhang R, Wang D J, Liu S Q, et al. Effect of microstructures on hot compression behavior of a Ti-43Al-2Si alloy fabricated by cold crucible continuous casting. *Materials Characterization*, 2018, 144: 424–430. <https://doi.org/10.1016/j.matchar.2018.07.042>.
- [18] Chen R R, Ding H S, Yang J R, et al. Temperature field calculation on cold crucible continuous melting and directional solidifying Ti50Al alloys. *Transactions of Nonferrous Metals Society of China*, 2012, 3(22): 647–653. [https://doi.org/10.1016/s1003-6326\(11\)61227-2](https://doi.org/10.1016/s1003-6326(11)61227-2).
- [19] Chen R R, Yang J R, Ding H S, et al. Effect of configuration on magnetic field in cold crucible using for continuous melting and directional solidification. *Transactions of Nonferrous Metals Society of China*, 2012, 2(22): 404–410. [https://doi.org/10.1016/s1003-6326\(11\)61191-6](https://doi.org/10.1016/s1003-6326(11)61191-6).
- [20] Liu S Q, Ding H S, Chen R R, et al. Microstructural evolution and mechanical properties of a Cr-rich β -solidifying TiAl-based alloy prepared by electromagnetic cold crucible continuous casting. *Materials Science and Engineering: A*, 2020, 798: 140205. <https://doi.org/10.1016/j.msea.2020.140205>.
- [21] Luo Q, Wang L, Zhou Z R, et al. The relationship between the thermophysical properties of TA16 and TA17 titanium alloys and temperature. *Journal of Mechanical Engineering Materials*, 2009, 10(33): 30–32, 67. (In Chinese)
- [22] Yang J R, Chen R R, Ding H S, et al. Numerical calculation of flow field inside TiAl melt during rectangular cold crucible directional solidification. *Transactions of Nonferrous Metals Society of China*, 2012, 1(22): 157–163. [https://doi.org/10.1016/s1003-6326\(11\)61155-2](https://doi.org/10.1016/s1003-6326(11)61155-2).
- [23] Ding X F, Zhang L W, He J P, et al. Numerical and experimental study on peritectic transition in TiAl-Nb alloys. *Computational Materials Science*, 2019, 158: 333–339. <https://doi.org/10.1016/j.commatsci.2018.11.046>.
- [24] Ding H S, Nie G, Chen R R, et al. Directional solidification of TiAl-W-Si alloy by electromagnetic confinement of melt in cold crucible. *Intermetallics*, 2012, 31: 264–273. <https://doi.org/10.1016/j.intermet.2012.07.018>.