Research on High-performance Precision Casting Technology for Large and Complex Titanium Alloys

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Abstract: With the continuous development in the field of high-end equipment, lightweight, ultra-pure, large-scale, complex, high-performance has become the basic requirements of structural materials applied in the field of cutting-edge engineering, and the traditional production and preparation processes have been challenged. In this paper, we will start from the large melting volume of titanium alloy purity melting and precise control of composition, large complex thin-walled precision complete forming and high-performance dense solidification organization control, high-strength heat-resistant and highly stable type / core preparation and deformation control of thin-walled complex cavities and large-capacity vacuum melting and casting equipment, the development of four key technologies, and finally, on the development trend of titanium alloy casting technology (such as: large-scale, digitalization, intelligence and low-cost, etc.) to carry out Summarize.

Keywords: Titanium alloys, Precision Casting, Large-scale, Complex

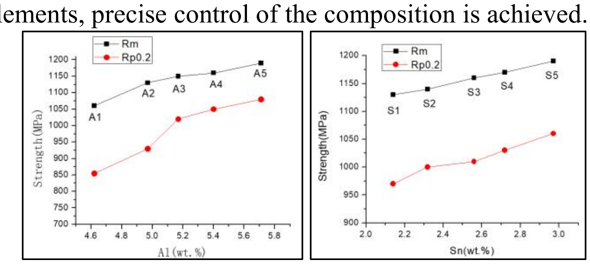
1 Introduction

Titanium alloys have become crucial structural materials for high-end equipment in aerospace, aviation, and marine fields due to their superior properties such as high specific strength, low density, low thermal conductivity, low coefficient of thermal expansion, excellent corrosion resistance, and high/low-temperature performance[1]. In the aviation field, titanium alloys are mainly used in aircraft structural parts, aircraft engine structural parts, and aviation fasteners, etc. In the aerospace field, titanium alloys are mainly used in carrier rocket engines, satellite antenna brackets, spacecraft cabin frames, etc., with their usage continuing to rise[2, 3].Currently, the global demand for lightweight titanium alloy castings exhibits a diversified and high-standard trend, particularly focusing on requirements for ultra-large sizes, extreme weights, intricately complex structures, extreme thin-wall designs, and exceptional service performance. Specifically, there is an urgent market need for titanium alloy castings capable of producing large outer contour structures exceeding 4 meters in size while meeting load-bearing requirements of over 2 tons. These castings must also possess extremely complex structures featuring multiple flow channels and narrow, multi-layered twisted cavities to cater to demanding operating conditions. Furthermore, challenges arise from designing large-scale extreme thin-wall structures with thicknesses approaching 1mm, necessitating rigorous technological advancements. In terms of performance, these titanium alloy castings must exhibit exceptional service characteristics, including high strength, resistance to high and low temperatures, and wear resistance, ensuring stable operation in various extreme environments.

2 Key technology

The key technologies of high-performance precision casting of large-scale complex titanium alloys face four major engineering challenges: ① large-capacity titanium alloy purification melting; ② high-precision forming of large-scale complex structures; ③ metallurgical defect control of large-scale complex castings; ④ development of ultra-large-capacity vacuum melting equipment. The following methods are adopted to solve the above problems:

1) Large-capacity titanium alloy purification melting and precise composition control: For Ti-6Al-4V and Ti-5Al-2.5Sn alloys, by studying the influence of fine-tuning the main components (Al, Sn, V, etc.) and interstitial impurity elements (C, N, H, O) on the macro- and micro-structures, cryogenic tensile properties, and impact properties of titanium alloys, the mechanism affecting the cryogenic mechanical properties is clarified. An ultra-low interstitial phase cast titanium alloy is invented to achieve a reasonable match between strength and toughness at -253°C. Meanwhile, a large-capacity titanium alloy vacuum levitation + consumable arc hybrid melting technology is developed. By studying the influence of levitation melting process on alloy elements and the effect of levitation melting times on composition purification, the change mechanism is clarified. By adjusting the melting process, compensating for element burnout, and adding trace elements, precise control of the composition is achieved.



(a) (b)

Figure 1:(a)The Effect of Al Element on the Properties of Ti-5Al-2.5Sn Alloy, (b) The Effect of Sn Element on the Properties of Ti-5Al-2.5Sn Alloy

2) Precision integral forming of large-scale complex thin-walled structures and control of high-performance dense solidification structures: High-precision investment casting patterns are prepared through photosensitive resin laser forming technology. Through research on the preparation technology of composite rare earth oxide ceramic shells, the thermophysical and chemical interaction laws between the shell surface and titanium melt are discovered. New processes such as yttrium rare earth composite surface layers, anti-back-dissolution binders, and flexible reinforcement are developed to solve problems such as interface contamination, mold shell deformation, and thermal shock cracking during pouring. This enables high-precision, high-stability, and high-cleanliness preparation of the mold shell. Applying this technology, large-scale thin-walled frame titanium alloy castings such as aircraft wings and carrier rocket grid frames have been developed, with the largest dimension exceeding 2700mm. The pollution layer thickness is ≤ 6μm, the dimensional accuracy is CT6-7 grade, and the roughness Ra is ≤3.2μm.

3) Preparation of high-strength, heat-resistant cores/molds and deformation control of thin-walled complex cavities:By studying the influence of mold thermal properties on the filling and solidification processes of titanium alloys, a low-thermal-conductivity, high-stability coating for graphite molds is invented. This addresses the issues of insufficient filling capacity caused by graphite chilling and graphite carbon contamination, effectively improving the forming quality of complex thin-walled titanium alloy structures. It solves the challenges of controlling the solidification rate in structures with large wall thickness differences and variable cross-section flow channels, overcomes the difficulties in forming and cleaning extremely narrow structures, and achieves precise forming of complex narrow cavities with a maximum size of 3.6m and a maximum single-piece weight exceeding 2000kg.

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4) Development of Large-Capacity Vacuum Melting and Casting Equipment: A mathematical-physical model for high-power vacuum arc melting is established, and components such as a double-chamber U-shaped furnace body, flexible centrifugal mechanism, high-conductivity electrodes, and a coaxial symmetric potential trap arc stabilization device are developed. This achieves arc fluctuation suppression and automatic adjustment, breaking through the challenges of pressure resistance, vibration resistance, and explosion-proof capabilities of large vacuum chambers. A 3-ton titanium melting capacity, 4-meter internal cavity ultra-large vacuum consumable crust melting and casting furnace is developed and manufactured. Through technological breakthroughs in high-power/high-frequency induction power supplies and the development of large-capacity cold crucibles, issues such as multi-station power interference and suspension matching effects are resolved. The world's first 100kg suspension furnace is developed, achieving high-homogeneity, high-purity melting and pouring of titanium alloys.

(a) (b)

Figure 2:(a)3tTitaniumArc Self-consuming Skull Melting Furnace, (b)100kg Titanium Vacuum Magnetic Suspension Melting Furnace

3 Development trend

Titanium alloys hold significant application prospects in high-end equipment fields such as aviation, aerospace, and national defense weapons. The author believes that the development trends of titanium alloy casting technology mainly focus on: ① pushing the limits of casting equipment technology; ② integrated manufacturing through multi-process and multi-technology combinations; ③ digitization and intelligentization of the casting process; and ④ green and low-cost manufacturing