Study on the Counter Gravity Adjusted Pressure of Large and Complex Thin-Wall Ni-Based Superalloy Components

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Abstract: Counter-gravity casting (CGC) is a widely adopted material processing technique in metals due to its notable benefits, including enhanced filling behavior, reduced defect occurrence, and elevated mechanical properties. It plays a pivotal role in fabricating intricate, high-quality components. Casting experiments and multi-scale numerical simulations were conducted to examine the microstructure characteristics of K4169 nickel-based superalloy casting with varying cross-sections during the investment casting process. First, microstructure analysis was conducted on the casting using scanning electron microscopy (SEM) and electron backscatter diffraction (EBSD). Moreover, the Cellular Automaton Finite Element method was employed to study the pressure on the dendrite growth and filling behavior in the thin-wall structure. The experimental results revealed that the samples fabricated by counter gravity adjusted pressure investment casting perform finer microstructure and superior mechanical properties. Recently, the CGC was applied to producing large, thin-wall Ni-based superalloy components. Compared to traditional gravity casting, the filling speed, holding pressure, and solidification rate during CGC can be controlled. With a high filling pressure, the defects in the solidification microstructure decreased, and the strength and ductility improved. The large-size CGC facility for large and complex thin-wall Ni-based superalloy components was designed and fabricated in our group; moreover, some representative productions with high quality were successfully made by the large-size CGC facility.

Keywords: Conter gravity adjusted pressure investment casting, K4169 alloys, Microstructure, mechanical properties

1 Introduction

Counter-gravity Nickel-based superalloys have a good combination of performance at high temperatures [1-2], making them widely used in hot-end components, such as aero-engines and gas turbines [3]. Most of these castings are Al, and Mg alloys, which have lower densities, casting temperatures, and narrower solidification ranges than superalloys. Due to these differences in physical properties, the fabrication of superalloy castings is more challenging because of the back pressure brought by the Laplace effect and higher requirements for equipment caused by the high casting temperature. The study studied the filling behavior, microstructure and mechanical properties of K4169 fabricated by counter gravity adjusted pressure investment casting (CG-APC). The results indicated that the K4169 alloy fabricated by CGAPC exhibited superior mechanical properties compared to the K4169 alloy fabricated by gravity casting. These results could be attributed to the forced convection imposed on the dendrites during filling and solidification processes, which was also numerically studied. The purpose of this investigation is two-fold: (1) to investigate how the forces convection affects the microstructure and mechanical properties; (2) to gain a deeper understanding of the dynamics of the melt pool, which can lead to improvements in CG-APC fabricated Ni-based superalloys in industry.

2 Experimental procedure

The raw material used in the casting experiments was the as-cast K4169 nickel-based superalloy. The investment casting experiments were conducted. The mold shell was preheated to 850 ℃ and held for 3hours in a resistance furnace. 5kg of K4169 alloy was melted in a vacuum induction furnace. The preheated mold shell was placed in a vacuum chamber, and the pouring temperature was approximately 1500 ℃. The specimens were machined, ground, and corroded using a ratio of $CuSO_2$: HCl: H_2SO_4: = 30: 100: 7 and a corrosion time of 10 seconds. The microstructures of the specimens were analyzed using optical microscopy and electron microscopy.

3 Result and discussion

Numerical Simulation

In order to study the pressure on the dendritic growth during the thin-wall structure, the simulation on different pressure on the convection and dendritic growth was performed, as shown in Fig. 1. The results show that the dendrite growth from crucible wall to the center due to the temperature gradient. Meanwhile, with the melt flow up which may break the dendrite and even remelt it. For a 5 kPa/s pressure, the dendrite tips lap joint together at 0.8 s. For a higher 7 kPa/s pressure, the dendrite tips lap joint together at 1.1 s. The simulation results demonstrated that the dendrite tips lap joint can be restrained for a higher-pressure during counter-gravity casting, which can decrease the porosity at the end of solidification period.

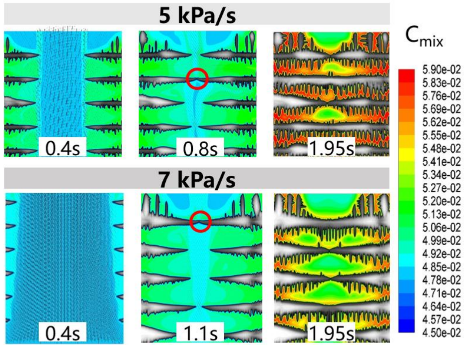

Fig. 1 Dendrite evolution in thin-wall structure with various pressure during counter-gravity casting.

Moreover, the simulation to predict the solid phase fraction and defects was performed by ProCAST, as shown in Fig. 2. Comparing two methods, the final solidification area of the casting is located near the upper inner wall surface connected to the main runner. Due to insufficient shrinkage, there are certain defects in this area. However, by using the counter gravity adjusted pressure investment casting, the shrinkage defects in the thin-walled area have been significantly decreased. Due to the effect of pressure, the shrinkage defects in the lower thin-walled area have been significantly eliminated, and the effect of pressure closer to the gate is more apparent.

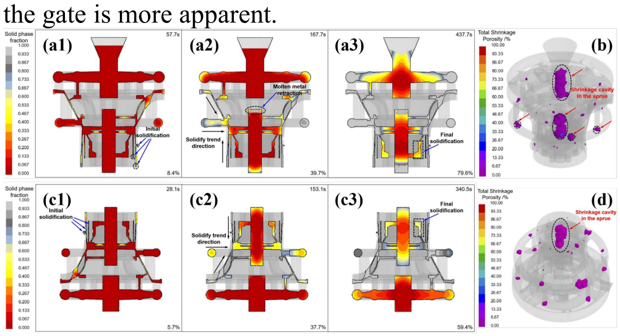

Fig. 2 Comparing the solid phase fraction distribution at different time points (a and c) and defect distribution (b and d) during traditional gravity casting (a-b) and counter gravity casting (c-d) by numerical simulation.

Microstructure and mechanical property

Moreover, the microstructure of K4169 alloys for two casting methods was analyzed as shown in Fig. 3. It is obviously that the grain size is smaller by using counter gravity adjusted pressure investment casting. This may be attributed to the remelt of dendrite due to the melt flow during forced convection, the fragments would a new nucleation and refine the microstructure. For this reason, it is easy to associate with that the samples fabricated by counter gravity adjusted pressure investment casting can perform higher mechanical property. Compared with the gravity process, the room temperature tensile yield strength of the alloy has increased from 487.5MPa to 533.4MPa, and the ultimate tensile strength has increased from 678.7MPa to 858.7MPa. The plasticity has decreased to a certain extent, from 26.1% to 13.3%.

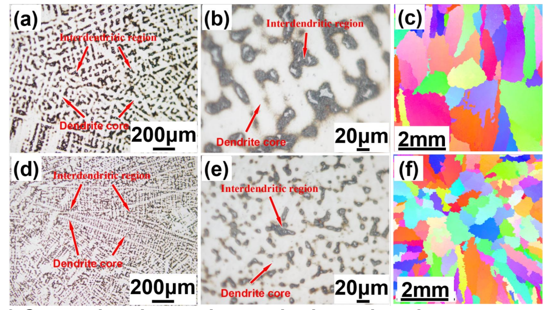

Fig. 3 Comparing the casting methods on the microstructure and grain morphology of as cast K4169 alloys: (a)-(c) Gravity investment casting; (d)-(f) Counter gravity adjusted pressure investment casting.

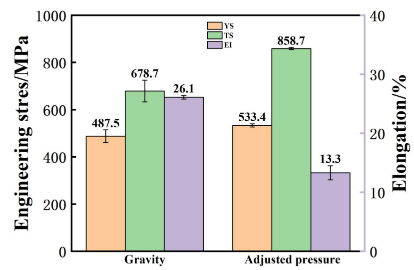

Fig.4 Room temperature tensile properties of as-cast K4169 alloy under different casting processes

4 Conclusions

The filling solidification process of the complex thin-walled casting of K4169 alloy was analyzed by numerical simulation for gravity precision casting and pressure regulating precision casting. Present results indicate that pressure-controlled precision casting has the characteristics of smoother filling speed, better cooling effect, and fewer pore defects for complex thin-walled parts. In addition, the use of pressure regulating precision casting technology can reduce the secondary dendrite spacing of the alloy. The average grain size and improved element segregation of the alloy result in excellent tensile properties at room temperature.

References

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