

Postprint of Optimization of Complex Stainless Steel Impeller Investment Casting Process

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Abstract

The complex geometry and thin-wall structure of stainless steel impellers predispose investment-cast stainless steel impeller castings to defects including shrinkage porosity and misrun. These defects are intimately associated with the mold filling and solidification processes of the casting. This investigation utilizes ProCast software to numerically simulate the impeller's mold filling and solidification behavior, with subsequent experimental validation. The results demonstrate that a pouring temperature of 1550°C combined with a pouring velocity of 0.75 m/s promotes complete filling of the impeller casting and precludes misrun defects. Nevertheless, even optimal pouring parameters cannot prevent shrinkage porosity formation within the impeller casting. Based on the structural characteristics of the impeller casting, the strategic placement of chills within the hollow section effectively eliminates shrinkage porosity defects, achieving maximal defect removal when the chill height equals one-third of the casting's internal height.

Full Text

Preamble

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Optimization of Investment Casting Process for Stainless Steel Impeller with Complicated Geometry

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Abstract

Due to the complicated geometry and thin walls of stainless steel impellers, investment casting often produces defects such as shrinkage porosity and incomplete filling. These defects are closely related to the mold filling and solidification processes. This study employs ProCast software to numerically simulate the filling and solidification processes of an impeller casting, with results validated against experimental data. The findings indicate that a pouring temperature of 1550°C and a filling velocity of 0.75 m/s facilitate complete mold filling and prevent incomplete filling defects. However, even with optimal pouring parameters, shrinkage porosity defects cannot be entirely avoided. Based on the structural characteristics of the impeller casting, placing chill blocks in the hollow central region effectively eliminates shrinkage defects. When the chill height equals one-third of the internal cavity height, the defect elimination is most effective, yielding high-quality castings.

Keywords: materials synthesis and processing, investment casting, stainless steel impeller, filling and solidification, casting defects

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Introduction

Impeller castings are critical components in large-scale equipment for shipbuilding, power generation, pharmaceutical, pump and valve, and transportation industries, significantly influencing overall equipment performance. Current impeller casting processes present considerable challenges, making this a longstanding research focus in the casting industry [1]. Investment casting of stainless steel impellers improves dimensional accuracy and reduces post-casting machining, yet defects such as shrinkage porosity and incomplete filling persist [2]. Research demonstrates that these defects are intimately linked to the filling and solidification processes during casting [3,4]. To address these issues, this study utilizes ProCast simulation software to model the filling and solidification of complex stainless steel impellers during investment casting. The simulations incorporate solidification during filling and fluid flow during solidification to accurately capture melt flow behavior and temperature field evolution, thereby identifying defect formation mechanisms and optimizing process parameters to achieve high-quality castings.

1. Mathematical Models

1.1 Filling Process Model

Mold filling of molten metal represents an unsteady, viscous flow of incompressible Newtonian fluid accompanied by unsteady heat transfer [5], described by continuity, momentum, energy, and volume-of-fluid equations [6].

Continuity Equation:

$$\frac{\partial u_x}{\partial x} + \frac{\partial u_y}{\partial y} + \frac{\partial u_z}{\partial z} = 0$$

where u_x , u_y , u_z are velocity components in the X, Y, Z directions.

Momentum Conservation Equation (Navier-Stokes): Turbulence is modeled using the standard k - ε model. The momentum equations are:

$$\frac{\partial u_x}{\partial t} + u_x \frac{\partial u_x}{\partial x} + u_y \frac{\partial u_x}{\partial y} + u_z \frac{\partial u_x}{\partial z} = -\frac{1}{\rho} \frac{\partial P}{\partial x} + \mu \nabla^2 u_x + g_x$$

$$\frac{\partial u_y}{\partial t} + u_x \frac{\partial u_y}{\partial x} + u_y \frac{\partial u_y}{\partial y} + u_z \frac{\partial u_y}{\partial z} = -\frac{1}{\rho} \frac{\partial P}{\partial y} + \mu \nabla^2 u_y + g_y$$

$$\frac{\partial u_z}{\partial t} + u_x \frac{\partial u_z}{\partial x} + u_y \frac{\partial u_z}{\partial y} + u_z \frac{\partial u_z}{\partial z} = -\frac{1}{\rho} \frac{\partial P}{\partial z} + \mu \nabla^2 u_z + g_z$$

where ρ is metal density, t is time, P is pressure per unit density, μ is kinematic viscosity, and g is gravitational acceleration.

Energy Conservation Equation:

$$\rho c \left(\frac{\partial T}{\partial t} + u_x \frac{\partial T}{\partial x} + u_y \frac{\partial T}{\partial y} + u_z \frac{\partial T}{\partial z} \right) = k \nabla^2 T$$

where c is specific heat, k is thermal conductivity, and T is temperature.

Volume Function Equation:

$$\frac{\partial F}{\partial t} + u_x \frac{\partial F}{\partial x} + u_y \frac{\partial F}{\partial y} + u_z \frac{\partial F}{\partial z} = 0$$

where F is the volume fraction ($F = 1$ for filled regions, $F = 0$ for empty space, $0 < F < 1$ for free surfaces).

1.2 Solidification Process Model

Solidification is calculated using the established nonlinear finite element method for transient heat conduction [7]. The nonlinear transient heat conduction equation is:

$$\rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left(k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(k \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left(k \frac{\partial T}{\partial z} \right) + q_v(x)$$

where $q_v(x)$ is the volumetric heat source from latent heat release during solidification.

Latent heat treatment methods include temperature recovery, equivalent heat capacity, and enthalpy methods [8,9]. Given the solidification characteristics of stainless steel and heat transfer features of investment casting, this study employs the enthalpy method by introducing enthalpy $H = \rho c(T)$.

1.3 Boundary Conditions and Parameters

Simulation accuracy depends critically on boundary conditions and thermophysical properties. The casting material is 304 stainless steel. For simplification, only the impeller casting is modeled with heat transfer boundary conditions applied at the mold boundaries: heat transfer coefficient of $500 \text{ W/m}^2 \cdot \text{K}$ and ambient temperature of 300°C .

Thermophysical properties of 304 stainless steel and investment casting parameters are listed in and .

1.4 Finite Element Meshing

The UG model was exported in IGES format and imported into ProCAST. After mesh repair in MeshCAST, a gmrst file was generated for preprocessing. To balance accuracy and computational efficiency, non-uniform mesh sizes were employed. The model dimensions are $338 \times 158 \times 146 \text{ mm}$ [Figure 1a: see original paper]. The final mesh contains 302,567 elements and 201,326 nodes [Figure 1b: see original paper].

2. Results and Discussion

2.1 Effect of Pouring Velocity on Mold Filling

The blade region is the thinnest and most challenging section to fill. Analysis focuses on how pouring velocity affects blade filling. At low velocities, while metal can enter the blades, the slow flow combined with stainless steel's high thermal conductivity causes premature solidification before the bottom blade regions fill, resulting in unfilled sections [Figure 2a: see original paper]. At high velocities, turbulent effects prevent complete filling of thin blade sections, causing incomplete filling defects [Figure 2b: see original paper]. Therefore, a moderate velocity of approximately 0.75 m/s achieves optimal filling [Figure 2c: see original paper].

2.2 Effect of Pouring Temperature on Mold Filling

Pouring temperature determines melt viscosity and thus filling capability. Low temperatures increase viscosity, impeding filling of thin blade sections and causing defects [Figure 3a: see original paper]. At 1500°C , incomplete filling occurs,

while temperatures above 1550°C produce complete castings. However, excessive temperatures cause coarse grain structure and degrade mechanical properties. Consequently, 1550°C was selected as the optimal pouring temperature.

2.3 Effect of Casting Process on Solidification

Based on filling analysis, parameters of 1550°C pouring temperature and 0.75 m/s velocity were selected to avoid incomplete filling. Solidification simulation yields temperature contours and shrinkage porosity distribution maps. Despite optimal filling parameters, non-uniform wall thickness creates hot spots in thick sections, generating shrinkage defects [Figure 4: see original paper]. The experimental casting [FIGURE:4b right] shows clear shrinkage porosity when sectioned. Thus, process improvement is required. Given the impeller's structural features, placing chill blocks in the central hollow region was proposed to eliminate shrinkage defects.

[Figure 5: see original paper] illustrates three chill placement configurations. Solidification simulations with chills are shown in [Figure 6: see original paper]. When the chill extends through the entire internal cylinder, it interrupts feeding from the gating system, causing final solidification in the thickest blade-cylinder junction where shrinkage defects form [Figure 6a: see original paper]. Since this region experiences high stress, defects here pose safety risks, making this configuration unsuitable. When the chill occupies two-thirds of the internal cylinder height, feeding interruption shifts downward but final solidification remains in the thickest section, still producing defects [Figure 6b: see original paper]. When the chill height is one-third of the internal cylinder, fully covering the thickest region, final solidification shifts upward to the cylinder near the gating system [Figure 6c: see original paper]. As this region experiences lower stress, defects there do not compromise performance. Results demonstrate that while chills cannot completely eliminate shrinkage porosity, proper chill height effectively relocates defects to non-critical areas, meeting service requirements.

[Figure 7: see original paper] shows the improved investment casting process with chill height at one-third of the internal cylinder. Ultrasonic non-destructive testing confirms the casting is sound and free from porosity defects.

Conclusions

1. ProCast simulations of stainless steel investment casting reveal that appropriate pouring temperature (1550°C) and velocity (0.75 m/s) facilitate complete mold filling and prevent incomplete filling defects. However, even optimal parameters cannot prevent shrinkage porosity in impeller castings. These findings align with experimental results.
2. Placing chill blocks in the central hollow region eliminates shrinkage defects in critical areas. When chill height equals one-third of the internal

cylinder height, shrinkage porosity is effectively relocated from critical regions, yielding high-quality impeller castings.

References

1. YANG Bingbing, *The Processes Research on Large Complicated Stainless Steel Impeller by Melting Modules-Sand Mould Composite Casting*, PhD Dissertation, Xi'an University of Technology (2007).
2. JIANG Buju, *Investment Casting*, (Beijing, Machinery Industry Press, 2004) p.309.
3. JIE Feng, ZHENG Fusheng, WANG Gang, DAI Penglong, ZHANG Jie, Numerical simulation of solidification process for impeller investment casting based on ProCAST, *Hot Working Technology*, 42(7), 55(2013).
4. SHI Yuanjin, ZHANG Zhanchang, LIU Rui, Shrinkage defects improvement of steel casting investment casting based on flow field optimization, *Foundry*, 163(9), 910(2014).
5. YAN Kai, LIU Hanwu, DU Yunhui, ZHANG Hui, Dynamic simulation of the filling process and temperature field analysis of Al-4%Cu alloy in solidification, *Foundry Technology*, 30(2), 510(2009).
6. YAO Binye, MAO Hongkui, XU Hong, MENG Xianbao, Status and development trend of numerical simulation of flow field in casting process, *Foundry Technology*, 33(10), 1211(2012).
7. XIONG Shoumei, XU Qingyan, KANG Jinwu, *Casting Process Simulation Technology*, (Beijing, Machinery Industry Press, 2004) p.39.
8. DENG Kang, SUN Huanchun, Method for latent heat treatment in solidification calculation of heavy castings, *Journal of Dalian University of Technology*, 32(5), 531(1992).
9. LI Donghui, GAO Yunbao, XIN Qibin, QIU Yiqing, LIU Xianghua, WANG Guodong, The processing method and application study for latent heat releases in alloy castings, *Foundry*, 53(12), 1005(2004).

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