Preventing shrinkage defects in investment casting of SUS310 stainless steel feather keys

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Abstract. In this study, we employed computer-aided engineering (CAE) analysis technology to examine the casting scheme used in the fabrication of SUS310 stainless steel feather keys. Our focus was on the evolution of thermodynamic behavior and the formation of porosity defects in the casting scheme. Our results provide a valuable reference for the elimination of defects and the formulation of design solutions aimed at reducing the time and costs associated with trials and production development.

1. Introduction

Double-headed round keys, also known as feather keys, are used in power transmission mechanisms, such as pulleys, gears, and cranks, to prevent rotation between two mechanical parts. The materials used in these keys should be resistant to compression as well as shear forces. Internal defects in these keys could reduce their service life. The lack of a realistic model pertaining to the flow and solidification of metal within a mold cavity means that casting manufacturers must develop new products via trial and error [1,2]. This also prevents them from exerting control over the formation of shrinkage cavities or pores in the castings [3,4]. Computer-aided engineering (CAE) analysis programs and related techniques have been developed to reduce casting defects while streamlining the early and trial production phases of development [5,6]. You et al. [7] employed AnyCasting to simulate the filling and solidification of complex magnesium alloy housings for die casting, with the aim of reducing the shrinkage cavity and porosity defects. Kuo et al. [8] sought to enhance the structural integrity and effective lifespan of impellers by applying mold flow analysis to the design of gating systems for 17-4PH stainless steel enclosed impellers. Their research proved highly effective in reducing the shrinkage and porosity defects common in investment casting. Huang and Chen [9,10] conducted computer-aided modeling in conjunction with experimental verification to optimize the investment casting of rotors. They assessed the probability of defect formation during casting based on the retained melt modulus incorporated with the Niyama criterion model. Huang et al. [11] employed mold flow analysis to optimize the design of the pouring system to achieve casts of high quality. In this paper, we used the techniques of metallic mold flow analysis to trial production runs of high-value stainless steel feather keys for using in critical purposes of transmission power. Optimizing the design of the gating system and various process parameters greatly promoted casting quality and shortened the production line development time.
2. Experimental and numerical methods

2.1. Gating system design and process parameters for initial scheme
In this study, we examined the gating system used in the production of double-headed round keys. The initial scheme employed a horizontal runner (as shown in Fig. 1(a)) to increase yield and minimize unnecessary waste. SUS310 stainless steel was used as the casting material and zircon sand was used in the ceramic shell. The other relevant process parameters were as follows: sintering temperature (1,050 °C), casting temperature (1,600 °C), shell thickness (6.5 mm), and pouring time (6 s).

2.2. Fundamentals of metal mold flow analysis
The solidification of castings is generally characterized using transient thermal analysis, wherein the temperature field, time domain, and space domain, are partially differentiated to develop a finite element format, based on the fact that the time and space domains cannot be coupled directly. The governing equations of thermodynamics are as follows [12]

2.2.1. Continuity equation. Here, the law of the conservation of mass refers to the continuity equation of liquid metal. This indicates that within the simulation domain, increases in the mass of the liquid metal are equal to the mass of the liquid flowing from the surrounding region into the simulation domain.

\[
\frac{\partial \rho}{\partial t} + \mathbf{\nabla} \cdot (\rho \mathbf{u}) = 0
\]  

(1)

Where \( \rho \) denotes the density of the liquid, and \( \mathbf{u} \) denotes the flow velocity vectors.

2.2.2. Energy equation
\[
\rho \frac{\partial T}{\partial t} + \rho \mathbf{u} \cdot \nabla T - \nabla \cdot (k \nabla T) - q = 0
\]  

(2)

Where \( t \) denotes time, \( k \) is the coefficient of thermal conductivity, \( T \) is the thermodynamic temperature, \( q \) symbolizes the volume heat flux, and \( H \) is enthalpy.

2.2.3. Navier-Stokes equations
\[
\rho \frac{\partial \mathbf{u}}{\partial t} + \rho \mathbf{u} \cdot \nabla \mathbf{u} = -\nabla p + \mu \nabla^2 \mathbf{u} + \mathbf{f}
\]  

(3)

Where \( \mu \) is the dynamic viscosity of the molten flows, \( p \) stands for pressure, and \( \mathbf{f} \) represents body force of particles.

Fig. 1. Initial casting scheme for double-headed round keys: (a) gating system; (b) filling state at time of 2.8 s; (c) solidification state at time of 140 s; the probability of forming shrinkage cavities (d) and porosities defects (e).
3. Results and discussion

3.1. Results of initial scheme analysis
Casting quality largely depends on the filling of the mold and solidification of the liquid metal. In this study, we employed the AnyCasting software package to determine the order in which the liquid metal fills the mold cavities and solidifies. We also sought to characterize air entrapment and turbulent flow conditions. Figure 1(e) shows severe shrinkage porosity in the center of keys fabricated using the initial scheme. We speculate that the shrinkage pores are associated with physical hot spots at the ingate of keys, which formed during pouring. Figure 1(c) shows that the solidification sequence resulted in a short pour from the ingates, which resulted in the formation of shrinkage pores. The round key in the middle was the least susceptible to defects because the runner helped to maintain it at a higher temperature while providing sufficient feed. During pouring, the liquid metal first filled the cavities below the ingates before flowing to the sides (as shown in Fig. 1(b)). This greatly hindered the filling process and thereby increased the likelihood of shrinkage defects.

3.2. Analysis of the improved scheme
Severe defects in the center of the keys indicated the need for improvements in the design scheme. As shown in Fig. 2(a), we adopted a single vertical sprue in the revised scheme, while retaining the process parameters used in the initial scheme. The revised scheme helped to maintain the melt modulus, which in turn significantly reduced the likelihood of forming shrinkage pores (Fig. 2(e)) and nearly eliminated the formation of shrinkage cavities (Fig. 2(d)). Overall, the revised scheme greatly reduced the probability of shrinkage defects. The filling sequence of the revised scheme (Fig. 2(b)) and solidification sequence (Fig. 2(c)) also revealed substantial improvements over those of the initial scheme. An increase in the likelihood of shrinkage defects in the bottom key can be attributed to the fact that the ingate is too close to the bottom runner. Thus, liquid metal flowing into the runner ran back and forth continuously between the bottom runner and the ingate, resulting in turbulent flow. Increasing the length of the bottom runner or moving up the wax piece on the right side should reduce the probability of shrinkage pores forming at the bottom.

![Fig. 2. Improved casting scheme for double-headed round keys: (a) gating system; (b) filling state at time of 2.3 s; (c) solidification state at time of 223 s; the probability of forming shrinkage cavities (d) and porosities defects (e).](image)

3.3. Flow velocity analysis for initial and improved schemes
Defect formation is associated with pour velocity; i.e., higher velocity causes turbulent flow in the mold cavities, which in turn creates defects. Thus, reducing pour velocity should decrease the
probability of defect formation. In the initial scheme, the maximum velocity detected by Sensor 01 was 140 cm/sec, whereas the maximum velocities detected by Sensors 02 and 03 were 72 cm/sec, as shown in Fig. 3(b). In the revised scheme, the maximum velocity of approximate velocity of 82 cm/sec was detected by Sensor 01, as shown in Fig. 4(b). The velocities detected by the other sensors were all below 70 cm/sec. The revised scheme clearly reduced the pour velocity, which resulted in the formation of fewer defects.

Fig. 3. Sensors in initial scheme (a) locations of sensors; (b) velocities detected by sensors.

Fig. 4. Sensors in the improved scheme (a) locations of sensors; (b) velocities detected by sensors.

4. Conclusion
This study examined the evolution of thermodynamic behavior and the formation of porosity defects in casting systems. Our results provide a valuable reference for the formulation of schemes aimed at eliminating defects, while reducing the time and expense of trials and production development. The revised scheme in this study did not eliminate all defects; however, it greatly reduced the likelihood. A comparison of Figs. 2(d) and 1(d) illustrates how the revised scheme outperformed the initial scheme. Figs. 3(d) and 4(b) show how the revised scheme reduced the flow velocity and with it the turbulent flows associated with higher velocities. The high likelihood of defects forming in the bottom key can be attributed to the fact that the ingate is too close to the bottom runner, such that liquid metal flowing into the runner flows back and forth between the bottom runner and the ingate, resulting in turbulent flow. Lengthening the bottom runner or moving up the wax piece on the right side should reduce the likelihood of turbulent flow.

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