Gating System Design of Investment Casting for SUS316 Spray Nozzle

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Abstract. Spray nozzles operate in harsh conditions with heat, corrosive substances, and high liquid pressure, which can easily cause corrosion and cavitation in the nozzle structure and threaten the safety of users. To reduce defects occurring during the casting process of spray nozzle and increase their service life, this study applied mold flow analysis to the casting process of a SUS316 stainless steel spray nozzle. We improved the configuration of the gating system, added water-cooling to the improved scheme, and examined the resulting filling and solidification conditions of the molten metal in the mold cavity. We employed the Niyama criterion to predict the probabilities of shrinkage defect formation in the spray nozzle and improve defect formation, thereby effectively lengthening the service life of the spray nozzle and increasing product quality.

1. Introduction
Casting dates back thousands of years. New developments occur every day in industrial technology, and with them are rising standards in workpiece quality. Correcting defects in workpieces to reach specifications has become a common goal in the entire casting industry [1-4]. To improve workpiece quality and yield while reducing personnel costs, a number of researchers have developed computer-aided engineering (CAE) software technology to increase the accuracy of defect predictions in mold flow analysis with the aid of software [5-8]. Most of the casting manufacturers in Taiwan search for optimal casting schemes through trial and error. In the event of defects, they use welding to repair the defects. Figure 1 displays a spray nozzle workpiece with severe shrinkage defects that welding cannot repair. Thus, finding a casting solution for spray nozzles is imperative. Wang et al. [9] employed ProCAST, a software program for casting process simulations, to simulate and optimize the investment-casting scheme for a thin-walled cylinder comprising aluminum alloy. They chose a bottom gating scheme, improved the gating system, and optimized the pouring parameters so as to prevent shrinkage defects and enhance workpiece quality. Zhou et al. [10] used the software Magmasoft to simulate the solidification processes of workpieces and determine where shrinkage pores and cavities are likely to appear in the workpiece. They added a cooling mechanism and risers and redesigned the casting parameters. Huang et al. [11, 12] used AnyCasting software to optimize various processing parameters for A356 aluminum alloy castings with the aim of minimizing shrinkage and porosity defects. Xie et al. [13] used ProCAST to analyze filling and solidification processes, predict shrinkage defects, and optimize the parameters of the pouring process. Their results indicated that the improved scheme could indeed reduce shrinkage defects. Zhen et al. [14] conducted numerical simulations of a wheel casting process and analyzed the temperature field of the solidification process and the causes of defect formation. Based on their
simulation results, they optimized the pouring system. Using AnyCasting, Zhang et al. [15] simulated the shrinkage defects that appear in the workpieces of steam generator supports in nuclear power plants with pressurized water reactors and optimized the process parameters. Huang et al. [16] used numerical software to simulate transient turbulence in a gating system in which the cross-sections were constricted using a V-shaped notch. Tian et al. [17] used AnyCasting to analyze the filling and solidification processes of ductile iron crankshafts and predict where shrinkage defects may appear. This study used metal mold flow analysis to analyze the design of a gating system for spray nozzle and revise process parameters. We also applied water-cooling to reduce the defect formation probability and distribution and improve the output value and yield.

Figure 1 Defects in spray nozzle casting: (a) location of defects in spray nozzle; (b) red arrow indicating surface at the bottom of the spray nozzle; (c) red arrow indicating the shrinkage defects after grinding.

2. Experimental and numerical methods

2.1. Parameter settings of investment casting process.

We used SUS316 stainless steel for the spray nozzle due to its resistance to heat, corrosion, acidity, and alkalinity. We input the physical properties of SUS316 into the formulas for mold flow analysis, including density ($\rho$) 7,930 kg/m$^3$, specific heat ($S$) 494 J/kg·K, latent heat ($L$) 290 KJ/kg, thermal conductivity ($K$) 14.39 W/m·K, liquidus temperature ($T_l$) 1,454 °C, and solidus temperature ($T_s$) 1,392 °C, as shown in Table 1.

We designed the process parameters of the initial scheme and the improved scheme based on the physical properties of the stainless steel spray nozzle. These process parameters included casting material, shell mold material, mesh number, ceramic shell temperature $T_{\text{ceramic}}$ (°C), casting temperature $T_{\text{casting}}$ (°C), pouring time $T_{\text{pouring}}$ (sec), ceramic shell thickness $\delta$ (mm), soaking depth $W_{\text{cooling}}$ (mm), gravity casting, and water soaking, as shown in Table 2.

Table 1. Thermophysical properties of SUS316 stainless steel [18].

| $\rho$ (kg/m$^3$) | $S$ (J/kg·K) | $L$ (kJ/kg) | $K$ (W/m·K) | $T_l$ (°C) | $T_s$ (°C) |
|------------------|-------------|-------------|-------------|-----------|-----------|
| 7930             | 494         | 290         | 14.39       | 1454      | 1392      |
Table 2. Process parameter design of gating system.

| Initial scheme | Improved scheme |
|----------------|-----------------|
| Casting material | SUS 316 |
| Shell mold material | Zircon sand |
| Mesh number | 3,000,000 |
| $T_{\text{ceramic}}$ ($^\circ$C) | 950 | 950 |
| $T_{\text{casting}}$ ($^\circ$C) | 1,580 | 1,580 |
| $t_{\text{pouring}}$ (sec) | 6 | 6 |
| $\delta$ (mm) | 6.5 |
| $W_{\text{cooling}}$ (mm) | None | 60 |

3. Results and discussion

3.1. Mold flow analysis of initial scheme

The filling conditions as the molten metal is poured into the mold cavity and the later solidification directions are major factors of workpiece quality. We therefore used AnyCasting to analyze the filling, solidification, poured short, and turbulent flow phenomenon, as displayed in Fig. 2. Figure 2(a) shows that the molten metal enters the ingate into the nozzle mold and quickly fills the bottom of the cavity. The molten metal collides with round opening of the nozzle, which creates splashes and turbulent flows during the filling process. Some air is trapped within the molten metal under the round opening, which disrupts the filling process. We can thus determine that the ingate is not positioned appropriately. The red circles in Fig. 2(b) indicate large portions of isolated residual melt at the bottom of the spray nozzle and below the round nozzle. Furthermore, no effective feeding channel is present near the ingate, so the feeding channel is broken during the solidification process, which leads to casting defects in the interior of the nozzle. Figure 3 presents the probability distributions of shrinkage defects resulting from the initial scheme. The color code shows that colors closer to dark red indicate higher probabilities of shrinkage defects, whereas colors closer to dark blue represent lower probabilities of shrinkage defects. Figure 3(a) displays the locations of the cross-sections in Figs. 3(b) through 3(d), which present the casting defects resulting from the initial scheme. As can be seen, the shrinkage defects all appear where the spray nozzle is thicker or where its geometric shape changes significantly. Due to the lack of consideration for the flow direction of the molten metal and feeding issues, the design of the initial scheme produced shrinkage defects in the casting structure.
Figure 2. Analysis of filling and solidification sequence in initial scheme of spray nozzle: (a) filling sequence \((t=1.80\text{ s})\); (b) solidification sequence \((t=316.0\text{ s})\).

Figure 3. Probability distributions of shrinkage defects resulting from initial scheme of spray nozzle: (a) locations of cross-sections displaying casting defects; (b) side sectional view of pattern tree; (c)-(d) top sectional view of spray nozzle.

3.2. Gating system design and mold flow analysis of improved scheme

After examining the simulation results of the initial scheme, we moved the spray nozzle into a horizontal position in the improved scheme so that the molten metal flows in from the side. To improve the flow of the molten metal and achieve good feeding at the sprue and the ingate, the ingate was also slanted along the tangent of round opening to prevent the molten metal from directly hitting the round opening, dividing into two flows, and entrapping air at the bottom. Finally, we hoped to use water-cooling to reduce the casting defects during solidification and attain a good temperature gradient. Figure 4 displays the design of the water-cooling method applied to the improved casting scheme. As shown in Fig. 5(a), the molten metal slowly flows upward and can more effectively avoid the round opening than in the initial scheme so that there are no turbulent flows. As shown in Fig. 5(b), the soaking the bottom of the spray nozzle can accelerate the cooling rate, improve the solidification directions so that they are steadier and smoother than those in the initial scheme, and reduce the probabilities of defect formation. As shown in Figs. 6(b) through 6(d), an appropriate soaking depth can effectively improve the temperature gradient during solidification and narrow down the shrinkage defect distributions. The results were significantly improved defect distributions and probabilities when compared to those in Fig. 3.
4. Conclusions
Moving the spray nozzle into a horizontal position so that the molten metal flows in from the side and slanting the ingate along the tangent of round opening in the improved scheme effectively prevent the molten metal...
from directly hitting the round opening and creating turbulent flows in the mold cavity as it did in the initial scheme. The thicker structure of the spray nozzle caused inadequate feeding during the solidification process, which led to defect formation. We thus added a water-cooling method with a suitable soaking depth to the improved scheme to solve the solidification defect problems, thereby producing a good temperature gradient and better solidification directions and process. The simulation results indicated significant improvements in the probability distributions of shrinkage defects in the improved scheme compared to those in the initial scheme. Water-cooling with a soaking depth of 60 mm was especially effective in improving workpiece quality and reducing defects in the cross-section and bottom of the spray nozzle.

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