Solidification forming and numerical simulation of 90° wear-resistant bend with high-vanadium cast iron

P H Chen¹, Y Zhang², R Q Li²*
¹School of Advanced Materials, Peking University Shenzhen Graduate School, Shenzhen 518055, P.R. China
²Light Alloy Research Institutes and State Key Laboratory of High Performance Complex Manufacturing, Central South University, Changsha, 410083, P.R. China
Email: liruiqing@csu.edu.cn

Abstract. Casting defects and macro-segregation had greatly affected the product quality. This paper revealed the effects of the arrangement of the gating system and superheat of molten iron on solid fracture, shrinkage porosity, cooling cracks, and effective stress-strain by simulation with the commercial software Pro-cast. Optimized parameters were used to produce a batch of 90° bends. The microstructure of an as-cast bend was characterized by scanning electron microscopy, and the service life of the bend was evaluated with delivery capacity. Simulation results showed that a 30° arranged location on the outer bend and superheat of 60 K comprised the optimized parameters. A batch of bends were produced with the optimized casting system and superheat, and in contrast to the simulation results. The simulation results were in accordance with the experimental results. In addition, the delivery capacity of high-vanadium cast iron, which was heat-treated using Quenching-partitioning process, was 26000 m³ and the economic costs were effectively reduced.

1. Introduction
Wear-resistant bends are regarded as thin-walled terminal products that can be used directly in mechanical equipment [1]. It is also widely used in various fields, such as metallurgy, mining, and civil engineering [2-4]. However, casting defects [5], including shrinkage porosity, cooling cracks, and macro-segregation, have been observed in the solidification process. Damage or destructive failure can lead to serious economic losses and environmental pollution when bend parts are used to connect pipes in a concrete pump truck with severe impact and wear of the ore. Therefore, the quality of bend parts should be ensured during production and subsequent processing.

The casting system and casting process parameters can play key roles in improving product quality. Compared with numerical simulation, the experimental method involves more costly testing and requires a long period of study [6, 7]. Optimized parameters, have recently been necessary for high-quality production, such as the casting system and casting process parameters. The location arrangement, shape, and dimension of the gating system and the riser, superheat, casting speed, as well as the strength, hardness, and machinability [8-10] of the material can be improved by reducing several defects, such as shrinkage porosity, cooling cracks, and macro-segregation [11-17]. By simulation and analysis, the parameters of the casting process have been optimized to obtain a high-quality product [12]. In addition, heat treatment can be crucial in improving the properties and service life of materials in subsequent processing. Heat treatment has been applied to change the microstructure and consequently enhance the...
hardness, compressive strength, and toughness [18] of materials, among others. A study by Hui Mei et al. indicated that the strength and toughness of C/SiC composites were enhanced by heat treatment [19].

In the present study, the commercial Pro-cast software was used to optimize the location arrangement of the gating system and superheat by simulating the temperature field, stress field, and casting defects of a 90° wear-resistant bend. And then the accuracy of the simulation was then verified.

2. Methodology

2.1. Geometric models

A new material has been reported in the literature [20], the chemical composition consist of 2.8% C, 3.0% Mn, 2.0% Cr, 1.5% Si, 1.5% Mo, 8.1% V and Balance of Fe. For 90° wear-resistant bend, the wear position is located at the lateral inner wall where impact wear and friction wear are simultaneously generated. Therefore, the lateral wall has a 10 mm maximum thickness, and the medial wall has a 5 mm minimum thickness, as shown in Figure. 1(a).

Table 1. The designed parameters of the casting system and their corresponding names

| Designed location | Angle(°) | Corresponding names |
|-------------------|----------|---------------------|
| Outside           | 15       | 15-O                |
|                   | 30       | 30-O                |
|                   | 45       | 45-O                |
| Middle            | 45       | 45-M                |
| Inside            | 45       | 45-I                |

Figure 1. Size of the bend and arrangement of the casting system.(a) Size of the bend; (b) 15-O; (c) 30-O; (d) 45-O; (e) 45-M; (f) 45-I.

In accordance with the enterprise requirement, defects (such as cracking, porosity, and loosening) should not be observed in the internal structure of the cast. Some reasons result in the development of these defects. Firstly, the melted temperature is lower than the appropriate temperature of fully melt and diffusion of alloy element, lead to alloy elements of the molten iron is not melted and diffused fully. Secondly, solidification feeding is incomplete because thickness of the bend is thin and cooling speed is quick in the process of casting. Thirdly, the casting system is inappropriately designed to impossibly exhaust all the air. Therefore, the casting system and casting process should be optimized to improve product quality. In this paper, the main designed locations of the casting system are shown as Figure. 1(b)-(f). And the corresponding names are presented in Table.1.
2.2. Governing equations and heat transfer

The continuity equation [21] can be expressed as (1), the transient Navier-Stokes equation [22] for momentum conservation as (2), and the energy conservation equation [23] for solidification as (3).

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \tag{1}
\]

\[
\nabla \cdot (\rho \mathbf{u} \mathbf{u}) = -\nabla p + \nabla \left[ \left( \mu + \mu_t \right) \left( \nabla \mathbf{u} + \nabla \mathbf{u}^T \right) \right] + \rho \mathbf{G} + \mathbf{S} \tag{2}
\]

\[
\rho \frac{\partial \mathbf{H}}{\partial t} + \rho \nabla \cdot (\mathbf{u} \mathbf{H}) = \nabla \cdot (k_{\text{eff}} \nabla T) + Q_L \tag{3}
\]

\[
H = h + \Delta H = h_{\text{ref}} + \int_{T_{\text{ref}}}^{T} C_p dT + L \cdot f_L 
\tag{4}
\]

\[
\rho \frac{\partial k}{\partial t} + \rho \nabla \cdot (\mathbf{n} \mathbf{k}) = \nabla \cdot \left( \mathbf{a} \left( \mu + \mu_t \right) \nabla k \right) + G_k + \rho \varepsilon + S_k 
\tag{5}
\]

\[
\rho \frac{\partial e}{\partial t} + \rho \nabla \cdot (\mathbf{u} \varepsilon) = \nabla \cdot \left( \mathbf{a} \left( \mu + \mu_t \right) \nabla e \right) + C_{\text{ke}} \frac{\varepsilon}{k} G_k - C_{\text{se}} \rho \varepsilon^2 + S_k
\tag{5}
\]

\[
\mathbf{S} = -\frac{(1 - f_i)^2}{f_i^2 + \beta} A_{\text{mush}} (u - u_{\text{cast}}) \tag{6}
\]

Where \(\rho\) = density; \(\mathbf{u}\) = velocity; \(\mathbf{G}\) = gravity vector; \(\mu\) and \(\mu_t\) are the dynamic and turbulent viscosities, respectively; \(Q_L\) = source term. \(H\) is the enthalpy of the materials and can be computed as the sum of sensible heat \(h\) and latent heat content \(\Delta H\), which can be expressed as (4). The 2 partial equations for turbulent energy \(\varepsilon\) and dissipation rate \(\varepsilon\) model can be expressed as (5); \(k_{\text{eff}}\) = effective conductivity; \(C_p\) = specific heat; and \(L\) = latent heat of the material. The momentum sink can be expressed as (6), and \(A_{\text{mush}}\) is the mushy zone constant.

2.3. Initial and boundary conditions

In this study, all physical parameters (density, thermal conductivity, viscosity, etc.) are calculated using the commercial Pro-cast software, and all of the parameters are variable value with heating/cooling temperature, as shown in Figure. 2. Sudden changes of density and thermal conductivity existed in the temperature of 770-800 °C because of the transformation of pearlite and ferrite. Meanwhile, sudden changes of density, thermal conductivity, enthalpy and poison’s ratio existed in the temperature of ~1210 °C because of the melting of cast iron. And the liquid temperature is 1363 °C, whereas the solid temperature is 1210 °C. Based on the previous experimental work, serious shrinkage porosity and cooling cracks can be formed in the filling process of faster/slower speed and unsteady state. Simultaneously, oxide inclusion can occur in the bend. For the casting quality, the flow rate of the inlet is 1.747 kg/s (casting weight of the casting system are about 10.5±0.5 kg, pouring time is approximately 6 s). In addition, the molding material is green sand, and the initial temperature is 30 °C. And according to the field test data of temperature and the calculation of heat transfer coefficient, The heat transfer coefficient is defined between metal and green sand/green sand and air, set to 750 and 7 W/m·K, respectively. In this paper, Superheat, which is great important parameter, should be optimized to improve the product quality. Superheat conditions are set to 20, 40, 60, and 80 °C.
Figure 2. Physical parameters of high-vanadium cast iron. (a) Density; (b) Conductivity; (c) Enthalpy; (d) Viscosity; (e) Poisson’s ratio; (f) Young’s modulus.

2.4. Verified experiment

The internal defects of 90° wear-resistant bend were examined by CD-90BX/μCT of Chongqing University. To prepare site-specific samples for industrial CT analysis with 4 mm×4 mm×4 mm and 1 mm×1 mm×1 mm at the junction between the riser and the bend (the defects are most easily formed at the position). CT was performed at 80 kV Voltage, 120 mA Current and 5 mm Focus Size for X-Ray source. And the microstructure was examined by scanning electron microscopy (SEM). SEM examination was conducted in a field-emission gun SEM (TESCAN, MIRA 3 LMH/LMU) operated at 15~25 kV. A batch of 90° bends are produced with the optimized casting system and process parameters, the bends were heat-treated using an optimized parameters of heat treatment which has been reported in the early work [20], and then these bends were installed in the concrete pump truck to do the life testing.

3. Result and discussion

3.1. Effect of the location arrangement of the gating system

Figure 3 shows several parameters of the casting system with varying degrees resulting from the arrangement of the gating system in the casting system. The solid fractures are 2.2%, 1.7%, 1.6%, 2.7%, and 2.9% when the filling fracture is 100%, as shown in Figure 3(a). The simulation results for effective stress-strain, shrinkage porosity, and cooling cracks are presented in Figure 3(b)-(e). The shrinkage porosity values of the 15-O and 30-O gating systems are less than those of the others. The cooling cracks and effective strain of the 30-O and 45-I gating systems are less than those of the other gating systems. However, the effective stress of the 30° gating system is the minimum, with a value of 482 MPa. Contrast the shrinkage porosity, cooling cracks, and effective stress-strain of 30-O gating system with 45-I gating system, as shown in Figure 4, the maximum shrinkage of 30-O gating system is only 1.98% and existed in the riser and gating system. But the maximum shrinkage of 45-I gating system is larger than 60% and existed in the outer of the bend, which is a main loading position. Meanwhile, the cooling cracks also existed in this position, and then early failure of the bend is caused by shrinkage porosity and cooling cracks. Therefore, the casting system of 30-I type is an optimized design scheme. However, the casting process is of great importance to improve the produce quality of bend. And in this paper, Superheat of molten iron, which is the important parameter when the pouring time is fixed as a constant, should be optimized except the optimization of casting system.
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3.2. Effect of superheat

Figure 5 shows the solid fracture with filling time during filling for 30-O type casting system. Molten iron starts to solidify when the filling time is 1s with different superheat of 20, 40, 60 and 80 °C. Solid fracture decreases gradually with an increase in superheat. The solid fracture reaches the maximum (3.95%) with a filling fracture of 100% when superheat is 20 °C. The molten iron with superheat of 80 °C starts to solidify when the filling time is 4s, and the solid fracture is 0.289% when the filling rate is 100%.

Figure 3. Defects and effective stress–strain of bend during solidification and cooling. (a) Solid fracture when the filling fracture is just 100%; (b), (c), (d), (e) Effective strain, effective stress, cooling cracks, and shrinkage porosity when the molten iron solidified completely.

Figure 4. Simulation results of shrinkage porosity, cooling cracks and effective stress-strain with 30-O and 45-I casting system at room temperature. (a), (b), (c), (d) Shrinkage porosity, cooling cracks, effective stress, and effective strain of 30-O casting system; (e), (f), (g), (h) Shrinkage porosity, cooling cracks, effective stress, and effective strain of 45-I casting system.
By the comprehensive comparison, the superheat of 60 ℃ is the optimized parameter, its bend has low shrinkage porosity, cooling cracks, and effective stress-strain, as shown in Figure. 6(a)-(d). And the values of shrinkage porosity, cooling cracks, and effective stress-strain are 1.85%, 5.58%, 482 MPa, and 5.7%, respectively. The shrinkage porosity and cooling cracks are mainly distributed in the riser, they have no impact on the performance of their application. Meanwhile, the maximum value of effective stress is only 482 MPa and existed in the inner/outer of the bend, which is not main loading position and the effective stress can be eliminated after heat treatment. In addition, fluidity and feeding of molten iron can be improved by increasing superheat, but for thin-walled bend, a closed thin-shell of the bend is formed because of greater thermal diffusion between the surfaces of the bend and molding sand, and thus resulting in the increasing of shrinkage porosity, the value is shown in Figure. 6(a-4).
3.3. Experimental verification

Figure 7 shows the industrial CT internal defects of the boundary location between the bend and the riser of 45-I type gating system. Many shrinkage porosity existed in the sample, meanwhile, Aggregation of alloy elements and precipitation of graphite are discovered, as shown in Figure 8. However, shrinkage porosity is not discovered obviously in the sample of 30-O type casting system and superheat of 60 °C. The experimental results revealed that the simulated results are in good agreement with the experimental results.

In addition, some bends after heat treatment, which is considered as a connect component for slurry pipelines, were installed in a concrete pump truck to do service-life testing. In contrast with high-chromium wear-resistant alloy, our designed high-vanadium cast iron and commercial high-chromium alloy exhibit delivery capacities of 26000 m³ and 5000-10000 m³, respectively. The service life is above 2.6 times that of a commercial high-chromium wear-resistant bend. Some reasons for excellent wear resistance of high-vanadium cast iron can be stated as follows. On the one hand, vanadium carbide is in-situ formed with vanadium and carbon element during the solidification. And it is well-known that hardness of materials is one of an important performance index of wear resistance, the micro-hardness of vanadium carbide is about 2800HV [24, 25], which is only inferior to the micro-hardness of silicon carbide. On the other hand, retained austenite, which is formed in the matrix after heat treatment of austenitizing-quenching-partitioning (Q&P) [26], enhance impact toughness of bend. Meanwhile, the strength is greatly improved because retained austenite is transformed into martensite under the loading condition(TRIP effect) [27].
Figure 8. Defects in the castings. (a), (b) Shrinkage porosity; (c) Segregation of alloying element; (d) Deposition of cementite and graphite.

Figure 9. Industrial CT 3D perspectives after the optimization of casting system and casting process.

4. Conclusion
1) The arrangement of the gating system in the casting system was optimized. Shrinkage porosity, cracked cooling, and effective stress-strain of 30° arrangement in the outer part of the bend are 1.98%, 4.3%, 482 MPa, and 5.6%, respectively. The values obtained are less than those of other arrangements.

2) Superheat of 60 K is considered the optimized parameter. A batch of bends with VCp reinforced Fe-matrix composites are produced by sand casting. The experimental results are in accordance with the simulated results.

3) Quenching and partitioning are adopted to improve the microstructure, mechanical property, and wear resistance of the 90° bend. In contrast with the commercial high-chromium wear-resistant bend, the delivery capacity of high-vanadium cast iron is 26000 m³, which decreased economic loss.

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