Application of 3-D numerical simulation software SRIFCAST to produce ductile iron castings

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Abstract: Based on a method using numerical simulation equations and their solution schemes for liquid metal flows and heat transfer during mold filling and the solidification process of casting, 3-D numerical simulation software SRIFCAST was created. This includes enmeshment of casting; velocity and temperature fields calculation; displaying iso-temperature lines; velocity vectors and 3-D temperature fields on a Windows 9x operating system. SRIFCAST was applied to produce sound castings of automobile and diesel engines, and also to connect with microstructure simulation for ductile iron castings.

Keywords: ductile iron castings; mold filling and solidification; velocity and temperature fields; microstructure modeling; numerical simulation software

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1. Introduction

Since the 1960’s, there have been 3 progressive periods for modeling and simulation of the technological process of castings. In 1988, 3-D temperature fields were calculated successfully during the solidification process of steel castings in many countries [1-4]. In 1995, 3-D velocity fields calculations of metal flow in mold filling were also achieved by advanced researchers [5-8]. From 1990 until now, the new task has been to model and simulate the microstructure and morphology of crystal grains. In order to calculate nucleation in a macroscopic mesh, undercooling at each microscopic cell, and the random number of nuclei by using the Monte-Carlo method, the 3-D velocity, temperature and concentration fields among meshes in the casting should be computed. Some researchers tried to simulate the 3-D microstructure of super alloy and ductile iron castings [9-11]. The trend is to combine macroscopic and microscopic simulations to optimize technological parameters of castings production. Lipinski, Bingqian

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\begin{align*}
\frac{\partial (\rho u_i)}{\partial t} + \frac{\partial (\rho u_i u_j)}{\partial x_j} &= \frac{\partial (\mu \frac{\partial u_i}{\partial x_j})}{\partial x_j} - \frac{\partial P}{\partial x_i} + \frac{\partial (\mu \frac{\partial u_i}{\partial x_j})}{\partial x_j} + \rho g, \\
\frac{\partial F}{\partial t} + \frac{\partial (F_u)}{\partial x_j} &= 0, \\
\frac{\partial (\rho T)}{\partial t} + \frac{\partial (\rho u_i T)}{\partial x_j} &= \frac{\partial (\mu \frac{\partial T}{\partial x_j})}{\partial x_j} + q_v, \\
\frac{\partial (\rho K)}{\partial t} + \frac{\partial (\rho u_i K)}{\partial x_j} &= \frac{\partial (\mu_k \frac{\partial K}{\partial x_j})}{\partial x_j} + G - \rho \varepsilon, \\
\frac{\partial (\rho \varepsilon)}{\partial t} + \frac{\partial (\rho u_i \varepsilon)}{\partial x_j} &= \frac{\partial (\mu_k \frac{\partial \varepsilon}{\partial x_j})}{\partial x_j} + c (f_1 C G - f_2 C_i \rho \varepsilon) / K.
\end{align*}
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3. Compile SRIFCAST software

3.1 3-D constructive solid geometry and its enmeshment of castings

For the numerical simulation software, the solid geometry of castings can be obtained by using many commercial softwares, such as Pro-E, UG, Solid-work, Solid-edge, Chinese CAXA and so on, which is shown in Fig. 1. The enmeshment code of castings was achieved, which fit for solid geometry file with STL form, then 8 materials, including casting, mould, core, riser, chill, insulating sleeve, cover flux and air will be assigned to mesh attribute. Displaying is shown all enmeshing and sectional enmeshment of bearing case casting by FDM in Fig.2 and Fig.3 respectively.

3.2 Vectors drawing and displaying velocity and temperature fields

For engineering analysis it is often necessary to draw vectors in a section of casting. Figure 4 shows velocity vectors and liquid metal distribution at 6 s in mold filling of an impeller casting by vacuum anti-gravity pouring. In the code reflecting scheme is adapted from numerical results to make figure on screen for displaying temperature, only the meshes filled fully by metal with a color are piled up on the screen. 3-D temperature fields in mould filling of a wheel casting are shown in Fig.5.
3.3 Drawing iso-temperature line in 2 dimensions

In order to predict shrinkage and V-type segregation defects, there is a function of drawing iso-temperature lines in a section of casting. Normally the numerical result indicates a temperature at the center of a mesh. The temperature at any node of the mesh can then be calculated from the temperature of 4 meshes around the node by the scheme of interpolation. The temperature at e, f, g, h node of mesh is $T_{i,j}$, $T_{i+1,j}$, $T_{i,j+1}$, respectively in Fig. 6. If there are some points of $T$ iso-temperature in the mesh, it must have intersection between $T$ iso-temperature line and mesh side. If there is a $T$ iso-temperature point at $ef$ side then

$$X_i = (T - T_{i,j}) \cdot \frac{\partial x}{\partial T_{i,j}}$$

(16)

In the same way, there is a $T$ iso-temperature point at $eh$ side then

$$Y_i = (T - T_{i,j}) \cdot \frac{\partial y}{\partial T_{i,j}}$$

(17)

for $fg$, $gh$ sides will judge $T$ iso-temperature point in $(i+1, j)$ and $(i, j+1)$ mesh respectively. After these calculations the coordinates of dots 1 and 2 are obtained. Using SRIFCAST software iso-temperature lines shows in Fig. 7, which is the Benchmark Test by B. Sirrel[15].

3.4 Setting up data base for thermal properties of casting materials

Based on measurements by TC-3000H-NC and HC-60 apparatus and some collection, a data base of thermal physical properties was established, in which there are heat conductivity, specific heat, thermal diffusivity and etc. from ambient temperature to 1400 °C for metallic materials of grey cast iron, ductile iron, carbon steel, chromium steel, manganese steel, austenitic stainless steel, super alloy, Al-Si and Al-Cu alloy, as well as molding materials of silica, chromite, zircon sands, coatings and etc.

4. Application of SRIFCAST software to produce ductile iron castings

4.1 Production of ductile iron castings for automobile.

This was done in cooperation with First Automobile Works. Their technicians made the solid geometry of a wheel casting using Pro-E software and transmitted the STL file to us by Internet. Then using SRIFCAST it was enmeshed as shown in Fig. 8 (a) and (b) respectively. The casting is divided into 3 parts, shown in Fig. 9. The moduli are calculated by the software, as $M_1 = 1.02$ cm for part 1; $M_2 = 1.91$ cm for part 2; $M_3 = 1.12$ cm for part 3, key module $M_5 = M_7 = 1.91$ cm, according to Cather principle transmitting modulus $M_T = 1.25$ cm. The riser modulus is $M_R = M_T = 1.25$ cm (original design is 1.62 cm), and the modulus of riser neck is $M_n = 0.6M_T = 0.75$ cm (original
design is 0.45 cm). If the riser is connected to the edge of part 1, there will be a shrinkage in part 2 because the feeding is not enough, if the riser is put on the edge of part 3, the problem is the same. It is best to connect the riser to part 2 after the casting has been turned through 180°.

4.1.2 Numerical simulation results
The simulated results of mold filling and the solidification processes of castings are shown in Fig. 10 and Fig. 11 respectively. The filling time for the mold is 15 s. This fits the design requirement. The solidification time is 24 min. for thick part of the casting, 0.5 min. for the in-gate, 24 min. for the riser, and 3.4 min. for the neck of the riser. But the solidification time for the riser neck should be 0.23 times of that for the thick part of the casting, 3.4/24=0.14 which is <0.23, so the riser neck is small. Improving the design will allow sound castings to be obtained.

4.2 Producing ductile iron castings by metallic mould for a truck’s diesel engine
Ductile iron castings produced by a metallic mold cooled by water have the advantages of a smooth surface, fine and uniform graphite distribution, good machining property, and high productivity, so it is often applied by Japanese companies. In order to understand its cooling pattern the mold filling and solidification processes of gear and guide pulley ductile iron castings are simulated. The results are shown in Fig. 12 and Fig. 13 respectively. The temperature of the liquid metal in contact with the wall of the mould decreases quickly in Fig. 12 because of the high heat flux conducted from the liquid to the mold. The filling process finishes smoothly in 3 s. The solidification time of the feeding neck is 10 s and that of the casting is 26 s in Fig. 13. Optimizing the technological parameters allows sound castings to be produced.
4.3 Modeling and simulation of microstructure for ductile Iron casting

An experiment is carried out: the sizes of samples 1\#, 2\#, and 3\# are 10×10×10 mm, 20×20×20 mm, and 30×30×30 mm respectively, as shown in Fig. 14 (a). In Fig.14 (b) a substitute mesh is used for modeling the microstructure, which is able to be any mesh with variable temperature and cooling rate in the samples. Temperature field, cooling rate and solid fraction are calculated by using SRIFCAST software for the samples.

The results are used to simulate the nucleation and crystal growth in cells which are generated by the substitute mesh. Combining the macroscopic and microscopic simulations, the morphology of the microstructure of the casting can be obtained.

The test density of nodular graphite (1/mm\(^3\)) decreases and the radius of nodular graphite (μ m) increases, as found by using image analyzing system IAS-4, while the cooling rate of samples decreases from 1\# sample to 3\# sample, as is shown in Table 1. Metallographs of the samples are shown in Fig. 15.

![Fig.14 Enmeshment of sample and substitute mesh](image1)

![Fig.15 Metallograph of samples](image2)

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\begin{align*}
\text{Number of nucleation} & = \frac{dN}{d\tau} = A_n n(\Delta T_{l})^{\beta} f_c \frac{d(\Delta T_{l})}{d\tau} \\
\text{Dynamic growth coefficient} & = \frac{dR_g}{dt} = k \rho^d \cdot \frac{(w^l - w^{l,G})}{(w^c - w^{l,c})}
\end{align*}
\]

where \( N \) — Number of nucleation [s\(^{-1}\)⋅mm\(^{-3}\)]

- \( A_n \) — Coefficient related with inoculation
- \( t \) — Time [s]
- \( \Delta T_{l} \) — Undercooling for primary graphite nucleation [°C]
- \( f_c \) — Liquid fraction [%]
- \( R_g \) — Radius of nodular graphite [μ m]
- \( k \) — Dynamic growth coefficient
- \( \rho^l \) — Density of liquid metal [1/mm\(^3\)]
- \( \rho^d \) — Density of graphite [1/mm\(^3\)]
Table 1 Test results of samples

<table>
<thead>
<tr>
<th>Sample number</th>
<th>1*</th>
<th>2*</th>
<th>3*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percent of graphite area (%)</td>
<td>0.29</td>
<td>0.29</td>
<td>0.29</td>
</tr>
<tr>
<td>Average number of nodular graphite</td>
<td>406</td>
<td>483</td>
<td>449</td>
</tr>
<tr>
<td>Average percent of spheriodization (%)</td>
<td>90.9</td>
<td>90.3</td>
<td>90.0</td>
</tr>
<tr>
<td>Grade of nodular graphite</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>radius of nodular graphite [μ m]</td>
<td>7.88</td>
<td>7.22</td>
<td>7.49</td>
</tr>
<tr>
<td>Area density of graphite [1/mm²]</td>
<td>1.491</td>
<td>1.776</td>
<td>1.639</td>
</tr>
<tr>
<td>Volume density of graphite [1/mm³]</td>
<td>141 563</td>
<td>184 042</td>
<td>164 648</td>
</tr>
</tbody>
</table>

The number, growth rate and radius of nodular graphite, and growth rate of austenite shell will be calculated using another program and the above equations. It is then integrated with SRIFCAST to develop a new technique for modeling microstructure of ductile iron castings. Based on the calculation of nucleation and crystal growth, the processes of microstructure formation are dynamically shown in Figs. 16, 17 and 18 for samples 1*, 2*, and 3* respectively. It is clear, from the nucleation time, that nucleation occurs earliest in 1* sample and latest in 3* sample. When the temperature is higher than liquidus, primary graphite nuclei appeared in the liquid metal according to different undercooling and number of efficient heterogeneous nuclei. When the temperature is lower than liquidus, eutectic graphite nuclei and austenite shells around them appeared in the mushy zone. At the beginning nuclei of nodular graphite and austenite shells grow slowly because the temperature of the liquid is high, undercooling is low. Then the growth of nodular graphite and austenite shells is speeded up. The final growth speed decreases, as the liquid fraction is lower and lower. The nucleation and crystal growth of 1*, 2*, and 3* samples follow the same regulation. The simulated morphology of microstructure and test metallographs of samples agreed well.

In Table 2 it is shown that the volume density of nodular graphite (1/mm³) decreases, the radius of nodular graphite (μm) increases, and the cooling rate of 1*, 2*, and 3* samples decreases. Comparisons were made between test and simulated results. For example, in 1* sample, average radii of nodular graphite are 7.53 and 7.73 (μm) for test and simulation respectively; volume densities of nodular graphite are 163 484 and 143 402 (1/mm³) for test and simulation respectively; the values are the same quantity level, they agree quite well.
5. Conclusions

(1) The engineering turbulent and laminar models are used for simulation of mold filling and solidification process of castings, to set up time-averaged continuity, momentum, volume fraction, energy, turbulent kinetic energy, dissipate rate of turbulent kinetic energy equations. The continuous and grain growth models are adapted to simulate the microstructure of ductile iron casting.

(2) For files of solid geometry with STL form, 3-D automatic enmeshment of hexahedron with variable geometric step, 2-D velocity vectors and iso-temperature line, 3-D displays of temperature field were achieved, plus calculating u, T, F, K, ε program to form SRIFCAST software.

(3) The software can be used to simulate mold filling of castings, provide filling sequence, flow pattern, evolution of free surface, and combined with temperature calculation to simulate the solidification process to provide 3-D velocity, temperature, temperature gradient, solid fraction fields. These results provide a scientific basis for optimizing gating and feeding systems.

(4) The software can be used to predict if castings would have such defects as cold shut, blow hole, shrinkage, porosity, inclusion, segregation, and to simulated the microstructure of ductile iron casting. This allows the optimization of the technological parameters for the production of wheel, gear and guide pulley to make sound castings.

Reference


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