The Segregation Microstructure of Q235 as-Casting Steel Through ProCast® Simulation

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Keywords: ProCast® simulation, Q235 steel, Segregation, Solidification, Heat flow.

Abstract. The segregation behavior through vary cooling speed conditions are achieved through grain redistribution. The result shows that, the severe cooling conditions, such as powerful water and air cooling, perform a great role in fast solidification and texture modification. It is suggested that a fast solidification achieves finer grains at the edges of 60t Q235 steel-casting model. At the same time, the columnar grains under extremely cooling circumstances are gradually formed along heat flow redistribution for high density of grain distribution. In summary, the segregation preparation of 60t Q235 steel-casting is completely realized by ProCast® software simulation.

Introduction

The thick steel plates are largely demanded by airplane engine and nuclear power plant. Traditionally, the continuous casting is the dominant methods to produce thick steel plates through directional solidification. At the same time, W. Kurz et al. believe that the solidification microstructure is the key factor influencing the quality of casting steel production. That means, shrinkage, porosity, segregation and cracks are the majority problems which are influenced by processing temperature, pressure distribution, the density of heat flow, even the shape of crystal grain [1-3]. Therefore, it is believed that the progress of segregation leads to shrinkage and porosity. That because, firstly, random elements distribution leads to a difference in tensile strength and rupture behavior. Even more, ‘A’ shape and ‘V’ shape are formed by pores aggregation because solidification shrinkage and density difference of liquid formation [4]. Secondly, the shape of pores is the most important factor for pores elimination. Xu Bin et al. (2012) believes the larger ratio of casting steel model between height and radius size, the elimination of harder pores happens [5].

Recent report shows that Shigo Tsuchiya et al. (2009) studied as-cast γ grain structures through hyperperitectic carbon steels with 0.15-0.45 mass% carbon concentrations. Firstly, when the carbon concentration is less than 0.38 mass%, the microstructure consists of equiaxed grains and coarse columnar γ grains with minor axis diameter 1-3 mm $d_m$. When the carbon concentration is higher than 0.38 mass% columnar γ grains with average minor axis diameter 200-500µm $d_m$. Certainly, as the carbon concentration above 0.43 mass% consists of columnar γ grains. It is fundamentally demonstrated that the carbon concentration influence the shape and size of crystal grain. Secondly, the columnar γ grains transform to coarse columnar γ grains because mold interface have a great temperature variation. Which means that, the heat flow distribution also influences the grain shape and size by supercooling [6]. Therefore, the segregated carbon concentration and heat flow distribution determine the texture of grains distribution.

Under the practical productions, the reducing macro-segregation is connected to carbon concentration and heat flow redistribution. For example, Suzuki and Tniguchi (1981) investigated the mobility of interdendritic liquid during solidification. A-segregate would be significantly solved by lowering Si content and raising the Mo content. This method limited to Si-steel and no element addition steel. In case of electromagnetic method, Griffiths and MaCartney (1997) studied the effect of electromagnetic stirring and low-frequency electromagnetic field for 7150 aluminium texture.
distribution. But, this method is not practical. The long time-consuming leads to a high-cost production with electric and water waste. In case of multiple pouring, Tateno (1985) adopts multiple pouring to control macrosegregation in practical. Importantly, the precised pouring time should be long enough to allow sufficient solidification in vacuum. Thus, the traditional method (Brody and Fleming, 1966; Suzuki and Miyamoto, 1978) on segregated liquided and solid during a slow freezing is still used to control fluid flow [7].

In summary, the segregation should be controlled through pores size and shape, crystal grain size and shape, segregated carbon concentration and heat flow distribution. As the practical production is hard to satisfy the size of 60t specimen, it is fact that simulation is deemed to estimate the final results through ProCast® software. In this experiment, the temperature influence is the dominant factors for heat flow and grain texture distribution.

Experimental Methods

The Boundary Conditions of 60t Q235 Casting Model

The composition of Q235 is listed in the Table 1. According to the impurity elements in the Table 1, through experience equation from appendix 1.1, the liquid phase line is $T_L = 1521^\circ C$ and the solid phase line is $T_S = 1490^\circ C$, respectively. The mech of 60t model is presented in the Figure 1.

![Figure 1. 60t ingot body.](image)

<table>
<thead>
<tr>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Mo</th>
<th>Ni</th>
<th>Ti</th>
<th>Cu</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.06</td>
<td>0.3</td>
<td>1.6</td>
<td>0.01</td>
<td>0.003</td>
<td>0.025</td>
<td>0.4</td>
<td>0.017</td>
<td>0.15</td>
</tr>
</tbody>
</table>

The Parameters of Thermal Expansion and Heat Transfer under Different Cooling and Heat Transfer Coefficient

For the ProCast® simulation, the heat flow is the most important factor which influence the heat transfer coefficient, potential heat and thermal expansion coefficient. In detail, the heat transfer efficient is divided into two categories, solid heat transfer efficient and liquid heat transfer coefficient. In order to achieve boundary conditions, the heat transfer coefficient and potential heat are determined through appendix 1.2. Certainly, the thermal expansion coefficient is determined by linear regression in appendix 1.3 and the Table 2, respectively. And, the interface of heat transfer efficient is determined by refractory brick from Table 3. Therefore, the thermal expansion coefficient, interface heat transfer coefficient, ingot mold under different cooling heat transfer
coefficient and the environment are fundamentally confirmed in the Table 4. For the experience of steel casting forming, the casting speed is carried 1500 mm/s within 300s.

Appendix 1.1

\[ T_L = 1536 - (90C + 6.2Si + 1.7Mn + 28P + 40S + 2.9Ni + 1.8Cr + 2.6Cu + 5.1Al) \] (1)

\[ T_s = 1536 - (415.3C + 12.3Si + 6.8Mn + 124.5P + 183.9S + 4.3Ni + 1.4Cr + 4.1Al) \] (2)

As the solidification of pure ferrous is 1536°C, the results show that the liquid phase line is \( T_L = 1521°C \) and the solid phase line is \( T_s = 1490°C \), respectively.

Appendix 1.2

The solid heat coefficient is accepted as equation:

\[ K(T) = 18.4 + 9.6 \times 10^{-3} \cdot T \quad W / (m \cdot °C) \] (3)

The liquid heat coefficient is accepted as equation, the m is experience parameter, m=4 is used in these relationships:

\[ K_{L}(T) = m \cdot k(T) \quad W / (m \cdot °C) \] (4)

In this experiment, the solid-liquid relationship is distributed as equation:

\[ K_{L}(T) = k(T) \cdot \left[ 1 + (m-1)(1-f_s)^2 \right] \quad W / (m \cdot °C) \] (5)

Thus, the variation of heat transfer coefficient is determined by temperature shown in the Figure 2. Similarly, the potential heat is determined as well.

Appendix 1.3

According to soild density and liquid density mixing of 60t steel slab, the thermal expansion coefficient is realized.

\[ \rho_L = 7000(\text{kg} / \text{m}^3) \] (6)

\[ \rho_s = 7400(\text{kg} / \text{m}^3) \] (7)

\[ \rho_{LS} = f_s \cdot \rho_s + (1-f_s) \cdot \rho_L (\text{kg} / \text{m}^3) \] (8)

Thus, combing above relationship, it is deduced as following.

\[ \lambda = (0.5731 + 0.0076T) \times 10^{-6} \] (9)

Figure 2. Heat coefficient relationship: (a) The heat transfer coefficient is influenced by temperature; (b) The potential heat is determined by temperature influence.
Table 2. The relationship between temperature variation and thermal expansion coefficient (W m\(^{-2}\) K\(^{-1}\)).

<table>
<thead>
<tr>
<th>Temperature</th>
<th>850°C</th>
<th>900°C</th>
<th>950°C</th>
<th>1000°C</th>
<th>1050°C</th>
<th>1100°C</th>
<th>1150°C</th>
<th>1200°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal Expansion Coefficient</td>
<td>12.3</td>
<td>12.41</td>
<td>12.91</td>
<td>13.37</td>
<td>14.16</td>
<td>14.50</td>
<td>14.81</td>
<td></td>
</tr>
</tbody>
</table>

Table 3. Interface heat transfer coefficient (W m\(^{-2}\) K\(^{-1}\)).

<table>
<thead>
<tr>
<th>Steel slab</th>
<th>Insulation board / steel slab</th>
<th>Insulation board / steel slab mold</th>
<th>Steel slab / Refractory brick</th>
<th>Steel slab mold / Refractory brick</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2000</td>
<td>20</td>
<td>200</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 4. Ingot mold under different cooling heat transfer coefficient and the environment (W m\(^{-2}\) K\(^{-1}\)).

<table>
<thead>
<tr>
<th>Air cooling</th>
<th>Weak air cooling</th>
<th>Powerful air cooling</th>
<th>Air and water mixing</th>
<th>Weak water cooling</th>
<th>Powerful water cooling</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10</td>
<td>500</td>
<td>1000</td>
<td>2000</td>
<td>3000</td>
</tr>
</tbody>
</table>

Results and Discussion

The Influences of Critical Solidification Rate to the State of Steel-Cast Finishing

Figure 3 shows that a large temperature difference between inserside and mold edges is influenced by diffusion and heat transmission. The highest temperature is approximately 1580°C and lowest temperature is approximately 251°C, respectively. Vividly, with a comparison to air cooling and powerful water cooling, the surface of mold wall achieves 1137°C to 1524°C and 915°C to 1137°C, respectively. At the same time, in the Figure 4, as powerful water cooling provide high cooling speed, it leads to 20.5% solidification of 60t Q235 steel provides strong cooling effect. That means, a higher cooling speed produces thick equiaxed grains at the edge of steel cast finishing and less columnar grains are shown. Therefore, the high cooling speed with large amount of equiaxed grains is beneficial to ordered grain distribution of the 60t Q235 steel casting.
Figure 3. The 3 dimensional thermal field Steel-cast finishing: (a) Air cooling; (b) Weak air cooling; (c) Powerful air cooling; (d) Air and water mixing; (e) Weak water cooling; (f) Powerful water cooling.

Figure 4. The solidification ratio of steel cast finishing.
The Density of Heat Flow is Influenced under Different Cooling Speed

The preferable orientation distribution of columnar grains plays a key role in mechanical property of 60t Q235 steel casting. Precisely, the preferable orientation is not only influenced by static mold pressure and temperature distribution but also heat flow behavior. As the static mold pressure could not influence microstructure largely, the 60t casting of Q235 steel is too large to be influenced from Figure 5. Thus, the heat flow is the majority causes for texture distribution.

With the cooling speed increasing, the direction of heat flow changes rapidly. In the Figure 6, the greater cooling style, the density of cooling flow leads to specifically direction of columnar grain formation. At the same time, the columnar grain formation is parrelled to the density of heat flow. Figure 6 (c) shows that the columnar grain distribution is achieved through vary directions of columnar grains. For the mechanisms of flow and heat formation, similarly to electromagnetic methodology, a difference distribution of crystal grains leads to better compact and tensile strength in all directions. In that way, the failure of 60t Q235 could be prevented through multiple force direction. Furthermore, the density of heat flow to grain formation is summarized as Figure 6 (f) is the 2nd best choice, Figure 6 (b) (d) (e) is the 3rd choice, Figure 6 (a) is the weakest choice, respectively.

Figure 5. The static pressure of 60t steel casting: (a) Air cooling; (b) Weak air cooling; (c) Powerful air cooling; (d) Air and water mixing; (e) Weak water cooling; (f) Powerful water cooling.
Figure 6. The heat flow distribution through 40000 mech formation: (a) Air cooling; (b) Weak air cooling; (c) Powerful air cooling; (d) Air and water mixing; (e) Weak water cooling; (f) Powerful water cooling.

Conclusion

Powerful air and water cooling contributes to the model and sample preparation of as-casting Q235 steel. Admittedly, the heat flow distribution and cooling speed leads to anisotropy and equiaxed grain contacted to mold surfaces, respectively.

Acknowledgement

This work is financially supported by Ministry of Education of P.R. China (20112120120003). Specifically, it is grateful for Dr. Yao Dawei to assist heat and flow distribution under ProCast® simulation.

References


