Research on Formation of Oscillation Marks from Continuous Casting of Automobile Steel Plate and its Solidification Process Simulation

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Abstract. This paper expounds that the influence of oscillation marks of steel billet on the fatigue strength and the tensile strength of steel plate used in automobile, and the mold model with meniscus in the Crystallizer was established by MSC.MARC software. The solidification law of the shell and the solidification process at the meniscus region are analysed through the temperature field simulation results, which validates that the solidification simulation results of the shell at the meniscus were consistent with the actual production. Changes of initial freezing point position at the meniscus at different drawing speeds are researched, Indirectly the relationship between the depth of oscillation marks and the drawing speed was analysed, At the same time, the relationship between the initial solidification point and the drawing speed was plotted.

1. Introduction
Automobile special steel plate includes carbon structural steel plate and the high strength steel plates which are used for the production of automotive frame, drive shaft, and sheet stamping parts (such as door reinforcement plate, trunk cover plate and other safety parts). Sometimes the steel plates of automobile need to have the high fatigue strength, the high elasticity and the impact strength. Research shows that the fatigue strength and the tensile strength of the steel plates are often related to the heterogeneity of the material structure and the shape of the plate's oscillation marks. In addition, automobile steel plate gradually to "more strength and less weight" development, and plate thinning itself will make its strength reduced. If this kind of steel plate has other surface defects such as oscillation marks, steel plate in the stamping (cold processing) processing or steel plates used on automobile will be more likely to produce cracking, deformation, fold and other phenomena, which affects automobile safety.

Continuous casting is the production stage of forming vibration mark in automobile steel plate production process, in this paper a billet simulation model with the meniscus is built for the slab temperature field analysis, and the slab temperature distribution, the shell thickness variation, and the effect of drawing speed on the initial freezing point at the meniscus are researched. The results are
helpful to optimize the casting process of automobile steel plate, so as to weaken the depth of oscillation marks of automobile steel plate and improve its endurance strength and fatigue strength.

2. Automobile Steel Billet Heat Transfer Model

2.1. Geometric Model of Casting Billet

2.1.1. Curve equation of the casting billet meniscus. The formation of oscillation marks is directly related to the solidification process and the shape of the solidified shell at the meniscus surface of the billet, therefore, the temperature field model must have a meniscus structure. The two-dimensional shape curve of the meniscus can be calculated by the following Bikeman equation [2].

\[ x = \sqrt{2a^2 - (-y)^2} + \frac{a}{\sqrt{x}} \ln \left( \frac{\sqrt{2a^2 - (-y)^2}}{-y} \right) + 0.3768a \]  

(1)

Where, \( a^2 \) is the capillary length, \( x \) is the value of radius direction for the meniscus surface, \( y \) is the height of meniscus surface from 0 to \( a \), \( \rho_{slag} \) is the density of protection slag, \( \rho_{steel} \) is the density of molten steel.

2.1.2. Geometry of the Casting Billet Model. Oscillation marks are formed at the high temperature and the most easily deformed billet. Based on analysis, the heat dissipation rate of the wide surface center is smaller than that of the corner, and the temperature is higher. Therefore, a model of two dimensional longitudinal section sheet at the center of the wide surface of billet will be selected. \( X \) is the direction of thickness for the billet, \( Y \) is the direction of the height. Origin of coordinates is the bottom of the billet position. The model considers the heat transfer at the meniscus. The shape of the meniscus is calculated to be about 7mm.

2.2. The Basic Assumptions of the Heat Transfer Model of Casting Billet

(1) Ignore the heat transfer effect in the direction of the vertical crystallizer.

(2) Consider the heat transfer on the meniscus and ignore the effect of steel wave on the shape of the meniscus. It is considered as a steady state invariant shape.

(3) Neglect the taper effect of the crystallizer in the calculation.

(4) The pouring temperature of molten steel is uniform and stable at the initial state.

(5) The effect of steel convection on heat transfer is treated by equivalent thermal conductivity.

(6) The solidification latent heat of the two-phase region is converted to equivalent specific heat for treatment.

2.3. The Basic Equation of Billet Model

The heat transfer model adopts two dimensional model of longitudinal section. Therefore, the corresponding temperature field should satisfy the differential equation is:

\[ \frac{\partial}{\partial y} \left[ k(T) \frac{\partial T}{\partial y} \right] + \frac{\partial}{\partial z} \left[ k(T) \frac{\partial T}{\partial z} \right] + S = \rho(T) c(T) \frac{\partial T}{\partial t} \]  

(2)

Where, \( T \) is the temperature, \( \rho(T) \) is the density of billet with temperature, \( x, y, z \) are three directions in Rectangular coordinate system, \( t \) is the time, \( k(T) \) is the thermal conductivity of billet with temperature change, \( S \) is the heat source, \( c(T) \) is the specific heat that changes with temperature.

2.4. The initial Conditions and Boundary Conditions of Billet Casting Model

2.4.1. Initial conditions. When \( t=0 \), the initial temperature is 1545°C, the degree of superheat:
\[ \Delta T = T_0 - T_L = 27^\circ C \]  

2.4.2. **Boundary conditions**

(1) Liquid surface boundary conditions: The billet temperature at the liquid level is casting temperature, and its expression is:

\[ T|_{y=80} = T_0 = 1545^\circ C \]  

(2) Plane of symmetry and export boundary conditions: All in an adiabatic state:

\[ q|_{x=85} = 0, q|_{y=0} = 0 \]  

(3) Surface boundary conditions of casting billet: Instantaneous heat flow density of billet surface depends on crystallizer height. This article uses the empirical formula proposed by Svage and Pritchard [3-4]

\[ q = -\lambda \frac{\partial q}{\partial x} = \left[ 2.64 \exp \left( -\frac{60y}{v_c} \right) + 0.91 \exp \left( -\frac{60y}{113v_c} \right) + 0.93 \right] \times 10^6 \]  

Where, \( q \) is the heat flux, \( y \) is the distance to the meniscus, \( v_c \) is the lift speed, the heat flux at the corner is one third of the heat flux at the center.

2.4.3. **The numerical value of thermal property parameter of casting billet**

(1) Phase line temperature:

Liquid phase line temperature:

\[ T_L = 1536.6 - (90C + 8Si + 5Mn + 30P + 25S + 5Al + 2Cu + 1.5Cr + 4Ni + 2Mo + 80N + 2Ti) \]  

Solid phase line temperature:

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

(2) Solid Phase Ratio:

\[ f_s = \sqrt{(T_L - T)/(T_L - T_S)} \]  

(3) The density of molten steel:

\[ \rho = 7500 \text{kg/m}^3 \]  

(4) Coagulation potential heat of casting billet \( L_f \) [5]:

\[ L_f = \Delta H(Fe) \times 99.34\% + \Delta H(C) \times 0.16\% + \Delta H(Si) \times 0.08\% + \Delta H(Mn) \times 0.3\% \]  

Where, \( \Delta H(Fe), \Delta H(C), \Delta H(Si), \Delta H(Mn) \) is the element solidifies latent heat.

(5) Heat capacity: Solid phase area
Liquid phase area

\[ C_L = 867 \text{ J/kg} \cdot ^\circ \text{C} \quad (13) \]

Considering the potential heat of solidification in two-phase zone, treatment by equivalent specific heat, its formula is as follows [6-7]:

\[ C_{eff} = f_S C_S + (1 - f_S) C_L - L_f 1000 \frac{\partial f_s}{\partial T} \quad (14) \]

Where, \( C_{eff} \) is the equivalent specific heat capacity, \( C_S \) is the solid heat capacity, \( C_L \) is the liquid heat capacity, \( f_s \) is the solid ratio, \( L_f \) is the latent heat of solidification.

(6) Thermal conductivity: solid phase area:

\[ k = 18.4 + 9.6 \times 10^{-3} T \quad (15) \]

Liquid phase area:

\[ k_{eff} = m \cdot k \quad (16) \]

Two-phase area:

\[ k_{eff} = [1 + (m - 1) \cdot (1 - f_s)^2] \cdot k \quad (17) \]

Where, \( k \) is the solid thermal conductivity, \( T \) is the temperature, \( k_{eff} \) is the equivalent thermal conductivity, \( m \) is the correction factor, value is taken as 4. The effective length time of automobile steel casting slab passing through the crystallizer at a speed of 0.75 m/min is the solidification time.

3. Analysis of Simulation Results of Steel Billet Temperature Field

3.1. Temperature Field Results of Automobile Steel Billet

![Figure 1. Temperature field cloud diagram](image-url)
Figure 2. Temperature curve of the surface

It can be seen from the color change in figure 1 that the core temperature of the casting billet is higher than the liquid phase line and the core state is liquid state. Billet surface temperature decreases from the meniscus rapidly. A large temperature gradient is formed, and the lowest temperature of the billet can be 1028°C. The shell thickness at the crystallizer outlet can be up to about 18 mm. It can be seen from the color change that the continuous casting billet shell is in a bending state at the meniscus. During the negative sliding stage of the crystallizer, as the casting blank moves downward, the liquid steel overflows, solidifies into a shell and forms the oscillation marks together with the original bending billet shell. Therefore, the depth of oscillation marks is related to the shape of the curved shell.

As can be seen from the curve in Figure 2, the temperature gradient at the meniscus is large, because the heat flux density is large, and the heat transfer is fast. In the area below the meniscus, the heat flux density decreases linearly with height, so the temperature curve is decreasing linearly. According to the solidus temperature of billet, at the meniscus part of the curved shell will be formed. The simulation results are consistent with the actual production results, therefore, the accuracy of the simulation of meniscus solidification process is verified. So the simulation model can be used to analyze the solidification of other special steel plate for automobile.

3.2. Influence of Drawing Speed on the Quality of Automobile Steel Slab

The initial solidification point directly reflects the inwardly curved value of the shell called of the depth value of oscillation marks at the meniscus, and the value will affect the fatigue strength and the tensile strength of the steel plate. Figure 6 shows the solidification law of the shell at the meniscus when the drawing speed is 0.75m/min, 1.0m/min and 1.25m/min.
According to Figure 3, with the drawing speed increasing, slab meniscus shell’s thickness decreases and the location of the initial freezing point gradually approaches the Crystallizer wall. Figure 4 can be used for quantitative analysis that: When the drawing speed is 0.75 m/min, the initial freezing point is 4.39 mm away from the liquid level and 0.86 mm away from the Crystallizer wall. When the drawing speed is 1.25 m/min, the initial freezing point is 5.29 mm away from the liquid level and 0.34 mm away from the Crystallizer wall. Therefore, with increasing of drawing speed, the inwardly curved value of the shell is reduced at the meniscus, and oscillation marks become shallower. So, in order to reduce oscillation marks, the drawing speed should not be too slow. At the same time the drawing speed is not too fast, because it's easy to have a leakage phenomenon. Therefore, reasonable drawing speed has an important effect on reducing oscillation marks, improving the quality of steel billet and improving the service life of special steel plate for automobile. For the analysis results, the 1.0 m/min drawing speed is preferred.

![Figure 4. Temperature curve at the meniscus](image1)

![Figure 5. Initial freezing point change curve](image2)

The relationship between the initial solidification point and the casting speed can be established based on the above simulation results. According to Figure 5, the proper drawing speed can be obtained, which can not only ensure the shallowness of oscillation marks but also avoid the leakage. The reasonable process parameters can be set in steel casting, which helps producing the high-strength steel billet with better surface quality, improving the service life and protection strength of the steel used in automobile passive protection system.

4. Conclusion
This paper expounds that oscillation marks structure is the decisive factors to the machining properties of automobile steel and the fatigue strength of automobile steel in the casting stage of steel. The temperature field of steel in continuous casting Crystallizer is simulated and analyzed. The mold model with meniscus in the Crystallizer is established by MSC.MARC software. It is analyzed that the thickness of the billet shell will increase with the height of Crystallizer decreasing gradually. Analysis was made that at the three tensile speeds of 0.75 m/min, 1.0 m/min and 1.25 m/min, the distance from the initial solidification point to Crystallizer wall at the meniscus decreased from 0.86 mm to 0.68 mm and finally to 0.34 mm. Finally, the relationship between the distance from the initial solidification point to Crystallizer wall and drawing speed is analyzed, which provides a reference for selecting a reasonable drawing speed value. The simulation model can be used to simulate the solidification process of other kinds of automobile steel plates.

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