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Prediction of centerline cracks incurred in the bloom continuous casting of steel

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Abstract: An elastic-viscoplastic model is used on the finite element package Abaqus to simulate the thermal and mechanical behavior of bloom casting strand and predict the location and scale of centerline cracks. The formation of centerline cracks can be investigated by the application of this model, which is of benefit to the improvement of processing.

Key words: continuous casting; finite element; Abaqus; solidification

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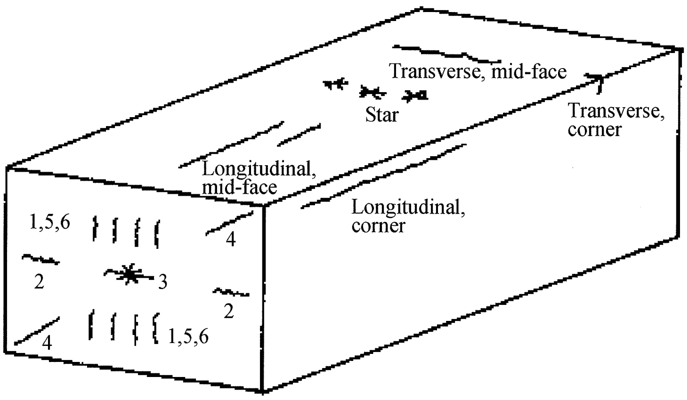
1 Introduction

The formation of cracks has long been recognized as a problem in the continuous casting of steel. Cracks have been observed at almost every conceivable location in cast steel sections as shown schematically in Fig. 1[1]. In the interior, cracks may be seen near the corners at the centerline or diagonally between opposite corners. On the surface, transverse and longitudinal cracks may appear both on the mid-face and in the corner regions.



Internal cracks:
1–Midway; 2–Triple-point; 3–Centerline; 4–Diagonal; 5–Straightening/bending; 6–Pinch roll surface cracks.

Fig. 1 Schematic drawing of a strand cast section with different types of cracks

The reason for the profusion of crack types lies in the nature of the continuous casting process itself. The rapid cooling process results in steep temperature gradients in the solid shell that can change rapidly and generate thermal strains as the shell expands or contracts[1-3]. In addition, because the semisolid section is required to move through the machine, it is subjected to a variety of mechanically induced stresses caused by friction in the mould, roll pressure, ferrostatic pressure, machine misalignment, bending and straightening operations[1]. Depending on their magnitudes, any of these stresses and strains may result in crack formation.

Lankford has discussed the nature of the stresses and strains that can give rise to cracks in the solidifying shell[4]. Tensile force and expanding strain may result in crack formation at low ductility zones.

There are three temperature zones where steel is susceptible to crack.

(1) High temperature zone: ~1340℃ to solidus.
(2) Intermediate temperature zone: 800 – 1200℃
(3) Low temperature zone: 700 – 900℃

Above about 1340℃, the low strength and ductility seem to be due to the presence of liquid films in the interdendritic regions, which do not freeze until temperatures reach well below the solidus. The liquid films apparently contain a high level of sulphur, phosphorus and other elements, which have a segregation coefficient less than unity and concentrate between the growing dendrites.

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In the intermediate temperature zone, the loss of ductility during the cooling below 1200℃ is strongly dependent on the Mn/S ratio and the thermal history of the steel. Lankford[4] has proposed a mechanism by suggesting that the low ductility should result from the precipitation of liquid droplets of FeS in planar arrays at austenite grain boundaries, which are the paths of easy crack propagation. Lankford has further shown that slower cooling rates improve the ductility even with a low Mn/S ratio because manganese has time to diffuse to the grain boundaries.

The third temperature zone of low ductility is associated with soluble aluminum in the steel, the precipitation of AlN and the pre-ferrite at grain boundaries.

Centerline cracks occur in the central region of a cast section and form towards the end of solidification. Cracks can be found in all grades of steel independent of composition and superheat. In the casting of blooms, the sudden drop in the centerline temperature at the completion of solidification generates cracking strains. The drop in the centerline temperature is considerably more sudden than the decrease in the surface temperature with the result that the central region contracts. The center is constrained from contraction, however, by the surrounding colder steel and thus is in tension.

Computational models are important tools to gain an insight into the thermal and mechanical behavior incurred in continuous casting. Brimacombe and his co-workers[5] first applied the computational thermal stress model of a two-dimensional billet section under plane stress as it moved down the caster. Recently, several improved models of the thermal-mechanical behavior of continuous cast steel have been developed. Although they have provided important insights, previous thermal-mechanical models of shell solidification in the mold still oversimplify some phenomena or are too computationally expensive to simulate large-scale problems. Thomas and his co-worker[6] developed an elastic-viscoplastic model to simulate temperature and stress development of a slice through the solidifying steel shell in a continuous casting mold under practical operating conditions including a stress state of generalized plane strain with dependent properties.

In this study, a similar elastic-viscoplastic model is used on the finite element package Abaqus to simulate the thermal and mechanical behavior of bloom casting strand and predict the location of centerline cracks.

2 Thermal governing equations

The model solves the transient heat-conduction Equation (1) using the commercial finite element package Abaqus, where $H(T)$ and $K(T)$ are the isotropic temperature-dependent enthalpy and conductivity respectively.

$$\rho\frac{\partial H(T)}{\partial t} = \nabla(K(T)\nabla T) \qquad (1)$$

A 2-D simplification of the full 3-D process is reasonable, because axial (Z direction) heat conduction is negligible in relation to the advection at the high Peclet number.

Along with boundary conditions:

Prescribed temperature on A_T

$$T = \hat{T}(\vec{X},t) \qquad (2)$$

Prescribed surface flux on A_q

$$(-k\nabla T)\vec{n} = \hat{q}(\vec{X},t) \qquad (3)$$

Surface convection on A_h

$$(-k\nabla T)\vec{n} = h(T - T_\infty) \qquad (4)$$

where ρ is density, k the isotropic temperature-dependent conductivity, and H the temperature-dependent enthalpy, which includes the latent heat of solidification. $\hat{T}$ is a fixed temperature at the boundary A_T, $\hat{q}$ is the prescribed heat flux at the boundary A_q, and h is film convection coefficient prescribed at the boundary A_h. T_∞ is the ambient temperature, and $\vec{n}$ is the unit normal vector of the surface of the domain.

3 Mechanical governing equations

Inertial effects are negligible in solidification problems, so using the static mechanical equilibrium in Equation (5) as the governing equation is appropriate:

$$\nabla\sigma(x) + b = 0 \qquad (5)$$

where σ is the Cauchy stress tensor, and b is the body force density vector.

The rate representation of total strain in this elastic-viscoplastic model is given by Equation (6):

$$\dot{\varepsilon} = \dot{\varepsilon}_{el} + \dot{\varepsilon}_{ie} + \dot{\varepsilon}_{th} \qquad (6)$$

where $\dot{\varepsilon}_{el}$, $\dot{\varepsilon}_{ie}$, $\dot{\varepsilon}_{th}$ are the elastic, inelastic, and thermal strain rate tensors respectively.

Viscoplastic strain includes both strain-rate independent plasticity and time dependant creep. Creep is significant at the high temperatures of the solidification processes and is indistinguishable from plastic strain.

Kozlowski, *et al*[7] proposed a unified formula-tion with the following functional form to define inelastic strain.

$$\dot{\varepsilon}(1/s) = f(\%C)[\sigma(MPa) - f_1(T(^oK))\varepsilon|\varepsilon|^{f_2(T(^oK))-1}]^{f_3(T(^oK))}\exp(-4.465\times 10^4(^oK/T(^oK)))$$

$$f_1(T(^oK)) = 130.5 - 5.128\times 10^{-3}T(^oK)$$

$$f_2(T(^oK)) = -0.6289 + 1.114\times 10^{-3}T(^oK)$$

$$f_3(T(^oK)) = 8.132 - 1.54\times 10^{-3}T(^oK)$$

$$f(\%C) = 4.655\times 10^4 + 7.14\times 10^4\%C + 1.2\times 10^5(\%C)^2 \qquad (7)$$

Where f_1, f_2, f_3, f_C are empirical temperature, and steel-grade-dependant constants.

4 Treatment of liquid/mushy zone

The great variation in material properties among liquid, mush, and solid crates is a significant numerical challenge to make accurate thermo-mechanical simulations. In this model, we choose an isotropic elastic-perfectly-plastic rate-independent constitutive model that enforces negligible liquid strength when the temperature is above the solidus temperature. The chosen yield stress 0.03 MPa, is small enough to effectively eliminate stresses in the liquid-mushy zone, but large enough to avoid computational difficulties.

5 Model applications

The domain adopted for this problem is a single layer of 3 - D elements through the bloom thickness, which goes down in the axial Z direction (the casting direction) with zero relative rotation. X is the direction of thickness and Y is the direction of width. In the continuous casting process, one dimension of the casting is much longer than the other, and otherwise, unconstrained. It is reasonable to apply a condition of generalized plane strain on down face in the long direction (Z) and fixed upper face. The strain in Z direction does not vary with $X - Y$ coordinates. For the nodes on other faces, the displacements can be dealt with as shown in Fig. 2.

The casting velocity is 0.6 m/min. The strand material is the steel containing 0.1% of carbon with temperature dependant properties, including conductivity, specific heat, enthalpy, elastic modulus, and thermal expansion coefficient. The liquidus temperature is 1510℃ and the solidus temperature is 1461℃.

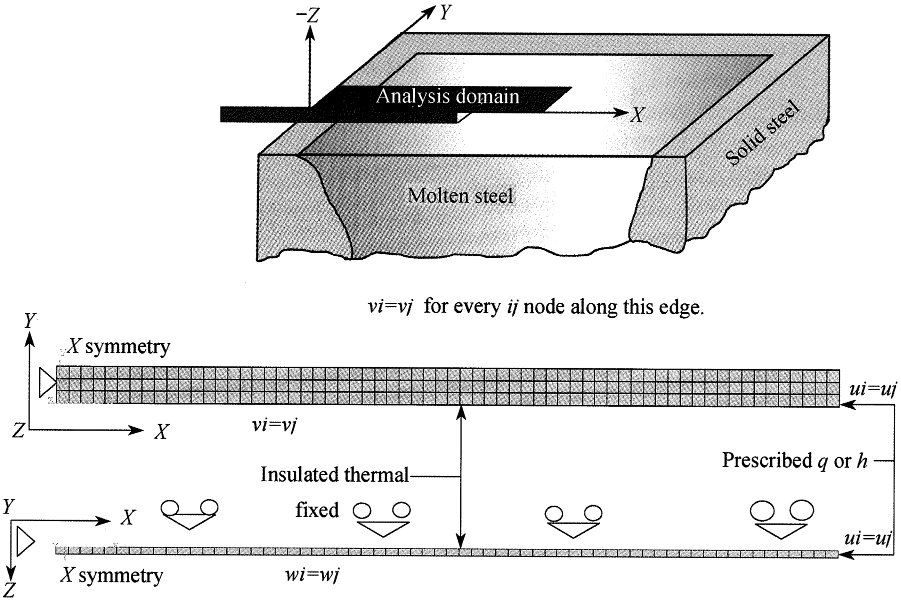

Fig. 2 Mechanical FE domains of a 3 - D single layer model

6 Results

Fig. 3 shows the temperature simulation results and the measurement with a thermal pyrometer at Baosteel. The temperatures at the centerline, the corners, the broad face and the narrow face were simulated. The temperatures at the broad face and the narrow face were measured with a thermal pyrometer.

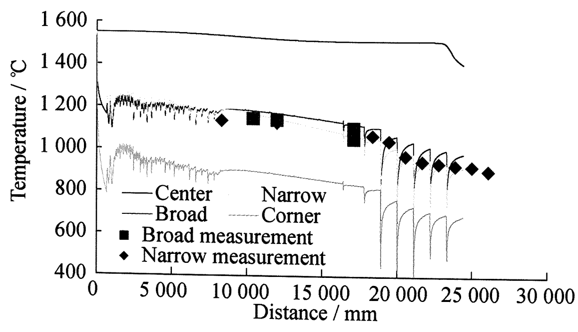

Fig. 3 Temperature simulation results and measurements

The solid fraction, the temperature distribution and the temperature evolution of steel were calculated on the thermal model with the Abaqus package and listed in Figs. 4, 5 and 6.

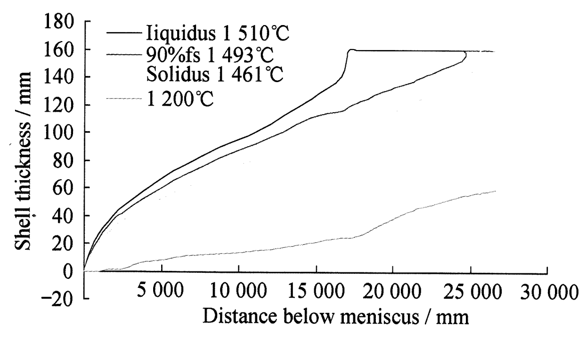

Fig. 4 Solid fraction of steel

Fig. 7 shows the variation of inelastic strain from 90% fraction of solid (fs) to 99% fs at different shell thickness. Inside the area which is 20 mm from the center, the variation of inelastic strain is greater than zero, and cracks are susceptible to form. At other places, where the inelastic strain is smaller than zero, cracks are not easily to form.

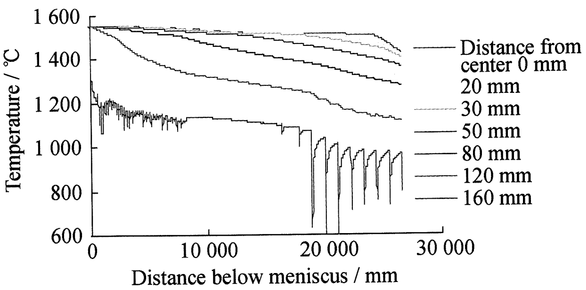

Fig. 5 Temperature distribution simulated by Abaqus at different shell thickness

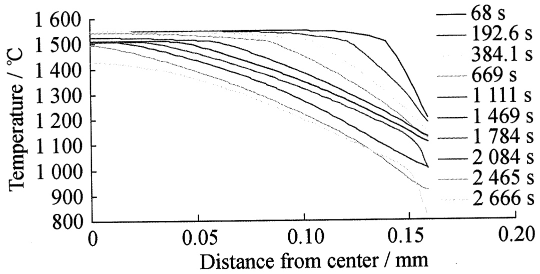

Fig. 6 Temperature evolution simulated by Abaqus

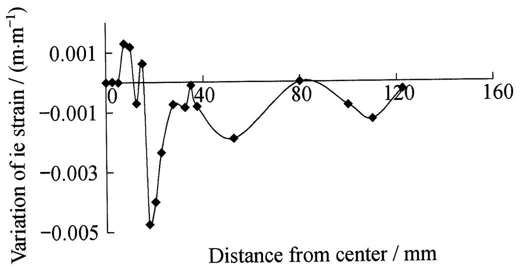

Fig. 7 Variation of inelastic strain from 90% fs to 99% fs

Fig. 8 shows the sulphur print of the steel. There are centerline cracks near the area which is 20 mm from the center. The simulation results match the sulphur print of the steel grade very well.

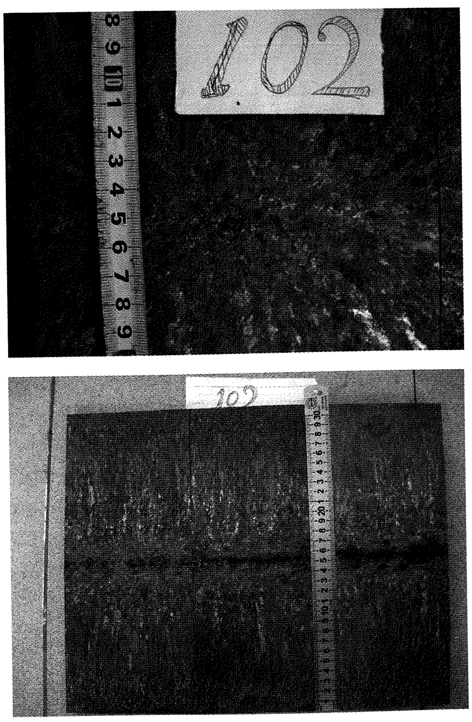

Fig. 8 Sulphur print of the steel

7 Conclusion

The purpose of this research is to predict the centerline cracks incurred in the bloom continuous casting. A 3 - D finite element thermal-mechanical model was established to calculate the temperature and the stress of continuous casting strands. An elastic-viscoplastic model was used on the finite element package Abaqus to predict the location and scale of centerline cracks. The formation of centerline cracks can be investigated by the application of this model, which is of benefit to the improvement of processing. The centerline cracks of bloom strands form at the end of solidification due to the sudden drop of the centerline temperature at the completion of solidification. In the mushy zone, when the variation of inelastic strain from 90% fs to 99% fs is more than one, cracks are susceptible to form. It is suggested that severe cooling and small soft-reduction at the end of solidification may contribute to the prevention of crack from formation.

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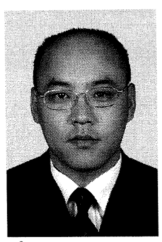

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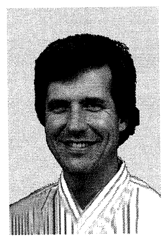

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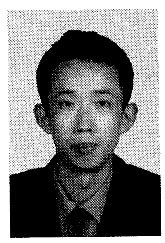

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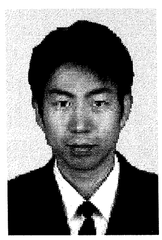

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