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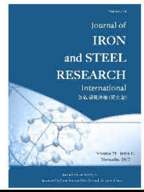

Thermo-elasto-visco-plastic finite element analysis on formation and propagation of off-corner subsurface cracks in bloom continuous casting

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ABSTRACT

The formation and propagation of the popular off-corner subsurface cracks in bloom continuous casting were investigated through thermo-mechanical analysis using three coupled thermo-mechanical models. A two-dimensional thermo-elasto-visco-plastic finite element model was developed to predict the mould gap evolution, temperature profiles and deformation behavior of the solidified shell in the mould region. Then, a three-dimensional model was adopted to calculate the shell growth, temperature history and the development of stresses and strains of the shell in the following secondary cooling zones. Finally, another three-dimensional model was used to analyze the stress distributions in the straightening region. The results showed that the off-corner cracks in the shell originated from the mould owing to the tensile strain developed in the crack sensitive regions of the solidification front, and they could be driven deeper by the possible severe surface temperature rebound and the extensive tensile stress in the secondary cooling zone, especially upon the straightening operation of the bloom casting. It is revealed that more homogenous shell temperature and thickness can be obtained through optimization of mould corner radius, casting speed and secondary cooling scheme, which help to decrease stress and strain concentration and therefore prevent the initiation of the cracks.

Symbol List

A—Constant related to effective strain, s^{-1};
C_{eff}—Effective specific heat including solidification latent heat of steel, $J \cdot kg^{-1} \cdot ℃^{-1}$;
C_p—Specific heat at constant pressure, $J \cdot kg^{-1} \cdot ℃^{-1}$;
C_w—Specific heat of water, $J \cdot kg^{-1} \cdot ℃^{-1}$;
E—Temperature dependent Young′s modulus;
f_s—Solid fraction;
f_α—Solid fraction of α phase;
f_δ—Solid fraction of δ phase;
f_γ—Solid fraction of γ phase;
f_{ZST}—Solid fraction at zero strength temperature;
h—Strand thickness, m;
h_s—Integrated heat transfer coefficient at strand surface, $W \cdot m^{-2} \cdot ℃^{-1}$;
k—Temperature dependent thermal conductivity of steels, $W \cdot m^{-1} \cdot ℃^{-1}$;
K—Strength coefficient;
K_T—Boltzmann′s constant, $W \cdot m^{-2} \cdot ℃^{-4}$;
L—Local distance to meniscus, m;
L_f—Solidification latent heat, $kJ \cdot kg^{-1}$;
L_m—Effective length of mold, m;
m—Constant related to strain-rate sensitivity;
m_w—Water flowrate for mould cooling, $kg \cdot s^{-1}$;
n—Strain-hardening exponent;
$\bar{q}$—Average heat flux in mold zone, $J \cdot m^{-2} \cdot s^{-1}$;
Q—Activation energy for deformation, $kJ \cdot mol^{-1}$;
q_0—Surface heat flux, $J \cdot m^{-2} \cdot s^{-1}$;
R—Gas constant, 8.314 $J \cdot mol^{-1} \cdot K^{-1}$;
S_{eff}—Effective area of mould, m^2;
ΔT—Temperature difference of mould cooling water, ℃;
t—Time, s;
T—Temperature, ℃;
T_0—Local surface temperature of strand, ℃;
T_a—Ambient temperature, ℃;
T_m—Casting temperature, ℃;
T_{ws}—Temperature of cooling water, ℃;
v—Casting speed, $m \cdot min^{-1}$;
w—Secondary cooling water density, $L \cdot m^{-2} \cdot s^{-1}$;
W—Strand width, m;
x—Coordinate along width direction, m;
y—Coordinate along thickness direction, m;
$\dot{\varepsilon}$—Effective strain;
ε_p—Effective plastic strain;
ε^δ—Strain of δ phase;
ε^γ—Strain of γ phase;
σ—Flow stress, MPa;
B—Blackness;
β—Constant related to flow stress, MPa^{-1};

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σ^{δ}—Flow stress of δ phase, MPa;
σ^{γ}—Flow stress of γ phase, MPa;
ρ—Temperature dependent density, kg · m^{-3};
υ—Poisson's ratio.

1. Introduction

For bloom and/or billet castings of steel, the off-corner regions of the strand often experience local surface depression together with subsurface longitudinal cracks. These cracks are usually located at 10－20 mm from the corner and 7－15 mm from the surface. This phenomenon was believed to result from bulging of the solid shell in the lower part of the mould. As bulging occurs, a hinging action develops near the corners, which could initiate shell cracks owing to the tension strain at the local solidification front. This bulging was considered to be caused by the ferrostatic pressure and thermal distortion or wear in the lower region of the mould[1]. Brimacombe et al.[2] believed that the cracks could be driven deeper owing to the tension caused by the temperature rebound of the surface solid shell in the secondary cooling zone. Besides the mechanical stress, the thermal stress caused by temperature gradient in the solidified shell is another important factor to influence the formation of cracks. According to previous studies[3,4], the stress near solidification front is mainly in the status of tension around 1－2 MPa which will be deteriorated by reheating because of a decrease in secondary cooling intensity. As temperature rises at surface region of the solid shell, surface expansion occurs, leading to the tension beneath the surface. Thomas et al.[5,6] developed a two-dimensional (2D) thermo-elastic-plastic-creep finite element model to study the thermo-mechanical behavior of the solidified shell in and just below a bloom mould and investigated the influence of corner radius on longitudinal crack formation. According to their work, longitudinal off-corner subsurface cracks are predicted to form more easily in the small corner radius bloom.

This paper aims at investigating origin and propagation of off-corner cracks in the entire continuous casting processes with a modified thermo-elasto-visco-plastic finite element model[7], through which special attention is given to the effect of mould radius, casting speed and cooling scheme on the crack tendency.

2. Model Conditions

The entire continuous casting process was divided into three parts: the mould process, the secondary cooling and air cooling processes, and the straightening process. Every roll of the strand was assumed to be set properly. The major casting conditions used in the model simulation are given in Table 1.

Table 1
Main casting parameters

Parameter	Value	Unit
Bloom size	250×280	mm×mm
Casting speed	1.0	m · min^{-1}
Machine radius	16.5	m
Straightening radius	23, 40, ∞	m
Straightening length (distance from meniscus)	25.0－27.2	m
Chemical composition	Fe-0.1C-0.2Si-0.5Mn-0.03P-0.03S	wt.%
Mould length	780	mm
Mould active length	645	mm
Meniscus level	135	mm
Casting temperature	1547	℃
Mould taper at different distance from tube top	2.45 (0－190 mm), 1.25 (190－400 mm), 0.50 (400－780 mm)	% · m^{-1}
Mould cooling water flowrate	3400	L · min^{-1}
Pouring mode	Submerged	
Secondary cooling zone	Four segments; the first segment: water spray; the other segments: air-mist spray	
Secondary cooling zone length	0.35＋1.8＋2.2＋3.5	m

3. Model Description

A transient, thermo-elasto-visco-plastic finite element model was developed to calculate temperature, stress, strain and deformation in a 2D transverse slice through the solidified shell in mould effective length with the given casting speed, as shown in Fig. 1(a). Through the mould/shell interface, the heat transfer coefficient is evaluated on the basis of the calculated distance between the shell and mould. When a detachment caused by shell contraction occurs, an air gap is formed, and an appropriate heat transfer coefficient