311 Analysis of Stresses Distribution and Evaluation of Crack Pregnant during Twin-roll Strip Casting Process

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Abstract: To compute the thermal mechanical stresses and susceptibility of the material to crack during strip casting process, a coupled finite element simulation on temperature, solidification and inelastic deformation was carried out based on a unified viscous fluid model including elastic, visco-plastic deformation, thermal expansion and dilatation due to solidification. The distribution of temperature and stresses on strip surface and in nip zone was analyzed with various casting speeds. Possibility of the solidifying material to fracture was evaluated with a stress-crack criterion. The weakest position and effect of casting speed were clarified.

Key Words: Strip Casting, Inelastic Deformation, Solidification Crack Criterion, Finite Element Method

1. INTRODUCTION

Strip casting by twin reverse rotating mould rollers is an effective manufacturing process to save energy and cost as well as to improve material strength. Since it was first conceived by H. Bessemer in the nineteenth century, although understanding of the process have developed much during the intervening years, commercial production of steel strip has not been achieved.

To keep steady casting production for strip casting, not only control of cooling and solidification but also stresses and crack formation shall be taken into consideration. One of great difficulties in steady production is crack occurrence and fracture break in strip, which is resulted from complex thermal mechanical stresses due to solidification and deformations. From the viewpoint of mechanics, fracture occurrence is determined by the material strength at high temperature and stresses level. Generally the thermal-mechanical stresses in casting strip are caused by elastic, visco-plastic deformation, thermal expansion and solidification dilatation. Stresses analysis by a coupling method considering flow, solidification and inelastic deformation is a very important problem to analysis crack pregnant and then to determine optimum steady strip casting process conditions.

Many theoretical and numerical analysis works have been done on twin roll casting process in recent two decades years, and most of them are engaged in flow, heat transfer and solidification. Based on these results, prediction on temperature and solidification finish point could be available [1-4]. However, analysis on thermal and visco-plastic deformation stresses and accordingly prediction of pregnant of cracks still is an open work. A. Ramacciotti [5] once predicted crack susceptibility in solidifying shell of thin slab in funnel shaped mould using a crack criterion. He evaluated rating of possible critical conditions from the principal stresses based on an approach beam model. In his model, the effect of flow and solidification on stresses level were neglected. M.Gupta etc predicted the crack susceptibility of casting strips in twin roll drag casting process employing the same crack index model [6]. They used a fluid model in which viscosity of solid phase is very high and mushy zone is represented by setting the value of power for desired slope of viscosity. By this model, they analyzed the crack possibility by computed maximum principal stress. However they only considered the thermal stresses generated in the strip.

One of the authors has proposed a simplified inelastic model that deformation in solid and semisolid is treated as a modified viscosity which is a function of temperature and strain rate [7,8]. To compute the thermal mechanical stresses in casting strip and susceptibility of material to crack, a coupling thermo-mechanical analysis of solidification and inelastic deformation has been developed. In this paper, thermal mechanical stresses of strips under various casting speeds are analyzed. Crack susceptibility in casting strip was analyzed by a crack index model and the weakest positions are predicted.
2. SIMULATION MODEL AND METHOD

2.1 Constitutive Relationship

During strip casting process, complex thermal mechanical deformations generates in the strips. The total strain rate of the strip is consisted of elastic, visco-plastic and thermal strain as well as dilatation due to solidification strain rate.

\[ \dot{\varepsilon}_y = \dot{\varepsilon}_y^p + \dot{\varepsilon}_y^\sigma + \dot{\varepsilon}_y^\nu + \dot{\varepsilon}_y^T. \]  

Here thermal strain rate and solid fraction rate could be indicated as simplified formula,

\[ \dot{\varepsilon}_y^T = \alpha \dot{T} \delta_y \quad \text{and} \quad \dot{\varepsilon}_y^\nu = \beta \xi \delta_y, \]

where \( \delta_y \) indicates solid fraction in mushy zone which obeys lever law, \( \alpha \) and \( \beta \) are thermal expansion coefficient and solidification contraction coefficient, respectively.

According to the unified theory of visco-plasticity in which all aspects of inelastic behavior are represented by same variable. The models for inelastic strain rate are the modified Perzyna's model based on the excess stress theory.

\[ \dot{\varepsilon}_y^\nu = \frac{1}{2 \mu} \left< \frac{\sigma - \sigma_T}{3 J_2^{1/2}} \right> S_y, \]

where \( \mu, S_y \) and \( J_2 \) denote the viscosity coefficient, deviation stress and the second invariant of the stress respectively. When the visco-plastic model tends to unity, Eqn.(4) is reduced to uniaxial stress-strain relation of monotonic tension expressed as [7,8]

\[ \dot{\varepsilon}_y^\nu = \frac{1}{3 \mu} \left< \left| \frac{\sigma}{\sigma_T} - 1 \right| \right> S_y, \]

where the viscosity coefficient is a function dependent on temperature and strain rate. By assumption that the viscosity coefficient \( \mu \) is an exponential function of the strain rate and temperature,

\[ \mu = (a_0 + a_1 \dot{T}) e^{-(b_0 + b_1 \dot{T})}. \]

Here \( a \) and \( b \) are coefficients related to materials properties, which have been determined from the experimental method and results presented in former paper [9,10].

2.2 Finite Element Model

Figure 1 shows the finite element model and mesh including the total domain of strip and roll. A plane strain model was employed to simplify the calculation process. Taking into account of the symmetry, half of the geometry is calculated. The coordinate X indicates the thickness direction of strip and Y indicates casting direction. A kink of Al-Mg-Si Alloy was employed in this research that the liquidus and solidus point are 654 °C and 639 °C, respectively. The diameter of the rollers is 300 mm and thickness of strip is 2mm. The casting temperature and meniscus level in calculation are 720°C and 70 mm, respectively.

Fig.1 Finite element model of casting pool and roll

2.3 Simulation Algorithm

With the above theoretical equations, finite element formulas are introduced as follows. In the calculation of the temperature field, to determine the heat transfer along the contact boundary between the strip and rolls, interactive calculation between the strip and the cooling roll is performed by the substructure method when solving the heat conduction equation. The finite element formulas of heat conduction equation for the strip and roll are obtained by applying Galerkin method with the boundary conditions,

\[ [H^S][T] = \{Q_m \} + \{Q_r \} \]

and that for the rolls it leads to

\[ [H^R][T] = \{Q_m \} + \{Q_r \} \]

Here, \([H^S]\) and \([H^R]\) are the stiffness matrices of strip and rolls considering material flow and solidification. \(\{Q_m\}\) and \(\{Q_r\}\) denote the vectors of latent heat and heat transfer, respectively.
\[ \{ \mathbf{q}_s \} = \int \rho \, \left[ N^T \right] \left( \mathbf{v} \cdot \frac{\partial \mathbf{F}}{\partial \mathbf{v}} \right) d\mathbf{v} \]  
\[ \{ \mathbf{q}_g \} = \int_n \left[ N^T \right] f(T) \mathbf{n}_s \, d\Gamma \]  
\{ \mathbf{q}_s \} \text{ and } \{ \mathbf{q}_g \} \text{ are heat input vectors through contact surface with the strip and roll, respectively, which are defined as,}  
\{ \mathbf{q}_s^R \} = \int_{r_s} h_s \left[ N^T \right] T_s \, d\Gamma  
\{ \mathbf{q}_g^R \} = \int_{r_s} h_g \left[ N^T \right] T_s \, d\Gamma  
\text{where } T_s \text{ and } T_h \text{ are the temperature on the contact surface belong to the strip and the rolls.}  

An interactive algorithm which is to solve the temperature distribution of one side by substituting the temperature of the other side as boundary condition is successively repeated till the convergence of the solutions is satisfied.  

Based on elastic-viscoplastic constitutive models, finite element equation for stress analysis of the strip is reduced to  
\[ \{ [K] \} \mathbf{F} = \{ \mathbf{f}_e \} + \{ \mathbf{f}_t \} + \{ \mathbf{f}_v \} + \{ \mathbf{f}_\varphi \} \]  
where \([K]\) and \(\{ \mathbf{f} \}\) are the stiffness matrix, deformation rate vector, \(\{ \mathbf{f}_e \}\), \(\{ \mathbf{f}_t \}\) and \(\{ \mathbf{f}_v \}\) denote force vectors of the elastic deformation, thermal expansion, solidification extraction and inelastic deformations. Based on this algorithm, the finite element codes are developed to analyze the twin roll casting process.  

2.4 Evaluation Model of Crack Criteria  
The susceptibility to crack induced by stresses in material could be evaluated from follow crack criterion defined based on the principal stress and a temperature dependent ultimate strength.  
\[ C.I. = \begin{cases} 0 & T > T_{\text{ZST}} \\ \xi_s \left( \sigma_p / \sigma_R \right) & T_s \leq T \leq T_{\text{ZST}} \\ \sigma_p / \sigma_R & T < T_s \end{cases} \]  
Here, the level of crack index could be used to evaluate crack susceptibility,  
\[ C.I. = \begin{cases} > 1, & \text{Dangerous} \\ \leq 1, & \text{Safe} \end{cases} \]  
In former models, \(\sigma_p\) and \(\sigma_R\) indicate the principal stresses and ultimate strength. \(\xi_s\) is solid volume fraction in mushy zone. When a positive value of cracking index at a point reaches greater than one, namely, which are subjected to tensile stresses more than the ultimate strength, it means that the material is subjected to crack.  

The critical strength is given by  
\[ \sigma_R = K (T_c - T)^0.5 \]  
where \(T_c\) indicates the critical temperature of the alloy. \(K\) is the coefficient of material derived from experiments.  

This critical strength model was originally employed by Ramacottico to carbon steel [5] which was interpolated from data produced by Weinberg [11]. He used \(K=1.2 \cdot 10^{-0.5}\) and \(T_c=T_s\) namely the solidus temperature. In his model, when the temperature reaches melting point namely solidus temperature, the ultimate strength of material will reduce to zero. However it does not correspond to reported results by Hiebler etc. [12].  

Solidus temperature (solidification fraction rate is 1 or relatively over 0.95) is equated with zero-duclity-temperature at which the liquid film between dendrites spoils the solid continuity and plasticity. The ramification of the secondary dendrites arms and capillary forces of the last residual liquid between the dendrite enables the solidifying material to transmit forces below zero-strength-temperature (ZST) according to solid fraction around 0.65. Therefore, in this research the ZST point that solid fraction is 0.65 is employed as the critical temperature for crack formation prediction. For the employed aluminum alloy in this casting, \(K\) was identified by the same method as \(K=1.067^{-0.5}\). The crack index of the material over solidus temperature is modified with a solid fraction factor to reflect effect of solid volume fraction in mushy zone. Based on the modified crack evaluation model, crack indexes are calculated from the simulated temperatures and stresses in casting strip.  

3. SIMULATED RESULTS  

3.1 Temperature Distribution of Casting Strips  
By the above finite element models, temperature distribution and solidification fraction in molten pool, as well as temperature of casting strip on surface and in center are clarified. Fig. 2 shows temperature distribution on surface and center as well as solid fraction on center of casting strip at casting speed 10 m/min. We could know the temperature on strip surface decreases rapidly as casting start. Due to center temperature lowers down relatively slow, there is a great difference of the temperature on surface and center. There is over 600°C temperature difference between surface and internal strip. After the strip runs out of exit point, there is an
obvious heat recovery and the temperature of the strip turns to accordance. In addition, the measured strip temperatures show good agreement with the simulation value, which verifies that the simulation is believable [3,10].

3.2 Distribution of the Stresses

Figure 3 presents the stresses on surface and center from meniscus to exit point under casting speed of 10m/min. Generally stresses on surface are much greater than that in center, and in nip zone greater than in upside. In the upside of pool, stresses are mainly thermal stresses due to great temperature gradient caused by chilling rolls. As solidification develops, visco-plastic deformation plays more and more role in devotion to stresses level. The compressive stresses on surface in strip thickness and height direction increase, meanwhile shearing stress increases and turns into tensile stress. On the center line of strip all the stresses in internal are tensile stresses and they generate more slowly than that on surface.

Figure 4 shows the stresses in nip zone near exit point (H=69 mm from meniscus) from surface to center while casting speed is 10m/min. We could know, stresses in internal are nearly uniform tensile stresses and the level are below than 10 MPa. Stresses on surface are complex, there are strong compressive stress in strip thickness direction and rather great shear stress due to plastic deformation. Compressive stresses on strips surface and near internal part are benefit to prevent crack formation.

3.3 Evaluation of Pregnant of Cracks

The crack susceptibility indexes calculated from temperature and maximum principal stress along strip length at various casting speeds are shown in Fig. 5. We could clearly know, at casting speed 10 m/min and 13 m/min, the crack indexes both on surface and in center are below than one, which implies that the strip are in security at these process condition and there will not occur to crack. In the case of speed at 8 m/min, the strip is subjected to fracture. These results were confirmed by microscope observations shown in Fig. 6. We could see the strip surface is rather tough and has many micro cracks about 2mm long at casting speed 8 m/min. Usually we regard that lower speed that increase the solidification finish point is benefit for enhancing the strength of casting strip. But from this result, it implies that increasing finish point will result in stress increase and then lead to crack.
3.4 Discussions on Dangerous Positions

The crack index curves shown in Fig. 5 have two parts along strip length coinciding with the first and second cooling stage. The crack indexes increase greatly in first cooling zone and have a small change in the second cooling zone. For the process condition at casting speeds 10 m/min and 13 m/min, the dangerous positions are on surface in first cooling and center in second cooling.

In the first cooling zone, rapid cooling and visco-plastic deformation plays main role to stress level which lead to crack index increase rapidly on surface. In the nip zone near exit point, because full solid zone is formed and pressed in high temperature, the crack index reaches high level. It implies that the weakest position of the cast strip is at nip zone near exit point, which coincides with the phenomenon that strip sometimes breaks in exit point. On strip surface there is a valley after exit point due to the effect of heat recovery. Due to tensile effect of thermal expansion near surface to internal part, crack index increase in center at the second cooling zone. Proper second cooling is very important to decrease the occurring possibility of cracks and improve the strip quality.

Figure 8 shows the cracking index of the cast strip from center to surface at the exit point in nip zone at three casting speeds. We could know that strip is safe for the casting speed 10 m/min and 13 m/min and is dangerous to crack at casting speed of 8 m/min. The uniform distribution of low-level tensile stresses in internal and effect of compressive stresses near strip surface keeps the strip in security.
3.5 Direction of Principal Stresses
Regarding the direction of first principal stress to be related to crack formation direction, the direction angle of computed maximum principal stress to strip thickness direction is analyzed. Figure 7 shows the calculated angle on surface and center at various casting speeds. The direction angle of the first principal stress varies quite great in two cooling stages. On the surface of strip, the direction angle of the first principal stress changes from positive 45 degree to minus 45 degree. This reflects the change of devotion stresses from thermal stress to visco-plastic deformation stress. There is a peak at the start of second cooling stage which is caused by the effect of heat recovery. The great sudden variations on center are resulted from influence of mushy zone and heat recovery at start stage of the second cooling. We could know direction angle changes susceptibly to the stress level variation. It gives an instructive factor to understand the change history of principal along the strip length.

4. CONCLUSIONS
In this study, stresses formation in twin roll strip casting process was analyzed considering thermal, solidification and inelastic deformation. The distribution of stresses was used to evaluate the formation of crack on the surface and at the internal of the strips. From the results, following conclusions can been drawn:

1. The weakest position of the cast strip is at nip zone near exit point vicinity, which is resulted from heat recovery and thermal expansion of strip.
2. It is confirmed that the casting strips are in security at the employed process conditions under casting speeds as 10 and 13 m/min. The distribution low-level tensile stresses and effect of compressive stresses decrease susceptibility of the solidifying material to crack.
3. Lower casting speed will lead to arise of solidification finish point and then result in high stress, which is unfavorable to strip.
4. Proper second cooling will decrease the occurring possibility of cracks and improve the strip quality.

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