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유한요소법을 이용한 열연중 워크롤의 온도 및 열응력 해석

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Finite Element Analysis of Temperature and Thermal Stress of Work Roll in Hot Strip Rolling

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Abstract

An integrated finite element-based model is presented for the prediction of the three dimensional, transient thermo-mechanical behavior of the work roll in hot strip rolling. The model is comprised of basic finite element models which are incorporated into an iterative solution procedure to deal with the interdependence between the thermo-mechanical behavior of the strip and that of the work roll, which arises from roll-strip contact, as well as with the interdependence between the thermal and mechanical behavior. Demonstrated is the capability of the model to reveal the detailed aspects of the thermo-mechanical behavior and to reflect the effect of various process parameters.

Key words : transient, three dimensional, thermo-mechanical, finite element model

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1. Introduction

Flat rolling is a process in which the thickness of a flat sheet is passing it between two counter-rotating cylinders separated by a fixed distance. In the past, various analytical and numerical techniques have been applied to predict the metal flow occurring in the strip in cold and hot rolling, to a degree far beyond the scope that the elementary rolling theories can cover. Among them, finite element models were especially successful with regard to revealing the most detailed aspects of the metal flow characteristics in two and three dimensional rolling. Examples are found in many more articles [1-3]. During rolling, the work roll receives heat from the strip while the strip surface is chilled as it contacts the roll. The roll is also subject to surface cooling by water spray and by air. Prediction of the detailed thermal behavior of the roll-strip system is of great interest. Tseng [4] used the finite difference method for analyzing the steady state thermal behavior of the strip and of the entire of work roll. As we know, metal flow is influenced by the temperature distributions in the strip since the flow stress is strongly dependent on temperatures. On the other hand, the temperature distributions in the strip are affected by the heat generation due to plastic deformation and interface friction and also by the velocity field in the strip, resulting in strong correlation between the metal flow and the thermal behavior of the strip. In the sense that the interdependence between the thermal behavior of the strip and that of the work roll, this relation should also be taken into account. Hwang[5] rigorously treated the interdependence by conducting a coupled analysis of the thermo-mechanical behavior of the strip and the thermal behavior of the entire work roll. However, all the aforementioned works were done by two dimensional models.

In this paper, a finite element based process model was presented for the three dimensional analysis of the transient thermo-mechanical behavior of the strip and of the work roll. Then, a series of process simulation were carried out to reveal the characteristics of the transient thermo-mechanical behavior.

2. Finite Element Models

For the modeling of the metal flow occurring in the strip, a penalty rigid-viscoplastic finite element formulation is used, as described in [6], and flow stress is considered as a function of strain, strain rate and temperature. In addition, the modified Coulomb friction model is applied, as interpreted in [7].

The governing equation for three-dimensional transient heat flow in the strip as well as in the work roll are given by

$$\rho c \frac{\partial T}{\partial t} + \rho c v_i T_{,i} = (k T_{,i})_{,i} + Q \tag{1}$$

Where Q represents the heat dissipated by plastic deformation. In order to avoid the spurious node to node numerical oscillations, the Petrov-Galerkin method is necessary.

The equilibrium equation for three-dimensional thermo-elastic deformation is given as follows :

$$\sigma_{ij,j} + f_i = 0 \tag{2}$$

Constitutive equation :

$$\sigma_{ij} = \lambda d \delta_{ij} + 2\mu \varepsilon_{ij} - 3K\alpha (T - T_{ref}) \delta_{ij} \tag{3}$$

where λ and μ are lame constant, K is bulk modulus. α is the coefficient of linear thermal expansion.

3. Results and Discussions

3.1 Transient thermo-mechanical behavior on initiation of rolling

Fig. 1 shows the finite meshes for the roll and strip selected for the three dimensional analysis of the transient themo-mechanical behavior of the roll-strip system. Note that the mesh density distributions adopted for the roll were non-uniform, to take into account the occurrence of relatively large temperature gradients at the bite region. As for the initial conditions, 20 ^{o}C was selected as the initial temperature of the roll, while the initial temperature of the strip was assumed to be equal to the inlet temperature of the strip, which was 1077 ^{o}C. The roll speed was selected about 75 *mpm* and radius of the roll was about 405 *mm*. It takes about 2 *s* for the roll undergoing one revolution and about 0.03 *s* for the strip passing through the roll gap. The simulation was continued until t = 0.45 second was reached. For comparison, simulation was also conducted to reveal the steady state thermo-mechanical behavior (time independent behavior which may be observed after rolling of an infinitely long strip).

Fig. 2-a shows the surface temperature distributions at the mid-plane of the strip at the different times. In 0.3 second after initiation of rolling, the surface temperatures of the strip almost reach the steady state, especially at the bite region. The maximum difference of temperature at the bite region, between the solution by transient and by steady state simulation, is less than $10\ ^{o}C$. The same observation was made for the core temperatures of the strip, as may be seen from **Fig. 2-b**. The present results indicated that variation of the strip temperatures with time can be neglected and the strip temperatures obtained from an analysis of the steady state thermo-mechanical behavior may be assumed all the time during rolling. Regarding the surface temperatures of the roll at the bite region on initiation of rolling, they may also be approximated by the steady state temperatures, as shown in **Fig. 3**. However, excluding the bite region, the surface and the core temperatures of the roll were found to be far smaller that what could be achieved at the steady state.

3.2 Transient thermo-mechanical behavior during rolling / idling

With regard to the computer memory and computing cost, complete three dimensional transient analysis of the roll-system becomes formidable. The fact that variation of the thermo-mechanical behavior of the strip with time was negligible had naturally led to a more efficient methodology for an analysis of the transient thermo-mechanical behavior of the work roll, as follows: First, conduct an analysis of the steady state thermo-mechanical behavior of the roll-strip system, to predict the distributions along the bite region of surface temperature of the strip, interface heat transfer coefficient, and heat flux due to friction. An analysis of the transient thermo-mechanical behavior of the work roll may then be performed, choosing the predicted surface temperatures of the strip and interface heat transfer coefficients as the time-independent constants characterizing the contact heat transfer boundary conditions as well as prescribing the heat flux due to friction at the bite region. With this approximation, investigated was consecutive rolling of five strips under the same process conditions. The rolling and roll idling time for each strip were assumed to be 80 second and 40 second, respectively.

The typical thermal stress distributions along the roll surface are illustrated in **Fig. 4**. Only the circumferential stress $(\sigma_{\theta\theta})$ shows abrupt variation, but radial stress (σ_{rr}) and shear stress $(\sigma_{r\theta})$ are nearly zero at surface. As far as circumferential stress is concerned, the compressive stresses occur at the bite region, while the tensile stresses occur in the rest of the roll surface. It should be noted that the roll main body temperatures would be smaller than what could be achieved at the steady state regardless of the number strips to be rolled, due to periodic roll idling during which roll cooling may be extensive. As a result, the thermal stress distributions in the roll during rolling of each strip would be such that the maximum compressive circumferential stress, which occurred near the roll exit, would be greater, and the maximum tensile circumferential stress, which occurred at one of the strip zones, would be smaller in magnitude than what could be achieved at the steady state, as may be confirmed from **Fig. 5**. In fact, the circumferential stresses at the spray zones were found to be still compressive at the completion of the fifth strip, as shown in **Fig. 5-a**.

4. Concluding Remarks

An integrated finite element-based model was developed for the prediction of the transient themo-mechancial behavior of the work roll in hot strip rolling. Capability of the model to reveal the detailed aspects of the transient behavior and to reflect the effect of various process parameters was then demonstrated through the present investigation. Further, from the observations of the characteristics of the thermo-mechanical behavior occurring on initiation of rolling, the simplified versions were derived for the prediction of the thermal stresses in the thin zone near the roll surface.

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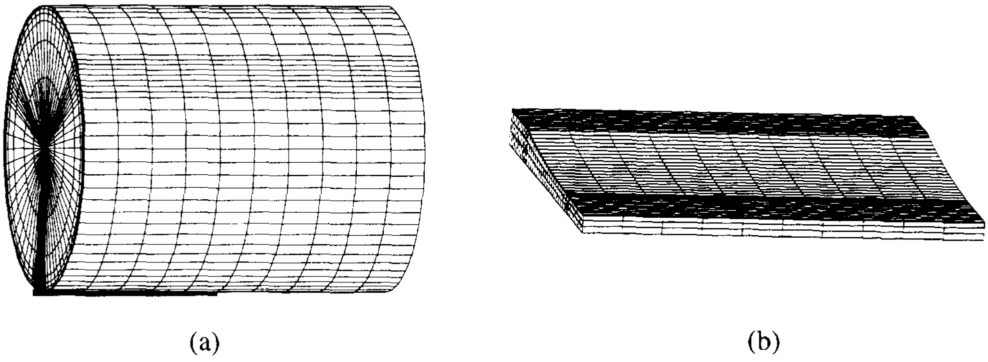
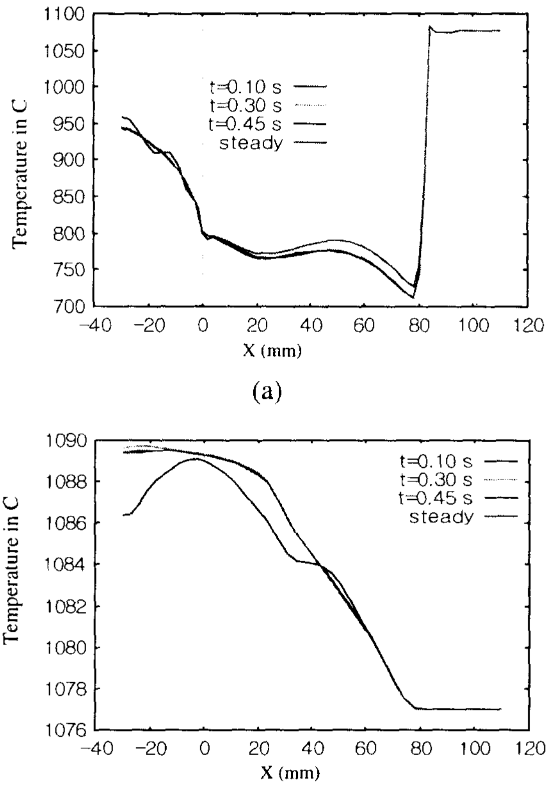

(a) (b)

Fig. 1: Finite element meshes (a) for the work roll, (b) for the strip.



(a)

(b)

Fig. 2: (a) Strip surface temperature distributions along the rolling direction, (b) Strip core temperature distributions along the rolling direction.

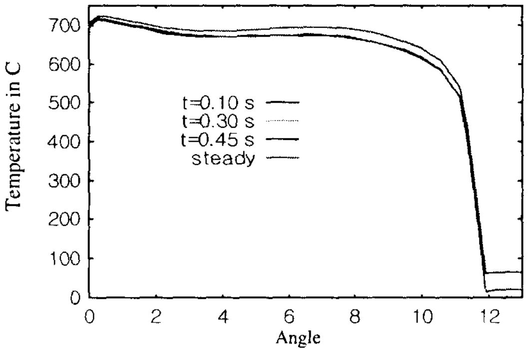


Fig. 3: Roll surface temperature distributions along the bite region.

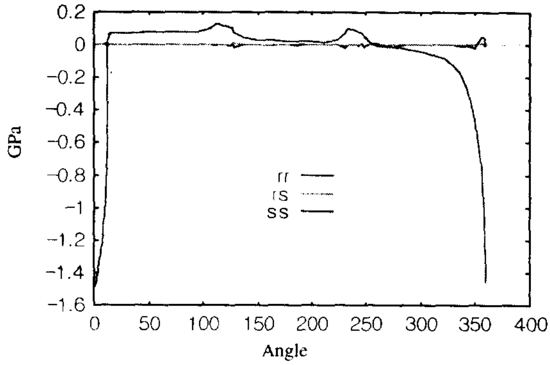
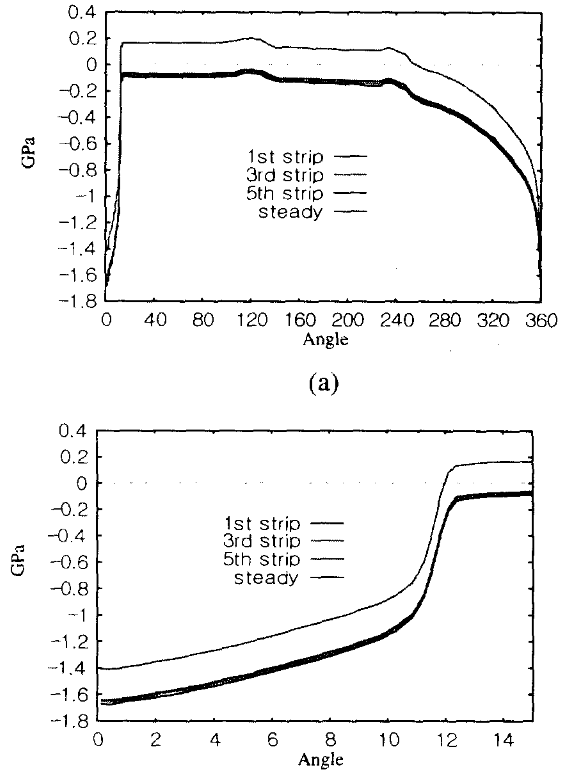


Fig. 4: Typical stress distributions at the surface in the midplane of the work roll.



(a)

(b)

Fig. 5: Circumferential stress distributions at the mid-plane of the roll, predicted at the completion of 1st, 3rd and 5th strip. (a) along the entire arc, (b) along the bite region.