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스테인리스 304 슬라브의 HCR 조건시 열적/기계적 거동

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Thermo-Mechanical Behavior of Type 304 Stainless Slab in Hot Charge Rolling Condition

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Abstract

A finite element-based, integrated process model is presented for a three dimensional, coupled analysis of the thermal and mechanical behavior of type 304 stainless slab during hot charge rolling (HCR) and cold charge rolling (CCR) processes. The validity of the proposed model is examined through comparison with measurements. The susceptibility on micro-crack initiation or propagation due to the thermal stress in these two different process conditions was examined. The model's capability of revealing the effect of diverse process parameters is demonstrated through a series of process simulation.

Key Words : Finite element method, HCR, CCR, thermo-mechanical behavior, three-dimensional, micro-crack.

1. Introduction

The high strength, work hardening capability and excellent corrosion resistance of austenitic stainless steels are of great interest for many structural and metal forming applications. Conventionally, the continuous cast austenitic stainless slabs are cooled in water pool to room temperature, which is called Cold Charged Rolling (CCR), and must be reheated before hot rolling process. Normally, when cooled in water pool, a relatively higher tensile thermal stress may be generated at surface of slab due to the high cooling rate, which may account for the propagation of the formed micro-crack in casting or initiation of the new micro-crack. Therefore, at room temperature, the surface damage including these enlarged micro-cracks can be detected and removed by the subsequent surface grinding. Precise modeling of the thermo-mechanical behavior of slab in water pool, however, is a difficult task, due to the complex mechanism of pool boiling process, also due to the strong interaction between the thermal and mechanical behavior, transient nature, and the three dimensional aspects.

Nowadays, Hot Charge Rolling (HCR) process[1,2] has gradually replaced CCR process to be a new process – a connection between the continuous casting and the hot strip rolling. In this way, the cast slabs are directly charged to the furnace for the subsequent hot rolling.

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Consequently, HCR process not only leads to a saving in energy but also affects the microstructure development during the subsequent processes.

Presented in this paper was a integrated, three dimensional, finite element(FE)-based approach for the prediction of the thermo-mechanical behaviors of a type 304 stainless (STS 304) slab in CCR and HCR processes. The validity of the proposed models was examined through comparison with measurements. Through a series of process simulation, the advantage of HCR process in the sense of the surface cracking was also determined.

2. Finite Element Process Modeling

A 3-D non-steady state FE model was developed for the analysis of the heat transfer occurring in the slab during HCR and CCR. The governing equation for non-steady-state heat flow in the slab during cooling is given by

$$\rho C_p \frac{DT}{Dt} = (kT_{,i})_{,i} + \dot{Q} \qquad (1)$$

where ρ , C_p and k are density, heat capacity and thermal conductivity, respectively, and $\dot{Q}$ represents the heat generation due to plastic deformation. The Updated Lagrangian FE model was adopted in the thermo-elastoplastic analysis. The total strain rate was assumed as :

$$\dot{\varepsilon} = \dot{\varepsilon}^p + \dot{\varepsilon}^e + \dot{\varepsilon}^{th} \qquad (2)$$

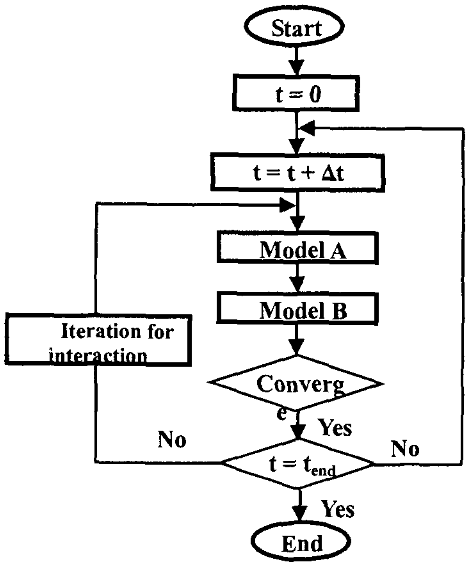
Where $\dot{\varepsilon}^p$ and $\dot{\varepsilon}^e$ are plastic and elastic strain rate, respectively. $\dot{\varepsilon}^{th}$ denotes the strain rate due to thermal expansion. The constitutive relationship is assumed to obey the Prandtl-Reuss flow rule and Von Mises's yield criterion. As shown in Fig. 1, interaction between the thermal behavior and the mechanical behavior of the slab was taken into account by an iterative solution scheme.

3. Results and Discussion

Investigated was the thermo-mechanical behavior of the STS 304 slab occurring in HCR and CCR processes of POSCO no. 2 stainless steel casting works.

3.1 Application in CCR Process

When hot plate immersed into the water pool, if its initial temperature is well above the boiling temperature of water, a successive stages of heat transfer will govern the cooling process: film boiling, transient boiling, nucleate boiling and convection stage[3]. If the flat plate is horizontally immersed into the water pool, the heat transfer at top surface may obey the aforementioned mechanism; on the contrary, only the film boiling stage may characterize the heat transfer at the bottom surface[4].



Model A : Analysis of transient heat transfer

Model B : Analysis of thermo-elastoplastic deformation

Fig. 1 An integrated FE process model

The predicted temperature distributions at the top and bottom surface and center of hot plate were compared to the experiments by Mitsutsuka[4] for the low carbon steel when horizontally immersed into water, and a good agreement was obtained, as shown in Fig. 2.

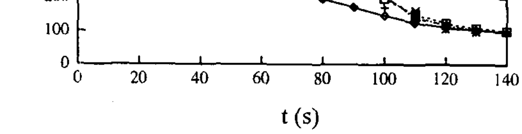


Fig. 2 Predictions and measurements of slab temperatures when immersed in water.

It should be noted that STS 304 slab was normally stored in water pool for about 30 seconds and the water temperature in the pool was assumed as 70 °C. The time step size used in current analysis is 0.1 second. Owing to the fact that the surface cracking of austenite stainless steel, located in the vicinity of strip edge in hot strip rolling, was mostly taken place along the rolling direction, the mean edge thermal stress (σ_{xx}) at surface along the rolling direction was mainly revealed in the current investigation. The detailed variation of mean temperatures along the rolling direction with time for the four representative points (mid-plane surface, edge surface, mid-plane center and edge center) was illustrated in Fig. 3. The cooling rate at top surface of slab edge appeared remarkably higher from the initiation to the first 10 seconds' immersion, in the mean while, the temperature at center of mid-plane looked hardly affected, indicating the observation of the noticeable higher edge stress in tension from the initiation of immersion cooling, which was depicted in Fig. 4. After 30 seconds' immersion, the slab will be pulled out from the water pool and stored in the yard, therefore, the heat recovery and air cooling may govern the subsequent processes. As a result, the temperature gradient between the surface and center becomes smaller due to the heat recovery, indicating that the edge stress in tension can arrive to the highest magnitude at 30 seconds after immersion. These relatively higher tensile stress in the slab edge occurred when the slab was immersed in water pool may have a close correlation with the aforementioned initiation or propagation of the micro-crack with high susceptibility, which may be relevant to the surface edge cracking in hot strip rolling.

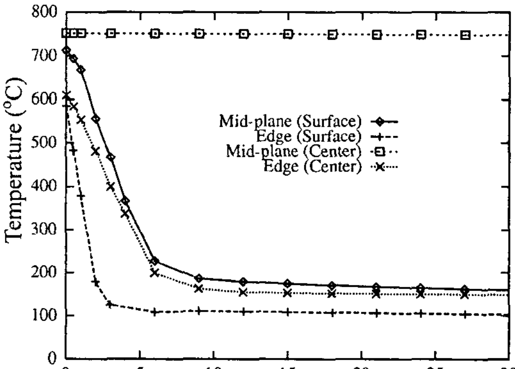


Fig. 3 The variation of the predicted temperatures with time when CCR process

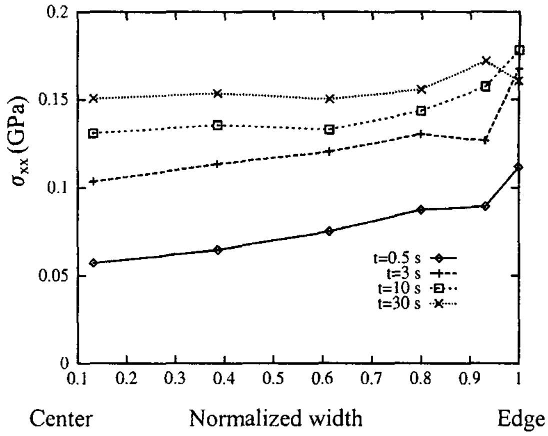


Fig. 4 Variation of σ_{xx} at top surface along the slab width with time in CCR process

3.2 Application in HCR Process

Since the surface scale generated in casting process may become one of the inclusions which contribute to surface damage during the subsequent hot rolling process, it is generally detached by the spray water, which is also adopted in HCR process, as demonstrated in Fig. 5.

Since the slab head suffered from the concentrated spray cooling in the first 90 seconds, the lower temperature distributions were found in the slab head, and due to the subsequent cooling by the remained water, the unsymmetric temperature distributions between the top and bottom surface can be observed from the slab edge surface. As a result, the front area of the slab showed the rather higher tensile stress distributions, which can be found in Fig. 6a, indicating that the plastic deformation seemed mainly occurred at the front area of slab. With respect to the proper comparison, it is suitable to separate the whole top surface into three zones in sequence along the moving direction, as named Zone I, II and III, to demonstrate the different behaviors in HCR process. The surface temperature of first zone reached the smallest when the front area just left the cooling zone, resulting in the highest tensile stress at the surface of slab at this moment, as shown in Fig. 6a. As the process progressed, the surface tensile stresses appeared much decreased as the surface temperatures were increased due to the heat recovery. On the contrary, the surface stresses showed extremely small for the other zones in the first 90 seconds mainly arising from only air cooling, as described in Fig. 6b and 6c. Owing to the different location when leaving spray cooling area, the moment associated with exhibiting the maximum tensile stress was diverse for these two zones: 105s for the Zone II and 110s for Zone III.

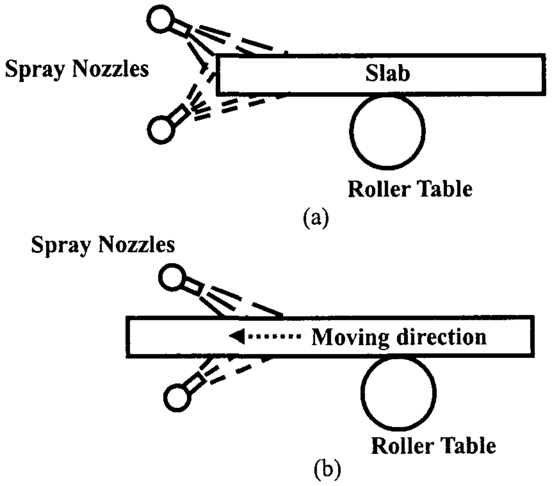
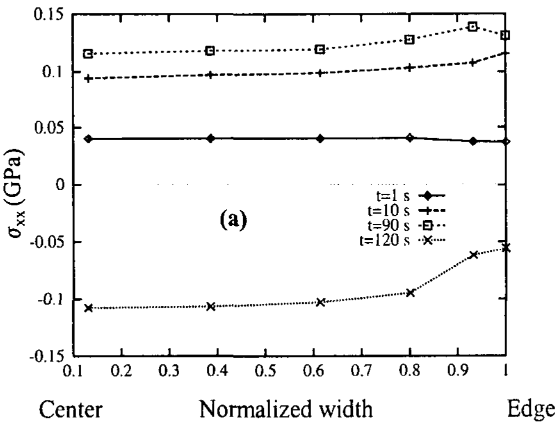


Fig. 5 Spray cooling in HCR process: (a) fixed cooling for 90 seconds, (b) moving cooling for 30 seconds



4. Conclusion

A finite element-based process model was presented for the precise prediction of the thermo-mechanical behavior of slab occurring in CCR and HCR processes. It was demonstrated through the present investigation that the model is effective for acquiring the knowledge regarding the susceptibility on surface edge cracking of slab between these two different processes, and consequently, for the successful exploring the higher resistance to surface deterioration by HCR than CCR process.

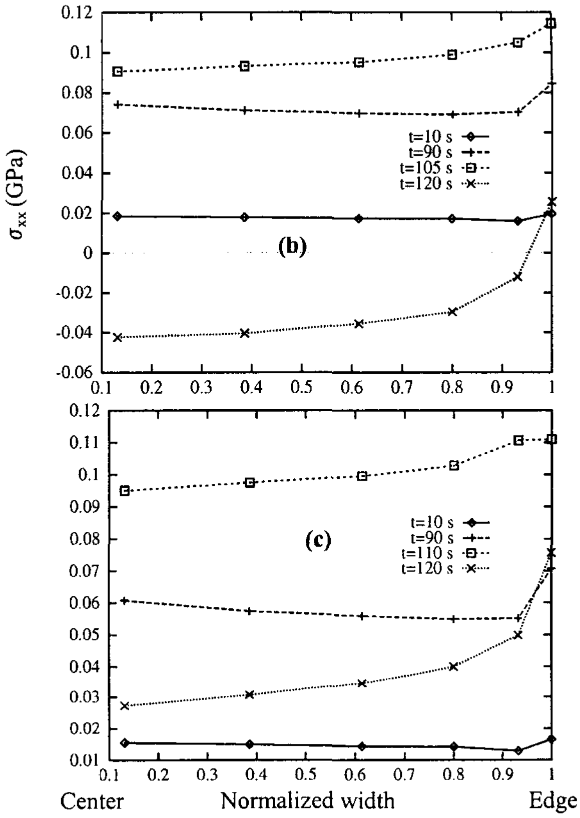


Fig. 6 Variation of surface σ_{xx} at zone I (a), zone II (b) and zone III (c) along the slab width with time in HCR process.

References

(1) G. Matsumura, Y. Inoue, S. Sanagi, K. Honda and H. Kato, 1981, *Tetsu-to-Hogane,* Vol. 67, pp. 110.

(2) Y. Kamada and T. Hashimoto and S. Watanabe, 1990, *ISIJ Int.*, Vol. 30, pp. 241.

(3) A.F. Mills, 1999, "Basic Heat and Mass Transfer", Prentice-Hall, New Jersey, USA, pp. 603.

(4) M. Mitsutsuka and K. Fukuda, 1977, *Tetsu-to-Hogane,* Vol. 63, pp. 110.