Investigation of the Thermo-mechanical Behavior of Type 304 Stainless Slab in Hot Charge Rolling Condition by the Finite Element Method

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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. Generally, the surface micro-cracks are often found on the continuous cast austenitic stainless slabs,1–3) which may arise from the non-homogenous solidification, the high hydrostatic stress within the liquid part of the strand and friction between the surface of the material and the mould in the continuous casting process, et al. Such micro-cracks, mostly hundreds of micrometers, are not easily visible. However, they may grow to be long cracks in the subsequent processes, which act as surface damage to deteriorate the corrosion resistance and formability of the product.4,5)

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. As a result, most of the modeling efforts were concentrated only on the local heat transfer characteristics in the water pool over the decades.6,7) Recently, Katsuki8) determined the potency on the crack initiation of ferritic stainless steel (SUS 430) during the immersion cooling in water by the thermo-mechanical analysis, but limited in two dimensional analysis.

Nowadays, Hot Charge Rolling (HCR) process9–11) 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. Consequently, HCR process not only leads to a saving in energy but also affects the microstructure development during the subsequent processes. Kamada et al.12) demonstrated the comparison of strength and toughness for Nb bearing steel under HCR and CCR conditions by experiment. The evolution of microstructure during HCR process was also simulated by Li et al.13) However, very few studies have been undertaken on the surface cracking in both HCR and CCR processes.

Presented in this paper was an 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

2.1. FE Heat Transfer Model

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_v \frac{DT}{Dt} = (kT)_p \dot{Q} \quad \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots 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Table 2. The thermal and mechanical properties of STS 304.

(thermal properties)

| Temperature (°C) | k (W/mm°C) | Specific Heat Capacity (J/mm°C) |
|------------------|------------|--------------------------------|
| 27               | 0.0150     | 27 0.003768                     |
| 127              | 0.0170     | 127 0.004068                    |
| 227              | 0.0180     | 227 0.004258                    |
| 527              | 0.0220     | 527 0.00440                     |
| 727              | 0.0250     | 727 0.004827                    |

(mechanical properties)

| Linear Thermal Expansion Coefficient | Young’s Modulus (E) | Possions’ Ratio (ν) |
|-------------------------------------|---------------------|---------------------|
| Temperature (°C) | α (10⁻⁵/K) | Temperature (°C) | E (GPa) | Temperature (°C) | ν |
| 20           | 16.0       | 20           | 193     | 20           | 0.2515 |
| 200          | 17.0       | 100          | 191     | 100          | 0.2733 |
| 400          | 18.0       | 200          | 183     | 200          | 0.2708 |
| 600          | 19.0       | 400          | 168     | 400          | 0.3125 |
| 800          | 19.5       | 600          | 148     | 600          | 0.3704 |
| 1000         | 20.0       | 800          | 128     | 800          | 0.28  |

$h_{top}$, a strong function of slab temperatures, was adopted according to the reference,\(^7\) as shown in Fig. 5, on the other hand, the heat transfer coefficient at the bottom surface, $h_{bottom}$, was adopted as the well developed, analytic form from the reference.\(^17\)

$$h_{bottom} = 0.425 \left[ \frac{(\rho_s - \rho_v)gh_vk_v^3}{v_s \Delta T_s - T_{sat}} \right]^{1/4} \tag{8}$$

Where, $\rho_s$ is the density of liquid; $k_v$, $\Delta T_s$ and $v_s$ are the den
sity, conductivity and kinematic viscosity of vapor, respectively; \( L \) is the characteristic length; \( h_L \) denotes the enthalpy of vaporization; \( T_w \) and \( T_{sat} \) are the temperature of wall (slab surface) and saturation, respectively. These temperature dependant parameters can be found in the reference.\(^{17}\) The predicted temperature distributions at the top and bottom surface and center of hot plate were compared to the experiments by Mitsutsuka\(^{6}\) for the low carbon steel when horizontally immersed into water, and a good agreement was obtained, as shown in Fig. 6.

It should be noted that STS 304 slab was normally stored in water pool for about 30 s and the water temperature in the pool was assumed as 70 \(^\circ\)C. The time step size used in current analysis is 0.1 s. The typical temperature, thermal stress, and plastic strain distributions of STS 304 slab at the moment when pulled out from water pool were demonstrated in Fig. 7. Due to the rather small heat transfer coefficients (only film boiling stage) at bottom surface, the heat loss from the bottom surface looked quite small, as shown in Fig. 7(a). On the contrary, the heat seemed to be extracted substantially higher from top surface according to the aforementioned boiling mechanism, resulting in the considerably lower temperatures at top surface of slab as about 140 \(^\circ\)C; on the other hand, the decrease of the center temperatures of slab appeared to be quite small, indicating the occurrence of the relatively higher tensile stress at top surface, as illustrated in Figs. 7(b) and 7(c). And the concave shape of slab was encountered due to the higher thermal contraction at top surface. It is apparent that the plastic deformation can be mainly generated at top surface, as shown in Fig. 7(d).

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,\(^{15}\) as shown in Fig. 8, the mean edge thermal stress (\( \sigma_{xx} \)) 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. 9. The cooling rate at top surface of slab edge appeared remarkably higher from the initiation to the first 10 s’ immersion, in the meanwhile, 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. 10. After 30 s’ 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 about more than 160 MPa at 30 s 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.

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. 11. The value of heat transfer coefficient under the water spray was assumed as 0.004 W/mm²°C according to the references, and one fourth of this value was used at the surface with the remained water. The predicted and measured slab temperatures were shown in Fig. 12, and a good agreement was obtained. The typical slab temperature, thermal stress, and plastic strain distributions after water spray cooling were shown in Fig. 13. Since the slab head suffered from the concentrated spray cooling in the first 90 s, the lower temperature, thermal stress, and plastic strain distributions were observed at the surface and center, respectively.

The variation of $\sigma_{xx}$ at top surface along the slab width with time in CCR process was shown in Fig. 10. The variation of the predicted temperatures with time for the representative four points when CCR process was illustrated in Fig. 9.
perature 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 shown in Figs. 13(a) and 13(b). As a result, the front area of the slab showed the rather higher tensile stress distributions, which can be found in Figs. 14(a) and 15(b), indicating that the plastic deformation seemed mainly occurred at the front area of slab, as in Fig. 13(d). With respect to the proper comparison, it is suitable to separate the whole top surface into three zones, as named Zone I, II and III, to demonstrate the different behaviors in HCR process. From Fig. 12, 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. 14(a). 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 Figs. 14(b) and 14(c). 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: 105 s for the Zone II and 110 s for Zone III.

In the light of the comparison between HCR and CCR on the potency of edge cracking, a severity factor, $S$, was introduced in terms of as follows,$^{21)}$

$$S = 1000 \times \int \sigma_x \, d\varepsilon$$

Curves about edge $\sigma_x$ versus $d\varepsilon$ for CCR as well as HCR process were depicted in Fig. 15. In order for the proper comparison, components of stress and strain in CCR were also chosen at the corresponding three zones selected in HCR process. Regarding $S$, it was found that $S$ estimated in CCR was about 2 times higher than that in HCR at the first zone; on the other hand, since the other two zones underwent rather light plastic deformation as shown in Fig. 13(d).
and Fig. 15(b), $S$ predicted at these zones in CCR was about 7 times higher than that in HCR. As a result, zone II and III exerted the extremely higher susceptibilities on edge cracking in CCR than that in HCR process. Figure 16 showed integration of $S$ over the whole surface for CCR as well as HCR, accounting for about 5 times higher severity in CCR than HCR process, which was consistent with the industry observation for the edge cracking deterioration termed as
the Cold Grinding ratio (CG ratio).

4. Concluding Remarks

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. However, the model addresses only a part of surface cracking-related problems, which including the effect of mould oscillation mark depth, δ ferrite distributions, different slab materials and hot rolling process et al. They should constitute a part of the future works to be done to achieve the sound product quality.

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