Finite Element Modeling of Thermo-mechanical and Metallurgical Behavior of Type 304 Stainless Steel in Cold Strip Rolling

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A finite element-based, integrated process model is presented for the coupled analysis of the thermo-mechanical and metallurgical behavior of type 304 stainless steel occurring in the entire tandem mill during cold strip rolling. The validity of the proposed model is examined through comparison with measurements. The model’s capability of revealing the effect of diverse process parameters is demonstrated through a series of process simulation.

KEY WORDS: Type 304 stainless steel; finite element method; thermo-mechanical behavior; metallurgical behavior; cold strip rolling.

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. Recently, with the considerable increase of practical application of stainless steels, the stainless steel strip was newly produced in the tandem mill in the cold rolling process due to its high productivity. However, precise control of product quality, as well as enhancing the production economy, may greatly depend on the mechanical/thermal/metallurgical behaviors of the strip and also on those of the roll during cold rolling, and therefore, in order to achieve successful process design and control, it is highly desirable to be capable of predicting the detailed aspects of these behaviors through sound process modeling.

It was well known that some austenite stainless steels, such as type 304, undergo the deformation induced bcc martensite (α’) transformation from fcc austenite (γ) during cold deformation process. Thus, this transformation kinetics had been extensively studied in the past decades. Olson–Cohen first gave a reasonable estimation for the martensite transformation by the shear-band intersection mechanism under uni-axial strain. Hecker et al. extended the Olson–Cohen relation for the reasonable prediction of the kinetics of γ→α’ transformation under a general strain state. Furthermore, a generalized rate form of Olson–Cohen model for the evaluation of the martensite evolution, which was function of plastic strain, temperature, and stress state, was proposed by Stringfellow et al. Then, a constitutive relationship defining the flow strength of the coexist of two-phase composite was proposed. Recently, Tomita et al. further spread the generalized constitutive relationship by Stringfellow by taking the strain rate effect into account only in tension state; and the extensive application both in tension and compression state was made by Iwamoto et al.

In the past, various numerical techniques have been applied to predict the metal flow and heat transfer occurring in the strip in rolling process, to a degree far beyond the scope that the elementary theories can cover. Among them, finite element (FE) model was especially successful with regard to revealing the most detailed aspects of the metal flow characteristics and thermal behaviors in rolling process. (However, the related works were mostly limited to examining the mechanical/thermo-mechanical behaviors of low carbon steel or Al occurring at a single mill stand. In the sense of thermo-mechanical/metallurgical behavior of austenite stainless steel, recently, Ding et al. well applied the finite volume method to simulate the forging process by considering the aforementioned strain induced martensite transformation, however, very few studies have been undertaken on the application in the cold rolling process.

Presented in this paper was an integrated FE-based approach for the prediction of the mechanical/thermal/metallurgical behaviors that a type 304 stainless strip would reveal as it passes through the entire cold tandem mill. The validity of the proposed models was examined through comparison with measurements. Then, a series of process simulation were conducted to investigate the effect of various process parameters on the detailed aspects of the thermo-mechanical and metallurgical behavior of the strip.

2. Kinetics of Strain-induced Martensite Transformation

In this investigation, considering that the rolling process is rather like the compression than tension state, Iwamoto
model was adopted for the prediction of the evolution of the martensite during cold rolling.

Under constant temperature, strain rate and stress state, volume fraction of martensite may be described as:

\[ f_m = 1 - \exp \left\{ -\beta \left[ 1 - \exp(-\alpha \varepsilon) \right]^n \right\} \] ..........................(1)

\[ \alpha = \alpha_0 \left( \frac{\varepsilon}{\varepsilon_y} \right)^M \] ..........................(2)

Where the kinetic parameter \(\alpha_0\) and \(\beta\), strong function of temperatures, were determined from the experimental observation, which were shown in Figs. 1(a) and 1(b), respectively. \(n\), \(\varepsilon_y\), and \(M\), taken from the references, are described in Table 1. The predicted fraction of martensite evolution was in good agreement with the measurements, as shown in Fig. 2.

Considering that the aforementioned martensite is mainly generated under the condition of the deformation in the rolling process, the fraction of martensite evolution can be determined based on the strain and temperature fields, as follows:

\[ f_m (\varepsilon + \Delta \varepsilon, T) = f_m (\varepsilon, T) + \frac{df_m}{d\varepsilon} \bigg|_{\varepsilon, T} \Delta \varepsilon \] ..........................(3)

Where, \(df_m/d\varepsilon\) may be determined from Eq. (1).

### 3. FE Model for Analysis of Rigid-viscoplastic Deformation

A steady-state, rigid-viscoplastic deformation behavior of the strip was adopted in the present investigation. The detailed finite element formulation may be seen in the references. The flow stress \(\bar{\sigma}\) of the strip within two phases of austenite and martensite may be represented by the mixed rule:

\[ \bar{\sigma} = \bar{\sigma}_{a} (1 - f_m) + \bar{\sigma}_{m} f_m \] ..........................(4)

\[ \bar{\sigma}_{a} = C_{a4} \varepsilon + C_{a5} (1 - \varepsilon) \] ..........................(5)

\[ \bar{\sigma}_{m} = C_{m4} \varepsilon + C_{m5} (1 - \varepsilon) \] ..........................(6)

Where, \(C_{a4}\), \(C_{m4}\), \(C_{a5}\), and \(C_{m5}\) taken from the references, were described in Table 2.

Assume that the strain rate may be decomposed into

\[ \frac{df}{d(e, T)} = \left( \frac{df}{d\varepsilon} \right) \frac{d\varepsilon}{d(e, T)} \] ..........................(7)

Table 1. Material parameters in kinetics of deformation induced martensite transformation.

| \(n\) | \(\varepsilon_y\) | \(M\) | \(R\) | \(\beta\) |
|------|------------|------|------|------|
| 4.5  | \(5.0 \times 10^5\) (1/s) | 0.01 | 0.04 | 0.02 |

Table 2. Material constants in flow stress of austenite and martensite phases.

| \(C_{a1}\) | \(C_{a2}\) | \(C_{a3}\) | \(C_{a4}\) | \(C_{a5}\) |
|------|-----|-----|------|-----|
| 1273.0 | 1.3 | 0.86 | 657.0 | 0.0038 |

| \(C_{m1}\) | \(C_{m2}\) | \(C_{m3}\) | \(C_{m4}\) | \(C_{m5}\) |
|------|-----|-----|------|-----|
| 1191.0 | 1.33 | 0.54 | 1056.0 | 0.0013 |
following three components:

\[ \dot{\varepsilon} = \dot{\varepsilon}^{\text{trans}} + \dot{\varepsilon}^{\text{v}} + \dot{\varepsilon}^{\text{p}} \]  

Where \( \dot{\varepsilon}^{\text{trans}} \) and \( \dot{\varepsilon}^{\text{v}} \) denote the phase transformation induced plastic strain rate and volume change rate due to phase transformation, respectively, which were taken from the references.\(^4,5\) and shown as follows:

\[ \dot{\varepsilon}^{\text{trans}} = R \dot{\varepsilon}^{\text{f}} \]  

\[ \dot{\varepsilon}^{\text{v}} = \Delta \eta \dot{\varepsilon}^{\text{f}} \]  

Parameters \( R \) and \( \Delta \eta \), taken from the references,\(^4,5\) may be found in Table 1. With respect to the high process speed in the tandem cold rolling process, \( \dot{\varepsilon}^{\text{trans}} \) and \( \dot{\varepsilon}^{\text{v}} \) may be neglected when comparing to \( \dot{\varepsilon}^{\text{p}} \), which was verified from the comparison of mean values among these three components by FEM analysis. We found that plastic strain rate \( \dot{\varepsilon}^{\text{p}} \) (=32.8 (1/s)) was extremely much less than the summation of the other two components \( \dot{\varepsilon}^{\text{trans}} \) and \( \dot{\varepsilon}^{\text{v}} \) (=1.04 (1/s)).

4. FE Model for Analysis of Heat Transfer in the Strip and in the Roll

The governing equation for steady state heat transfer in the strip as well as that in the roll is given by

\[ \rho c_{\text{u}} \frac{T}{T_i} = (kT)_{\frac{\text{in}}{\text{out}}} + Q + \dot{Q} \]  

where \( \rho \) is the density; \( c_{\text{u}} \) represent the components of the velocity vector and \( Q \) represents the heat dissipated by plastic deformation. Note that \( \dot{Q} = \Phi \dot{e} \) in the strip and \( \dot{Q} = 0 \) in the roll, when the roll deformation is purely elastic. \( Q \) represents the latent heat discharged during phase transformation according to the references.\(^4,5\)

\[ \dot{Q}_l = \rho \dot{f}_m \]  

\[ l = 1.5 \times 10^4 \text{(J/kg)} \]  

Where, \( \dot{f}_m \) the rate of the fraction of marten site was determined by finite difference method.

In the strip and also in the roll, a large amount of heat is transported to the downstream by convection due to high processing speed. It is well known that when the convection term governs heat transfer more significantly than the diffusion term, solutions based on the standard Galerkin formulation are often corrupted by spurious node to node oscillations. To remove such a numerical instability, proper modification of the standard Galerkin formulation is necessary. The detailed description may be also seen in the references.\(^4,10\)

5. Integrated Process Model

An integrated process model for the coupled analysis of the thermo-mechanical and metallurgical behavior of the strip and thermal behavior of work roll consisted of the aforementioned three basis models—the model for martensite transformation kinetics, rigid-viscoplastic metal flow model, and steady state heat transfer model. Interaction among the thermo-mechanical/metallurgical behavior of the strip and the thermal behavior of the work roll may be summarized as follows: The heat transfer and plastic deformation occurring in the strip affect each other, since the flow stress is temperature dependent while plastic deformation generates heat; plastic deformation and evolution of the martensite phase occurring in the strip are interdependent, since flow stress is function of fraction of martensite phase while evolution of martensite is induced by plastic deformation; the heat transfer and evolution of martensite phase occurring in the strip are interdependent, since evolution of martensite is also affected by temperature while latent heat is discharged during martensite phase transformation; and thermo-mechanical/metallurgical behavior of the strip is coupled to thermal behavior of the work roll due to roll-strip contact. In the present investigation, the interaction was taken into account by adopting an iterative solution scheme, as shown in Fig. 3.

6. Simulation Strategy and Process Conditions

Investigated was the thermo-mechanical/metallurgical behavior of the strip occurring in POSCO no. 2 tandem cold strip mill, pohang works. The tandem mill consists of four mill stands (from stand\(_1\) to stand\(_4\)), with each interval being 4.6 m long. With respect that the tandem cold mill has an extremely large line length compared to the strip thickness, finite element simulation considering the entire mill as a single analysis domain is impractical in the light of the computational efficiency. An alternative choice would be to divide the tandem mill into several sub zones. As shown in Fig. 4(a), each zone may be classified into one of the following two types: stand, zone which represents a mill stand zone occupied by the roll-strip system, and stand\(_i\)–stand\(_{i+1}\) zone, an inter-stand zone. As shown in Fig. 4(b), simulation may be performed for each zone in se-
quence, starting from the first zone until the simulation for the last zone. Note that the temperatures predicted at the current zone were employed as the inlet boundary conditions for the next thermal simulation. Also to be mentioned was that the accumulated strain and fraction of martensite phase from the previous stand, zones \( i = 1, \ldots, n \) were adopted as the inlet boundary conditions for the current mechanical simulation in the stand, \( i+1 \) zone.

The thermal and mechanical properties of the strip and roll, and a variety of process variables selected for the present investigation were summarized in Tables 3 and 4, respectively. Note that the initial temperature of the strip before entering into the stand 1 and the lubricant temperature for each mill stand were measured as about 30 and 45°C, respectively. Also there was no martensite at the initial state. The thermal and mechanical boundary conditions were illustrated in Fig. 5. In the first three stands, the inlet zone is provided with a surplus of lubricant; on the other hand, only little lubricant is supplied in the last stand, instead, because it would generally be desirable for the strip surfaces to be devoid of any residual rolling lubricant after the cold rolling. As a result, the convective boundary conditions were applied to the inlet zone of strip in the thermal analysis for the first three stands. Figure 6 shows the finite element meshes representing the work roll and the strip in a mill stand zone, and a finite element mesh representing the strip in other zones. Note that the mesh density distributions in the work roll were designed so as to take into account the occurrence of the large temperature gradients at the bite region.

Factors affecting the interface heat transfer coefficient between roll and strip under rolling are diverse. They include surface roughness, pressure, temperature, and lubricant. Many studies\(^{12,13} \) have been performed to quantify the relation among them. However, most equations were based on the surface roughness and asperity slope, which were not commonly specified. Recently, Atonetti and Whittle\(^{14} \) developed a simple relationship which can address the effect of the average surface roughness and asperity slope based on the published surface texture data. This equation was also adopted by Tseng and Wang\(^{15} \) to investigate the interface resistance on heat transfer in cold rolling, which was described as follows:

\[
h_{\text{hub}} = 4.748 \times 10^{3} k_{r} R_{a}^{0.257}(P/(P+H))^{0.94} \quad (13)
\]

\[
k_{s} = k_{r} + k_{s} \quad (14)
\]

Where \( R_{a} \) (\( \approx 0.5 \times 10^{-5} \) m) is the mean surface roughness of the roll and strip; \( k_{r} \) and \( k_{s} \) are the conductivity of the roll and strip, respectively; \( P \) is the mean roll pressure; \( H \) is the hardness of the strip, which is generally assumed to be approximately 3 times of the bulk flow stress.\(^{16} \) Implementation of Eq. (13) into the model required an

![Diagram](image)

Fig. 4. (a) Division of a tandem mill into several sub zones, (b) computational procedure.

**Table 3.** Thermal and mechanical properties of the strip and roll.

| Material       | Chemical Composition(%) | Flow stress | \( k \)  | \( \rho c \) |
|----------------|--------------------------|-------------|---------|-----------|
| Type 304 Stainless Steel | C = 0.049, Cr = 18.31, Ni = 8.64, Si = 0.6, Mn = 1.08 | From references\(^{25} \) | Temp. (K) | (W mm\(^{-1}\)°C\(^{-1}\)) |
|                |                          |             | 200.0   | 0.013     |
|                |                          |             | 300.0   | 0.015     |
|                |                          |             | 400.0   | 0.017     |
|                |                          |             | 500.0   | 0.018     |
|                |                          |             | 600.0   | 0.02      |
|                |                          |             | 200.0   | 0.0031758 |
|                |                          |             | 300.0   | 0.0037683 |
|                |                          |             | 400.0   | 0.0040685 |
|                |                          |             | 500.0   | 0.0042581 |
|                |                          |             | 650.0   | 0.0044003 |

Note: \( k \): thermal conductivity, \( \rho c \): specific heat capacity.

| Material | \( k \) | \( \rho c \) |
|----------|---------|-------------|
| AISI 1078 | 0.0452  | 0.00423     |

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additional iteration loop, as shown in Fig. 3, starting from an initial guess of the interface heat-transfer coefficients.

The friction coefficient coherent to the individual mill stand was determined according to the supply of lubricant. The friction coefficient in the first three stands, which apply excessive lubricant, was adopted as 0.06; and that in the last stand, which serves as the nearly dry rolling, was used as 0.2, instead, according to the reference. The predicted roll forces were in excellent agreement with the measurements, as shown in Fig. 7. The mean fraction of martensite along the strip thickness was compared with the experiments, which were conducted by a total 40% reduction within four passes under the room temperatures in four high pilot mill. The initial strip thickness, work roll diameter and rolling speed were 3 mm, 100 mm and 15 m/min, respectively. And

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**Table 4. Process conditions used in simulation.**

| Case No. | Stand No. | D (mm) | H0 (mm) | r (%) | Vθ (m/min) | Tem (°C) | Tαι (°C) |
|----------|-----------|--------|---------|-------|------------|----------|----------|
| 1        | Stand 1   | 422.0  | 2.60    | 26.0  | 160.0      | 30       | 45       |
| 2        | Stand 2   | 426.0  | 1.924   | 14.0  | 180.0      | 30       | 45       |
| 3        | Stand 3   | 435.0  | 1.674   | 10.0  | 200.0      | 30       | 45       |
| 4        | Stand 4   | 448.0  | 1.3066  | 2.0   | 214.0      | 30       | 45       |
| 5        | Stand 1   | 422.0  | 2.60    | 26.0  | 160.0      | 250      | 45       |
| 6        | Stand 1   | 422.0  | 2.60    | 26.0  | 160.0      | 30       | 150      |
| 7        | Stand 2   | 426.0  | 1.924   | 14.0  | 180.0      | 30       | 150      |
| 8        | Stand 1   | 422.0  | 2.60    | 26.0  | 50.0       | 30       | 45       |
| 9        | Stand 1   | 422.0  | 2.60    | 26.0  | 320.0      | 30       | 45       |

Note: 1. D : diameter of work roll, H0 : strip entry thickness, r : reduction ratio.
2. Vθ : rolling speed, Tem : temperature of lubricant
3. Tαι : initial temperature of strip before entering the first stand.

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**Fig. 5.** Thermal boundary conditions for (a) the work roll in a mill stand zone, for (b) the strip in a mill stand zone, and for (c) the strip in other zones, and for (d) the strip in a mill stand zone.

**Fig. 6.** Finite element meshes for (a) the work roll, for (b) the strip in a mill stand zone, for (c) the strip in other zones.
The thickness of the strip was exaggerated.

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a good agreement was obtained, as shown in Fig. 8.

7. Results and Discussion

7.1. Temperature, Effective Strain, Fraction of α at Single Stand

The typical distributions of temperature, effective strain, fraction of evolved martensite in the strip for the first stand zone, were illustrated in Fig. 9. As previously mentioned, the diverse heat generations due to plastic deformation, phase transformation and frictional force at the contact surface between the strip and roll may contribute to the non-symmetric increase of the strip temperatures, as shown in Fig. 9(a). Thank to the small friction coefficient, the nearly homogenous deformation along the strip thickness was found, as in Fig. 9(b), indicating that the nonsymmetric distributions of fraction of the evolved martensite along the strip thickness may be mainly dependent on the previous described nonsymmetric temperature distributions, as depicted in Fig. 9(c). After passing through the first stand, the fraction of martensite evolved at strip center seemed higher than that at surface even though the temperature was observed higher at strip center (the higher temperature, the smaller fraction of evolved martensite when homogenous deformation). This may be inferred from the history of the strip temperatures. Figure 10(a) showed the variation of the surface and center temperatures of strip in the bite region. Before reaching the neutral point, the heat dissipated by the frictional force at the contact surface may play a more dominant effect on the temperature increase comparing to the heat extracted by the chilled work roll at the surface of the strip, resulting in the occurrence of the lower fraction of martensite at the strip surface, as depicted in Fig. 10(b). After then, such difference between the surface and center
in the fraction of was still remained as process continued.

7.2. Temperature, Effective Strain, Fraction of α’ at Entire Mill Stand

Illustrated in Fig. 11 were the distributions of temperature, effective strain and the evolved martensite through the entire mill at the surface and center of the strip. In the bite region, because of the aforementioned heat generation in rolling process, the strip temperatures were quickly raised with the higher temperature at center than that at surface of strip. As described in Fig. 5, after leaving the mill stand, the strip surface is still covered with the retained lubricant film due to the spray at the exit, giving rise to the continuous decrease of the strip temperatures in the interstands. The predicted surface temperatures were in good agreement with the measurements, as shown in Fig. 11(a). Before entering into the mill stands, the excessive lubricant covered at the surface of strip may lead to the over drop of the strip temperatures in the neighborhood of the entry zone except the first stand, where the strip temperatures were increased arising from the higher temperature of lubricant than the initial temperature of strip. Consequently, the similar strip temperatures were observed when the strip entering the mill stands. As shown in Fig. 11(b), the effective strain was dramatically accumulated as rolling progressed, due to the work hardening characteristics. The maximum increase in effective strain was found at the first stand due to its highest reduction ratio. From Eq. (3), the martensite evolution is keenly dependent on the variation of the effective strain, resulting in the similar trend of the martensite evolution as the effective strain accumulation with maximum increment at the first stand, as depicted in Fig. 11(c).

7.3. Effects of Process Parameters on Reducing Rolling Force

With respect to the phenomena about the deformation induced martensite transformation for the type 304 stainless steel, the Sendzimir mill has been generally applied in the conventional stainless steel industry, which possesses the reverse rolling process. With the substantial increase in the practical application of stainless steel, such reversible process with the lower productivity was inevitably needed to be replaced by the tandem mill. However, the characteristics of deformation induced martensite transformation limits the total reduction of the strip under the current mill capacity within 42%. In the mean time, we still meet the broad thirst for the thinner strip from the customer which requires the heavier reduction ratio. From the description of flow stress in Eqs. (4)–(6), to lower the deformation resistance may be acquired by the increase of the temperature, as well as the decrease of the fraction of martensite. Furthermore, raising the strip temperatures can also result in the reduction of the fraction of martensite, as observed in Fig. 2, indicating that the thinner strip may be feasibly produced by improving the strip temperatures. In the current investigation, the augment of strip temperatures may be dealt not only with (I) the rise of inlet temperatures of the strip, or (II) lubricant temperatures, but also with (III) the increase of rolling speed when considering the heat generation by plastic deformation. Since the severe reduction and the increment of the fraction of the martensite phase were concentrated in the front stands as Stand I and II, as shown in Figs. 11(b) and 11(c), the effect of previous mentioned process parameters were focused on these two stands.

By way I, improving the inlet temperatures of the strip may have a practical effect on reducing the rolling force as well as fraction of the evolved martensite, as shown in Fig. 12. The increase of strip inlet temperatures as about 60°C may bring one fifth of fraction of evolved martensite and about 14% decrease in rolling force. However, it should be
mentioned that the excessive lubricant in the entry zone greatly affects the strip inlet temperatures, indicating that the initial strip temperatures raised as 250°C can only result in a rise of about 60°C in strip inlet temperatures. Also to be noted is that such effect seemed limited to the first stand. As depicted in Fig. 11, the increased temperatures in the first stand may undergo the great decrease in the interstand due to the heat extracted by the remained lubricant, resulting in the minor effect to the second stand. Instead, by way II, the augment of the lubricant temperature sounds to have the noticeable effect to match our purpose, because not only the front stands but also the rear stands can be affected as raising the lubricant temperatures for each stand. As shown in Fig. 13, the increment of 100°C for the lubricant temperature may give rise to almost no occurrence of the martensite in both stand I and stand II, and the decrease of the roll force as about 22% in stand I and 20% in stand II, respectively.

Also in the sense of the thermal crown of work roll, raising the strip temperatures as way I may only lead to the rise of the roll temperatures within the strip width, which can aggregate the thermal crown of work roll; on the contrary, by way II, the roll temperatures may be improved in the entire area of covering the sprayed lubricant along the roll axis, which seemed to mainly increase the roll radius in the whole area without building up the thermal crown. Therefore, way II may be preferred.

Improving the rolling speed may certainly raise the strip surface temperatures due to the increase of the frictional heat as well as the decrease of heat loss to the work roll because of the less contacting time between the roll and strip in rolling process, as illustrated in Fig. 14(a), indicating that the noticeable variation of fraction of martensite was also restricted to the surface, as shown in Fig. 14(b). The minor increase of fraction of martensite found at the strip center may be attributed to the enlarged parameter by raising rolling speed, according to Eq. (2). As a result, in spite of the large variation of the fraction of martensite within the vicinity of the surface, the effect of rolling speed on mean fraction of martensite along the strip thickness seemed minor. Even though the increase of strain rate may give rise to the increase of the flow stress as described in the reference,4) due to the fact that the increase of temperature may also cause the decrease of the flow stress, the influence of increasing rolling speed on rolling force appeared minor, as shown in Fig. 14(c). Consequently, increasing the rolling speed sounds not to reach our goal—to produce the thinner strip.

8. Concluding Remarks

A finite element-based approach was presented for the prediction of the thermo-mechanical and metallurgical behavior that a strip reveals as it passes through the entire tandem cold mill. The merits of the present approach lied in many aspects, for example,
(1) its capability of taking into account the strong interaction among the thermal, mechanical and metallurgical behavior of the strip, and also between the thermal behavior of the roll and that of the strip;

(2) its extensive application to the Sendzimir mill though the current application was focused on tandem cold mill;

(3) its application for diverse austenite stainless steels, especially, for type 301, which is to improve the evolved martensite for the application in vehicle; instead, the main work in this study is to reduce the evolved martensite.

Though the raise of the lubricant temperature may be preferred in producing the thinner strip in the current analysis, the effect of increasing the lubricant temperature on lubrication and on the strip surface quality, such as brightness, et al. should become a part of the future works to be done to achieve precise process control.

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