Side-surface Shape Optimization of Heavy Plate by Large Temperature Gradient Rolling

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In order to decrease widthwise trimming loss of heavy plate, the metal deformation in width direction has to be controlled to ensure that the side-surface shape of plate is close to flatness. A method called large temperature gradient rolling (LTGR), which combines rolling with water cooling at the slab surface, is suggested to improve side shape of heavy plate. The process is studied by means of both simulations and experiments. LTGR process can correct the double bulge deformation effectively so as to avoid metal overlaps on the edge of plate by comparing with conventional rolling (CVR) process. The temperature gradient can result in deformation resistance gradient through the thickness of slab. The degree of width spread in the central region of the rolling piece increases under the condition of temperature gradient. It indicates that the deformation penetration deepens into the core area of the plate and the internal metal flow enhances. These results provided guidelines for further investigation and application on side-surface shape control of heavy plate.

KEY WORDS: heavy plate; side-surface shape optimization; large temperature gradient rolling; finite element method.

1. Introduction

Plate rolling technology has progressed rapidly, and the developments of gauge control,1 crown control1 and plan view control2 have contributed to decreasing the yield loss. Some noteworthy rolling methods for getting a better plan view pattern were applied in commercial producing and obtained a certain effect, such as MAS rolling (Mizushima Automatic plan view pattern System rolling)3 and DBR (Dog-Bone Rolling).4

Besides, the profile shape control in width is very important as well. Moazeni and Salimi5 investigated the non-uniformity of thin sheet deformation in width direction by 3D FEM (finite element method). Ruan et al.6 simulated the broadside-longitudinal rolling process and found the different width spread in the rolling direction, which contributes to the formation of convex shapes. For heavy plate rolling, the lateral surface usually takes on a shape known as "double bulge", a concave profile, with maximum spread as "double bulge", a concave profile, with maximum spread on the slab surface is studied. Finite element method (FEM) is applied to explore the variation of widthwise metal flow in temperature gradient rolling. The experimental results verify the feasibility of side-surface shape improvement of heavy plate.

2. 3D FE Simulations

A 3D rigid-plastic thermo-mechanical FE model used in the rolling process was developed by the DEFORM-3D program. The roller was considered as a rigid body. The work piece was defined as a rigid-plastic material with the tetrahedral mesh. The original simulated conditions are shown in Table 1, and the geometry models are illustrated in Fig. 1(a).

The chemical composition of the slab in these simulations and experiments was 0.18C-0.26Si-0.95Mn (wt-%). Based on the results of hot compressive deformation experiments which were measured on a Gleeble thermo-mechanical simulator, the deformation resistance was formulated as:

\[
\sigma = 1.410e^{0.237\varepsilon + 0.09523 \exp\left(6.359 \times 10^3 / T \right)} \quad (1)
\]

where \(\sigma\) is stress (MPa), \(\varepsilon\) is strain, \(\dot{\varepsilon}\) is strain rate (s\(^{-1}\)) and \(T\) is temperature (°C)

The friction between the work roller and the slab adopted the shear friction model

\[
\tau = mk \quad (2)
\]

where \(\tau\) is the friction stress (MPa), \(m\) is the friction factor and \(k\) is the shear yield stress (MPa). Due to the fast cooling during rolling process, the influence of various interface temperatures on the friction coefficient \(m\) should be considered. Referring to Sun,7 friction coefficient decreases as the temperature increases in the hot rolling state. Therefore, the \(m\) is expressed as:

\[
m = 1.06 - 0.00067T_f \quad (T_f > 700°C) \quad (3)
\]

Table 1. Main parameters of the simulations.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roll diameter/mm</td>
<td>450</td>
</tr>
<tr>
<td>Rolling speed/rpm</td>
<td>71.3</td>
</tr>
<tr>
<td>Initial temperature of roller/°C</td>
<td>50</td>
</tr>
<tr>
<td>Initial temperature of slab/°C</td>
<td>1 100</td>
</tr>
<tr>
<td>Young’s modulus/MPa</td>
<td>206</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.3</td>
</tr>
<tr>
<td>Deformation resistance/MPa</td>
<td>Eq. (1)</td>
</tr>
<tr>
<td>Friction coefficient</td>
<td>Eq. (3)</td>
</tr>
</tbody>
</table>

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where $T_f$ is the interface temperature of the rolling piece ($^\circ$C).

The initial conditions of slabs temperature field were homogenous at $1\ 100^\circ$C. The convection boundary condition was described by

$$-\lambda \frac{\partial T}{\partial n} = \alpha (T_f - T_m), \ n = x, y, z \ \ \ \ \ \ \ \ \ \ \ (4)$$

where $T_f$ is the external surface temperature of rolling piece ($^\circ$C), $T_m$ is the object temperature of water or air ($^\circ$C), and $\alpha$ is the convection coefficient (W m$^{-2}$°C$^{-1}$). The value of convection coefficient here for water cooling was 2 000 and air cooling was 100.

The models of two slabs were 100 mm thick, 120 mm wide and 180 mm long. The roll gaps were both 85 mm. One slab was rolled directly in a single pass with natural temperature distribution, namely conventional rolling (CVR) process shown in Fig. 1(b). The other slab was rapidly cooled for 5 s, then had a process of reheating for 20 s, and subsequently was rolled with the same reduction as the former by a single pass, namely large temperature gradient rolling (LTGR) process, as illustrated in Fig. 1(c).

3. Experimental Procedure

Based on the same material properties as those of above simulations, there were two 120 mm wide and 180 mm long slabs. Both of them were rolled from 100 mm to 85 mm by a single pass. The first slab was directly rolled without water cooling. The second one was cooled from $1\ 100^\pm 10^\circ$C to $750^\pm 10^\circ$C at the slab surface with the cooling rate of about $30^\circ$C s$^{-1}$ by ultra-fast cooling (UFC) process,$^{18,19}$ then was reheated to $960^\pm 10^\circ$C at the slab surface and followed by rolling. The prime cooling parameters are the density of water flow of each top header was $1\ 666 \pm 30$ l m$^{-2}$ min$^{-1}$ and that of each bottom header was $2\ 082 \pm 40$ l m$^{-2}$ min$^{-1}$. The internal temperature of each slab was measured by using fine-wire thermocouples in 1/4, 1/2 width and 1/8, 1/4, 1/2 thickness layers. The surface temperature was acquired by using the infrared temperature instrument.

4. Results and Discussion

The temperature distribution along the thickness direction at the exit of rolling deformation zone is depicted in Fig. 2. In CVR process, the temperature field of the whole rolling piece is almost uniform, except for a slight rising of the surface temperature of the slab. It can be explained by the fact that deformation heat is more than the heat loss. However, the temperature distribution of the whole slab has a great gradient through thickness in LTGR process, because of the water cooling at the slab surface before rolling. The simulated results of temperature field are well consistent with the measured ones.

Figure 3 shows the temperature distributions of slab in the width direction at the rolling entrance by CVR and LTGR. There is an obvious difference among the average...
temperatures in different thickness layer. However, the simulated temperature gradients along the width direction by CVR and LTGR are both small and similar in each thickness layer. The measured values also have the same trend. The reason is that the large temperature gradient through thickness is mainly caused by water cooling only in LTGR process, but the temperature distributions through width are caused by air cooling for both of these two rolling method. Based on the above results, the influences of cooling on temperature distribution along the width direction by CVR and LTGR are similar. Therefore, it mainly analyzes the effects of large temperature gradient through thickness on deformation.

Figure 4 presents the broadside-longitudinal rolling and entire longitudinal rolling process. In broadside rolling phase, the end shape of rolling piece, in the rolling direction, will determine the lateral shape of plate in the subsequent longitudinal rolling process. Thus, the end shape and the lateral shape of rolling piece were needed respectively to observe and compare in the analysis of simulations and experiments. In the simulation environment, the end of plate in CVR process shows double bulge and the disparity of lengthwise displacement between top and bottom of bulge is 4.8 mm in Fig. 5(a). It can be found the similar double bulge at the end of plate in CVR experimental process in Fig. 5(b). The extended difference of bulge through thickness is 5.1 mm. As it can be seen in Figs. 5(c) and 5(d), the end shape of rolling piece changes from double bulge to single bulge by LTGR process, the disparity between top and bottom of bulge decreases to 1.5 mm in simulation and 2.0 mm in experiment. These mean that the degree of improvement of side-surface shape increases more than 60% if the slab turns 90° into the subsequent rolling phase. It is noted that metal spread at top side is larger than that at bottom side in Fig. 5(d), because the precision of experimental conditions is difficult to ensure the completely symmetrical rolling bite and symmetrical temperature distribution (the temperature at top side is slightly higher than that at bottom side). According to Figs. 6(b) and 6(d), it is obviously found that the flatness of side-surface shape improves about 50% by LTGR process. This phenomenon of side shapes is similar with that of the
Fig. 8. The distribution of temperature and deformation resistance along the thickness direction in LTGR process. (Online version in color.)

Fig. 9. The maximum rolling force in CVR and LTGR process.

end shapes. As illustrated in Figs. 6(a) and 6(c), the simulated results are in good agreement with the measured ones.

Figure 7(a) shows the metal flow in width direction at the exit of deformation zone in CVR process. The majority of deformation concentrate in the area from 1/4 thickness layer to plate surface. The center metal of plate belongs to hard deformation area and its simulated width spread is less than 1.78 mm. On the contrary, it can be seen an obvious distinction of the metal flow in LTGR process in Fig. 7(b). The larger deformation permeates into the region which is closed to the plate inner. The simulated width spread of internal metal of plate can attain close to 2.35 mm. It is increased by about 30% as compared with the CVR process. From the perspective of experiments, the measured results have the similar variation as well. It is noted that the position of measured maximum width spread by CVR slightly migrates down along the thickness direction compared with the simulated one. The reason is the measured temperature difference through thickness is larger than the simulated result at the edge of slab, as depicted in Fig. 3(a).

Depending on the magnitude of the slab surface heat transfer efficiency by water cooling, there is a large temperature gradient from slab surface to the center. This phenomenon during non-isothermal status leads to the deformation resistance gradient as shown in Fig. 8. In the region below slab surface of low temperature the flow stress increases and the metal flow becomes more difficult, the rolling force can transmit to a deeper seat in the thickness direction of slab. On the other hand, the central temperature of slab keeps still higher, because of the short water cooling procedure. The metal in the neighboring region of slab center can deform more readily, due to the higher temperature and the lower resistance. The temperature gradient increases average deformation resistance, so the simulated and experimental rolling force of LTGR are both slightly larger than that of CVR, as shown in Fig. 9. In a word, in the condition of higher central temperature and lower surface temperature, a great resistance gradient can conspicuously enhance the deformation penetration through thickness of rolling piece and promote the central metal flow.

5. Conclusion

In this research, large temperature gradient rolling technology, in which cooling cooperates with rolling process, was studied. The edge deformation and metal flow through thickness of heavy plate in large temperature gradient rolling process have been investigated and compared with those of plate under conventional rolling process. The following results are concluded.

(1) As a cause of the deformation resistance through thickness of rolling piece, large temperature gradient is generated by a transitory water cooling in hot rolling process. The deformation penetration can deepen into the plate center.

(2) Under the same rolling parameters, the widthwise flow of internal metal increases and that of surface metal decreases in large temperature gradient rolling process by contrast with conventional rolling process. This phenomenon changes the section shape of plate after exiting from the roll gap.

(3) Large temperature gradient rolling can mend the side-surface shape of heavy plate. It is beneficial to eliminate the defect of double bulge and drastically reduce the widthwise loss of trimming.

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