Deformation behaviors of non-oriented silicon steel plate in hot rolling process

Qiang Dong¹, Huihui Liu²

¹School of Mechanical Engineering, Shandong Jiaotong University, Jinan 250357, China
²Shandong Institute for Product Quality Inspection, Jinan 250102, China

successin2010@163.com

Abstract. In this paper, the flow stress behaviors of non-oriented silicon steel are investigated by hot compressive experiments and a constitutive model is built based on the experimental data. The constitutive model provides material model for FE numerical investigation. The deformation behaviors of the non-oriented silicon steel during hot rolling process are investigated by a 3D FE model. Contact stress and plate shape in different working conditions are presented. The FE results can provide primary data for the precise shaping of non-oriented silicon steels in hot rolling process.

1. Introduction

Silicon steel, also known as electrical steel, is an important metallic functional material, which is used to make core plates of transformer, electromotor and generator. Non-oriented silicon steel is the largest consumed ferromagnetic alloy in the world. The deformation of silicon steel plate has important effects on its magnetic property. Landgraf et al.[1] found that magnetic properties of silicon steels are more sensible to small deformation. Paepke et al.[2] pointed out that hot rolling parameters have significant influence on the magnetic properties of a low silicon steel. Hot rolling is a critical process for silicon steel strip production. The defects produced in hot rolling process have a genetic effect on cold rolling strip, ultimately degrading its magnetic property. The quality of final product in hot rolling process depends mainly on the material properties, thickness and plate shape.[3] At present time, the most common defects in hot rolling process are plate shape defects. The hot strip mill is subject to adverse service conditions when producing silicon steel due to its strict technique. [4] The desired plate shape of silicon steel is difficult to achieve because of its inconclusive high temperature deformation characteristic in rolling process. The quality defects generated from hot rolling process are difficult to eliminate in cold rolling and other processes afterwards. The topic of this work is to investigate deformation behavior of a non-oriented silicon steel in hot rolling process by thermal simulation experiment and finite element (FE) caculation, thereby providing guidance for precise shaping of silicon steel.

2. Experiment

2.1. Experimental procedure

Rolling is a process to reduce the thickness of a steel plate from the initial thickness to a pre-determined final thickness with revolving rolls.[5] The HSM in this work consists of a 2-high roughing mill R1, a
4-high roughing mill R2 and seven 4-high finish rolling stands from F1 to F7 [4]. The work piece is heated up to more than 1200°C in the reheating furnace. When passing through the finishing mill, the plate temperature decreases from 945°C in stand F1 to 860°C in stand F7 with the cooling process. Chemical compositions the investigated non-oriented silicon steel is shown in Table 1.

The obtained sample from rolling mill was processed into dozens of standard cylindrical specimens with the diameter of 8 mm and height of 15 mm. Before hot compressive tests, the start and finish temperatures of phase transformations were determined using a dilatometer based on the principle of the expansion differences between austenite and ferrite. The critical temperatures $A_r1$ and $A_r3$ at the average cooling rate of 9.8°C/s in actual steel rolling process are 940°C and 858°C respectively. Therefore, work piece in almost all the finishing stands is in austenite-ferrite dual-phase region. The hot compressive experiments were conducted on Gleeble 1500 thermo-mechanical simulator in the temperature range of 1050~750°C with strain rates of 0.05~10 s$^{-1}$.

### Table 1. Chemical composition of the investigated non-oriented silicon steel

| Element | C  | Si  | Mn  | Al  | Cu  | Cr  | Ni  | Mo  |
|---------|----|-----|-----|-----|-----|-----|-----|-----|
| Wt, %   | 0.001 | 0.301 | 0.249 | 0.053 | 0.032 | 0.024 | 0.012 | 0.003 |

#### 2.2 Flow stress behaviors

Figure 1(a-c) show stress-strain curves of silicon steel in austenite-ferrite region. The test results show that dynamic recovery plays a leading role in silicon steel hot compressive deformation. The flow stress increases with increasing strain rate, while it increases as well when deformation temperature increases at this temperature range from 900~950°C. Figure 1(d) shows stress-temperature curve at different strain rates with the strain of 0.6. The flow stress increases in austenite or ferrite region with the decreasing deformation temperature. The flow stress tendency is on the contrary when the steel is in austenite-ferrite region. The experimental data has great significance for constitutive model and numerical simulation of the non-oriented silicon steel.

![Figure 1. Flow stress behaviors of non-oriented electrical steel. (a) stress-strain curve at 950°C (b) stress-strain curve at 900°C (c) stress-strain curve at 850°C and (d) stress-temperature curve](image)

#### 2.3 Constitutive model

The constitutive model is used to predict mechanical response of materials during deformation in a certain range of temperature and strain rate [6]. Many constitutive models for steel have been proposed. Arrhenius-type model[7,8] is applied extensively recently to describe hot deformation of materials. In this work, the constitutive model of non-oriented silicon steel during hot compression was constructed based on Arrhenius-type model. The established model manifests excellent property to predict the flow stress of non-oriented silicon steel in hot compressive deformation process. The average absolute relative error of this model is 4.98. The constitutive model can provide material property of the silicon
steel in numerical modeling with various temperatures and strain rates.

3. Numerical simulation

3.1. Modeling
FE method is widely used in material forming process. Thermodynamics, edge defect formation and microstructure evolution during rolling process were investigated by FE method in previous studies. In order to investigate the deformation behaviors of the silicon steel plate in actual hot rolling process, a three-dimensional (3D) FE model for roll system of the finishing mill is built based on ANSYS/LS-DYNA software package. The modeling parameters are presented in Table 2. The FE modeling is constructed by Ansys parametric design language. To get accurate nodes solutions, mesh refinements are performed around the contact surface, which is shown in Figure 2. The rolls in the model are elastic with the elastic modulus of 210 GPa and Poisson's ratio of 0.3. The material property of steel plate is elastic-plastic. As shown in Table 3, temperature of the steel plate decreases and strain rate elevates during finish rolling, resulting in different material properties. The material model of the steel plate is acquired from the thermal simulation test and the above constitutive model.

| Table 2. Geometric parameters of the FE model |
|-----------------------------------------------|
| Entry | Parameters [mm] |
| Work roll barrel size, $D_W \times L_W$ | Φ 820×1880 |
| Work roll neck size, $D_N \times L_N$ | Φ 480×610 |
| Backup roll barrel size, $D \times L_B$ | Φ 1600×1550 |
| Backup roll neck size, $D \times L_E$ | Φ 960×725 |
| Plate thickness, $H$ | 40 |

Table 3. Rolling parameters of non-oriented silicon steel in the finishing mill

| Finishing mill NO. | Rolling parameters [non-oriented silicon steel] |
|--------------------|-----------------------------------------------|
|                     | Reduction rate [%] | F1 | F2 | F3 | F4 | F5 | F6 | F7 |
|                     | Strain rate [1/s]  | 4.2 | 10.4 | 16.9 | 47.6 | 89.5 | 126 | 143 |
|                     | Temperatures [℃]  | 945 | 907 | 890 | 874 | 868 | 865 | 863 |

3.2. Results
The deformation behaviors of the steel plate in hot rolling process were demonstrated below with the following outputs: contact stress and plate shape. The outputs were obtained from FE calculation with various inputs, such as reduction rate, entrance crown, thickness, width, rolling temperatures and strain rate of the work piece. Reduction rate ($R_d$) is defined as the ratio between work piece thickness reduction ($\Delta H$) during a rolling pass and the original thickness ($H$), i.e., $R_d = \Delta H / H$. Entrance crown of the work piece is defined as the thickness difference between the central point of the work piece and the edge along transverse direction, i.e., $C_{st}=H_{cen}-H_{edg}$.

3.2.1. Contact stress
Contact stress distributions between work roll and the plate in transverse direction (plate width direction) with different working conditions are shown in Fig. 3. Reduction rate, plate width, rolling temperature
and strain rate are the main influence factors of contact stress. The previous studies have revealed that unrealistically large contact stress would be obtained with the elastic-perfectly materials[9]. Actually, when plastic dominates the total deformation, contact stress increases slightly. Stress concentrations locate about 80 mm from the plate side in all the working conditions. The locations of “cat ear” type wear[10] and surface spalling[4] on work roll are coincide with the position of stress concentrations, which indicates that contact stress distributions are closely related to localized wear and fatigue of rolls.

Figure 3. Contact stress distribution with different working conditions: (a) reduction rate (b) plate width (c) deformation temperature and (d) strain rate

3.2.2. Plate shape
Plate shape is defined as the thickness profile of steel plate along transverse direction. Plate shape is the core quality factor of the final product, especially for silicon steel plate. The production of plates with high mechanical yield stress, low thickness and less flatness defects is a major challenge for plate steel.[11] Plate shape is drawn the most attention in hot rolling process. The objective of the shape control in steel rolling process is to minimize the thickness deviation and asymmetrical shape in the transverse direction of the plate.[12] The plate shape is influenced by many rolling parameters. In actual steel production, work roll bending is the main on-line control approach, while the other parameters are mostly presetting ones. Plate shape is sensitive to rolling parameters. Almost all the main rolling parameters would affect plate shape, just as shown in Figure 4. The steel plate will get larger crown with the reduction rate, entrance plate crown and harding level (mainly influenced by deformation temperature and strain rate) in hot deformation (Figure 4 a, b, e, f). Contrarily, thicker and wider plates are liable to get smaller crown, which are demonstrated in Figure 4 c,d.

Figure 4. Plate shape change in hot rolling process: (a) reduction rate (b) plate width (c) deformation temperature and (d) strain rate
4. Discussion and outlook

Thinner and more flat steel sheet is the target of HSM, which made a direct challenge to the rolling strategy of the finish rolling process. A large amount of silicon steels with the minimum thickness of 2 mm and maximum width of 1280 mm are yielded in the HSM studied in this paper. In actual rolling production, the desired plate profile is difficult to achieve and “edge wave” occurs frequently. The knowledge of silicon steel deformation behaviors in rolling process is crucial for its precise shaping.

The deformation behaviors of the silicon steel will provide basis for predicting and controlling the plate profile during rolling process with real-time control systems. Moreover, the optimization and decision of rolling strategy, including the selections of suitable roll profile and adjustment of load sharing in different stands, must base on the steel deformation behaviors in order to improve the plate product quality.

5. Conclusions

The main findings and contributions from this work are as follows:

(1) The flow behaviors of the silicon steel investigated in this work during hot compressive process were investigated by thermal simulation experiments. The silicon steel showed strain hardening and thermal softening effects in single-phase region, while it appeared strain hardening and low temperature softening in dual-phase region.

(2) Stress concentrations exist adjoin the plate sides, which are related to localized roll wear and fatigue. Rolling parameters, plate sizes and material properties have significant influence on plate shape. Larger convexity strip will acquired by larger reduction rate, narrower and thinner plate, higher flow stress of the steel.

Acknowledgment

The authors would like to acknowledge the financial support provided by the Shandong Jiaotong University Doctorial Scientific Research Fund and Climbing Project for Advanced Equipment and Control.

References

[1] Landgraf, F.J.G., et al., Effect of plastic deformation on the magnetic properties of non-oriented electrical steels. Journal of Magnetism and Magnetic Materials, 2000. 215-216: p.94-96.
[2] De Paepe, A., et al., Effect of hot rolling parameters on the magnetic properties of a low-silicon ultra-low-carbon steel. Journal of Magnetism and Magnetic Materials, 1996. 160: p.129 - 130.
[3] Schausberger, F., A. Steinboeck and A. Kugi, Mathematical modeling of the contour evolution of heavy plates in hot rolling. Applied Mathematical Modelling, 2015. 39(15): p.4534-4547.
[4] Dong, Q., et al., Analysis of Spalling in Roughing Mill Backup Rolls of Wide and Thin Strip Hot Rolling Process. steel research international, 2015. 86(2): p.129-136.
[5] Lenard, J.G., Primer on Flat Rolling. 2007: Elsevier Science.
[6] Puchi-Cabrera, E.S., et al., Constitutive description for the design of hot-working operations of a 20MnCr5 steel grade. Materials & Design, 2014. 62: p.255-264.
[7] Zener, C. and J.H. Hollomon, Effect of Strain Rate Upon Plastic Flow of Steel. Journal of Applied Physics, 1944. 15(1): p.22.
[8] Sellars, C. and W. McTegart, On the mechanism of hot deformation. Acta Metallurgica, 1966. 14: p.1136-1138.

[9] Liu, M., Finite element analysis of large contact deformation of an elastic–plastic sinusoidal asperity and a rigid flat. International Journal of Solids and Structures, 2014. 51(21-22): p.3642-3652.

[10] Li, W., et al., Roll shifting strategy with varying stroke and step in hot strip mill. Journal of Central South University, 2012. 19(5): p.1226-1233.

[11] Tran, D.C., N. Tardif and A. Limam, Experimental and numerical modeling of flatness defects in strip cold rolling. International Journal of Solids and Structures, 2015.

[12] HUR, Y. and Y. CHOI, A Fuzzy Shape Control Method for Stainless Steel Strip on Sendzimir Rolling Mill. Journal of Iron and Steel Research, International, 2011. 18(3): p.17-23.