

Rolling Technology for Thin Steel Strip in Hot Strip Mill Train

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Thin steel strip rolling performance in the hot strip mill train has been investigated, mainly the metallurgical microstructure. A compact hot mill train producing ordinary steel strip with 1.2 mm final thickness was assumed, and the characteristics were theoretically calculated and analyzed. Strip temperature drop is large due to the thin thickness causing higher flow stress and higher rolling load. Finishing mill delivery temperature (FDT) falls under the Ar3 transformation temperature. Nevertheless, the calculated results have shown similar microstructure as that of cases with FDT above the Ar3 temperature, suggesting normal metallurgical quality of the thin strip. Besides temperature control, various mechanical devices must be taken into consideration to achieve thin strip rolling. Major mill components for the purpose are explained.

1. Introduction

It has been reported that high speed thin strip rolling mills with bar connecting devices are used for hot steel strip rolling as endless type mill.⁽¹⁾ Meanwhile, the conventional non-endless type rolling mills are still used for thin strip rolling. In case fewer stands are used in the conventional non-endless type rolling mills to reduce the cost, the rolling speed is in general a little lower. In a compact hot strip mill, which is smaller than other conventional rolling mills, the rolling speed is also low. Especially in thin strip rolling, because strips are rolled with a higher rolling load and low motor speed, the rolling temperature further decreases and is more likely to drop to around the ferritic rolling temperature. The advantages in ferrite rolling under low temperature conditions have been analyzed and reported.⁽²⁾

This paper reports the study on thin strip rolling characteristics and equipment characteristics, focusing on the above-mentioned metallurgical characteristics with non-endless type rolling mills.

2. Study with a continuous hot steel strip rolling

2.1 Calculation model for hot steel strip rolling

The hot strip mill shown in Fig. 1 was assumed as a calculation model for analysis. This facility consists of one rougher and six finishing stands.

Table 1 shows the rolling conditions (Case-R) based on the assumption that low carbon steel strips which

are 1.2 mm thick are produced by this hot strip mill train. Based on the calculated rolling load and heat transfer, these rolling conditions were calculated so that the finishing mill delivery temperature (FDT) is relatively lower. The reported finish rolling in the ferrite region is classified into ① the method by which all stands can perform ferritic rolling by installing a water-cooling system in the delay table,⁽³⁾ and ② the method by which only the upstream and intermediate stands perform finish rolling above Ar3 temperature (austenite temperature range), and only the downstream stand performs finish rolling below Ar3 temperature (ferrite temperature range).⁽²⁾

For this paper, the following analysis was conducted assuming the latter method.

2.2 Rolling load and temperature characteristics around the ferrite temperature range

As a preliminary test, a hot rolling test was conducted by rolling low carbon steel in temperature ranges including ferrite temperature range with the experimental rolling mill of Osaka University. The rolling test conditions are as follows.

Materials used in the rolling test

Steel type	Low carbon steel (C 0.04%, Mn 0.12%, Si 0.02%)
Dimensions	3 mm (strip thickness) × 30 mm (width) × 500 mm (total length)

Experimental equipment

Equipment name	Experimental high speed hot
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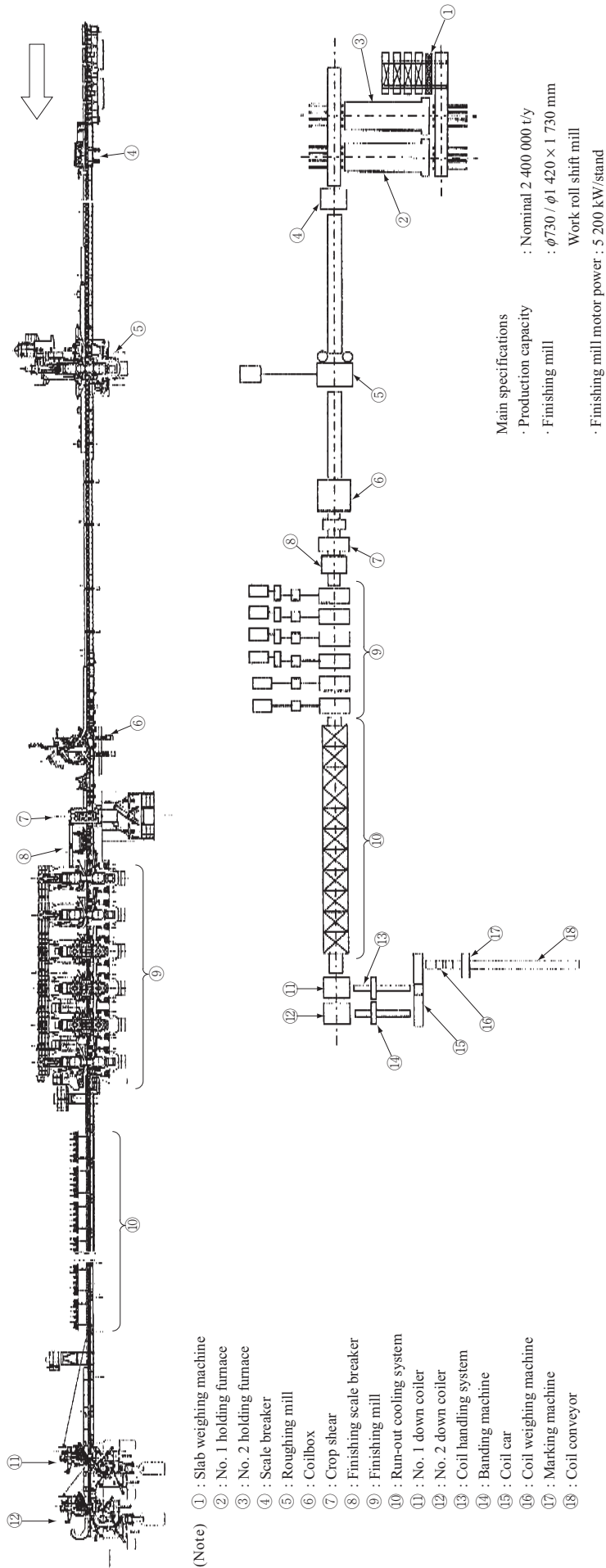


Fig.1 Configuration of the compact hot strip mill train

Table 1 Calculated temperature and rolling load of finishing train (Case-R)

Finishing stand		Strip thickness at the delivery (mm)	Rolling speed (m/min)	Temperature at the delivery (strip top end) (°C)	Average deformation resistance (N/mm ²)	Rolling load (MN)	Torque (MN·m)
No.	Nominal						
		26.4	28	955			
F1	No. 1 stand	10.8	58	949	145.0	18.98	1.257
F2	No. 2 stand	5.13	123	924	193.1	19.71	0.759
F3	No. 3 stand	2.87	224	901	223.4	18.32	0.425
F4	No. 4 stand	1.86	365	877	251.9	17.02	0.241
F5	No. 5 stand	1.4	497	842	262.6	14.01	0.122
F6	No. 6 stand	1.2	595	801	243.0	8.88	0.050

(Note) Rolling conditions

- Nominal work roll diameter : 730 mm
- Slab thickness : 229 mm
- Strip width : 950 mm
- Temperature when slab is taken out of the furnace : 1 230 °C
- Roughing mill rolling work : Roughing 7 passes

rolling equipment (Belong to Osaka University)

Rolling mill
 Model 2HI rolling mill
 Roll diameter 530 mm
 Rolling speed 6 to 45 m/s

Heating furnace
 Model Electric furnace on entry side of mill (2 units)
 Temperature From room temperature to 1 400 °C

Rolling conditions
 Target reduction rate 40%
 Roll peripheral speed 900 m/min
 Furnace temperature settings 700, 750, 775, 800, 850, 900 and 1 000 °C

Figure 2 shows a comparison between the measured and calculated rolling loads. In the figure, the measured

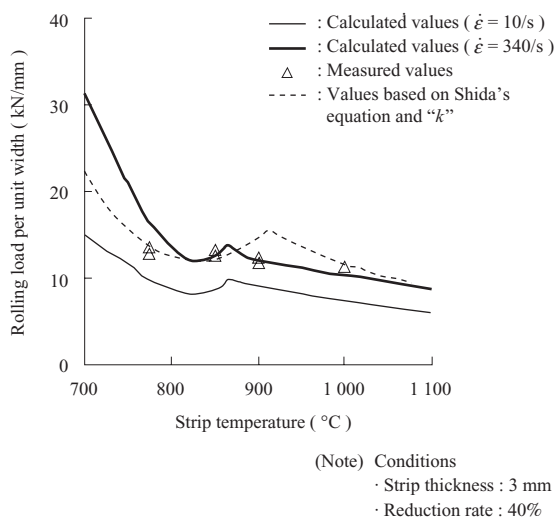


Fig. 2 Comparison of the calculated rolling load with the experimentally measured results

rolling loads are indicated by the symbol “△”. This figure shows the rolling loads calculated by the equation for deformation resistance based on the measured values “m” and “n” (strain rate $\dot{\epsilon} = 10/s, 340/s$) and by the theoretical equation for rolling loads,⁽⁵⁾ which was obtained by Shida applying Sims’ equation using Shida’s equation.⁽⁴⁾ The strain rate in the rolling test is equivalent to 340/s.

It is already known, in and around the ferrite temperature range, that deformation resistance decreases with temperature. **Figure 2** shows that when the temperature decreases, the increase in the rolling load around 800°C is less significant than that around 700°C. Therefore, it can be expected that rolling in and around the ferrite temperature range will not cause abnormal rolling loads. In continuous rolling, however, the rolling load is corrected taking into account the increase in deformation resistance caused by the accumulation of dislocation density, because the transit time between the stands is shorter. **Figure 3** shows the result of comparing equation for deformation resistance by Misaka’s equation⁽⁶⁾ (based on the assumption that recovery is made after each pass) with the calculated flow stress obtained by microstructure calculation in continuous rolling with this Case-R (with the accumulation of dislocation density at each pass taken into account). The results were used to correct the deformation resistance calculated based on the rolling loads.

For comparison with Case-R, shown in **Table 1** as a representative case, the rolling load and temperature change were calculated under various rolling conditions (Cases-S, -T and -U). The strip temperature was calculated based on the assumption that the temperature was evenly distributed in the thickness direction. The results are shown in **Tables 1, 2, and Figs. 4, 5**. The average deformation resistance was obtained by correcting the values obtained by Misaka’s equation as shown above, and the theoretical equation for rolling

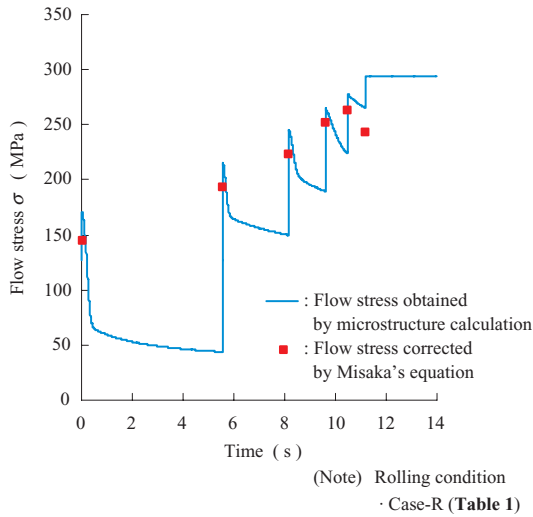


Fig. 3 Modification of the flow stress by the transition of dislocation density

loads, obtained by applying Sims's equation.⁽⁶⁾ As shown in **Table 1** and **Fig. 4**, in rolling with the six stands with a final thickness of 1.2 mm, both the rolling load and torque (motor overload value) are close to the allowable limits, and as a result, the rolling speed is as low as the motor base speed (speed at the maximum torque). Because the strip thickness is small, it cools down quickly and the deformation resistance increases, causing the rolling load to increase. Therefore, it is difficult to increase the rolling speed and keep the strip temperature high. As shown in **Fig. 5**, the final finish rolling temperature is as low as 800°C, and is below the Ar3 transformation temperature.

2.3 Results of metallurgical microstructure analysis and consideration

Based on the rolling load and temperature shown in **Tables 1** and **2**, the microstructure of coiled strips was calculated using a microstructure simulator. This simulator was developed by improving the computer program⁽⁷⁾ distributed at the ISIJ Rolling Theory Sub-Committee for FEM Analysis for Creating Steels with Ultimate Performance, held by the ISIJ Rolling Theory Committee in June 2001. This simulator, which was

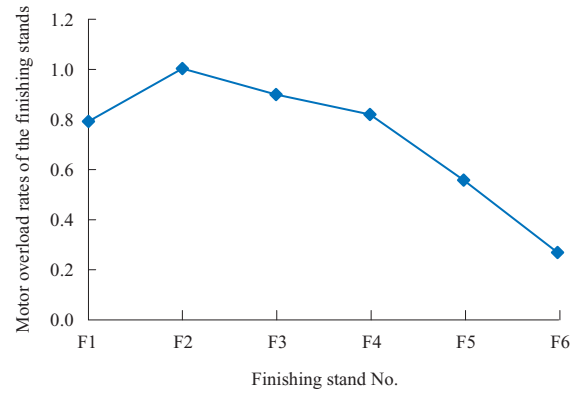


Fig. 4 Calculated motor overload in Case-R

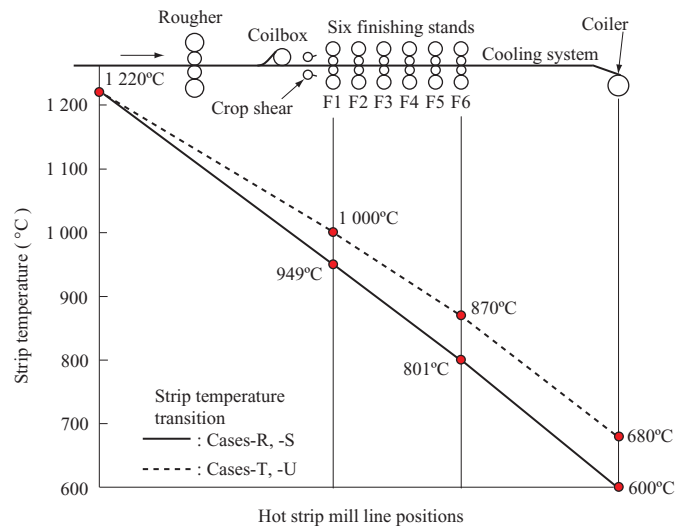


Fig. 5 Temperature transition in compact hot strip mill

originally designed for austenite rolling, was used for this calculation because it was determined that reasonable macro results could be obtained even when Ar3 temperature was not reached around the last stand.

Table 2 Calculation condition and calculated results of hot strip rolling

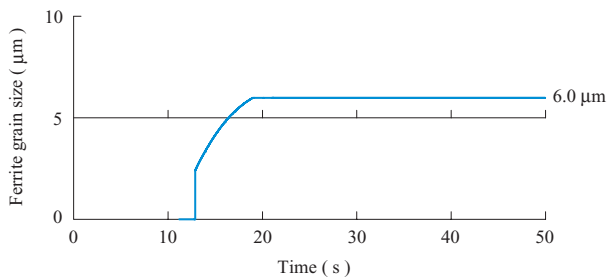
Case	Analytical condition						Analysis/Calculation result				
	Strip thickness Bar thickness/ Finished thickness (mm)	Carbon content C (%)	Temperature (strip top end)			Rolling speed F6 (m/min)	Characteristics	Time needed from the No. 1 finishing stand to the coiler (s)	Ferrite grain sizes (μm)	Volume fraction a : Austenite f : Ferrite p : Pearlite b : Bainite	Recrystalli- zation ratio Dynamic/Static
			F1 entry (°C)	F6 delivery (°C)	Coiling temperature (°C)						
R	26.4 ⇒ 1.2	0.150	949	801	600	595	Dual phase rolling with ferrite phase	21.6	6.00 (Fig. 6)	(Fig. 9)	(Fig. 12)
S	26.4 ⇒ 1.2	0.045	949	801	600	595	Dual phase rolling with ferrite phase	21.6	7.57 (Fig. 8)	(Fig. 11)	
T	26.4 ⇒ 1.2	0.150	1 000	870	680	740	Presumed austenite rolling	17.3	6.65		
U	30.4 ⇒ 2.0	0.045	1 000	870	680	740	Representative austenite rolling	17.3	8.85 (Fig. 7)	(Fig. 10)	

(Note) The relevant figures are indicated in parenthesis. The details are as shown in this figure.

The austenite grain size at the entry of the No. 1 stand of the finishing mill train was set to 80 μm .

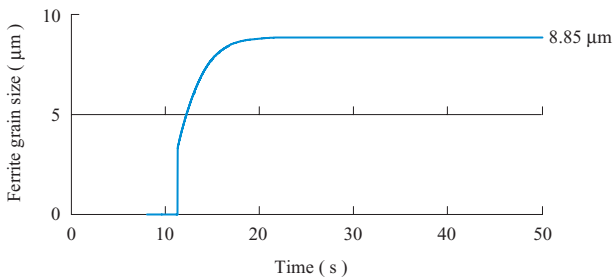
The right half of **Table 2** shows a list of results of calculation by the microstructure simulation. Case-R corresponds to operation at a thin strip rolling temperature, which can be performed with a compact hot strip mill, and Case-U corresponds to operation in the austenite temperature range. **Figures 6, 7 and 8** show the changes in crystal grain size when this analytical model was used.

Figures 9, 10 and 11 show the analytical results of the volume fraction of the coiled strips. **Figure 12** shows the changes in the recrystallization rate. In **Fig. 9**, “a” indicates the austenite structure; “f” indicates the ferrite structure; “p” indicates the pearlite structure; and “b” indicates the bainite structure. In these figures, the horizontal axis indicates the elapsed rolling time from



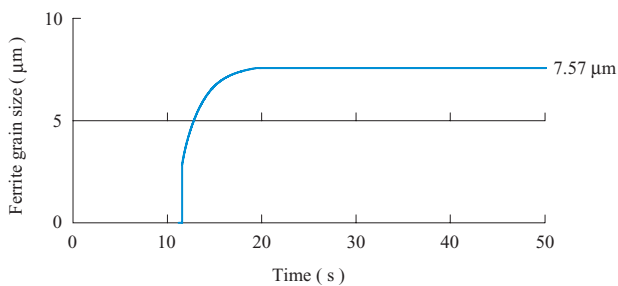
(Note) The time needed to reach the delivery of F6 was 11.175 s.

Fig. 6 Ferrite grain size transition in Case-R



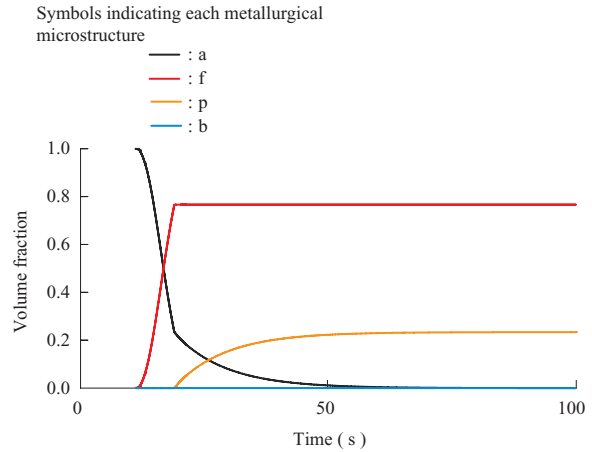
(Note) The time needed to reach the delivery of F6 was 8.047 s.

Fig. 7 Ferrite grain size transition in Case-U



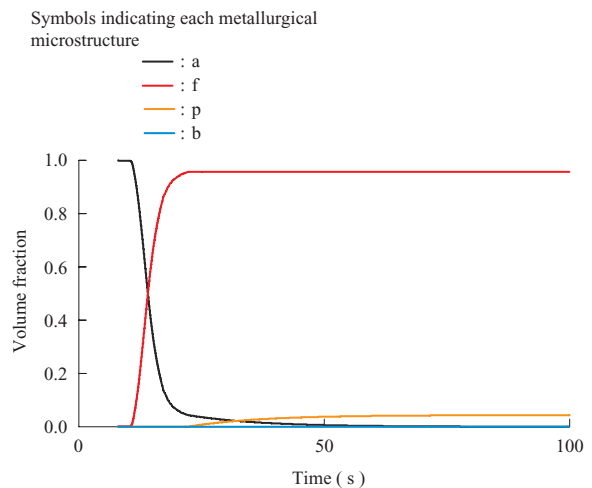
(Note) The time needed to reach the delivery of F6 was 11.175 s.

Fig. 8 Ferrite grain size transition in Case-S



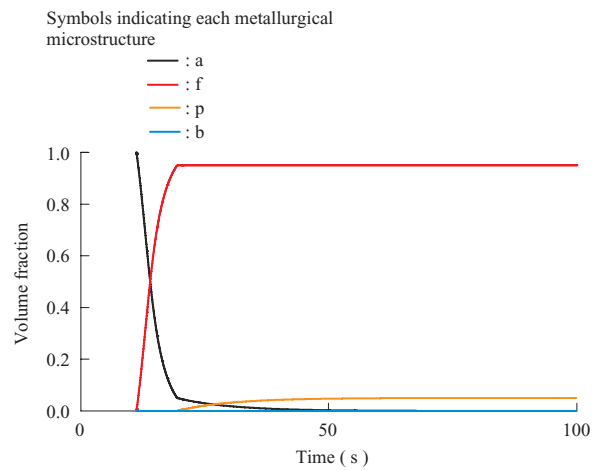
(Note) The time needed to reach the delivery of F6 was 11.175 s.

Fig. 9 Transition of volume fraction in Case-R



(Note) These are structure calculation values. The time needed to reach the delivery of F6 was 8.047 s.

Fig. 10 Transition of volume fraction in Case-U



(Note) The time needed to reach the delivery of F6 was 11.175 s.

Fig. 11 Transition of volume fraction in Case-S

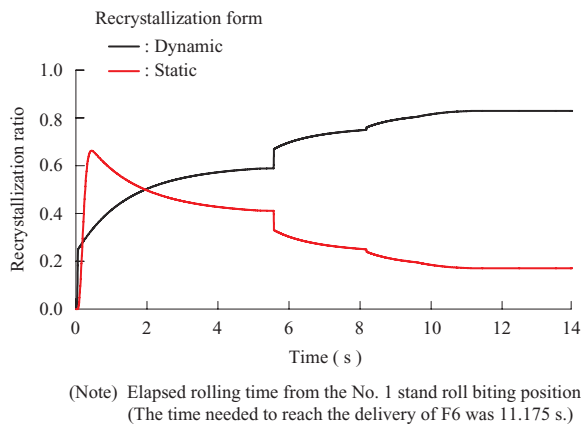


Fig. 12 Transition of recrystallization ratio in Case-R

the No. 1 stand roll biting position. Because in **Table 2** the rolling conditions in Cases-R and-S were similar to those in typical hot thin strip rolling used in this study, the study was focused on the properties based on metallurgical microstructure in Cases-R and -S. As a result, the following five items were found.

- (1) Although the FDTs in Cases-R and-S were below Ar3 temperature as shown in the analytical conditions in **Table 2**, the FDTs at the upstream and intermediate stands were above Ar3 temperature. Although the FDT was equal to or less than Ar3 temperature around the last stand, it can be seen from the transformation time in **Figs. 6, 7 and 8** that rolling was performed mainly in the austenite range, and ferrite transformation was started from the run-out table.
- (2) Generally, the crystal grain size of commercially available low carbon steel strips is from 5 to 10 μm , and the crystal grain size in Case-U corresponds to that of such strips produced in general austenite rolling. The crystal grain size in Case-R was similar to metallurgical microstructure in Case-U; therefore, this calculation result demonstrates that even when FDT is below Ar3 temperature, the quality does not significantly differ from the strips produced in general austenite rolling.
- (3) As results of comparisons between Cases-R, -S, and Cases-T, -U, in rolling both in the austenite temperature range and in and around the ferrite temperature range, it was found that the ferrite grain size became greater if the carbon content was lower.
- (4) Case-T assumes that the decrease in the rolling temperature in thin strip rolling is less than that in Case-R. Case-T operations is achieved by taking measures such as increasing the equipment motor power above that shown in the equipment example (Case-R) in **Fig. 1** to increase rolling speed and to increase the rough rolling temperature and the finish rolling temperature to a level like that for medium-thickness steel strips.
- (5) The microstructure in Case-R was similar to

that in Case-T, and the microstructure similar to that in austenite rolling could be achieved although the temperature was in and around the ferrite temperature range when rolling was finished. Therefore, it is found that the quality of the metallurgical microstructure of thin steel strips can be maintained without improving equipment specifications such as equipment motor power.

3. Influence of the temperature distribution in the strip thickness direction on the metallurgical microstructure

Chapter 2 has described the results of calculating the microstructure, assuming the evenness of the temperature distribution in the strip thickness direction. Generally, in hot rolling, when the rolling speed is low, the roll contact time becomes longer. And this causes the strip temperature to decrease locally at the contact portion. It can be qualitatively expected that the temperature becomes uneven in the strip thickness direction, and accordingly, the microstructure becomes more uneven in the strip thickness direction.

By setting a virtual two-stand hot strip mill train for thin steel strips and rolling conditions, the strain stress distribution along the roll contact arc was simulated using the CORMILL simulator,⁽⁸⁾ and the temperature distribution was separately calculated. These results were input into the microstructure simulator to simulate the microstructure distribution on the strip surface and strip center. **Table 3** shows the analytical conditions.

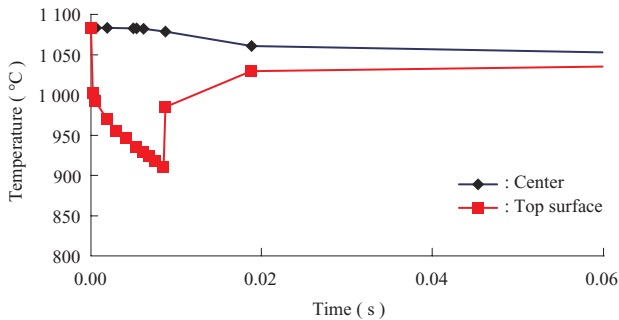
Figures 13 and 14 show the temperature distribution in Cases-I and-J, and **Figs. 15 and 16** show the changes in ferrite grain diameter in Cases-I and-J. In the figures, the horizontal axis indicates the elapsed rolling time from the No. 1 stand roll biting position. The following show the results of weighing the facts in **Figs. 13 to 16**.

- (1) Because the total reduction rate was set to a smaller value than that of the example in **Chapter 2**, the ferrite grain size became about 15 μm , almost twice as large as that in **Chapter 2**. It can be expected that by repeating hot rolling passes until the same total reduction rate as in **Chapter 2** is achieved, the same size as that in **Chapter 2** can be achieved.
- (2) Although the strip temperature decreased significantly on the strip top surface just after roll bite, the temperature did not decrease significantly on the strip center. Because the temperature of the strip top surface recovered rapidly after the strip has passed through the rolling contact arc, the strip thickness direction temperature distribution of a stand was not significantly affected by that of the preceding stand.
- (3) The crystal grain size at the strip center in rolling with one stand (Case-I) at a total reduction rate of 44% was about one-tenth smaller than that in rolling with two stands (Case-J) at the same total reduction

Table 3 Calculation condition and calculated results for microstructure distribution along thickness

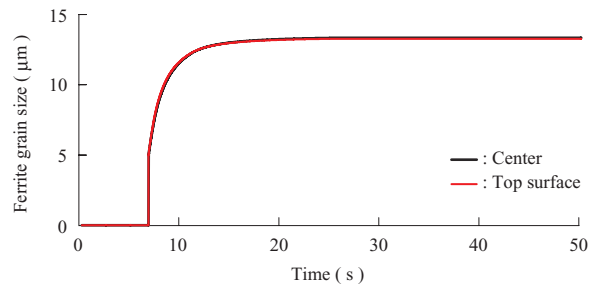
Case	Analytical condition					Analytical result		
	Total reduction rate 44% (mm)	Pass No. 1 Rolling speed at the entry (m/min)	Pass No. 1 Strip temperature at the entry (°C)	Coiling temperature (°C)	The time needed from No. 1 finishing stand to the coiler (s)	Transition in strip temperature (°C)	Positions in the thickness direction	Ferrite grain diameter after coiling (μm)
I (Rolling in No. 1 stand)	1.7 ⇒ 0.952	90	1 083	685	11.2	(Fig. 13)	Strip top surface	13.3 (Fig. 15)
							Strip center area	13.3 (Fig. 15)
J (Rolling in No. 2 stand)	1.7 ⇒ 1.36 ⇒ 0.952	90	1 083	685	12.0	(Fig. 14)	Strip top surface	12.5 (Fig. 16)
							Strip center area	14.8 (Fig. 16)

- (Note) 1. This table shows the results with a rolling model with fewer stands.
 2. The diameter of all the rolls of the rolling mills is 560 mm.
 3. The carbon content (C) is 0.045%.
 4. In Cases-J and-I, the equipment was designed so that strips after rolling pass through the water cooling bank before they are coiled.
 5. The relevant figures are indicated in parenthesis. The details are shown in this figure.



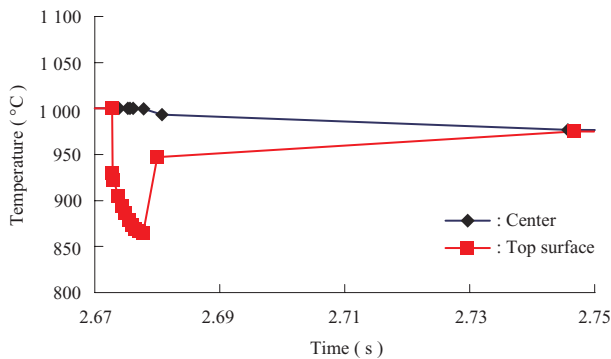
(Note) Elapsed rolling time from the No. 1 stand roll biting position

Fig. 13 Transition of temperature distribution in Case-I



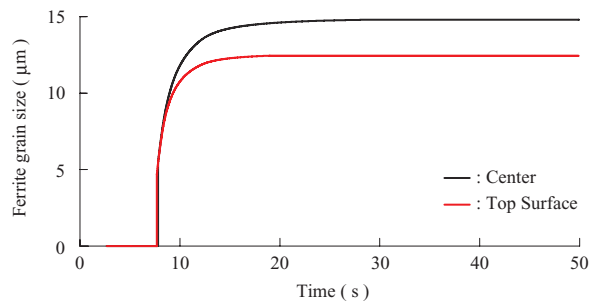
(Note) The carbon content (C) is 0.045% and the reduction rate is 44%.

Fig. 15 Transition of ferrite grain size distribution in Case-I



(Note) Elapsed rolling time from the No. 1 stand roll biting position

Fig. 14 Transition of temperature distribution in Case-J



(Note) · The carbon content (C) is 0.045% and the reduction rate went from 20% to 30%.
 · The time needed to reach the delivery of Pass No.2 is 2.677s.

Fig. 16 Transition of ferrite grain size distribution in Case-J

rate.

- (4) Under these conditions, the ferrite grain sizes at the strip top surface were smaller by 15% than the ferrite grain size at the strip center in Case-J. In Case-I, the grain size at the strip top surface was almost the same as that at the strip center. This is presumably because the reduction rate in Case-J

was smaller at a pass and the strip center was less subjected to plastic deformation.

- (5) It was found that when the microstructure of a strip is analyzed and evaluated in a schematic manner, no significant differences occur even if the temperature distribution in the strip thickness direction is assumed to be even, as shown in **Tables**

1 and 2.

4. Necessary functions for thin strip rolling train

In thin strip rolling with a non-endless type mill train with fewer stands, it is necessary to prevent instability during thin strip rolling, resulting from the increase in the rolling load as described in **Chapter 2**, in addition to meeting the product quality requirements related the metallurgical microstructure. As shown in **Figs. 9** and **11**, although Ar3 temperature was not reached in finish rolling, ferrite transformation began after finish rolling was complete. Therefore, although no shape instability from metallurgical transformation occurs during rolling, threading and tailing out in non-endless type operation is more likely to cause instability during high-load/high torque rolling for thin steel strips, causing the rolling load to fluctuate more frequently; therefore, it is recommended the following equipment be installed depending on the operating environment:

- (1) Measures against the deteriorating nature of the roll surface caused by the increase in the rolling load

In order to properly control the black scale that forms on the work roll, the adoption of cyclic operations in which lots with the same thickness are rolled at a time,⁽⁹⁾ or high-speed tool steel rolls⁽¹⁰⁾ is recommended. Adopting a lubricative hot rolling system is also effective in maintaining the nature of the roll surface.

- (2) Measures against the deterioration of flatness caused by the increase in the rolling load

In order to prevent flatness from deteriorating, it is necessary to improve the shape control performance by adopting a roll shift type mill, and to develop a shape control system.⁽¹¹⁾ For a work roll shift type mill, adopting the wear dispersion system with cyclic roll shift also prevents uneven wear on the roll.

- (3) Adoption of a hydraulic looper⁽³⁾

A hydraulic looper, driven by a hydraulic cylinder, is suitable for preventing strip necking and pincher because it has lower inertia and higher response than an electric looper does. **Figure 17** shows the displacement in the measured hydraulic looper arm angle. This figure shows an example of the

movement of the hydraulic looper when the tension is controlled by PT (hydraulic pressure detection system) in the finishing stand No. 3 of the hot strip mill train. For higher precision tension control, a hydraulic looper equipped with a load cell is recommended.

- (4) Adoption of machines used for threading and coiling thin steel strips at the run-out table

Installing high-speed threading devices, coil dividing just before the down coiler, and coiling equipment⁽¹²⁾ enables smooth acceleration of the rolling speed just after the strip top-end wrapping, and enables easy coil-dividing rolling. This is effective in dividing coils from a long sheet while preventing the strip temperature from dropping.

- (5) Installation of a stabilizing devices for roll chock⁽¹³⁾

It is recommended that equipment to prevent vibration in the roll chock while threading and to improve the threading performance be installed. **Figure 18** shows an example of the calculated behavior of a chock stabilizer. This figure shows an example of the calculated behavior of a chock when a horizontal pressing load per chock was installed in the finishing stand No. 3 of the hot strip mill train. **Table 4** shows the calculation conditions. The measurement results also found that the displacement of a chock could be reduced by installing such equipment.

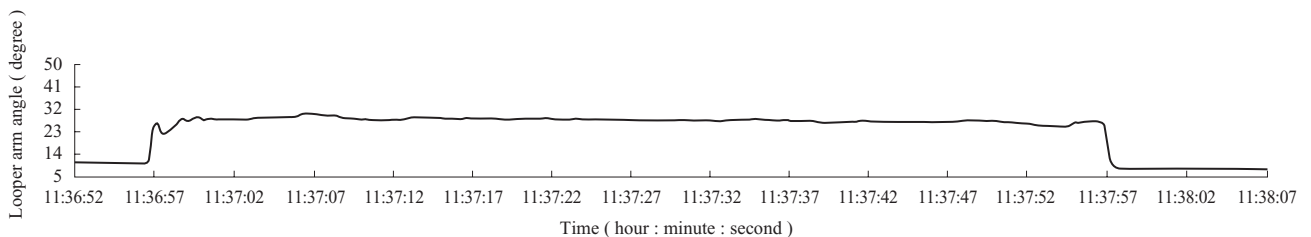
- (6) Side walk control system

A system to prevent side walk may be installed as a threading and tailing out stabilizer.⁽¹⁴⁾

5. Conclusion

In this paper, the rolling characteristics in hot rolling for thin steel strips have been analytically examined, focusing on the metallurgical microstructure. Mainly, the ideal rolling equipment in rolling thin steel strips of 1.2 mm thick have been studied with a hot strip mill train consisting of as few as six finishing stands.

- (1) In thin steel thin rolling (about 1.2 mm) with the non-endless type finishing six-stand hot strip mill train, the strip temperature easily decreases. Therefore, FDT is more likely to drop below Ar3 temperature.
- (2) As a result of the phenomenon described in (1),



(Note) · A hydraulic looper is installed at the delivery side of the finishing stand No. 3 of the hot strip mill train.
 · The strip thickness between stands was 11 mm.

Fig. 17 Measured arm angle transition at hot strip mill hydraulic looper

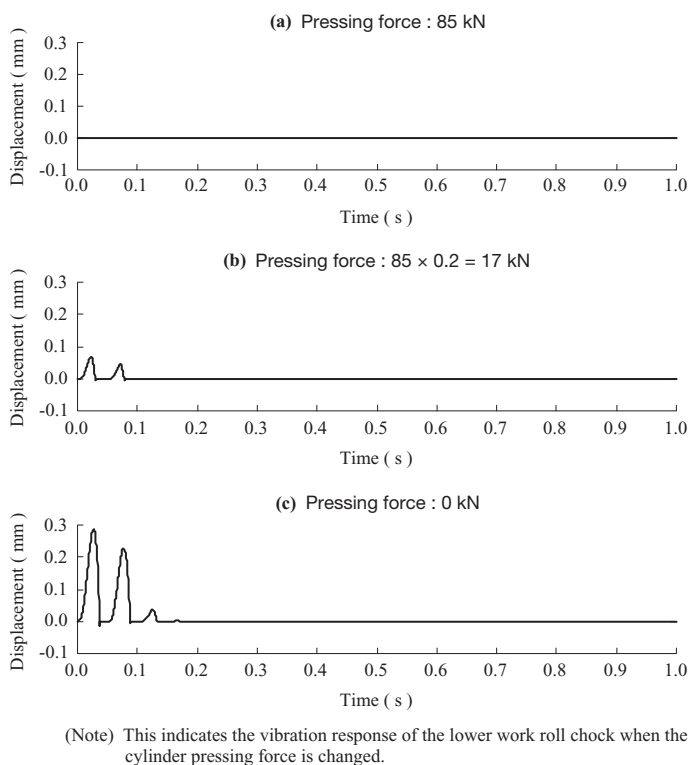


Fig. 18 Calculated chock position transition in hot strip mill

Table 4 Calculation condition for the chock stabilizer

Item	Unit	Calculation condition	
Calculation model for hot strip rolling	—	Finishing stand No. 3 of the hot strip mill train	
Rolling roll	mm	$\phi 760 / \phi 1\,520 \times 1\,730$	
Work roll chock weight	kN/chock	32	
Torsional natural frequency in drive train	Hz	20	
Presumed dumping ratio	Rolls	—	0.08
	Chocks	—	0.05
Rolling force	MN	21.6	
Rolling torque	kN·m	635	
Strip thickness	mm	$9.5 \Rightarrow 5.0$	
Strip speed at the delivery	m/min	144	

the deformation resistance increases, causing the rolling load to be relatively high. Therefore, the rolling speed will be relatively low because of the motor output, and the rolling temperature will also be relatively low. However, because the increase in the deformation resistance is less significant in and around the ferrite temperature range, the increase and decrease in the rolling load are also less significant until the temperature reaches around 800°C, and the mill is able to operate normally, whereas this tendency is offset by the accumulation of dislocation density.

- (3) As a result of analyzing the metallurgical microstructure of a strip coiled under the conditions

described in (1) and (2), using the microstructure simulator, it was found that the metallurgical microstructure was similar to that of strips produced austenite rolling, where rolling is finished with the rolling temperature higher than Ar3 temperature.

- (4) Additionally, the temperature and strain rate distribution in the thickness direction were calculated with the thin steel strip hot rolling model, and the results were input into the microstructure simulator to analyze. From the analytical result, it was found that the unevenness of the microstructure in the thickness direction was not significant, so the results of analysis with the even temperature distribution in the thickness direction can be used for usual evaluation.
- (5) From these analytical results, it was found that, for example, when thin steel strips that are 1.2 mm thick are rolled with FDT of 800°C and a coiling temperature of 680°C, the quality of the metallurgical microstructure does not differ significantly from that of strips with a usual thickness (for example, 2 mm) produced in austenite rolling.
- (6) However, in thin strip rolling, various instability phenomena could occur because of high-load rolling and strip flatness deterioration ; therefore, equipment and functions are required to prevent such phenomena from occurring.

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