Fundamental Studies for Application of New Compact
Multi-reduction Mill*

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Synopsis

A new compact multi-reduction mill (NCM), which can substitute one stand for two or three stands in a cold tandem mill, has been developed. This new mill is based on a three-pass rolling in one stand and enables a 70 % reduction in thickness in the cold rolling of mild carbon steel. The rolling experiments and numerical calculations showed that a strip-pulling-out type NCM rolling was more suitable than a strip-enveloping type NCM rolling and gave excellent characteristics in rolling lubrication, roll cooling and preventing heat scratch.

Key words: cold rolling; cold rolling mill; lubrication; shape control; gauge control; edge-drop.

I. Introduction

An increase of reduction in thickness in a single rolling mill has been demanded recently in order to reduce the number of mill stands and to decrease both the cost of mill construction and the operating cost of rolling. Nippon Steel Corp., Ishikawajima-Harima Heavy Industries Co., Ltd. and Toshiba Corp. have developed a new compact multi-reduction mill (NCM) based on three-pass rolling in one stand, which enables a 70 % reduction in thickness in the cold rolling of mild carbon steel. This mill has two variations as shown in Fig. 1. One is a strip-enveloping type NCM and the other is a strip-pulling-out type NCM. A strip-enveloping type NCM makes

a strip pass around two work rolls, while a strip-pulling-out type NCM makes a passing strip pulled out by two side-rolls.

Miyasaka *et al.*¹⁾ explain the rolling characteristics of NCM such as rolling load, rolling torque, slip ratio *etc.* This paper explains the characteristics of NCM rolling with phosphate pre-coating lubrication, automatic gauge controllability, strip shape controllability, characteristics of edge-drop and comparison of NCM rolling types.

II. Rolling Characteristics and Effects of Phosphate Pre-coating

The rolling characteristics of a strip-pulling-out type NCM, and the effects of phosphate pre-coating on rolling stability are explained in this section. Table 1 shows the experimental conditions for NCM rolling mill. The experimental rolling mill is a four-high mill with four work rolls of 300 mm in diameter and 350 mm in length. Figure 2 shows the experimental rolling mill; The #2 to #4 work rolls are driven and the #1 work roll is non-driven (refer to Fig. 1). The roll speed difference in the second pass $X_2 (=V_3/V_2-1, V_3$ is the peripheral speed of the #3 work roll, V_2 is that of the #2 work roll) can be set up to 0, 0.11, 0.24 and 0.35 by changing the gear ratio of the speed reducer. The roll speed difference

t_1, t_2, t_3, t_4 : Strip tensions
Fig. 1. Mill types of NCM rolling.

Table 1. Experimental conditions of NCM rolling.

1.	Work roll size: Diameter: $\phi 300$ mm Length: 350 mm
2.	Driven work rolls: #2, #3, #4 work rolls
3.	Rolling method: Strip-pulling-out type Strip-enveloping type
4.	Rolling speed (V_4): Maximum 200 m/min Usual 10 m/min
5.	Roll speed difference (a) Second pass $X_2=V_3/V_2-1$: 0, 0.11, 0.24, 0.35 (b) Third pass $X_3=V_4/V_3-1$: 0~0.5
6.	Material: Mild carbon steel (SPC) Thickness: 2.3 mm, Width: 100 mm
7.	Lubrication: 6 % emulsion of fat oil, 60°C

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Fig. 2. Experimental new compact multi-reduction mill.

in the third pass X_3 ($=V_4/V_3-1$, V_4 is the peripheral speed of the #4 work roll) can be changed from 0 to 0.5 because #3 and #4 work rolls are driven independently. The amount of phosphate pre-coating on strip surfaces in the case of phosphate pre-coating rolling was 0.3 to 0.6 g/m².

Figure 3(a) shows the relation between the rolling load and a reduction in thickness in the case with or without phosphate pre-coating, and Fig. 3(b) shows the relation between the rolling energy²⁾ and a reduction in thickness under the same conditions, where t_1 is an entry tension and t_4 an exit tension. The rolling load and rolling energy with phosphate pre-coating are a little less than those without phosphate pre-coating. Figure 4 shows the effect of phosphate pre-coating on rolling torque. The rolling torque of #3 work roll increases abnormally in the case of $X_3=0$ with no phosphate pre-coating, while the rolling torque of #3 work roll decreases and becomes almost the same as that of #2 work roll in the case of $X_3=0$ with phosphate pre-coating. In the case of $X_3=0.2$ with phosphate pre-coating the rolling torques of #2 to #4 work rolls become nearly the same.

The lubrication in NCM rolling is severe because the slip ratio between a rolled material and the work rolls in NCM rolling is larger than that in normal rolling such as four-high or six-high rolling because of the different roll speed rolling.^{1,3)} In a strip-enveloping type NCM rolling particularly, heat scratch is apt to break out at the second and third passes as shown in Fig. 5, because of an insufficient supply of lubricant on the materials. Thus, in order to prevent heat scratch, the lubrication of phosphate pre-coating is used in addition to the 6 % emulsion lubrication of fat oil. The phosphate is pre-coated on strip surfaces with an amount of 0.3 to 0.6 g/m² before rolling experiments.

Figure 6 shows the effect of phosphate pre-coating on the amount of steel powder adhering to the rolled strip surfaces in a strip-pulling-out type NCM rolling,

Fig. 3. Effect of reduction in thickness on rolling load and rolling energy.

Fig. 4. Effect of phosphate pre-coating on rolling torque.

Fig. 5. Heat scratch caused on a surface of rolled strip in a strip-enveloping NCM (no phosphate pre-coating).

Strip-pulling-out NCM rolling, $r_t=70\%$

Fig. 6.
Effect of phosphate pre-coating on the amount of adhering steel powder.

Strip-pulling-out NCM rolling, $r_t=70\%$

Fig. 7. Comparison of steel powder formation between phosphate pre-coating and no phosphate pre-coating.

where the amount of steel powder was measured in weight by an even balance. The adhering amount of steel powder in the case of phosphate pre-coating is 30 % less than that in the case of no phosphate pre-coating, which shows that the phosphate pre-coating has a significant effect on the prevention of steel powder formation. Figure 7 shows the photographs where Fe elements in oil stains on a piece of cellophane tape attached on a rolled strip surface was analyzed by a scanning electron microscope.

Table 2 shows the effect of phosphate pre-coating and strip-pulling-out on the heat scratch caused on rolled strip surfaces. In the case of no phosphate pre-coating and 200 m/min rolling speed with a 70 % reduction in thickness, a strip-enveloping type NCM rolling caused heat scratch and a strip-pulling-out type NCM rolling seemed to cause rolling instability such as the loosening of strip tension. In the case of phosphate pre-coating, a strip-enveloping type NCM rolling caused no heat scratch at a rolling speed of 10 m/min but some heat scratch at a rolling speed of 200 m/min, while a strip-pulling-out type NCM rolling caused no heat scratch and gave stable rolling at a rolling speed of 200 m/min. These results suggest that a strip-pulling-out type NCM rolling with phosphate pre-coating is most desirable.

Next, the effect of rolling types on roll cooling was examined by measuring the temperatures of a work roll. Figure 8 shows an experimental method for measuring the temperatures.⁴⁾ The temperatures of six thermocouples embodied in the #3 work roll were measured by allowing the rolling types and the number of lubrication nozzles to change. Figure 9 shows the time change of the temperatures measured at a depth of 3 mm under the roll surface and under the condition of a 70 % reduction in thickness and a 200 m/min rolling speed. The temperatures at about 3 min after the rolling start indicated 160°C in the case of a strip-enveloping type with 4 nozzles, 135°C in

Table 2. Effect of phosphate pre-coating and strip-pulling-out on heat scratch on surfaces of rolled strip. ($r_t=70\%$)

			Rolling speed V_n , m/min		
			10	100	200
No phosphate pre-coating	enveloping		×	×	×
	pulling-out		○	△	△
			△Rolling instability		
Phosphate pre-coating	about 0.5 g/m ²	enveloping	○	×	×
		pulling-out	○	○	○
	about 1.0 g/m ²	enveloping	○	×	×
		pulling-out	○	○	○

○: Good △: Some problems except heat scratch
×: Heat scratch, dotted line shows anticipation

the case of a strip-pulling-out type with 4 nozzles and 105°C in the case of a strip-pulling-out type with 6 nozzles. These results suggest that a strip-pulling-out type NCM rolling is superior to a strip-enveloping type NCM rolling in roll cooling and that sufficient roll cooling is necessary even in a strip-pulling-out type NCM rolling.

III. Automatic Gauge Controllability

The automatic gauge control (AGC) system for NCM rolling, which consists of a decoupling AGC with constant volume flow and a monitor-type AGC with an X-ray gauge sensor, has been developed as shown in Fig. 10. The decoupling AGC with constant volume flow can control only the strip thickness at the third pass with the constant strip thickness at the first and second passes. The terms, α and β , in Fig. 10 are the control gains for the decoupling AGC. Figure 11 shows the results of AGC experiments made under the condition of a 60 % reduction in thickness

Fig. 8. Method for measuring temperatures.

Fig. 9. Effect of rolling types and the number of lubrication nozzles on roll temperatures at the position of 3 mm under the roll surface.

and a 70 m/min rolling speed. The thickness deviation of a strip at the exit of the third pass indicated $\pm 9 \mu\text{m}$ (± 0.98 %) with no AGC system and $\pm 6 \mu\text{m}$ (± 0.65 %) with the present AGC system, which assured the effectiveness of the AGC system in NCM rolling. The present decoupling AGC, as shown in Fig. 10, uses the hydraulic screwdown as the main actuator and the entry and exit tensions as the auxiliary actuators, but the roll speed difference at the second or third pass can be used for the decoupling AGC instead of the entry or exit tension.

Figure 12 is the relation between the periodic length of thickness variation in the initial strip and the thickness accuracy of the rolled strip, which was theoretically calculated in the case of a usual three-stand tandem rolling with four-high mills and a strip-pulling-out type NCM rolling. This result shows that

Fig. 10. Automatic gauge control system for NCM rolling.

Rolling speed : $V_4=70$ m/min

Reduction in thickness: $r_t=60$ %

Strip tensions : $t_1=7.0, t_4=15.0$ kgf/mm²

Roll speed difference : $X_2=0.35, X_3=0.2$

Other conditions are the same as those in Table 1.

Fig. 11. Automatic gauge controllability in NCM rolling.

the automatic gauge controllability for NCM rolling is almost the same as that of the usual three-stand tandem rolling.

IV. Strip Shape Controllability

The strip shape controllability was theoretically investigated with the shape analysis model,⁵⁾ as it is difficult to clarify the strip shape controllability of NCM rolling experimentally because of the restrictions on

Fig. 12. Relation between periodic length of thickness variation of initial strip and thickness accuracy.

roll and strip sizes (refer to Table 1). The calculation of strip shape adopted a divided model⁶⁾ that divided a strip width and a roll length into about 40 elements, and a combination model that gave the rolling types with two-high rolls and one roll at the first and third passes and with one roll and one roll at the second pass. The entry tension at each pass was assumed to be independent of the strip shape, and the exit tension at each pass was assumed to affect the exit shape of the rolled strips.⁵⁾ In this calculation of strip shape, the flatness distribution of a rolled strip was first calculated in the width direction, and then by approximating the flatness distribution to a regression equation of four degrees, the strip shape was evaluated in the (λ_2 , λ_4) coordinate,⁷⁾ where λ_2 is a flatness difference of the obtained regression equation of four degrees between the edge and center positions of strip width and λ_4 is that between the quarter and center positions.

Table 3 shows the calculation conditions. The NCM considered in the calculation was assumed to have four work rolls and two backup rolls with actual mill sizes and two roll benders at the first and third passes. The thermal crown of each work roll was 40 μm , and the initial parabolic crowns were 40 μm for the #1 and #3 work rolls and 100 μm for the #4 work roll. Figure 13 shows the calculation result, where the curve of strip shape controllability at the exit of the third pass is given as a bold dash-dot line. This result suggests that NCM rolling with the appropriate initial crowns on the work rolls and an adequate control of the roll benders enables good shape controllability.

V. Characteristics of Edge-drop

Figure 14 shows the comparison of edge-drop between NCM rolling and normal rolling. In the normal rolling one-pass rolling was performed three times with the same reductions and strip tensions as in each pass of NCM rolling with the upper and lower work rolls at the same speed. The thickness distribution

Table 3. Calculation conditions.

- 1. Roll size Work roll: $\phi 500\text{ mm} \times 1\,400\text{ mm/l}$
Backup roll: $\phi 1\,240\text{ mm} \times 1\,400\text{ mm/l}$
- 2. Distance between screwdowns: 2 500 mm/l
- 3. Distance between roll benders: 2 500 mm/l
- 4. Bending force of work roll
1st pass F_1 : +50 ~ -50 tf/chock
3rd pass F_3 : +50 ~ -50 tf/chock
- 5. Initial crown of work roll: parabolic
- 6. Material: Mild carbon steel (SPCC)
- 7. Strip size Thickness: 2.3 mm
Crown: 90 μm
Width: 1 200 mm
- 8. Total reduction in thickness: 60 %
- 9. Reduction, tension and friction coefficient at each pass

Rolling schedule				
		1st pass	2nd pass	3rd pass
Reduction		28.8 %	24.5	25.5
Thick-ness	Entry	2.3 mm	1.64	1.24
	Exit	1.64 mm	1.24	0.92
Tension	Entry	13.8 tf (5.0 kgf/mm ²)	21.2 (10.8)	21.8 (14.7)
	Exit	21.2 tf (10.8 kgf/mm ²)	21.8 (14.7)	16.6 (15.0)
Friction coeffi- -cient		0.045	0.055	0.065
Rolling load		$W=800\text{ mm}$: 700 tf $W=1\,200\text{ mm}$: 1 050 tf

Fig. 13. Strip shape controllability in NCM rolling.

was measured at each pass in both the NCM and normal rolling. The edge-drop was defined as a thickness difference between two positions of 20 and 5 mm from a strip edge. The edge-drop in NCM rolling was less than in the normal rolling at the exit of each pass, and in particular the edge-drop in NCM rolling was 30 to 50 % less than in the normal rolling at the exit of the third pass. The decreasing of edge-drop in NCM rolling is due to the different roll speed rolling,³⁾ where the peripheral speed of the upper work roll is different from that of the lower work roll.

Fig. 14. Comparison of edge-drop between NCM rolling and normal rolling (NR).

VI. Comparison of NCM Rolling Types

According to the characteristics of NCM rolling described in this paper, the comparison between a strip-pulling-out type and a strip-enveloping type for NCM rolling was shown in Table 4. It seems that there is no significant difference between a strip-pulling-out type and a strip-enveloping type in high reduction per one stand, automatic gauge controllability, strip shape controllability and edge-drop. However, heat scratch is apt to break out in a strip-enveloping type, while a strip-pulling-out type causes no heat scratch. Also a strip-pulling-out type is superior to a strip-enveloping type in roll cooling. Therefore, a strip-pulling-out type NCM rolling is more suitable than a strip-enveloping type NCM rolling.

VII. Conclusion

A new compact multi-reduction mill (NCM), which can substitute one stand for two or three stands in a cold tandem mill, has been developed. This new mill is based on a three-pass rolling in one stand and allows a 70 % reduction in thickness in the cold rolling of mild carbon steel. The following is a summary of the results.

(1) The lubrication of phosphate pre-coating is used in addition to an emulsion lubrication, because the slip ratio between a rolled material and the work

Table 4. Comparison of NCM rolling types.

	Strip-pulling-out type	Strip-enveloping type
Structure		
High reduction	—	—
Gauge control-lability	—	—
Shape control-lability	—	—
Heat scratch	○	△
Roll cooling	○	△
Edge-drop	—	—
Total evaluation	○	△

(○:better, —:equal, △:worse)

rolls in NCM rolling is larger than that in normal rolling such as in four-high or six-high rolling. The rolling load and rolling energy with phosphate pre-coating are a little less than those with no phosphate pre-coating.

(2) The phosphate pre-coating shows a major effect on the prevention of steel powder formation.

(3) A strip-pulling-out type NCM rolling with phosphate pre-coating causes no heat scratch and gives stable rolling at a rolling speed of 200 m/min with a 70 % reduction in thickness.

(4) A strip-pulling-out type NCM rolling is superior to a strip-enveloping type in roll cooling.

(5) The automatic gauge control (AGC) system for NCM rolling, which consists of a decoupling AGC with constant volume flow and a monitor-type AGC with an X-ray gauge sensor, has been developed. The rolling experiments and theoretical calculations showed this new AGC system to have effective automatic gauge controllability.

(6) The theoretical calculations of strip shape suggested that NCM rolling with the appropriate initial crowns on the work rolls and an adequate control of the roll benders enabled good shape controllability.

(7) At the exit of the third pass the edge-drop of NCM rolling is 30 to 50 % less than that of a normal rolling with three one-pass rollings.

(8) Therefore, a strip-pulling-out type NCM rolling is more suitable than a strip-enveloping type NCM rolling and shows excellent rolling characteristics as a compact high-reduction mill.

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