# 6-high Cold Rolling Mill (HYPER UC-MILL*))
# with Smaller Work Roll Diameter for Thin Gauge Rolling


A. Yamamoto[1], S. Koga[2], Y. Kojima[1], S. Ozeni[1], T. Saito[1], Y. Shiga[2], K.H. Lam[2]

[1]Primetals Technologies Japan, Ltd.
6-22, Kanonshin-machi 4-Chome, Nishi-ku, Hiroshima, 733-8553 Japan
Phone: +81 082 291 2181

[2]MARUICHI SUN STEEL JOINT STOCK COMPANY
DT743Rd., Dong Tac Quarter, Tan Dong Hiep Ward, Di An City, Binh Duong Province, Vietnam. 3700236207
Phone: +84 274 3742 777



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## INTRODUCTION

Primetals Technologies (PT) has developed a 6-high HYPER UC-MILL [1], which utilizes a small-diameter work roll (WR) for the purpose of reducing the rolling load to roll high-strength steel and electrical steel sheets with high deformation resistance. The HYPER UC-MILL is a recent development by improving our 6-high UC-MILL technology. Figure 1 shows the average WR diameter derived from plant-specific data of rolling mills worldwide, according to the type of mill and strip width. In overall comparison, the WR diameter of the UC-MILL is approximately 25% smaller than that of the typical 4-high mill. The HYPER UC-MILL's WR diameter is further reduced by 20 to 30% from that of UC-MILL.

We recently installed No.2 CRM in Maruichi Sun Steel Joint Stock Company (abbreviated as SUNSCO), located in Binh Duong Province, Vietnam. It specializes in rolling soft and medium hardness materials, a single-stand reversing HYPER UC-MILL. Figure 2 shows a photograph of the mill. On this mill, we have succeeded in producing 0.1 mm thickness steel sheets from an entry thickness of 2.0 mm, which are often produced by mills that have more than 6 roll stack configurations. In this paper, the analysis and testing of rolling conditions down to 0.1 mm are investigated. Furthermore, verification rolling was performed on a test mill and then on the actual mill.

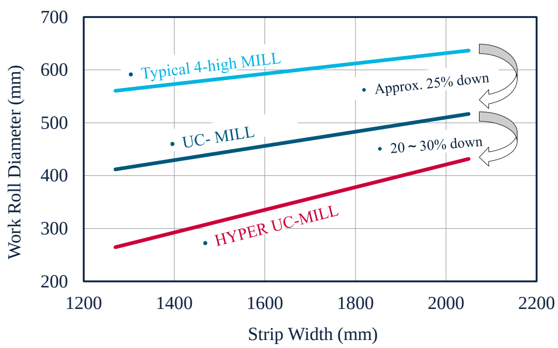


Figure 1. Comparison of work roll diameter

Figure 2. Overview of SUNSCO No.2 CRM

## EQUIPMENT CONFIGURATION

Figure 3 shows a schematic illustration of the equipment configuration at SUNSCO's No.2 CRM. The pay-off reel (POR) is located on the right side (entry side) when viewed from the work side, and the first pass rolling is from right to left.

After the hot-rolled coil from a pickling line is inserted into the POR, the head-end of the coil is bent by the three-roll feeder, through the mill and sent to the delivery side tension reel (TR). After the first pass rolling between the POR and the delivery side TR, the tail-end of the coil is completely unwound from the POR and transferred to the entry side TR. Multi-pass rolling is performed between both tension reels until the desired thickness is achieved.

*) "HYPER UC-MILL" is a registered trademark of "Primetals Technologies Japan, Ltd." in Japan, China, and India.

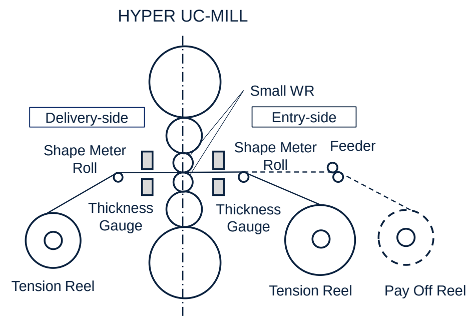


Figure 3. Equipment configuration of single-stand reversing mill

During rolling, the thickness and the shape of the strip are measured by thickness gauges and shape meter roll, respectively, on the delivery side of each pass and used for online feedback control.

The maximum coil weight is 25 tons, and the mill is capable of rolling strip width between 700 to 1,250 mm at a maximum of 1,200 meters per minute (mpm). At 1,200 mpm, a maximum tension of 57.1 kN can be applied. By adopting a WR diameter of 260 mm, the rolling load is reduced with an optimized facility with a maximum rolling load of 12,000 kN and 3,000 kW mill motor.

## THEORETICAL ANALYSIS

There is a correlation between the change in WR dimeter and the coefficient of friction between the rolled strip and roll during rolling. The theoretical minimum strip thickness can be determined with the attributing rolling force. We analyzed, in the following, the steps to determine the optimum WR diameter to roll a low-carbon steel strip down to 0.1 mm thickness.

### Correlation between coefficient of friction & work roll (WR) diameter

The roll bite angle changes when the WR diameter changes. This results in differing lubricity conditions, namely coefficient of friction, as the amount of lubrication drawn into the roll bite changes. Various methods for analyzing the friction coefficient based on lubrication theory have been studied by Suganuma et al. [2] [3] [4].

The relationship between the coefficient of friction and the WR diameter for cold rolling is depicted in below equation (1). Figure 4 shows the graph of the coefficient of friction for the WR diameter range.

$$\mu \propto \frac{1}{\sqrt{D_{wr}}} \quad (1)$$

$\mu(-)$ : Coefficient of friction (COF)
$D_{wr}(\mathrm{mm})$ : WR diameter

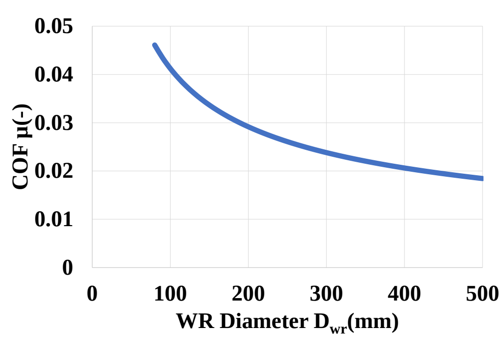


Figure 4. Relationship between WR diameter and the coefficient of friction

### Analysis of rolling forces

It's been known that as the WR diameter decreases, the contact arc length becomes shorter, and the rolling load becomes smaller. The rolling load was calculated using the Bland & Ford theory [e.g., 5] with the pre-condition that WR drive was selected for maintaining maximum strip shape controllability in determining the optimum WR diameter.

Table 1 shows the rolling parameters for this study. This condition is based on the final pass in the rolling of thin-gauge low-carbon steel material. To avoid underestimation of the rolling load, the strip tension was assumed to be the same level as in the middle passes.

Figure 5 shows the simulation results when the unit rolling force was plotted per WR diameter using a constant or changing coefficient of friction. It can be seen that the rolling load is underestimated compared to under the constant friction coefficient condition. From the viewpoint of strip shape controllability, the unit rolling force should be less than 10 kN/mm. Therefore, the WR diameter selection of 280 mm or less is optimal.

Conversely, the rolling torque from the motor is transmitted through the spindle to the WRs. Considering this limit of torque transmission, there is a lower limit for WR diameter.

Table 1. Rolling parameters

| | | |
|---|---|---|
| Strip thickness | mm | 0.169→0.108 |
| Back tension | MPa | 100 |
| Front tension | MPa | 100 |
| Average deformation resistance | MPa | 1,000 |

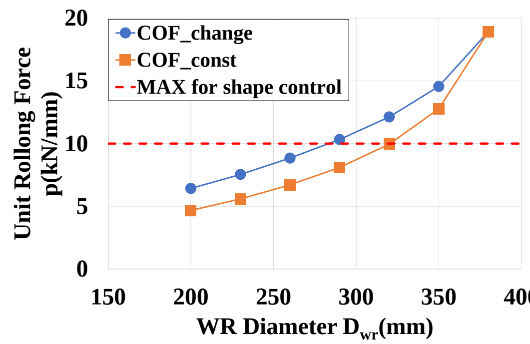


Figure 5. Relationship between WR diameter and unit rolling force

**Analyzing limits of minimum strip thickness**

It has been widely known that there is a minimum thickness limit at which further reduction is impossible. This is a phenomenon where further reduction in the WR gap only leads to the elastic deformation of the rolls. The rolled strip no longer goes through plastic deformation. Following Stone's theory [6], Ford et al. [7] and Shida et al. are used to determine the minimum rollable thickness.

Stone theory

$$h_{min} = 3.58 \times \frac{\mu(k_m - t_m)D_{wr}}{E} \quad (2)$$

Ford theory

$$h_{min} = (4.12 + 6.47\mu) \times \frac{\mu(k_m - t_m)D_{wr}}{E} \quad (3)$$

Shida theory

$$h_{min} = (4.13 - 13\mu^2) \times \frac{\mu(k_m - t_m)D_{wr}}{E} \quad (4)$$

$\mu(-)$ : Coefficient of friction
$D_{wr}$(mm) : WR diameter
$k_m$(MPa) : Average deformation resistance
$t_m$(MPa) : Average front & back tension
$E$(MPa) : Young modulus of rolling material

By using Stone's theory (2), Ford's theory (3), and Shida's theory (4) as illustrated above, WR diameter was determined for limits of minimum plate thicknesses of less than 0.1 mm.

Table 2 shows the conditions for determining the limits of minimum strip thickness. Since the target is to roll a strip down to 0.1 mm, the tension is set at the higher ranges of the TR’s capacity.

Figure 6 shows the calculated results with Stone’s theory providing the smallest minimum thickness, followed by Shida and Ford. The differing results of the three approaches can be attributed to approximating the distribution of rolling stress in the rolling direction. This difference is mainly due to the method of approximating the distribution of rolling stress in the rolling direction. It can be debated which theory best fits the reality, but Shida's theory was selected considering there is still a margin for increase in tension capacity in the TRs.

Table 2. Limits of minimum strip thickness study conditions

| | | |
|---|---|---|
| Average front & back tension | MPa | 250 |
| Average deformation resistance | MPa | 1,000 |
| Young modulus | GPa | 206 |

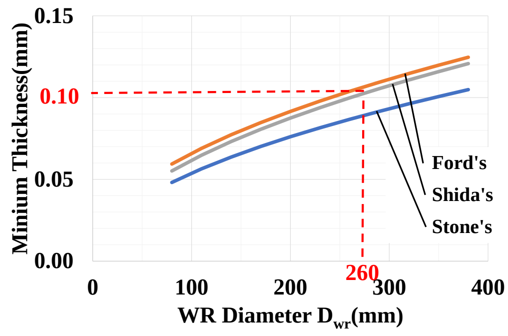


Figure 6. Minimum strip thickness based on WR diameter

**Summary**
Based on the results that the friction coefficient is dependent on WR diameter and rolling load consideration, it can be said a WR diameter of less than 280 mm is appropriate. Furthermore, a WR diameter less than 260 mm is optimal for obtaining the limits of minimum strip thickness.

## ROLLING ON THE TEST MILL

PT has a 6-high cold rolling test mill in Hiroshima, Japan. A rolling test was carried out using this mill to verify the rolling capability of the 0.1 mm strip before the trials at SUNSCO.

Figure 7 shows a photograph of the test mill, and Table 3 shows the basic specification of this test mill. The test mill is equipped with the same control software as those supplied to our customers to simulate those conditions on production lines.

Table 4 shows the conditions for the test mill. Test rolling was carried out down to 0.108 mm thickness according to similar real-world pass schedule, and the effects of the coolant concentration and the WR surface roughness implications on the friction coefficient were also evaluated.


Figure 7. Test mill

Table 3. Specification of test mill

| | | |
|---|---|---|
| WR diameter | mm | 200 |
| IMR diameter*) | mm | 300 |
| BUR diameter**) | mm | 630 |
| | | |
| Max. rolling speed | mpm | 1,000 |
| Max. roll force | kN | 5,000 |
| | | |
| Input strip thickness | mm | Max. 6.0 |
| Product strip thickness | mm | Min. 0.1 |
| Strip width | mm | 300~800 |
| | | |
| Max. tension | kN | 98 |
| | | |
| Main moor Power | kW | 650 |

*) IMR stands for Intermediate roll

**) BUR stands for Back-up roll

Table 4. Test conditions

Material: Low-Carbon Steel
Coolant concentration: 1%, 3%
WR surface roughness: Ra0.1µm, Ra0.3µm
Strip width: 400mm

Pass schedule

| Pass | Thickness (mm) | Reduction (%) | Rolling speed (mpm) |
|---|---|---|---|
| | 2.000 | | |
| 1 | 1.220 | 39.0 | 100 |
| 2 | 0.744 | 39.0 | 150 |
| 3 | 0.454 | 39.0 | 200 |
| 4 | 0.277 | 39.0 | 200 |
| 5 | 0.169 | 39.0 | 200 |
| 6 | 0.108 | 36.4 | 200 |

**Deformation resistance**

In order to improve the accuracy of the friction coefficient calculated from the rolling test results, the strip material was cut out after the tests and subject to a tensile test to obtain the uniaxial deformation resistance.

Figure 8 shows the deformation resistance obtained from the tensile tests and the approximation derived from Swift's formula, known as a deformation resistance approximation formula for steel materials. When the reduction ratio exceeds 90%, the deformation resistance obtained through the tensile test is higher than the value calculated from the approximation formula. The use of the conventional deformation resistance prediction formula may underestimate the deformation resistance of the material during the final rolling pass when the reduction ratio is greater than 90%.

Furthermore, from Equations (2), (3) and (4), the limit of minimum strip thickness is affected by the average deformation resistance of the material. It is highly possible that the limits of minimum strip thickness can be reduced by increasing the reduction ratio on the final rolling pass in order to reduce the average deformation resistance.

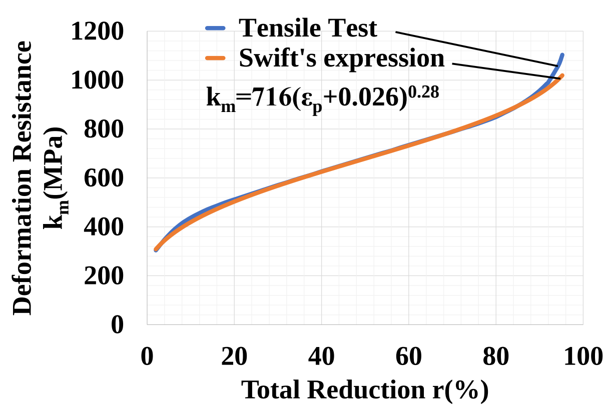


Figure 8. Deformation resistance

**Relationship between WR surface roughness, coolant concentration and coefficient of friction**

Using the values of deformation resistance from the test results shown in Figure 8, the coefficient of friction during rolling was calculated using the Bland & Ford equation. Figure 9 shows the friction coefficient obtained for rolling passes when WR surface roughness is altered, all the while the coolant concentration is kept the same. Although there are slight variations for

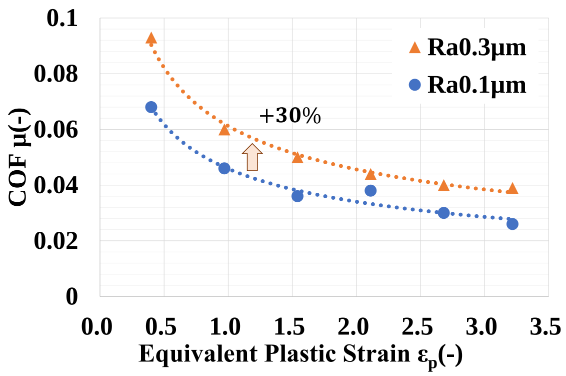


Figure 9. Change in coefficient of friction in relation to WR surface roughness

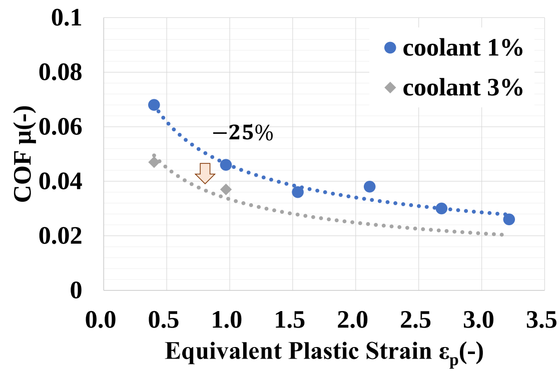


Figure 10. Change in coefficient of friction in relation to coolant concentration

each rolling pass, the friction coefficient increases by about 30% when the WR surface roughness is changed from Ra 0.1 μm to Ra 0.3 μm.

Figure 10 shows the friction coefficient obtained for each rolling pass when coolant concentration is altered, and the WR surface roughness is kept the same. Slippage occurred during rolling after 1st and 2nd passes, so data was not obtained. The friction coefficient after the 3rd pass was assumed to be same as shown in Figure 9. The friction coefficient was reduced by approximately 25% after increasing the coolant concentration from 1% to 3.

**260 mm diameter WR rolling conditions**

From the test mill, the deformation resistance of the material and the friction coefficient during rolling were confirmed. The pre-set condition to roll strip down to thickness of 0.108 mm using a WR diameter of 260 mm was determined based on the most stable pre-set condition on the test mill.

Figure 11 shows the predicted results of the possible range of rolling down to 0.1 mm using a WR diameter of 260 mm and average front-back tension of 250 MPa. The test results showed that a friction coefficient of 0.026 is obtainable under the conditions of using WR surface roughness of Ra of 0.1 μm and coolant concentration of 1% for the last pass rolling. By linearly interpolating the effects of WR surface roughness and coolant concentration on the friction coefficient, the limits of minimum strip thickness were calculated numerically.

Figure 11 shows that higher the coolant concentration and smoother the WR surface roughness, a lower friction coefficient increases the possibility of rolling down to 0.1 mm. In light of the formula for the minimum thickness limit, we decided to reduce the risk of strip breakage by lowering the strip tension. We selected the condition for WR surface roughness of Ra around 0.25 μm and coolant concentration of 4% with 260 mm WR diameter for rolling on the mill at SUNSCO.

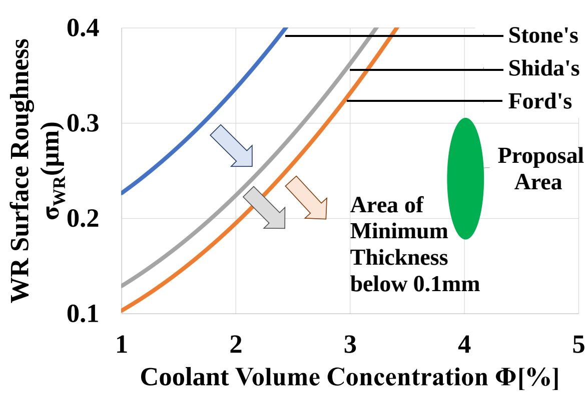


Figure 11. Predicted range of 0.1mm rolling

Finally, the friction coefficient is also dependent on rolling speed, which was not taken into consideration in obtaining the results for Figure 11. Test rolling was performed up to a maximum of 200 mpm. Maximum speed rolling on the actual mill would certainly be higher, so the friction coefficient would be further reduced. Therefore, the results obtained in Figure 11 can be considered conservative.

## ROLLING ON PRODUCTION MILL

### Specification of SUNSCO No.2 CRM

Table 5 shows the basic specification of SUNSCO's No.2 CRM. As introduced earlier, this mill has a maximum WR diameter of 260 mm in a 6-high HYPER UC-MILL configuration. Figure 12 shows the photo of the mill from the work side. This rolling mill has a highly capable strip thickness control by performing feedback control from measuring the delivery strip thickness. Additionally, the mill is equipped with WR-bending, IMR-bending, and spot coolant headers, together with pre-set IMR shifting for strip shape control actuators within this feedback control.

Figure 13 shows an image of the strip shape controlling principle by using the roll bending and IMR shifting in the 6-high UC-MILL. The HYPER UC-MILL is a recent development that utilize a smaller diameter WR in a WR drive mill configuration.

Table 5. Specification of SUNSCO's No.2 CRM

| | | |
|---|---|---|
| WR diameter | mm | 260 |
| IMR diameter | mm | 440 |
| BUR diameter | mm | 1,030 |
| | | |
| Max. rolling speed | mpm | 1,200 |
| Max. roll force | kN | 12,000 |
| | | |
| Input strip thickness | mm | 1.0~3.0 |
| Product strip thickness | mm | 0.10~2.0 |
| Strip width | mm | 700~1,250 |
| | | |
| Max. tension (at 1,200mpm) | kN | 57.1 |
| | | |
| Main moor Power | kW | 3,000 |

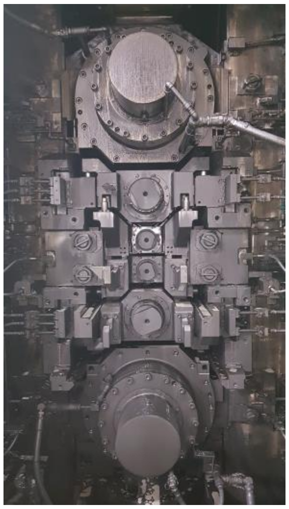

Figure 12. SUNSCO's No.2 CRM rolling mill

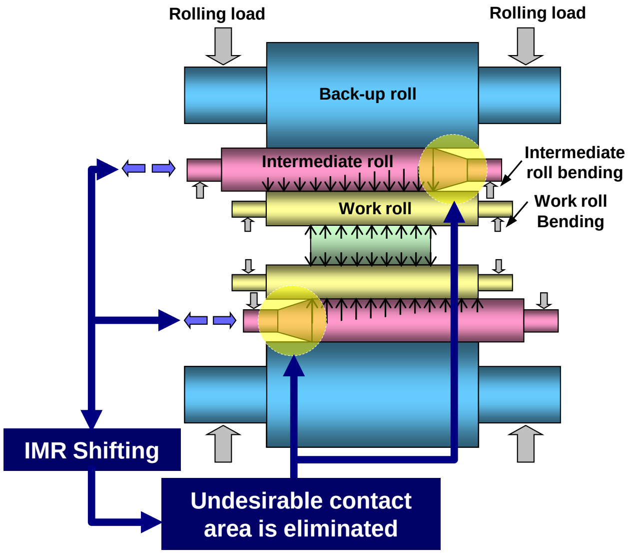


Figure 13. Conceptual image of strip shape controlling with IMR shift effect

The 6-high mill with IMR shifting changes the contact range between the IMR and WR to control the stress distribution. WR deflection outside the strip width can be suppressed. Since there is a large range where rolls are not in contact, WR bending is effective in counteracting the WR deflection. Next, roll bending of differing roll diameters of the WR & IMR leads to the possibility of strip shape controllability of compound shapes.

While roll bending can apply strip shape controllability over the entire strip width, spot coolant is used for local strip shape corrections. Based on the measured strip shape data, the thermal expansion of the WR is suppressed by injecting coolant intensively to the places where the strip elongation is large through feedback shape control.

**Thin gauge rolling**

Table 6 shows the rolling conditions. The number of rolling passes was increased to 7, compared to 6 passes on the test mill, in order to improve rolling stability by reducing the rolling load on each pass. The surface roughness of the WR was modified slightly to Ra 0.2µm.

Table 6. Rolling conditions

| Material: Low-Carbon Steel<br>Coolant concentration: 4%<br>WR surface roughness: Ra0.2µm<br>Strip width: 920mm | | | |
|---|---|---|---|
| Pass schedule | | | |
| Pass | Thickness<br>(mm) | Reduction<br>(%) | Rolling speed<br>(mpm) |
| | 2.000 | | |
| 1 | 1.340 | 33.0 | 210 |
| 2 | 0.880 | 34.3 | 415 |
| 3 | 0.568 | 35.3 | 610 |
| 4 | 0.367 | 35.5 | 755 |
| 5 | 0.237 | 35.4 | 1,030 |
| 6 | 0.154 | 35.0 | 1,200 |
| 7 | 0.100 | 35.1 | 1,200 |

Figure 14 shows the comparison between the predicted and actual rolling load. The predicted value of the rolling load was calculated from the friction coefficient result obtained on the test mill and through the Bland & Ford equation with the deformation resistance taken from Figure 8. Figure 15 shows the calculated friction coefficient from the actual rolling data. Generally, the predicted friction coefficient and the actual results between the 3rd to 7th final passes agree, but especially in the 1st pass, the predicted friction coefficient and calculated actual values deviates greatly. The reason for this discrepancy is thought to be the effect of the surface roughness of the rolled material, which is much rougher than first predicted. After the second pass, the surface roughness of the rolled material becomes similar to the WR surface roughness. In the first pass, the

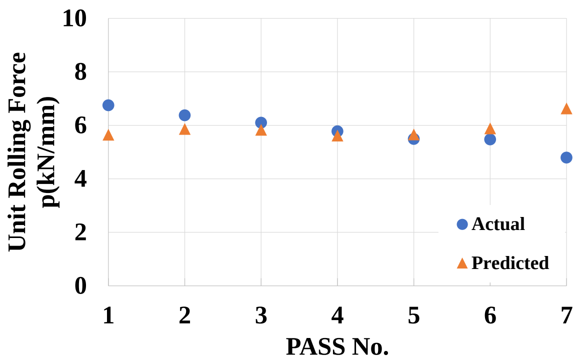


Figure 14. Unit rolling force – Predicted vs. actual

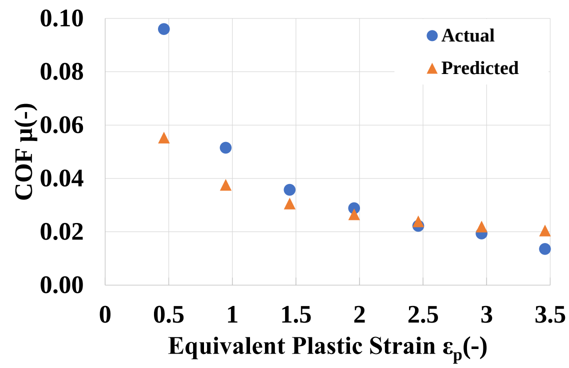


Figure 15. Coefficient of friction – Predicted vs. actual

surface roughness of the rolled material is highly dependent on a pickling process. In this case, the surface roughness of the material coming out of the pickling process was vastly rougher than initially predicted as calculated per friction coefficient. On the 7th pass, there is a somewhat large difference between the predicted value and the actual value of the rolling force despite minimal variation in the predicted value and the actual value of the friction coefficient. The reason for this is thought to be the high deformation resistance of the rolled material. Even if the error margin in the coefficient of friction is about the same, the larger absolute value for deformation resistance will result in the corresponding greater increase in rolling load over predicted values.

Rolling accuracy can be evaluated using the thickness deviation and strip shape standard deviation after the final pass. Figure 16 shows the strip thickness deviation on the delivery side of the rolling mill during the final pass. Figure 16 includes the acceleration & deceleration portion at the head and tail end of coil where thickness deviation is larger, but in the maximum speed rolling range, an accuracy of ±2.5 μm or less concerning the target thickness was achieved.

Figure 17 shows the strip shape deviation from the target shape on the delivery side of the rolling mill during the final pass. Similar to Figure 16, the acceleration & deceleration portion at the head and tail end values are included, while an accuracy of 2.5 I-unit or less was achieved at the maximum speed rolling range. In the acceleration & deceleration ranges, the stress distribution on the strip changes due to the amount of coolant flowing into the roll bite, which is a factor in the deviation of the strip shape. In Figure 17, the deviation of less than 5.0 I-units is still achieved in most of this range owing to the superior strip shape controllability of the mill with its WR and IMR bender. The bottom right of Figure 17 shows the strip shape distribution over the entire width at the indicated point of rolling, and it can be said that good shape is achieved.

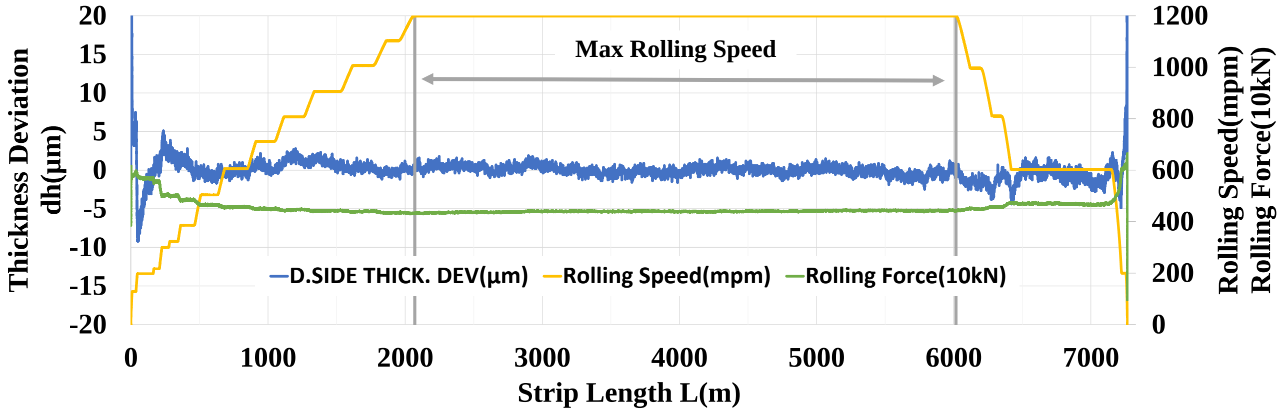


Figure 16. Last pass strip thickness deviation

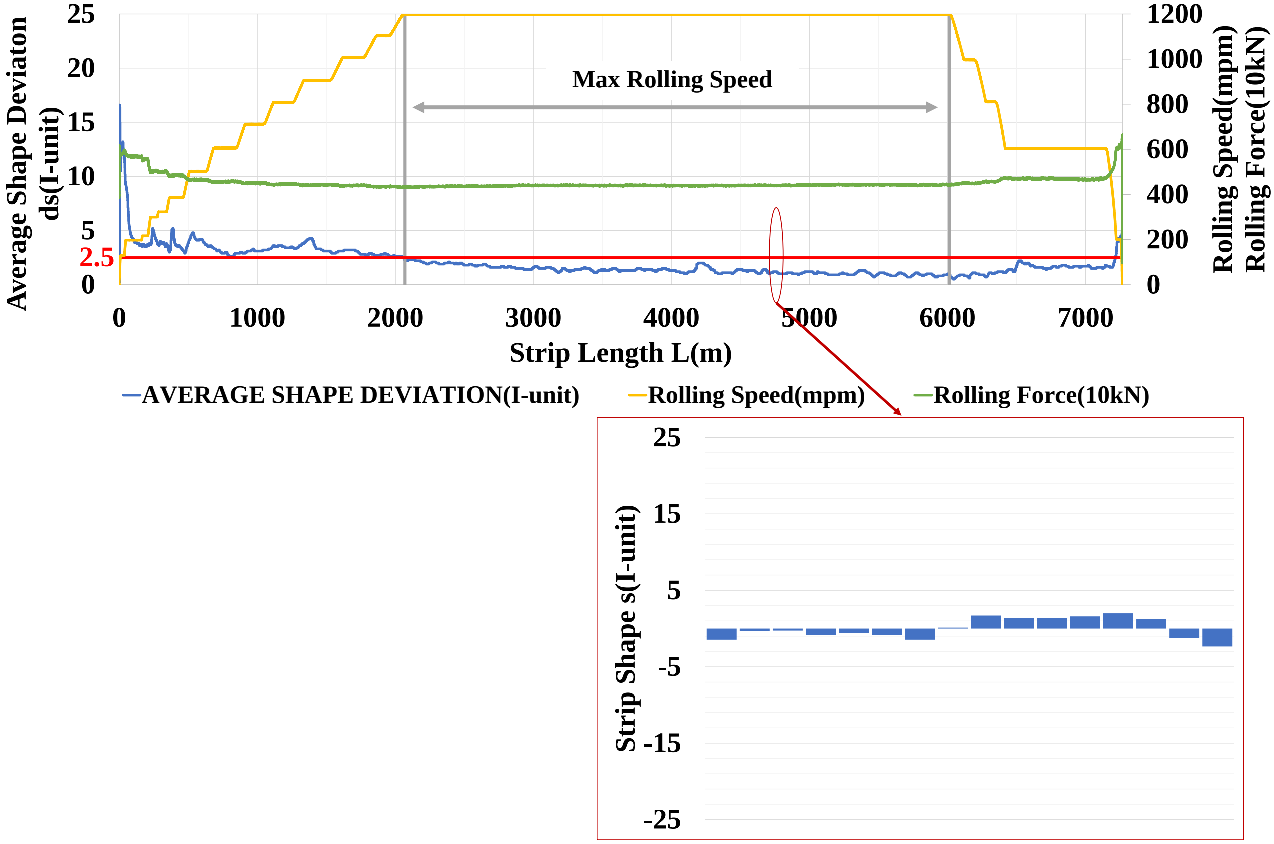


Figure 17. Last pass strip shape deviation

## CONCLUSIONS

A small WR diameter of 260 mm was adopted for SUNSCO's No.2 CRM. Based on the theoretical studies and the results of rolling on the test mill, the conditions necessary for rolling a thin strip of low-carbon steel down to 0.1 mm were established. The results obtained on rolling at SUNSCO's No.2 CRM showed:

1) It was confirmed that the friction coefficient depends on the WR surface roughness and coolant concentration on the test mill and actual rolling.
2) Friction coefficient's dependency on the WR diameter, WR surface roughness, and coolant concentration showed that predicted values and actual values were generally in agreement in the latter passes of rolling.
3) The strip thickness control and the strip shape control of the HYPER UC-MILL are such that even when rolling a final product thickness of 0.1 mm strip with a total reduction ratio of 95%, the strip thickness deviation of ±5 µm or less and shape accuracy of less than 2.5 I-Units were obtained.

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