Strip Shape and Profile Control with a New Type of the Variable Crown Roll System

By Takeshi MASUI,** Junzo YAMADA,*** Toshihiko NAGAI**** and Takao NISHINO*****

Synopsis

In order to obtain well shaped strips, the deflecting of rolling mill rolls that occurs during rolling must be compensated for. To solve this problem, a new type of the variable crown roll has been developed which by expanding the sleeve by internal oil pressure can control the strip shape. This VC roll consists of an arbor and a sleeve. Both ends of the sleeve are securely joined to the arbor by shrink fitting, making a circumferential oil chamber between the sleeve and the arbor. A pressurized oil is supplied into the chamber through a passage in the arbor so as to control the quantity of the roll crown, then the strip profile and shape can be controlled optionally by changing the oil pressure. This VC roll system performs excellently, namely by a wide control range, easy operation, and good controllability. Other salient points of this system are wide applicability in both 2 high (2Hi) and 4 high (4Hi) mills, and easy installation in already existing mills, without any modifications made in the mill stand.

I. Introduction

By introducing the AGC system and process computers into the rolling process, the quality of rolled strips and plates, especially the accuracy of thickness has been greatly improved in recent years. However, the flatness and thickness uniformity across the strip width still remain insufficient. Since these problems are considered to be due to the deformation of the rolls which is caused by rolling force, many studies have been carried out to control the deflection of the rolls during rolling operation.

Sumitomo Metal Industries, Ltd. has developed a new roll crown control system, VC (Variable Crown) roll system, based on its years of experience of roll manufacturing and rolling technology, and put it in practical use with a good success. This new roll system, featuring that the deflection of the rolls is offset in an instant by expanding the rolls through hydraulic pressure, was first introduced in the 2Hi skinpass mill for hot-rolled coils in 1977. Ever since, its application range has been widened one after another to the 4Hi reversing mill, 4Hi temper mill, tandem cold strip mill and tandem hot strip mill, where the shape and profile control of the strips is successfully performed. In this paper we present the outline of the VC roll system and the strip shape and profile control effect of the VC mill (a VC roll and bender combination), along with the details of the development.

II. VC Roll System

Figure 1 shows the outline of the VC roll system.

This system consists of a VC roll assembly, hydraulic power unit, control unit and operating panel.

1. Structure of VC Roll

The VC roll is a sleeve type assembly roll which has an oil chamber between the sleeve and the arbor and both ends of the oil chamber are shrink-fitted. The high pressure oil from the hydraulic power unit flows through the rotary joint and the passage of the arbor to the oil chamber and then enlarges the sleeve to make up for the deflection of the rolls caused by rolling force. In other words, the sleeve can be expanded by oil pressure to meet any rolling force. This is exactly the same method as an initial roll crowning in the conventional solid roll. The shrink-fitting ratio and length are determined so that the shrink-fitted section can give a strong holding capability to the sleeve and arbor and provide a good sealing effect against high pressure oil. Also, adequate design consideration is given to facilitate the entrance of oil and to minimize the oil flow.

2. Hydraulic Control Device

The standard specifications of the hydraulic power unit and the rotary joint are shown in Tables 1 and 2. The hydraulic power unit is set for a standard maximum operating pressure of 500 kgf-cm⁻². This high pressure oil is controlled with the hydro-electric servo method to have a response velocity of more than 100 kgf-cm⁻² sec⁻¹ and to precisely maintain the variation of oil pressure within ±5 kgf-cm⁻² of the setting value. Two types of rotary joints are used according
to the size of the VC roll employed. Each type has a high pressure circuit and bearing cooling circuit, and the pressure balance structure at the contacting parts of the rotary permits continuous operation under high pressures.

### III. Application of VC Roll to 2Hi Mill

After making certain of the effect of the VC roll system in the model mill, the first VC roll was introduced into the skinpass mill of hot-rolled coils (825 mm dia. × 1 950 mm length; rolling speed, 400 m·min⁻¹ max.; rolling force, 1 000 tf max.) of Kashima Steel Works on a practical basis.

The sleeve expansion was up to 0.31 mm (radius) at the middle of the roll. To obtain good rolled shape of strips, the sleeve thickness was varied in the barrel direction to give a gradual bulge.

With the VC roll as the top roll and a solid roll as the bottom roll, some coils were rolled under a constant rolling force. Figure 2 shows the effect of shape control. When the internal pressure is relatively small, edge waves are observed on the strip, and gradually fade away with the internal pressure developed. As an appropriate internal pressure is attained, the strip shows good flatness at first and then center buckle. Thus, it is understood that the VC roll holds a sufficient strip shape control capability.

In addition, we performed test rollings of aluminum strips (1.2 mm thickness×1 020 mm width) and stainless steel strips (0.4 mm thickness×1 000 mm width, SUS304) and obtained the same strip shape control capability as seen in Fig. 2.

### IV. Application of the VC Roll to 4Hi Mill

We examined the possibility of using the VC roll as the work roll (WR) and back-up roll (BUR). As a result of investigations on the model mill, however, we found that it was effective to use the VC roll as the back-up roll.

#### 1. Practical Use of the VC Roll in the Reversing Mill

The first VC back-up roll was introduced in the cold reversing mill of Wakayama Steel Works on a practical basis. The specifications of this mill are shown in Table 3 and the specifications of the VC roll used in this mill shown in Table 4. The operation of this mill consists of a combination of cold reduction rolling and temper rolling. This mill is equipped with a decrease type roll bender. Figure 3 shows the roll

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**Table 1. Specifications of the hydraulic power unit.**

<table>
<thead>
<tr>
<th>Hydraulic pressure</th>
<th>0~500 kgf·cm⁻²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed of response</td>
<td>Increase 100 (kgf·cm⁻²)/s</td>
</tr>
<tr>
<td>Accuracy of setting pressure</td>
<td>±5 kgf·cm⁻²</td>
</tr>
<tr>
<td>Oil</td>
<td>Polyol ester</td>
</tr>
</tbody>
</table>

**Table 2. Specifications of the rotary joint.**

<table>
<thead>
<tr>
<th>Type</th>
<th>2 types of 250 dia. &amp; 160 dia.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. hydraulic pressure for continuous rotation</td>
<td>500 kgf·cm⁻²</td>
</tr>
<tr>
<td>Max. resisting pressure</td>
<td>750 kgf·cm⁻²</td>
</tr>
<tr>
<td>Max. rotating speed</td>
<td>500 rpm</td>
</tr>
<tr>
<td>Guarantee number of revolution</td>
<td>1 × 10⁷ revolution</td>
</tr>
</tbody>
</table>

**Table 3. Specifications of 80" combination mill.**

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness (Entry/Exit)</th>
<th>Width</th>
<th>Max. rolling speed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.6<del>6.0/0.4</del>3.2 mm</td>
<td>610~1 880 mm</td>
<td>760 m/min</td>
</tr>
<tr>
<td>Roll</td>
<td>WR</td>
<td>580×2 032 mm</td>
<td>1 422×2 007 mm</td>
</tr>
<tr>
<td>Dia.×barrel length</td>
<td>BUR</td>
<td>Polyol ester</td>
<td></td>
</tr>
<tr>
<td>Roll bender</td>
<td>BUR-WR bending type 66.4 tf/chock</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 4. Specifications of the VC roll.**

<table>
<thead>
<tr>
<th>Rolling load</th>
<th>Cold rolling</th>
<th>Temper rolling</th>
<th>Abnormal load</th>
<th>Max. 2 000 tf</th>
<th>Max. 500 tf</th>
<th>4 500 tf</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roll dimension</td>
<td>Diameter</td>
<td>1 447 mm</td>
<td>1 447 mm</td>
<td>2 006.6 mm</td>
<td>2 006.6 mm</td>
<td></td>
</tr>
<tr>
<td>Barren length</td>
<td>2 006.6 mm</td>
<td>Polyol ester</td>
<td>Polyol ester</td>
<td>Polyol ester</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Fig. 2.** Shape control with variable internal pressure.

**Fig. 3.** Relation between roll crown and internal pressure.
crown of the VC roll. With the maximum operating pressure of 500 kgf/cm², it shows a roll crown of up to 0.27 mm (radius) at the center of roll barrel.

Figure 4 shows thickness rigidity in (a) and width rigidity in (b) of the mill using the VC roll, compared with mill using a solid roll. As seen from Fig. 4, the VC roll stands comparison with the solid roll. In order to examine work roll deflection due to the roll crown of the VC roll under loaded condition, we measured the thickness distribution of the roll contour under various conditions by compressing an aluminum plate of 5 mm thickness between the work rolls. Figure 5 shows the results of this measurement. From Fig. 5, we find that the deflection of the work roll varies with the roll crown of the VC roll; the control range widens by combining the bender with the VC roll and a complicated roll deflection curve is obtained; and the wider the strip becomes, the more the control effect results. Using the VC mill with an increased roll deflection control capability, some test cold rollings of steel strips (0.75 mm thickness × 1615 mm width) were performed with the screw down position and front/back tension kept constant and reduction ratio at 20%. Figure 6 shows photographs of the strips produced by such test rollings.

As the VC roll internal pressure is increased, an extreme center buckle appears. This proves that the control effect of the VC roll is excellent. By combining the VC roll with the bender, the coexistence of center buckle and edge wave is observed. As a result, it supposes the possibility of controlling complex shape defect by combining two different mode control methods. The above description is the results of the experiments in which one VC back-up roll is used. We, at the same time, found that the control effect was doubled by using the VC roll for both the top and bottom rolls and that a larger effect was obtained by decreasing the diameter of the work roll.

Then, we describe the analysis model of the VC mill control effect briefly below. Figure 7 shows the calculation model and symbols of the VC mill. This model was worked out based on the point matching method of Shohet and Townsend, taking into account the expansion and depression of the VC roll. With regard to the rolled material, the distribution of front tension was considered from elongation deviation that allowed for the lateral flow of metals. In the rolling of extreme thin strips there occurs the so-called...
kiss rolling, in which the top and bottom work rolls cause an elastic contact at both outsides of the material, so we took this kiss load \( (q_{ki}) \) into consideration. The details of this model are left to the separate paper.4~ We show only the calculation flow chart in Fig. 8.

In this chart, we, at first, gave a rolling force and reduction ratio at the width center and then calculated the strip crown and tension distribution (strip shape) accordingly. Figures 9 and 6 show the calculation results of this model and measured values. Figure 9 shows the comparison of the strip crowns in the aluminum strip compression test, and Fig. 6 shows the comparison of strip shapes. These figures show that this model can be used for discussing about not only the roll deflection but the strip shape.

2. Application to Tandem Cold Strip Mill 7'8~

1. Strip Shape Control Characteristics of Final Stand

After used in the 2Hi mill and 4Hi mill, the VC roll was, as the next step, introduced into the final stand of the 68” 5 stand cold tandem mill at Kashima Steel Works. This mill is a high speed mill with a maximum rolling speed of 1 812 m·min⁻¹. The VC roll (1524 mm dia.×1704 mm length) is designed so that it has a maximum normal load of 1 600 tf and an expansion of 0.23 mm (radius) at the maximum oil pressure of 500 kgf·cm⁻².

By combining the VC roll with the existing bender, a greatly increased shape correction performance was achieved. In addition, the quality in flatness was increased and work roll initial crown integration was made possible. It was also found that the VC roll was not inferior to the solid roll in roll strength and eccentricity against an abnormal load when strip wreck or break occurred.

2. Heavy Reduction Rolling at the Up-stream Stands

We theoretically examined the possibility of heavy reduction rolling (increase of hot coil thickness) at upstream stands of which roll deflection control performance was increased by the VC roll. Figures 10 and 11 show the results of the calculations. The VC roll used was set for a hydraulic pressure of 500 kgf·cm⁻² and had an expansion of 0.214 mm (radius). The present schedule A (2.3 mm thickness×1224 m width→0.5 mm thickness), in Fig. 10, is compared with the schedule B in which the hot coil whose thickness is increased to 3.8 mm is put in heavy reduction rolling by No. 1 and No. 2 stands. At this time, the existing work roll diameters of the No. 1 and No. 2 stands are compared with those decreased to 420 mm dia. Although the rolling load is largely increased in the existing work roll, the increment is reduced by decreasing the diameter of the work roll. Figure 11 shows the “out” side strip shape (elongation deviation from the center of strip width) of the No. 2 stand. If the hot coil thickness is

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Fig. 7. Calculation model and symbols of the VC mill.

Fig. 8. Flow chart for the estimation of VC effect.

Fig. 9. Comparison between calculated plate crown and measured one. (80H/200×460³ pilot mill)

Fig. 10. Comparison of strip crown in the aluminum strip compression test. (80H/200×460³ pilot mill)
increased to 3.8 mm with the work roll diameter unchanged, an extreme edge wave appears due to the roll deflection caused by increased load, preventing normal rolling operation. When the VC roll is used for both the top and bottom rolls and a smaller diameter work roll is combined with them, an extreme center buckle is observed. This sufficiently compensates for roll deflection caused by increased load during heavy reduction rolling. In principle it is also possible to improve final profile after heavy reduction rolling, and this problem remains to be studied in future along with the metal flow of material.

3. Application to Tandem Hot Strip Mill

We are now examining the possibility of hot strip shape and profile control by the VC roll at the Wakayama 80” tandem hot strip mill. This VC roll (1 382 mm dia.×2 038 mm length) has an expansion of 0.26 mm (radius) at 500 kgf·cm⁻². After confirming that when the VC roll is applied to the bottom back-up roll of the final stand, there is no problem in regard to the hardware and a sufficient control effect is expected for wide strip, we used the VC roll for both the top and bottom back-up rolls to improve the control effect for narrow strip. Also, we performed a control effect test by decreasing the diameter of either of the work rolls (500 mm dia./720 mm dia.) and examined the shape control and profile control effect on narrow strips (2.3 mm thickness×950 mm length) in four cases, present combination (bender only: \( f_w \text{ max.} = 195 \text{ tf} \)), one VC back-up roll, two VC back-up rolls, and one VC back-up roll plus one smaller diameter work roll combination.

Figure 12 shows the comparison of the four cases. The flatness index means the grade of strip shape by visual inspection. From the figure, we find that the VC roll has a sufficient shape control performance even for narrow strips if the two-VC back-up roll combination or one-VC back-up roll plus a smaller diameter work roll combination is employed.

The same result is obtained concerning the profile control, so the two-VC back-up roll combination or one-VC back-up roll plus a smaller diameter work roll combination proves to be capable of controlling the strip crown of 20~30 μm against narrow strip. Since the profile control capability is limited in relation with allowable shape defect, the profile control by the multi stands is necessary. We performed some tests to see how far the profile control is possible keeping allowable strip shape, namely, leaving the work roll diameter unchanged while using the VC roll in either of the back-up rolls of the down-stream 3 stands. Figure 13 shows the thickness distribution obtained in these tests. It was confirmed that a multi-stand VC roll system application is effective to control strip profile keeping it in good shape.

Figure 14 shows the relation between the number of VC mill applied stands and simulation result of profile control capability in 7-stand 80” tandem hot strip mill with the representative size of 2.3 mm thick and 1 250 mm wide. A comparison between the usual mill (bender force \( f_w = 50 \text{ tf} \) and 200 tf) and the VC mill (internal pressure \( p' = 500 \text{ kgf·cm}^{-2} \), \( f_w = 200 \text{ tf} \) ) was performed. The vector chart analysis with the strip crown and shape as elements was used based on a single stand control performance which allows for tension distribution, with the interstand shape allowable limit at a steepness of
±2.5 % (elongation deviation: ±0.1544 %) and final shape at a steepness of ±1 % (elongation deviation: ±0.0247 %).

In either case, when the VC roll is used only in the final stand, an effective shape control is attained, but less effect is found in profile control. When the VC roll is used in more than two stands, a remarkable control effect is expected. In other words, the more the number of stands using the VC roll, the larger the strip crown control capability results. Although a single stand control capability becomes larger as the work roll diameter decreases, in some cases, a small strip crown control amount \( \Delta CR_{25} \) (variation of the strip crown \( CR_{25} \) which is the difference between the strip thickness at the center of width and the one at a point 25 mm away from the strip edge in the width direction) appears. This is due to the fact that the less the diameter of the work roll, the smaller the lateral flow becomes and thereby the shape limitation is likely to be applied. We consider it possible to combine the VC roll with other control methods that will be put in practical use in the future.

Figures 15 and 16 show the calculated examples of the profile control capability of a single stand using the VC roll/work roll shift combination and the VC roll/skew rolling combination, respectively. These combinations are expected as promising technologies that can meet the schedule-free rolling, in addition to their improved control capability.

4. Application to Non-ferrous Metal Mill

Needless to say, the VC roll develops the same effect for not only in the steel mill but also in the non-ferrous metal mill. Especially, in shape and profile control of aluminum or copper, the effect of the VC roll will become greater since the deformation resistance

![Fig. 13. Multi-stands (down-stream 3 stands) one side VC roll effects on strip profile.](image)

![Fig. 14. Relation between No. of VC mill applied stands in 80" production finishing mill and strip crown control range. (2.3x1 250x: slab 55) ](image)
of material is smaller. Moreover, because of its low rolling force, a VC roll with a larger roll crown can be engineered. Consequently, the above description also holds true for the shape and profile control of non-ferrous metals.

Here, we describe the calculated results of aluminum foil kiss rolling. One of the back-up roll of an aluminum foil mill is changed to the VC roll with the following conditions:

\[
\begin{align*}
RL2 &= 1683 \text{ mm}, \\
RL4 &= 2184 \text{ mm}, \\
RL4D &= 2123 \text{ mm}, \\
DW &= 270 \text{ mm}, \\
DB &= 635 \text{ mm}.
\end{align*}
\]

For the symbols, see Fig. 7.

The VC roll has an expansion of 0.133 mm (radius) at 500 kgf·cm⁻².

With such a mill, rolling of aluminum foil (30 µm thickness and 1100 mm width) was performed with the rolling force at 300 tf, front/back tension kept constant at 10 kgf·mm⁻² and reduction ratio at 50 %.

Figure 17 shows the comparison of the VC roll effect and bender effect \((F_W = -40 \text{ to } 20 \text{ tf})\). In both cases, kiss rolling is performed. Especially, when \(F_W\) is \(-40 \text{ tf}\), kiss rolling force accounts for about 22 % of the whole. The strip thickness distribution varies largely with the VC roll pressure change, but the bender effect is small. This is because the aluminum foil mill is a slim mill of which WR barrel/WR dia. ratio is relatively large, so that the roll bender effects largely on work roll deflection at barrel sides but has little effect at the strip portion, while the VC roll effects on work roll deflection along with the whole barrel length.

This VC roll effect is greater than the changes (Fig. 18) in strip thickness caused by changing the rolling load by \(\pm 50 \text{ tf}\). In the decrease bender, the distribution of the strip thickness shows a slight concave, compared with the case of \(F_W = 0\). This is a phenomenon peculiar to the kiss rolling and is considered due to the fact that the work roll deflection slightly shifts in

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**Fig. 15.** VC+WR shift effect (80" hot strip mill). (3.91×1 250" → 2.9")

**Fig. 16.** VC+SKEW effect (80" hot strip mill). 3.91×1 250" → 2.9")

**Fig. 17.** Comparison of VC roll effect with bender effect on kiss rolling with aluminum foil. (15 µm thickness)

**Fig. 18.** Changes in thickness distribution with rolling load ±50 tf.
the direction that permits the strip crown to decrease at the strip portion due to kissing of the roll barrel ends.

V. Conclusion

A new type of the VC roll system was introduced into the 2Hi mill, 4Hi mill, tandem cold strip mill and tandem hot strip mill, and large shape and profile control effect was obtained. Also by combining the VC roll with the pre-existing bender, shape and profile control effect was increased especially complex shape defect during cold rolling became controllable. And when the work roll diameter was decreased, control effect was greatly increased. We confirmed the above description from the theoretical and practical point of view, and thereby showing that this VC roll system was effective as shape and profile control means. In addition, we showed that this system developed the same effect for the non-ferrous metal mill as for the steel mill, and especially was effective for aluminum foil mills in which the bender effect was relatively small.

We are planning to study the application of the VC roll to the plate mill, while developing the technology for heavy reduction rolling at the up-stream stand of the tandem cold strip mill and multi-stand control in the tandem hot strip mill.

REFERENCES