Selection of Work Roll Diameter for Cold Rolling Mill*

By Hajime WATANABE, Hisashi HONJO and Kiyoto MIYASAKA

Synopsis
The work roll diameter is a very important factor which influences the overall specifications of rolling equipment. A number of studies have been reported in the past on the selection of the most suitable diameter. Here we have taken up this problem in consideration of more recent developments in rolling equipment and operation techniques in cold rolling, such as the advent of the fully continuous mill, new techniques for automatic gauge control especially in threading, the rolling of high tensile strength steel, effective shape control devices, energy saving in rolling, reducing production costs, and increasing reduction per pass. In order to choose the optimum roll diameter, it is necessary to consider such factors as the minimum gauge in rolling, consumption of energy, shape control faculty, allowable roll contact pressure. These factors are not necessarily compatible with each other, and the dominant factors determining the optimum diameter differ from pass to pass in rolling. Therefore, in the case of a tandem mill, it should be necessary to consider the optimization of roll diameter individually as well as for the total system.

I. Introduction
There have been reports on the selection of the most suitable diameter of work roll in rolling mills. Recent technological advances in the rolling equipments and their operation, however, require the modification and addition of the presently adopted principles for the selection of roll diameter. The recent developments in the conditions of cold rolling equipment and their operation include the following.

1. The advent of the continuous rolling mill and the progress in the techniques of gauge alteration during the running have relaxed the limitations imposed by strip threading and tailing out.

2. For the conventional tandem cold mills operating on the batch system, progress has been made on the study of transient phenomena occurring at sheet threading. Automatic gauge control (AGC) is now actively adopted for sheet threading to ensure the stable operation under very stringent rolling conditions.

3. An increasing portion of rolling work is now on the materials with a high flow resistance, such as high tensile and silicon steel strips.

4. Production of extra-light-gauge steel sheets is increased.

5. Progress in shape controlling devices is calling for a revision of the current considerations concerning the shape instability experienced with small-diameter rolls.

6. The merits of small-diameter rolls are now re-appreciated from the viewpoint of energy conservation and cost savings.

7. Similar merits as in (6) are sought by realizing ever higher draft.

8. The practice of rolling in multiple widths for subsequent slitting has accentuated the demand for rolling mills of greater widths.

In this paper the selection of work roll diameter is re-examined in the light of the foregoing observations and with a particular reference to cold rolling of steel strip. For the reason given in (3), the calculations presented in this paper cover cases of steels with higher flow resistance than encountered in the current rolling practice, even when the procedure of roll diameter selection is conventional. Also for the reason given in (7), the calculations are for cases of a large draft.

II. Factors to be Considered in Selecting Roll Diameter
The factors considered in selecting the work roll diameter are listed in the left-hand column of Table 1. The general considerations concerning each of these factors are presented in what follows. It should be noted, however, that these considerations are subject to modification according to the type of rolling mill and manufacturing conditions.

1. Minimum Producible Gauge
In conventional rolling, the minimum producible gauge \( h_{\text{min}} \) is expressed by

\[
h_{\text{min}} = \frac{a \cdot D_w \cdot \mu \cdot (k - s)}{E}
\]

where,
\( E \): elastic modulus of rolls
\( D_w \): work roll diameter
\( \mu \): rolling friction coefficient
\( k \): 2-dimensional mean flow stress
\( s \): strip tension.

Stone has given a value of 3.58 for \( a \), but it is 1.1 according to Roberts. This value should be chosen in accordance with the theoretical formula used to derive the friction coefficient \( \mu \). An experiment conducted by the present authors using a 400 mm dia. test mill resulted in a value of 1.94 for \( a \), when the data were fitted to Hill's formula for rolling. The results of the calculation with \( a = 1.94 \) in Eq. (1) at a late stage of cold working are shown in Fig. 1.

When rolling a narrow strip through a wide rolling
mill, there would be in addition to the above limitation the possible effect of direct contact between the rolls at their extremities beyond the strip edges. However, the plastic modulus of aluminum foil and other sheets of extra-light gauge is so high as to almost equal the spring constant along the roll contact line, that this consideration should not give a direct limitation such as that by Eq. (1).

On the other hand, in PV rolling at a prescribed ratio of peripheral roll speeds for reducing the rolling force, the friction hill is theoretically reduced to zero. This eliminates the gauge limitation by Eq. (1) and only the direct contact between rolls beyond the strip edges is considered. In either event, a smaller roll diameter permits rolling down to lighter gauges.

### Table 1. Concept of choice of work roll diameter in cold rolling.

<table>
<thead>
<tr>
<th>Factors governing selection of work roll diameter</th>
<th>Overall choice of roll diameter would tend toward:</th>
<th>Influence of change in diameter of rolls of different stages</th>
<th>Remarks</th>
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</thead>
<tbody>
<tr>
<td>A. To diminish limiting producible strip gauge</td>
<td>Smaller diameters</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B. To increase limiting transmissible torque</td>
<td>Larger diameters</td>
<td></td>
<td></td>
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<tr>
<td>C. To increase limiting roll surface pressure</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>D-1. Bite angle friction</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D-2. Displacement of neutral point</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E. To reduce rolling energy</td>
<td>Smaller diameters</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F. To reduce rolling cost</td>
<td>Larger diameters</td>
<td></td>
<td></td>
</tr>
<tr>
<td>G. To reduce rolling force (Equipment capacity/cost)</td>
<td>Smaller diameters</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Physical limitations

- **Possibility/stability of rolling operation**
  - A. To diminish limiting producible strip gauge: Smaller diameters
  - B. To increase limiting transmissible torque: Larger diameters
  - C. To increase limiting roll surface pressure:"
  - D. To increase draft limited by:
    - D-1. Bite angle friction:"
    - D-2. Displacement of neutral point:"

### Direct rolling costs

- E. To reduce rolling energy: Smaller diameters
- F. To reduce rolling cost: Larger diameters
- G. To reduce rolling force (Equipment capacity/cost): Smaller diameters

### Quality of rolled product

- H. To improve lubrication (Surface properties)
  - H-1. By increasing oil film thickness: Larger diameters
  - H-2. By lowering roll temp:"
  - H-3. By lowering specific rolling force: Smaller diameters

### Policy-related considerations

- I. To improve product strip shape by diminishing:
  - I-1. Simple deformation across strip: (Larger diameters) +
  - I-2. Center crown:"
  - I-3. Edge drop: Smaller diameters
  - I-4. Multiple deformation: (Larger diameters) +

(Note): 1. (): Increasing roll diameter will contribute strongly; (): Increasing roll diameter will contribute moderately;
   \[\Delta\]: Decreasing roll diameter will contribute strongly; \[\Delta\]: Decreasing roll diameter will contribute moderately.

2. (): Influence will be reversed to favor smaller diameters if weight is accorded to sensitivity of shape control rather than to immunity from external disturbances.
limited by the distance between their installed centers, i.e., by the minimum roll diameter envisaged after final regrinding. In other words, the maximum torque required by the rolling mill production set-up will in turn determine the required diameters of the couplings and roll necks, and consequently the roll diameter.

In the case of rolling mills with a high sheet threading speed, the torque amplification factor should also be considered. As a general rule, the rolling torque at a given rolling force will increase with the work roll diameter, but the limit to the transmissible torque imposed by the mechanical strength of the drive system will increase with roll diameter at an even more rapid rate so that the safety factor of the roll driving system will improve with increasing roll diameter. Figure 2 shows an example of the relation between required rolling torque and the maximum transmissible torque on a specific cold rolling mill.

In this paper, theoretical calculations of roll force, torque, and forward slip are computed by the program based on Karman's theorem including the effect of entrance and exit elastic deformation by Ford and Ellis. It should be noted that the permissible torque will vary from case to case according to the type of coupling and the conditions governing service life. With batch-type tandem cold mills, AGC is also applied in most cases to threading operations. The dashed curves in Fig. 2 represent the situation during threading, in which AGC is applied with tension exerted only on the entry side strip and not on the exit side strip.

The limit of transmissible torque for a rolling mill driven by back-up roll is expressed approximately by

\[ D_w \geq \frac{G}{\mu_R P_R} \]  \hspace{1cm} (2)

where, \( G \): rolling torque (total for both rolls)  
\( \mu_R \): coefficient of friction between rolls  
\( P_R \): rolling force.

This equation again indicates that a larger roll diameter ensures greater safety.

3. Roll Surface Pressure (Pressure Acting between Work Roll and Back-up Roll)

The roll surface pressure varies with the combination of diameters of the work and back-up rolls. The pressure increases with decreasing roll diameter. But assuming a permissible roll surface pressure of about 200 kg/mm² (1960 MPa), this will not constitute a limitation under normal rolling schedules. The pressure would approach closely to such a limit in the initial pass with rolls of 500 mm diameter or smaller in the cold rolling of steel.

4. Limit of Draft at Threading (Limiting Angle of Bite)

In a batch-type rolling mill, the limiting permissible angle of bite which is determined by the friction coefficient between strip and roll at the time of threading is expressed by

\[ \theta_{th} \approx \sqrt{\frac{2}{D_w} \left( \Delta H + \frac{P_R}{K} \right)} \]  \hspace{1cm} (3)

where, \( \theta_{th} \): friction angle  
\( \Delta H \): draft  
\( K \): mill modulus.

Measures that have been adopted for increasing the permissible friction angle include: (a) selectively changing the conditions of lubrication for the leading edge of strip, (b) adoption of special threading device, and (c) modifying the roll opening for threading, applicable to quickly adjustable hydraulic screw-down device. These developments have made it possible to realize values of draft at threading such as indicated in Fig. 3.
5. Allowable Range of Neutral Point Displacement in Stable Rolling (Conditions for Maintaining the Neutral Point within Contact Arc)

The neutral angle $\phi_n$ in normal rolling is expressed, for example, by

$$
\phi_n = \sqrt{\frac{h_a}{R'}} \tan \left( \sqrt{\frac{h_a}{R'}} \frac{H_n}{2} \right) \quad \ldots \ldots \ldots (4)
$$

where $H_n$ is given by

$$
H_n = \frac{H_t}{2} - \frac{1}{2\mu} \ln \left( \frac{h_t}{h_n} \left( \frac{1-\sigma_n}{1-\sigma_t} \right) \right) \quad \ldots \ldots \ldots (5)
$$

where, $R'$: flattened radius of roll
$\mu$: rolling friction coefficient
$H_t$: 2 $\sqrt{R'h_t \arctan (\sqrt{R'/h_t} \phi_t)}$
$k$: flow stress
$\sigma$: tension

<table>
<thead>
<tr>
<th>Item</th>
<th>(a)</th>
<th>(b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incoming strip thickness (mm)</td>
<td>2.50</td>
<td>1.0</td>
</tr>
<tr>
<td>Outgoing strip thickness (mm)</td>
<td>1.25</td>
<td>0.5</td>
</tr>
<tr>
<td>Reduction ratio (%)</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Average flow stress (kgf/mm²) [MPa]</td>
<td>50[490]</td>
<td>80[784]</td>
</tr>
<tr>
<td>Friction coefficient</td>
<td>0.08</td>
<td>0.04</td>
</tr>
</tbody>
</table>

Note 1.
Case A: Examples of a curve derived from maximum transmissible torque limited by mechanical strength
Case B: Ditto (Another example)
$W$: Strip width (mm)

Note 2.

Fig. 2. Relation between work roll diameter and rolling torque.
\[ f = \frac{h_n \cos \phi_n - \sigma}{h_o} \] ..........................(6)
where,  \( h_n = h_o + 2R'(1 - \cos \phi_o) \) ...........................(7)

Fig. 3. Permissible draft from angle of bite.

\( h \): strip thickness
Subscripts \( i, o, n \): incoming, outgoing and neutral point, respectively.

Equations (4) and (5) with the theoretical equation of rolling and roll flattening give the following expression for forward slip \( f \). This ascertains whether or not the neutral point is kept within the contact arc and it is given by

in a tandem cold mill, the strip tension is sometimes greater on the entry side than on the exit side. In such circumstances examination of the forward slip should be necessary.

(3) The tendency to the higher draft diminishes the forward slip. The rolling instability is a phenomenon that occurs in an extremely small fraction of time during rolling operation. It is emphasized that the elimination of this trifling period of anomaly is well worth the effort. It means the necessity to check these states deviated from normal condition. Figure 4(I) for the fore stands and Fig. 4(II) for the hind stands show the results of the calculated forward slip, including the cases of reduced strip tension at exit sides. It is seen that the neutral point risks overstepping the contact arc in a certain range of friction coefficient with rolls of diameter around 400 mm. It is further indicated from Fig. 4(II-b) that the forward slip will diminish with increased strip tension even for the same values of the difference in the tension at entry and exit sides.

6. Rolling Energy

As mentioned in Section II. 2, a decrease of the roll diameter will reduce the required rolling torque, but will on the other hand increase the roll rotating speed, resulting in no rapid decrease in the rolling power requirement. An example of the effects on rolling power by the change in the roll diameter is shown in Fig. 5. It is seen that a 100 mm decrease of roll diameter will lower the rolling power only 5 % or less. It is said that savings in the overall energy consumption of a steel plant can be realized by optimizing the original hot coil gauge, and one report has put this optimum hot coil gauge at 2.5 mm. The requisite draft to be applied to this hot coil would be given by selecting appropriate values of roll diameter according to the items D, H and I in Table 1. Thus, the choice of the preferable diameter of the roll depends on the circumstances.

7. Roll Cost

Today it is possible to repeatedly harden the roll surface for the reutilization of worn rolls. This made the roll cost largely dependent on the roll recycling policy of the steel plant. If one considers that the rolls are finally discarded at a given common diameter, the roll cost would obviously decrease if the diameter of newly installed rolls is increased.

8. Rolling Force

The smaller the required rolling load, the smaller will be the equipment cost—with the smaller back-up roll and less powerful hydraulic screw-down mechanism demanded. Theoretically, if roll flattening is disregarded, the required rolling force should be proportional to the square root of the roll diameter, but the detailed calculations and actual measurements indicate nearly linear dependence on the diameter as shown in Fig. 6.
9. Rolling Lubrication

The ever higher speeds and larger drafts in modern mill practice have accentuated the importance of the surface quality of the products. It would appear premature to associate the heat-streaks with differences in roll diameter, when the real cause of this phenomenon has not yet been determined. Under these circumstances, the surface properties will be evaluated below in terms of lubricant film thickness, roll temperature and specific rolling force.

1. Oil Film Thickness

All the published calculations of the thickness of the lubricant film remaining between the strip and roll surfaces in the roll bite are based on the assumption of fluid lubrication. Although variation of the oil film thickness with the roll diameter is rather small, the larger the roll diameter, the smaller becomes the draw-in angle for the lubricant, to ensure a thicker oil film. This will provide better lubrication, but on the other hand, tend to dull the surface of the rolled product into a mat finish. When rolling aluminum foil, for instance, a thinner oil film will actually allow higher rolling speeds. The effect of roll diameter on oil film thickness at different rolling speeds is shown in Fig. 7.

2. Roll Temperature

Excessive strip temperature is considered to be a cause of heat-streaks. A lower roll temperature
for the lower strip temperature will be ensured by a larger diameter roll. Increased flow rate of the coolant also lowers the strip temperature. Figure 8 shows the relationship between coolant flow and roll diameter for a given temperature range calculated for the rolling of high resistance materials at the No. 6 stand of a tandem cold mill.

3. Specific Rolling Force

The relation between heat-streak occurrence and surface pressure in the roll bite or specific rolling force is not yet clearly known. In shop practice, it has been recommended to maintain the specific rolling force within the range of 1.5–1.2 tf/mm (15.0–12.0 kN/mm). This requirement together with what has been discussed in Sections II.1 and II.8 would accentuate the necessity of adopting small-diameter rolls for the rolling of high flow resistance materials.

10. Relation between Strip Shape and Roll Diameter

The choice of roll diameter will strongly influence the quality of the product shape. In what follows, this will be discussed in terms of (a) simple shape across strip width, (b) strip crown, (c) edge drop, (d) multiple flatness and (e) multiple strip crowning, since
these phenomena manifest different characteristics. On the side of the rolling mill, its performance in respect of product shape is related (i) to its capacity of preventing external disturbances from affecting the strip shape, and (ii) to the sensitivity of response provided by the shape control device. A sensitive shape control device could mean that the mill is susceptible to external disturbances. Consequently, such a device would cause an adverse effect on the quality of product shape, unless it is always maintained and employed under the most suitable conditions. Thus, the factors (i) and (ii) are not necessarily compatible, and the appropriate combination of the two factors would have to be decided in consideration of the type of shape control actuator, and the quality of the automation system and of the sensors that are incorporated in the mill.

1. Flatness Deformation across Strip (Simple Mode)

The minimization of simple flatness deformation across the strip must be sought from the early passes with thick strip, in order to ensure correct flatness of the final product, as well as for preventing the jamming between passes and achieving stable operation. A study has been reported on the interrelationship between susceptibility to external disturbances and control capability for the case of a Double Chock Work Roll Bending (DC-WRB). The balance between the susceptibility and the control capability did not vary significantly between large and small diameter rolls, but the susceptibility decreased with increasing roll diameter.

2. Strip Crown

Cold rolling is said to change the strip crown very little, and the center crown in particular is generally considered to remain unaltered from that of the original entering strip. One report, however, notes that with strips of small width-thickness ratio, the crown changes with cold rolling. The effect of the roll diameter on the change of strip crown is similar to that on simple shape across strip, discussed in Section II. 10.1.

3. Edge Drop

Smaller diameter rolls are less liable to generate edge drop. The edge drop which affects the quality of the final products can be reduced by diminishing the roll diameter in an individual pass. This reduction, however, is quite small. Appreciable results can only be obtained through cumulation of the benefits of small diameter rolls adopted throughout a series of passes. Figure 9 shows the variation of the edge drop on outgoing sheet calculated by an empirical formula with the number of passes for different roll diameters.

4. Multiple Deformation across Width of Strip

Of the two factors to be considered in multiple deformation across strip, (a) multiple flatness undulation and (b) multiple strip crowning, (a) is the more important factor in cold rolling. The growing practice of rolling in multiple widths for subsequent slitting has created a rising call for wider rolling mills. The resulting increase of the ratio of roll barrel length \( L \) to the work roll diameter \( D_w \) could lead to flexure of the roll causing multiple deformation. In general, however, the roll axis rarely deforms into \( W \) shape, and the multiple deformation should be attributed to other causes. Nevertheless, it has hitherto been considered prudent to keep the ratio \( L/D_w \) below 4, though a more recent approach is to let this ratio exceed this value and to control the multiple deformation by more positive means, using rolling mills with a newly deviced mechanism.

III. Overall Considerations in the Selection of Roll Diameter

The factors discussed in Chapter II for selecting the work roll diameter can be separated into two categories; (a) physical limitations beyond which rolling is no longer possible, and (b) policy-related considerations such as rolling cost and product quality. Factors in the latter category (b) vary with the user’s judgement of values and therefore give different optimum roll diameters even for identical manufacturing conditions. In Table 1, the two categories of factors are listed separately.

1. Factors Governing Roll Diameter Selection Which Depend on the Type of Equipment Adopted

In the selection of the work roll diameter, it should not be necessary to consider all factors listed in Table I since certain factors will be automatically eliminated once the system of production and the product mix are set down.

For example, if mainly mild steel strip of a large width is to be rolled using a batch-type tandem cold
mill, only the factors B, D-1, D-2, E, F, G, I-1, I-3 and I-4 need to be considered in Table 1 (Case X). If, on the other hand, continuous rolling in a narrow-width tandem cold mill is envisaged on light-gauge materials or materials of high flow resistance, the factors to be taken in the Table 1 will then be A, (B for certain materials), C, D-2, E, F, G, H, I-1 and I-4 (Case Y). Still other combinations of factors will apply in a case where non-ferrous metals or foil is to be rolled.

2. Factors Varying from Pass to Pass

The effects brought by the factors listed in Table 1 will change from pass to pass. The points to be borne in mind will differ between the earlier passes on a still pliant thick material showing a relatively high friction coefficient and passes in the later stage on a work-hardened light-gauge material with a small friction coefficient. This change in the factors to be considered with the progress of rolling passes is indicated in the center columns of Table 1. With a multi-pass single mill, most of the factors listed in Table 1 will be effective, that is, with a tandem cold mill, the optimum roll diameter can be varied, within the limits, from pass to pass. In the case of a single mill with only a single pair of rolls, the operation depends solely on the manipulation of gauge and the profit control.

3. Example of Work Roll Diameter Selection

An example of roll diameter selection is presented in Table 2(a), for the Case X. The factors of particular importance are those framed within double lines. Case Y is similarly presented in Table 2(b), in which it is assumed to include extremely light-gauge products around 0.1 mm. It is seen that the Cases X and Y result in appreciable different combinations of optimum diameters. These are but examples, and the optimum roll diameters will vary for every combination of conditions of production and of equipment and the variations are unlimited. It should nevertheless be useful and necessary to have a consistent and universally applicable basic principle for optimizing work roll diameters.

IV. Conclusion

A procedure for selecting the optimum work roll diameter in cold rolling has been examined, taking into account the latest developments in rolling technology. The results are summarized in Table 1. The actual values of the optimum work roll diameter will vary in an infinite combinations of the conditions of production and equipment. Nevertheless, their optimization based on universally applicable principles is considered possible by following the correct procedure.

REFERENCES

1) W. L. Roberts: Iron Steel Eng., 46 (1969), No. 12, 93.

Table 2. An example of choice of work roll diameter.

<table>
<thead>
<tr>
<th>(a) Case X</th>
<th>(b) Case Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>Factors considered for roll diam. of different stages</td>
<td>Fore-stage passes</td>
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<tr>
<td>Physical limitation</td>
<td>Larger diameters</td>
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<td>Smaller diameters</td>
<td>–</td>
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<tr>
<td>Policy-related conditions</td>
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<tr>
<td>Smaller diameters</td>
<td>E,G,J-3</td>
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<td>Examples of finally selected optimized roll diameters (mm)</td>
<td>600~550</td>
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<td>Factors considered for roll diam. of different stages</td>
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<tr>
<td>Examples of finally selected optimized roll diameters (mm)</td>
<td>550~500</td>
</tr>
</tbody>
</table>

Note 1.

Conditions assumed for rolling
Case X : Mainly mild steel strip of large width (max. about 2000 mm) and heavy gauge: tandem cold mill in batch operation.
Case Y : Material that may cause high flow stress, small width (max. about 1200 mm) and light gauge: tandem cold mill in continuous operation.

Note 2.

Symbols A to I are as indicated in Table 1.
(1979), 1088.


19) H. Ford and F. Ellis: *JISI, 171* (1952), 239.


21) For instance, T. Iwanami: Japan Pat. Applic. SHO-54-134444.