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OVER the past few years, a number of 6-h rolling mills have been installed where 4-h mills would ordinarily have been used. Inasmuch as a 6-h mill is more expensive (taller housing, more rolls) and less stiff (one extra pair of roll contacts subject to roll flattening) than a 4-h mill, the question arises why a 6-h mill would be selected in preference to a 4-h mill.

Two types of 6-h mills have been installed in recent years; the conventional type and the Sendzimir Z-high type. The latter has the advantage of a work roll diameter one-third to one-half that of a 4-h mill. This feature, which makes possible higher pass reductions and higher total reductions together with the ability to roll tougher materials to lighter gages and to improved gage accuracy, is sufficient to justify selection of the Sendzimir Z-high mill for applications where these factors are important.

For the conventional 6-h mills recently installed, however, most of which are Hitachi HC mills, the advantages are not so obvious, lying in the behavior of the rolls. This article describes this behavior and reviews its advantages.

Roll behavior of 4-h mill

The deflected form of the rolls on a 4-h mill when rolling full width strip is shown in Fig. 1a. The primary factor affecting strip profile is the backup roll deflection, because these rolls are loaded on the body and supported at the ends. A backup roll crown can be provided which will compensate for the backup roll deflection and make possible uniform strip profile (Fig. 1b). However, this crown is correct at only one value of roll separating force.

The foregoing case is hypothetical, since it is not possible to roll with strip width equal to the roll face width. If the strip width is reduced to less than the roll face width, bending moments develop on the work roll because it is supported beyond the strip edges by the backup roll (Fig. 2a). In this case, a computer model has been used to make the backup roll artificially rigid, thus eliminating its deflection. The deflection of the work roll was first described by Saxl,[1] and its effects examined by the author.[2]

To compensate for work roll deflection, a work roll crown can be provided (Fig. 2b), which is normal practice on 4-h mills. It is also normal practice to provide hydraulic cylinders in work roll chocks which apply bending forces giving some adjustment to the work roll profiles. To achieve uniform strip profile, the work roll axis must be bent which is a characteristic of 4-h mills.

Recent studies made at Sendzimir have shown that the mathematical form of the work roll deflection curve varies with the ratio of the work roll diameter to strip width (D/F_2) whether the work roll deflection is caused by rolling forces or by work roll bending. The relationship between the mathematical form of work roll deflection curve and D/F_2 is shown in Fig. 3. The required form of the work roll crown profile for 4-h mills is given by the equation

$$y = k\left(\frac{2x}{F}\right)^n$$

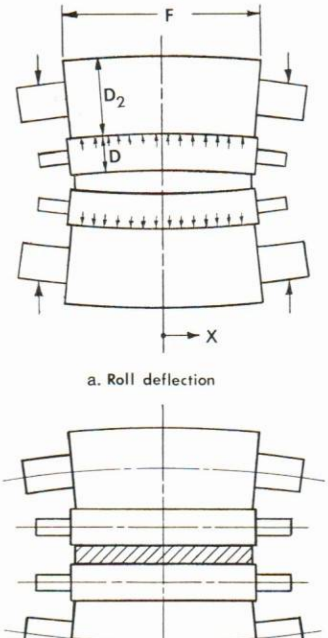
where

F = roll face width
k = diametral relief at roll ends
x = axial distance from roll center
y = diametral relief at x

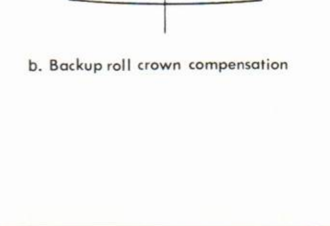
The deflection curve is exponential in form, with the value of the exponent n decreasing as D/F_2 increases. When the work roll diameter exceeds approximately 45% of the strip width, the exponent approaches the value of 2 (corresponding to parabolic form). Hence, for 4-h mills with a D/F_2 ratio of over 45%, the normal form of crown profile produced by existing roll grinding machines (which usually approximates a parabola) is satisfactory, and good strip flatness should be obtainable on such mills.

On the other hand, 4-h mills having relatively small work rolls are more likely to produce unsatisfactory results, primarily because the ground-in profile has an exponent n

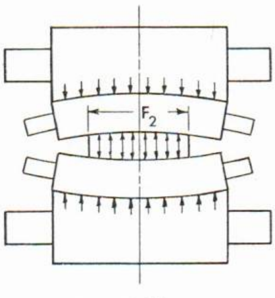
Fig. 1 — Roll deflection and backup roll crown compensation when rolling full width strip.



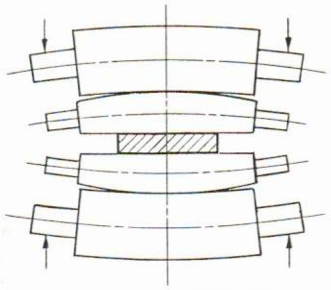
a. Roll deflection



b. Backup roll crown compensation



a. Work roll deflection



b. Work roll crown compensation

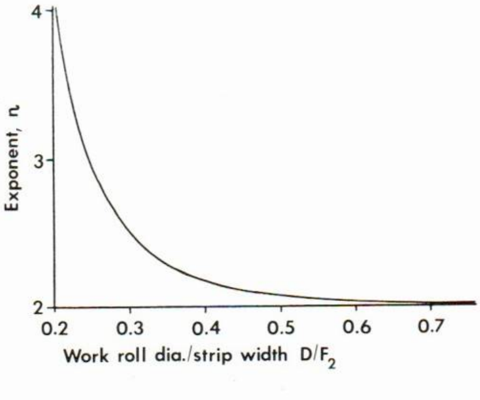
Fig. 2 — Work roll deflection and crown compensation when rolling strip widths less than the roll face width.

which is too low. The effect is to under-roll the strip at the quarter band and to produce strip having a characteristic long-middle/long-edge shape. This effect is illustrated in Fig. 4, which shows the distribution of separating force resulting from use of a work roll with a parabolic crown to compensate for work roll deflection when $D/F_2 = 0.25$, in a 6 x 30 x 30-in. 4-h mill rolling 24-in. wide strip.

Sendzimir is collaborating with ASKO Inc. in the development of a microprocessor-based roll grinding machine profiler, which can be retrofitted to existing roll grinders and used to obtain a profile of any desired mathematical form. Furthermore, a method has been developed to calculate the required magnitude as well as the mathematical form of work roll crown for any given rolling situation (patents pending).

Thus, on 4-h mills, the mathematical form and magnitude of work roll crown vary with the ratio of work roll diameter to strip width. Hence, for a given mill, a work roll change is desirable whenever the strip width is to be changed. Even so, for 4-h mills with relatively small work rolls, flatness is still likely to be a problem, due to the inadequacy of present roll grinders.

Fig. 3 — Mathematical relation between work roll deflection curve and work roll diameter/strip width ratio for 4-h mills.



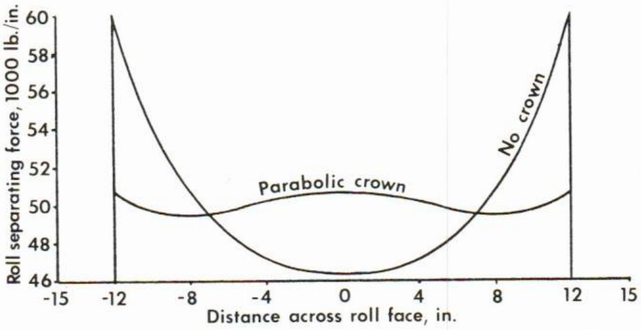


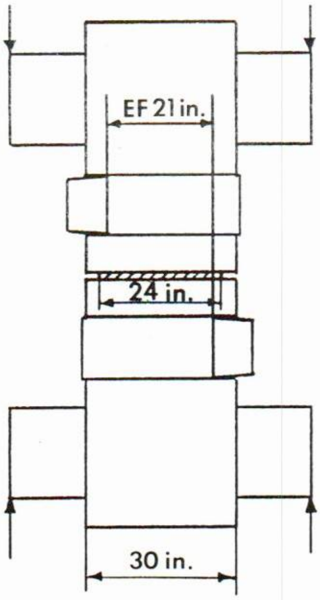
Fig. 4 — Distribution of roll separating force in 6 and 30 in. x 30 in. 4-h mill when rolling 24-in. wide strip with and without parabolic crown (D/F_2 = 0.25).

Roll behavior of 6-h mill

Except for the ability to adjust the intermediate roll in an axial direction, conventional 6-h mills offer no advantages over 4-h mills. The axial adjustment method of profile control was first proposed by Sendzimir in 1948,[3] and has been used on Sendzimir 20-h mills since. It was adopted by Hitachi for the HC mills after the Sendzimir patent expired in 1974. The lateral adjustment feature enables the work rolls to operate in an almost straight condition and mill adjustment to suit a range of strip widths without the necessity to change work rolls.

A typical 6-h mill, 30-in. wide, rolling 24-in. wide strip, is depicted in Fig. 5. The backup roll diameter is 30 in., intermediate roll diameter is 12 in. and work roll diameter 7.5 in. The mill has a backup roll crown of 0.0044 in., (parabolic) uncrowned work rolls and tapers of 0.0012 in./in. (on diameter) on the intermediate rolls, with an effective flat width (EF) of the unrelieved portion of intermediate roll face of 21.0 in. A typical roll separating force distribution for this mill during rolling is shown in Fig. 6, Curve a. The separating

Fig. 5 — Typical 6-h mill, 30-in. wide for rolling 24-in. wide strip: effective flat width (EF) 21 in.



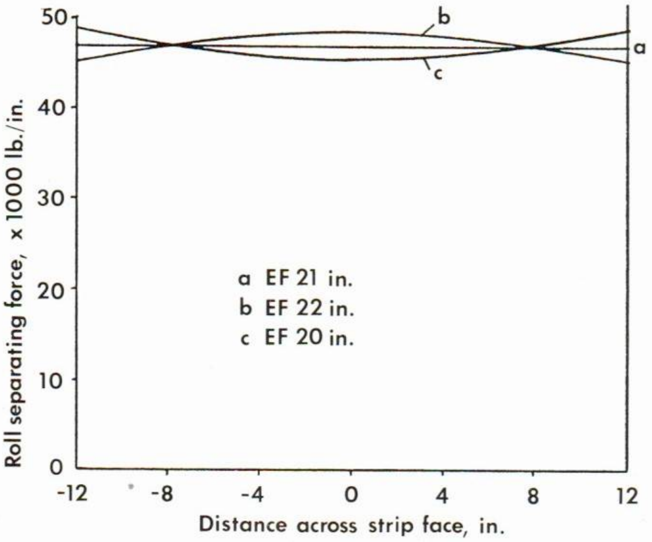


Fig. 6 — Typical roll separating force distribution experienced in rolling 24-in. wide strip with different effective flat widths (EF) on 30-in. wide 6-h rolling mill.

force distribution when the effective flat width is increased to 22.0 in. (edges over-rolled) are shown in Curve b and when reduced to 20.0 in. (center over-rolled) in Curve c. The general appearance of strip which would be produced by separating force distributions in Curves a, b, and c in Fig. 6, respectively, is shown in Fig. 7a, 7b and 7c.

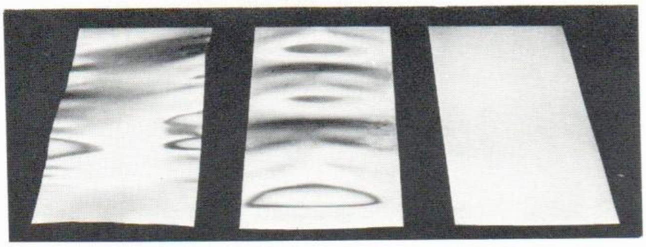
A virtually perfect separating force distribution, similar to that shown for the 24-in. wide strip in Curve a, Fig. 6, is also obtained on the same mill in rolling 18-in. wide strip with an effective flat width set at 15 in. The correct effective flat width of 15 in. for 18-in. strip is exactly 6 in. less than the correct effective width for 24-in. strip; the movement of the lateral adjustment is exactly equal to the change in strip width.

The foregoing results are typical for 6-h mills with lateral intermediate roll adjustment. Little or no work roll crown is required; a work roll change is not necessary for a strip width change; and a strip width adjustment usually requires simply a corresponding effective width adjustment, which is easy for mill operators to make.

Lateral adjustment indicators used on current Z-high mills, which are similar to those used on 20-h mills, are shown in Fig. 8. When making intermediate roll changes, the operator sets the length of taper pointer on the indicators to correspond to the new intermediate roll. The indicators then automatically show the effective width values. Digital indicators can also be adopted, but are no less expensive; operator preference is for the traditional type.

In the previous two examples, no work roll bending forces were applied, but virtually perfect roll separating force distribution (hence strip flatness) can be achieved. If the same mill configuration is used as that shown in Fig. 5 (ie, a strip width of 24 in. with an effective flat width of 21-in.) except that each intermediate roll is tapered at both ends with tapers of 0.006 in./in. on the diameter (instead of being tapered at one end with a taper of 0.0012 in./in. on the diameter), the model gives virtually the same results. In this case, the work roll axes remain perfectly straight (unbent) during rolling. Either arrangement can be adopted but the arrangement of Fig. 5 is preferred as it allows for adjustment of the effective flat width. It is not necessary to apply bending forces to the work roll ends, because, apart from the slight bending of the work roll ends resulting from the use of the skew symmetric arrangement of Fig. 5, best results are obtained without bending. In fact, for 6-h mills with small work rolls such as Z-high mills, it is not practical to apply bending forces to the work roll ends, since these have no chocks; but excellent strip flatness has been achieved on all these mills.

Fig. 7 — General appearance of strip produced with various separating force distributions achieved with different effective flat widths.



Effective flat width

a. 21 in. b. 22 in. c. 20 in.

Fig. 8 — Lateral adjustment indicators.

However, if insufficiently steep tapers are adopted for the intermediate rolls, it will be difficult to obtain satisfactory strip flatness. Because the question of required taper steepness is often raised, computer investigations have been made for various mill sizes with the following results.

With respect to product flatness and shape stiffness, the steeper the taper the better. Theoretically, a taper is not required; a step reduction in diameter in line with the strip edge (ie, the effective width equals the strip width) is all that is needed. However, such an intermediate roll profile would cause problems due to marking of the backup and work rolls by the edge of the shoulder on the intermediate roll and difficulties in insuring that the strip tracks perfectly (ie, strip edges remain in line with shoulders of the intermediate roll).

A taper of up to 20 minutes angle (corresponding to 0.012 in./in. on diameter) can be used without serious roll marking problems, especially if the intersection between cylindrical and tapered portions of the intermediate roll is stoned smooth.

Required taper depends to some extent on the roll separating force levels and work roll diameters. In general, larger work roll diameters and higher roll separating forces require steeper tapers.

The results obtained for the mill configuration shown in Fig. 5 when the taper is reduced from 0.012 to 0.003 in./in. are shown in Fig. 9. To equalize the separating forces between the work roll at the middle and edge of the strip, the effective flat width must be reduced to 9.5 in. The $\frac{1}{4}$ bands are now under-rolled and the strip will have a flatness error of the long-middle/long-edge variety.

In general, steep tapers give better flatness, but are more likely to result in roll marking and will result in more sensitivity of the strip flatness to mistracking. In practice, tapers in the range of 0.004 to 0.012 in./in. usually give the best results.

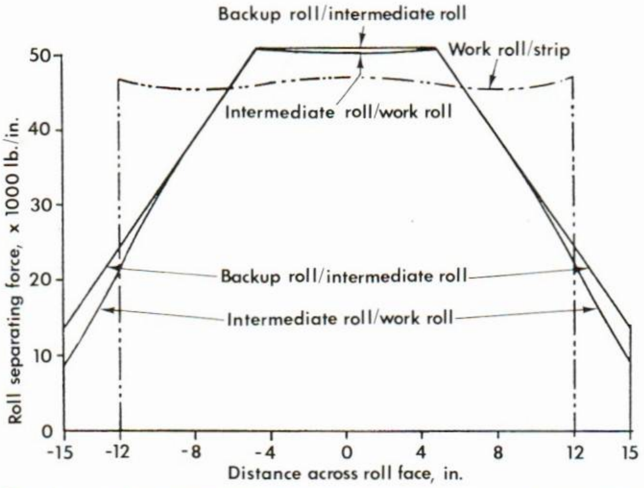


Fig. 9 — Roll separating force distribution obtained with 6-h mill configuration shown in Fig. 5 with taper on intermediate roll reduced to 0.003 in./in. and effective flat width reduced to 9.5 in. to equalize the separating forces between the work roll and the middle and edge of the strip.

Inter-roll force distribution

Roll force distribution between backup and intermediate rolls, between intermediate and work rolls, and between work rolls and strip is shown in Fig. 10 for the example shown in Fig. 5. Bending forces on the intermediate and work roll ends are virtually eliminated since the backup/intermediate and intermediate/work roll forces drop to zero just outside the strip edge. This is why, apart from the small effect of skew symmetry previously described, both intermediate and work rolls operate with their axes straight (in the vertical plane).

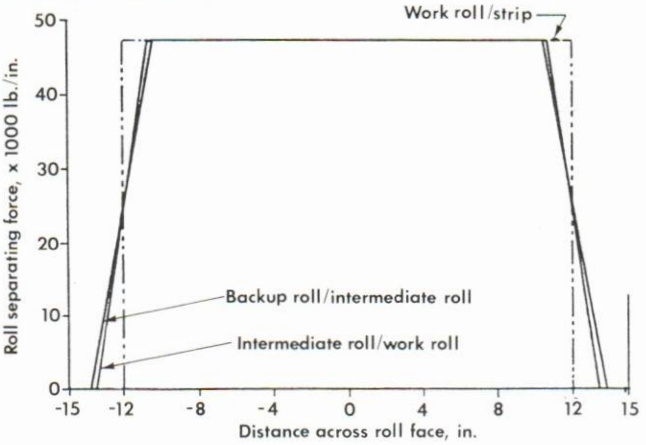
For comparison, Fig. 9 shows inter-roll force distribution when shallower intermediate roll tapers are used. In this case, there is a substantial force between the intermediate and work rolls beyond the strip edges, which gives rise to the nonuniform distribution of separating forces between the work roll and the strip.

Work roll stability

Although it has been claimed that conventional 6-h mills can be built with smaller work rolls than 4-h mills, stability equations indicate otherwise. In 1982, the author showed that, on the same basis of stability considerations, the minimum work roll diameter for a 4-h mill should typically be no less than 0.2 × the roll face width, whereas for a conventional 6-h mill the minimum work roll diameter should be no less than 0.22 × the roll face width.

If a smaller work roll diameter is needed, as is generally the case when materials are to be rolled to light gages, it is necessary to use a 6-h mill with side-supported work rolls, preferably a Z-high mill.

Fig. 10 — Roll separating force distribution obtained with 6-h mill configuration shown in Fig. 5 with taper on intermediate roll of 0.012 in./in. and effective flat width of 21.0 in.



Attenuation of backup roll deflection effect

In Fig. 6, Curve a, a backup roll crown of 0.0044 in. was used to compensate for the backup roll deflection of 0.0022 in. The same effect could be achieved by providing a work roll crown (parabolic) of only 0.0002 in. This is because the effect of the backup roll deflection is attenuated through the compliances presented by backup roll/intermediate roll and intermediate roll/work roll interfaces, in conjunction with the intermediate and work roll bending resistance. Looked at in another way, a backup roll deflection of 0.0022 in. can be said to have the same effect at the roll bite as a work roll crown of −0.0002 in. By any practical standard this is small, almost negligible.

The attenuation effect is important in Z-high mills where, because the work rolls are small, the roll separating force is low. Hence, much smaller backup rolls can be used than on 4-h or conventional 6-h mills of the same width (since smaller backup roll bearings can be adopted). These smaller backup rolls naturally tend to have larger deflections than those on a 4-h mill, even though the separating force is lower than that on a 4-h mill.

The attenuation effect is also important because it minimizes the effect of the larger backup roll deflections, enabling smaller backup rolls to be safely used. For example, a 54-in. wide 4-h mill rolling stainless steel would require 54 or 60-in. dia backup rolls, whereas a Z-high mill rolling the same material at the same width requires only 44-in. dia backup rolls with roller bearings or 38-in. dia rolls with Morgoil bearings. This makes large cost savings possible in the construction and installation of such mills.

Intermediate roll taper

Various forms of taper relief have been studied, including linear, parabolic and cubic. If tapers are steep enough, results are good in all cases, with cubic tapers being the best.

In the example shown in Fig. 6 (Curve a), and Fig. 10, the following diametral tapers were found to be effective:

- Linear, 0.012 in./in.
- Parabolic, 0.002 in. over the first inch (0.008 in. over the first 2 inches).
- Cubic, 0.001 in. over the first inch (0.008 in. over the first 2 inches).

Crowned strip compensation

In principle, to roll a flat product, the objective is to shape the profile of the roll gap so that the strip leaving the mill has the same profile (expressed as a percentage of the strip thickness at the middle) as the strip entering the mill. In general, the strip entering the mill will have a crowned profile, with the edges being slightly thinner (usually up to approximately 3%) than the middle. Because this effect can be considerable at heavier gages, the mill must be adjusted so that the roll gap is smaller at the strip edges than at the middle.

On a conventional 6-h mill there are three methods:

- Change the intermediate roll lateral adjustment to increase the effective flat width.
- Use work rolls having a smaller crown, even a negative crown if required.

- Use counterbending forces on the work roll (using hydraulic cylinders mounted between the work roll and intermediate roll chocks).

On a Z-high mill, the first two methods can also be used, but for the third, counterbending of intermediate rather than the work roll must be used.

The required adjustment depends on the form of incoming strip profile. If parabolic (as can be expected for strip coming from mills with work roll diameters greater than approximately 40% of the strip width), best results are obtained using work roll counterbending (or intermediate roll counterbending in Z-high mills). If lateral adjustment only is used with parabolic profiled strip, there is a tendency to under-roll the ¼ bands (producing long-middle/long-edge strip). However, for strip having an exponential profile, with the exponent being greater than 2, operation of lateral adjustment only gives the best results normally.

Effect of roll balance forces

In general, conventional 6-h mills require work roll balance cylinders to support the upper work rolls and upper intermediate rolls, and Z-high mills require intermediate roll balance cylinders. These have a small but definite effect on the strip flatness which must be taken into account. Since the effect of the balance force is to tighten the strip edges, it can be compensated by three methods:

- Using smaller work roll crown.
- Applying 6-h work rolls or Z-high intermediate roll counterbending forces to counteract the roll bending forces (these must be interlocked to operate only when the rolls are loaded), or releasing roll balance forces during rolling only.
- Operating the intermediate roll lateral adjustment to increase the effective flat width.

The second method is preferred, since it eliminates the effect of the roll balance force. The first method is satisfactory if the work roll is relatively large, in which case the form of the profile error due to work roll balance forces is approximately parabolic; hence, a parabolic work roll crown (negative if necessary) can compensate properly for this error.

Effect of roll separating force

As on a 4-h mill, increasing the roll separating force tends to over-roll the strip edges and reducing the separating force tends to cause center buckle. For the conventional 6-h mill, it is usually sufficient to adjust the effective flat width slightly; that is, increase the effective flat width (which tends to roll edges more) when the separating force is low, and reduce the effective flat width when the separating force is high.

For the Z-high mill, adjusting the effective flat width is the first step to take and usually gives excellent results. At higher separating force levels, however, a tendency remains to over-roll the ¼ bands, which can be corrected by making a small increase in the intermediate roll balance force or by using crowned work rolls. Similarly, a tendency to under-roll the ¼ bands at lower separating force levels can be corrected by making a small decrease in the intermediate roll balance force or by using concave work rolls.

Resistance of the mill profile to the effect of roll separating force variations is known as the shape stiffness. If the intermediate roll tapers are reasonably steep, the shape stiffness of 6-h mills is much higher than that of 4-h mills.

Effect of crowned work rolls

For the conventional 6-h mill, the objective is to avoid the necessity of work roll changes, which are as time consuming on 6-h as on 4-h mills. Hence, the usual practice on such mills is to use flat cylindrical work rolls and, in principle, to use roll bending controls, if required, to adjust for any small flatness imperfections which the lateral adjustment has not removed. At least, such roll bending controls are provided on the conventional 6-h mills, although the computer model indicates that these controls should not be required if correct intermediate roll tapers are used.

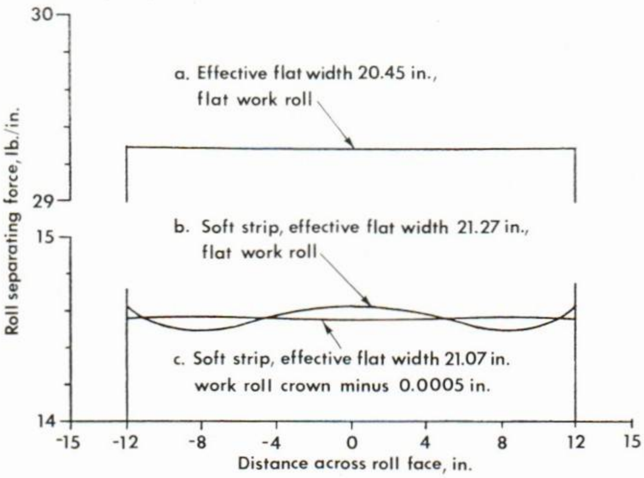
For the Z-high mill, however, work roll crowns can be useful if the mill has to operate at a wide range of separating force levels, as may be the case if a wide range of materials and gages are rolled on one mill. As in all rolling mills, optimum flatness is obtained if rational rolling schedules are adopted (similar separating force levels on every pass). However, if a material is rolled which requires much heavier separating force levels than normal, there will be a slight tendency to produce ¼ buckle, which can be corrected by using a small convex crown in the work roll. Similarly, operation at much lighter separating force levels than normal produces a tendency for tight ¼ bands (long-middle/long-edge condition), which can be corrected using a small concave crown in the work roll.

In Fig. 11, Curve a, the roll separating force distribution is shown for a 3.15 and 7.5 and 30 x 30-in. Z-high mill rolling the same 24-in. wide strip as the 6-h mill shown in Fig. 6, Curve a, with the same reduction. The separating force is much less (due to the smaller work roll) and is uniformly distributed. In Fig. 11, Curve b, the separating force distribution is shown for the same Z-high mill rolling a softer material requiring only 60% of the separating force level in Fig. 11, Curve a. The lateral adjustment has been moved outward (the effective flat width increased) to balance the separating forces at center and edges, but the separating force at the ¼ bands is low, indicating long-middle/long-edge condition. In Fig. 11, Curve c, work rolls with a concave crown of 0.0005 in. are used, and the effective flat width is again adjusted to equalize the separating forces at center and edges. The concave work roll crown corrects the condition of under-rolled ¼ bands.

With the Z-high mill, work roll changing is not a great inconvenience, requiring only a few minutes.

An interesting theoretical point is that best results are obtained from crowned work rolls if they are ground with an exponential crown, with the exponent selected from Fig. 3, but with the ratio D/F_2 taken for the intermediate roll. This suggests that, at extreme separating force deviations from normal, lateral adjustment can eliminate work roll deflection but does not entirely eliminate intermediate roll deflection. In the Z-high mill, the work rolls are sufficiently flexible to follow the remaining intermediate roll deflection, thus transferring its effect to the strip. In the 6-h mill, the work

Fig. 11 — Roll separating force distribution obtained with Z-high mill rolling the same 24-in. strip as that rolled on the 6-h mill (Curve a), softer strip (Curve b) and work rolls with a concave crown (Curve c).



rolls are much stiffer, so the effect of the remaining intermediate roll deflection is greatly attenuated at the strip. This is confirmed by the results from the computer model, which show no requirement for work roll crowning or roll bending in the 6-h mill.

Effect of strip tension

The effect of strip tension is to reduce the effect of mill profile errors on product flatness. In the Appendix and Fig. A1 it is shown how strip tension introduces a feedback loop at each position across the width of the strip. This attenuates draft variations or elongation variations across the width of the strip by a factor as low as 25 (hard materials, light reductions) to as high as 1200 (soft materials, heavy reductions), or even higher if roll flattening between work roll and strip is taken into account.

Although the computer model does not take this tension effect into account (because of the large increase in computation time involved), it can be allowed for in the model by relaxing the requirements for uniformity of elongation distribution across the width of the strip. For virtually perfect flatness, elongation variation of no more than 1 part in 10,000 is known to be permissible. In the model, it is only necessary to achieve a variation of no greater than approximately 1 part in 100 (depending on the attenuation factor for the rolling conditions given in the Appendix) to achieve good flatness.

Rolling with 6-h mills

Rolling with 6-h mills is straightforward; none of the Z-high retrofits has taken more than two or three days to start rolling production coils. In one case, in a plant where all the previous experience was with 4-h mills, the 6-h mill was on full 3-shift production four days after start-up.

The reasons for this are as follows:

- Correct intermediate roll tapers are established with the Sendzimir computer model and incorporated in the first fill of rolls. Similarly, correct work roll profile (usually flat) is incorporated.
- Orientation sessions are held for operators, supervisors and engineering/maintenance personnel immediately before start-up. Behavior of rolls and mill profile controls are fully described during these sessions.
- The correct setting of lateral adjustment drives (usually to give effective flat widths a few inches less than strip width at heavy gages, a few inches longer at light gages) previously obtained from the computer model can be used on the first pass on the first coil, and only fine adjustments may be required after that. These adjustments are made (at the end of each pass) by the operator under the instructions of a Sendzimir engineer. The adjustment need not be perfect on every pass; usually slightly tight edges are preferred on early passes, particularly at heavy gages, to insure stable tracking through the mill.
- Although trimming of the roll balance controls and use of different work roll crowns are theoretically useful in Z-high mills, such adjustments have been found unnecessary to obtain good flatness in practice. The reason is that strip tension greatly attenuates profile errors predicted by the computer model. For conventional 6-h mills, there appears to be not even a theoretical requirement to trim roll balance controls. The computer model shows that with properly selected intermediate roll taper profiles, operation of lateral adjustment is all that is required to obtain good flatness.

Summary

For all practical purposes, a 6-h mill, if it has laterally adjustable intermediate rolls, can be adjusted to roll virtually any width of product, at any separating force level, with any incoming profile, without the necessity for changing rolls. This represents a big advance in the state of the art relative to 4-h mills, which require different work roll crowns depending on incoming strip profile, width and roll separating force level. Thus, the 4-h mills need a large work roll inventory and suffer considerable production delays due to the frequent roll changes.

Appendix—Effect of strip tension on flatness

Assume that the average strip elongation is e (see Nomenclature) and the additional elongation at a certain location across the roll face, distance x from the strip center line, is ∂e.

If the average back tension is S_1 psi, the average front tension is S_2 psi, and $S = (S_1 + S_2)/2$ psi, then the resultant change in S at location x from the strip center line will be $-\partial e \cdot E$. That is, $\partial S/\partial e = -E$ (provided that tension does not drop to zero at any location).

Ignoring the effect of roll flattening (a conservative assumption since tension has an even greater effect when work rolls flatten against the strip), the roll separating force, $F_{RS} = (K - S)\sqrt{Rd}$ lb/in.

Assume that F_{RS} stays constant, regardless of the local elongation (a valid assumption for a reasonably flexible work roll) and when the mill spring is considerably larger than the draft, then the average draft

$$d = \frac{1}{R}\left(\frac{F_{RS}}{K - S}\right)^2 \text{ and } \frac{\partial d}{\partial S} = \frac{2\,(F_{RS})^2}{R\,(K - S)^3} = \frac{2d}{K - S}$$

Elongation, e, is related to draft, d, as follows:

$$e = \frac{1}{\left(1 - \dfrac{d}{H_1}\right)} \quad \text{and} \quad \frac{\partial e}{\partial d} = \frac{1}{H_1\left(1 - \dfrac{d}{H_1}\right)^2} = \frac{e^2}{H_1}$$

As shown in Fig. A1, it becomes possible to construct a tension feedback loop for each location across the width of the strip. The loop gain of each feedback loop is given by the relationship

$$G = \frac{2d}{K - S} \cdot -E \cdot \frac{1}{H_1\left(1 - \dfrac{d}{H_1}\right)^2} =$$

$$\frac{-2E}{K - S} \cdot \frac{H_1(H_1 - H_2)}{{H_2}^2} = -G_1 \cdot G_2$$

where $G_1 = \dfrac{2E}{K - S}$ and $G_2 = \dfrac{H_1(H_1 - H_2)}{H_2}$

The value of G_1 will generally range from approximately 200 for hard alloys such as stainless steels to approximately 600 for low carbon steels. The value of G_2 will generally range from about 0.12 at 10% reduction to 2.0 at 50% reduction. Hence, depending on material and percent reduction, the effect of the tension feedback will be to attenuate elongation variations by a factor of $1/(1 + G)$; that is, by 1/26 to 1/1201.

Elongation differences of about 1 part in 10,000 are just sufficient to cause visible flatness errors. Consequently, in the computer model (which does not take tension feedback into account), elongation matching within 1 part in 10,000/26 or 1 part in 400 (hard materials, light reductions) to 1 part in 10,000/1201 or 1 part in 8 (soft materials, heavy reductions) is required. However, because the assumption regarding flexibility of the work roll is less valid for soft materials, elongation matching within 1 part in 100 (1%) or better is normally sought in all cases.

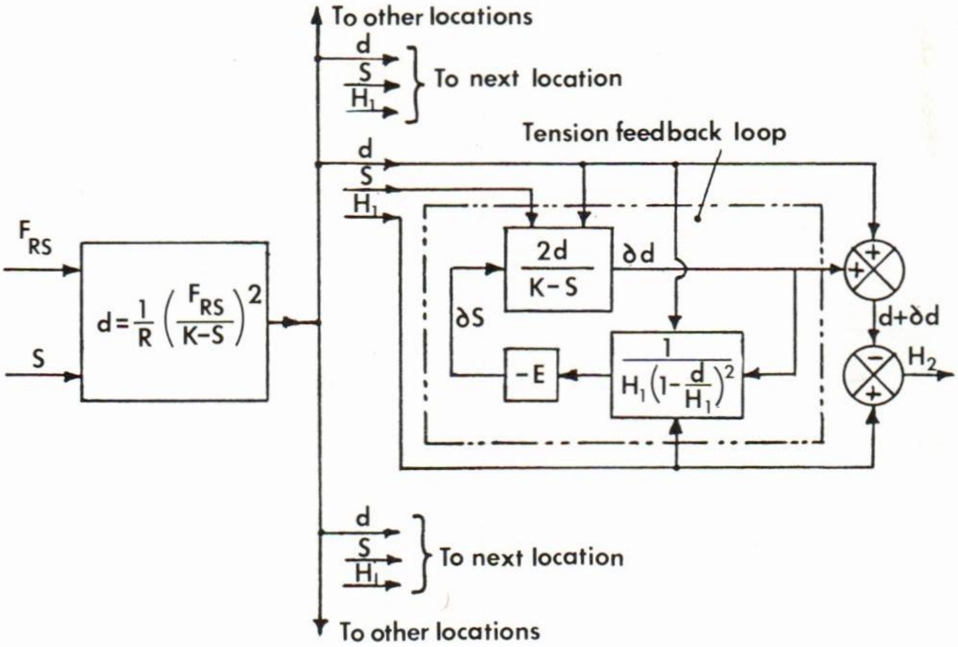


Fig. A1 — Tension feedback loops.

Nomenclature

F_{RS} = specific roll separating force, lb/in.
F = roll face width (backup and work rolls), in.
F_2 = strip width, in.
D = work roll dia, in.
H_1 = average entry gage, in.
H_2 = average exit gage, in.
R = work roll radius = $D/2$, in.
S_1 = average back tension, psi
S_2 = average front tension, psi
S = average tension = $(S_1 + S_2)/2$, psi
d = average draft = $H_1 - H_2$, in.
e = average elongation = H_1/H_2
K = constrained yield strength of rolled material, psi
E = elastic modulus of rolled material, psi
∂d = deviation from average draft at a particular location across the strip, in.
∂e = deviation from average elongation at the same location
∂S = deviation from average tension at the same location, psi

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