A flexible backing shaft and segmented idler roll have been developed that provide the ability to increase control of flatness by a factor of 2 to 6. Mills with automatic shape control can operate with high pass reductions while achieving target flatness profiles.

Control of quarter buckle on sendzimir 20-h mills

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THE problem of control of strip flatness in cold rolling has challenged the industry for a long time. The problem can be separated into two parts: measurement of flatness; and adjustment of roll gap profile to correct any deviation from the target detected by the measuring device.

The flatness measurement problem has largely been solved, and several flatness measuring devices (shapemeters) are now available. These devices all have their limitations, eg, high cost, some are suitable for low tensions only, and frequent discrepancies may be found between their indicated flatness values and actual flatness (as measured subsequently on the strip). However, in general, for a given application, it is possible to obtain a shapemeter that will perform satisfactorily.

The problem of roll gap profile adjustment is considerably more difficult. There can be no general solution because there are many different mill types in operation, having different roll configurations (such as 4-h; 6-h; Z-h; one and two stands; one, two and three stands; and one, two, three and four stands; etc). In addition, to have the possibility of dynamic roll gap profile adjustment, it is necessary to bend the work rolls, either directly or indirectly, but because of the inherent roll rigidity, it is difficult to induce a roll to bend in the desired manner.

The amount of dynamic roll gap profile adjustment that is needed can be reduced (or even eliminated) in many cases by the use of preset roll gap profiles produced, for example, by grinding a profile (usually a crown, a complex curve or cylindrical form with one end tapered) into one or more work rolls or support rolls in the mill, and/or axially shifting one or more rolls (usually rolls having complex crowns or cylindrical with a tapered form) to adjust the effective profile.

Current methods of dynamic gap control commonly in use are:

- Work-roll bending (4-h, 6-h).
- Backup-roll bending (including dynamic shape roll) (4-h, 6-h)
- Intermediate-roll bending (6-h, Z-h).
- Intermediate-roll shifting (6-h, Z-h, 20-h).
- Work-roll shifting (6-h).
- Work-roll shifting (4-h) (mostly used on hot mills).
- Backing-shaft bending (20-h).
- Thermal profile control (4-h, 6-h).

Of all these methods, the only strictly dynamic control methods are roll bending and backing-shaft bending. This is because they can be used at any rolling speed (down to zero) and with a consistent, fast-response time.

Thermal profile control can also be used dynamically, but it has only been successful in aluminum rolling, and to be effective, the work roll diameter has to be large. The control is only partially dynamic in that one of the associated time constants is long. However, the method is attractive in that small-magnitude, high-order errors such as local buckles or quarter buckles can be corrected.

Intermediate-roll shifting is not strictly dynamic because shifting speed, and hence roll gap profile adjustment speed, is proportional to rolling speed. Shifting speed, because it is also a function of rolling load, for a given shifting force, is much slower if the rolling load is high. From tests on several rolling mills, it has been established that the first intermediate rolls on 20-h mills cannot be shifted faster than 0.5 mm/m of rolled strip. For mills having larger rolls, it is doubtful if shifting speeds greater than 0.25 mm/m are possible.

Thus, when rolling at threading speeds, eg, 20 m/min (65 fpm), shifting speed will generally be 5 to 10 mm/min, which is too slow to be practicable.

Dynamic control of quarter buckle

One common form of quarter buckle results when attempting to roll strip with edge drop using a roll gap that is parabolic. (Edge drop profile approximates 8th order or 10th order profile, Fig. 1.)

On a mill having complex crowns (such as an SMS CVC mill), it is possible, by grinding the appropriate (8th or 10th order) crowns, to create a roll gap profile corresponding to the strip profile, thus eliminating the quarter buckle. However, this effect is satisfactory only for one value of strip width (unless rolls are changed) and, as it utilizes a shifting method, it is not strictly dynamic.

As discussed, thermal profile control can be used on 4-h and 6-h mills. However, for most steel mills, this control is ineffective.
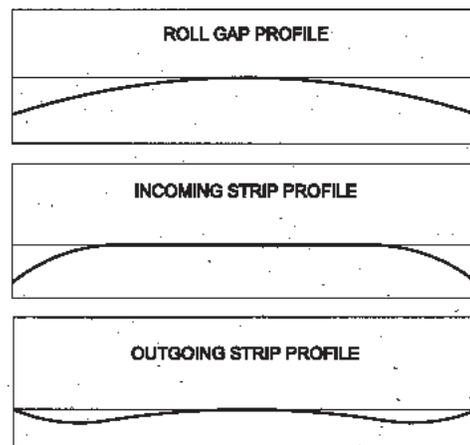

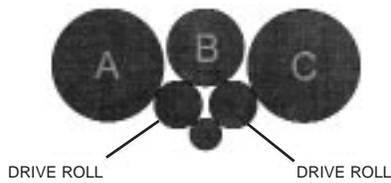Fig. 1 — Development of quarter buckle.

Fig. 2 — Mitsubishi CR mill.

Mitsubishi introduced a new type of mill (Fig. 2) which was a variation on the classical (but obsolete) sendzimir 1-2-3 mill, in which the B shaft backing bearings were reduced in size. This mill is known as the CR mill. The mill incorporated an impressive form of quarter-buckle control that was superior to any other method available at the time.

On the CR mill, instead of bending the A and C shafts using saddle-mounted eccentric rings for crown control, eccentric sleeves were mounted under each bearing on A and C shafts. This enabled crown to be applied without bending the shafts. Provided the shafts had five or more bearings each, it would also be possible to set the bearings into an M or W pattern to provide quarter-buckle correction. The authors have established from studies using beam on elastic foundation models that, because of drive roll rigidity, any quarter-buckle corrections made on the A and C shafts will have greatly diminished effect at the roll gap of the CR mill. However, the concept was good.

A similar capability has been developed for the sendzimir 20-h mill, but without the limitations caused by drive roll rigidity.

Flexible backing assemblies (FSBA)

Dynamic crown control on sendzimir 20-h mills is achieved using eccentric rings on B and C shaft saddles (Fig. 3).

Fig. 3 — Sendzimir 20-h mill with eccentric rings on B and C shaft saddles to achieve dynamic crown control.

The range of control and ability to control quarter buckle are severely limited by the rigidity of backing shafts B and C. The limitations depend on the length: diameter ratio of the shafts, which is usually a function of the number of backing bearings on each shaft. If there are four bearings or less, the ability to control 2nd order profile (simple parabolic crown) is severely limited by shaft rigidity. For five bearings, this ability is somewhat limited, and for six bearings or more it is not really limited. However, regardless of the number of bearings, the ability to control quarter buckle is virtually nonexistent.

The results of a survey of large sendzimir 20-h mills (ZR21, ZR22 and ZR23) are summarized in Table I.

When work started on the development of the FSBA, the adoption of eccentric sleeves under the bearings was considered. (This approach was employed in a mill built in 1965 that had three bearings for each shaft.)

TABLE I   Mill survey (ZR21, ZR22 and ZR23)

Number of bearings/shaft	2	3	4	5	6	7	8	9	10
Number of mills		1	32	73	83	106	20	4	1	1

Fig. 4 — Corner loading effect with eccentric sleeves under bearings.

Fig. 5 — Standard eccentric rings mounted on saddles.

However, because of retrofit difficulties and the tendency for corner loading using this system (Fig. 4), it was decided to attempt to find a solution using standard eccentric rings mounted in the saddles (Fig. 5). For this solution, it was necessary to make the B and C backing shafts considerably more flexible.

The objective was to design a shaft that could bend by 0.002 radians between any backing bearing and the adjacent backing bearing. This has been achieved with the ability to permit an offset of a single saddle of up to 50% of the full range of crown adjustment when FSBAs are installed. This is considerably greater than is required for quarter-buckle correction.

The problem in designing the FSBA was that the B and C shafts had to perform the following functions:

- To provide a rigid connection between backing bearings and saddles, and avoid reducing the mill stiffness, the shafts must provide transversely rigid bridges between the saddles.
- To deliver the screwdown torque to the saddles, the shafts must have sufficient torsional strength and rigidity.
- Provide oil passages for the backing bearing lubrication oil.
- Provide sufficient transverse flexibility to enable the required offset to be achieved without exceeding permissible shaft stresses.

These functions created a major problem because some of the requirements were apparently incompatible with others. The first approach was to separate the shaft into several pieces that would form separate bridges between saddles, use a system of keys connecting the shaft pieces to provide the torsional rigidity, and employ a system of sealed sleeves to provide the lubrication connections. This solution was feasible but complicated. The thinking was that it should be possible to keep the shaft in one piece, and to machine slots and/or holes or grooves in the correct locations to achieve the desired functions. Although finding the solution took more than two years, the final solution was relatively simple. It required cutting a series of slots in the shaft in the area of the saddles, using a machining process known as wire EDM.

The next problem to be solved was to determine whether such a shaft could be manufactured. The first test involved an existing backing shaft (carburized and hardened alloy steel). After checking for straightness, slots were cut relatively easily in the shaft at an EDM facility. However, it was found that the shaft developed a bend in the cut area. Although not unexpected, it indicated that a different shaft material and heat treatment process would be necessary. A suitable material was found and a manufacturing procedure established.

The FSBA also required changes to the screwdown eccentrics (located at each saddle) to enable the structure

to be assembled without axially clamping all the bearing inner rings and eccentrics together along the shaft. (Clamping, as employed for standard backing assemblies, effectively forms a rigid tube around the backing shaft, which would be contrary to the concept of a flexible shaft.)

Segmented idler roll

In general, on a 20-h mill, the diameter of the second intermediate rolls is larger than the diameter of the backing shaft. Examples are shown in Table II.

TABLE II   Examples of second intermediate roll and backing shaft diameters

	Diameter, in.		
Mill type	Backing bearing	Shaft	Second intermediate roll
ZR22	11.811	5.118	6.81
ZR21	16.00	7.05	9.25

It was thus considered that making the B and C backing shafts more flexible would have a diminished effect at the roll gap, because of the rigidity of the second intermediate rolls through which any profiles set on the B and C shafts would have to be transferred.

The rigidity of the second intermediate rolls was of particular concern, compared with the work rolls and first intermediate rolls that were of smaller diameter and, therefore, more flexible.

Initially, making all the second intermediate rolls more flexible was considered. This would be done by constructing each roll as a series of rings mounted concentrically on a small diameter shaft passing through the roll. However, this was not possible for the drive rolls because drive rolls had to transmit torque to the mill, and a segmented roll would not be able to transmit this torque. In addition, the high radial load on the contact line between drive rolls and first intermediate rolls (IR) might produce roll marks at the interface between adjacent rings.

However, an examination of the path of the roll separating force from the B and C bearings to the work roll (Fig. 3) indicated that the primary path was through the idler roll (IDL). The path through the drive rolls (DR) was oblique, and probably of lesser importance. Therefore, it should be sufficient to have a segmented idler roll and to use standard (nonsegmented) drive rolls. Also, the idler roll would not have the same roll marking potential as the drive rolls because the maximum radial loading on the idler roll is approximately 20% of the rolling load, less than a third of the corresponding load on each drive roll (close to 60% of the rolling load).

Typical segmented idler roll construction is shown in Fig. 6. The outline is identical to that of the standard roll, and the number of rings is usually equal to the number of saddles, with segment gaps approximately 0.02 in. wide and located in line with the saddles. Internal springs are mounted in pockets in the sides of each segment to ensure that all segment gaps are equal. The springs are removed for roll grinding, and the segments are clamped tightly together.

In practice, the segment gaps do not give rise to marking, even when rolling high-luster strip. It is considered that this
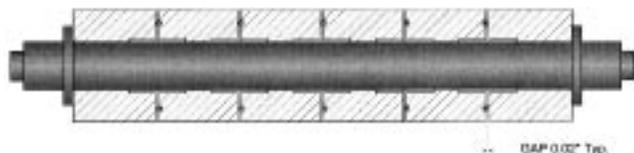

GAP 0.02" Typ.

Fig. 6 — Segmented idler roll.

is because of the low contact pressure on the idler roll, coupled with the fact that the segment gaps are small. Thus, stress concentration effects at segment gaps are negligible.

Comparative flexural stiffness of new designs

As a first estimate of the improvement, the calculated flexural stiffnesses of flexible backing shafts (FBS) and segment idler rolls (SIR) were compared with those of standard design.

It was found that, for a ZR22-52 mill, the flexible backing shaft is 16 times less stiff than a standard shaft, and the segment idler roll is 37 times less stiff than a standard design. In the case of a ZR21BB-54 mill, the corresponding reductions in stiffness are 17 and 50.

Theoretical performance comparisons

Bending of backing shaft — The ability to bend the backing shaft by adjustment at one saddle location only is an important measure of the effectiveness for adjustment of complex flatness errors such as quarter buckle or local chop.

In the case of standard backing assemblies for a ZR21 BB-54 mill, for example, if the shaft is deflected by only 0.00053 in. (2% of full stroke) at one saddle, a shaft bending stress of 15,400 psi results and the saddle load increases by 20% (32,400 lb) relative to normal maximum. This condition is considered to be the maximum realistic deflection for standard backing assemblies, to avoid saddle roller problems.

In the case of flexible backing assemblies for the same mill, the shaft can be deflected by 0.009 in. at one saddle, with a bending stress of 16,700 psi and a saddle load that increases by 8.8% (14,200 lb) relative to normal maximum. It is possible to deflect the shaft even more. A deflection up to 0.015 in. (50% of full stroke) would result in a saddle load increase of only 17.6% and a stress of 27,800 psi, which is acceptable for an alloy steel shaft.

Thus, with flexible backing assemblies, the ability to bend the shaft by adjustment at one saddle location only is increased dramatically, ie, from 0.00053 to 0.015 in., a factor of approximately 28:1 for a ZR21 mill, for example.

Effect of adjustment at one saddle location on roll gap — The kinematics of the cluster dictate that roll gap changes by 0.8 to 0.9 times the deflection of B and C shafts.

However, because of the flexural rigidity of the rolls in the stack, the effect is attenuated and spreads width-wise across the face of the rolls. The effect of deflecting the central saddle pair on strip flatness when rolling full-width strip from 0.10 to 0.07 in. thick at a rolling load of 33,000 lb/in., with and without the segmented idler roll, is illustrated in Fig. 7. (This effect was obtained using a beam on elastic foundation model of the roll cluster.)

The effect of using the segmented idler roll is to concentrate the strip flatness change in that region of the strip corresponding to the deflected form of the backing shaft
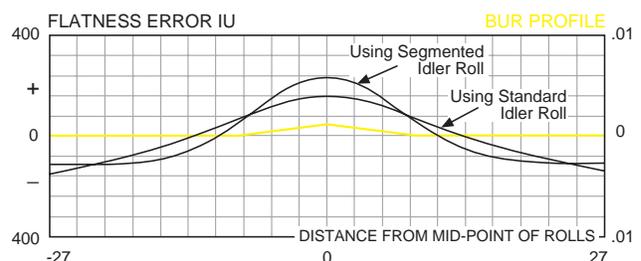

Fig. 7 — Effect of deflecting central saddle pair on strip thickness with and without segmented idler roll.

and to ensure that the effect is maximized. By contrast, with the standard idler roll, the induced flatness change is reduced by a factor of approximately one-half, and is spread over a region of the strip considerably wider than the width of the deflected portion of the backing shaft, thus defeating the objective of obtaining a localized effect.

Variable width quarter-buckle control

To achieve variable width quarter-buckle control, it is necessary to have at least seven points of independent adjustment spaced across the mill. If the adjustment is at the saddles, then at least six bearings/shaft are needed. Over 40% of the mills summarized in Table I meet this criterion. The possibility of varying the positions of the quarter-buckle correction peaks is illustrated in Fig. 8, which shows the effect of varying the relative positions of the adjustments at saddle No. 2 and 6, relative to saddle No. 3 and 5. This feature is valuable when a mill is to roll strip of different widths.
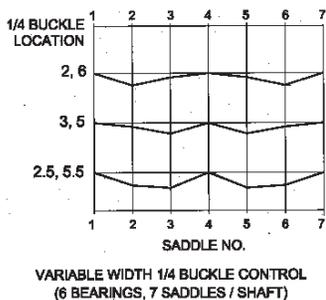

Fig. 8 — Effect of varying position of saddles on quarter-buckle location (six bearings, seven saddles/shaft).

First tests

Hardware performance — To minimize costs, tests were performed on a relatively small mill. A ZR23SC-25 mill was selected that has four 8.858-in. dia backing bearings on each backing shaft.

The bend that had occurred in the test shaft (described previously) created a dilemma: whether to finish grind the shaft after cutting the slots, in which case supporting the shaft during grinding would be difficult because of the high flexibility; or to cut the slots after finish grinding the outside diameter of the shaft, in which case the shaft could bend after cutting the slots.

For the first test, it was decided to make the shaft from heat treated alloy steel, but not to harden the surface. It was also decided to finish grind the shaft after cutting the slots.

It was found that finish grinding could be done if the shafts were stiffened by partially filling the slots with a compound that could be removed after grinding and if the shaft was well supported during grinding. However, after several weeks in service, minor plastic deformation of the shaft surface in the area of the keys was observed. It was, therefore, concluded that it was necessary to increase the shaft surface hardness. The shaft design was also modified to allow keyway stresses to be reduced.

Results with the segmented idler roll were encouraging and indicated that there was no need to alter the design. However, to grind the roll straight, it was found that it was necessary to tighten the squareness tolerances and to remove the internal springs during grinding.

Rolling results — To make the tests as realistic as possible, and to minimize disruption of production, test samples

were cut from the ends of production coils. The mill settings were changed back from test settings to normal rolling settings after the test samples had been rolled and cut.

Rolling tests were performed under three conditions:

- Using standard B and C backing assemblies and idler roll.
- Using flexible B and C backing assemblies and standard idler roll.
- Using flexible B and C backing assemblies and segmented idler roll.

For each condition, the same material (24-in. wide annealed 201 stainless steel) was rolled, from 0.012 to 0.0088 in. at the same speed, approximately 100 fpm. Two samples were rolled, the first with a full positive crown setting and the second with a full negative crown setting.

For all cases, the rolling load was approximately 16,000 lb/in. (65% of maximum) with tensions of approximately 8000 lb. Tapers were set at approximately 17 in. effective flat x 0.001 in./in. taper.

Strip samples produced in each case were laid along the floor, labeled and photographed. Subsequently, test samples approximately 4 ft. long were cut out using hand shears.

The test samples were taken to a guillotine shear, and two transverse cuts were made nominally 40 in. apart and parallel to each other. The 40-in. test sample could then be cut into a series of 40-in. long mults.

Subsequently, a test fixture was used to measure the length of each mult, and the camber of each mult was measured, using a straight edge and a ruler, to permit a calculation of the actual (curved) length of each mult.

In all cases, typical flatness profiles were similar to those shown in Fig. 9. In general, variations up to approximately 0.1 in. (on the 40-in. gage length) were measured, corresponding to a flatness error of approximately 250 I-units. The form of the profiles included a central portion (varying in height from 0 to 140 I-units long middle) and a portion covering approximately 1 in. at each edge varying from approximately 50 to 200 I-units long edge. For test purposes, only the effect of crown adjustment on the central portion was considered. The long edge portion is primarily controlled by the tapered first intermediate roll positions. It was found, in additional tests, that the amount of long edge could be varied by shifting the first intermediate rolls without any significant effect on the flatness of the central portion. A modest amount of long edge is desirable to avoid strip breaks.

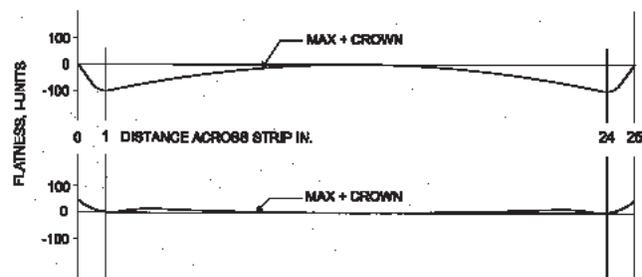The results obtained are summarized in Table III.

Fig. 9 — Typical flatness profiles.

TABLE III   Flatness control results

Test condition		Flatness control, I-units		
Backing assembly	Idler roll	100% positive crown*	100% negative crown*	Range
Standard	Standard	65	35	30
Flexible	Standard	80	30	50
Flexible	Segmented	140	0	140
* Long middle.				

For the ZR23SC-25 mill or, more generally, for mills having four backing bearings for each shaft, the following conclusions were drawn:

- Changing from standard backing assemblies and idler roll to the new flexible backing assemblies and segmented idler roll increases the actual range of crown adjustment by 367% (ie, a factor of 4.67).
- Changing from standard backing assemblies to flexible backing assemblies, but using standard idler roll, increases the actual range of crown adjustment by 67% (ie, a factor of 1.67).

Tests with closed loop flatness control

The first tests were made on the ZR22-42 mill at Acciai Speciali Terni's Torino plant in Nov. 1994. The brief report issued at that time indicated that improvement in flatness was so satisfactory that it was possible to increase maximum reduction/pass by approximately 23% and to reduce the number of passes by close to 11%.

A second series of tests was conducted in Dec. 1994. Typical results are shown in Figs. 10 and 11. The amount of flatness correction is relatively small when the amount of bending of the backing shaft is limited because of the rigidity of the backing shaft (Fig. 10). There are substantial deviations from the target flatness profile. However, a large amount of profile correction is available with a flexible backing shaft (Fig. 11). The result is that the flatness profile achieved is much closer to target.

Typical crown profiles used under automatic flatness control (AFC) with flexible backing assemblies and segmented idler roll for the same mill are shown in Fig. 12. The degree of curvature of the backing shaft required by the AFC is extremely high, and up to four points of inflection are used. These crown profiles cannot be achieved with standard backing shafts, which, typically, are approximately 16 times stiffer than flexible backing shafts.

The results of rolling several coils, with automatic flatness control, on a ZR22-52 mill and for the following three
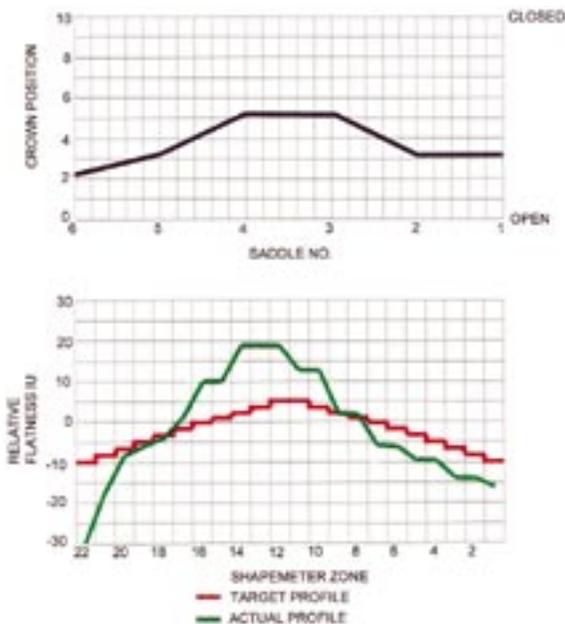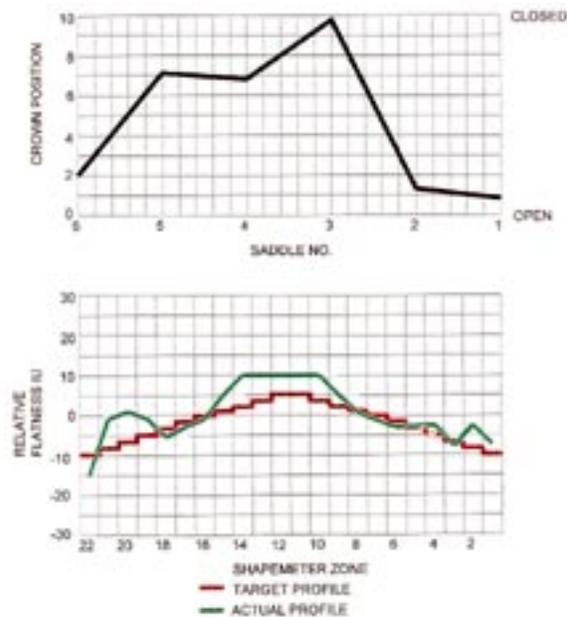

Fig. 11 — Typical crown and flatness profiles with flexible backing assemblies and automatic flatness control (strip 304 stainless steel, 1015 x 1.6 mm).

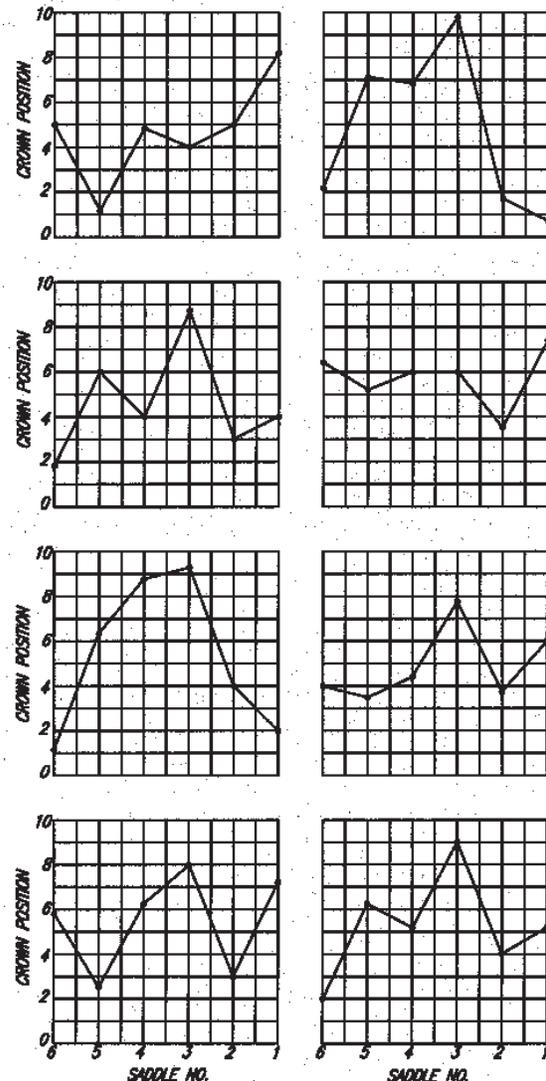**Fig. 12** — Typical crown profiles with flexible backing assemblies, segmented idler roll and automatic flatness control.

Fig. 10 — Typical crown and flatness profiles with manual flatness control (strip 304 stainless steel, 1015 x 2.2 mm).

TABLE IV   Performance

Practice *	Number of passes	Gage, mm	Width, mm	Flatness error, I-units Local	Flatness error, I-units Gross
Standard	3	2.01	1285	25	10
Standard	7	1.43	1285	40	10
Standard	2	2.222	1285	25	7.5
Standard	4	1.833	1285	35	5
Standard	5	1.684	1285	32	5
FSBA	6	1.549	1285	30	5
FSBA	8	0.549	1310	50	5
FSBA	9	0.48	1310	40	0
FSBA + SIR	2	2.222	1285	20	0
FSBA + SIR	3	2.010	1285	20	0
FSBA + SIR	4	1.833	1285	17	0
FSBA + SIR	5	1.684	1285	17	0
FSBA + SIR	6	1.549	1285	20	0
FSBA	2	1.794	1310	32	5
FSBA	5	0.933	1310	40	7.5
FSBA	6	0.771	1310	47	10

* Standard — conventional backing assemblies and standard idler roll.
  FSBA — flexible backing assemblies and standard idler roll.
  FSBA + SIR — flexible backing assemblies and segmented idler roll.

cases are shown in Table IV: (a) conventional backing assemblies and standard idler roll; (b) flexible backing assemblies and standard idler roll; and (c) flexible backing assemblies and segmented idler roll.

The summarized results are:

- Flatness error (middle to edge) average:
    Case (a)—Conventional, 7.5 I-units.
    Case (b)—Flexible backing assemblies and standard idler roll, 5.3 I-units.
    Case (c)—Flexible backing assemblies and segmented idler roll, 0.0 I-units.
- Flatness error (local deviation) average:
    Case (a)—Conventional, 32 I-units.
    Case (b)—Flexible backing assemblies and standard idler roll, 37 I-units.
    Case (c)—Flexible backing assemblies and segmented idler roll, 19 I-units.

Conclusions

Replacing conventional backing assemblies with a flexible design and conventional, solid idler roll with segmented units provides a major improvement in theoretical flatness adjustability, because of reductions in stiffness of approximately 16:1 and 37:1, respectively, for a typical sendzimir mill.

The improvement in flatness adjustability is particularly important in the case of quarter buckle and similar high-order flatness defects, which may require backing-shaft profiles with multiple points of inflection for their correction.

It is difficult to evaluate the amount of improvement in flatness that can be obtained unless the mill under consideration has automatic flatness control, because the mill operator may not take full advantage of the improved flatness adjustability. Even with AFC it is essential that the shaft curvature limits set into the AFC are correctly increased to take advantage of the increased flatness adjustability.

Test results indicate that local flatness errors (such as quarter buckle) are reduced by a factor of approximately two, and gross errors (such as long middle/long edge) are reduced by a factor of approximately three.

The improvement obtained is insufficient to eliminate the need for stretcher leveling, but it does provide for two major possibilities. In the case where flatness limits the pass reductions (eg, when rolling light gages), pass reductions can be increased while still obtaining satisfactory flatness. This can result in a substantial increase in production (10% or more). In cases where the need for stretcher leveling is normally marginal, it would be possible to eliminate this process with resultant cost savings.

Summary

An innovation is described that provides the sendzimir mill with the ability to control high-order flatness defects such as quarter buckle in addition to the more common center buckle/wavy edge defects.

This ability is achieved using a new design of backing shaft that has increased transverse flexibility relative to the traditional design, and by a new design of idler roll that enables the crown profile set by the shape of the backing shafts to be transferred to the roll gap with minimum attenuation due to intermediate roll rigidity.

Depending on mill size, the range of 2nd order crown control, as measured by strip flatness, is increased by a factor of two to six, and mills with automatic shape control have been able to operate with higher pass reductions, while still achieving target flatness profiles.   ▲