Control of Quarter Buckle on Sendzimir 20-H Mills

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Background

The problem of control of strip flatness in cold rolling has challenged the best minds in the industry for a long time. The problem can be separated into two parts, the first part being measurement of flatness, and the second part being that of adjusting the roll gap profile in order to correct any deviation from the target detected by the measurement device.

The flatness measurement problem has largely been solved, and a number of flatness measuring devices (shapemeters) are now available on the market. These devices all have their limitations, e.g. high cost, some are suitable for low tensions only, and there are frequently discrepancies between their indicated flatness values and actual flatness (as measured on the strip subsequently) but, by and large, for a given application, it's possible to obtain a shapemeter that will do the job.

The problem of roll gap profile adjustment is much more difficult. Firstly there can be no general solution because there are many different mill types in operation, having different roll configurations (such as 4h, 6h, Zh, 1-2, l-2-3, l-2-3-4). Secondly, in order to have the possibility of dynamic roll gap profile adjustment, it's necessary to bend the work rolls; (either directly or indirectly) but because of the inherent roll rigidity, it's very difficult to induce a roll to bend in the desired manner.

The amount of dynamic roll gap profile adjustment that's needed can be reduced (or even eliminated) in many cases by the use of preset roll gap profiles produced, for example, by

(a) 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 mill.

(b) Axially shifting one or more rolls (usually rolls having complex crowns or cylindrical + tapered form) in order to adjust the effective profile.

Methods of dynamic gap control commonly in use today are:

1. Work roll bending (4h, 6h).

2. Back up roll bending (including dynamic shape roll) (4h, 6h)
3. Intermediate roll bending (6h, Zh)
4. Intermediate roll shifting (6h, Zh, 20h)
5. Work roll shifting (6h)
6. Work roll shifting (4h) (mostly used on hot mills)
7. Backing shaft bending (20h)
8. Thermal profile control (4h, 6h)

Of all these methods, the only truly dynamic control methods are roll bending and backing shaft bending. These methods are truly dynamic 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 is really only successful in aluminum rolling, and to be effective the work roll diameter needs to be large. The control is only partially dynamic in that one of the associated time constants is very long. However the method is attractive in that small magnitude high order errors such as local buckles or 1/4 buckles can be corrected.

Intermediate roll shifting is not truly dynamic because shifting speed (and hence roll gap profile adjustment speed) is proportional to rolling speed, and is also a function of rolling load (for a given shifting force, the shifting speed is much lower if the rolling load is high). In tests done on a number of rolling mills, it has been established that first intermediate rolls on 20 mills cannot be shifted faster than 0.5mm per meter of rolled strip. For mills having larger rolls it is doubtful if shifting speeds greater than half of this are possible.

So, when rolling at threading speeds (20 MPM = 65 FPM) shifting speed will generally be 5-l Omm per minute which is too slow to be practicable.

Dynamic Control of 1/4 buckle

One common form of 1/4 buckle results when trying to roll strip with edge drop (edge drop profile approximates 8th order or 10th order profile - see fig. 1) using a roll gap which is parabolic - the result is strip having a characteristic 1/4 buckle.

1. On a mill having complex crowns (such as an SMS CVC® mill) it's possible by grinding the appropriate (8th or 10th order) crowns, to create a roll gap profile corresponding to the strip profile, in order to eliminate the 1/4 buckle. However, this effect is only OK for one value of strip width (unless rolls are changed), and, as it utilizes a shifting method, it's not truly dynamic.

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

3. A few years ago Mitsubishi introduced a new type of mill (fig. 2) which was a variation on the classical (but obsolete) Sendzimir l-2-3 mill, on which the B shaft backing bearings were reduced in size. This mill is known as the CR® mill. While we did not agree with many of the claims made regarding the advantages of such a mill, the mill incorporated a form of 1/4 buckle control which impressed us, as it was better than anything 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 & C shafts. This enabled crown to be applied without bending the shafts. Provided the shafts had 5 or more bearings each, it would also be possible to set the bearings into a "M" or "W" pattern to give 1/4 buckle correction.

We now know (from our studies using beam-on-elastic foundation models) that, because of drive roll rigidity, any 1/4 buckle corrections made on the A & C shafts will have greatly diminished effect at the roll gap of the CR® mill, but even so, the idea was good..

The following describes how a similar capability was developed for the Sendzimir 20h mill, but without the limitation to its effectiveness caused by drive roll rigidity.

Flexible Backing Assemblies (FSBA)

The dynamic crown control on Sendzimir 20h mills is achieved using eccentric rings on B and C shaft saddles (see fig. 3).

The range of control and ability to control 1/4 buckle are severely limited by the rigidity of backing shafts B and C. The limitations depend upon the length: diameter ratio of the shafts - this is usually a function of the number of backing bearings on each shaft. If there are 4 bearings or less, the ability to control 2nd order profile (simple parabolic crown) is severely limited by shaft rigidity. For 5 bearings this ability is somewhat limited, and for 6 bearings or more it is not really limited. However, regardless of the number of bearings, ability to control 1/4 buckle is virtually non-existent.

A survey of larger (ZR21, ZR22 & ZR23) Sendzimir 20h mills in the world reveals the results shown in table 1:

TABLE 1

No. of bearings/shaft	2	3	4	5	6	7	8		9‘10
No. of mills	1	32	73	83	106	20	4	1	1

When work started on the development of the FSBA, we considered the adoption of eccentric sleeves under the bearings (we had done this for one mill having 3 bearings/shaft in 1965).

However, because of the tendency for corner loading using this system (see fig. 4) and because it would make retrofits more difficult, it was decided to try to find a solution using standard eccentric rings mounted in the saddles (see fig. 5). Clearly this meant that it was necessary to make the B and C backing shafts much more flexible.

In fact, our objective was to design a shaft that could bend by 0.002 radans between any backing bearing and the adjacent backing bearing. This has been comfortably achieved and we now permit an offset of a single saddle of up to 50% of the full range of crown adjustment when FSBA are installed. This is considerably greater than is required for 1/4 buckle correction.

The problem that was faced in designing the FSBA was that the B and C shafts had to perform several functions as follows:

1. 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.

2. To deliver the screwdown torque to the saddles, the shafts must have sufficient torsional strength and rigidity.

3. To provide oil passages for the backing bearing lubrication oil to be supplied.

4. To provide sufficient transverse flexibility to enable the required offset to be achieved (fig. 6) without exceeding permissible shaft stresses.

This was a formidable problem as some of the above requirements were apparently incompatible with others. Our first approach was to separate the shaft into a number of pieces which would form separate bridges between saddles, and to use a system of keys connecting the shaft pieces to provide the torsional rigidity, and a system of sealed sleeves to provide the lubrication connections. This solution was feasible but complicated, and we thought it should be possible to keep the shaft in one piece, and to machine slots and/or holes or grooves in the right places in order to achieve the desired functions. It took more than two years to find the solution, which turned out to be simple, only requiring a number of slots to be cut in the shaft in the area of the saddles, which we proposed to produce using a machining process known as "wire EDM".

The next problem to be solved was to see if such a shaft could be manufactured in practice. The first test was to take an existing backing shaft (carburized and hardened alloy steel) to an EDM shop, after first checking its straightness. The slots were cut quite easily, but it was found that the shaft developed a bend in the cut area. This was not unexpected, but it confirmed what we thought - that we would have to find another shaft material, and use a different heat treatment process in order to succeed. After trying 3 or 4 materials, and with close co-operation between Sendzimir and Redex, a suitable material was found, and a manufacturing procedure established.

The FSBA also required some 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. Such clamping (used on standard backing assemblies) effectively forms a rigid tube around the backing shaft and would defeat the purpose of the flexible shaft.

Seamented Idler Roll

In general, on a 20h mill, the diameter of the second intermediate rolls is larger than the diameter of the backing shaft

e.g. ZR 22, backing bearing dia. 11.811 in., shaft dia. 5.118 in., 2nd IR dia. 6.81 in.
ZR 21, backing bearing dia. 16 in., shaft dia. 7.05 in., 2nd IR dia. 9.25 in.

Therefore, it seemed to us that the effect of making the B & C backing shafts more flexible would not be felt at the roll gap, because of the rigidity of the 2nd intermediate rolls through which any profiles set on the B & C shafts would have to be transferred.

We were not concerned so much about work rolls and first intermediate rolls, which were of smaller diameter and so relatively flexible. The question was - how could we solve the problem of 2nd intermediate roll rigidity?

Initially, we considered making all the 2nd intermediate rolls more flexible by constructing each roll as a series of rings mounted concentrically upon a small diameter shaft passing through the roll. However, this could not be done for the drive rolls - firstly because drive rolls had to transmit torque to the mill, and a segmented roll would not be able to transmit this torque, and, secondly, because the high radial load on the contact line between drive rolls and first intermediate rolls (IR) might produce roll marking at the interface between adjacent rings.

However, in examining the path of the roll separating force from B and C bearings to the work roll, (fig. 3) it was clear 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 (non-segmented) drive rolls. The idler roll would not give the same roll marking potential as drive rolls anyway, because the maximum radial loading on the idler roll is about 20% of the rolling load, less than a third of the corresponding load on each drive roll (about 60% of the rolling load).

Typical segmented idler roll construction is shown in fig. 7. 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 about 0.02 in. wide, and located in line with the saddles. Internal springs are mounted in pockets in the sides of each segment - these are used to ensure that all segment gaps are equal. For roll grinding the springs are removed and the segments clamped tightly together.

In practice we have found that the segment gaps do not give rise to marking, even when rolling high luster strip. It is believed that this is because of the low contact pressure on the idler roll, coupled with the fact that the segment gaps are very small, so stress concentration effects at segment gaps are negligible.

Comoarative flexural stiffness of the new designs

As a first estimate of the amount of improvement we compared calculated flexural stiffness of flexible backing shaft (FBS) & segment idler roll (SIR) with those of standard design.

Results ZR 22-52 (ZR 21 BB-54) FBS is 16 x less stiff than standard shaft (17x)
SIR is 37 x less stiff than standard idler roll (50x)

Theoretical Performance Comparisons

1. Ability to bend the backing shaft by adjustment at one saddle location only. Adjustment at one saddle location is an important measure of the effectiveness for adjustment of complex flatness errors such as 1/4 buckle or local "chop".

   1.1. Standard backing assemblies (ZR 21 BB-54 example)
   If the shaft is deflected by only 0.00053 in. (2% of full stroke) at one saddle, shaft bending stress of 15,400 psi results, and saddle load increases by 20% (32400 lb) relative to normal maximum. We consider this to be the maximum realistic deflection for standard backing assemblies, to avoid saddle roller problems.

   1.2. Flexible backing assemblies (same ZR 21 BB-54 mill)
   The shaft can be deflected by 0.009 in. at one saddle, with bending stress of 16,700 psi, and saddle load increases by 8.8% (14200 lb) relative to normal maximum. It's possible to deflect the shaft even more - up to 0.015 (50% of full stroke) would give saddle load increase of only 17.6% and stress of 27800 psi is still acceptable for alloy steel shaft.

   1.3. Thus, with flexible backing assemblies, the ability to bend the shaft by adjusting at one saddle location only is increased dramatically, i.e. from 0.00053 in. to 0.015 in., a factor of about 28:1 (ZR 21 example).

2. Effect of adjustment at one saddle location on the roll gap

   2.1. The kinematics of the cluster dictate that roll gap changes by 0.8 - 0.9 x the deflection of B & C shafts.

   2.2. However, because of the flexural rigidity of the rolls in the stack, the effect is attenuated and spreads widthwise across the face of the rolls. Fig. 8, which was obtained using our beam-on-elastic foundation model of the roll cluster, illustrates the effect of deflecting the central saddle pair upon strip flatness when rolling full width strip from 0.1 to 0.07 in. thick at a rolling load of 33,000 lb/in, with and without the segmented idler roll.

It can be seen that the effect of using the segmented idler roll is to concentrate the strip flatness change to that region of the strip corresponding to the deflected form of the backing shaft, 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 about one half, but it is spread over a region of the strip much wider than the width of the deflected portion of the backing shaft, thus defeating the objective of obtaining a localized effect.

Variable Width 1/4 buckle control

To achieve this control it's necessary to have at least 7 points of independent adjustment spaced across the mill. If the adjustment is at the saddles, then at least 6 bearings per shaft are needed. Over 40% of the mills in table 1 meet this criterion. In fig. 11 we show how by varying the relative positions of the adjustments at saddles 2 and 6, relative to saddles 3 and 5, it's possible to vary the positions of the 1/4 buckle correction peaks. Clearly this feature is valuable when a mill is to roll strip of different widths.

First Tests - Hardware performance

To minimize costs, it was decided to do the work on a relatively small mill. The mill selected was a ZR 23SC-25 mill - this mill has four 8.858" diameter backing bearings on each backing shaft.

Because of bend that had taken place in the test shaft (described above) we were faced with a dilemma - whether (a) to finish grind the shaft after cutting the slots (in which case supporting the shaft during grinding wouid be difficult because of the high flexibility) or (b) 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 this first case we decided to make the shaft from heat treated alloy steel, but not to harden the surface. We also decided to finish grind the shaft after cutting the slots. It was found that finish grinding could be done if shafts were stiffened by partially filling the slots with a compound that could be removed after grinding, and the shaft was well supported during grinding. However, after some weeks in service, some minor plastic deformation of the shaft surface in the area of the keys was observed, and it was therefore determined 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 quite encouraging and indicated that there was no need to alter the design. However, in order to grind the roll straight and true we found that it was necessary to tighten up some squareness tolerances, and to remove the internal springs during roll grinding (a small additional step in the roll grinding procedure).

First Tests - Results of rolling

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 being changed back from test settings to normal rolling settings after the test samples had been rolled and cut. We chose to make the tests for coils that were commonly rolled, to enable any future tests to be done at fairly short notice, and with minimum effect on production"

Rolling tests were done under 3 conditions:

1. Using standard B & C backing assemblies and idler roll.
2. Using flexible B & C backing assemblies and standard idler roll.
3. Using flexible B & C backing assemblies and segmented idler roll.

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

For all cases rolling load was approx. 16,000 lb/in (65% of maximum) and tensions were approx. 8000 lb. Tapers were set to approx. 17" effective flat x 0.001 in/in. taper.

Strip samples produced in each case were laid out along the floor (on a mat of corrugated cardboard) and were labeled and photographed. Subsequently test samples approx. 4 ft. long were cut out using hand shears.

The test samples were taken to a guillotine shear which had a stop bar mounted square to the shear blade, and two transverse cuts were made (with one side of sample pressed against the strop bar) which were nominally 40" apart, and were parallel to each other. This produced a 40" long test sample in each case. Each sample was labeled using masking tape across the whole width at each end, and the masking tape at each end was marked with equal spaced longitudinal marks to delineate intended cutting lines, and to ensure that individual molts would still be labeled after cutting. The 40" test sample could then be cut into a series of 40" long molts using the shear.

Subsequently the test fixture shown in fig. 9 was used to measure the length of each molt, and the camber of each molt was also measured, using a straight edge and a ruler, to enable true (curved) length of each molt to be calculated.

In all cases typical flatness profiles were of similar form to that shown in fig. 10. In general, variations up to about 0.1 in. (on the 40 in. gauge length) were measured, corresponding to about 250 IU flatness error. The form of the profiles included a central portion (varying in height from 0 to 140 IU long middle) and a portion covering about 1 in. at each edge varying from about 50 to 200 IU long edge. For the purposes of our tests, we only considered the effect of crown adjustment on the central portion. The long edge portion is primarily controlled by the tapered 1 st intermediate roll positions - it was found (by further tests) that we could vary the "amount" of long edge by shifting the 1 st intermediate rolls without any significant effect upon the flatness of the central portion. Note that a modest amount of "long edge" is desirable to avoid strip breaks.

Results were as follows:

1. Using standard backing assemblies and standard idler roll
100% +ve crown: central portion flatness error = 65 IU long middle
100% -ve crown: central portion flatness error = 35 IU long middle
Range of crown control = 30 I units

2. Using flexible backing assemblies and standard idler roll
100% +ve crown: central portion flatness error = 80 IU long middle
100% -ve crown: central portion flatness error = 30 IU long middle
Range of crown control = 50 I units

3. Using flexible backing assemblies and segmented idler roll
100% +ve crown: central portion flatness error = 140 IU long middle
100% -ve crown: central portion flatness error = 0 IU long middle
Range of crown control = 140 I units

Conclusion

For ZR 23-25, or, more generally, for mills having 4 backing bearings per shaft,

1. Changing from standard backing assemblies & idler roll to the new flexible backing assemblies and segmented idler roll increases the actual range of crown adjustment by 367% (i.e. by a factor of 4.67).

2. Changing from standard backing assemblies to flexible backing assemblies, but using standard idler roll, increases the actual range of crown adjustment by 67% (i.e. by a factor of 1.67).

Tests while rolling with closed loop flatness control

The first testing was done on the ZR 22-42 mill at AST's Torino plant in November 1994, the assemblies having been operating for approx. 1 month. The brief report that was issued at that time indicated that improvement in flatness was so good that it was possible to increase maximum reduction per pass by about 23% and to reduce the number of passes by about 11%.

The second test on the same mill in December 1994 resulted in the following comments. “It shows on the flatness screen - that the flexibility makes a wide difference compared to the rigid BC backup” (Sendzimir service engineer C. Martin) “Having flexible BC makes (it) more easy to drive the mill” (mill operator Sr. Martini).

Typical results from this mill are shown in figs. 12 and 13. In fig. 12 we have an example where the amount of bending of the backing shaft is limited due to the rigidity of the backing shaft so that the amount of flatness correction is not very high. The result is that there are substantial deviations from the target flatness profile. In fig. 13 it can be seen that the amount of profile correction that can be applied is very high because of the use of flexible backing shaft. The result is that the flatness profile achieved is much closer to target.

On fig. 14, we show for the same mill, typical crown profiles used under automatic flatness control (AFC) with flexible backing assemblies and segmented idler roll. It can be seen that the degree of curvature of the backing shaft required by the AFC is extremely high, and up to 4 points of inflection are used. Such crown profiles just cannot be achieved with standard backing shafts, which are typically about 16 times stiffer than flexible backing shafts.

For the case of a ZR 22-52 mill we studied the results of rolling several coils, ail with automatic flatness control, and for the 3 cases (a) conventional backing assemblies and standard idler roll (b) flex backing assemblies and standard idler roll and (c) flex backing assemblies and segmented idler roll. The results are given in table 2.

The summarized results are:

1. Flatness error (middle to edge) average: case (a) (conventional) 7.5 IU
   case (b) (flex BA + std. idler roll) 5.3 IU
   case (c) (flex BA, segmented idler roll) 0 IU

2. Flatness error (local deviation) average: case (a) (conventional) 32 IU
   case (b) (flex BA + std. idler roll) 37 IU
   case (c) (flex BA, segmented idler roll) 19 IU

Case	Pass No.	Gauge mm	Width mm	(a) Std. (b) FSBA only (c) FSBA +SIR	Flatness error IU* Local	Gross
1	3	2.01	1285	STD.	25	10
2	7	1.43	1285	STD.	40	10
3	2	2.222	1285	STD.	25	7.5
4	4	1.833	1285	STD.	35	5
5	5	1.684	1285	STD.	32	5
6	6	1.549	1285	FSBA	30	5
7	8	0.549	1310	FSBA	50	5
8	9	0.48	1310	FSBA	40	0
9	2	2.222	1285	FSBA + SIR	20	0
10	3	2.010	1285	FSBA + SIR	20	0
11	4	1.833	1285	FSBA + SIR	17	0
12	5	1.684	1285	FSBA + SIR	17	0
13	6	1.549	1285	FSBA + SIR	20	0
14	2	1.794	1310	FSBA	32	5
15	5	0.933	1310	FSBA	40	7.5
16	6	0.771	1310	FSBA	47	10

TABLE 2 - PERFORMANCE COMPARISON

Conclusions

1. Replacing conventional with flexible backing assemblies and replacing conventional, solid idler roll with segmented idler roll provides a big improvement in theoretical flatness adjustability, due to the reduction in stiffness of approx. 16:1 and 37:1 respectively, for a typical Sendzimir mill.

2. This improvement is particularly important in the case of 1/4 buckle and similar high order flatness defects, which may require backing shaft profiles with multiple points of inflection for their correction.

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

4. As far as can be judged from the test results, local flatness errors (such as 1/4 buckle) are reduced by a factor of about 2, and gross errors (such as long middle/long edge) are reduced by a factor of about 3.

5. The improvement obtained is not sufficient to eliminate the need for stretcher levelling, but it does provide for two major possibilities.

   5.1. In case where flatness limits the pass reductions (as it does mostly when rolling light gauges) the pass reductions can be increased while still obtaining satisfactory flatness. This can enable a substantial increase in production (10% or more).

   5.2. In cases where the need for stretcher levelling is normally marginal, it would be possible to eliminate this process with resultant cost savings.

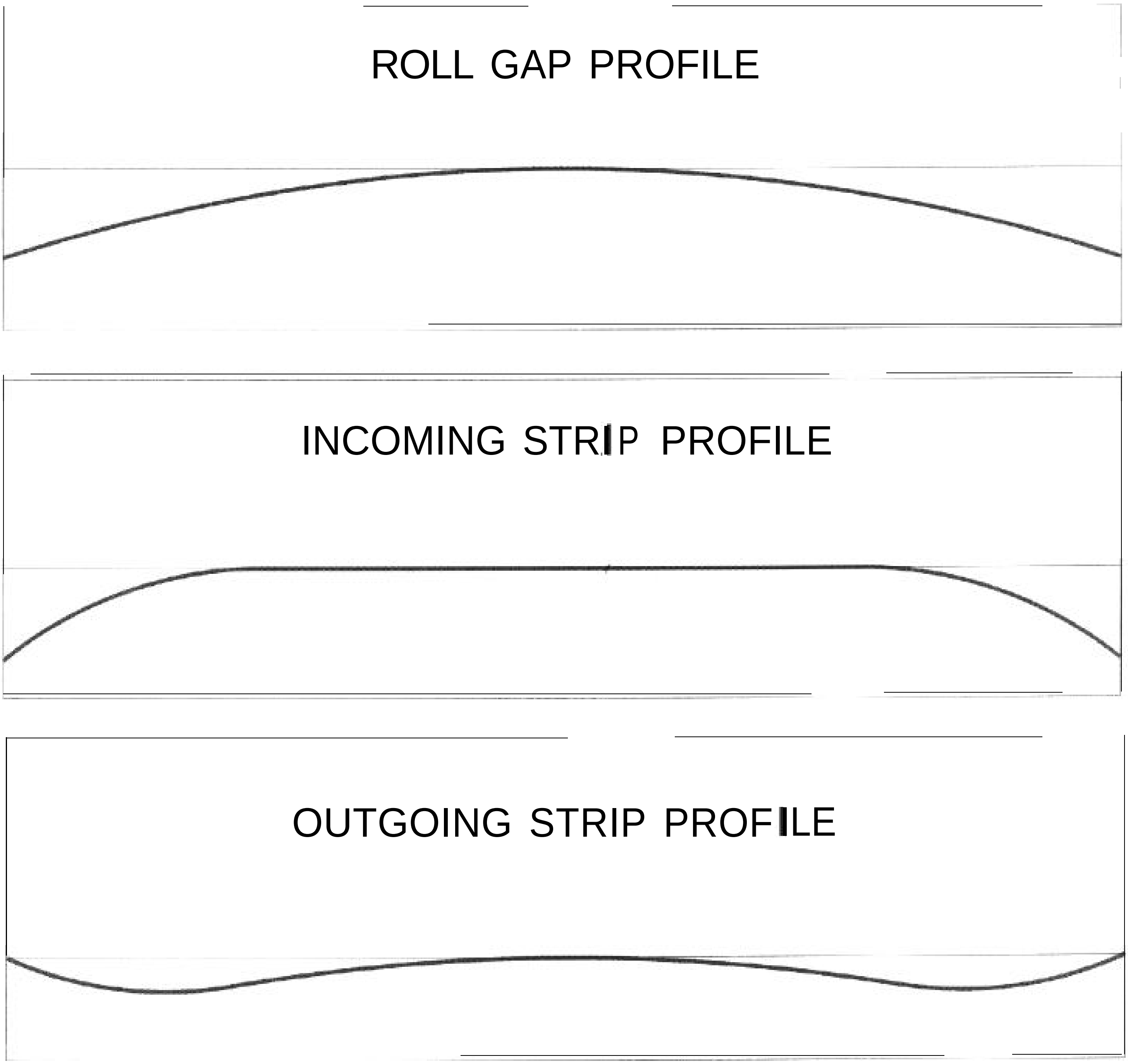

FIG. 1

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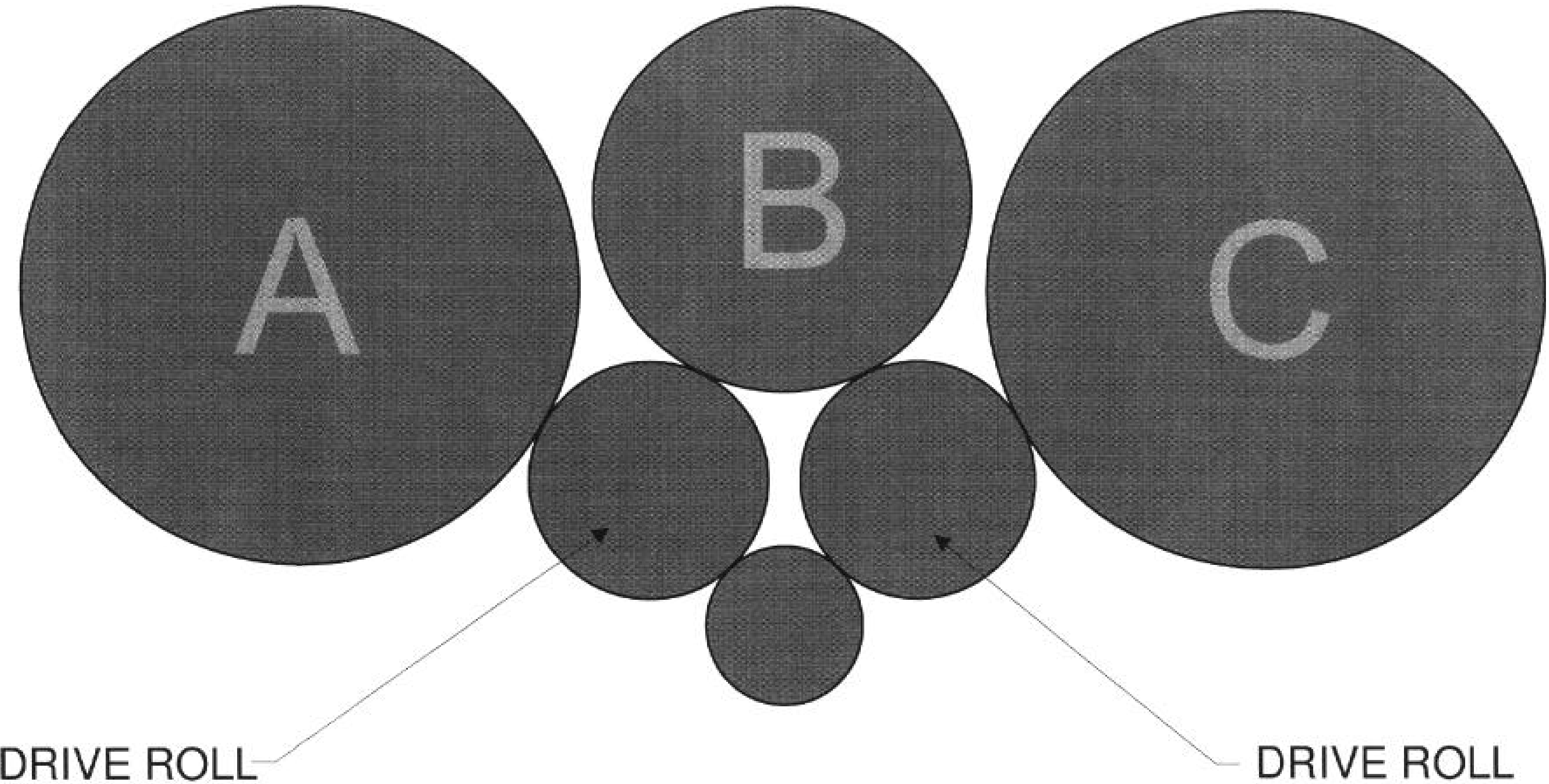

FIG. 2

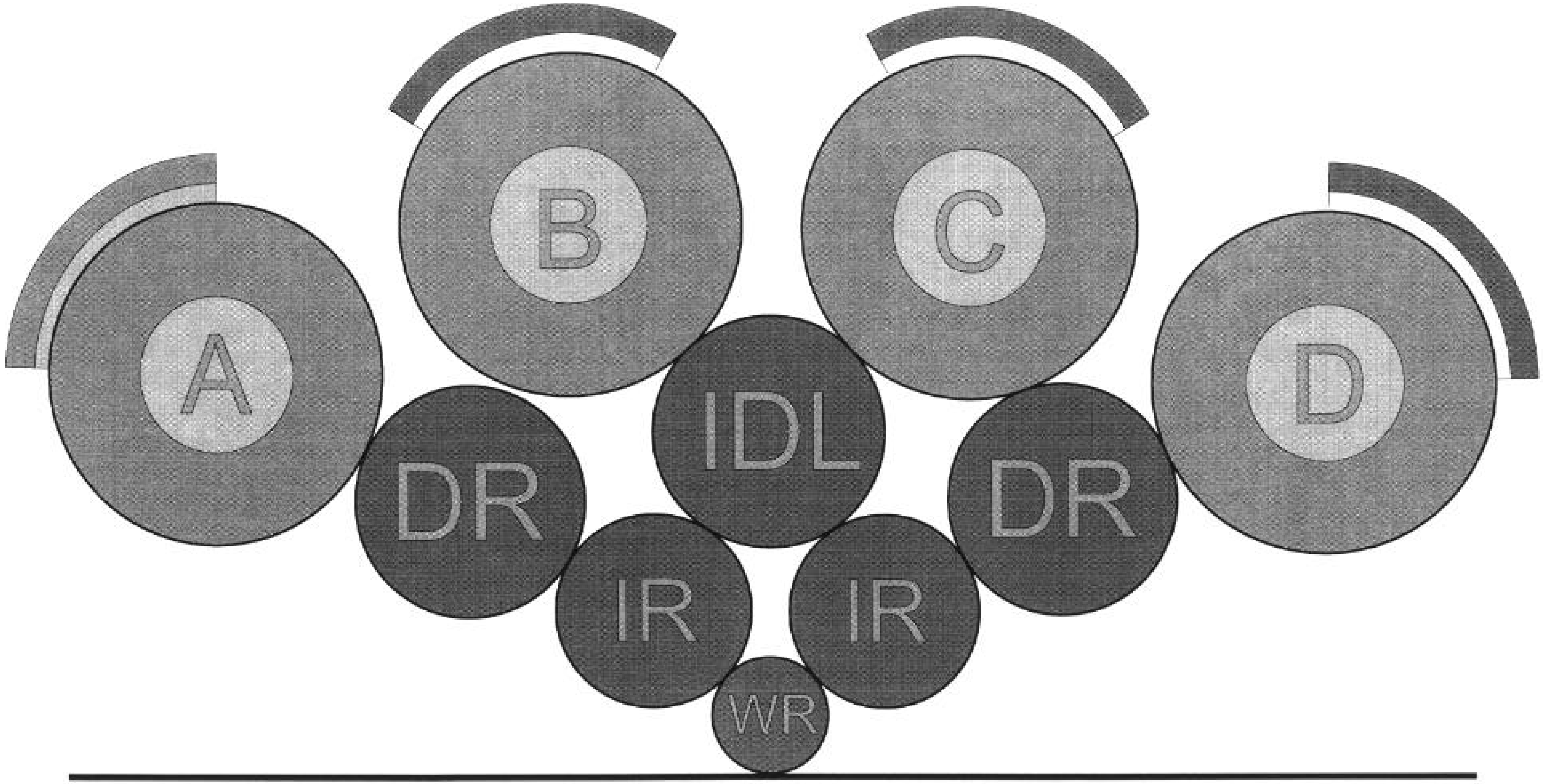

FIG. 3

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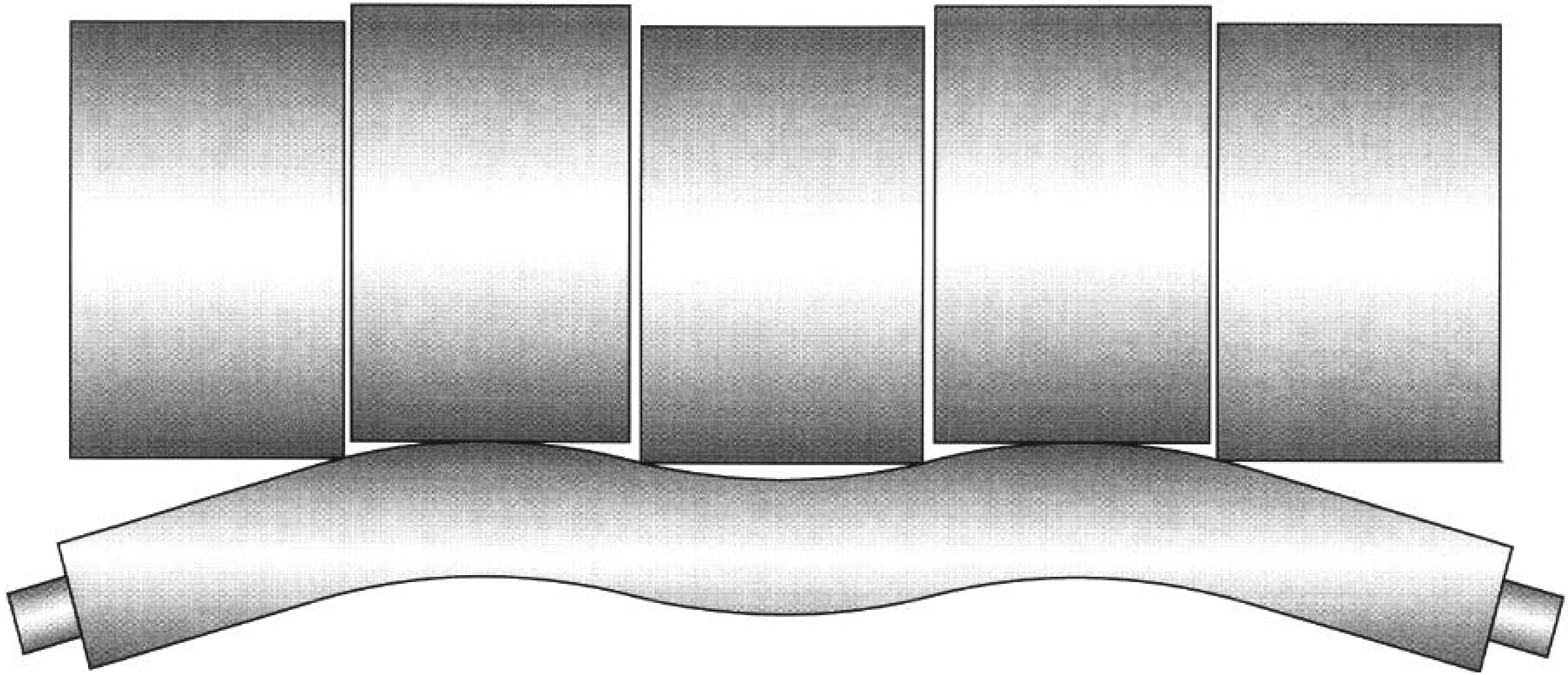

FIG. 4

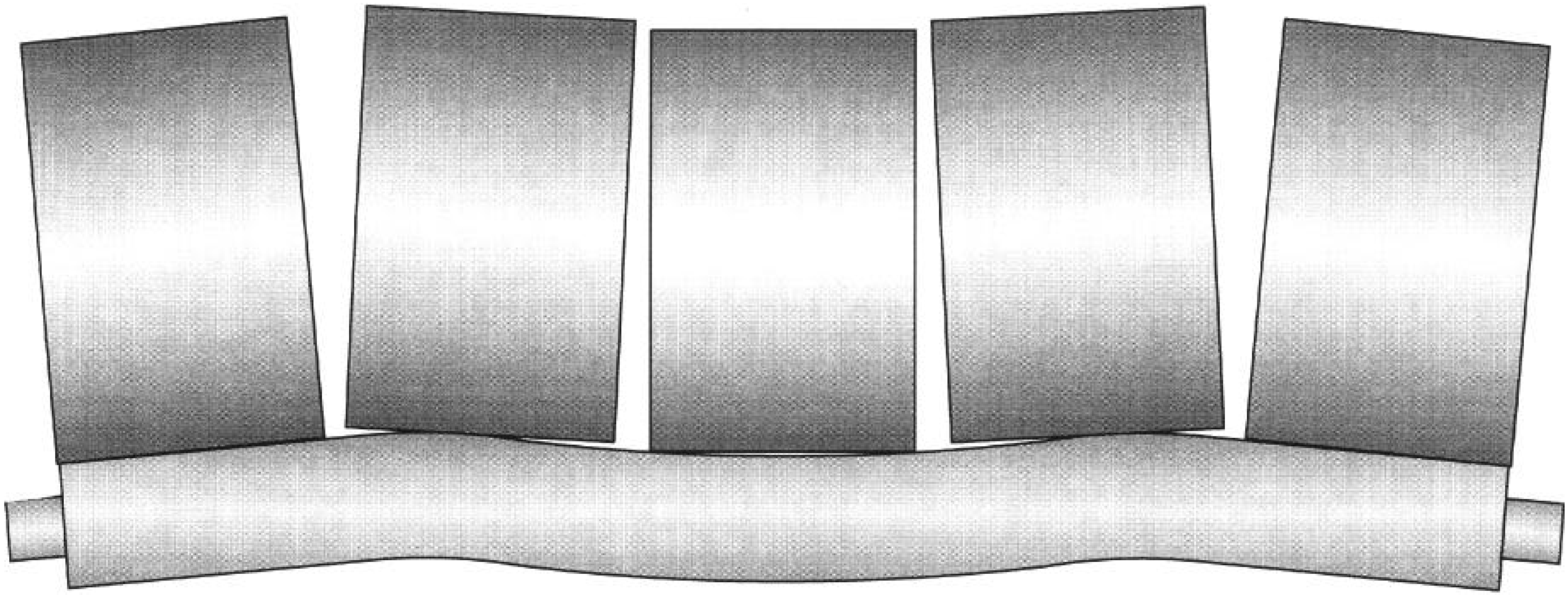

FIG. 5

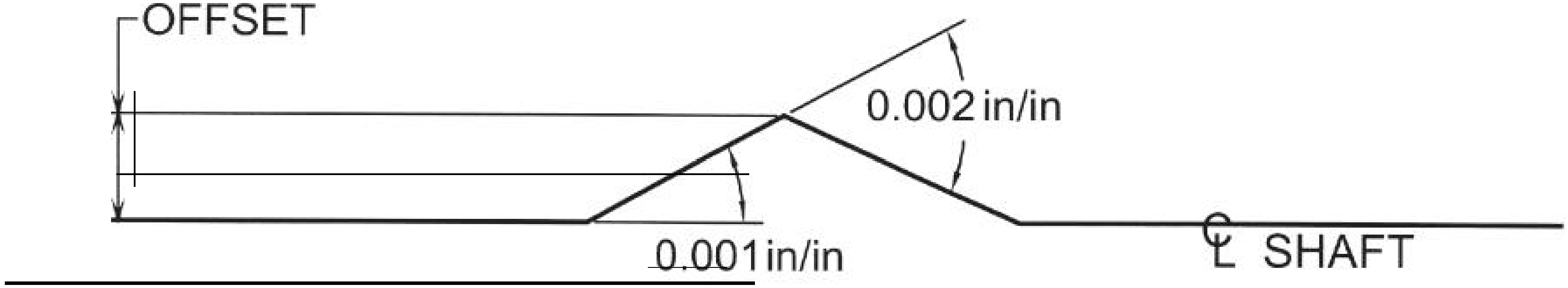

FIG. 6

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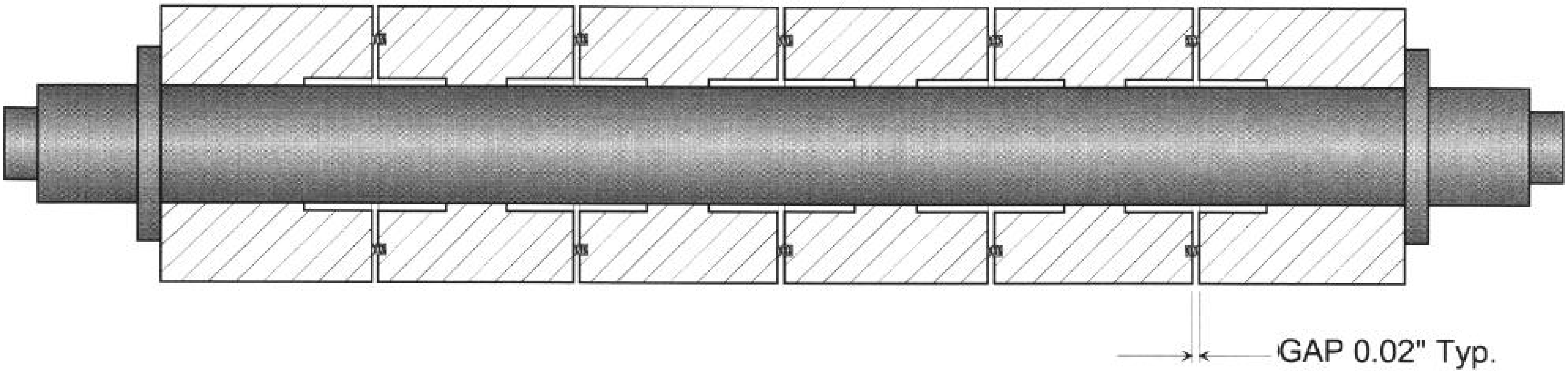

SEGMENTED IDLER ROLL

FIG. 7

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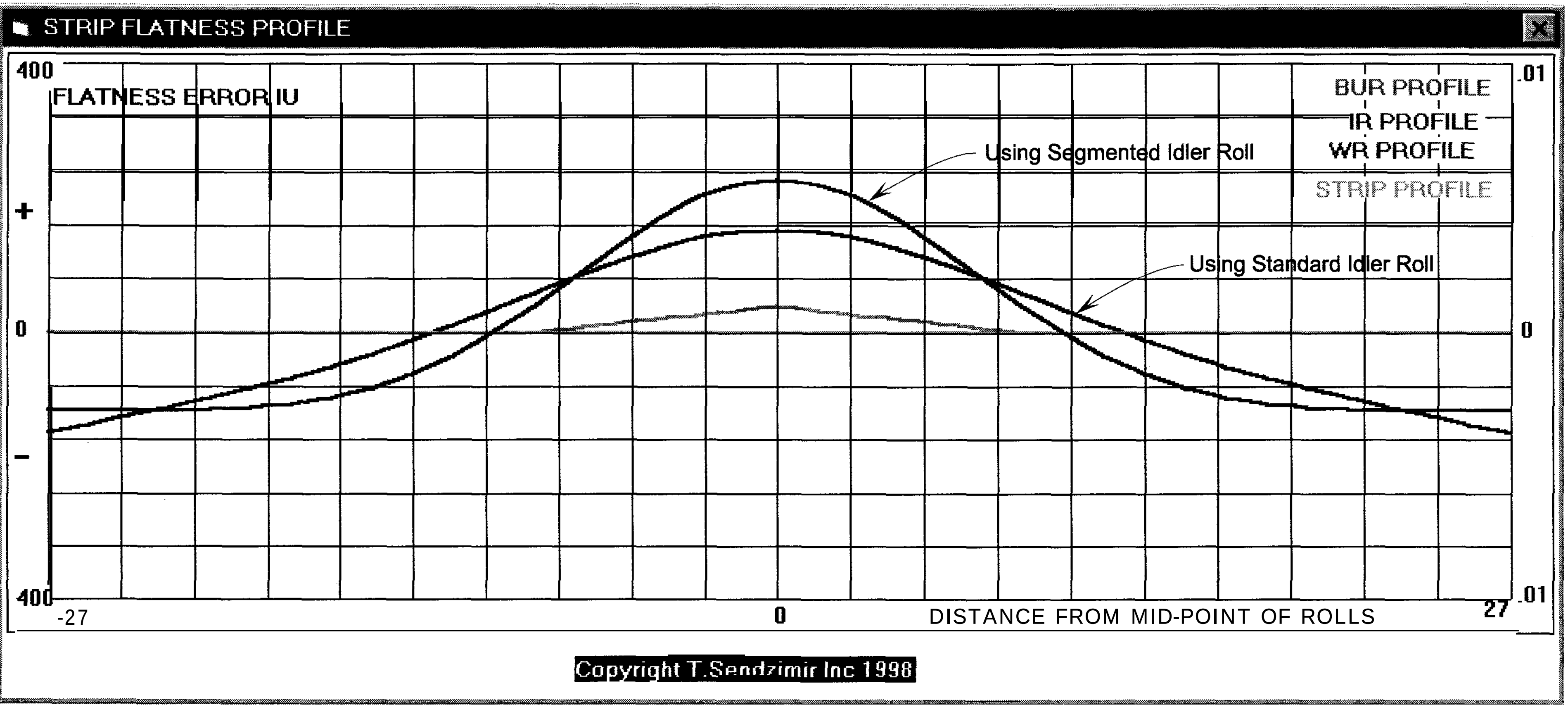

FIG. 8

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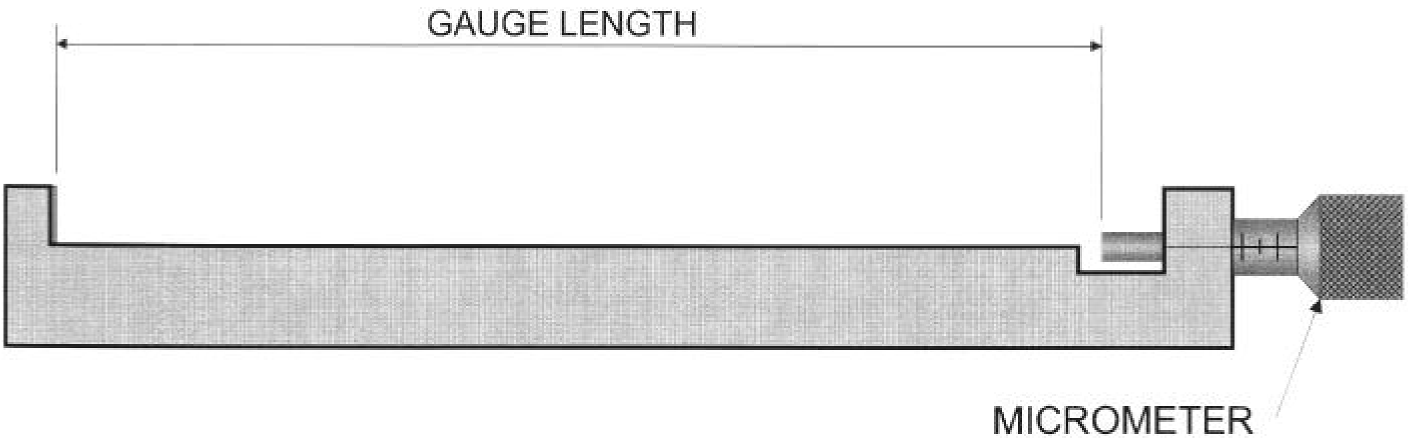

TEST FIXTURE

FIG. 9

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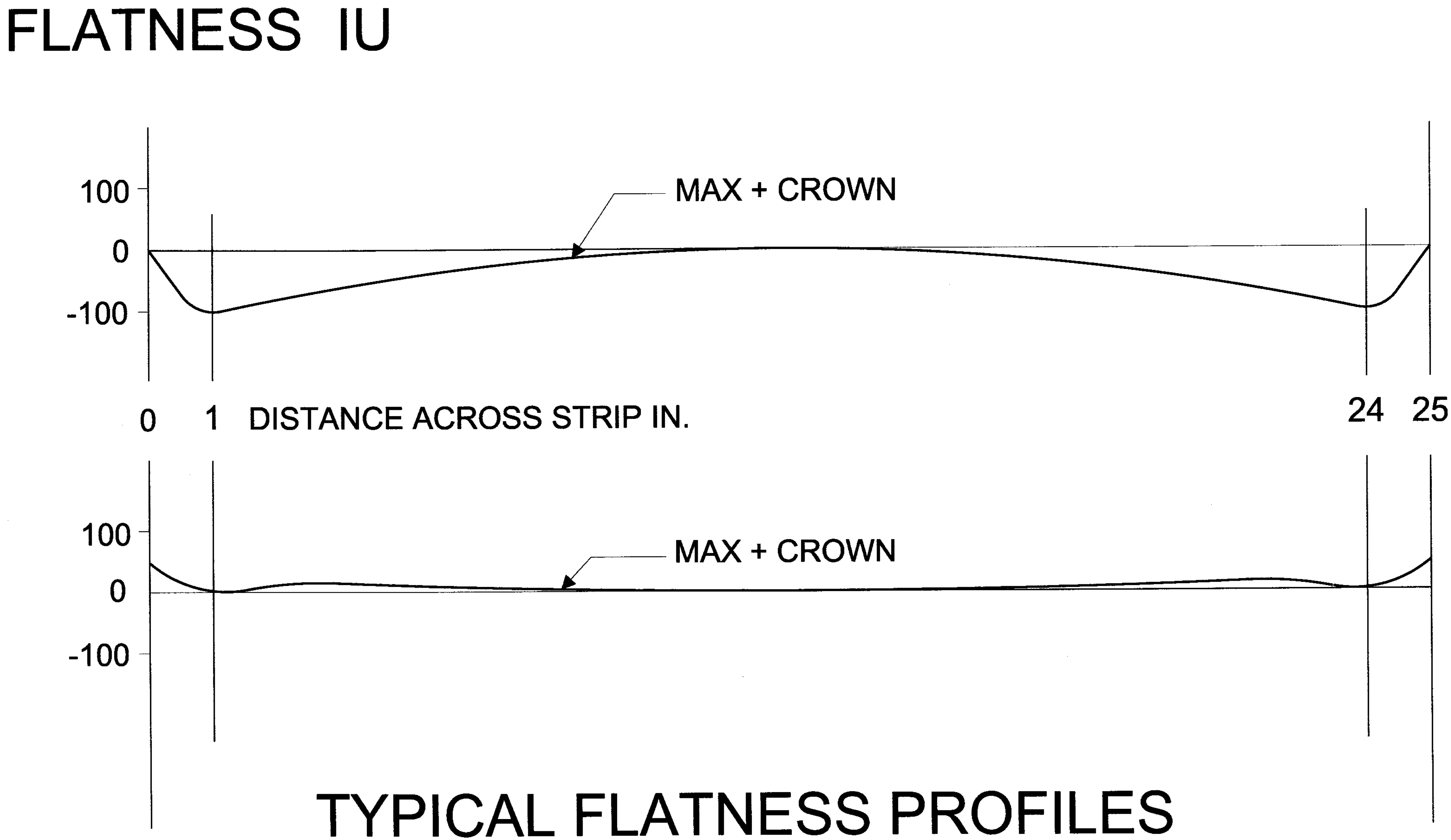

FIG. 10

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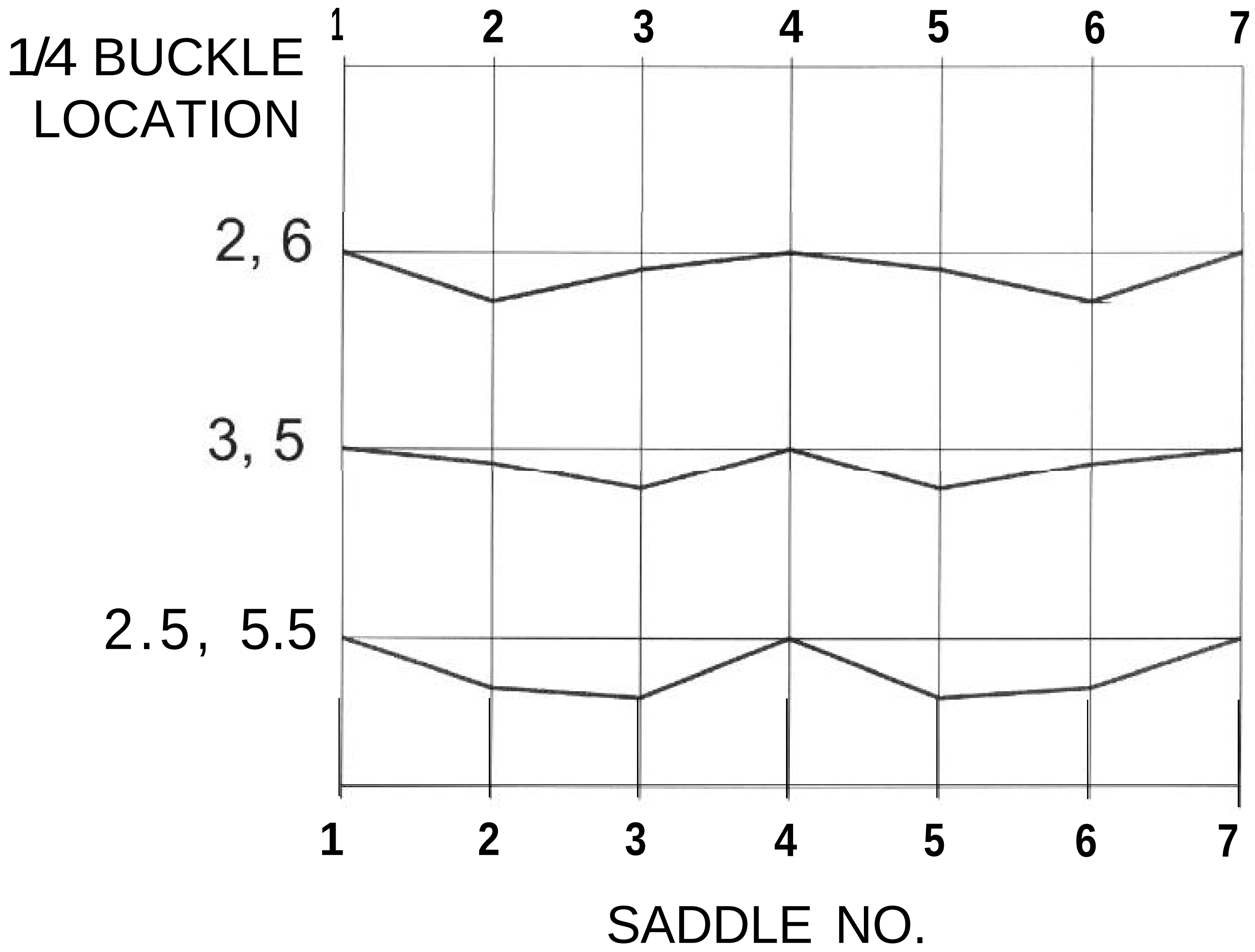

VARIABLE WIDTH 1/4 BUCKLE CONTROL
(6 BEARINGS, 7 SADDLES / SHAFT)

FIG. 11

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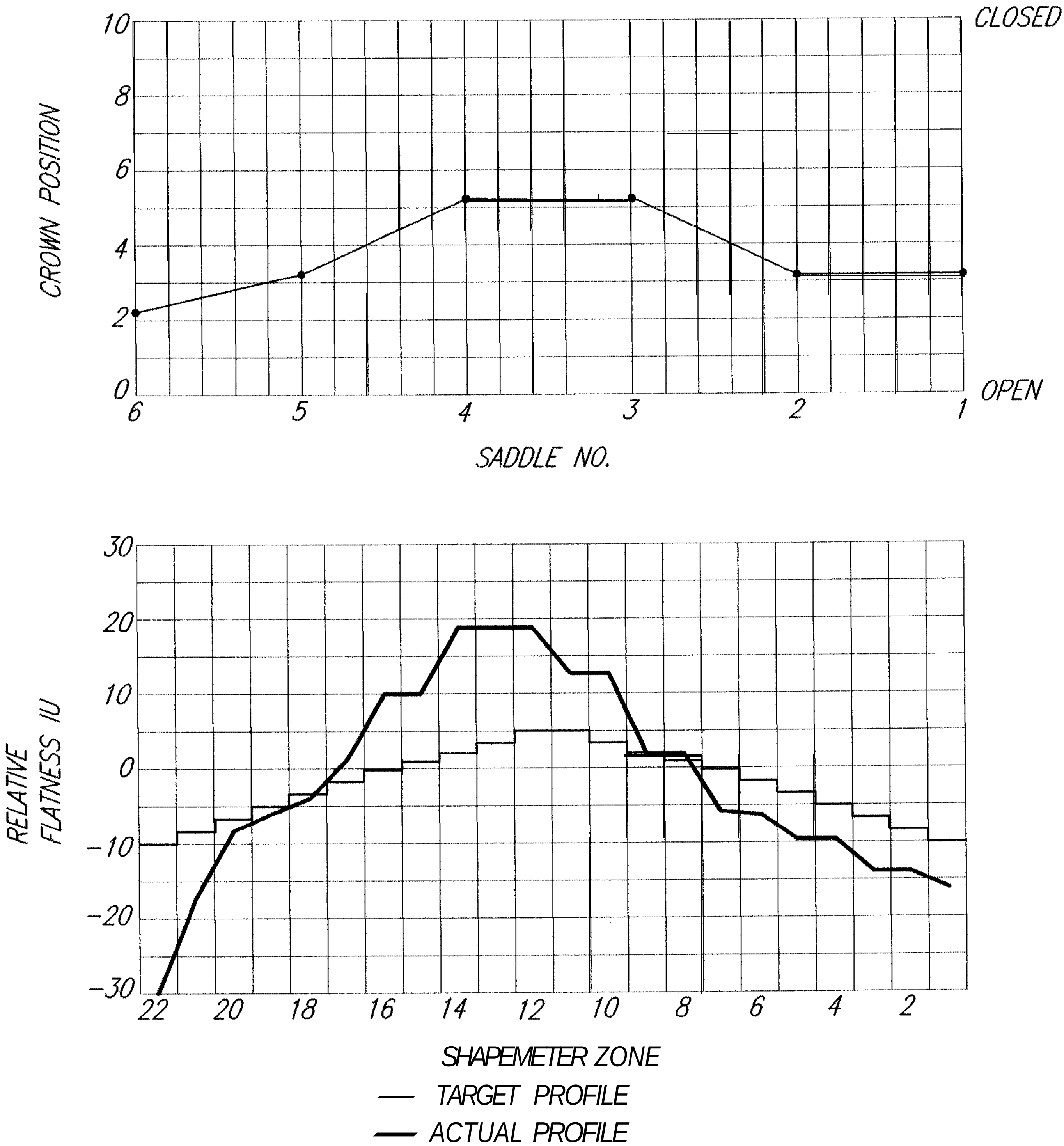

FIG. 12

TYPICAL CROWN AND
FLA TNESS PROFLIE
MANUAL FLATNESS CONTROL
STRIP 10 15 x 3,3 mm (304 ss)

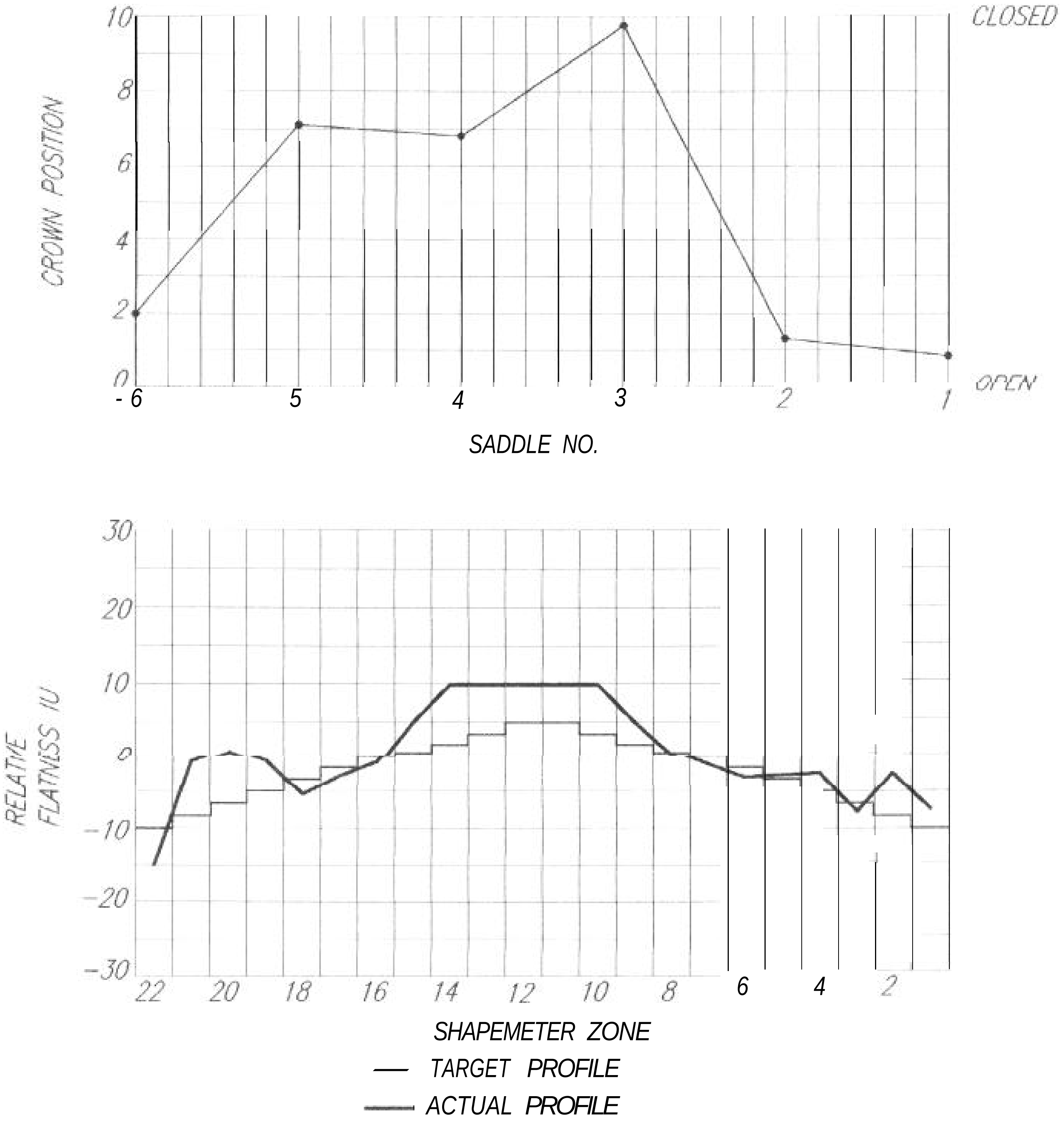

FIG. 13

TYPICAL CROWN AND
FLATNESS PROFILES
WITH FLEX ASSEMBLIES
& AUTO FLATNESS CONTROL
STRIP 1015 x 1.6 mm (304 SS)

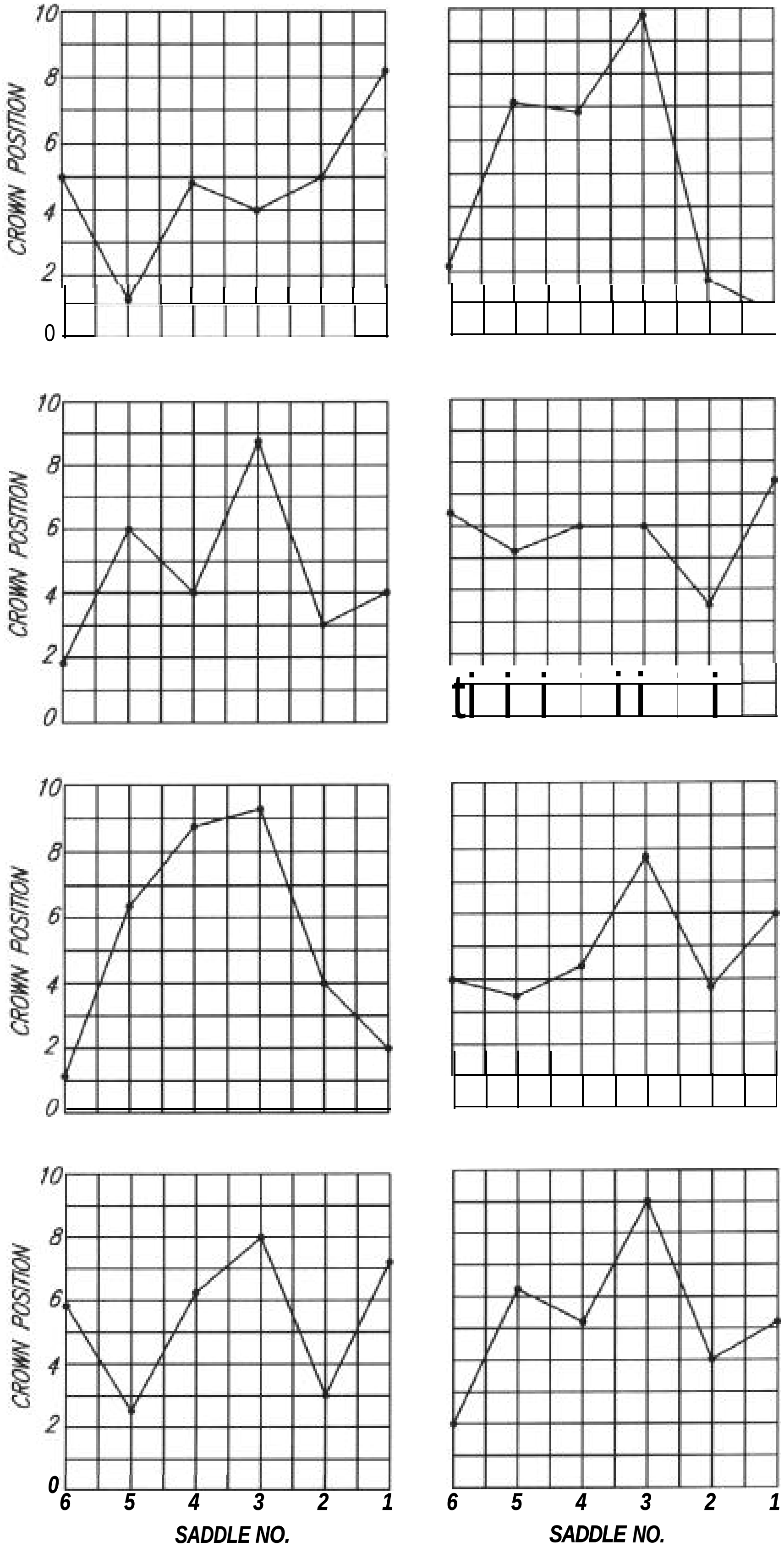

FIG. 14

TYPICAL CROWN PROFILES WITH FLEX ASSEMBLIES & AUTO FLATNESS CONTROL