

- [54] **ROLLING MILL GAUGE CONTROL METHOD AND APPARATUS INCLUDING X-RAY CORRECTION**
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- [73] Assignee: **Westinghouse Electric Corporation**, Pittsburgh, Pa.
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- [52] U.S. Cl. **72/9, 72/16**
- [51] Int. Cl. **B21b 37/02**
- [58] Field of Search **72/6-9, 16**

- 3,561,237 2/1971 Eggers et al. 72/7
- 3,625,037 12/1971 Michel 72/21 X

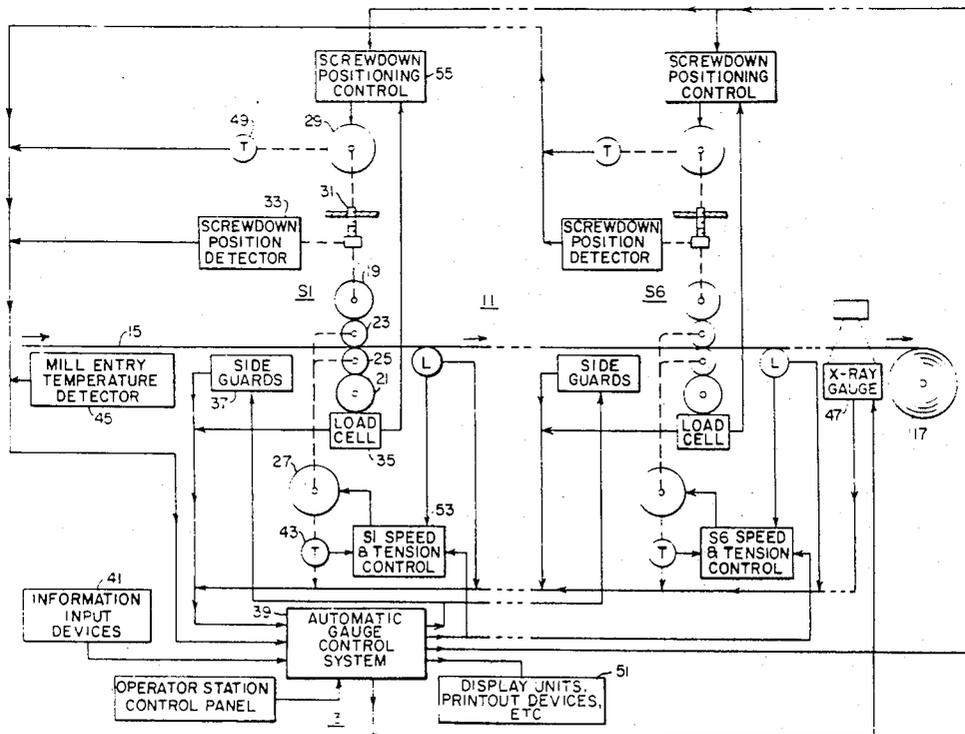
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[57] **ABSTRACT**

An automatic gauge control is disclosed to provide on line control of the delivery gauge or thickness from at least one roll stand of a rolling mill. The gauge error of the workpiece strip leaving that one roll stand is determined to include an X-ray gauge error portion and is corrected by predetermined adjustment of that one roll stand to provide a desired gauge correction in relation to that one roll stand.

- [56] **References Cited**
UNITED STATES PATENTS
 3,328,987 7/1967 Ferace 72/8

10 Claims, 6 Drawing Figures



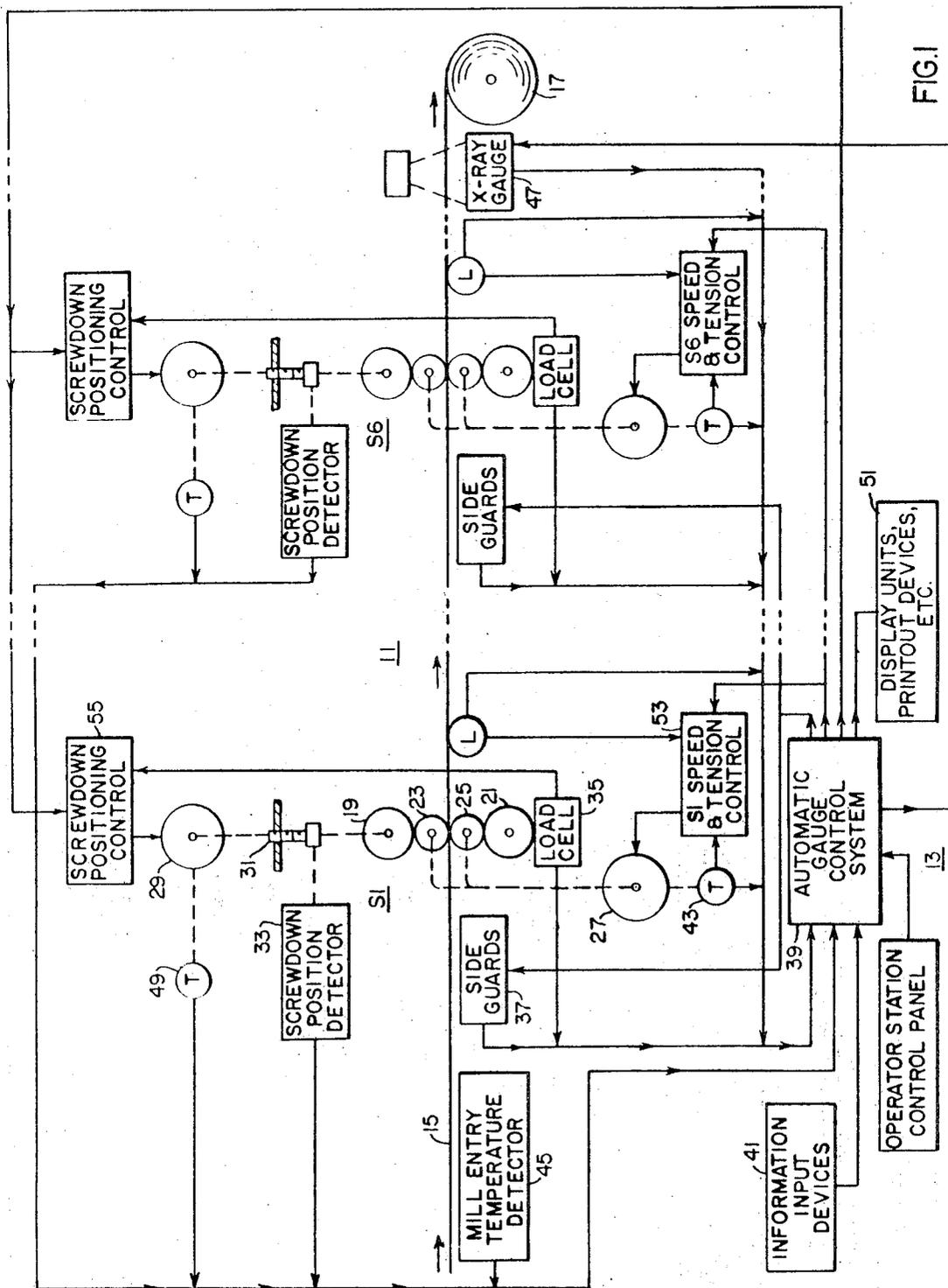


FIG. 1

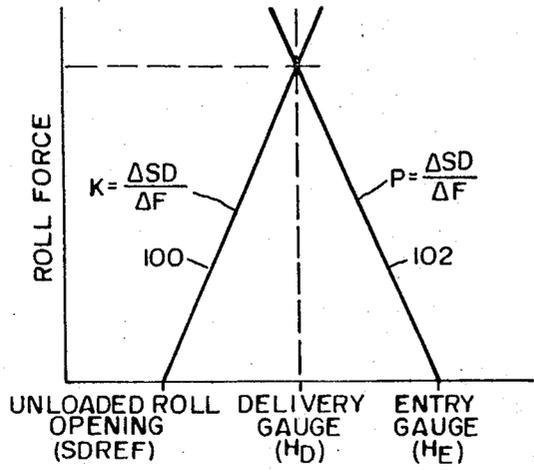


FIG. 2

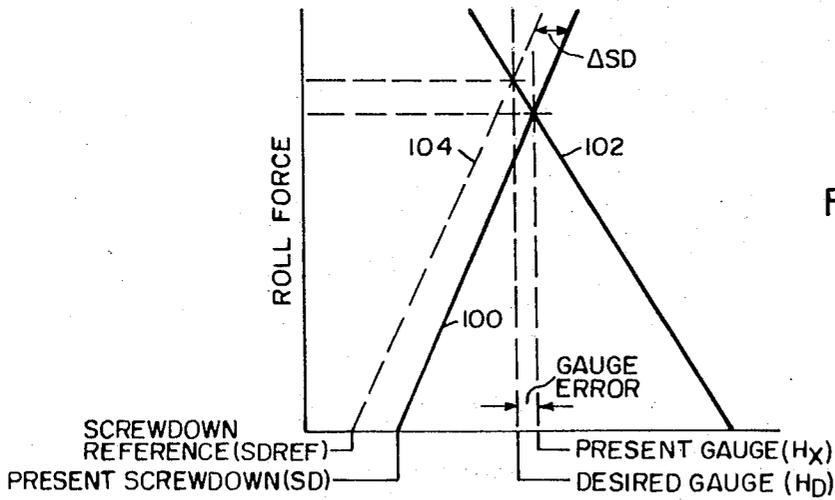


FIG. 3

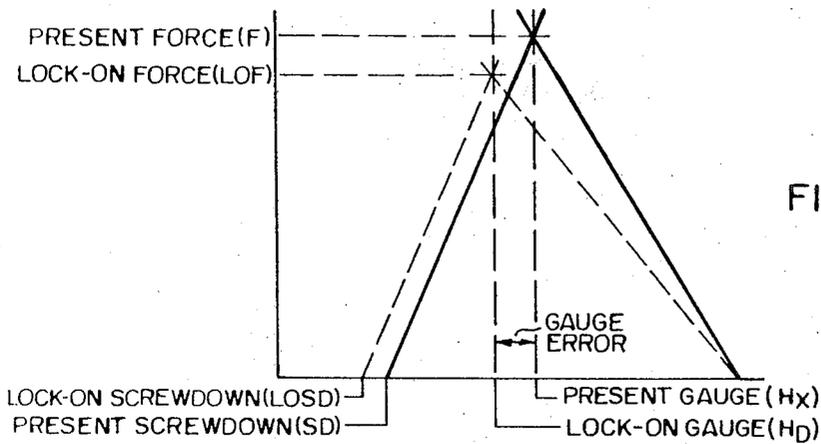


FIG. 4

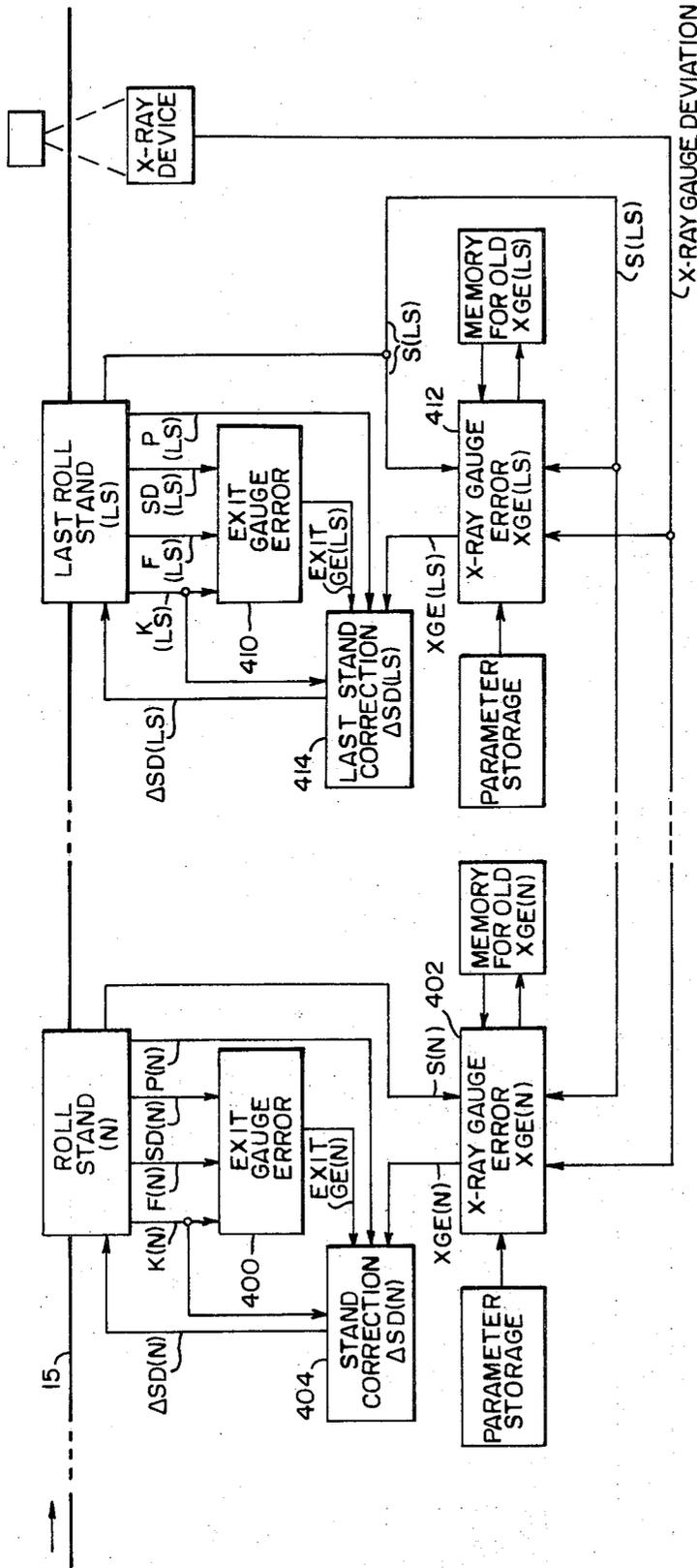


FIG. 5

ROLLING MILL GAUGE CONTROL METHOD AND APPARATUS INCLUDING X-RAY CORRECTION

CROSS REFERENCE TO RELATED APPLICATIONS

Reference is made to the following previously filed and related patent application which is assigned to the present assignee:

U.S. Pat. Ser. No. 215,743, filed Jan. 6, 1972 and entitled Gauge Control Method and Apparatus For Metal Rolling Mills and filed by A. W. Smith and R. Q. Fox.

Reference is made to the following concurrently filed, on Nov. 6, 1973, and related patent applications which are assigned to the present assignee:

U.S. Pat. Ser. No. 303,723 entitled Rolling Mill Gauge Control Method and Apparatus Including Temperature and Hardness Correction and filed by A. W. Smith.

U.S. Pat. Ser. No. 303,721 entitled Rolling Mill Gauge Control Method and Apparatus Including Entry Gauge Correction and filed by A. W. Smith and R. Q. Fox.

U.S. Pat. Ser. No. 303,725 entitled Rolling Mill Gauge Control Method and Apparatus Including Speed Correction and filed by R. Q. Fox.

U.S. Pat. Ser. No. 303,722 entitled Rolling Mill Gauge Control Method and Apparatus Including Feedback Correction and filed by R. Q. Fox and D. J. Emberg.

U.S. Pat. Ser. No. 303,726 entitled Rolling Mill Gauge Control Method and Apparatus Including Plasticity Determination and filed by R. Q. Fox.

BACKGROUND OF THE INVENTION

The present invention relates to workpiece strip metal tandem rolling mills and more particularly to roll force gauge control systems and methods used in operating such rolling mills.

In the operation of a metal or steel reversing or tandem rolling mill, the unloaded roll opening and the speed at each tandem mill stand for each reversing mill pass are set up to produce successive workpiece strip or plate reduction resulting in work product at the desired gauge. Generally, the loaded roll opening at a stand equals the stand delivery gauge or thickness on the basis of the usual assumption that there is little or no elastic workpiece recovery.

Since the operator provided initial roll opening setup conditions, or the initial roll opening settings provided by an associated digital computer control system operative with model equation information to calculate the setup screwdown schedules for the respective stands of the rolling mill, can be in error and since in any event certain mill parameters affect the stand loaded roll opening during rolling and after setup conditions have been established, a stand automatic gauge control system is employed if it is necessary that the stand delivery gauge be closely controlled. Thus, at the present state of the rolling mill art, and particularly the steel rolling mill art, a stand gauge control system is normally used for a reversing mill stand and for predetermined stands in tandem rolling mills.

The well known gagemeter or roll force system has been widely used to produce stand gauge control in metal rolling mills and particularly in tandem hot steel

strip rolling mills and reversing plate mills where experience has demonstrated that roll force control is particularly effective. Earlier publications and patents such as an article entitled Installation and Operating Experience with Computer and Programmed Mill Controls by M. D. McMahon and M. A. Davis in the 1963 Iron and Steel Engineer Year Book at pages 726 to 733, an article entitled Automatic Gauge Control For Modern Hot Strip Mills by J. W. Wallace in the December 1967 Iron and Steel Engineer at pages 75 to 86, U.S. Pat. No. 3,561,237 issued to Eggers et al. and U.S. Pat. No. 2,726,541 issued to R. B. Sims describe the theory upon which operation of the roll force and related gauge control systems are based. Attention is also called to U.S. Pat. Nos. 3,568,637, 3,574,279, 3,574,280 and 3,600,920 issued to A. W. Smith, which relate to roll force automatic gauge control systems. In referencing prior art publications or patents as background herein, no representation is made that the cited subject matter is the best teaching prior art.

Briefly, the roll force gauge control system uses Hooke's law in controlling the screwdown position at a rolling stand, i.e., the loaded roll opening under workpiece rolling conditions equals the unloaded roll opening or screwdown position plus the mill stand spring stretch caused by the separating force applied to the rolls by the workpiece. To embody this rolling principle in the roll force gauge control system, a load cell or other force detector measures the roll separating force at each controlled roll stand and the screwdown position is controlled to balance roll force changes from a reference value and thereby hold the loaded roll opening at a substantially constant value. Hot strip mill automatic gauge control (AGC) including evaluation of roll force feedback information involves the combination of a number of process variables, such as roll force, screw position, and mill spring which are all used to evaluate the gauge of the strip as it is worked in each stand. In addition, an X-ray gauge is used on the strip as it passes out of the last stand to evaluate the absolute strip gauge produced.

The two gauge error detection system that are commonly used are the X-ray and roll force. X-ray gauges can be placed between each stand, but they are expensive, difficult to maintain, and can detect errors only as the strip passes between stands. The roll force error detection system is much less expensive, and can be more easily implemented in relation to the operation of all stands, to detect errors in gauge as the strip passes between the rolls of a particular roll stand, providing immediate evaluation of desired corrections to the roll openings. The roll force system, however, provides only a relative evaluation of the gauge, since it measures the amount of gauge deviation from a reference gauge, such as the gauge at the head end of the strip.

A practical combination of the two systems uses roll force feedback to calculate fast corrections to fluctuations on gauge, and an X-ray to evaluate the absolute gauge of the strip coming out of the last stand. The fast corrections are calculated from the roll force feedback, the stand screwdown position, and the modulus of elasticity of the rolling stand. The slower X-ray gauge evaluation calculates simultaneous corrections to several stands, so that the absolute value of the gauge may be brought to the desired value.

The output of both of these systems is a change in the position references supplied to the screwdowns of selected roll stands.

The following well known formula expresses the basic roll force gauge control relationship:

$$h = SD + F * K$$

(1)

where:

h = loaded roll opening (workpiece delivery gauge G or thickness)

SD = unloaded roll opening (screwdown position)

K = stand mill spring constant

F = stand roll separating force.

Typically, the roll force gauge control system is an analog arrangement including analog comparison and amplification circuitry which responds to roll force and screwdown position signals to control the screwdown position and hold the following equality:

$$\Delta SD = - \Delta F * K$$

(2)

where:

ΔF = measured change in roll force from an initial force

ΔSD = controlled change in screwdown position from an initial screwdown position. After the unloaded roll opening setup and the stand speed setup are determined by the mill operator for a particular workpiece pass or series of passes, the rolling operation is begun and the screwdowns are controlled to regulate the workpiece delivery gauge from the reversing mill stand or from each roll force controlled tandem mill stand. By satisfying Equation (2), and the assumptions implicit in Equation (1), the loaded roll opening H in Equation (1) is maintained constant or nearly constant.

As the head end of the workpiece strip enters each roll stand of the mill, the lock-on screwdown position $LOSD$ and the lock-on roll separating force LOF are measured to establish what strip delivery gauge G should be maintained out of that roll stand. As the strip rolling operation proceeds, the roll stand separating force F and the roll stand screwdown position value SD are monitored periodically and any undesired change in roll separating force is detected and compensated for by a corresponding correction change in screwdown position. The lock-on gauge LOG is equal to the lock-on screwdown $LOSD$ plus the lock-on force LOF multiplied by the mill stand spring modulus K . The workpiece strip delivery gauge G leaving the roll stand at any time during the rolling operation is in accordance with above Equation (1) and is equal to the unloaded screwdown position SD plus the roll separating force F multiplied by the mill spring modulus K . The roll force determined gauge error GE in relation to a particular roll stand is derived by subtracting the lock-on gauge LOG from the delivery gauge G . The following Equations 3, 4 and 5 set forth these relationships.

$$LOG = LOSD + K * LOF$$

(3)

$$G = SD + K * F$$

(4)

$$GE = G - LOG = [SD - LOSD] + (F - LOF) * K$$

(5)

To provide steady state gauge error correction, the well known X-ray monitor gauge control system is usually employed to produce screwdown offset for the roll force control. In the monitor system, an X-ray or other radiation gauge sensing device is placed at one or more predetermined process points and usually at least at a process point following the delivery end after the last roll stand of the mill in order to sense actual delivery gauge after a workpiece transport delay from the point in time at which the actual delivery gauge is produced at the preceding stand or stands. The monitor system compares the actual delivery gauge with the desired delivery gauge and develops an X-ray gauge error as an analog feedback control signal to adjust the operation of the reversing mill roll force gauge control system or one or more predetermined tandem mill stand roll force gauge control systems to supply desired steady state mill delivery gauge. In this manner, the conventional monitor system provides for transport delayed correction of steady state gauge errors which are caused or which are tending to be caused by a single mill variable or by a combination of mill variables.

It is known in the teachings of the prior art that the mass flow volume of material passing through the multiple stands of a tandem rolling mill remains substantially constant, such that the following relationship is satisfied:

$$G(1) * S(1) * W(1) = G(2) * W(2) = G(N) * S(N) * W(N)$$

(6)

where:

G is the delivery gauge or thickness of the material leaving a given roll stand.

S is the workpiece speed leaving that same roll stand.

W is the width of the workpiece leaving that same roll stand.

Since the workpiece width remains substantially constant during the passage through the rolling mill, this mass flow relationship becomes:

$$G(1) * S(1) = G(2) * S(2) = G(N) * S(N) = G(LS) * S(LS)$$

(7)

When the last stand delivery gauge $XG(LS)$ is measured by an X-ray gauge, this enables a mass flow delivery gauge to be established for an earlier stand N , as follows:

$$XG(N) = XG(LS) * S(LS) / S(N)$$

(8)

where:

$XG(N)$ is the calculated mass flow delivery X-ray gauge leaving stand N .

$XG(LS)$ is the X-ray measured delivery gauge leaving the last stand.

S(N) is the measured speed of the workpiece leaving stand N.

S(LS) is the measured speed of the workpiece leaving the last stand.

It is known in the teachings of the prior art to establish an offset correction for the screwdown positioning mechanism of stand N in accordance with the difference between the desired reference exit or delivery gauge at the last stand and the X-ray exit or delivery gauge at the last stand as follows:

$$SD \text{ Offset}(N) = (\text{desired exit gauge at last stand minus} \quad (9))$$

X-ray gauge at last stand) * S(LS)/S(N)

In operator controlled mills, some steady state gauge correcting operations can eventually be taken off the monitor system by screwdown recalibration, and the like. Between similar workpiece passes if steady state gauge error tends to exist along the entire workpiece and persists from workpiece to workpiece. In this manner, some reduction is achieved in the length of off gauge workpiece material otherwise associated with monitor transport delay. Similarly, corrective monitor system operation caused by head end gauge errors can be reduced by changes in the operator or associated computer control system provided setup from workpiece to workpiece.

A background general teaching of stored program digital computer control system operation is set forth in a book entitled *Electronic Digital System* by R. K. Richards and published in 1966 by John Wiley and Sons.

An additional detailed description of computer programming techniques in relation to the control of metal rolling mills can be found in an article in the *Iron and Steel Engineer Yearbook* for 1966 at pages 328 through 344 entitled "Computer Program Organization For an Automatically Controlled Rolling Mill" by John S. Deliyannides and A. H. Green, and in another article in the *Westinghouse Engineer* for January 1965 at pages 13 through 19 and entitled "Programming For Process Control" by P. E. Lego.

A programmed digital computer system can be employed to make the gauge error correction screwdown movement determinations as well as to perform other mill control functions. The computer employs a programming system including an automatic roll force gauge control program or AGC program which is executed at predetermined periodic intervals to calculate the desired screwdown movement required at each roll force gauge controlled stand for gauge error correction including that stemming from roll force error detection at that stand.

SUMMARY OF THE INVENTION

In accordance with the broad principle of the present invention, a system and method for controlling workpiece delivery gauge in a metal rolling mill in relation to both the roll force determined exit gauge error in the workpiece delivered from a given roll stand and the determined X-ray gauge error in that workpiece leaving the same roll stand, and controlling the screwdown position of that one roll stand of the mill for correcting the delivery gauge in relation to that given roll stand.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 shows a schematic diagram of a tandem hot steel strip rolling mill and an automatic gauge control system arranged for operation in accordance with the present invention;

FIG. 2 illustrates the typical mill spring curve and workpiece reduction curve for a given rolling mill stand and the operation of that roll stand for reducing the gauge of a workpiece passed through the roll stand;

FIG. 3 illustrates, in relation to the mill spring curve and the workpiece reduction curve, the effect of a correction made to the screwdown position setting for changing the unloaded roll opening of a roll stand to provide a desired change in the workpiece gauge delivered from that roll stand;

FIG. 4 shows an illustrative gauge error detection operation in relation to the initial lock on conditions at the head end of the workpiece;

FIG. 5 shows a schematic illustration of the gauge error correction operation in accordance with the present invention; and

FIG. 6 shows an illustrative logic flow chart of a suitable gauge error correction control program operative in accordance with the present invention.

DESCRIPTION OF THE GAUGE CONTROL SYSTEM AND ITS OPERATION

There is shown in FIG. 1 a tandem hot strip steel finishing mill 11 operated with improved gauge control performance by a process control system 13 in accordance with the principles of the invention. Generally, however, the invention is applicable to various types of mills in which roll force gauge control is employed.

The tandem mill 11 includes a series of reduction rolling stands with only two of the stands S1 and S6 shown. A workpiece 15 enters the mill 11 at the entry end in the form of a bar and it is elongated as it is transported through the successive stands to the delivery end of the mill where it is coiled as a strip on a downcoiler 17. The entry bar would be of known steel grade class and it typically would have a known input gauge or thickness of about 1 inch and a width within some limited range such as 20 inches to 80 inches. The delivered strip would usually have approximately the same width and a thickness based upon the production order for which it is intended.

In the reduction rolling process, the successive stands operate at successively higher speeds to maintain proper workpiece mass flow. Each stand produces a predetermined reduction or draft such that the total mill draft reduces the entry bar to strip with the desired gauge or thickness.

Each stand is conventionally provided with a pair of backup rolls 19 and 21 and a pair of work rolls 23 and 25 between which the workpiece 15 is passed. A large DC drive motor 27 is controllably energized at each stand to drive the corresponding work rolls at a controlled speed.

As previously described, the sum of the unloaded work roll opening and the mill stretch substantially defines the workpiece gauge delivered from any particular stand in accordance with Hooke's law. To vary the unload work roll opening at each stand, a pair of screwdown motors 29 (only one shown at each stand) position respective screwdowns 31 (only one shown at each stand) which clamp against opposite ends of the

backup rolls and thereby apply pressure to the work rolls. Normally, the two screwdowns 31 at a particular stand would be in identical positions, but they can be located in different positions for strip guidance during threading, for flatness or other strip shape control purposes or possibly for another purposes.

A conventional screwdown position detector or encoder 33 provides an electrical signal representation of screwdown position at each stand. To provide an absolute correspondence between the screwdown position and the unloaded roll opening between the associated work rolls, a screwdown position detection system which includes the screwdown position detectors 33 can be provided and calibrated from time to time.

Roll force detection is provided at each of predetermined stands by a conventional load cell 35 which generates an electrical analog signal in accordance with the stand roll force. At the very least, each roll force controlled stand is provided with a load cell 35 and in many cases stands without roll force gauge control would also be equipped with load cells. The number of stands to which roll force gauge control is applied is predetermined during the mill design in accordance with cost-performance standards, and increasingly there is a tendency to apply roll force gauge control to all of the stands in a tandem hot strip steel mill. In the present case, a roll force gauge control system is assumed to be employed at each of the stands.

Conventional motorized sideguards 37 are located at predetermined points along the mill length. The sideguards are operated during mill setup on the basis of the widths of the upcoming workpiece 15 thereby defining the sides of the workpiece travel path for guidance purposes.

The process control system 13 provides automatic control for the operation of the tandem mill 11 as well as desired control for associated production processes (not indicated) such as the operation of a roughing mill. The process control system 13 can include a programmed process control digital computer system which is interfaced with the various mill sensors and the various mill control devices to provide control over many of the various functions involved in operating the tandem mill 11. According to user preference, the control system 13, can also include conventional manual and/or automatic analog controls for selected process control functions.

On the basis of these considerations, automatic gauge control system 39 can include a digital computer system operative to provide the finishing mill on-line roll force gauge control function, such as a Prodac 2000 (P2000) sold by Westinghouse Electric Corporation. A descriptive book entitled Prodac 2000 Computer Systems Reference Manual has been published in 1970 by Westinghouse Electric Corporation and made available for the purpose of describing in greater detail this computer system and its operation.

There is disclosed in the above referenced previously filed U.S. Pat. application Ser. No. 215,743 the logic flow chart of an illustrative automatic gauge control suitable for operation with the X-ray correction operation of the present invention. It should be readily understood by persons skilled in this art that the present invention is also suitable for operation with other well known automatic gauge control systems for controlling the delivery gauge of a workpiece strip passed through at least one stand of a rolling mill.

The digital computer processor can be associated with well known predetermined input systems typically including a conventional contact closure input system which scans contact or other signals representing the status of various process conditions, a conventional analog input system which scans and converts process analog signals, and operator controlled and other information input devices and systems 31 such as paper tape teletypewriter and dial input systems. It is noted that the information input devices 41 are generally indicated by a single block in FIG. 1 although different input devices can and typically would be associated with the control system. Various kinds of information are entered into control system through the input devices 41 including, for example, desired strip delivery gauge and temperature, strip entry gauge and width and temperature (by entry detectors if desired), grade of steel being rolled, plasticity tables, hardware oriented programs and control programs for the programming system, and so forth. The principal control action outputs from the automatic gauge control or AGC system include screwdown positioning reference commands which are applied to respective screwdown positioning controls 55 for operating the screwdown motors 29 for screw movement, and speed control signals which are applied to the respective speed and tension control system 53 to cause a change in drive speed to compensate for a change in thickness being made by a screwdown movement.

Display and printout devices 51 such as numeral display, tape punch, and teletypewriter systems can also be provided to keep the mill operator generally informed about the mill operation and in order to signal the operator regarding an event or alarm condition which may require some action on his part. The printout devices are also used to log mill data according to computer log program direction.

Generally, the AGC system uses Hooke's law to determine the total amount of screwdown movement required at each roll force controlled stand at the calculating point in time for roll force and gauge error correction, i.e., for loaded roll opening and stand delivery gauge correction to the desired value. The calculation defines the total change in the unloaded roll opening required to offset the gauge error causing condition.

During rolling operation, the on line gauge control system operates the stands to produce strip product having desired gauge and proper shape, i.e., flat with slight crown. On line gauge control is produced by the roll force gauge control loops at the stands and the previously noted X-ray monitor gauge control system.

In the monitor system, the X-ray gauge 47 produces the X-ray gauge error or deviation signal which indicates the difference between actual strip delivery thickness and desired or target strip delivery thickness. In other cases, it may be desirable to employ an absolute thickness measurement X-ray gauge signal to form a basis for monitor control actions or, more generally, for screwdown offset control actions.

To effect on line gauge control in the closed loops, the AGC system operates at predetermined time periods such as every 2/10 second with the screwdown position detector and load cell provided signals from each stand as well as the X-ray gauge error signal to determine the respective stand screwdown adjustment control actions required for producing desired strip delivery gauge.

In FIG. 2, linear approximations of the roll stand characteristic curves as shown to illustrate the application of Hooke's law to a rolling mill stand and to illustrate the basis upon which the on line gauge control system provides improved gauge control, accuracy and stability and other operating benefits. A mill modulus characteristic or mill spring curve **100** defines the separation between a pair of workpiece reducing mill stand work rolls as a function of separating force and as a function of screwdown position. The slope of the mill spring curve **100** is the well known mill spring modulus or constant K which is subject to variation as well known to persons skilled in the art. When a correct screwdown calibration is known and the screwdowns are positioned such that the empty work rolls are just facing, the unloaded screwdown zero position is defined. The workpiece deformation characteristic or reduction curve **102** is shown. The entry gauge H_E of the workpiece passed through the roll stand is reduced to the indicated delivery gauge H_D as defined by the intersection of the mill spring curve **100** and the product reduction curve **102** to establish the stand roll force required for the indicated operation. The unloaded roll opening, sometimes called the screwdown because of the screw and nut system used for adjusting the roll opening, is the gauge that would be delivered if there were no roll separating force. As the force increases with a constant roll opening, the delivery gauge increases, since the mill deflects as shown by the mill spring curve **100**. If no force was exerted on the product being rolled, the gauge would not be reduced and the delivery gauge would be equal to the entry gauge. When the roll force increases, the product is plastically deformed and the delivery gauge decreases. The slope of the mill spring characteristic line is called the mill modulus (K) and the slope of the product reduction characteristic is called the product plasticity (P). The delivery gauge is determined by the equilibrium point at which the force exerted by the mill is equal to the force required to deform the product. Changes in entry gauge and product hardness result in a change in roll force and delivery gauge. The automatic gauge control moves the screwdown to correct for these gauge changes. The main advantage of the roll force gauge control system is its ability to detect changes in gauge the instant they take place, as the product is being rolled in the stand. A shift in delivery thickness can be caused by a change in entry thickness or a change in hardness (usually caused by a change in temperature). This change in delivery gauge is immediately detected by monitoring the roll separating force of the roll stand.

When the screwdowns are opened (positive movement) the unloaded roll opening increases as reflected by a change to the right in the graphical location of the mill spring curve **100** such that the theoretical spring curve intersect equals the new unloaded roll opening. With screwdown closing the mill spring curve is shifted to the left in a similar manner.

At any particular screwdown position and with correct screwdown calibration, the stand workpiece delivery gauge H_D equals the unloaded roll opening as defined by the screwdown position $SDREF$ plus the mill stretch ($F \cdot K$) caused by the workpiece. If the screw-

down calibration is incorrect, i.e., if the number assigned to the theoretical roll facing screwdown position is something other than zero because of roll crown wear or other causes, the stand workpiece delivery gauge H_D then equals the unloaded roll opening plus the mill stretch, plus or minus the calibration drift.

The amount of mill stretch depends on the product deformation characteristic or reduction curve **102** for the workpiece. As shown in FIG. 2, the reduction curve **102** for a strip of predetermined width represents the amount of force F required to reduce the workpiece from the stand entry gauge (height) H_E . The workpiece plasticity P is the slope of the curve **102**, and the curve **102** is shown as being linear although a small amount of nonlinearity would normally exist.

Desired workpiece delivery gauge H_D is produced since the amount of force F required to reduce the workpiece from H_E to H_D is equal to the amount of roll separating force required to stretch the rolls to a loaded roll opening H_D , i.e., the intersection of the mill spring curve **100** and the workpiece reduction curve **102** lies at the desired gauge value H_D .

As shown in FIG. 3, if the actual stand present gauge H_x is not the same as the desired gauge H_D , there is a gauge error GE to be corrected. This condition can be corrected by changing the provided screwdown position reference $SDREF$ to the stand, such that a new mill spring curve **104** becomes operative to result in the desired gauge H_D being delivered from the roll stand and the gauge error GE is now removed.

It is known in accordance with the teachings of above referenced U.S. Pat. No. 3,561,237 that the required corrective screwdown adjustment ΔSD to correct a stand delivery gauge error GE is equal to the product of that gauge error GE times the sum of the ratio of the workpiece plasticity P for that same stand with the mill spring modulus K for that same stand and one, as follows in relation to stand (N):

$$\Delta SD(N) = \text{exit } GE(N) * [(P(N)/K(N)) + 1] \quad (10)$$

In the teachings of the latter patent, the mill spring constant $K(N)$ was defined in terms of millions of pounds of roll force per inch of screwdown position change. The workpiece plasticity $P(N)$ was similarly defined. It has been established in relation to the practice of the present invention that these values are preferred in terms of inches of screwdown position change per millions of pounds of roll force. Thusly, the above equation (10) will be rewritten and utilized in accordance with the relationship:

$$\Delta SD(N) = \text{exit } GE(N) * [K(N)/P(N) + 1] \quad (11)$$

The stand (N) exit gauge error $GE(N)$ determined by the roll force system at stand (N) is established by the relationship of above equation (11) as follows:

$$GE(N) = [SD(N) - LOSD(N)] + [F(N) - LOF(N)] * K(N)$$

(12)

In reference to FIG. 4, in general the workpiece strip gauge error delivered by a given stand, and as determined by the sensed operational variable at that same stand, is in accordance with the roll force system relationship shown in above equation (12). The exit gauge error leaving stand (N), for example, equals the sum of a first quantity, which is the difference between the presently measured screwdown position LOSD(N), and a second quantity, which is the determined mill spring modulus K(N) times the difference between the presently measured roll separation force P(N) and the initial lock on roll force LOF(N).

DESCRIPTION OF EMBODIMENT OF PRESENT INVENTION

In reference to FIG. 5, there is shown a portion of a tandem rolling mill including a last roll stand (LS), and an earlier roll stand (N), with the workpiece strip 15 moving in the direction indicated by the arrow. At block 400 there is determined the roll force exit gauge error leaving stand (N) in relation to the operational variables sensed at stand (N). This determination utilizes above Equation (12) for this purpose. At block 402 there is determined the stand (N) X-ray gauge error XGE(N) leaving stand (N).

The roll force gauge control system maintains substantially constant delivery gauge out of reach roll stand in relation to the initially setup lock on gauge at the head-end of each workpiece strip. The X-ray gauge sensing device located after the last roll stand is used to determine the X-ray delivery gauge deviation leaving the rolling mill, in relation to the measured actual gauge and the desired reference gauge. The particular roll stands selected by the operator for X-ray monitor correction are adjusted in operation to bring the final delivery gauge or thickness leaving the rolling mill into agreement with the desired reference gauge, if the X-ray gauge deviation is not too large. The measured output X-ray gauge deviation from the X-ray device is processed by the following Equation relationship:

$$\begin{aligned} XGE(N) = & \text{X-ray Deviation} * [(S(LS)/S(N))] * \\ & [(J1/J2 + OLDXGE(N)) \\ & * [(J3/J4)] \end{aligned} \quad (13)$$

to determine the X-ray gauge error XGE(N) for stand (N) in relation to the measured speed S(LS) of the last stand, the measured speed S(N) of stand (N), a first preselected adjustment parameter J1/J2 for stand (N), the previous determined value of the X-ray gauge error OLDXGE(N) for stand (N) in accordance with this same Equation (13) and a second preselected adjustment parameter J3/J4 for stand (N). The speed S(N) of stand (N) and the speed S(LS) of the last stand are measured in relation to the operational speed of these respective roll stands, since the forward slip consideration at stand (N) balances the forward slip consideration at the last stand (LS). Assuming stand (N) is selected for X-ray monitor correction, at block 404 the X-ray gauge error XGE(N) at stand (N) is utilized in combination with the roll force determined exit gauge error GE(N) to establish the desired screwdown position adjustment ASD(N) in accordance with the rela-

tionship of above Equation (11) modified as follows:

$$\Delta SD(N) = [GE(N) + XGE(N)] * [(K(N)/P(N)) + 1] \quad (14)$$

At block 410 there is determined the exit gauge error leaving last stand (LS) in relation to the operational variables sensed at the last stand (LS), and this utilizes above Equation (5) for this purpose. At block 412 there is determined the calculated last stand (LS) X-ray gauge error XGE(LS) for the last stand (LS), and this utilizes above Equation (13) for this purpose. At block 414 there is determined the last stand (LS) screwdown position correction needed to remove both the exit gauge error GE(LS) at the last stand (LS) as well as the X-ray gauge error XGE(LS) at the last stand (LS), and this utilizes above Equation (13) for this purpose with the ratio of S(LS)/S(LS) being used here.

In relation to the X-ray gauge error correction, there is shown in FIG. 6 a flow chart to illustrate the operation of this program. At step 600 a check is made to see that the operator has selected the X-ray monitor operation to be operative. At step 602 a check is made to see that a particular X-ray device is selected for operation in the event that two X-ray devices are provided after the last stand. At step 604 a determination is made that the selected X-ray device is measuring strip gauge. If any one of the determinations at steps 600, 602 and 604 is negative then the program ends. At step 606 the operator desired target or nominal workpiece strip gauge leaving the rolling mill is read from storage. It should be understood that gauge is herein used to mean the same as workpiece strip thickness, and it is commonly also spelled gage by persons skilled in this art. At step 608 the percent deviation between the desired nominal or reference gauge and the X-ray device measured actual gauge is now determined. At step 610 a limit check is made, and if it is too large a flag is set and an alarm message printed at step 612 and the program ends. If the percent deviation is not too large, at step 614 a check is made to see if the head-end time delay has expired; and if it has not the program ends. At step 618 a determination is made to see if this is the first check on this strip. If it is, at step 620 a check is made to see if monitor hold is selected by the operator and if so at step 622 the present gauge is held. If the check at step 618 was negative, the program goes to step 624 to set the drive number equal to last stand. If the check at step 620 was negative, the program goes to step 626 to determine if the gauge deviation gauge error is the maximum allowable. At step 628 a selection is made of the closest alternate gauge from the stored gauge table provided by the operator. From step 622 the program goes to step 630 to calculate a new percent deviation. At step 632 the monitor hold light is turned on. The comparison made at step 626 is provided to determine if the percent deviation is greater than some operator predetermined limit value, such as 10 percent. At step 628 a look-up table operation is provided in relation to operator provided values to reapply the desired or nominal strip gauge. At step 630 a new percent deviation is determined in relation to this new desired strip gauge.

At strip 624 the drive number is set equal to the last stand in preparation of determining the last stand speed

and a mass flow relationship including proportional integration of the established gauge error to be performed on a selected stand by stand basis, generally three such stands are selected by the operator. At step 624 the last stand is addressed, and now the correction of the selected stand occurs. At step 626 a check is made to see if the selected stand has calibrated screws, and at step 628 a check is made to see if the X-ray monitor operation has been selected by the operator for this stand. At step 630 the X-ray correction is determined for the selected stands in accordance with above Equation (13), including the proportional integration function. This operation is continued for all selected stands. If the checks made at step 626 or 628 are failed, then the stand drive number is decremented at step 632 and a check is made at step 634 to see if this stand is number zero. At steps 636 and 638 the correction is limited. At step 640 if the stand roll force gauge control system is turned off, at step 642 the present screw position is read and an X-ray correction is output for this stand at step 644; this permits providing only the X-ray correction with the roll force system turned off for a given stand when desired by the operator. At step 646 a check is made to see if enough stands have been corrected. At step 634 a check is made to see if this stand under consideration is the first stand and at step 634 the stand number is decremented to continue the operation for all selected stands.

The typical AGC control program is written as a loop operation such that one set of coding processes all of the roll stands, and every time the program operates through the loop a calculation is made when appropriate for each of the roll stands in relation to the gauge error and the X-ray gauge error correction.

The following table shows illustrative values of the first adjustment factor J1/J2 as utilized in relation to above Equation (13) as well as the second adjustment factor J3/J4 when plotted in relation to the respective stand numbers of a typical tandem rolling mill.

Stand No.	J1/J2	J3/J4
1	0.40	1.00
2	0.50	1.00
3	0.60	1.00
4	0.70	1.00
5	0.80	1.00
6	0.90	1.00
7	1.00	1.00

The above Equation (13) relationship operates on the X-ray gauge deviation as a proportional integrator, such that the first term of the Equation provides a substantially instantaneous response to changes in the X-ray gauge deviation measured by the X-ray device, while the second term of the Equation provides an integral response to the long term trends of the X-ray gauge deviation measured by the X-ray device.

Previous gauge control systems used the X-ray device to measure the deviation in gauge from the nominal selected value of desired delivery gauge by a comparison of the actual delivery gauge with the desired target delivery gauge to give this gauge deviation. This gauge deviation was applied as the offset recalibration to the screw position reading. The present control arrangement takes a different approach, by determining the

X-ray correction and applying the correction to the roll force gauge control Equation as an additional term in relation to the gauge error. The previous offset was not applied to this same roll force gauge control Equation but rather was used as a change in the lock-on screwdown. The teachings of the present invention is to make a correction every time the correction is calculated and not a sustained correction such as would occur by changing the lock-on screwdown, with the X-ray correction for each selected stand (N) being calculated from the X-ray deviation periodically, such as every 2/10 of a second.

GENERAL DESCRIPTION OF INSTRUCTION PROGRAM LISTING

In the Appendix there is included an instruction program listing that has been prepared to control the roll force automatic gauge control operation of a tandem rolling mill in accordance with the here disclosed control system and method. The instruction program listing is written in the machine language of the PRODAC P2000 digital computer system, which is sold by Westinghouse Electric Corporation for real time process control computer applications. Many of these digital computer systems have already been supplied to customers, including customer instruction books and descriptive documentation to explain to persons skilled in this art the operation of the hardware logic and the executive software of this digital computer system. This instruction program listing is included to provide an illustration of one suitable embodiment of the present control system and method that has actually been prepared. This instruction program listing at the present time has been partially debugged through the course of practical operation for the real time automatic gauge control of a tandem rolling mill, but it is understood and well known by persons skilled in this art that most real time process control application programs contain some bugs or minor errors, and it is within the routine skill of such persons and takes varying periods of actual operation time to identify and correct the more critical of these bugs.

A person skilled in the art of writing computer instruction program listings, particularly for an invention such as the present roll force automatic gauge control system and method for a tandem rolling mill must generally go through the following determinative steps:

Step One — Study the workpiece rolling mill and its operation to be controlled, and then establish the desired control system and method concepts.

Step Two — Develop an understanding of the control system logic analysis, regarding both hardware and software.

Step Three — Prepare the system flowcharts and/or the more detailed programmer's flowcharts.

Step Four — Prepare the actual computer instruction program listings from the flowcharts.

What we claim is:

1. A gauge control system for a rolling mill having at least one roll stand (N) operative to reduce the gauge of a workpiece passed through said roll stand and including a device for measuring the gauge deviation of the workpiece leaving said rolling mill, said system comprising:

means for determining a gauge error of said workpiece leaving said one roll stand in relation to said measured gauge deviation,

means operative in relation to said gauge error for determining the required adjustment of said one roll stand in accordance with a predetermined relationship including the mill spring modulus of said one roll stand and the workpiece plasticity in relation to said one roll stand, and

means for controlling the operation of said one roll stand in accordance with said required adjustment.

2. The gauge control system of claim 1, with said predetermined relationship being as follows:

$$\Delta SD = XGE * [(K/P) + 1]$$

where ΔSD is the required adjustment of said one roll stand,

where XGE is the gauge error of said one roll stand in relation to said gauge deviation,

where K is the mill spring modulus of said one roll stand, and

where P is the workpiece plasticity of said one roll stand.

3. The gauge control system of claim 1, including means for determining a second gauge error of said workpiece leaving said one roll stand in relation to the roll force and screwdown position of said one roll stand,

with said means for determining said required adjustment being operative in relation to said second gauge error.

4. The gauge control system of claim 3, with said predetermined relationship being as follows

$$\Delta SD(N) = [GE(N) + XGE(N)] * [(K(N)/P(N)) + 1]$$

where $\Delta SD(N)$ is the required adjustment for said one roll stand (N),

where GE(N) is said second gauge error,

where XGE(N) is the gauge error in relation to said gauge deviation,

where K(N) is the mill spring modulus of said one roll stand (N), and

where P(N) is the workpiece plasticity in relation to said one roll stand (N).

5. A gauge control system for a rolling mill having at least a first roll stand and a last roll stand operative with respective initial roll opening settings to reduce the gauge of a workpiece passed through said rolling mill and including a device positioned after said last roll stand for measuring the gauge deviation of said workpiece leaving said rolling mill, said system comprising:

means for determining a gauge error of said workpiece in accordance with a predetermined relationship between said gauge deviation of said workpiece, the operating speed of said first roll stand and the operating speed of said last roll stand and a response factor,

means for determining a correction to the roll opening setting of at least said first roll stand in accordance

with said gauge error, the mill spring modulus of said first roll stand and the workpiece plasticity, and

means for controlling the roll opening of said first roll stand for the passage of said workpiece in accordance with said correction.

6. The gauge control system of claim 3, with said predetermined relationship being as follows:

$$XGE(N) = \text{Gauge Deviation} * (S(LS)/S(N)) * RF(1) + \text{OLDXGE}(N) * RF(2)$$

where XGE(N) is a gauge error at said first roll stand (N) in relation to said gauge deviation,

where S(LS) is the speed of the last stand,

where S(N) is the speed of the first stand (N),

where RF(1) is a first predetermined response factor,

where OLDXGE(N) is the integral of the gauge error XGE(N) for this workpiece, and

where RF(2) is a second predetermined response factor.

7. A gauge control system for a rolling mill having a plurality of roll stands operative to reduce the gauge of a workpiece passed through each of said roll stands and including a device for measuring the gauge deviation of the workpiece leaving said rolling mill, said system comprising:

means for determining a gauge error of said workpiece leaving each said roll stand in relation to said measured gauge deviation,

means operative in relation to said gauge error for each roll stand for determining a respective required adjustment for each said roll stand in accordance with a predetermined relationship including the mill spring modulus of the same roll stand and the workpiece plasticity in relation to the same roll stand, and

means for controlling the operation of each said roll stand in accordance with its respective required adjustment.

8. The gauge control system of claim 7, with said required adjustment for each roll stand (N) being as follows:

$$\Delta SD(N) = XGE(N) * [(K(N)/P(N)) + 1]$$

where $\Delta SD(N)$ is the required adjustment of each said roll stand (N),

where XGE(N) is the gauge error in relation to each roll stand (N),

where K(N) is the mill spring modulus in relation to each roll stand (N), and

where P(N) is the workpiece plasticity in relation to each roll stand (N).

9. A method of controlling the workpiece gauge leaving a rolling mill having at least one roll stand operative with an initial roll opening setting to reduce the gauge of a workpiece passed through said rolling mill and including a device for measuring the gauge deviation of said workpiece leaving said rolling mill, the steps of said method comprising:

determining a gauge error of said workpiece leaving said one roll stand in relation to the measured gauge deviation and a predetermined response factor,

determining a roll opening correction for application to said one roll stand during the passage of said

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workpiece in accordance with a predetermined relationship including said gauge error, the mill spring modulus of said one roll stand and the workpiece plasticity in relation to said one roll stand, and

controlling the operation of said one roll stand in accordance with said roll opening correction.

10. The method of claim 9, with the gauge error being determined by the following relationship:

$$XGE(N) = X\text{-ray Deviation} * (S(LS)/S(N)) * RF(1) + OLDXGE(N) * RF(2)$$

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where XGE(N) is the gauge error leaving said one roll stand (N),

where S(LS) is related to the speed of the workpiece leaving the rolling mill,

where S(N) is related to the speed of the workpiece leaving said one roll stand (N),

where RF(1) is a first predetermined response factor,

where OLDXGE(N) is the integral of the gauge error in relation to said one roll stand (N), and where RF(2) is a second predetermined response factor.

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