ROLLING MILL GAUGE CONTROL
METHOD AND APPARATUS INCLUDING
SPEED CORRECTION

Inventor: Richard Q. Fox, Pittsburgh, Pa.
Assignee: Westinghouse Electric Corporation,
Pittsburgh, Pa.

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Primary Examiner—Milton S. Mehr
Attorney, Agent, or Firm—R. G. Brodahl

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 tandem rolling mill. The gauge error of the workpiece strip leaving that one roll stand is determined in relation to the speed of that one roll stand and is corrected by predetermined adjustment of that one roll stand.

9 Claims, 7 Drawing Figures
ROLLING MILL GAUGE CONTROL METHOD AND APPARATUS INCLUDING SPEED 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:

S.N. 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 and related patent applications which are assigned to the present assignee:

S.N. 303,723 entitled Rolling Mill Gauge Control Method and Apparatus Including Temperature and Hardness Correction and filed by A. W. Smith.

S.N. 303,721 entitled Rolling Mill Gauge Control Method and Apparatus Including Entry Gauge Correction and filed by A. W. Smith and R. Q. Fox.

S.N. 303,724 entitled Rolling Mill Gauge Control Method and Apparatus Including X-Ray Correction and filed by R. Q. Fox.

S.N. 303,722 entitled Rolling Mill Gauge Control Method and Apparatus Including Feedback Correction and filed by R. Q. Fox and D. J. Emberg.

S.N. 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 opening and the speed at each tandem mill stand or for each reversing mill pass are set up to produce successive workpiece strip or plate reductions 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 work-piece 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 set 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 gaugemeter 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 Operative 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 Augmatic Gage 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 work-piece. 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 systems 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 in gauge, and an X-ray gauge 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:
3,851,509

\[ h = SD + F*K \]  

(1)

where:

\( h \) = loaded roll opening (workpiece delivery gauge 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:

\[ \Delta SD = - \Delta F \times K \]  

(2)

where:

\( \Delta F \) = measured change in roll force from an initial force

\( \Delta SD \) = 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-off 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-off 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 present delivery gauge \( G \). The following Equations 3, 4 and 5 set forth these relationships.

\[ LOG = LOSD + K \times LOF \]  

(3)

\[ G = SD + K \times F \]  

(4)

\[ GE = G - LOG = (SD - LOSD) + (F - LOF) \times K \]  

(5)

To provide steady state gauge error correction, the well known X-ray monitor gauge control system is usually employed to producescrewdown 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 work-piece 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 roll roll force gauge control system or one or more predetermined tandem roll 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.

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 produce screwdown in the operator or associated computer control system provided setup from workpiece to workpiece.


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 334 entitled “Computer Program Organization for an Automatically Controlled Rolling Mill” by John S. Deliyannis 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. Legg.

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 gauge in a metal rolling mill employs means for determining gauge error in the workpiece delivered from a given
roll stand in relation to the force and speed of that roll stand, and means for controlling the screwdown position of that one roll stand of the mill for correcting this determined gauge error.

**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 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 speed correction operation in accordance with the present invention;

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

FIG. 7 shows a graphical illustration of the nonlinear relationship provided for the speed correction 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 51 and 56 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 unloaded 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 guide during threading, for flatness or other strip shape control purposes or possibly for other 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 detection 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 sidguards 37 are located at predetermined points along the mill length. The sidguards 37 are operated during mill setup on the basis of the widths 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 Prodec 2,000 (P2,000) sold by Westinghouse Electric Corporation. A descriptive book entitled Prodec 2,000 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 patent application S.N. 215,743 the logic flow chart of an illustrative automatic gauge control suitable
for operation in conjunction with the speed 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 delivering 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 41 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 the 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 are shown to illustrate the application of Hooke's law to a rolling mill stand and to illustrate the basis upon which the AGC 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 this 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 $H_2$ 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 intersects 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 $H_p$ equals the unloaded roll opening as defined by the screwdown position SDREF plus the mill stretch ($F*K$) caused by the workpiece. If the screwdown 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 $H_p$ 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 linear although a small amount of nonlinearity would normally exist.

Desired workpiece delivery gauge $H_p$ is produced since the amount of force $F$ required to reduce the workpiece from $H_e$ to $H_p$ is equal to the amount of roll separating force required to stretch the rolls to a loaded roll opening $H_p$, i.e., the intersection of the mill spring curve 100 at an initial screwdown opening SDREF indicated by mill spring curve 100 and the workpiece reduction curve 102 lies at the desired gauge value $H_p$.

As shown in FIG. 3, if the actual stand present gauge $H_x$ is not the same as the desired gauge $H_p$, 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 $H_p$ being delivered from the roll stand and the gauge error $GE$ is now removed.

It is known in accordance with the teachings of referenced U.S. Pat. No. 3,561,237 that the required corrective screwdown adjustment $\Delta SD$ 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 stand and the mill spring modulus $K$ for that stand and one, as follows in relation to stand $N$:

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

(6)

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 as indicated in FIG. 2. Thusly, the above equation (7) will be rewritten and utilized in accordance with the relationship

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

(7)

The total stand $N$ gauge error $GE(N)$ that it is desired to be corrected by screwdown adjustment at stand $N$ is equal to the roll force system determined gauge error at stand $N$ as modified by the speed correction $SC(N)$ for stand $N$ that is determined at stand $N$ by the following relationship:

$$\text{Speed Correction for stand } (N) = \text{function of Speed of stand } (N)$$

$$SC(N) = [S(N) - \text{LOS}(N)\text{LOS}(N)]* CF(N)$$

(8)

The speed correction $SC(N)$ is a non-linear adjustment to the measured roll force $F(N)$, in which the adjustment becomes greater as the change in speed $S(N)$ from the lock on speed LOS(N) becomes greater. For one particular actual application of the present invention, the lock on speed LOS(N) was substantially the operational thread speed of the rolling mill stand $N$ and the normal run speed was approximately twice the thread speed. The quantity $S(N) - \text{LOS}(N)\text{LOS}(N)$ in increased in value from zero when the speed $S(N)$ was equal to the lock on speed LOS(N) to one when the speed $S(N)$ was twice the lock on speed LOS(N). The correction factor $CF(N)$ for stand $N$ is a multiplier provided to convert the speed correction into units of tons, and may typically have a value between 200 and 400 metric tons depending upon the rolling mill involved.

The stand $N$ exit gauge error determined by the roll force system at stand $N$ is established by the relationship of above equation (5) as follows:

$$GE(N) = \text{SD}(N) - \text{LOS}(N) + [F(N) - \text{LOF}(N)] * K(N)$$

(10)

The above equation (10) calculates the exit gauge error of the workpiece strip leaving each individual stand in relation to the roll force and screw position conditions measured for that stand.

In reference to FIG. 4, in general the workpiece strip gauge error delivered by a given stand, and as determined by the sensed operational variables at that same stand, is in accordance with the roll force system relationship shown in above equation (10).

The normal 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 SD(N) and the initial lock on 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 F(N) and the initial lock on roll force LOF(N).

For rolling mills which accelerate at a high rate, the gauge error determined by above equation (10) does not account for the effect of changes in speed. To correct this inaccuracy, the AGC gauge error equation is modified to contain a term that is a function of the stand rolling speed, as follows:

$$GE(N) = [\text{SD}(N) - \text{LOS}(N)] + [F(N) - \text{LOF}(N) - SC(N)]* K(N)$$

(11)

where the speed correction $SC(N)$ is determined by above equation (9). The screwdown correction needed at stand $N$ for correcting both the normal exit gauge error measured...
at stand (N) and the speed correction portion of the gauge error is determined by above equation (7).

DESCRIPTION OF EMBODIMENT OF PRESENT INVENTION

In reference to FIG. 5, there is shown a portion of a tandem rolling mill including a roll stand (N), with the workpiece strip 15 moving in the direction indicated by the arrow. At block 400 there is determined the speed correction SC(N) in relation to the operational speed S(N) and lock on speed LOS(N) sensed at stand (N). This determination utilizes above equation (9) for this purpose. The speed correction SC(N) is shown in FIG. 7 plotted as a function of the quantity

\[ S(N) = \frac{LOS(N)}{LOS(N)} \]

to illustrate one suitable memory storage operation such that the desired nonlinear adjustment of the gauge error is thereby provided. If desired, a well known function generator could be provided for this purpose. At block 402 there is determined the stand (N) gauge error GE(N) and this utilizes above equation (11) for this purpose. At block 404 there is determined the screwdown position correction for stand (N) in relation to the operational variables sensed at stand (N), and this determination utilizes above equation (7) for this purpose.

In reference to the flowchart shown in FIG. 6, the speed correction SC(N) in the equation (11) is first determined. At step 500 there is a calculation of the change in speed from lock on speed LOS(N), with these values being provided by a digital hardware system that is directly readable by the computer. The computer here reads the present speed S(N) of stand (N) and compares it with the initial lock-on speed LOS(N) for the present workpiece strip. At step 502 there is calculated the percentage change in the speed from the lock-on speed, relative to the lock-on speed being 100 percent. It is determined if this percentage is negative at step 504 to see if stand (N) has slowed down below lock-on speed. If it is negative it is not desired to use this percentage, so at step 506 the percentage is made equal to zero. If it is not negative, at step 508 the percentage is used as an index for the look up of the desired speed correction at step 510. The percentage change in relation to speed lock-on is linearly related or proportional to the speed itself. The speed correction needed here for the control of the process operation is the nature of a nonlinear exponential, so a look up table having about 5 or 6 indices can be provided and it can be indexed by the linear speed percentage. The typical value for the percentage used as an index would be in the order of 10 percent, 20 percent, 30 percent, 40 percent and 50 percent, with the speed correction determined in this manner having a value between 0 correction to 400 correction maximum, which value is in tons metric. The next operation at step 512 is to calculate the change in force F(N) between the present stand N roll force and the initial lock-on force LOF(N). Then at step 514 the speed correction SC(N) is subtracted as a direct correction to this roll force difference. The speed correction SC(N) is utilized as a correction to the force which is related to the speed. In other words, the force reading is a function of speed and the look up operation provides the desired relationship between the force reading correction and the speed S(N).

For example, a typical minimum speed or speed lock-on LOS(N) for the last stand would be 400 meters per minute; the typical maximum speed is about 800 meters per minute, and the minimum desired speed correction is 0 tons and the maximum desired correction is 400 tons. In effect a speed compensation for gauge control is provided in terms of roll force correction as a predetermined relationship to stand speed, since some variable has changed in the gauge control operation. The above gauge error equation (5) becomes somewhat inaccurate when a stand speed changes. In practical operation of the gauge control system, the gauge can be proper at one speed but upon a change in the speed at the same roll force and that same screw setting, the delivery gauge will change leaving stand N. In terms of broad function the BISR A gauge error equation is affected by speed. In effect a force difference is established and then a speed correction is subtracted from that force difference, with the speed correction being in units of tons; if this speed correction was found by look up to be 400 tons and the value of K was 1.4 millimeters per Kiloton, then the resulting change in screw position would be 0.56 millimeters.

At step 516, the adjusted force is multiplied by the mill spring constant. At step 518 the change in screw position is subtracted. At step 520 the determined gauge error GE(N) is stored in memory. The adjusted force is the quantity equal to the present measured force F(N) minus the lock-on roll force LOF(N) minus the speed correction SC(N) for stand N. It should be understood that the here described calculation is made in succession for each stand of the rolling mill.

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.

GENERAL DESCRIPTION OF INSTRUCTION PROGRAM LISTING

Reference is here made to an instruction program listing disclosed in above related application Ser. No. 303,726 and 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 P2,000 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 flow charts 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 operative to reduce the gauge of a workpiece passed through said roll stand, said system comprising:
   means for determining the delivery gauge error of said workpiece leaving said one roll stand of said rolling mill in accordance with the measured roll force of said one roll stand and a predetermined correction to said measured roll force, said predetermined correction being established in magnitude as a function of a change in speed of said one roll stand,
   means operative in relation to said delivery gauge error for determining a required adjustment in the operation of said one roll stand to remove said gauge error, and
   means for adjusting said one roll stand in accordance with said required adjustment.

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

   \[ SC(N) = (S(N) - LOS(N)/LOS(N)) \times CF \]

   where \( SC(N) \) is the predetermined correction, \( S(N) \) is the present speed of said one roll stand, \( LOS(N) \) is the initial speed of said one roll stand, and \( CF \) is a predetermined multiplier factor to convert said correction into desired units.

3. A gauge control system for a rolling mill having at least one roll stand operative with an initial operator provided roll opening setting to reduce the gauge of a workpiece passed through said rolling mill, said system comprising:
   means for determining the delivery gauge error of the workpiece leaving said one roll stand in accordance with a predetermined relationship including the measured roll force of that one roll stand and a speed correction to said measured roll force and established as a function of the change in speed of said one roll stand,
   means for determining a correction for adjusting the roll opening setting of at least said one roll stand for the passage of said workpiece in accordance with a predetermined relationship between said delivery gauge error of said workpiece, 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 roll opening of said one roll stand for the passage of said workpiece in accordance with said correction.

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

   \[ GE(N) = (SD(N) - LOSD(N)) + F(N) - LOF(N) - SC(N) \times K(N) \]

   where \( GE(N) \) is the delivery gauge error for said one roll stand,
   where \( SD(N) \) is the present screwdown position to determine the present roll opening of said one roll stand,
   where \( LOSD(N) \) is the initial screwdown position to determine the initial roll opening of said one roll stand,
   where \( F(N) \) is the present roll force of said one roll stand,
   where \( LOF(N) \) is the initial roll force of said one roll stand,
   where \( SC(N) \) is the speed correction, and
   where \( K(N) \) is the mill spring modulus of said one roll stand.

5. The gauge control system of claim 4, with the speed correction \( SC(N) \) being established as follows:

   \[ SC(N) = (S(N) - LOS(N)/LOS(N)) \times CF \]

   where \( S(N) \) is the present speed of said one roll stand,
   where \( LOS(N) \) is the initial speed of said one roll stand, and
   where \( CF \) is a predetermined multiplier factor to convert said correction into desired units.

6. The gauge control system of claim 4, with \( SC(N) \) being a predetermined non-linear speed correction related to the magnitude of the change in speed of said one roll stand,

7. A method of controlling the workpiece gauge leaving a rolling mill having at least one roll stand operative with an initial operator provided roll opening setting to reduce the gauge of a workpiece passed through said rolling mill, the steps of said method comprising:
   determining the delivery gauge error of said workpiece leaving said one roll stand in accordance with the measured roll force of that one roll stand and a speed correction to the measured roll force established in magnitude as a function of a change in the speed of said one roll stand,
   determining a roll opening adjustment for application to said one roll stand during the passage of said workpiece in accordance with a predetermined relationship with said gauge error of said workpiece, 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 adjustment.

8. The method of claim 7, with said speed correction being related to the change in speed of said one roll stand established by a comparison of the present speed and the initial speed of said one roll stand.

9. The method of claim 7, with said predetermined relationship being as follows:
where $GE(N)$ is the delivery gauge error leaving said one roll stand,
where $SD(N)$ is the present screwdown position of said one roll stand,
where $LOS(D)$ is the initial screwdown position of said one roll stand,

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

where $F(N)$ is the present roll force of said one roll stand,
where $LOF(N)$ is the initial roll force of said one roll stand,
where $SC(N)$ is the speed correction for said one roll stand, and
where $K(N)$ is the mill spring modulus of said one roll stand.