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3,312,092 4/1967 Neumann 72/13
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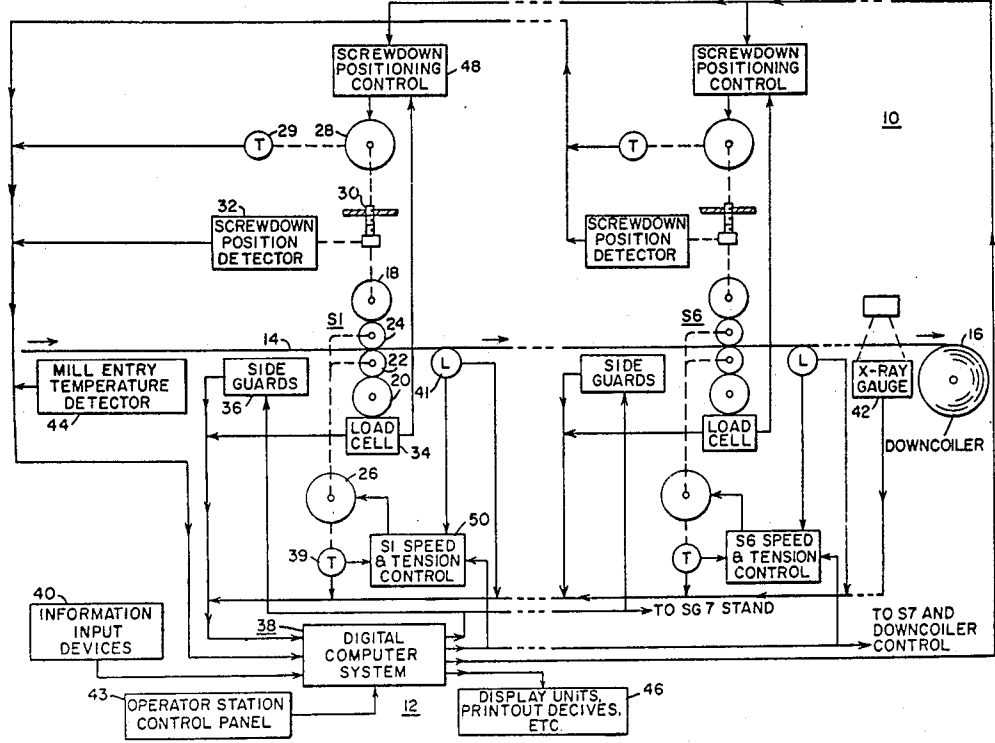
[54] PREDICTIVE GAUGE CONTROL METHOD AND APPARATUS WITH ADAPTIVE PLASTICITY DETERMINATION FOR METAL ROLLING MILLS
12 Claims, 4 Drawing Figs.

[52] U.S. Cl. 72/8, 72/16, 72/21
[51] Int. Cl. B21b 37/12
[50] Field of Search. 72/7, 8, 10, 11, 16

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ABSTRACT: A programmed computer control system provides on line predictive roll force gauge control and screwdown offset gauge control for a tandem hot steel strip mill. A gauge control program calculates corrective screwdown movement including that predictively required at each gauge controlled stand for optimum or near optimum gain correction of roll force error on the basis of on line detected roll force and screwdown position values at that stand and on the basis of a mill spring constant which is predetermined for that stand and a determined workpiece plasticity value for that stand.

The workpiece plasticity values in determining the screwdown control action at each stand are adaptively modified during the workpiece rolling period on the basis of in process measurements of roll force and screwdown position at that stand. The control system operates the mill screwdowns in accordance with the program calculations made from the updated plasticity values.



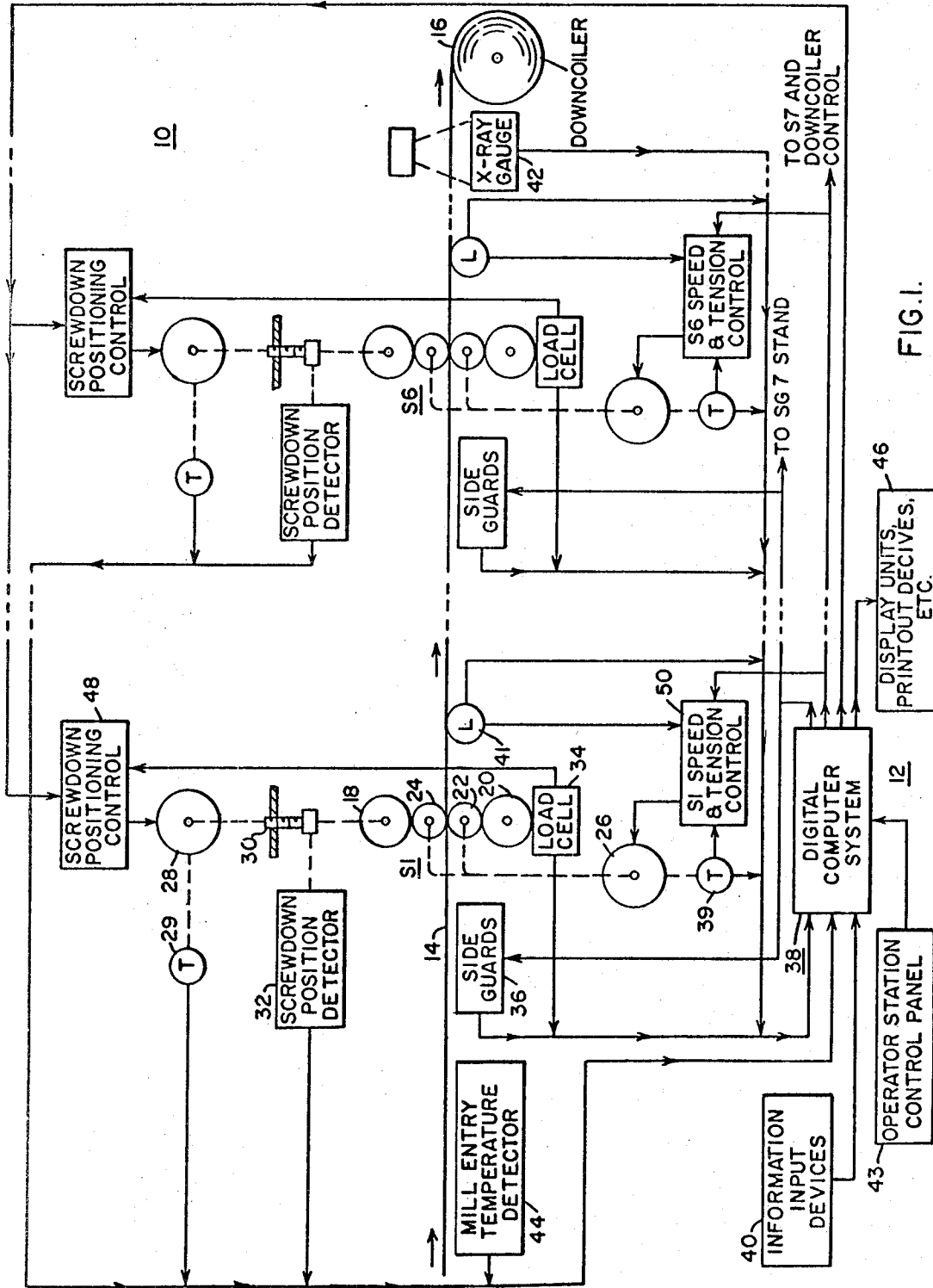


FIG. 1.

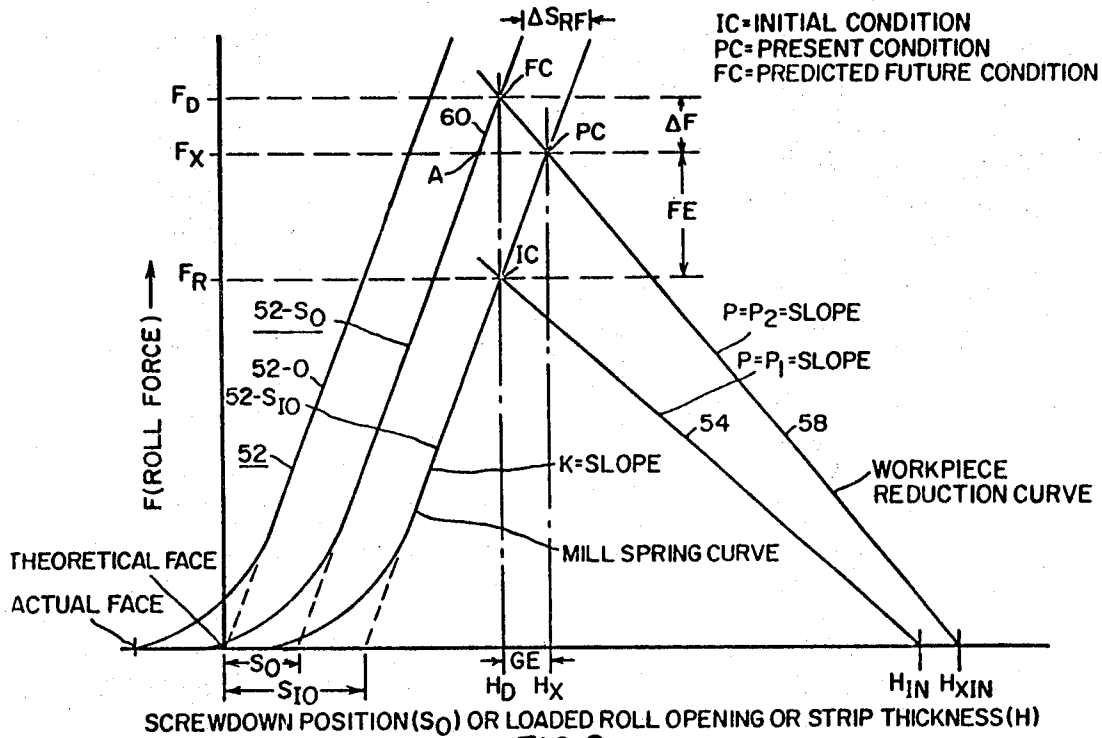


FIG. 2.

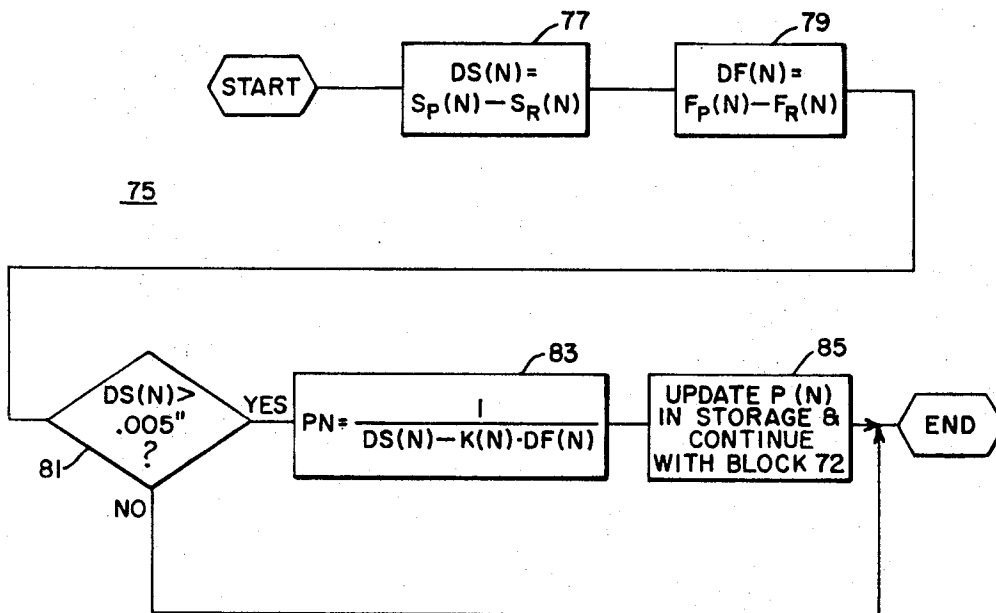


FIG. 3

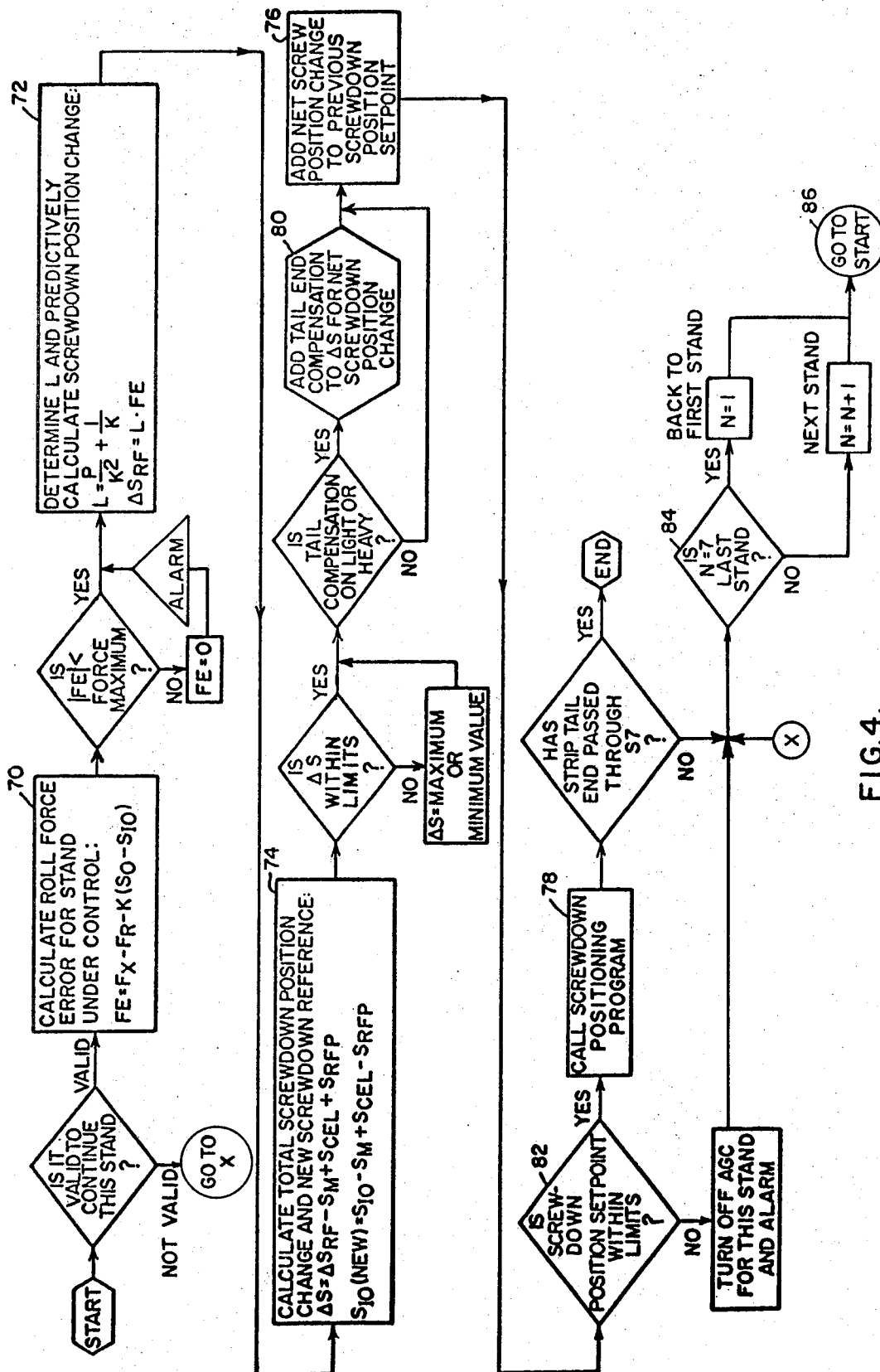


FIG. 4.

PREDICTIVE GAUGE CONTROL METHOD AND APPARATUS WITH ADAPTIVE PLASTICITY DETERMINATION FOR METAL ROLLING MILLS

CROSS-REFERENCE TO RELATED APPLICATIONS

Reference is made to the following copending applications; Ser. No. 686,783 entitled Predictive Gauge Control Method And Apparatus For Metal Rolling Mills and filed by C. W. Eggers and K. E. Csonka for J. C. Csonka on Nov. 29, 1967. Ser. No. 702,713 entitled Predictive Gauge Control Method And Apparatus With Automatic Plasticity Determination For Metal Rolling Mills and filed by A. W. Smith, Jr. on Feb. 2, 1968.

BACKGROUND OF THE INVENTION

The present invention relates to metal rolling mills and more particularly to roll force gauge control systems and methods used in operating such 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 or for each reversing mill pass are set up by the operator or by a computer 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 on the basis of the usually justifiable assumption that there is little or no elastic workpiece recovery.

Since the setup conditions 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 gauge control system must be 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.

More particularly, 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 U.S. Pat. No. 2,726,541, issued Dec. 13, 1955 to R. B. Sims describe the theory upon which operation of the roll force system is based.

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 (screwdown position) plus the mill spring stretch caused by 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 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. The following formula expresses the basic relationship:

$$\text{Equation (1)} \quad h = S_o + \frac{F}{K}$$

where:

h =loaded roll opening (output workpiece thickness)

S_o =unloaded roll opening (screwdown position)

K =mill spring constant

F =roll separating force.

The roll force gauge control system is often 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:

$$\text{Equation (2)} \quad \frac{\Delta}{i} S = \frac{-\Delta F}{K}$$

where:

ΔF =measured change in roll force from a force reference

ΔS =controlled change in screwdown position from a screwdown reference.

After the unloaded roll opening setup and the stand speed setup are determined by the mill operator or the mill computer 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.

Since the roll force gauge control system functions without sensing actual stand delivery gauge, screwdown offset is required for the roll force gauge controlled screwdowns during rolling operation to correct steady state mill delivery gauge errors which stem from various causes. By screwdown offset, it is herein meant to refer to a change in screwdown position made to correct a gauge error which is caused or expected to be caused by a single mill variable or by a combination of mill variables and which is uncorrectable or inadequately correctable by internal roll force gauge control operation alone. By steady state gauge error, it is meant to refer to an error which is correctable by screwdown offset.

There are various causes involved in steady state gauge error. These include incorrect setup, screwdown calibration drift, a changed mill spring constant, strip temperature rundown, and mill acceleration and deceleration.

To provide steady state gauge error correction, the well-known monitor gauge control system is usually employed to produce screwdown offset for the roll force controls. In the monitor system, an X-ray or other radiation gauge is placed at one or more predetermined process points and usually at least at a process point following the delivery end 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 gauge and adjusts 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. More detailed consideration of the causes and correction of steady state gauge error in mills employing roll force stand gauge control is set forth in the aforementioned Csonka and Eggers application.

Experience with conventional roll force gauge control systems has demonstrated that the achievement of fast and accurate mill delivery gauge control with stability is a complicated and often very difficult task under the wide variety of rolling conditions and types and sizes of workpieces or strips encountered in metal rolling mills. It is particularly desirable that stand gauge control be performed fast since even a relatively short response time period can result in a substantial length of off gauge although not necessarily rejectable gauge work product at high delivery speed. Thus, particularly in tandem hot strip mills, strip delivery gauge accuracy is affected materially by the speed and the stability of stand gauge control because these factors determine the length of strip over which a gauge error persists. Delivery and stand gauge accuracies of course also depend on factors such as transport delay, accuracy of sensors, etc.

The roll force gauge control response speed depends principally on the system gain of the roll force gauge control, i.e. the rate of controlled screwdown movement per unit of detected roll force error (or other input error such as monitor error feedback). Since stand delivery gauge is determined by the intersection point of the mill spring curve (roll force versus roll opening) with the workpiece deformation curve (yield force versus thickness reduction), the total amount of screwdown movement required to correct a roll force error (or other detected error) depends primarily on the mill spring constant and the workpiece plasticity. The workpiece plasticity and the mill elasticity thus affect the rate at which corrective control actions should be applied, i.e. the system gain.

In conventional mill operation involving analog type roll force gauge control, an attempt is made to set the roll force gauge control system gain on the basis of a predetermined mill spring constant and the expected workpiece plasticity in order to produce corrective screwdown movement along the fastest nonovershoot screwdown position versus time curve. For convenience of description, the term workpiece plasticity is herein intended to refer to the magnitude of the slope of the roll force versus workpiece deformation (reduction) curve. On the basis of this definition, the width of the workpiece affects the workpiece plasticity since the roll force required for a particular reduction depends on the workpiece width.

If the system gain is tuned to a value which is too small, the control produces very stable overdamped screwdown operation with excessive correction time. On the other hand, if the system gain is tuned to a value too large, underdamped overcorrections or hunting can result and in some cases unstable screw runaway can occur.

Optimum or 100 percent gain tuning requires critical system damping and it produces the fastest stable nonovershoot screwdown response that the conventional analog type roll force gauge control system is capable of providing. However, in analog roll force control practice a 100 percent gain tuning condition has been difficult to achieve particularly on a continuous operating basis, and in many cases mill operators conservatively undertune the analog type control at about 90 percent in order to avoid the development of overtuning conditions caused by changes in mill parameters which affect the tuning condition. For example, changes in workpiece plasticity caused by factors such as skid marks or temperature rundown typically produce tuning changes within a band as great as ± 10 percent or more about the preset tuning condition corresponding to the preset system gain of the roll force gauge control system.

Some improvement in tandem mill delivery gauge control has been realized by subjecting the screwdown control of one or more slave stands to roll force control from an earlier master stand. However, the slave-type control is more or less limited to certain conditions such as skid marks under which effective improvement in gain tuning is provided. There has also been some effort made to improve gain tuning by placing the roll force system gain under limited monitor feedback control, but this approach involves the inherent monitor limitation of transport delay.

As already indicated, the principal mill parameters considered in tuning the gain are the mill spring constant and the workpiece plasticity. According, changes in these parameters are typically involved in gain tuning variations which occur during conventional roll force gauge controlled rolling mill operation with adverse effect on stand gauge control speed and accuracy and in some cases with adverse effect on stand gauge control stability.

The mill spring curve has typically and usually justifiably been treated as having a constant and uniform linear slope and is therefore commonly referred to as a spring line. Actually, at lower force levels which typically have been encountered infrequently in mill use the spring curve is nonlinear and the spring constant accordingly varies over the nonlinear portion of the curve. Without reflection of operating changes in the mill spring constant in the operation of the roll force gauge control particularly in the newer tandem hot strip mills which are designed to operate over wider roll force ranges to accommodate a greater range of strip widths, the gain tuning condition and in turn stand gauge control speed and accuracy are adversely affected.

It is also significant that the spring constant corresponding to the slope of the linear part of the spring curve in subject to change during mill operation. On the basis of present knowledge, the slope of the linear portion of the spring curve can be changed (perhaps as much as ± 10 percent) by individual changes or combinations of changes in certain mill parameters including the backup roll diameter and the workpiece width. Since the workpiece width and the backup roll

diameter values are known or detected at the beginning of a workpiece pass and normally would not change during the pass, they would normally not cause in process changes in the mill spring constant. However, without reflection of changes in the slope of the linear part of the mill spring curve possibly caused by other variables during operation of the roll force gauge control, gain tuning and stand gauge control speed and accuracy are adversely affected as in the case of uncorrected operation over the nonlinear portion of the mill spring curve. Changes in the mill spring constant can also directly cause steady state gauge error which can be corrected by screwdown offset as previously described.

In some cases, the mill may be under computer or operator setup control to reflect changes in the spring constant through the stand screwdown position setup value from setup calculation to setup calculation. However, this scheme has little or no bearing on the capability of the roll force gauge control to reflect in process changes in the spring constant in on line gauge control operation.

Workpiece plasticity variations probably constitute the most significant on line source of changes in the gain tuning condition. During conventional computer or operator controlled mill setup for each workpiece pass, the workpiece deformation curve is estimated for a particular workpiece through a particular stand and a fixed value or setting is then determined for the stand gain. Thus, at best, conventional mill setup operation involves only generalized adjustment for workpiece plasticity variations. Typically, no use is made of the previously noted monitor feedback scheme for analog roll force system gain adjustment and instead a "hardness" dial or the like is made available at each roll force gauge controlled stand in order to provide for operator adjustment of roll force gauge control system gain in the gain tuning setup procedure. The gain is set at a value which gives the analog system tuning condition desired, usually a conservative tuning condition of about 90 percent or so to allow for gain tuning variations as previously described. Without in process reflection of plasticity changes from the estimated workpiece plasticity in the operation of the roll force gauge control, gain tuning and stand gauge control speed and accuracy are adversely affected.

Various mill parameters can cause the workpiece plasticity to differ from the estimated value. More particularly, the slope of the deformation curve, i.e. the plasticity, depends on workpiece width as previously indicated and, further, it depends on workpiece thickness and temperature.

The type of material from which the workpiece is formed is also a basic determinant of workpiece plasticity and slight variations in material makeup can thus cause differences in the estimated and actual plasticity values. Similarly, the stand speed can affect the gain tuning condition and gauge control speed gauge and accuracy either independently or intermediately through the workpiece plasticity characteristic by causing plasticity variation, i.e. because the workpiece yield stress is a function of the strain rate (roll biting rate as determined by roll speed).

Insofar as the plasticity variable is concerned, the gain tuning condition changes with workpiece plasticity changes from workpiece to workpiece as well as along the length of a particular workpiece. For example, in a hot steel strip mill, the strip typically has the previously considered short longitudinally spaced portions called skid marks which cause gain tuning changes because they are cooler and harder than the rest of the strip. As another example, the roll force gauge control system gain at a late stand typically must have a value greater than that at an early stand to provide equal or nearly equal gain tuning conditions at the two stands since a later stand typically operates on substantially thinner harder material having a steeper deformation slope and thus requires as much as eight to ten times more screwdown movement than an early stand to correct a unit gauge error in the same workpiece material.

As an illustration of the effects of a changing mill spring constant or changing workpiece plasticity on the gain turning condition, assume that under one rolling condition the spring constant or the workpiece plasticity has one value and under a second rolling condition it has a second value as developed during an uninterrupted rolling operation without any change in the analog type roll force gauge control system gain. The control system gain setting may produce 100 percent turning under the first condition and could well produce only 90 percent tuning under the second condition. Thus, overall gauge control performance is diminished as a result of the occurrence of the second condition. Although some previous mills have involved the use of a workpiece width signal in providing analogue system gain compensation for changes in the mill spring constant and the workpiece plasticity caused by workpiece width changes from workpiece to workpiece, such compensation does not affect the gauge control performance when other parameters such as the roll force operating range or the workpiece temperature cause changes in the gain tuning condition.

If the analog or any other type roll force gauge control is too slow to correct a transient gauge error caused by any one or more causal variables, that error will persist to the delivery end of the mill unless it is corrected by an intervening rolling operation. Since the conventional monitor system cannot correct a delivered transient gauge error, it is particularly desirable that stand gauge control be fast for fast and accurate transient gauge error correction. However, conventional analog type controls have been limited in this respect by the described limitations on gain tuning adaptability which is required for faster and more accurate gauge control.

Although the conventional monitor system cannot correct delivered transient gauge errors, it does ultimately correct with transport delay unanticipated steady state gauge errors which are caused to accumulate at the delivery end of the mill by screwdown calibration changes and other causes. However, in addition to being limited in transient gauge control speed and accuracy per se, conventional gauge control schemes have been limited in performance by excessive requirements for transport delayed monitor corrections of steady state gauge errors that might otherwise be corrected without transport delay by improved on line roll force gauge control operation.

As summarized in the aforementioned Eggers and Csonka application, the present state of roll force gauge control metal rolling mill technology encompasses reasonably advanced and commercially developed gauge control concepts which have produced generally adequate performance. However, substantial opportunity has existed for material improvement in gauge control speed, accuracy and stability because the very nature of conventional roll force gauge control systems has limited the extent to which they can be modified to produce further gauge control improvement.

In the Eggers and Csonka application itself, there is described a predictive roll force gauge control which departs from the previous prior art and provides for basic improvement in rolling mill operation. In roll force systems, the improvement generally stems from improved roll force gauge control made possible by predictive feedforward screwdown control. More particularly, the improvement results from better roll force gain tuning control made possible by the use of on line determinations of mill spring constant and workpiece plasticity values.

In specifically implementing the Eggers and Csonka control concept, workpiece plasticity determinations are made on line from computer stored table values. Plasticity determination is thus predictive in nature, and the extent to which improvement is realized by Eggers and Csonka over the previous prior art is limited by the convenience and the accuracy with which predictive plasticity table values can be predetermined and organized for on line use.

In the aforementioned Smith application, there is described an improved computer gauge control system in which work-

piece plasticity determinations are made on line automatically from representations of stand entry and delivery gauge. The automatic plasticity determinations are made periodically during workpiece rolling to produce corrective updating of the plasticity values used in the gauge control action calculations. The automatic plasticity determinations can also be made during only part of a workpiece rolling time period and plasticity values determined from tables or by other means are then used during the rest of the workpiece rolling time period. In any case, better control can thus be realized especially where the exclusive plasticity table approach involves either excessive plasticity data or plasticity prediction difficulty.

Although the previous Smith scheme provides for improved control over the basic Csonka and Eggers improvement, some measure of difficulty is still encountered. Thus, in the previous Smith disclosure, workpiece plasticity is computed from measured stand roll force and stand entry and delivery gauges. For reversing mills, screwdown calibration error is cancelled in the plasticity calculation as indicated in the aforementioned Smith application. However, in tandem mills the screwdown calibration error can differ at one stand as compared to the screwdown calibration at an adjacent stand and accordingly does not cancel out in the plasticity calculations. Thus, good screwdown calibration is continuously required in tandem mills for best application of the earlier Smith scheme. Where such calibration capability is not available or if available but not selected for use, roll force or other stand gauge control accuracy and/or gauge control speed can be adversely affected.

In computing the workpiece plasticity at a particular stand in a tandem mill in accordance with the aforementioned Smith application, the delivery gauge from the next previous stand is used as the upcoming entry gauge, and a transport delay is applied to defer using the entry gauge result in the plasticity calculation until the portion of the workpiece corresponding to the prior stand delivery gauge calculation has advanced to the stand at which the plasticity is being calculated. Dependence on entry gauge transport delay can introduce error into the plasticity calculations because of delay time error particularly during periods of mill speed change. Even with consistently accurate transport delay calculations, the required associated computer capacity may not be desired by the tandem mill owner and some other and perhaps simpler yet accurate plasticity calculation scheme would then be required. Further, where roll force and screwdown position are used in trigonometric equations to compute stand delivery gauge as in the specifically described embodiment in the aforementioned Smith application, substantial lengths of the mill spring and workpiece deformation curves are involved and any non-linearity in these curves can accordingly introduce undesired error in the plasticity calculations. Gauge control accuracy and/or speed suffers to the extent that transport delay error or curve or other error enters into the plasticity calculations.

SUMMARY OF THE INVENTION

In accordance with the broad principles of the present invention, a system and method for controlling gauge in operating a metal rolling mill employs means for detecting the roll force and means for controlling screwdown position at each of one or more predetermined rolling stands of the mill. Means are also provided for determining the total amount of screwdown movement (position change) predictively required to correct an error condition representing gauge error at predetermined mill spring constant and workpiece plasticity values. The screwdown position controlling means positions the screwdowns with a system gain and a position-time profile dependent on the amount of predictively defined screwdown movement.

A digital computer system is preferably employed to make the screwdown movement predictions as well as to perform other mill control functions. The computer employs a programming system including a gauge control program which is executed at predetermined intervals to calculate the total pre-

dicted screwdow movement required at each gauge controlled stand for gauge correction including that stemming from the detected error condition at that stand. Screwdow movement for correcting the condition is made at each controlled stand on the basis of calculations which use a predetermined mill spring constant and an automatically determined workpiece plasticity value for that stand. Plasticity is automatically determined from roll force and screwdow position measurements at the controlled stand thereby enabling greater accuracy and/or convenience in workpiece plasticity prediction and, particularly in roll force stand gauge controls, improved control over gain tuning. In turn, better gauge control performance and improved mill operation are realized in reversing mills and especially in tandem mills.

It is therefore an object of the invention to provide a novel gauge control system and method for operating a metal rolling mill to produce work product with improved gauge uniformity and with improved productivity.

It is another object of the invention to provide a novel gauge control system and method for operating a metal rolling mill with improved roll force gauge control speed, accuracy and stability.

An additional object of the invention is to provide a novel roll force gauge control system and method for operating a metal rolling mill with improved transient and steady state gauge control.

Another object of the invention is to provide a novel roll force gauge control system and method for operating a metal rolling mill with improved gauge control capability which makes use of more accurately and/or more conveniently determined workpiece plasticity values.

It is an additional object of the invention to provide a novel roll force gauge control system and method for operating a metal rolling mill with improved on line control of stand gain tuning.

Another object of the invention is to provide a novel roll force gauge control system and method for operating a tandem metal rolling mill with improved predictive on line gauge control for which workpiece plasticity values are automatically determined from on line process measurements without need for transport delay calculations.

These and other objections of the invention will become more apparent upon consideration of the following detailed description along with the attached drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

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

FIG. 2 illustrates a mill spring curve and a workpiece reduction curve and the manner in which roll force screwdow correction is determined from these curves;

FIG. 3 shows a portion of an automatic gauge control program employed in the control computer to determine workpiece plasticity; and

FIG. 4 shows another portion of the automatic gauge control program employed with the program portion shown in FIG. 3 to predict corrective screwdow movement values.

DESCRIPTION OF THE PREFERRED EMBODIMENT

More specifically, there is shown in FIG. 1 a tandem hot strip steel finishing mill 10 operated with improved gauge control performance by a process control system 12 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. Thus, the invention can be suitably adapted for application in hot steel plate reversing and other rolling mills.

The tandem mill 10 includes a series of reduction rolling stands S1 through S7 with only two of the stands S1 and S6 shown. A workpiece 14 enters the mill 10 at the entry end in

the form of a bar and it is elongated as it is transported through the successive stands S1—S7 to the delivery end of the mill where it is coiled as a strip on a downcoiler 16. The entry bar would be known steel grade and it typically would have a 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 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.

Each stand is conventionally provided with a pair of work rolls 22 and 24 between which the workpiece 14 is passed. A large DC drive motor 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 screwdow motors 28 (only one shown at each stand) position respective screwdowns 30 (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 30 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 other purposes.

A conventional screwdow position detector or encoder 32 provides an electrical representation of screwdow position at each stand. To provide an absolute correspondence between the screwdow position and the unloaded roll opening between the associated work rolls, the screwdow position detection system which includes the screwdow position detector 32 can be calibrated from time to time in the manner previously described.

It is noted that screwdow calibration is to be distinguished from electrical screwdow system calibration which is directed to determining proper electrical representations for screwdow position and roll force. Thus, electrical calibration is obtained when the roll force required to cause a given mill stretch causes an electrical representation which is equal but opposite to the electrical representation obtained from the screwdow position detector 32 when the screwdowns are run to obtain a loaded roll opening change equal to the given mill stretch.

Roll force detection is provided at each of predetermined stands by a conventional load cell 34 which generates an electrical analog signal. At the very least, each roll force controlled stand is provided with a load cell 34 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 employed at each of the seven stands S1—S7.

Conventional motorized sideguards 36 are located at predetermined points along the mill length. The sideguards 36 are operated during mill setup on the basis of the widths of the upcoming workpiece 14 thereby defining the sides of the workpiece travel path for guidance purposes.

The process control system 12 provides automatic control for the operation of the tandem mill 10 as well as preceding production processes (not indicated) such as the operation of a roughing mill. Preferably, the process control system 12 comprises a programmed process control digital computer system 38 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 10. According to user preference, the control system 12 can also include conventional manual and/or automatic analog controls for backup operation in performing preselected mill functions.

The digital computer system 38 can employ a single large capacity central processor and associated input/output equipment, but at the present state of the steel mill control art there is a general user preference for using a separate central processor for each of predetermined basic mill functions. In this manner, the functioning of each central processor and its associated equipment can be made independent of the failure of any other computer processor, and disturbance to the overall mill control is limited to the span of control assigned to the failed computer. Automatic analog control or operator manual control would typically be used in place of the failed computer to provide continuance of control in the span of control associated with the failed computer.

On the basis of these considerations, the digital computer system 38 in the present case includes (1) a large capacity supervisory or setup computer system (not specifically indicated) including a central integrated process control or setup processor with associated input/output equipment (such as that included in the computer system known as the Prodac 250 (P250) and sold by Westinghouse Electric Corporation, (2) a roughing mill computer system (not specifically indicated) including a central processor with associated input/output equipment such as the computer system known as the Prodac 50 (P50) and sold by Westinghouse Electric Corporation, (3) a large capacity finishing mill logic control or director computer (not specifically indicated) such as that in a P250 system and (4) a finishing mill on line roll force gauge control computer such as a P50. The P250 large capacity processor typically uses an integral magnetic core 16,000 word (16 bit plus parity) memory with 900 nanosecond cycle time, and external magnetic core 12,000 word or more (16 bit plus parity) memory with 1.1 microsecond cycle time and a mass 375,000 word or more (16 bit plus parity) random access disc memory unit. The P50 processor typically uses an integral magnetic core 12,000 word (14 bit) memory with 4.5 microsecond cycle time.

To provide for process integration, the computers are appropriately tied together through data links or other means. More particularly, the setup computer has its input coupled to information input devices and to various mill sensors while its output is coupled to the other computers in the computer system 38. The finishing mill director computer has its input coupled to predetermined mill sensor devices as well as the setup computer output, and the director computer output is coupled to the input of the gauge control computer as well as to predetermined mill control devices.

The roughing mill computer has its input coupled to the setup computer output and to predetermined roughing mill sensors. Couplings are provided between the gauge control computer input and the setup and director computers and predetermined finishing mill sensors and between the gauge control computer output and predetermined finishing mill control devices.

Each computer processor is associated with predetermined input systems (not specifically indicated), 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 40 such as paper tape, teletypewriter and dial input systems. It is noted that the information input devices 40 are generally indicated by a single block in FIG. 1 although different input devices can and typically would be associated with different computers in the computer system 38. Various kinds of information are entered into computer system 38 through the input devices 40 including, for example, desired strip delivery gauge and temperature, strip entry gauge and width (by entry detectors if

desired), grade of steel being rolled, any selected plasticity tables, hardware oriented programs and control programs for the programming system, etc.

The contact closure input systems and the analog input systems interface the computer system 38 with the processes through the medium of measured or detected variables. The present invention as embodied in the process control system 12 is largely involved in the functioning of the automatic gauge control computer system, hereinafter referred to as the AGC computer. In one typical invention application, various mill signals are applied to the AGC computer input systems. These mill signals include the following:

1. A roll force signal from the load cell 34 at each stand S1—S7 proportional to stand roll separating force for use in predictive feedforward roll force gauge control.

2. Fourteen-bit screwdown position signals generated by the respective detectors 32 at the stands S1—S7 for use in predictive feedforward roll force gauge control.

3. Screwdown motor speed signals generated by respective tachometers 29 at the stands S1—S7 for use in programmed position regulation.

4. Position signals from respective loopers 41 for use in looper tension control.

5. Stand speed signals generated by respective tachometers 41, with the S6 speed signal and/or other stand speed signal used for calculation of acceleration compensation and for calculation of time delays in monitor operation.

6. A gauge deviation signal from an X-ray gauge 42 at the delivery end of the mill for programmed monitor gauge control through the predictive roll force control.

7. An entry temperature signal from a mill entry temperature detector or pyrometer 44; if references are not provided by the setup computer, the mill entry temperature for a first workpiece 14 is stored, and screwdown compensation is made for subsequent workpieces 14 if a temperature difference is detected from the stored value.

8. Width signals supplied by sideguard follow potentiometers for mill spring constant calculations, etc.

It is noted at this point in the description that the measure head end roll force is stored and used as a reference for roll force gauge control functioning at the respective stands if the AGC computer is in the lockon mode of roll force operation. On the other hand, if the AGC computer is in the absolute mode of roll force operation, the setup computer calculates a predicted head end roll force which is used as an absolute reference for roll force gauge control functioning.

Signals from an operator station control panel 43 and miscellaneous process status and interrupt signals coupled to the AGC computer through the contact closure input system include the following:

AGC On Roll Force—for on line gauge control.

AGC On Monitor—for on line gauge control including steady state gauge error correction.

X-Ray Light—enables monitor operation at small loop again.

X-Ray Heavy—enables monitor operation at large loop again.

X-Ray Gauge 1 On—enables monitor operation with gauge 1.

X-Ray Gauge 2 On—enables monitor operation with backup gauge 2.

Light Tail Comp—enables light anticipatory compensation for reduced tension at strip tail end.

Heavy Tail Comp—enables heavy anticipatory compensation for reduced tension at strip tail end.

Light Temp Comp—enables light anticipatory compensation for temperature rundown in accordance with bar entry temperature.

Heavy Temp Comp—same as next preceding, but with heavy anticipatory compensation.

Slow Accel Comp—enables slow or light anticipatory compensation for acceleration.

Fast Accel Comp—enables fast or heavy anticipatory compensation for acceleration.

Hold X-Ray—to lock gauge control system onto current delivery gauge value and ignore desired delivery gauge for remainder of current strip.

AGC On Lock—S(n)—puts roll force control in the lock on reference mode of operation on a stand by stand basis.

AGC On Computer—S(n)—puts roll force control in absolute reference mode of operation on a stand by stand basis and sets up the computer system for use of a predicted roll force reference supplied by the setup computer.

Mill On Computer—on selection, this signal enables the setup computer to be tied into the mill control.

SD On Auto—S(n)—required for functioning of roll force gauge control on stand by stand basis independent of operator selection signal AGC on Roll Force.

Strip In Stand—S(n)—based on load cell outputs, these signals enable the roll force gauge controls to function.

Reset Screws—S(n)—enables the gauge control computer to reset the screwdowns to the preset value plus head end memory plus any manual change at the various stands as the Strip In Stand signals go to zero after passage of the strip tail end—the Reset signals are zero if the operator selects manual preset or if the setup computer is making the mill setup.

Accel Mill—denotes mill is under director computer or manually controlled acceleration and enables acceleration compensation to be made as selected.

Input/Output Equipment Interrupts

ASR Set (Teletypewriter) Interrupts

Strip Anticipate Interrupt—a hot metal detector generates this signal to initiate the AGC program for a pyrometer temperature reading prior to strip entrance to S1.

Calibrate SD Interrupt—S(n)—for converting the relative reading of the screwdown position detector into an absolute screwdown position which is used in the AGC computer for estimation of the mill spring constant and for initial screwdown calibration.

The above station, status and interrupt signal list is not exhaustive and is presented only to illustrate the kind of details involved in applications of the invention. Some of the signals indicated above will be better understood with reference to subsequent portions of the present description.

A contact closure output system would normally be associated with each of preselected computers in the digital computer system 38. In this instance, contact closure output systems are respectively associated with the director computer, the roughing mill computer and the AGC computer. In the operation of the AGC contact closure output system, various control devices are operated in response to control actions calculated or determined by execution of control programs in the AGC computer.

To effect determined control actions, controlled devices are operated directly by means of output system contact closures or by means of analogue signals derived from output system contact closures through a digital to analog converter. The principal control action outputs from the AGC computer contact closure output system include screwdown positioning commands, which are applied to respective screwdown positioning controls 48 in operating the screwdown motors 28 for screw movement, and speed anticipate signals which are applied in the various looper tension control systems to cause a change in drive speed to compensate the force on the strip for a change in thickness being made by a screwdown movement.

Display and printout systems 46 such as numeral display, tape punch, and teletypewriter systems are also associated with the outputs of the digital computer system 38 in order 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 systems are also used to log mill data according to computer log program direction.

An external interrupt unit (not specifically indicated) would also be associated with each computer processor. It signals the associated processor when an input is ready for entry or when an output transfer has been completed. The central processor generally acts on interrupts in accordance with a conventional

executive program which is a part of a programming system for that processor and controls the use of central processor circuitry for periodic or other execution of the control and other programs. In some cases, particular interrupts are acknowledged and operated upon without priority limitations.

It is noteworthy that the interfacing shown in the drawing between the digital computer system 38 and the process are representative of the couplings between the director computer with the mill 10 as well as those between the AGC computer and the mill 10. For example, the initial screwdown position setups at the stands S1—S7 can be effected by the director computer through the AGC computer and its output and through the screwdown positioning controls 48. As another example, the initial speed setups at the stands S1—S7 are effected by the director computer through its own contact closure output system and through speed and tension controls 50 which operate the respective stand drives 26. The setup of the sideguards 36 are similarly controlled by the director computer. As a final illustration, the mill speed profile, i.e. mill acceleration or deceleration and constant mill speed conditions over the operating period of the mill, are also controlled by the director computer through control actions applied directly to the stand drive controls 50.

It is generally further noted that the related parts of the roughing mill and setup computer operations would typically provide for setup and sequencing of roughing mill rolling of known slabs into specified bars as well as control of material handling and other functions connected with entering slabs into the roughing mill and transporting bars for entry into the hot strip finishing mill 10. The setup computer would typically calculate the roughing mill drafting schedule which is used by the roughing mill computer to set up the roughing mill.

The setup computer calculates the mill speed profile and the drafting schedule, the screwdown position, stand speed and strip tension setup values for each finishing mill stands S1—S7. The director computer effects startup and sequencing of the finishing mill drives 26 and other mill equipment as required for the initiation of the rolling operation. The model equations used in the finishing mill setup program would typically provide for updating in order to provide better setups and improved head end gauge results on the basis of the results achieved with the setups for previous workpiece rolling operations. Other finishing mill functions such as mill entry scale breaker operation, spray operation and roll changing would also be controlled by the director computer.

Since the present invention pertains to on line gauge control in the finishing mill 10, more detailed control and computer system description will be so limited. Computer system description will thus be mainly directed to the AGC computer since it functions substantially separately to provide on line gauge control.

Generally, the AGC computer uses Hooke's law to predict the total amount of screwdown movement required at each roll force controlled stand at the calculating point in time for roll force error correction, e.e. for loaded roll opening and stand delivery gauge correction to the desired value. The predictive calculation defines the total change in the unloaded roll opening required to offset a new mill stretch value or other roll force and gauge error causing condition. The predictive corrective screwdown position change value is employed in a screwdown position control program in the AGC computer to define the screwdown motor position-time profile to be followed in making the corrective screwdown movement.

Since the total screwdown movement is defined, screwdown correction can be made with or nearly with an optimal or critical damping screwdown position-time profile depending on the accuracy with which the defined corrective screwdown movement is predicted. On this foundation, the previously indicated Eggers and Csonka control provided more consistent critical stand gain tuning, improved gauge control speed, accuracy and stability at each roll force gauge controlled stand, and improved uniformity of mill delivery gauge and improved

mill productivity. The previously indicated copending Smith patent application provided further improvement and the present invention provides still further improvement on this foundation.

Speedier stand gauge control operation generally results in a reduced need for transport delayed screwdown offset or monitor correction for temperature rundown and other ramp like conditions which might otherwise require screwdown offset. Such conditions tend to cause a persistent "transient" gauge error, or in effect a steady state gauge error, unless counter control action is taken, and controls prior to the previously indicated Eggers and Csonka control had been somewhat inadequate in this respect as already indicated. The controls disclosed in the Eggers and Csonka patent application and the copending Smith application provided substantial improvement and the present invention provides still further improvement in reduction of transport delayed screwdown offset as a result of improved stand gain tuning and faster more accurate roll force gauge control.

The overall on line gauge control system includes the roll force gauge controls of the individual stands and a screwdown offset control system. In turn, the screwdown offset control system preferably includes an X-ray monitor gauge control loop operated in response to the X-ray gauge 42.

At the startup of rolling mill operation, the setup computer generates respective screwdown preset outputs which are coupled as previously indicated to the screwdown positioning controls 48. The screwdown motors 28 are thereby controlled to drive the screwdowns 30 and produce the respective desired unloaded roll openings at the stands S1—S7. At the same time, the setup computer generates stand speed and interstand tension setups which are coupled as previously indicated to the speed and tension controls 50. In accordance with conventional practice, the setup values are based on bar entry data (such as bar width, thickness and temperature), data on desired strip delivery characteristics, programmed drafting rules, updating information from previous workpiece setup results, etc.

The director computer effects the setup conditions and also sequences all devices associated with initiating the rolling operation and threading the strip through the successive stands and onto the downcoiler. After the mill has been operated through the program determined mill speed profile such that the mill has been accelerated and thereafter decelerated to provide strip delivery and coiling on the downcoiler 16, new setup conditions are computed for the upcoming entry bar and the screwdowns 30 are reset, etc., i.e. the process is restarted.

Mill acceleration is useful for increasing productivity and for controlling finishing strip temperatures and product quality. It is noteworthy relative to gain tuning considerations that hot mill acceleration causes reduced strip temperature loss because of reduced heat transfer during the shortened rolling time, and as a consequence smaller strip plasticity changes are experienced particularly at later stands of the accelerated hot tandem mill.

During rolling operation, the on line gauge control system operates the stands S1—S7 to produce strip product having desired gauge and proper shape, i.e. flat with slight crown. On line gauge control is provided by the roll force gauge control loops at the stands S1—S7 and the previously noted screwdown offset gauge control system and its monitor gauge control system.

In the monitor system, the X-ray gauge 42 produces the previously indicated X-ray deviation signal which indicates the difference between actual strip delivery thickness and desired strip delivery thickness. In other cases, it may be desirable to employ an absolute thickness 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 programmed AGC computer system operates on the screwdown position detector and load cell signals from each stand as well

as the X-ray gauge deviation signal to determine the control actions required for producing desired strip delivery gauge. Screwdown motor speed is in this instance also applied to the computer system 38 in order to provide for programmed screwdown positioning control. In effecting control operations, the AGC computer employs an AGC programming system which forms a part of the total programming system for the computer system 38. The AGC programming system includes programs oriented to controlling the AGC computer system hardware and programs oriented to developing the control actions.

In FIG. 2, curves are shown to illustrate the application of Hooke's law to a rolling mill stand and to illustrate the unique basis upon which the process control system 12 and in particular the on line AGC computer gauge control system provides improved gauge control speed, accuracy and stability and other operating benefits. First, there is shown a mill spring curve 52 which defines the separation between a pair of mill stand work rolls as a function of separating force and as a function of screwdown position. The slope of the mill spring curve 52 is the mill spring constant K which is subject to variations as previously described. 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 zero screwdown spring curve location is indicated by the reference character 52-0.

At the correct calibration condition, the indicated theoretical face intersect represents theoretical roll facing and it is for this theoretical condition that the screwdown position is assigned a zero value. Under the correct calibration condition, roll facing actually occurs when the screwdown position is at a slightly negative value because of the nonlinearity of the lower part of the mill spring curve. A definition of the screwdown calibration as being correct for the indicated theoretical condition is, however, convenient and appropriate for mill operation.

When the screwdowns are opened (positive movement) the unloaded roll opening increases as reflected by a change in the graphical location of the mill spring curve as indicated generally at 52-S₀ 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 equals the unloaded roll opening as defined by the screwdown position S₀ plus the mill stretch 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 equals the unloaded roll opening plus the mill stretch plus or minus the calibration drift.

The amount of mill stretch depends on the characteristic reduction curve for the workpiece. As shown in FIG. 2, a reduction curve 54 for a strip of predetermined width represents the amount of force required to reduce the workpiece from a stand entry thickness (height) of H_{IN} . The workpiece plasticity P is the slope of the curve 54, and in this case the curve 54 is shown as being linear although a small amount of nonlinearity would normally exist.

Desired workpiece gauge H_D is the initial condition IC produced in this case since the amount of force required to reduce the workpiece from H_{IN} 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 at an initial screwdown opening S₀ indicated by mill spring curve locations 52-S₀ and the workpiece reduction curve 54 lies at the desired gauge value.

If the stand delivery gauge increases by an error amount GE to H_X during a workpiece pass to produce a present condition PC, in this instance because the workpiece plasticity increases

and because the workpiece entry thickness increases to H_{XIN} as represented by the reduction curve 58, the stand screwdowns must be closed to a value which causes a future correct gauge condition FC . At the condition FC , the intersection of the mill spring curve and the new reduction curve 58 lies at the desired gauge H_D as provided by a spring curve location indicated by the reference character 60 and previously generally referred to by the general reference character 52- S_0 . In other words, corrective screwdown closing causes the unloaded screw opening to be reduced by an amount ΔS_{RF} to a new value which adds with the new mill stretch to equal the desired gauge H_D .

As set forth in the aforementioned Eggers and Csonka application, ΔS_{RF} is predictively calculated to produce feedforward roll force gauge control operation as opposed to conventional feedback roll force gauge control operation. The feedforward operation is based on the following programmed algorithm:

Equation (3)

$$\Delta S_{RF} = \left[\frac{P}{K^2} + \frac{1}{K} \right] \cdot FE$$

$= L \cdot FE =$ required screwdown correction

where:

$$L = \frac{P}{K^2} + \frac{1}{K}$$

$$K = \text{mill spring constant} \left(10^6 \frac{LB}{IN} \right)$$

$$P = \text{workpiece plasticity} \left(10^6 \frac{LB}{IN} \right)$$

Equation (3) is derived with reference to Fig. 2 as follows:

Equation (4) $GE = \frac{FE}{K} =$ gauge error

Equation (5)

$\Delta F = P \cdot GE =$ expected change in roll force resulting from corrective screwdown movement

Equation (6)

$$\Delta S_{RF} = \frac{\Delta F}{K} + \frac{\Delta F}{P} = \Delta F \cdot \left[\frac{1}{K} + \frac{1}{P} \right]$$

Equation (7)

$$\Delta S_{RF} = P \cdot GE \cdot \left[\frac{1}{K} + \frac{1}{P} \right] = \frac{P}{K} \cdot FE \cdot \left[\frac{1}{K} + \frac{1}{P} \right] \\ = \left[\frac{P}{K^2} + \frac{1}{K} \right] \cdot FE$$

In order to calculate the predicted amount of screwdown movement required to correct a roll force error, the force error FE is calculated as follows:

Equation (8) $FE = F_X - F_R K (S_0 - S_{10})$

In providing for the roll force error calculations, Equation (8) defines the difference between the present roll force F_X and the reference roll force F_R (either lock on or absolute as predetermined) and subtracts from that difference the amount of change in roll force caused by screwdown movement made to correct previous roll force error. Thus, the roll force error as calculated at any point in time with the use of Equation (8) properly equals the amount by which the present measured roll force differs from the roll force required for correct gauge at the present screwdown position. For the condition PC shown in FIG. 2, $S_0 = S_{10}$ in Equation (8), but in general S_0 would typically have some value other than S_{10} .

Corrective screwdown movement in the predicted amount produces further roll force change and FE becomes zero if the system behavior corresponds to predictions and if no new roll force error develops during the period of correction. If the system does not behave as predicted, FE does not become zero and in effect a new roll force error FE is generated to the extent that the executed screwdown movement in the predicted amount fails to correct the stand delivery gauge.

It is also noted at this point in the description that the

screwdown reference S_{10} used as a base for determining the force error FE in Equation (8) is updated as follows:

Equation (9) $S_{10}(\text{new}) = S_{10} - S_M + S_{10} S_{RFP}$

where:

$S_M =$ offset produced by X-ray monitor operation

$S_{CEL} =$ screwdown offset produced for anticipatory gauge correction during mill acceleration or deceleration

$S_{RFP} =$ screwdown offset produced for roll force error anticipated by feedforward action.

These quantities will be considered more fully subsequently. By way of explanation, the screwdown reference S_{10} is updated in accordance with Equation (8) as changes occur in S_M and S_{CEL} and S_{RFP} in order to prevent the stand roll force gauge control system from responding to roll force changes caused solely by screwdown movement required by external screwdown offset system control for screwdown calibration, head end gauge error correction in the lock on mode of operation, anticipatory mill speed change compensation, anticipatory roll force error compensation or other gauge error correcting purposes. If monitor, acceleration or roll force profile gauge correction is not employed in the system 12, the corresponding term S_M or S_{CEL} or S_{RFP} is omitted from Equation (9).

In predicting and effecting the total amount of screwdown movement required to correct roll force errors in accordance with Equation (3), the process control system 12 is properly "electrically" calibrated similar to the manner previously defined and it is characterized with a controlled system gain which enables the screwdowns to be operated with critical or near critical damping more consistently than has heretofore been possible under dynamic mill operating conditions. In particular, the AGC computer has the capability of defining substantially critical damping screwdown operation as a function of the amount of corrective screwdown movement predictively required on the basis of automatically determined workpiece plasticity at any particular stand and at any preselected point in time.

One possible limiting factor on reaching critical damping screwdown movement and 100 percent gain tuning on a more or less continuous basis is the accuracy with which the corrective screwdown movement calculations correspond to actual screwdown movements required for correction of gauge errors. In turn, the accuracy of screwdown movement prediction depends on the accuracy of predicting the operative values of K and P . The present invention provides improvement over the Eggers and Csonka disclosure and the prior Smith disclosure in the means and manner by which the quantities P and L are determined for Equation (3) and thereby the accuracy and/or convenience with which corrective screwdown movement is predicted.

Generally the operative value of each stand spring constant K is relatively accurately known. It is first determined by the conventional work roll screwdown test, and it is recalculated prior to each workpiece pass on the basis of the workpiece width and the backup roll diameter. Each resultant spring curve 52 is stored for on line gauge control use.

The form in which the spring constant K is stored can vary. In the present case, the slope of the linear part of the spring curve is stored as a single value. The nonlinear part of the spring curve in this case is estimated by three straight lines of increasing slope with the respective slopes stored as three separate spring constant values which are respectively used when the mill stand is operated in the corresponding force range. As future mill data returns from computer data logging demonstrate presently unknown relationships which may define on line variations of the mill spring constant as a function of certain mill variables, provision can be made for programming on line calculations of the mill spring constant in accordance with such relationships under dynamic mill operating conditions.

In accordance with the present invention, the operative value of the workpiece plasticity P at each stand is automatically and adaptively determined with improved accuracy and/or convenience by means of calculations based on process

measurements at that stand. Specifically, these measurements include the roll force and the screwdow position at the stand for which the plasticity calculation is being made.

More particularly, the following relationship is employed to determine automatically the present workpiece plasticity P at a particular stand N :

Equation (10)

$$P(N) = \frac{1}{\frac{DS(N)}{DF(N)} - \frac{1}{K(N)}}$$

where:

$K(N)$ = mill spring constant for stand N

$DS(N)$ = change in screwdow position from reference position at stand N

$DF(N)$ = change in roll force at stand N resulting from screwdow position change.

The plasticity determinations and the screwdow positioning determinations based thereon are made during AGC program execution as subsequently more fully described. The derivation of Equation (10) is based on the application of trigonometric rules to the work curves of FIG. 2. For example, triangle A , FC , PC can be used to derive $P(N)$ and in that event $DF(N)$ equals F_D minus F_X and $DS(N)$ equals the position difference between PC and A .

To provide coordinated mill delivery gauge control, the computer process control system 12 provides steady state gauge correction by means of the previously described screwdow offset system in this case preferably including the X-ray steady state gauge correcting monitor system as well as an anticipatory acceleration or deceleration correction system and an anticipatory roll force error correction system. To tie these gauge correcting systems into the stand roll force gauge control systems, the following formula is used:

Equation (11) $\Delta S = \Delta S_{RF-M} + S_{ACEL} + S_{RFP}$

If monitor, acceleration or roll force profile gauge correction is not employed in the system 12, the corresponding term S_M or S_{CEL} or S_{RFP} is omitted from Equation (11). Monitor correction is selectively made at each stand for X-ray gauge error which may result from screwdow miscalibration, head end error in the lock on mode if applicable, and other causes, and each correction depends in this instance on whether the delivery error is at or above some minimum value characteristic to that stand and further on a preestablished control relationship characteristic to that stand.

The acceleration or deceleration correction made at each stand is in this instance related in a fixed program relationship to the amount of mil acceleration and deceleration scheduled by the director computer mill speed profile program for strip delivery temperature or productivity control. The timing of the correction in relation to the timing of mill speed changes is appropriately programmed. With anticipatory acceleration and deceleration correction, monitor system operation is reduced.

Anticipatory roll force error correction is provided at predetermined stands on the basis of the measured roll force history at one or more preceding stands. The correction made at any stand provided with the roll force profile feedforward feature is determined by AGC programming based on calculated transport delays and on the magnitude of the force error(s) in the feedforward profile(s). The main advantage of the anticipatory roll force error correcting system is that screwdowns at a subsequent stand can be started moving to meet an upcoming roll force error which is expected as a result of previous stand experience. Thus, faster roll force gauge control response is produced and better gauge control capability results especially with respect to skid marks and the like since conventional growback is reduced or eliminated. To some extent, transport delayed screwdow offset or monitor system operation can be reduced by roll force error profile feedforward action because faster roll force gauge control response is enabled for temperature rundown and other ramp like conditions as previously described.

In the AGC programming system, the hardware oriented programs include conventional analog scan and contact input status scan programs and a priority executive program. The analog scan rate can for example be 30 points per second and the complete scan of input contacts can for example be already about every 0.2 seconds.

The priority executive in the present case has two levels of operation, the dominant level and the secondary level but only the secondary level is employed. Each of these two levels can have a number of sublevels. In addition, as already noted, some interrupt routines run outside the priority structure.

The secondary level is provided with fifteen sublevels, and each of the sublevels can be in any of five states:

1. Bidding
2. Running
3. Time delay
4. Suspended
5. Turned off

When a program is running on a secondary sublevel, it cannot be interrupted by another secondary sublevel program, although it can be interrupted by an interrupt routine or by the dominant level (not used in this case). When a sublevel program goes into a time delay or suspension or turnoff, the priority executive searches for the highest priority sublevel which is bidding and places it in the running state. In one application of the invention, the following secondary sublevel control oriented programs were defined for the AGC programming system:

15. Screwdow Positioning Control Program
14. Screwdow Positioning Start-Stop
13. Input-Output Decode—for translation to and from machine language.
12. AGC Control Program
11. Periodic Level—various programs directed to miscellaneous housekeeping functions.
10. Display and Zero Error—for operator displays and indications.
9. (Not Used)
8. AGC Entry Panel Program—for engineering and maintenance adjustments to the system.
7. Programmers Console—for programmer entry or changes to data and programs.
6. AGC Initialization—run at the start of each strip to set buffers and flags and calculate K and other parameters which are a function of strip width and other entry characteristics.
5. (Not Used)
4. Screwdow Position Detector Calibration
3. Ex Post Facto Log—for diagnostic printout.
2. Screwdow Slowdown Profile Determination
1. Diagnostic And Alarm Messages.

The AGC program includes an anticipatory roll force error profile subprogram, a screwdow offset subprogram and an anticipatory mill acceleration-deceleration subprogram. The screwdow positioning control program functions in response to a screwdow position setpoint called for by the AGC program.

Generally, the screwdow offset subprogram in this case is nominally executed about every 0.2 seconds after every X-ray gauge reading. It performs functions including the following:

1. Check selector switches and permissives.
2. Check X-ray deviation against limits.
3. Calculate monitor control action S_M for each monitor controlled stand.
4. Maintain time delays between successive corrections on each stand.
5. Update parameters if operator selection switches change.
6. Retain the head end gauge error for screwdow reset at the end of the strip if the setup computer is off line.
7. Calculate light or heavy screwdow correction S_{CEL} to compensate for the effects of strip acceleration or deceleration.
8. Calculate anticipatory roll force S_{RFP} at stands S2—S7 from previous stand roll force profile or profiles as preselected.

9. Calculate heavy or light tail end compensation for tail end loss of tension.

The selector and permissives checking function of the program is executed before calculating any monitor control action. Thus, screwdown offset control actuation is made possible in this instance only if a master AGC selector switch is turned to MONITOR and an X-ray sensitivity switch and an X-ray gauge selector switch are in a position other than OFF. Further, the gauge selected must be the same one which had been selected at the start of the strip and the X-ray gauge signal must be available and within programmed limits. Another significant permissive is that a predetermined delay time period must have expired since the strip was first detected under the X-ray gauge 42.

The X-ray deviation signal is first converted to engineering units before it is checked against limits. Typically, a plus or minus 5 volt signal would correspond to a digital number range of plus or minus 4096 and a gauge range of plus or minus 10 mils. A plus sign would correspond to heavy gauge while a minus sign would correspond to light gauge. The absolute magnitude of the X-ray deviation signal is checked against a predetermined limit value and if the deviation is greater than that value no attempt is made at monitor correction because it is presumed that either the gauge reading is in error or an extremely bad setup has been made. In that event, a monitor hold pushbutton may be operated by the mill operator in which case the present erroneous gauge is stored as the new target value and appropriate compensation is then made in the AGC program control calculations at the new target value.

Calculation of the monitor control action S_M at the various stands is provided on the basis of two mode control, i.e. the correction is the sum of proportional and reset terms.

Equation (12) in $S_M(I) = M_1(I) \cdot (XD) + M_2(I) \cdot \int (XD) \cdot dt$ where:

$M_1(I)$ = proportionality constant as preselected for stand $S_1, \dots, S_7$

$M_2(I)$ = integration constant as preselected for stand $S_1, \dots, S_7$

XD = X-ray gauge deviation.

The integral quantity is checked against preset limits to prevent the integral form winding up during periods of sustained error and to allow rapid recovery when the error changes sign. The calculated result S_M for each stand is also checked against preset limits and stored for use in the AGC program.

A deadband is set for each stand in the monitor control action calculations. The deadband feature results in monitor system corrections for small delivery gauge errors in the last two or three mill stands. Larger delivery gauge errors cause control action to be extended backwardly in the mill toward earlier stands.

In order to maintain system stability, successive control actions at a particular stand must be spaced in time by an amount greater than the transport delay for the strip to travel from the stand to the X-ray gauge 42. The control calculations for monitor action preferably employ a distinct sampling rate for each stand to correspond to monitor control actions at that stand with the particular transport delay associated with it. In addition, the sampling rate for each stand is preferably also made adjustable by the initialization program within the limits of stability.

In making the monitor control calculations, the screw-down offset program preferably also provides for phase shifting the sampling system operative for each stand. Thus, the timing between successive X-ray gauge reading samples which are to be used for successive control calculations at a particular stand can be adjusted in dependence upon the error deadband. For example, the X-ray deviation signal is sampled every 0.2 seconds and a particular stand may have its sampling system set for a sampling rate of 1.0 seconds. Every fifth X-ray deviation reading would thus be used for control calculations

at that stand, but if the delivery gauge error is within the error deadband, i.e. no control action is necessary, the stand sampling rate is increased to a higher value such as the rate at which the X-ray deviation readings are being taken, i.e. one every 0.2 seconds. In this manner, corrective control actions can be developed more quickly following the development of a gauge error outside the error deadband. Following reinitiation of monitor control action, the stand sampling system is returned to its stable sampling rate.

To make the acceleration or deceleration correction calculation, the screwdown offset subprogram can for example determine the difference between the current speed of S_6 and the thread speed of S_6 and during mill acceleration make an accumulating screwdown opening correction equal to a predetermined constant times the difference and during mill deceleration make an accumulating screwdown closing correction equal to a predetermined constant times the difference. Anticipatory roll force corrections based on a previous stand roll force profile take into consideration the transport delay as previous indicated. The anticipatory roll force profile screwdown movement S_{RFP} is calculated as follows:

Equation (13) $S_{RFP} = C(I) \cdot (FE)_P$

where: $(FE)_P$ = feedforward roll force error

$C(I)$ = preselected constant for each stand I which provides weighted response to $(FE)_P$ from the particular forwarding stand; weighting is based in part on the typical or if desired actual on line stand I value of L in Equation (3).

Screwdown offset subprogram calculations for tail end compensation are made straightforwardly in accordance with preselected heavy or light compensation values.

Generally, the AGC program runs periodically for each stand in the mill 10, and it calculates the respective screwdown movements required to maintain interstand gauges which lead to a finished strip product having improved uniformity and accuracy of gauge at the desired value. Roll force readings from the load cells 34 are entered into the AGC computer and stand delivery gauge changes are inferred from roll force changes generally through the application of Hooke's Law and specifically by use of Equation (8). The screwdown position change required to correct a roll force error is predictively calculated in accordance with Equations (7) and (10), and the total screwdown position change as calculated by use of Equation (14) includes the screwdown position change required for roll force error correction and any screwdown position change required for screwdown offset.

Execution of the AGC program provides the following basic functions:

1. Check strip in stand logic for stand under control and adjacent stands.

2. Check operator selections and permissives.

3. Lock on to reference value of roll force or accept absolute reference roll force from setup computer.

4. Detect changes in roll force and calculate workpiece plasticity and corrective changes in screwdown position.

5. Calculate a screwdown reference position for the stand under control by combining the previous screwdown reference with the screwdown changes calculated in step (4) for roll force error compensation and in the screwdown offset subprogram for monitor compensation and anticipatory acceleration, tail end tension and roll force profile feedforward compensation.

6. Accumulate manual movement, if any, and reset screwdown at end of the strip if the screwdown reset function is not under setup computer control.

7. Call the screwdown positioning program.

More specifically, prior to determination of the control actions, the AGC program checks a number of operator selections and plant status contacts. The more significant checks include the following:

1. Master AGC selector must not be off.

2. AGC selector for the stand under control must not be off.

3. Strip in stand signal must be received.

4. Strip in next stand plus short time delay must be received.

5. Screwdown must be on automatic status. If any required

selection or permissive conditions is not satisfied, the roll force gauge control loop for the stand under program execution is made inoperative and roll force error and screwdown offset corrections are disabled for that stand.

The basic logic flow steps related to control action determination in the AGC program are illustrated in FIG. 3 and FIG. 4. Generally, the Eggers and Csonka approach involving Equation (3) is employed and the workpiece plasticity is automatically determined by the use of Equation (10).

Once a start determination and a validity determination have been made for control action at a particular stand (FIG. 4), the roll force error is calculated as indicated by the reference character 70. If the calculated roll force error is less than a predetermined maximum, it is multiplied by the quantity L as indicated by the reference character 72 to determine a predicted screwdown position change required for roll force error compensation. The quantity L is thus in effect a component of the overall roll force gauge control system gain and its improved automatic on line determination lays a foundation for improved gain tuning, etc. as previously described. In predicting corrective screwdown position change, the value of L is calculated from the workpiece plasticity P and the spring constant K .

The workpiece plasticity is automatically and adaptively determined for use in the block 72 for each roll force controlled stand throughout the workpiece length as illustrated more specifically by a subroutine diagram 75 in FIG. 3. An initialization plasticity value is determined for each stand, and the resulting values are stored for updating in accordance with the results of execution of the subroutine 75. The subroutine 75 is executed each time the AGC program is executed and the flow step 72 (i.e. calculation of L and ΔS_{RF}) is performed to determine screwdown control action at each force controlled stand.

After the subroutine is started, the change in screwdown position $DS(N)$ is determined in block 77 for the stand where the workpiece plasticity is being calculated. This position change is equal to the present screwdown position $S_p(N)$ minus the reference screwdown position $S_R(N)$ which equals the last screwdown position at which the workpiece plasticity was determined. Similarly, the roll force change $DF(N)$ is determined in block 79 from the difference between the present roll force $F_p(N)$ and the reference roll force $F_R(N)$ which had existed when the screwdowns were positioned at $S_R(N)$.

If the screwdown position change is less than a predetermined amount, preferably 0.005 inches, block 81 ends the subroutine execution. The presently stored plasticity $P(N)$ for the stand under program control thus is retained without updating until the next execution of the AGC program for the same stand. This feature accordingly defines a threshold level of position change which is required before plasticity updating is permitted. Erroneously detected small position changes are thus prevented from causing changes in stored plasticity values, yet the threshold level is low enough to provide for fast updating which enables roll force changes to be correlated substantially with screwdown position changes rather than workpiece temperature rundown or like effects. Further low threshold and fast updating assures the use of relatively short segments of the mill spring and workpiece deformation curves thereby reducing the error effects which can be created by nonlinearity in these curves.

When the screwdown movement $DS(N)$ is greater than 0.005 inches, the block 81 directs the program execution to block 83 where the updated plasticity $P(N)$ is computed with the use of Equation (10). Block 85 then updates the stored value of $P(N)$ and directs continued program execution to the block 72.

The subroutine 75 or the like can if desired be used in tandem or reversing mills for initialization and updating, or it can be used for initialization only with P values subsequently automatically determined as described in the aforementioned Smith application. Further, P table values can be employed for initialization with updating provided automatically by the

subroutine 75. Another feasible variation is to make P determinations by the calculation procedure described herein and to use such determinations only if they fall within certain limits and to use table or other stored values if they fall outside the limits. In any case, it may be desirable to make P calculations on a scheduled basis other than that implicit in periodic execution of the AGC program.

The screwdown movement or position change calculation for roll force error compensation produces a one-step feedforward correction. In the roll force error calculation in block 70, anticipation is used to prevent the correction from being repeated by a positive roll force feedback as previously described in connection with the explanation of Equation (9).

If a screwdown position change does not correct a roll force error as predicted, some small roll force error remains and in effect it is treated as a new roll force error. In practice, the analog scan rate would usually be faster than the rate at which screwdown movement can be made to compensate for at least some and probably most roll force errors, and the particular roll force error calculated in the block 70 at any particular point in time can thus comprise a portion of a previous roll force error still uncorrected, a new roll force error, a roll force error remaining after screwdown movement because of some inaccuracy in the predictive calculation, or some combination of these errors.

To determine the total screwdown position change required for gauge control action, screwdown position change calculated by execution of the screwdown offset program is combined with the quantity ΔS_{RF} as indicated in block 74. In turn, the total screwdown position change ΔS is checked to determine whether it is within limits and, subject to further adjustment as indicated by the reference character 80, it is added to the previous screwdown position setpoint to obtain a new position setpoint as indicated by the reference character 76. The new screwdown position setpoint is used in the screwdown positioning program as indicated by the reference character 78.

In the special situation where the tail end of the strip 14 goes through each stand, tail end compensation is added to ΔS in the block 80 in order to obtain a net screwdown position change. It is also noted that the calculated screwdown position setpoint is checked to determine whether it is within limits as indicated by the reference character 82 prior to the call for the screwdown positioning program.

After execution of the AGC program for the current stand, the execution of the AGC program is repeated for the next stand as indicated by the reference characters 84 and 86. In one invention application, AGC program execution occurs for each of the seven mill stands S1—S7 once every 0.2 seconds, i.e. at the analog scan rate for the roll force signals from the lead cells 34.

It is also noted that the AGC program is instrumental in effecting anticipatory control in tandem mill looper tension control systems. Thus, gauge correcting changes in screwdown setting cause changes in mass flow which would ultimately be taken up by changes in the height of the interstand strip loops, and these loop height changes would be detected by the looper controls to effect linear speed corrections leading to restoration of proper looper conditions. The AGC program includes appropriate logic for determining feedforward control actions such as actions directly applied to the speed controls in order to speed up the respective stand speed adjustment needed in response to screwdown changes.

When the screwdown positioning program is executed in response to a call from the AGC program, the present screwdown position and the screwdown position setpoint are compared for the particular stand under control and an output is developed to operate the stand screwdown motors with an optimum or critical damping screwdown position-time curve in accordance with the total amount of screwdown movement to be effected. As the screws approach the predicted corrective screwdown position, the screwdown motors are slowed down with critical damping. Normally, the speed-time and position-time screwdown motor curves which provide critical

damping response to differing amounts of screwdown position error are determined empirically for each stand or partly empirically and partly by calculation for each stand.

In summary, a process control system is uniquely organized to provide improved metal rolling mill gauge control performance. The control system preferably includes a digital computer system which provides predictive roll force gauge control operation of the screwdowns at each of one or more roll force gauge control stands in the mill as the workpiece plasticity and mill spring constant values undergo change. Improved stand gain tuning is achieved by the predictive nature of the control operation and by the automatic workpiece plasticity determination at each controlled stand from roll force and screwdown data at that stand. In turn faster, more accurate and more stable stand gauge control and reduced transport delayed monitor control action are achieved. Use of the process control system ultimately provides improved product gauge uniformity and improved mill productivity.

The foregoing description has been presented only to illustrate the principles of the invention. Accordingly, it is desired that the invention not be limited by the embodiment described, but, rather, that it be accorded an interpretation consistent with the scope and spirit of its broad principles.

I claim:

1. A gauge control system for a rolling mill having at least one rolling stand with a screwdown controlled roll opening through which a workpiece is transported, said system comprising means for detecting roll force at the rolling stand, means for detecting the rolling stand screwdown position, means for determining roll force error on the basis of detected roll force and screwdown position values and predetermined roll force and screwdown position reference values, means for determining screwdown movement to provide for correct gauge, said screwdown movement determining means including means for predictively determining the amount of screwdown movement needed for correcting determined roll force error in accordance with a predetermined relationship with determined roll force error and predetermined values of workpiece plasticity and the stand spring constant, said screwdown movement determining means further including means responsive to said roll force detecting means and said screwdown position detecting means for making at least one on line determination of a value of the workpiece plasticity substantially as a function of the change in roll force produced by a screwdown position change at the stand, and means for controlling screwdown position to effect corrective screwdown movement.

2. A gauge control system as set forth in claim 1 wherein said workpiece plasticity determining means operates repeatedly to update the workpiece plasticity value as the screwdowns undergo movement during at least a portion of the workpiece rolling period, each of the operations of said workpiece plasticity determining means involving determination of the roll force change associated with the screwdown position change for that operation.

3. A gauge control system as set forth in claim 2 wherein each of the operations of said workpiece plasticity determining means requires a predetermined minimum amount of screwdown movement before execution of the operation is permitted.

4. A gauge control system as set forth in claim 3 wherein the minimum screwdown movement is at least 0.005 inches.

5. A gauge control system as set forth in claim 2 wherein said workpiece plasticity determining means is operative substantially throughout the workpiece rolling period.

6. A gauge control system as set forth in claim 2 wherein the rolling mill is a tandem mill having a plurality of roll force gauge controlled stands, at least one of each of said detecting means is provided for each of the roll force gauge controlled stands, said roll force error and screwdown movement determining means determine roll force error and predictively determine roll force corrective screwdown movement for each of the roll force gauge controlled stands, said plasticity determining means makes on line updating plasticity determination for each of the roll force gauge controlled stands

respectively on the basis of roll force changes associated with screwdown position changes at those stands and said screwdown controlling means makes corrective screwdown movement at the corresponding roll force gauge controlled stands.

7. A gauge control system as set forth in claim 2 wherein said roll force error and screwdown movement determining means include a digital computer system, said computer system having an input coupled to said detecting means and an output coupled to said screwdown controlling means, and means for operating said computer system to make the updating workpiece plasticity determinations from the determined roll force and screwdown position changes, said computer operating means further making the roll force error and screwdown movement determinations.

8. A gauge control system as set forth in claim 1 wherein the workpiece plasticity is determined in accordance with the equation

$$P = \frac{1}{\frac{DS}{DF} - \frac{1}{K}}$$

where K equals the stand spring constant and DF equals the change in the stand roll force associated with DS which is the measured change in screwdown position.

9. A gauge control system as set forth in claim 8 wherein said determining means include a digital computer system having an input coupled to said detecting means and an output coupled to said screwdown controlling means, and means are provided for operating said computer system to determine the plasticity P and to determine roll force corrective screwdown movement from roll force error and the quantity

$$\frac{P}{K^2} + \frac{1}{K}$$

where P equals the workpiece plasticity in units of force divided by units of distance and K equals the stand spring constant in units of force divided by units of distance.

10. A method for providing gauge control in a rolling mill having at least one rolling stand with a screwdown controlled roll opening through which a workpiece is transported, the steps of said method comprising detecting roll force at the rolling stand, detecting the rolling stand screwdown position, determining roll force error on the basis of detected roll force and screwdown position values and predetermined roll force and screwdown position reference values, determining corrective screwdown movement to provide for correct gauge, said corrective screwdown movement step including predictively determining the amount of roll force corrective screwdown movement in accordance with determined roll force error and predetermined values of the workpiece plasticity and the stand spring constant, making at least one workpiece plasticity determination on line as a function of the change in roll force produced by a screwdown position change at the stand, and controlling screwdown position to effect corrective screwdown movement.

11. A method for operating a digital computer system employed for controlling the gauge of a workpiece transported through a screwdown controlled roll opening of at least one rolling stand, the steps of said method comprising determining roll force error on the basis of detected roll force and screwdown position values and predetermined roll force and screwdown position reference values, determining corrective screwdown movement to provide for correct gauge, said corrective screwdown movement step including predictively determining the amount of roll force corrective screwdown movement in accordance with determined roll force error and predetermined values of the workpiece plasticity and the stand spring constant, and making at least one workpiece plasticity determination on line as a function of change in roll force produced by a screwdown position change at the stand.

12. A computer method as set forth in claim 11 wherein the workpiece plasticity is determined in accordance with the equation

$$P = \frac{1}{\frac{DS}{DF} - \frac{1}{K}}$$

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where K equals the stand spring constant and DF equals the change in the stand roll force associated with DS which is the measured change in screwdown position, and wherein roll force corrective screwdown corrective movement is determined from roll force error and the quantity

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$$\frac{P}{K^2} + \frac{1}{K}$$

where P equals the workpiece plasticity in units of force divided by units of distance and K equals the stand spring constant in units of force divided by units of distance.

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