United States Patent [19]

Smith, Jr.

[11] 3,892,112

[45] July 1, 1975

[54] ROLLING MILL GAUGE CONTROL

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[73] Assignee: Westinghouse Electric Corp., Pittsburgh, Pa.

[22] Filed: Mar. 27, 1974

[21] Appl. No.: 455,159

[52] U.S. Cl. 72/11

[51] Int. Cl. B21b 37/08

[58] Field of Search 72/6–12, 16, 72/19, 20, 21

[56] References Cited

UNITED STATES PATENTS

2,726,541	12/1958	Sims	73/88.5
3,232,084	2/1966	Sims	72/16
3,332,263	7/1967	Beadle et al.	72/7
3,561,237	2/1971	Eggers et al.	72/7
3,592,031	7/1971	Sutton et al.	72/8
3,600,920	8/1971	Smith, Jr.	72/8

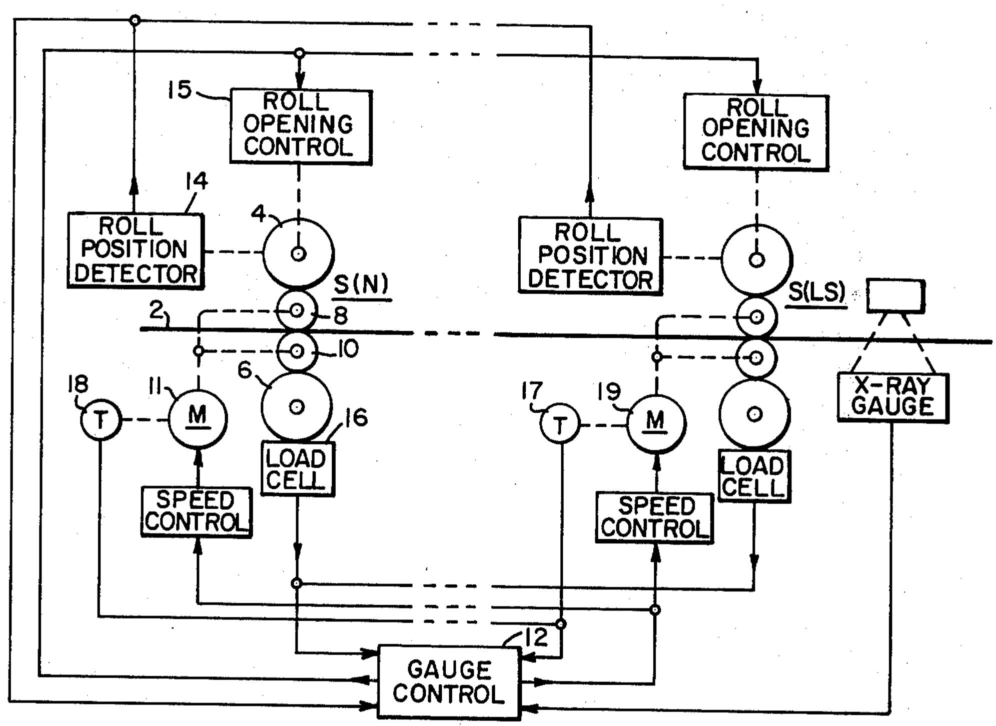
Primary Examiner—Milton S. Mehr

Attorney, Agent, or Firm—R. G. Brodahl

[57] ABSTRACT

A rolling mill gauge control system and method are disclosed for controlling the delivery thickness or gauge of a strip workpiece leaving one or more roll stands of a tandem rolling mill. The initial roll opening setting and the initial speed setting for each roll stand are typically provided by an operator or a schedule calculation computer system prior to the passage of the work strip through the roll stand. Assuming these initial speed settings are correct, the known mass flow operational condition of the work strip in relation to the last stand target delivery gauge is used to establish the initial desired mass flow delivery gauge from each controlled roll stand of the rolling mill in relation to the desired delivery gauge from the last roll stand. Then as the work strip passes through each successive roll stand, and before the work strip reaches the X-ray gauge measurement device following the last roll stand, the roll force determined actual delivery gauge from each roll stand is compared with the initial desired mass flow delivery gauge to determine a work strip gauge error leaving the latter roll stand, which gauge error is utilized for determining a desired correction in the roll opening setting for that roll stand before the work strip reaches the X-ray gauge device.

10 Claims, 8 Drawing Figures



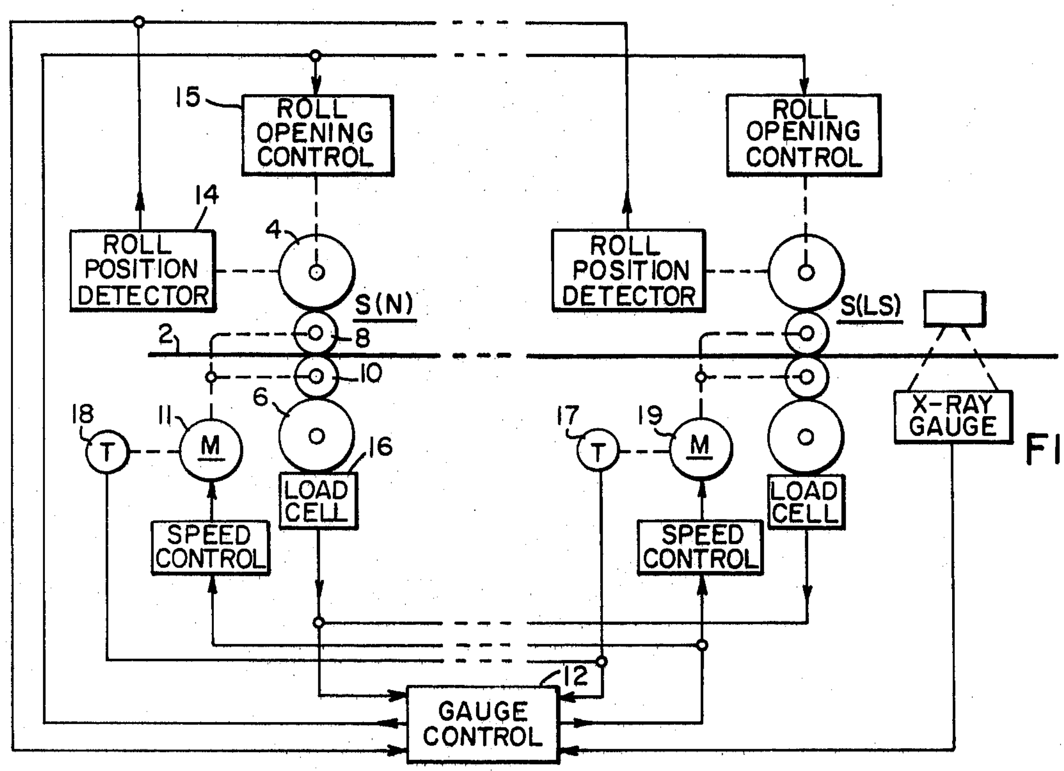

ROLL OPENING CONTROL
ROLL OPENING CONTROL
ROLL POSITION DETECTOR
ROLL POSITION DETECTOR
S(N)
S(LS)
X-RAY GAUGE
LOAD CELL
LOAD CELL
SPEED CONTROL
SPEED CONTROL
GAUGE CONTROL
T
M
T
M
15
14
4
8
2
10
6
18
11
16
17
19
12

FIG. 1

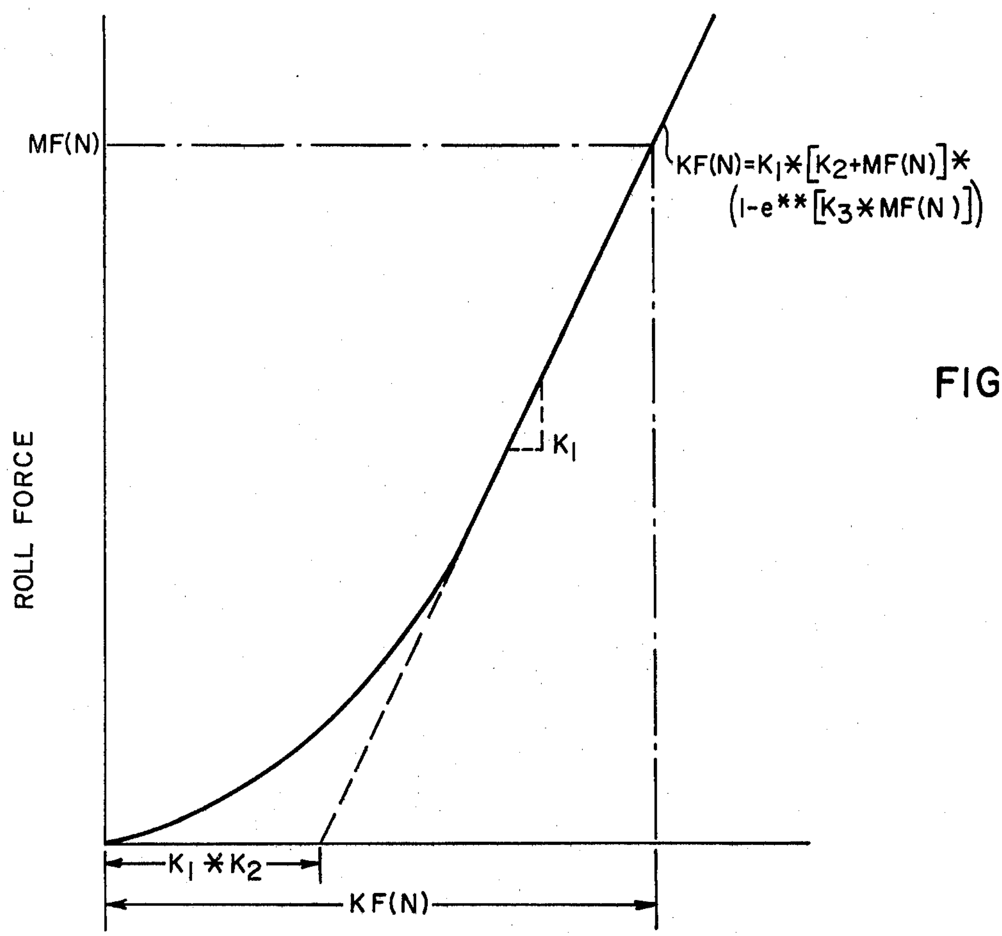

MF(N)
KF(N)=K1*[K2+MF(N)]*(1-e**[K3*MF(N)])
K1
ROLL FORCE
K1 * K2
KF(N)

FIG. 2

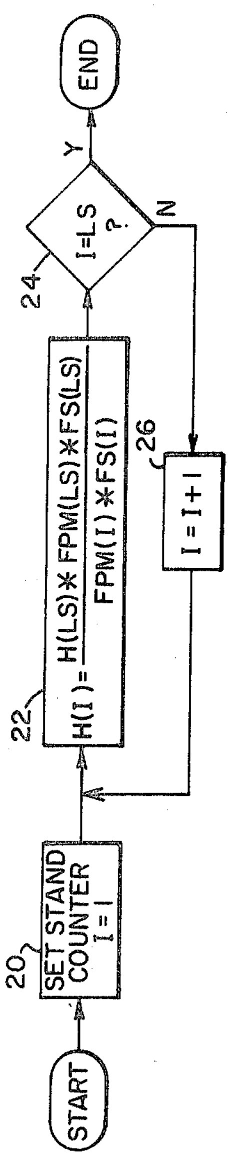

START
20
SET STAND COUNTER I=1
22
H(I) = H(LS)*FPM(LS)*FS(LS) / FPM(I)*FS(I)
24
I=LS ?
Y
END
N
26
I = I+1

FIG. 3

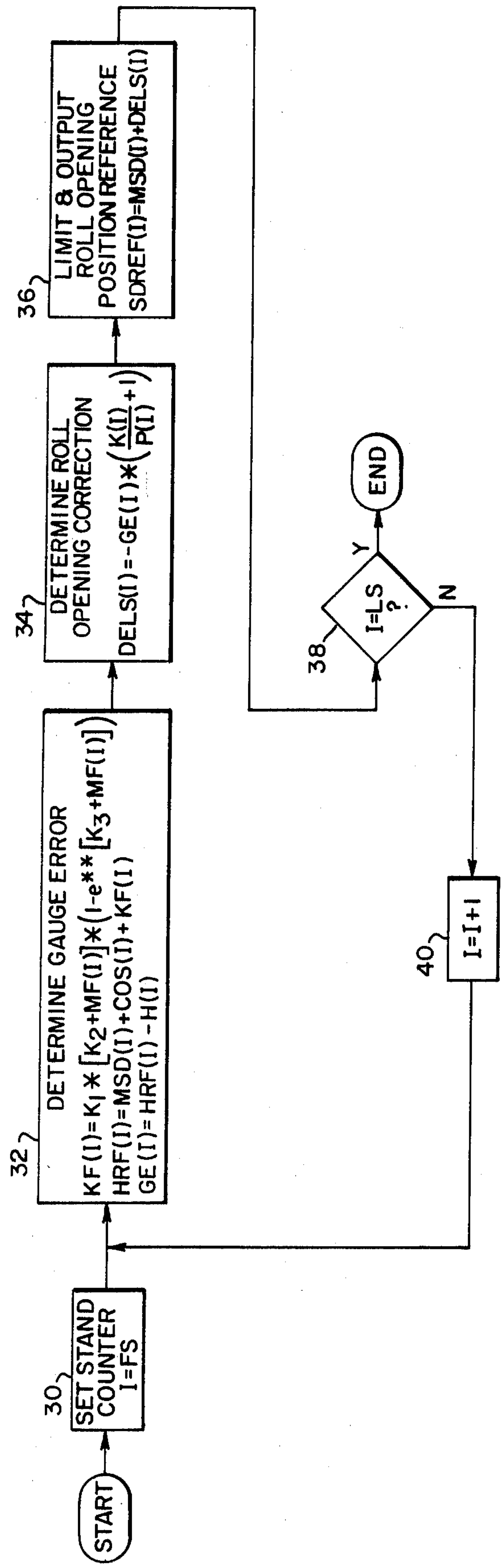

START
30
SET STAND COUNTER I=FS
32
DETERMINE GAUGE ERROR
KF(I)=K1*[K2+MF(I)]*(1-e**[K3+MF(I)])
HRF(I)=MSD(I)+COS(I)+KF(I)
GE(I)=HRF(I)-H(I)
34
DETERMINE ROLL OPENING CORRECTION
DELS(I)=-GE(I)*(K(I)/P(I)+1)
36
LIMIT & OUTPUT ROLL OPENING POSITION REFERENCE
SDREF(I)=MSD(I)+DELS(I)
38
I=LS ?
Y
END
N
40
I=I+1

FIG. 4

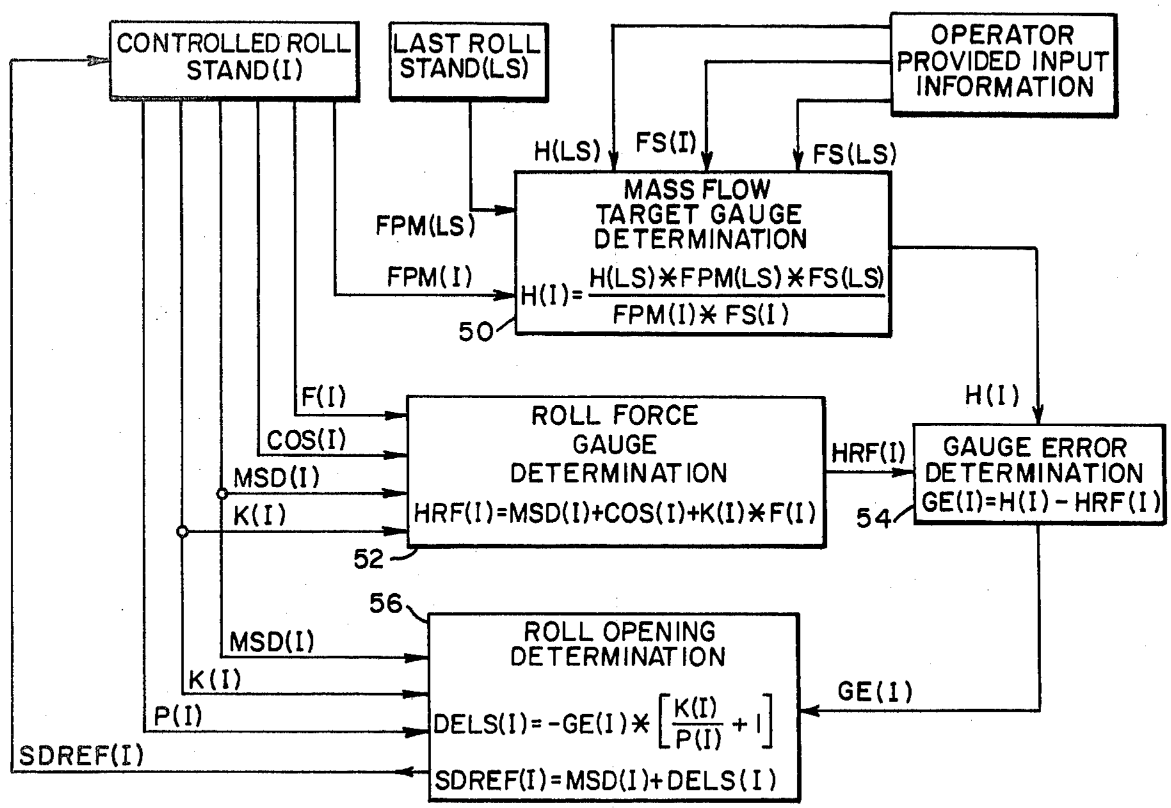

CONTROLLED ROLL STAND(I)
LAST ROLL STAND(LS)
OPERATOR PROVIDED INPUT INFORMATION
H(LS)
FS(I)
FS(LS)
FPM(LS)
FPM(I)
MASS FLOW TARGET GAUGE DETERMINATION
H(I)= H(LS)*FPM(LS)*FS(LS) / FPM(I)*FS(I)
50
H(I)
F(I)
COS(I)
MSD(I)
K(I)
ROLL FORCE GAUGE DETERMINATION
HRF(I)=MSD(I)+COS(I)+K(I)*F(I)
52
HRF(I)
GAUGE ERROR DETERMINATION
GE(I)=H(I)-HRF(I)
54
56
MSD(I)
K(I)
P(I)
SDREF(I)
ROLL OPENING DETERMINATION
DELS(I)=-GE(I)*[K(I)/P(I)+1]
SDREF(I)=MSD(I)+DELS(I)
GE(I)

FIG.5

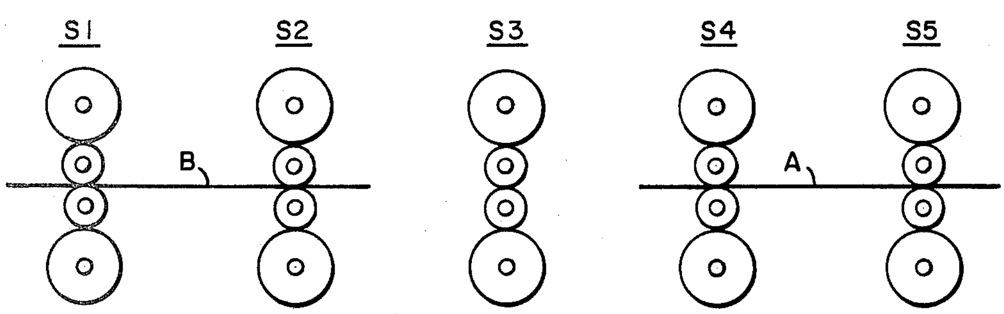

S1
S2
S3
S4
S5
B
A

FIG.6

```
C                                               FIGURE 3
C                                               ESTABLISHING DESIRED DELIVERY
C                                               GAGE,H(I),FØR EACH STAND
C                                               PRIØR TØ ENTERING FIRST STAND
C                                               USING REFERENCE INITIAL
C                                               STAND SPEED, FPM(I), AND
C                                               DESIRED DELIVERY GAGE,H(LS)
C
C                                               SET STAND CØUNTER
 20     I=1
C
 22     H(I)=H(LS)*FPM(LS)*FS(LS)/(FPM(I)*FS(I))
C                                               LAST STAND CHECK
 24     IF (I.EQ..LS) GØ TØ 100
C
 26     I=I+1
        GØ TØ 22
C
 100    END
```

FIG. 7

```
C                                               FIGURE 4
             C                                  CALCULATE GAGE ERRØR GE(I)
C                                               AND SCREWDØWN REFERENCE
C                                               SDREF(I) TØ CØNTRØL GAGE
C
C                                               SET STAND CØUNTER
 30     I=FS
C                                               DETERMINE GAGE ERRØR
 32     KF(I)=K1*(K2+MF(I))*(1.-EXP(K3+MF(I)))
        HRF(I)=(MSD(I)+CØS(I)*KF(I)
        GE(I)=HRF(I)-H(I)
C                                               DETERMINE RØLL ØPENING
C                                               CØRRECTIØN
 34     DELS(I)=-GE(I)*((K(I)/P(I))+1)
C                                               LIMIT AND ØUPUT RØLL ØPENING
C                                               PØSITIØN REFERENCE
 36     SDREF(I)=MSD(I)+DELS(I)
C                                               LAST STAND CHECK
 38     IF(I.EQ.LS)  GØ TØ 100
C
 40     I=I+1
        GØ TØ 32
 100    END
```

FIG. 8

ROLLING MILL GAUGE CONTROL

BACKGROUND OF THE INVENTION

The present invention relates to tandem metal workpiece reduction rolling mills and more particularly to such rolling mills including roll force sensing load cells operative with selected roll stands for controlling the delivery gauge of the work strip leaving those roll stands.

In the operation of a metal rolling mill, the unloaded roll opening and the speed of each roll stand are initially set up, before the work strip enters that roll stand, either by an operator or by a schedule calculation control computer to produce a work strip reduction resulting in a desired on-gauge finished work product leaving that roll stand. It is usually assumed that the loaded roll opening of a roll stand equals the stand delivery gauge, since there is little or no elastic workpiece recovery.

Because the provided roll stand set up conditions may be in error and since certain mill parameters affect the stand loaded roll opening during the actual rolling operation, a stand gauge control system is employed to control the stand delivery gauge.

The well known roll force gauge control system has been used to provide desired gauge control operation (the workpiece thickness is also sometimes spelled gage) for one or more stands of tandem rolling mills, using Hooke's law for controlling the roll opening position at a given roll stand. The loaded roll opening and hence the work strip delivery gauge from that given roll stand, under normal workpiece rolling conditions, equals the unloaded roll opening position plus the mill stand spring stretch caused by the roll separating force applied to the work rolls by the workpiece. The roll separating force is measured by a load cell or other suitable force detecting device operative with the roll stand. The roll opening position is then controlled to balance roll force changes from a reference or initial lock on value and thereby to hold the loaded roll opening at a substantially constant value. The following formula relationship can be used to establish the delivery gauge of the work strip leaving a controlled roll stand

$$h = S_o + K * F \tag{1}$$

where h is the loaded roll opening and the delivery gauge of the work strip, S_o is the unloaded roll opening position, and K is the roll stand mill spring constant multiplied by F, the measured roll separating force. The asterisk is the well known Fortran programming symbol for multiplication.

A typical prior art roll force gauge control system for a roll stand is an analog feedback system operative to make a comparison of the determined work strip delivery gauge with a desired reference gauge leaving the roll stand, and responsive to measured stand roll force and measured roll opening position to control the roll opening position in accordance with the following error condition

$$\Delta S = -K * \Delta F \tag{2}$$

where ΔS is the error in roll opening position to be corrected in relation to a reference roll opening position and ΔF is the measured change in roll force from a desired force reference and K is the roll stand mill spring constant.

Once the unloaded roll opening position and stand speed initial setups have been determined and made by either a mill operator or a schedule calculation computer system for a particular work strip passage through the roll stands to effect a desired gauge reduction, the actual rolling operation can be started and the controlled roll openings are then regulated to provide the desired work strip delivery gauge from each controlled roll stand of the rolling mill.

It is known in the prior art, as shown by U.S. Pat. No. 3,600,920 by the same inventor, to recalibrate the roll opening control for a given roll stand, after the work strip has passed through all of the roll stands of a tandem rolling mill, in relation to the last roll stand actual delivery gauge as measured by an X-ray gauge positioned after the last roll stand. The speed relationship of a given roll stand as compared to the last roll stand is utilized to determine the mass flow actual delivery gauge leaving that given roll stand. The difference between the roll force acutal delivery gauge of that given roll stand and the latter mass flow actual delivery gauge is utilized for recalibration of the roll opening control apparatus, such as a screwdown or hydraulic position control mechanism, for that given roll stand.

The well known gauge meter or roll force gauge control 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 demostrated that roll force control is particularly effective. Earlier publications and patents such as an article entitled Installation and Operating Experience with Computer and Programmed Mill Controls by M. D. McMahon and M. A. Davis in the 1963 Iron and Steel Engineer Yearbook at pages 726 and 733, an article entitled Automatic Gauge Control for Modern Hot Strip Mills by J. W. Wallace in the December 1967 Iron and Steel Engineer at pages 75 to 86, an article entitled "Control Computer Teaches Itself To Roll Metals" by A. W. Smith in the Westinghouse Engineer for July 1970 at pages 108 to 113, U.S. Pat. No. 3,561,237 issued Jan. 9, 1971 to Eggers et al. and 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 and related gauge control systems is based. Attention is also called to U.S. Pat. No. 3,568,637 issued Mar. 9, 1971, U.S. Pat. Nos. 3,574,279 and 3,574,280 issued Apr. 13, 1971 to A. W. Smith, which relate to roll force automatic gauge control systems.

SUMMARY OF THE INVENTION

In accordance with the principles of the present invention, a control system and method for controlling the delivery gauge or thickness of workstrip product leaving one or more roll stands of a tandem rolling mill includes the determination of the mass flow target delivery gauge of the work strip for each controlled roll stand in relation to the last stand target delivery gauge before the workstrip has arrived at the X-ray gauge following the last roll stand, and then comparing the roll force determined actual delivery gauge for the same roll stand with this mass flow target delivery gauge to establish a gauge error for correction by an adjustment of the roll opening position setting for that roll stand.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 shows a schematic diagram of a roll force gauge control arranged for operation with a tandem rolling mill in accordance with the present invention;

FIG. 2 shows a curve to illustrate the mill spring characteristic for a typical roll stand in relation to the determination of the stretch of a controlled roll stand;

FIG. 3 shows a flow chart to illustrate the determination of mass flow target delivery gauge for each roll stand before a given work strip passes through the rolling mill;

FIG. 4 shows a flow chart to illustrate the determination of the gauge error and roll opening position reference for each controlled roll stand;

FIG. 5 is a functional illustration of the control of workstrip delivery gauge from a roll stand in accordance with the present invention;

FIG. 6 illustrates the situation where the tail end of a previous work strip and the head end of a subsequent work strip are passing through the rolling mill at the same time;

FIG. 7 shows a program listing prepared in relation to the flow chart of FIG. 3; and

FIG. 8 shows a program listing prepared in relation to the flow cart of FIG. 4.

GENERAL DESCRIPTION OF THE GAUGE CONTROL SYSTEM AND ITS OPERATION

There is shown in FIG. 1 a controlled four high rolling mill stand S(N) operative with a gauge control 12 in accordance with the principles of the present invention. Generally, the invention is applicable to control the operation of one or more tandem rolling mill stands for which roll force gauge control is employed. The tandem rolling mill shown in FIG. 1 includes a last stand S(LS).

A workpiece 2 enters the roll stand S(N) at the entry end and it is reduced in thickness and transported through the succeeding roll stands to the delivery end of the rolling mill. The entry workpiece would be of known steel grade and it typically would have a known gauge or thickness. The delivered workpiece would have a desired target gauge or thickness H(LS) based upon the production order for which it is intended.

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

Each stand is conventionally provided with a pair of back-up rolls 4 and 6 and a pair of work rolls 8 and 10 between which the workpiece 2 is passed. A large DC drive motor 11 is controllably energized at each stand to drive the corresponding work rolls at a controlled speed.

In relation to roll stand S(N), the sum of the unloaded work roll opening MSD(N) and the mill stretch $K(N) * \Delta F(N)$ substantially defines the roll force determined workpiece gauge HRF(N) delivered from the controlled roll stand S(N) in accordance with Hooke's law. A well known calibration offset COS(N) can be included to provide desired calibration of the roll opening control apparatus operative with the roll stand S(N), which roll opening control apparatus could be a pair of screwdown motors or a hydraulic positioning apparatus, to position the back-up rolls and thereby apply pressure to the work rolls. A conventional roll opening position detector 14 provides an electrical signal representation MSD(N) of the unloaded roll opening position. Roll force detection is provided at the roll stand S(N) by a conventional load cell 16 which generates an electrical analog signal F(N) proportional to the roll separating force between the work rolls. A speed sensing transducer 18, such as a pulse transducer, generates a stand speed signal FPM(N).

The gauge control 12 provides automatic gauge or thickness for the operation of the mill stand S(N). The gauge control 12 can include a programmed general purpose process control digital computer system, which is interfaced with the various mill operational sensors and the various mill control devices to provide control over the operation of the mill stand S(N). According to user preference, the gauge control 12 can also include well known and conventional manual and/or automatic analog controls for back-up operation in performing other preselected mill functions.

On the basis of these considerations, a suitable digital computer system for the on-line roll force gauge control system 12 would be a Prodac 2000 (P2000) sold by Westinghouse Electric Corporation. A descriptive book entitled Prodac 2000 Computer Systems Reference Manual has been published in 1970 by Westinghouse Electric Corporation and made available for the purpose of describing in greater detail this computer system and its operation.

The digital computer system is associated with well known predetermined input systems, typically including a conventional contact closure input system which scans contact or other signals representing the sensed status of various process operating conditions, a conventional analog input system which scans and converts process analog signals, and operator controlled and other information input devices and systems such as paper tape, teletypewriter and dial input systems. Various kinds of information can be entered into the computer system through the input devices including, for example, desired strip delivery gauge H(LS) and temperature, strip entry gauge and width and temperature (by entry detectors if desired), grade of steel being rolled, plasticity P tables, hardware oriented programs and control programs for the programming system, and so forth. The contact closure input systems and the analog input systems interface the computer system with the process through the medium of measured or detected variables, which include the following:

1. A roll force signal F(N) from the load cell 16 at the roll stand S(N) proportional to stand roll separating force for use in roll force gauge control.

2. Roll opening position signal MSD(N) generated by the respective position detector 14 for use in roll force gauge control.

3. A roll stand speed signal FPM(N) from a pulse generator 18 operative with the drive motor 11 of the controlled roll stand S(N).

4. A roll stand speed signal FPM(LS) from a pulse generator 17 operative with the drive motor 19 of the last roll stand S(LS).

It is noted at this point in the description, that the measured stand roll force and the measured stand roll opening position in relation to the workpiece head end are stored and used as references for roll force gauge control system functioning, if it is desired to operate in the well known lock-on mode of roll force gauge control operation.

To effect determined output control actions, controlled devices are operated directly by means of output system contact closures or by means of analog signals derived from output system contact closure through a digital to analog converter. The principal control action outputs from the gauge control **12** includes a positioning command signal SDREF(N) applied to the roll opening control **15** for the controlled roll stand S(I) and other controlled roll stands, and a speed control signal applied to the drive motor **11** of roll stand S(N) and the other roll stands in accordance with respective desired speed setting for mass flow operational conditions.

Display and printout systems such as numeral display, tape punch, and teletypewriter systems also can be associated with the outputs of the digital computer gauge control system 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.

Generally, the gauge control **12** uses Hooke's law to determine the total amount of screwdown movement required at the roll force controlled stand S(N) at the calculating point in time for roll force and gauge error correction, i.e. for loaded roll opening and stand delivery gauge correction to the desired value. The calculation defines the total change in the unloaded roll opening position setting required to correct for determined gauge error causing conditions.

As well known to persons skilled in this art, the desired roll opening correction DELS(N) in relation to controlled roll stand S(N) is calculated to enable roll force gauge control operation in accordance with the following programmed relationship algorithm:

$$\mathrm{DELS}(N) = \left[\frac{K(N)}{P(N)} + 1\right] \quad {*}\mathrm{GE}(N) \qquad (3)$$

where:

$GE(N)$ = gauge error of controlled roll stand S(N)
$K(N)$ = stand S(N) mill spring constant (in/10^6 lb.)
$P(N)$ = workpiece plasticity (in/10^6 lb.) in relation to stand S(N).

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

The operative value of the workpiece plasticity P at each roll stand is also relatively accurately determined. If desired, P tables can be stored in the storage memory of the digital computer system associated with the gauge control **12** to identify the various values of P which apply to the controlled roll stand S(N) for various grade class and gauge class workpieces under various operating conditions and at various operating times during the rolling of the workpiece strip **2**.

A main advantage of using the roll force gauge control system is the ability to detect error changes in strip gauge the instant they take place as the product is being rolled in the roll stand. A change in strip delivery gauge or thickness can be caused by a change in entry thickness, or a change in hardness as usually caused by a change in temperature. This change in delivery gauge can be immediately detected by feedback information monitoring of the roll separating force on the roll stand.

There is shown in FIG. **2** a curve to illustrate the typical mill spring characteristic for a roll stand, such as controlled roll stand S(N). The curve is a plot of measured roll force MF(N) for a typical roll stand (N) against the resulting stretch KF(N) of the roll stand, or the product of K(N) the stand spring constant and F(N) the stand roll force. The curve shown in FIG. **2** can be mathematically represented by the relationship.

$$KF(N) = K_1 * [K_2 + MF(N)]* (1-e **[K_3*MF(N)]) \qquad (4)$$

where K_1, K_2 and K_3 are constants established by data collecting and curve fitting techniques well known and practiced for several years by persons skilled in this art. The curve is established by closing together the stand work rolls, through operation of the roll opening control of the roll stand, until some minimum roll force is sensed by the stand load cell, and then progressively closing the work rolls by predetermined incremental settings and reading the corresponding roll force for each such setting. Then, knowing the mill spring characteristic curve for a given roll stand of the rolling mill, the values of constants K_1, K_2 and K_3 for that roll stand are determined by well known curve fitting techniques. It should be noted in relation to above equation (4) that the double asterisk represents the well known Fortran programming symbol for an exponential and the single asterisk indicates multiplication.

There is shown in FIG. **3** the flow chart of a program utilized to determine the mass flow target delivery gauge for each controlled roll stand, such as roll stand S(I), where I is a roll stand index, before the work strip has passed through the rolling mill and become operative with the X-ray gauge positioned after the last roll stand S(LS). At step **20** a stand counter is initially set to one. At step **22** the mass flow target delivery gauge is determined for a given roll stand (I) successively indexed by the stand counter, firstly such as roll stand one and then secondly roll stand two and so forth. At step **24** a check is made to see if that given roll stand (I) is the last stand, and if it is not the program goes to step **26** where the stand index I is incremented by one to the next succeeding roll stand, and steps **22** and **24** are repeated until the check at step **24** indicates that index stand I is now the last roll stand S(LS), when the program operation ends.

There is shown in FIG. **4** the flow chart of a program utilized to determine the gauge error and roll opening position reference for each controlled roll stand of the rolling mill in accordance with the present invention, after the work strip has entered the first roll stand and before the work strip reaches the X-ray gauge positioned after the last roll stand S(LS). At step **30** the stand index counter is set to one. At step **32,** the mill stretch KF(I) for the indexed roll stand (I) is determined in accordance with above equation (4). Then the roll force determined actual delivery gauge HRF(I) leaving the roll stand (I) is determined in accordance with the well known relationship:

$$HRF(I) = MSD(I) + COS(I) + KF(I) \qquad (5)$$

where $MSD(I)$ is the unloaded roll opening position setting for roll stand (I), $COS(I)$ is the previously determined calibration offset for roll stand (I), and $KF(I)$ is the mill stretch for roll stand (I). The delivery gauge error $GE(I)$ for roll stand (I) is determined by the relationship:

$$GE(I) = HRF(I) - H(I) \quad (6)$$

where $H(I)$ is the mass flow target delivery gauge for indexed roll stand (I) determined at step **22** of the program flow chart shown in FIG. **3** and $HRF(I)$ is the roll force actual delivery gauge leaving roll stand (I). At step **34** the roll opening correction $DELS(I)$ for roll stand (I) is determined in accordance with the relationship of above equation (3), where roll stand (N) is now the index roll stand (I). At step **36** the roll opening position reference for indexed roll stand (I) is established by the relationship:

$$SDREF(I) = MSD(I) + DELS(I) \quad (7)$$

where $MSD(I)$ is the present unloaded roll opening position setting for roll and stand (I) and $DELS(I)$ is the desired roll opening correction for roll stand (I), which roll opening position reference $SDREF(I)$ can be limit checked and output to the roll opening control apparatus for index roll stand (I). At step **38** a check is made to see if roll stand (I) is the last stand of the rolling mill, and if not at step **40** the index (I) is incremented by one and the program step **32, 34** and **36** are repeated for succeeding roll stands of the rolling mill until the index roll stand (I) is the last roll stand (LS), when the program operation ends.

The program illustrated by FIG. **3** is intended to be run just before each work strip enters the first roll stand of the rolling mill, as can be monitored by well known work strip position sensing tranducer devices. The program illustrated by FIG. **4** is intended to be run periodically, such as five times per second, for all controlled roll stands through which the work strip is passing as can be sensed by strip-in-stand monitoring techniques well known to persons skilled in this art.

The functional illustration of the present invention set forth in FIG. **5** is in relation to index roll stand (I). At step **50** the mass flow target gauge is determined for roll stand (I) before the work strip is passing through roll stand (I), and in accordance with the initial set up speed reference FPM(I) for roll stand (I), the initial set up speed reference FPM(LS) for the last roll stand (LS) and the initial target delivery gauge H(LS) leaving the last roll stand (LS). The forward slip characteristic FS(I) for the controlled roll stand (I) and the forward slip characteristics FS(LS) for the last roll stand (LS) are predetermined and supplied by the operator. At step **52** the roll force determined actual delivery gauge HRF(I) leaving controlled roll stand (I) is established after the work strip is passing through the roll stand (I). At step **54** the gauge error GE(I) in the work strip leaving roll stand (I) is determined. At step **56** the roll opening correction DELS(I) and the associated roll opening position reference SDREF(I) are determined, with the position reference signal being output to the controlled roll stand (I), after limiting this reference signal for stability and related control system practical operation reasons.

The process control programs are organized in a way to accommodate the normal mill condition where the head end of one succeeding workpiece is entering the early stands while the tail end of the previous workpiece is still being rolled in the later stands. This condition is shown in FIG. **6** where workpiece A is being rolled in stands **S4** and **S5** when the new workpiece B is in stands **S1** and **S2.** It is necessary that the initial stand speeds, roll openings and desired delivery gauge be established by the operator or by the schedule calculation computer prior to the entry of the new workpiece into stand **S1** so that the mill setups may be changed to the new value as soon as the tail end of the previous workpiece leaves a particular stand. Just prior to the entry of the new workpiece into a first stand, the initial speed FPM(I) and desired target gauge or thickness H(LS) are used to determine the desired gauge from each stand as shown in FIG. **3** so that the desired gauge H(I) is available for the gauge error determination as shown in FIG. **4.**

This gauge error and screwdown reference calculation is initiated as soon as a workpiece enters a stand and repeated periodically (such as five times per second) until the workpiece leaves the stand.

For instance, under the conditions shown in FIG. **6,** the gauge error and screwdown reference calculations shown in FIG. **4** are being performed for workpiece A with a first stand FS value of **4** and a last stand LS value of **5.** The same calculations are used to control the gauge of workpiece B in stands **S1** and **S1** by using a first stand FS value of **1** and at last stand LS value of **2.** Each set of calculations used the desired stand delivery gauge H(I) value that was established by the procedure shown in FIG. **3** for that particular workpiece prior to its entry into the mill.

In FIGS. **7** and **8** there are included two instruction program listings that have been prepared to determine the roll force automatic gauge control operation of a tandem rolling mill in accordance with the here disclosed control system and method. The instruction program listings are written in Fortran language suitable for use with the PRODAC P2000 digital computer system, which is sold by Westinghouse Electric Corporation for real time process control computer applications. Many of these digital computer systems have already been supplied to customers, including computer instruction books and descriptive documentation to explain to persons skilled in this art the operation of the hardware logic and the executive software of this digital computer system. The instruction program listings are included to provide an illustration of one suitable embodiment of the present control system and method that has acutally been prepared. The instruction program listings have not been debugged through the course of extensive practical operation for the real time control of a rolling mill. It is well known by persons skilled in this art that most real time process control application programs contain some bugs or minor errors, and it is within the skill of such persons and takes varying periods of actual operation time to identify and correct these bugs.

The instruction program listings included in FIGS. **7** and **8** were prepared in relation to the flow charts shown in FIGS. **3** and **4.**

I claim as my invention:

1. A method of controlling the delivery gauge of a work strip passing through at least one roll stand of a tandem rolling mill in accordance with a desired delivery gauge leaving the last rolling stand of said rolling mill, with said one roll stand having a pair of work rolls and a roll force measurement device, said method including the steps of

establishing a target delivery gauge for said work strip leaving said one roll stand in relation to said desired delivery gauge, the speed setting of said one roll stand and the speed setting of the last roll stand,

establishing the actual delivery gauge of said work strip leaving said one roll stand in relation to the measured roll force of said one roll stand,

comparing said target delivery gauge with said actual delivery gauge to determine a work strip gauge error leaving said one roll stand, and

establishing the roll opening between said pair of work rolls of said one roll stand in relation to said gauge error.

2. The method of claim 1, with said target delivery gauge being established in accordance with the mass flow relationship including the speed setting of the last roll stand of said rolling mill before said work strip passes through said last roll stand.

3. The method of claim 1, with said target delivery gauge being established before said work strip passes through the last roll stand of said rolling mill.

4. The method of claim 1, with said target delivery gauge being established in relation to the operation of the last roll stand and before the work strip passes through the last roll stand of the rolling mill.

5. The method of claim 1, with said target delivery gauge being established before said work strip passes through the last roll stand of said rolling mill and with said actual delivery gauge being established after said work strip passes through said one roll stand.

6. In an apparatus for controlling the delivery gauge of a work strip passing through at least one roll stand of a tandem rolling mill having a plurality of roll stands and in accordance with the desired delivery gauge leaving the last roll stand of said rolling mill, with said one roll stand having a pair of work rolls and a roll force measurement device, the combination of

means for determining a desired delivery gauge of said one roll stand in relation to said desired delivery gauge, the speed setting of said one roll stand and the speed setting of said last roll stand,

means for determining the actual delivery gauge of said one roll stand in relation to a predetermined operation of said one roll stand,

means for determining a gauge error in the work strip leaving said one roll stand in relation to said desired delivery gauge of said one roll stand and said actual delivery gauge of said one roll stand and,

means for controlling the roll opening setting of said pair of work rolls of said one roll stand in relation to said gauge error.

7. The apparatus of claim 6, with said means for determining a desired delivery gauge of said one roll stand being operative before said work strip passes through the last roll stand of said rolling mill.

8. The apparatus of claim 6, with said means for determining the actual delivery gauge of said one roll stand being operative after said work strip passes through said one roll stand.

9. The apparatus of claim 6, with said desired delivery gauge of said one roll stand being determined in relation to the speed setting of said one roll stand before said work strip passes through said rolling mill.

10. The apparatus of claim 6, with said desired delivery gauge of said one roll stand being determined before said work strip passes through said rolling mill and with said actual delivery gauge of said one roll stand being determined after said work strip passes through said one roll stand.

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