United States Patent [19]

King et al.

[11] **3,787,667**

[45] **Jan. 22, 1974**

[54] **COMPUTER CONTROLLED METAL ROLLING MILL**

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[22] Filed: **Jan. 6, 1971**

[21] Appl. No.: **104,382**

[52] **U.S. Cl.** **235/151.1,** 72/8, 444/1

[51] **Int. Cl.** **G06f 15/46,** B21b 37/14

[58] **Field of Search** 235/151.1, 151, 150.1; 340/172.5; 72/7, 8; 444/1

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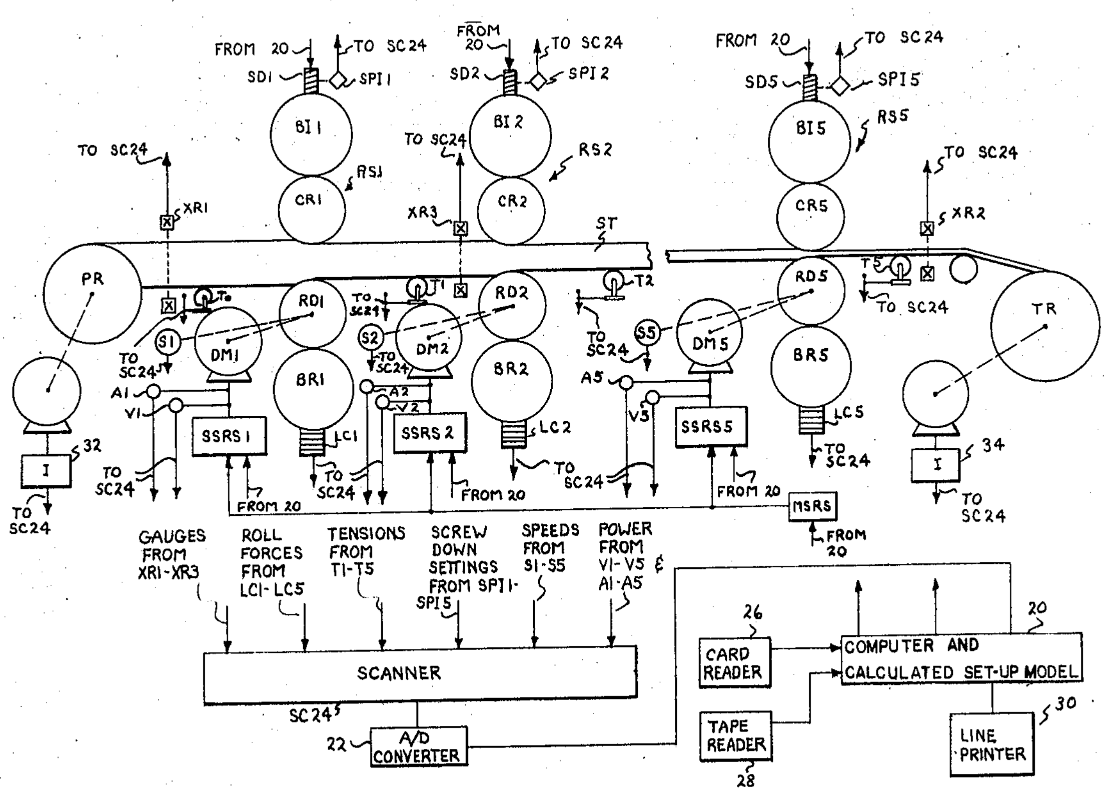
[57] **ABSTRACT**

A computer controlled cold metal rolling mill is described wherein force and power curves stored within a calculated set-up model are adapted in response to sensed on-line rolling conditions to optimize power distribution between stands of the mill. For maximum storage capacity and simplification of the adaptive feedback calculations, the power curves are stored in the set-up model by two numerals representing the slope and base of a graph of power per unit volume flow against elongation as plotted on log log-log scales. Thus, only the slope and base of the actual power curve need be calculated during operation to modify the power curves stored within the set-up model. Adaptation of the force curves within the model is accomplished in association with feedback logic for adjusting the value of the coefficient of friction (assumed for calculation of force) by an amount proportional to the difference between the observed and calculated force. Both fast and slow feedback terms are employed for this purpose with the fast feedback term approaching zero asymptotically as the slow feedback term approaches a coefficient of friction equating the measured and predicted forces. Integral scanning and comparison also are utilized to evaluate the quality of adaptive data before updating the stored curves. Also disclosed is the storage of mill stretch curves as functions of roll force against mill stretch for nominal constant roll force per unit width with a modifier being employed to correct for variations in force per unit width from nominal.

7 Claims, 7 Drawing Figures



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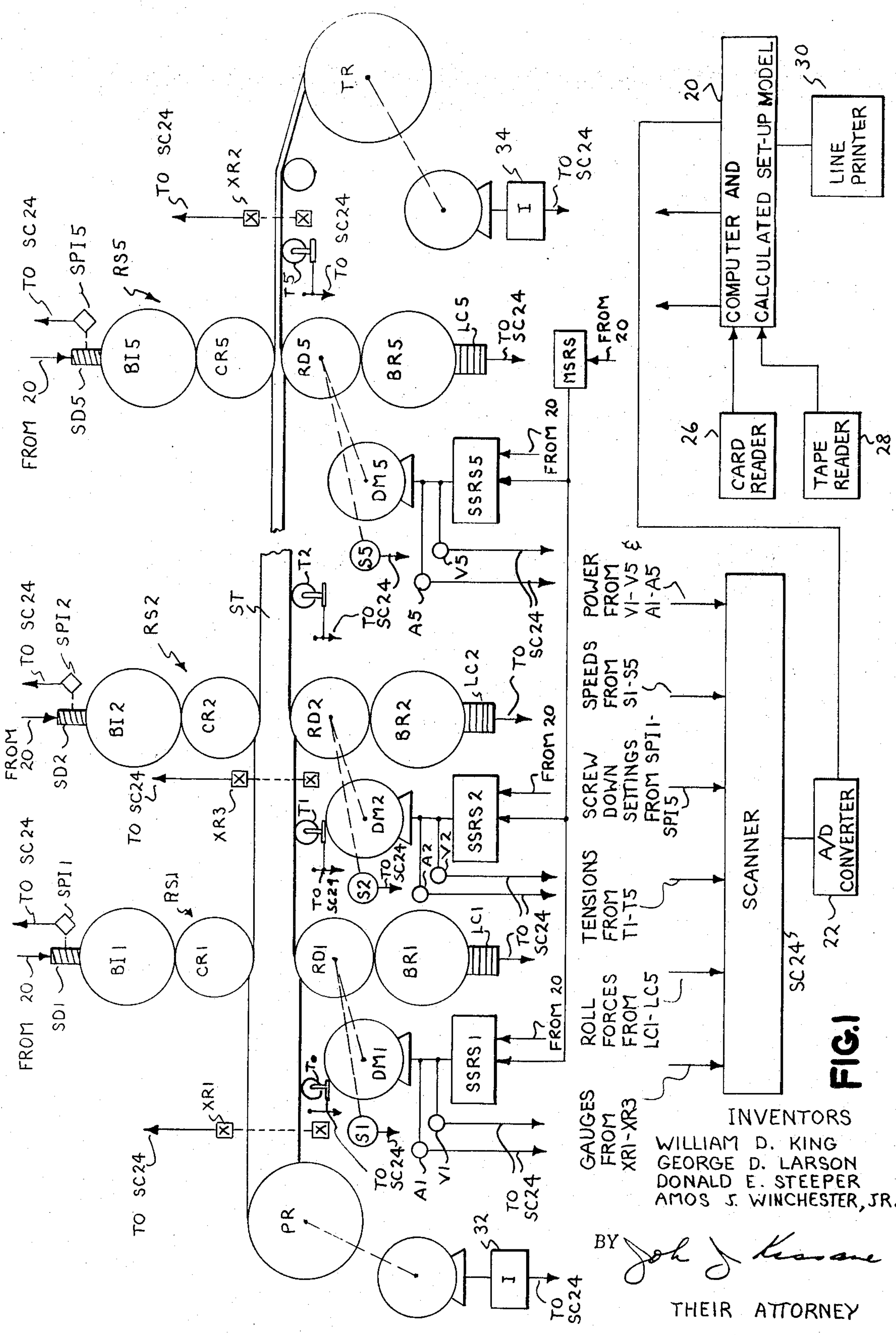

FIG.1

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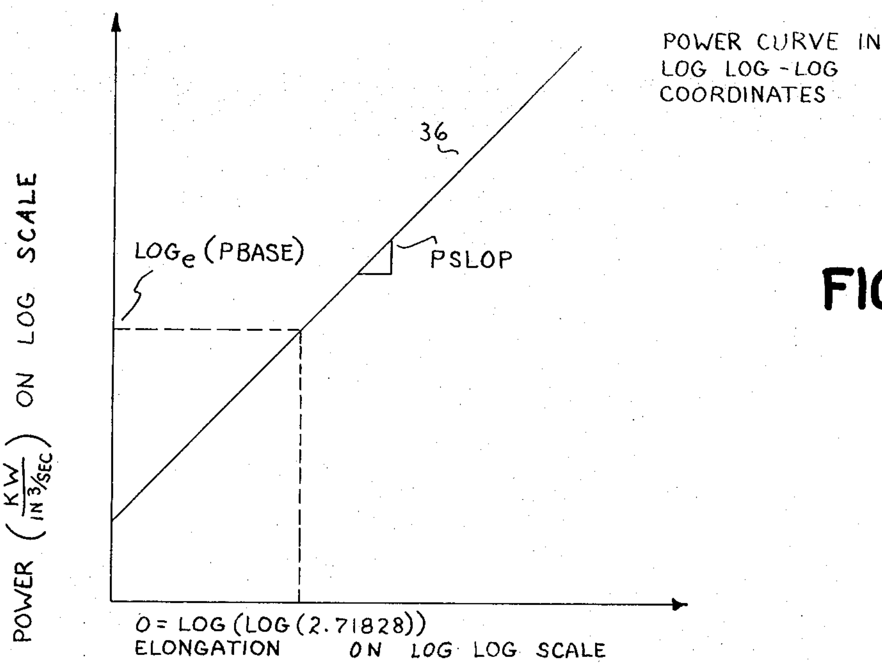
POWER CURVE IN LOG LOG-LOG COORDINATES
36
PSLOP
LOGe (PBASE)
POWER $\left(\frac{KW}{IN^3/SEC}\right)$ ON LOG SCALE
O = LOG (LOG (2.71828))
ELONGATION ON LOG LOG SCALE

FIG.2

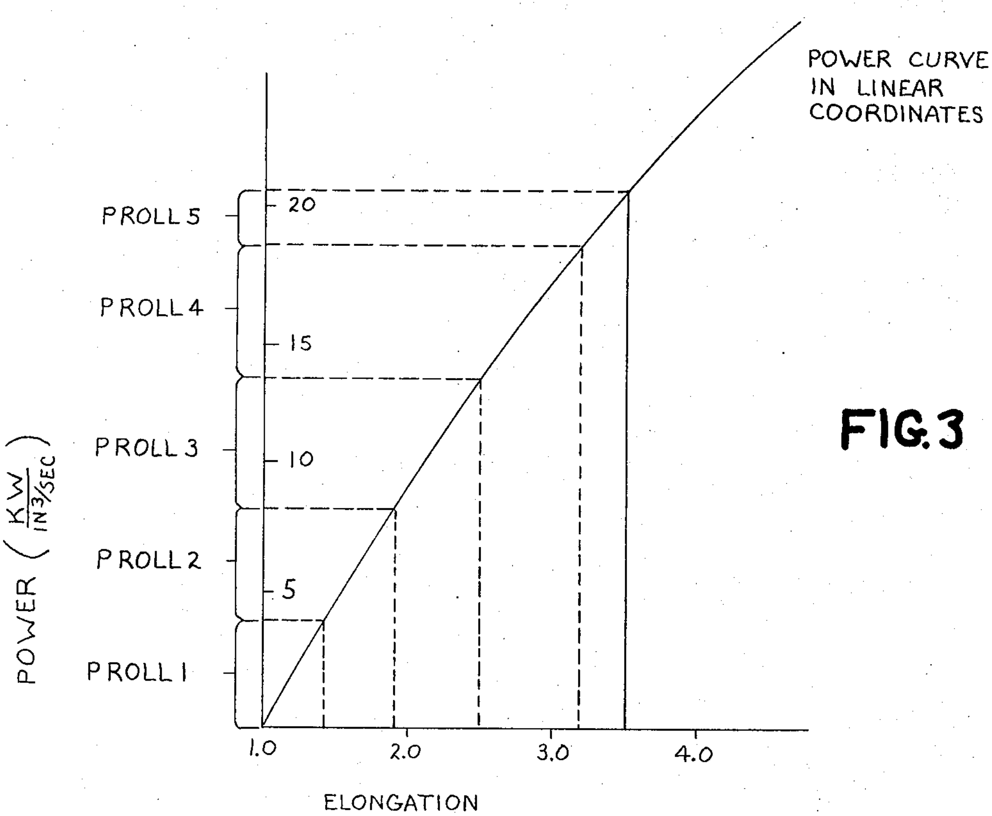
POWER CURVE IN LINEAR COORDINATES
PROLL 5
PROLL 4
PROLL 3
PROLL 2
PROLL 1
20
15
10
5
POWER $\left(\frac{KW}{IN^3/SEC}\right)$
1.0
2.0
3.0
4.0
ELONGATION

FIG.3

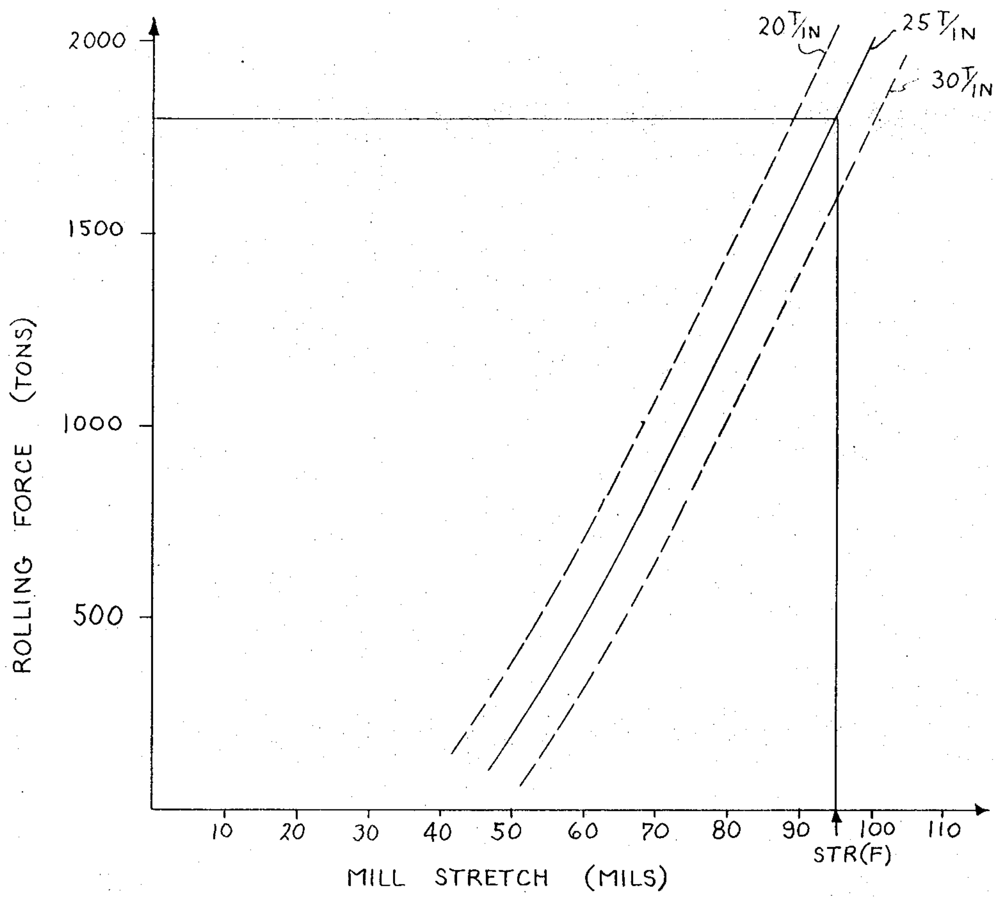
20 T/IN
25 T/IN
30 T/IN
2000
1500
1000
500
ROLLING FORCE (TONS)
10 20 30 40 50 60 70 80 90 100 110
STR(F)
MILL STRETCH (MILS)

FIG. 4

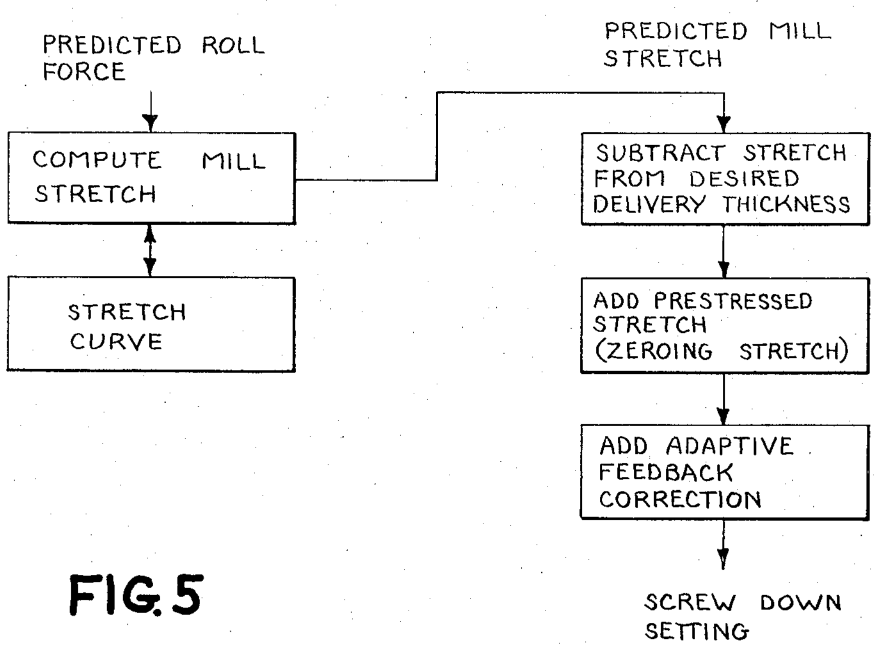
PREDICTED ROLL FORCE
COMPUTE MILL STRETCH
STRETCH CURVE
PREDICTED MILL STRETCH
SUBTRACT STRETCH FROM DESIRED DELIVERY THICKNESS
ADD PRESTRESSED STRETCH (ZEROING STRETCH)
ADD ADAPTIVE FEEDBACK CORRECTION
SCREW DOWN SETTING

FIG. 5

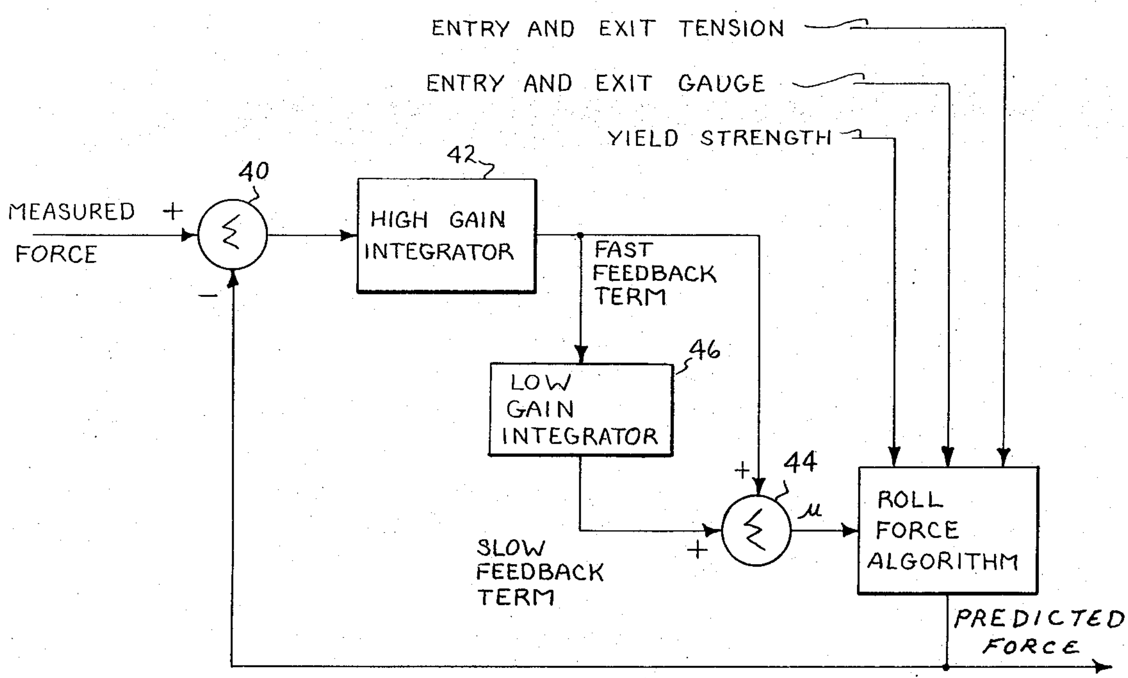
ENTRY AND EXIT TENSION
ENTRY AND EXIT GAUGE
YIELD STRENGTH
42
40
MEASURED FORCE
+
-
HIGH GAIN INTEGRATOR
FAST FEEDBACK TERM
46
LOW GAIN INTEGRATOR
+
44
μ
+
SLOW FEEDBACK TERM
ROLL FORCE ALGORITHM
PREDICTED FORCE

FIG. 6

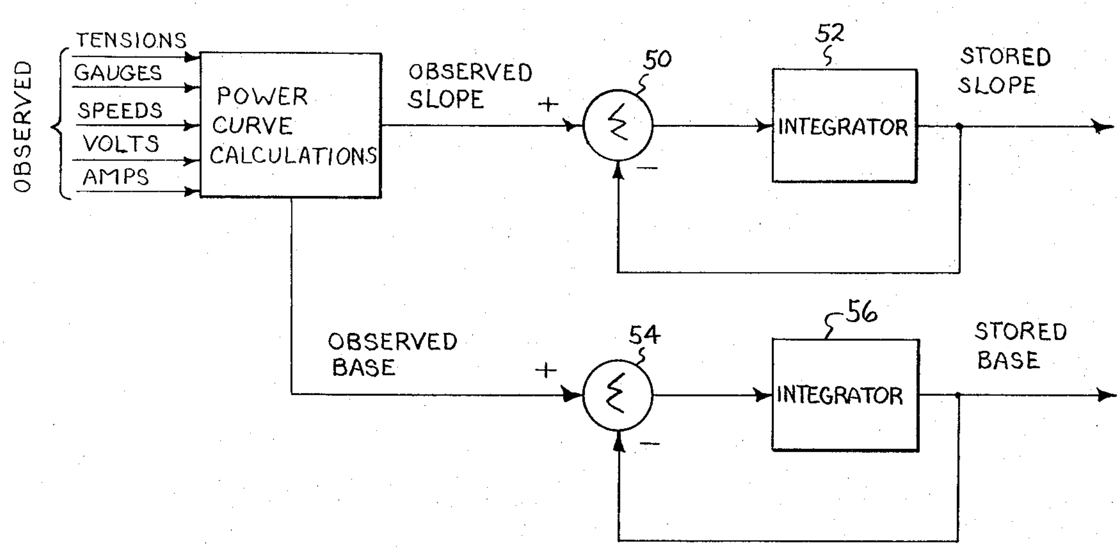
OBSERVED
TENSIONS
GAUGES
SPEEDS
VOLTS
AMPS
POWER CURVE CALCULATIONS
OBSERVED SLOPE
+
50
-
52
INTEGRATOR
STORED SLOPE
OBSERVED BASE
+
54
-
56
INTEGRATOR
STORED BASE

FIG. 7

COMPUTER CONTROLLED METAL ROLLING MILL

This invention relates to computer controlled metal rolling mills and in particular, to a computer controlled cold metal rolling mill having adaptive feedback to adjust stored variables within calculated set-up models in response to data measured during on-line operation.

Because high speed rolling of metals require the precise and rapid adjustment of a multitude of interdependent controls to produce high quality finished products, operator control of rolling mills is extremely difficult and substantially all recent rolling mill installations have a control computer to supervise the rolling process. When the metal sheet is rolled in tandem stands, the computer typically includes a calculated set-up model wherein is stored empirically or theoretically determined data defining relationships between critical parameters, e.g., variations in power with either strip thickness or elongation. This stored data is interrogated both during the initial set-up and operation of the mill to determine such factors as the optimum speed for each stand, the draft between rolls and the rolling power distribution between stands.

For a rolling mill to be capable of handling metals having diverse physical characteristics (such as hardness variations in steel sheet produced by diverse carbon contents in the steel), the number of curves required for storage within the set-up model to define relationships between critical parameters generally increases as a multiple of the different grades of metal to be rolled. Moreover, because each stored curve must be identified by an average of 10-15 points along the curve for reasonable accuracy in interpolating along the curve, a large memory bank generally has been required in the calculated set-up model to store sufficient process control information. In accordance with the teachings of this invention, however, the number of points required to define the power curve for control purposes is significantly reduced to only two indicia per curve. Moreover, mill stretch data is stored as a single curve plus a modifier (to correct for variations in force per unit width) rather than a plurality of curves.

During on-line operation, measured characteristics along the mill often will vary slightly from predicted characteristics requiring updating of the set-up model by adaptive feedback to optimize the accuracy of the model predictions for the rolling process. To inhibit alteration of the stored information by transient or incorrectly sensed data, the sensed data customarily has been evaluated to determine whether the data falls within a permitted tolerance before utilization for corrective purposes. While the foregoing data evaluation technique limits traumatic adjustments of the stored data, use of slightly incorrect data is not inhibited. In the optimized adaptive feedback system of this invention, the data sensed during on-line operation is averaged and stored for comparison with subsequently sensed data before being employed to up-date the information stored within the calculated set-up model. Thus, only during steady state conditions will data be acceptable for adaptation of the stored curves within the calculated set-up model.

Another feature of this invention resides in the employment of a feedback regulator system to alter variables assumed for calculation of on-line forces when the calculated forces fail to correspond with actual measurements in the rolling mill. The regulator system employs parallel feedback logics having fast and slow responses, respectively, to alter the assumed variables with the output signal from the fast feedback logic decreasing asymptotically towards zero as the output signal from the slow feedback logic approaches a correct assumption for the variable employed in the calculations. Thus, while control processes heretofore employed to calculate data from both assumed and measured variables normally iterate upon the assumed variable when the calculated data differs from measured data, the dual feedback system employed in this invention approaches the correct value of the variable by the cumulative effect of a rapid correction effected by a fast feedback term and a sustained correction effected by a slow feedback term.

Although the novel features of this invention are described with particularity in the appended claims, a more complete understanding of the principles of the invention may be obtained from the following detailed description of the specific embodiment illustrated in the appended drawings wherein:

FIG. 1 is a schematic view illustrating a cold rolling mill in accordance with this invention,

FIG. 2 is a graph illustrating the linear variation of power per unit volume flow versus elongation obtained when the functions are plotted on a log log-log scale,

FIG. 3 is a graph illustrating the adaptation of the power curve of FIG. 2 to linear co-ordinates,

FIG. 4 is a graph illustrating the variation of rolling force with mill stretch for a given force per unit width as stored within the calculated set-up model, of the computer

FIG. 5 is a flow chart illustrating adjustment of the screw down setting at a roll mill stand as determined from the rolling force at the stand,

FIG. 6 is a block diagram illustrating the force feedback scheme utilized in this invention and,

FIG. 7 is a block diagram illustrating the power feedback scheme of this invention.

A cold rolling mill in accordance with this invention is illustrated in FIG. 1 and generally comprises five individual rolling stands RS1–RS5 arranged in tandem for incrementally reducing the gauge of sheet metal strip ST as the strip passes between drive rolls RD1–RD5 and associated confronting rolls CR1–CR5 forming each respective stand. Because intermediate rolling stands RS2–RS4 are identical in configuration, rolling stands RS3 and RS4 have been omitted from FIG. 1 for clarity. Backing rolls BR1–BR5 butt the faces of drive rolls RD1–RD5 at each stand to inhibit bending of the drive rolls during gauge reduction while backing rolls BI1–BI5 perform a similar function for rolls CR1–CR5. In conventional fashion, the positions of backing rolls BI1–BI5 are controlled by screw down adjustments SD1–SD5 which are individually adjustable to regulate the gauge reduction at each stand while drive motors DM1–DM5 provide the required torque for drive rolls RD1–RD5 to move strip ST longitudinally within the mill at a predetermined speed.

Control of the rolling process is supervised by computer **20** typically having one or two central processing units with a core memory of about 400,000 bits and a working drum memory for the additional storage of one to three million bits of information. An analog to digital converter **22**, in association with a high speed scanner

SC24, provides the proper conditioning for entry to the computer of parameters sensed during on-line operations. The computer also normally would include such peripheral equipment as a card reader **26** and a paper tape reader **28** to input information relative to the order being processed while information supplied to or calculated by the computer may be visually recorded by line printer **30**. Computers having these characteristics are commercially available and can be obtained from the General Electric Company under the trademark GE/PAC 4020.

Among the process parameters fed to computer **20** for control purposes is the gauge of sheet metal strip ST as measured by X-ray devices XR1–XR3 situated at the entry and exit of the strip from the rolling mill and after the first rolling stand, respectively. If desired, the gauge of the sheet metal strip can be measured as the strip exits each stand although such precise measurement of strip gauge throughout the mill normally is not required. Load cells LC1–LC5 underlie backing rolls BR1–BR5 of each stand to generate an output signal proportional to mill stand roll force for transmittal to computer **20** through scanner SC24 while the tensiometers T1–T5 positioned intermediate the rolling stands produce output signals which are fed to the computer to indicate the tension in sheet metal strips ST. Other process control parameters fed to the computer through analog to digital converter **22** and high speed scanner SC24 include the speed of drive motors DM1–DM5 as measured by tachometers S1–S5 mechanically coupled to each drive roll, the screw down settings as measured by screw position indicators SPI-1–SPI5, and the power inputs to the drive motors as measured by ammeters A1-A5 and voltmeters V1–V5.

The relative speeds of each stand is adjustable by reference servos SSRS1–SSRS5 under the control of computer **20** while a master speed reference servo MSRS permits acceleration and deceleration of the mill as a unit in response to a control signal from the computer. If desired, such information as the footage of strip passed through the mill (as measured by tachometer S5 geared to the drive roll of stand RS5), current flow to payoff reel PR and take-up reel TR (as measured by ammeters **32** and **34**, respectively), and roll bending force [as measured by suitable bending pressure sensors (not shown)] also can be fed to computer **20** to permit supervision of the cold rolling process.

At the initiation of operation, a control card containing such information as the order number, width, entry gauge, desired exit gauge, steel specifications, chemistry, hot mill finishing practice, coil weight and the hardness group of sheet metal strip ST is entered directly into the computer by a suitably punched card. The card also can contain information concerning the load factor for any of the five stands which would limit the power available to the stand. After the information entered into the computer by card has been checked for reasonableness, the mill set-up is calculated from mathematical models stored within a calculated set-up model of the computer to optimize the distribution of power to drive motors DM1–DM5 and the roll force applied to the strip by screw down adjustments SD1-SD5.

The mathematical power model employed to calculate power distribution within the mill contains a plurality of, e.g., as many as forty, diverse power curves representing empirically determined relationships between elongation and power per unit volume flow (hereinafter power curves) for steels having different hardness classifications. Typically, these power curves are nonlinear and require storage of 10 to 15 points for each curve within the power model memory to define the desired relationship with reasonable accuracy. However, by plotting power per unit volume flow against elongation on a log log-log scale, linear power curves are obtained (as illustrated by the single power curve **36** of FIG. **2**) permitting storage of each power curve within the power model by indicia of the intercept and slope of the power curve.

The linear relationship between elongation and power per unit volume flow on a log log-log scale indicates the existence of the following mathematical relationship between the plotted variables:

$$KWSI = PBASE \times [\log_e (elong)]^{PSLOP} \text{ wherein}$$

KWSI is power per unit volume flow in kw sec./cu. in.,

PBASE is the chosen power base for storage of the linear function within the power model and typically is set equal to the value of KWSI when elongation is equal to e, the base of the natural logarithm, i.e., 2.7183; and

PSLOP is the slope of the power curve when plotted on log log-log co-ordinates.

Because only a proportionality factor, K, is required to convert kw sec./cu.in. to horsepower hr./ton, it will be appreciated that the power curves also could be stored by indicia of the base and slope of empirically determined relationships between elongation and horsepower hr./ton as plotted on a log log-log scale. While the power curves desirably are stored by the slope and base of the curves on a log log-log scale, these curves preferably are converted to rectangular co-ordinates (as illustrated by the graph of FIG. **3**) to simplify calculations after the desired operational curve has been identified from card entered parameters such as the hardness of the metal strip being rolled.

After identification of the operational power curve, the total reduction power to produce the elongation in strip ST resulting from the desired gauge reduction (assuming constant volume flow, i.e., the product of the width, thickness and speed of the strip at any one stand is assumed equal to the product of the width, thickness and speed at any other stand) is determined from the power curve. This reduction power, however, must be modified by power losses within the mill (a factor of the roll surface speed as determined by tachometers S_1–S_5) and power transmitted axially through the strip (as determined by the difference in tension on the entry and delivery sides of each roll) to calculate the total power requirements of the mill. Assuming top mill delivery speed and knowing volume flow from the assumed speed, strip width and exit gauge, the total required rolling power (if one were to temporarily ignore losses) may be expressed in kilowatts by the following formula:

PTREQ = (ROLLPOWT + TENSFAC (1) − TENSFAC (6))· VOLFLOW wherein ROLLPOWT is the total required rolling power per unit volume flow,

TENSFAC (1) is the entry tension power per unit volume flow in KW/in.^{3}/sec. at stand RS1, TENSFAC (6) is the exit tension power per unit volume flow in KW/in.^{3}/sec. at stand RS5, and

VOLFLOW is volume flow in in.^{3}/sec.

The rolling mill of FIG. 1 is tension regulated so that the mill runs at a predetermined tension, e.g., 15,000 psi dependent upon such factors as the width, thickness and hardness of the strip, assuming a perfect set-up wherein the gauges are identical to the predicted gauges and the gauge control does not adjust the pounds tension. Proper tensions are important because excessive tension can cause strip breakage or slippage in the roll bite while insufficient tension can allow the strip to move laterally or become wavy. The desired tension setting therefore is fixed by the computer. The delivery gauges at each stand, however, are adjusted by the computer to provide an equal ratio of shaft power to power available at all five stands. Thus, the shaft power at any stand (K) may be defined by the formula:

$$\text{PSTAND (K)} = \text{PTREQ/PTAVAIL} \cdot \text{PAVAIL (K)}$$

wherein

PTREQ is total mill power required in KW,

PTAVAIL is total mill power available in KW, and

PAVAIL (K) is power available at stand K in KW.

Because only a portion of the shaft power at the stand is utilized for gauge reduction of strip ST (with the remainder being required to overcome mill losses and the difference between entry tension power and delivery tension power), the stand rolling power per unit volume flow at any stand (K) is determined from the formula:

$$\text{PROLL } (K) = \text{PRED (K)/VOLFLOW} = (\text{PSTAND } (K) - \text{PML (K)}) \div \text{VOLFLOW} - \text{TENSFAC } (K) + \text{TENSFAC } (K+1)$$

wherein

PRED (K) is reduction or rolling power in KW at stand (K),

VOLFLOW is volume flow in in.^{3}/sec.

PSTAND (K) is total stand shaft power in KW,

PML (K) is stand mechanical losses in KW at stand (K) (as measured by running the mill empty at various speeds with a nominal rolling force),

TENSFAC (K) is entry tension in KW/in.^{3}/sec., and

TENSFAC (K+1) is exit tension from stand K in KW/in.^{3}/sec.

The cumulative power per unit volume flow through any stand of the mill is determined by summing the roll power of each of the preceding stands of the mill with the power roll of the stand in question and the elongation corresponding to the cumulative power is determined from the graph of FIG. 3. The five delivery gauges of each stand in the mill are then calculated assuming constant volume flow to determine the initial draft for each stand of the mill.

When load factors placing a limitation on the power available to any stand are entered into the computer by a punched card or manually from a data station, the mill set-up unloads any stand in proportion to the load factor associated with that stand by assuming a smaller drive motor at the stand, i.e., assuming a drive at the stand equal to the actual drive multiplied by the load factor for the stand. When the power then is divided between stands (as heretofore explained), the rolling power is reduced at the stand having the load factor allowing the stand to take less than an equal power division.

After the delivery gauges have been calculated, the draft limits on stands 1 and 5 are checked to assure that the gauge reductions at these stands are within the allowable draft limits for these stands based upon factors such as entry gauge, exit gauge, strip width and the surface finish desired for the strip. Should the maximum draft limit on stand RS1 be exceeded, the computer sets the elongation out of stand RS1 at the predetermined maximum for the stand. The rolling power corresponding to the maximum elongation then is determined from the corresponding power curve, i.e., the power curve of FIG. 3, and this power is subtracted from the total power required for the mill to effect the desired total reduction in gauge of strip ST. The available power of stand RS1 then is substracted from the total available power and the power is redivided (in the manner previously described) as if the mill were a four stand mill. Similarly, if the draft limit on stand RS5 were exceeded, the computer sets the elongation out of stand RS4 (since the elongation of stand RS5 then becomes fixed at the allowable maximum), subtracts stand RS5's contribution to the total available and required power, and redivides the power as if the mill were a four stand mill (or a three stand mill if the draft limit of stand RS1 also had been exceeded).

Should the draft limit on any of intermediate stands RS2–RS4 be exceeded, e.g., should the draft on stand RS3 be exceeded, computer **20** places as much of the excess draft on stand RS1 as permissible with any of the excess draft not absorbable by stand RS1 being shifted to stand RS2. Should stand RS3 still have an excess draft, the stand is set at maximum draft and any remaining draft is placed on stand RS4. Any of the draft not absorbable by stand RS4 then is shifted to stand RS5. If stand RS5 does not exceed the draft limit of the stand for the desired finish on the strip, the set-up is satisfactory. If the draft limit of stand RS5 is exceeded by the foregoing shift in draft between stands, rolling is not possible in accordance with the requested schedule.

Since the strip width, exit gauge, and exit speed of the mill are known, the delivery speed of sheet ST and the motor speed at each stand can be calculated. Assuming constant mass flow through the mill and constant width, the speed in rpm of the drive motor at any stand can be calculated by computer **20** from the formula:

$$\text{RPM } (K) = \text{VS } (K)/\pi \cdot \text{DIAM } (k)$$

wherein

VS (K) is the delivery speed of strip ST at the stand, and

DIAM (k) is the work roll diameter in inches.

If any motor is above a predetermined maximum speed, the whole mill must be slowed down by master speed reference servo MSRS.

Because the original power calculations did not include mill losses since stand delivery speeds were unknown, the ratio of required stand power to available stand power must again be checked by computer **20** utilizing mill losses empirically determined when the mill was run empty at the calculated operational mill speed. If one or more stands require more power than is available, the mill delivery speed is lowered and the power is redivided as heretofore described. If all stands are within the permissible draft limits, the power balance on stands RS2–RS4 is again checked to assure the stands are satisfactorily balanced. The tensiometer settings then can be calculated from the desired strip tension within the mill and power proportioning is terminated.

If the delivery speed of stand RS5 is limited because stand RS1 has reached the upper speed limit of the stand, higher mill exit speeds often are attainable by reducing the draft taken in stand RS1 while maintaining the stand at maximum speed. To achieve this result, a draft of stand RS1 is chosen at a value (in excess of the minimum allowable draft for the stand) which raises the required power of any other stand to somewhat less than maximum stand power, e.g., 90 percent of stand power, and the power is redivided among the remaining stands.

The screw down setting at each stand is determined by calculating rolling force and computing the mill stretch corresponding to the calculated rolling force from empirically determined curves representing the variation of rolling force with mill stretch for a constant force per unit width as illustrated in FIG. **4.** To calculate rolling force at any stand, computer **20** enters the entry and delivery tension at the stand, the yield strength of the strip, the hardness of the rolls and an assumed coefficient of friction into equations, such as are described by C.R. Bland et al. in an article entitled "The Calculation of Roll Force and Torque in Cold Strip Rolling with Tensions" published in the Institution of Mechanical Engineers Proceedings, Vol. 159, p. 144, 1948. The calculated force then is compared to the minimum and maximum rolling force per unit width stored within the computer and if the calculated force lies within the stored force limits, the calculated rolling force is employed to obtain mill stretch from the curve of FIG. **4.** Should the assumed coefficient of friction be too low resulting in a predicted rolling force less than the stored minimum, the minimum rolling force would be employed to determine mill stretch. Similarly, if the assumed coefficient of friction is too high resulting in no solution to the rolling force algorithm equations, mill stretch corresponding to the maximum force would be utilized. Other known methods suitable for calculating rolling force in accordance with this invention are described in an rticle by A.J.F. McQueen entitled "Finding a Practical Method for Calculating Roll Force in Wide Reversing Cold Mills" published in the June, 1967 edition of Iron and Steel Engineer on pages 95–110.

Although mill stretch can be stored within the calculated stretch set-up model by a plurality of curves illustrating the variation of rolling force with mill stretch for diverse widths of sheet ST, the number of curves required for storage is significantly reduced when stretch is plotted against rolling force for a constant rolling force per unit width of sheet. Desirably, the rolling force versus stretch curve is determined empirically as part of the start-up procedure and the constant force per unit width line chosen for storage is determined from observation of prior rolling conditions. Thus, if the mill previously has tended to roll with a force of 25 tons/inch, only the stretch curve corresponding to this rolling force density would be stored within the calculated set-up model with the stretch for differing rolling forces per unit widths being calculated by computer **20** in accordance with the formula:

$$\text{STRETCH} = \text{STR (F)} + \text{MODIFIER (F/width)} - \text{(Nom.Tons/inch)}$$

wherein

STR (F) is the value of stretch obtained from the stored stretch curve,

MODIFIER is a stored empirically determined correction constant,

F/width is the actual rolling force per unit width in tons per inch, and,

Nom. Tons/inch is the rolling force per unit width of the stored curve in tons/inch.

After computing mill stretch produced by the calculated rolling force, the computed stretch is substracted from the desired delivery thickness (as illustrated in FIG. **5**) and the pre-stressed stretch (i.e., the stretch imposed on the mill housing at the time of zeroing screw position indicators SPI1-SPI5) is added to the difference to determine screw setting. During operation of the mill, an adaptive feedback correction also would be added to the stretch to compensate for such factors as roll heating and wear (as will be more fully explained hereinafter).

As strip ST is threaded through the first stand RS1 to initiate actual rolling, computer **20** is fed a measurement of the actual force on stand RS1 by load cell LC1 while X-ray gauges XR1 and XR3 provide the computer with the entry and exit gauges of the strip. The computer then computes the force on stand RS1 from the measured gauges, the force and the scheduled steel grade to verify that the hardness of sheet ST is comparable to the sheet hardness fed to the computer through card reader **26.** Should the force calculated utilizing the scheduled hardness of the strip differ from the actually measured force, a correction factor is generated to modify the predicted force and therefore the screw setting at each stand. If the actual gauge of the strip differs by more than a predetermined amount, e.g., 5 mils, from the scheduled entry gauge, the computer redrafts the mill to determine new speed, tension and roll position settings for each stand.

During actual rolling of strip ST, the force, power, and screw down setting of each mill stand can be adapted to actual operating conditions to optimize the quality of the rolled sheet. Parameter optimization is performed before rolling each coil of strip by using observed mill measurements during rolling of the previous strip.

Force adaptation for each stand is achieved in accordance with the adaptive force feedback technique illustrated in FIG. **6** wherein, for example, the predicted force value for stand **1** is calculated from the known yield strength, the measured entry thickness as observed by X-ray **XR1**, the measured delivery thickness as observed by X-ray **XR3**, the measured entry tension detected by tensiometer To, the measured delivery tension sensed by tensiometer **T1**, and an assumed coefficient of friction utilizing a roll force algorithm such as is described in the heretofore cited Bland et al or McQueen publications. The predicted force then is compared to the force as actually measured by load cells LC1–LC5 in software summing junction **40** to generate an error signal having an amplitude corresponding to the difference between the compared signals whereupon the error signal is fed into high gain integrator **42** to obtain a fast feedback term which is applied to software summing junction **44.** Integrators are well known in the art and function to change value at each event point (e.g., once each coil) by an amount proportional to the signal applied to the integrator, the magnitude of the proportionality being the gain of the integrator. The integrators used in the illustrative embodiment of the invention may be comprised of suitable basic computer hardware such as a counter which performs the integration function under appropriate software control. It is, however, to be recognized that, as is well known in the art, hardwired equivalents such as an operational amplifier with a capacitor feedback exist to perform the integration function. The fast feedback term generated by integrator **42** also is fed to low gain integrator **46** to generate a slow feedback term which term is applied to software summing junction **44** to produce an output signal proportional to the sum of the fast and slow feedback terms for adjustment of the assumed coefficient of friction. The revised coefficient of friction then is stored in the memory of computer **20** to be used for more accurate force predictions on subsequent coils. As the slow feedback term generated by integrator **46** approaches a value producing a coefficient of friction equating the predicted force with the measured force, the fast feedback term (proportional to the difference between these values) approaches zero asymptotically.

Although adaptive feedback has been employed heretofore to up-date stored information in response to actually sensed operating conditions (see, for example, R.G. Beadle et al. patent RE 26,996), the correctness of the feedback information typically has been detrmined by observing whether the information falls within certain predetermined tolerances stored within computer **20.** Contrary to such systems, information feedback in accordance with this invention is digitally filtered over a long period, i.e., by repeatedly summing data sensed by scanner SC**24** and dividing the summed data by the number of scans, to obtain an average value of the feedback data. This average value then is stored and compared with subsequently observed data to determine whether or not the data is statistically stationary. After a set of measurements is determined to be stationary, it is further checked for reasonableness before being used. During normal steady state rolling conditions, the data should vary slowly over the sensing interval and adaptation of the data stored within the calculated set-up model is allowed only when the correlation between the average data sensed on a series of scans and the previously sensed average data is within an allowable tolerance.

To avoid detection of only repetitive peaks of cyclically changing data, it is highly desirable that the number of scans be varied with the speed of strip ST in the mill, e.g., although eight scans may be suitable to average data at mill speeds of 4,000–5,000 ft./min., as many as **64** scans may be desirable to average data at lower mill speeds of 1,500–1,600 ft./min.. Because the scan rate of scanner SC**24** is fixed, the increased number of scans at lower mill speeds results in data detection over an elongated period thereby reducing the possibility for error due to temporary synchronism between the rate of change of the observed data and the scan rate.

Adaptation of the stored power curves is accomplished by the technique illustrated in FIG. **7** wherein the tension of strip ST as observed by tensiometers T1–T5, gauge of the strip as measured by X-ray gauge XR1–XR2, speed as measured by tachometers S1–S5, and voltage and amperage to each drive motor are fed to the computer **20** to calculate power data points (e.g., utilizing techniques described in an article by A.J. Winchester entitled "How to Get and Use Rolling Mill Power Data" published in the July, 1961 edition of IRON and STEEL ENGINEER, page 2. After plotting these points on a log log-log scale, a least squared error line is passed through the calculated points to define the calculated power curve actually observed during rolling. The slope of the calculated power curve then is detected and fed to software summing junction **50** to produce an error signal proportional to the difference between the slope of the power curve stored within the set-up model and the slope of the calculated power curve. After the error signal is passed through software integrator **52,** the slope of the stored power curve is altered by an amount proportional to the error signal with the output from integrator **52** also being fed back to summing junction **50** to provide a stable software regulator. In a similar fashion, the base of the calculated power curve is compared to the base of the stored power curve in summing junction **54** to produce an error signal proportional to the difference therebetween. The error signal then is fed through software integrator **56** before being employed to adaptively update the base of the stored power curve. The newly revised base also is fed back to summing junction **54** for comparison with the base of subsequently calculated power curves to up-date the stored curves on a continuous basis.

Adaptation of the zero screw positions to compensate for wear and heating of the rolls is accomplished by calculating new screw settings from the forces and gauges fed to computer **20** utilizing the stored mill stretch curve (as previously explained with reference to FIG. 4). The predicted screw setting then is compared with the actual screw setting as observed by screwdown indicators SCI1–SCI5 and a portion of any difference between the compared settings is added as a correction factor to the next screw position calculation.

Although a specific preferred embodiment of this invention has been described, it will be apparent that many changes and modifications may be made without departing from this invention in its broader aspects. For example, tension regulation of the mill is not essential to practice the invention but rather the mill could be speed regulated, i.e., the tension that results from the mill set-up is a function of the mill set-up. Similarly, load cells LC1–LC5 could be positioned in an overlying, rather than an underlying,attitude relative to backing rolls BR1–BR5.

What we claim as new and desire to secure by Letters Patent of the United States is:

1. In a method of rolling metal of known composition from a first thickness to a second thickness within a plurality of tandem rolling stands by storing within a computer memory empirically determined power information corresponding to diverse metals to be rolled, proportioning the power requirements for each rolling stand from the stored power information for the rolled metal and adaptively up-dating the power information by feeding back to the computer measured parameters indicative of the actual power utilized during rolling, the improvement comprising employing data representing a plot of variables depicting the relationship between power per unit volume flow against elongation on a log log-log scale to provide a linear relationship between the plot of variables, calculating the slope and intercept of the linear relationship, storing the power information in the computer by indicia representing the slope and intercept of the linear relationship and accessing the stored slope and intercept indicia to obtain process parameters utilized to adjust the rolling stands and thereby control the rolling of the metal.

2. The method of rolling metal according to claim 1 further including converting, in said computer, the data representing the plot of variables depicting the relationship on a log log-log scale to data representing linear co-ordinates to be utilized in proportioning the power requirements between stands.

3. The method of rolling metal according to claim 1 further including calculating in the computer the relationship between power per unit volume flow and elongation from parameters observed during actual rolling of metal, determining the slope and intercept of a straight line passing through the power per unit volume flow relationship and adapting the stored power information to the calculated relationships by electrically comparing the slopes and intercepts of the stored information and the straight line and altering the stored slope and intercept by an amount proportional to the difference in the slopes and intercepts, respectively, of the straight line and the stored information whereby the stored power information is up-dated in accordance with the observed parameters.

4. The method of rolling metal of known composition from a first thickness to a second thickness according to claim 1 further including measuring a chosen process variable during on-line operation, electrically calculating in the computer the chosen variable from both actually sensed and assumed process parameters having a known relationship to said chosen variable, comparing said calculated variable with the measured variable and adjusting the assumed parameter upon a deviation between the measured and the calculated variables, said adjustment being accomplished by performing a dual integration function with respect to a signal proportional to the deviation, the two integration functions being performed using integration constants, and summing the output results of said dual integration function to obtain the total cumulative correction for said assumed parameter.

5. A method of rolling metal of known composition from a first thickness to a second thickness according to claim 1 further including storing within a computer memory information defining the relationship between rolling force and mill stretch for a single rolling force per unit width of metal being rolled, electrically calculating in the computer the actual force per unit width of metal at a rolling stand, modifying in the computer the stretch calculated from the stored information by an amount proportional to the variation between the actual rolling force per unit width and the rolling force per unit width of the stored information and adjusting the rolling force at a stand by an amount dependent upon the modified stretch.

6. In a method of rolling metal sheet of diverse composition and width to effect a change in the sheet thickness from a first thickness to a second thickness within a plurality of tandem rolling stands each having a controlled roll positioner to regulate the rolling force applied to the metal sheet at the stand by adaptively updating predetermined stored data, the improvement comprising storing within a computer memory information defining the relationship between rolling force and mill stretch for a single rolling force per unit width of metal sheet, calculating in the computer the rolling force per unit width of metal sheet at a rolling stand, modifying the stretch calculated from the stored information by an amount proportional to the difference in the actual rolling force per unit width and the force per unit width of the stored information and adjusting the rolling force at a particular stand by an amount dependent upon the rolling force as determined from the modified stretch.

7. In a method of rolling metal to effect a reduction in metal thickness from a first thickness to a second thickness wherein a critical process variable is measured during on-line operation and compared in a computer to a value of the variable as calculated from both actually sensed and assumed process parameters having known relationships to said variable, the improvement comprising adjusting said assumed parameter upon a deviation between the measured and the calculated critical process variables by an amount proportional to the deviation utilizing a dual integration function wherein each integration function has a different gain to generate output terms, said adjusting being accomplished by feeding the output term derived from the higher gain integration function as an input signal to the lower gain integration function, electrically summing the output terms of the dual integration functions to obtain a cumulative correction for said assumed parameter, and readjusting said assumed process parameter through the dual integration functions by an amount proportional to the deviation between the measured variable and the calculated variable utilizing the corrected assumed parameter.

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