

[54] **COMPUTER CONTROLLED ROLLING MILL**

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[52] U.S. Cl. **72/8, 235/151.1**
[51] Int. Cl. **B21b 37/00**
[58] Field of Search **72/7-10, 16**

[56] **References Cited**

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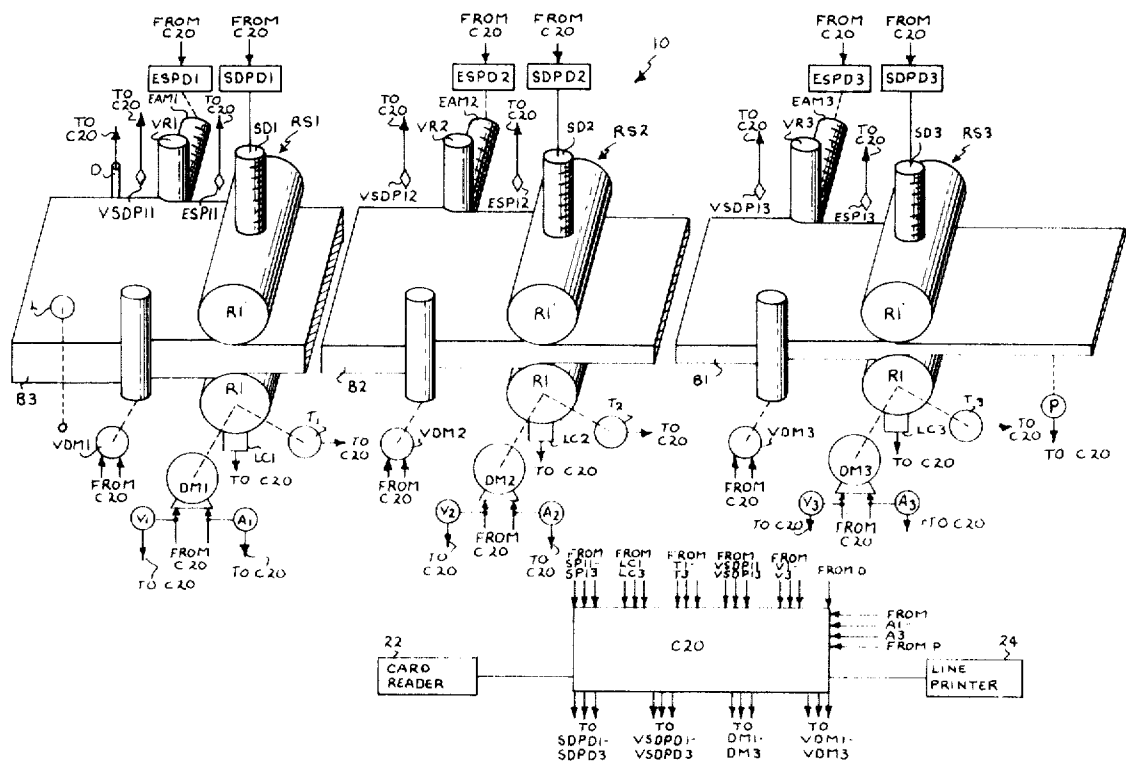
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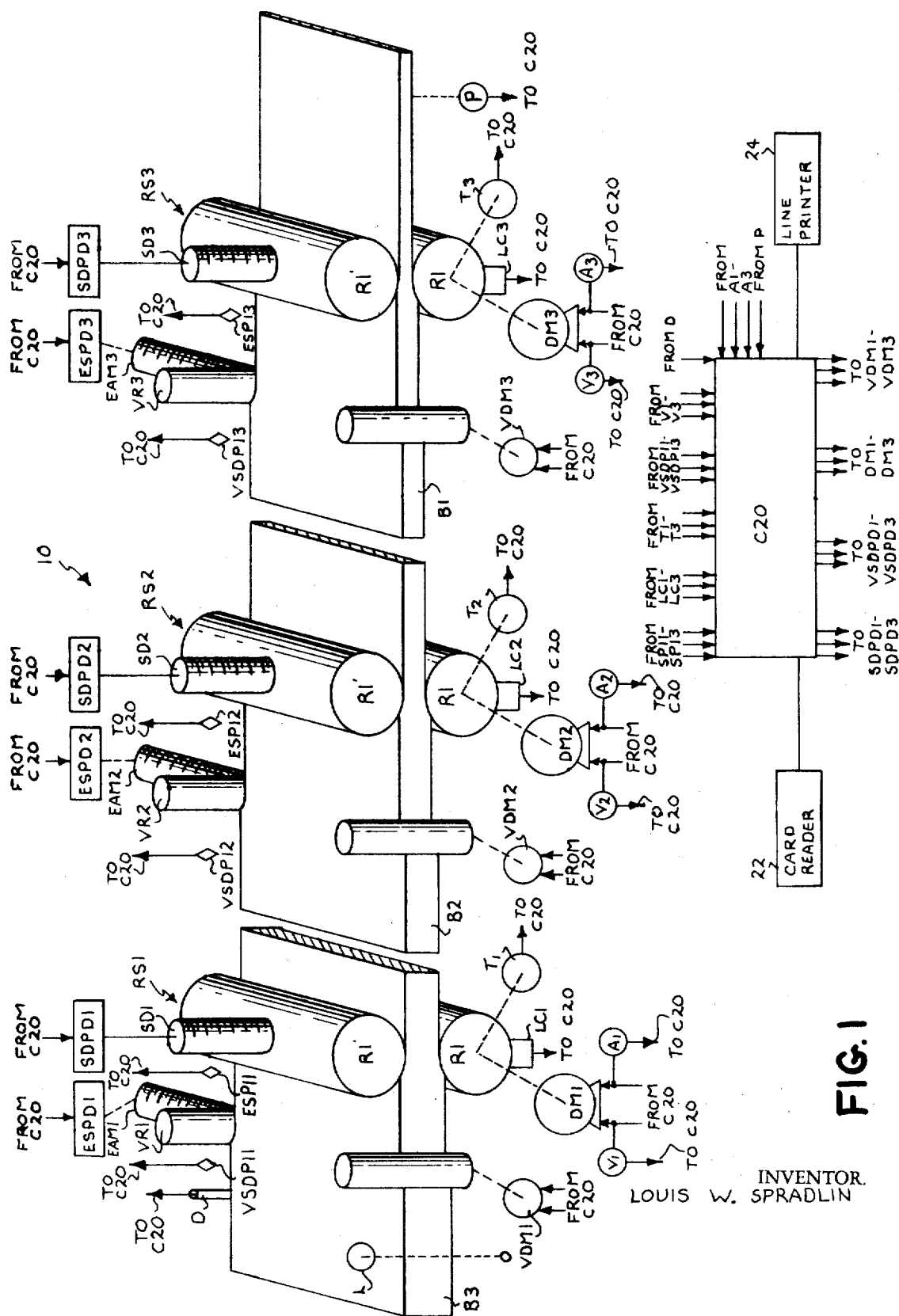
Primary Examiner—Milton S. Mehr
Attorney—John J. Kissane et al.

[57] **ABSTRACT**

A computer controlled rolling mill is described wherein the force (or power) model in the computer is stored as dual curves, i.e., (a) shaping curves wherein the ratio of the force required for actual rolling conditions relative to the force required for a chosen draft is plotted against elongation, and (b) magnitude curves wherein the force required for the chosen draft is plotted against inverse output thickness from the mill with each point of the magnitude curves having an associated stored temperature value. The arithmetic produce of the force ratio required for a desired elongation and the force magnitude for a desired output thickness (when corrected for width, hardness and temperature of the metal being rolled) provides the force required for the stand. Because the force ratio is normalized with respect to a chosen percentage draft, accurate adaptive updating of the process representation can be achieved conveniently by altering only the magnitude curves.

16 Claims, 13 Drawing Figures





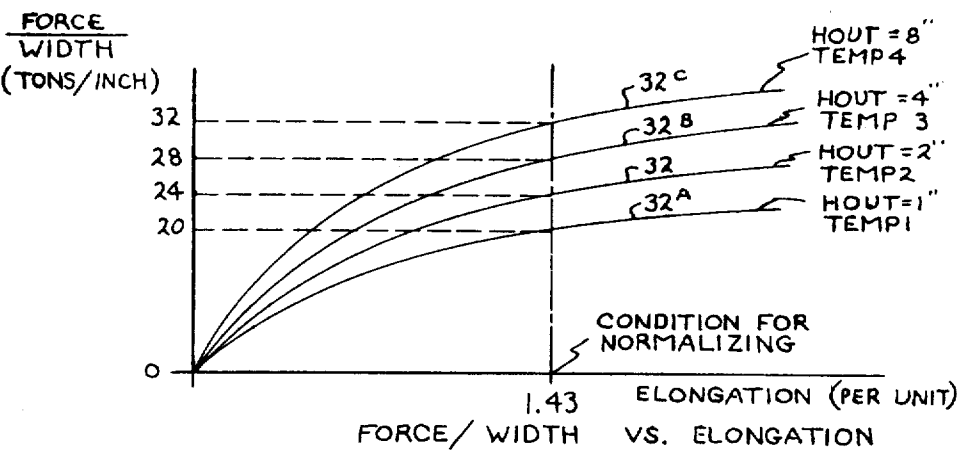


FIG. 2^a

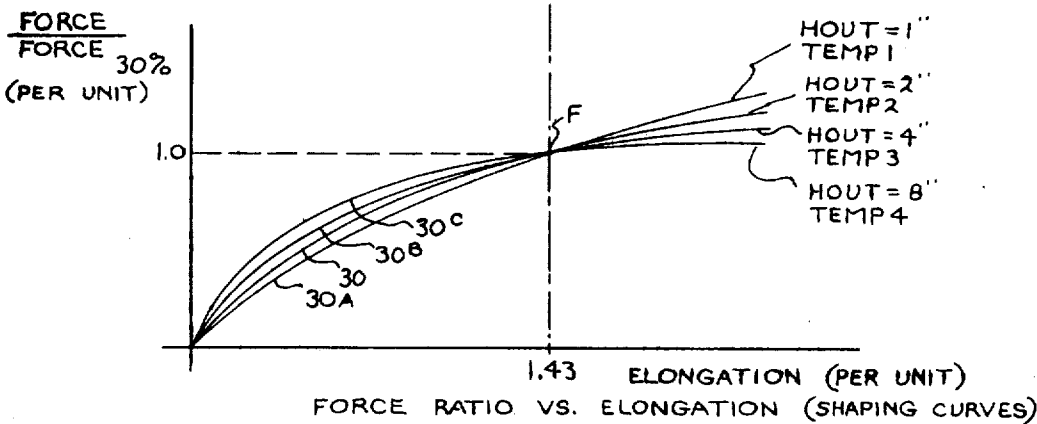


FIG. 2^b

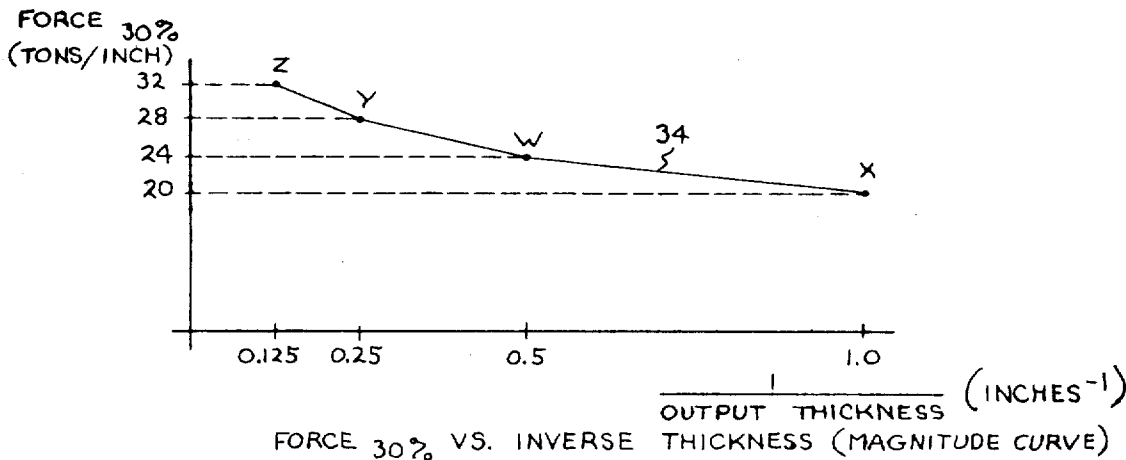


FIG. 2^c

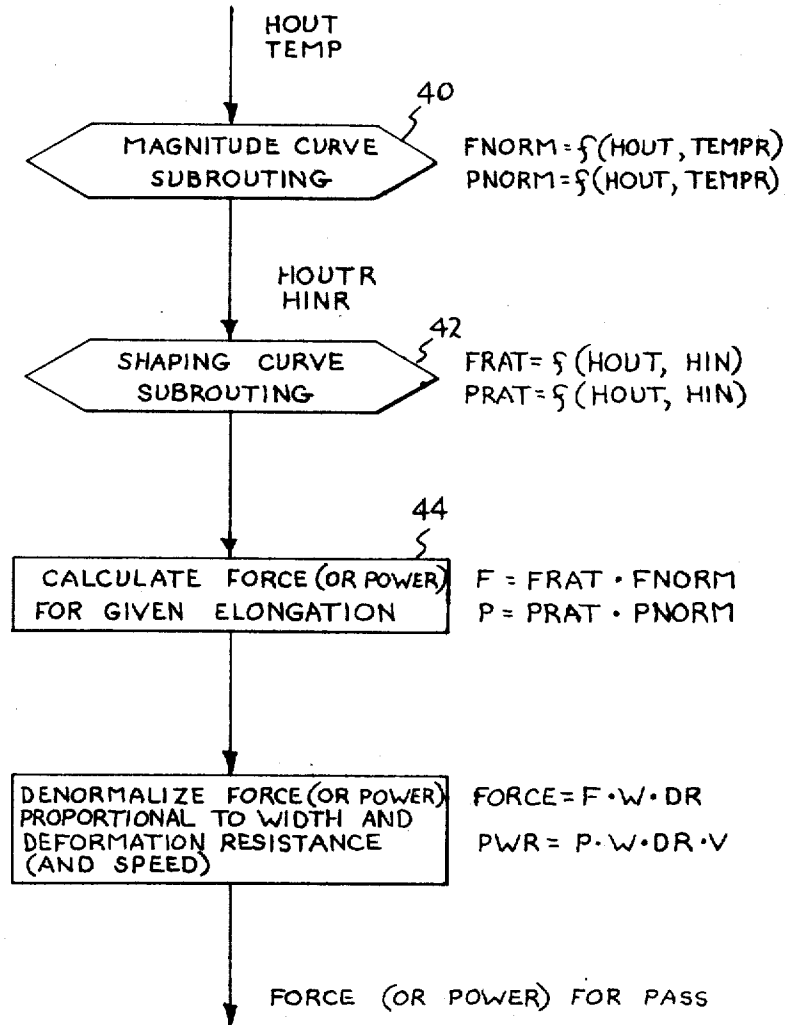


FIG. 3

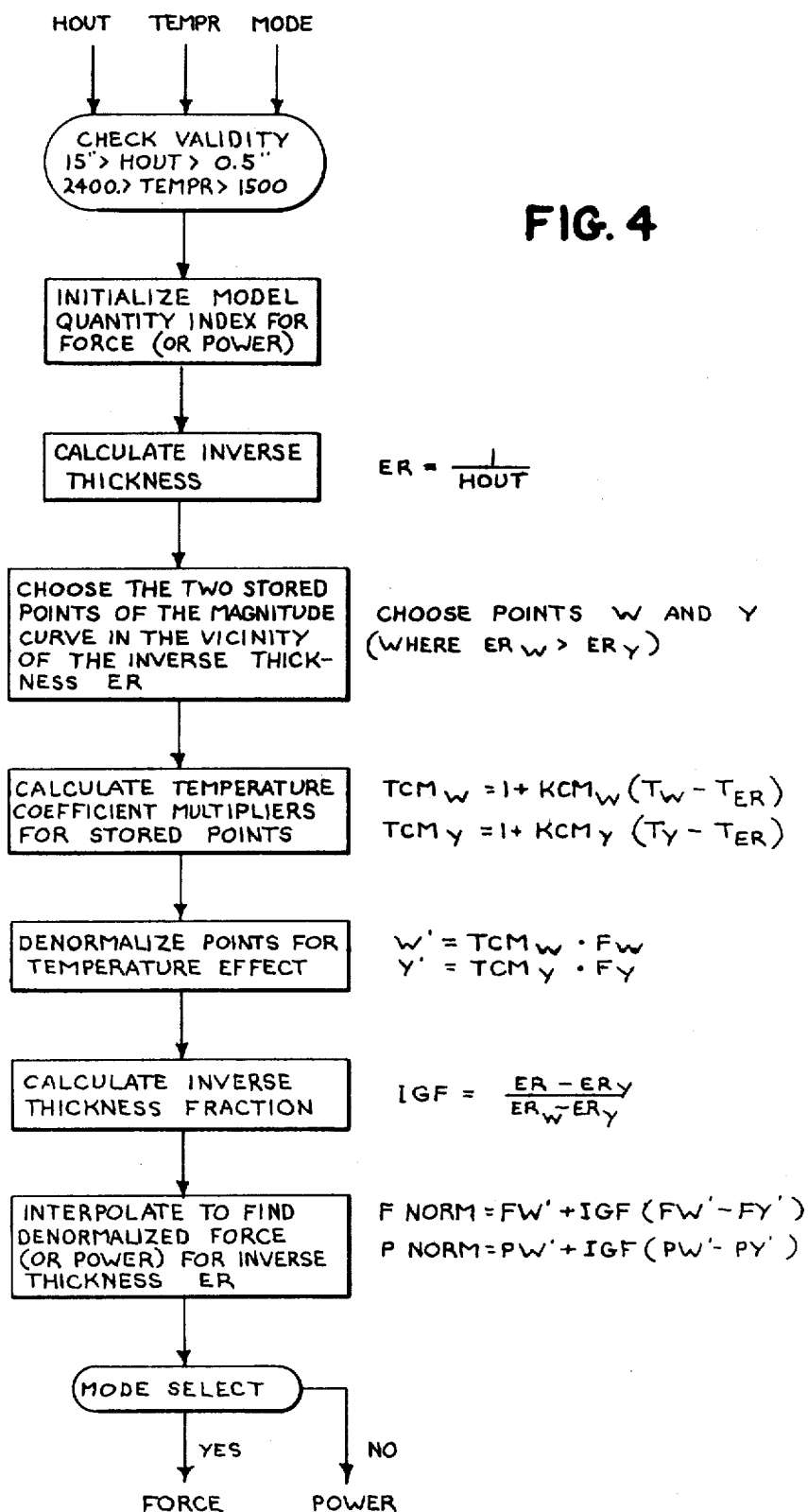


FIG. 4

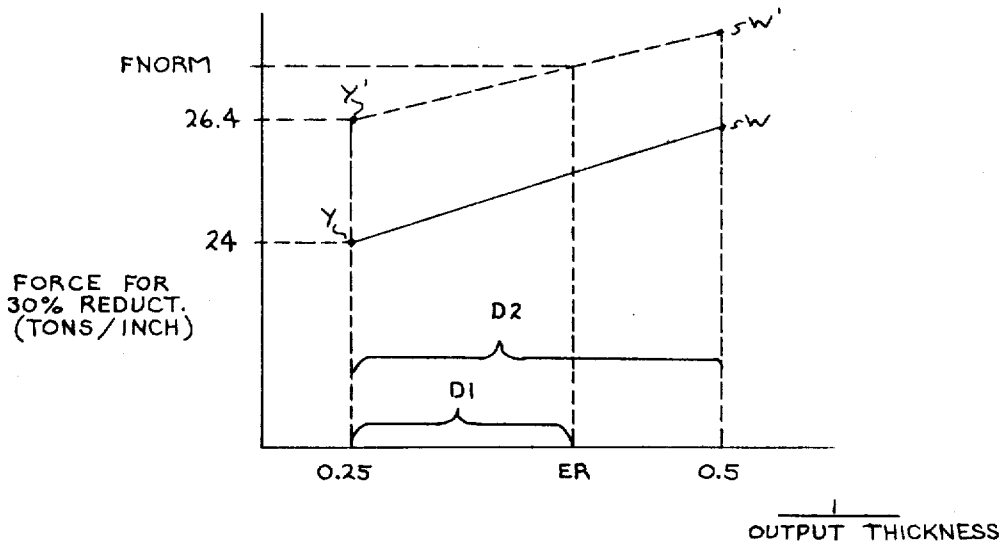


FIG. 5

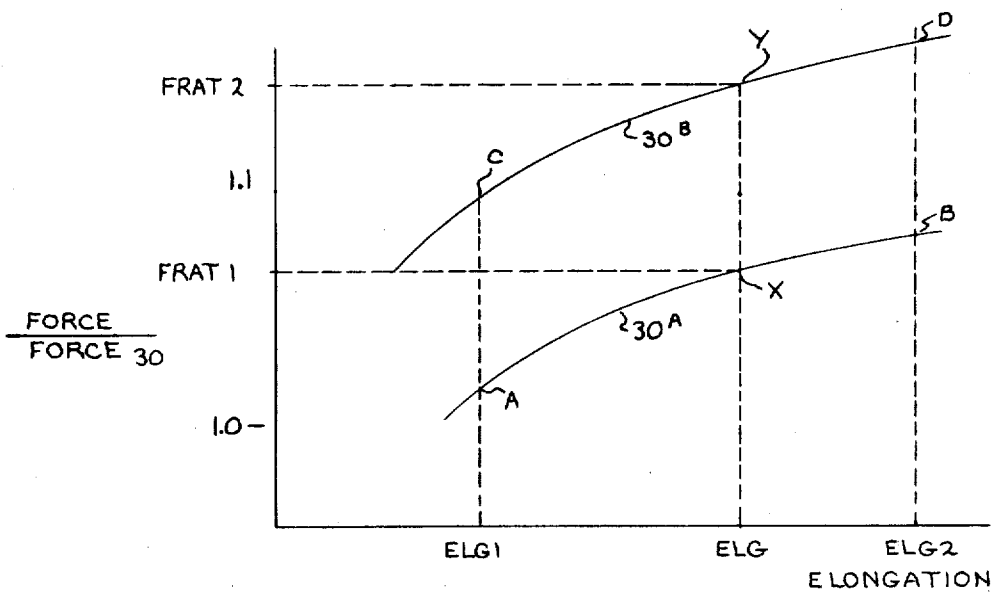


FIG. 7

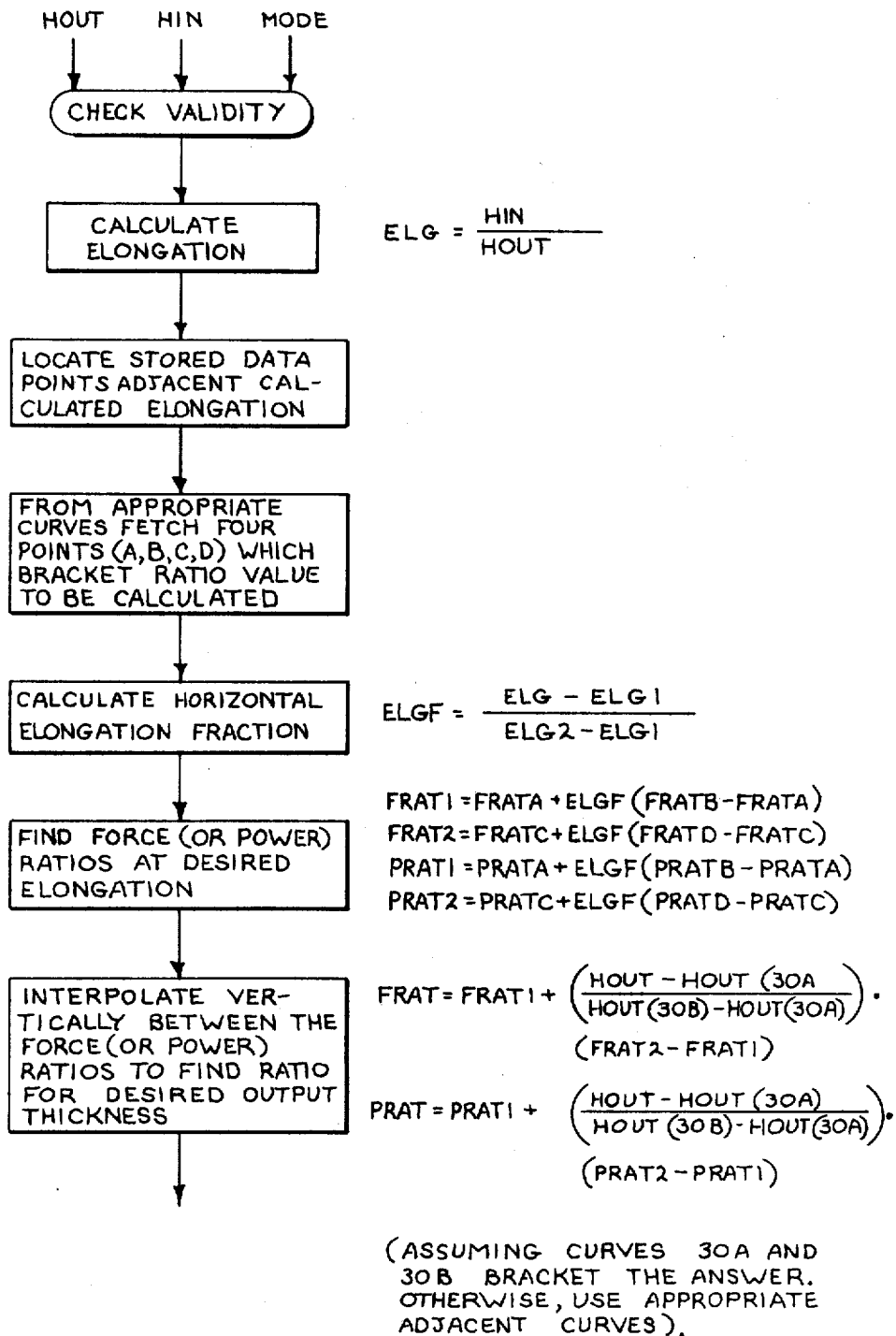


FIG. 6

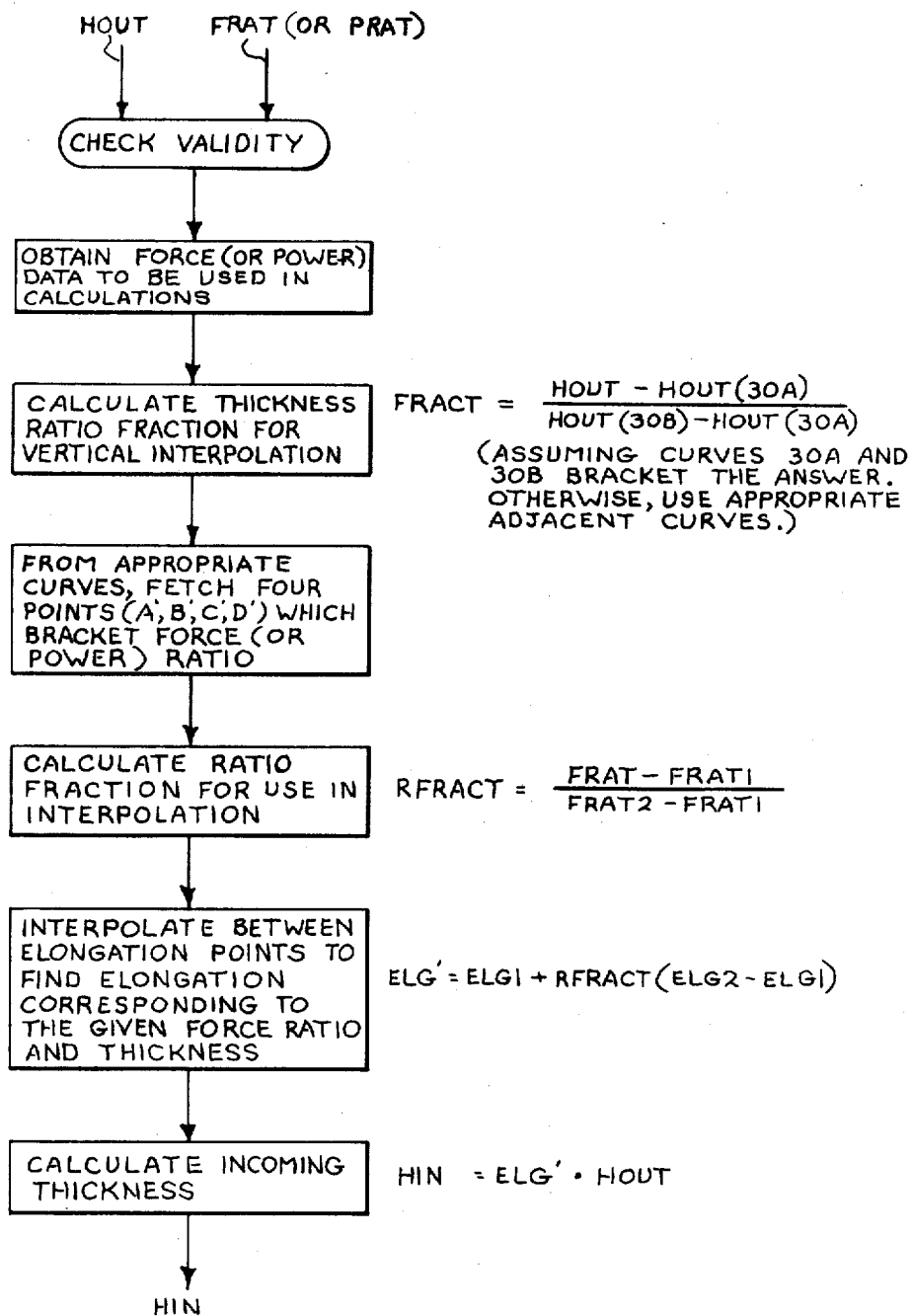


FIG. 8

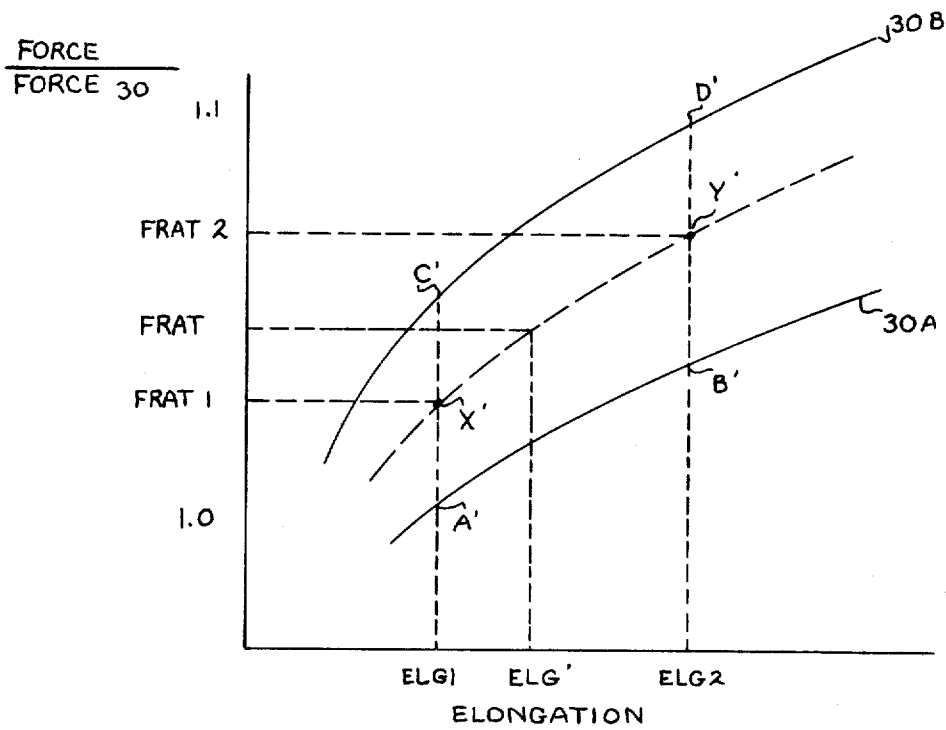


FIG. 9

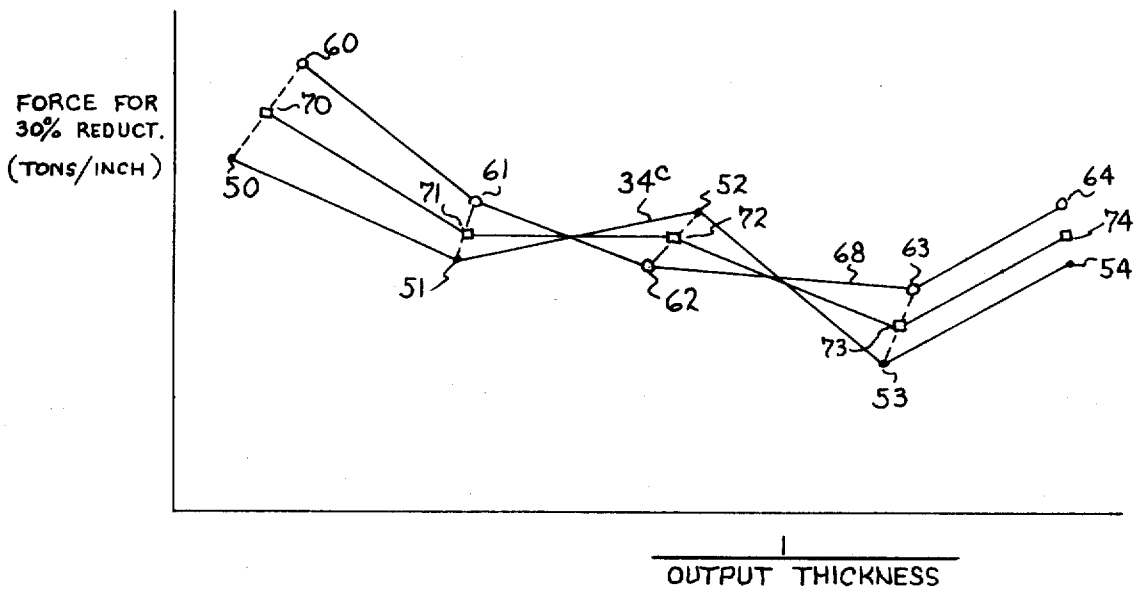


FIG. 11

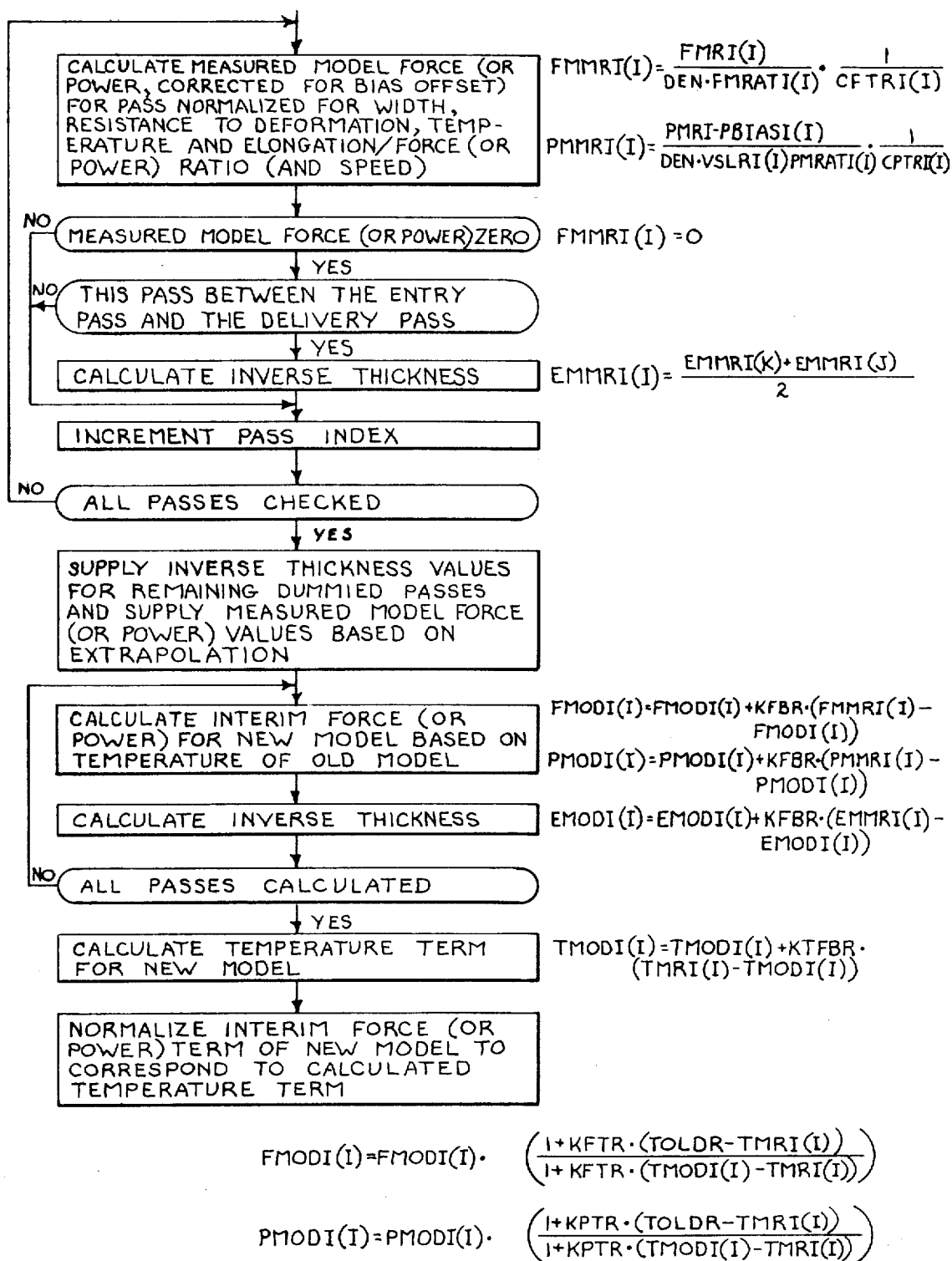


FIG. 10

COMPUTER CONTROLLED ROLLING MILL

This invention relates to a method and apparatus for rolling metal and, in particular, to a computer controlled rolling mill wherein the on-line mathematical models for force and/or power prediction are stored within the computer as both shaping data and magnitude data representations with the force and/or power required for the mill being calculated as an arithmetic product of data derived from the stored representations. This particular form for the on-line process representation permits accurate prediction of rolling parameters for a wide range of conditions, while still permitting convenient updating of the process model by adaptive feedback.

In computer controlled rolling mills, it is customary to determine predicted rolling parameters, such as rolling force or power, by reference to mathematical models stored within a computer by equations or coordinates defining families of curves representing the relationship between the rolling parameters and physical characteristics of metal being rolled, e.g., inverse output thickness, elongation, et cetera. After proper adjustment, these models may be considered to accurately represent the rolling process for the average operating condition, with variations from this average operating condition being taken into account for prediction of rolling parameters for a particular case. The accuracy of the predictions for each particular case will depend on the amount of variation from average operating conditions and how accurately variations from the average operating conditions are taken into account, the latter being a function of the form of the stored process representation. Depending on the form of the process representation, weaknesses may exist regarding the ability of the process representation to be used to accurately predict rolling parameters for a wide range of rolling conditions, and accurate updating of the process model by adaptive feedback may be difficult.

It is therefore an object of this invention to provide a method of rolling metal utilizing novel stored data to determine rolling parameters.

It is also an object of this invention to provide an accurate method of rolling metal in one or more passes wherein critical rolling parameters are predicted utilizing stored data representing both shaping and magnitude curves.

It is a further object of this invention to provide a computer controlled rolling mill wherein the accuracy of prediction of critical rolling parameters is maintained notwithstanding wide variations in operating conditions.

It is a still further object of this invention to provide a method of rolling metal wherein precise adaptive feedback of stored information can be accomplished by adaptively updating only one of two curves representing the parameter being updated.

These and other objects of this invention generally are achieved by storing the force (or power) models as dual curves, i.e., (a) a shaping curve depicting the ratio between actual force and force for a chosen percentage draft against a function of the deformation of the rolled metal, e.g., elongation or per unit draft, and (b) a magnitude curve wherein the force for the chosen percentage draft is plotted as a function of the thickness of the

rolled metal, e.g., inverse output thickness. The force for rolling then is determined by accessing each of the curves to determine, for example, (a) the force ratio value associated with the amount of deformation to be achieved and (b) the force magnitude value associated with the thickness of the rolled metal, and these values are multiplied to provide the force required for the mill during rolling. Typically, the ratio curves are plotted against elongation or per unit draft while the magnitude curves define force (or power) against workpiece thickness or inverse output thickness. In conventional fashion, the force (or power) thus determined from the dual curves is adjusted for such factors as workpiece width and hardness (and mill speed) prior to utilization in the mill.

Although the invention is described with particularity in the appended claims, a more complete understanding of the invention may be obtained by the following detailed description taken in conjunction with the accompanying drawings wherein:

FIG. 1 is an isometric view of a computer controlled roughing mill in accordance with this invention,

FIG. 2 is a pictorial illustration showing curves stored within the computer model and the source of their origin,

FIG. 3 is a flow chart illustrating a method of determining force or power in accordance with this invention,

FIG. 4 is a flow chart illustrating the force and power magnitude curve subroutines of FIG. 3,

FIG. 5 is an enlarged view showing a portion of the curve depicted in FIG. 2c,

FIG. 6 is a flow chart showing the force and power shaping curve subroutines of FIG. 3,

FIG. 7 is an enlarged view showing a portion of the curves depicted in FIG. 2b,

FIG. 8 is a flow chart illustrating a method of determining input thickness utilizing the curves of FIG. 2,

FIG. 9 is an enlarged view showing a portion of the curves depicted in FIG. 2b,

FIG. 10 is a flow chart depicting a technique for adaptively updating the magnitude curve of FIG. 2c, and

FIG. 11 are curves illustrating the method of adaptively updating the curve of FIG. 2c.

A roughing mill 10 in accordance with this invention is illustrated in FIG. 1 and generally includes a plurality of tandem rolling stands RS1-RS3 for incrementally reducing the thickness of bars B1-B3 as the bars pass sequentially from upstream stand RS1 to downstream stand RS3. It will be appreciated that an actual tandem roughing mill normally is characterized by more than three rolling stands and rolling stands RS1, RS2 and RS3 therefore should be considered to represent the first stand, an intermediate stand and the last stand of such roughing mills, e.g., the first, fourth and seventh stands, respectively, of a seven-stand roughing mill. In conventional fashion, each rolling stand is provided with a pair of confronting work rolls R1 and R1' with the work rolls at each stand typically being driven by synchronous motors DM1-DM3, respectively, to rotate the rolls at a predetermined speed. A load cell LC1-LC3 underlies the work rolls at each stand to measure the force at the stands although the load cells also could be situated at any other suitable position for

measuring rolling force, e.g., overlying the work rolls. The amount of reduction of the metal being rolled is determined by the separation between the work rolls which separation is established by screwdowns SD1-SD3 driven by screwdown position drives SDPD1-SDPD3, respectively. A screwdown position indicator ESP11-ESP13 also is provided at each stand to measure the position of the screwdowns at their respective stands.

Each stand also has a pair of vertically disposed rollers VR1-VR3 driven by motors VDM1-VDM3 to reduce the width of each bar, as desired. An edger adjust mechanism EAM1-EAM3 driven by edger screw position drives ESPD1-ESPD3 serves to establish the reduction of bar width while edger screw position indicators VSDP11-VSDP13 provide output signals indicative of the position of the width controlling screws at each stand. The output signals from all the screw position indicators and all the load cells along the mill are fed as inputs to computer C20 and the computer generates control signals for the screwdown position drives to establish the draft taken by each set of confronting rolls (as will be more fully explained hereinafter).

Drive motors DM1-DM3 generally are fixed speed synchronous motors with the span between rolling stands being slightly in excess of the length of each bar between the rolling stands. The current and voltage applied to each of the drive motors are sensed by current sensors A1-A3 and voltage sensors V1-V3, respectively, and fed to computer C20 to indicate the power supplied from computer C20 to the drive motors at each stand. Alternatively, a power sensor utilizing these inputs can supply a signal to the computer proportional to the measured motor power. Although not shown for the purpose of clarity, it will be appreciated that adjustable speed motors could be employed in conjunction with the constant speed drive motors DM1-DM3 to reduce the total span required for the roughing mill. Adjustment of the mass flow between stands driven by the constant speed and adjustable speed motors then would be accomplished under the control of computer C20 in conventional fashion using techniques such as are taught in U.S. Pat. No. 3,170,344, issued to R.E. Marrs and assigned to the assignee of the present invention. In similar fashion, the voltage and current inputs to drive motors VDM1-VDM3 can be monitored and fed to computer C20 by suitable measuring equipment (not shown).

Computer C20 is a conventional process control digital computer and typically may have one or two central processor units with a core memory of about 400,000 bits and a working drum memory for an additional 1 to 3 million bits of information. The computer normally includes a card reader 22 to input information relative to the order being processed, e.g., metallurgical composition of the bars, desired output gage, etc., while process information supplied to, or calculated by, the computer may be visually recorded by a typewriter or a line printer 24. Computers having these characteristics are commercially available and can be obtained from the General Electric Company under the Trademark GEPAC 4010 and GEPAC 4020.

Process control information fed to the computer typically would include the temperature of the steel being

rolled (as measured by pyrometer P disposed at a suitable location along the length of the rolling mill). A measured indication of the incoming thickness of each bar also desirably is fed to computer C20. This may be done by any suitable device for such purpose, e.g., a vertically scanning light source L having an elongated light detector D for observing interruption of the light beam by the bars. The incoming thickness of a bar at a given stand (other than for the first reduction) generally can be estimated by the computer to a high degree of accuracy from the observed gagemeter thickness of the bar at a previous stand.

During operation of the mill, a drafting schedule may be chosen wherein the final stands, e.g., RS3, effect maximum draft in the bars, with the upstream stands, e.g., RS1, producing little or no draft in the bars in order to conserve the heat content of the bars. In setting up such schedule, the downstream stand draft generally is determined in conventional fashion by the more stringent of such constraining limits as the maximum draft desired for the stand, the force limit imposed by the mechanical characteristics of the stand, the power limit of the drive motor and the permissible bite angle at the stand. Maximum draft then is taken at the final stand, e.g., RS3, and similarly for each of the successive upstream stands, to determine the maximum permissible reduction by the roughing mill. When the incoming bar to be rolled has a thickness less than the calculated maximum thickness capable of being rolled for the given conditions (width, temperature, and hardness of the workpiece), the upstream stands, e.g., RS1, are assigned a lesser draft by the computer drafting schedule calculation while the reductions for the downstream stands, e.g., RS3, are maintained at their previously calculated maximum permissible values. The desired screwdown positions (as determined in conventional fashion from the desired output thickness from the stand and the known spring of the stand for the force required to produce the desired draft) then are established by the computer. When operating on such a rolling schedule, the draft taken at a roughing stand, particularly the upstream stands, may vary considerably as a function of slab dimensions and defined limits. It will be appreciated, however, that the metal rolling method of this invention can be utilized with any conventional rolling schedule draft distribution calculation strategy which utilizes a mathematically or empirically determined relationship of force per unit workpiece width or power per unit workpiece width as a function of workpiece deformation, e.g., elongation or per unit draft.

In accordance with this invention, the mathematical model for rolling force is stored within the calculated model of computer C20 as (a) shaping curves, e.g., the ratio of force for actual rolling conditions to force for a chosen draft as plotted against elongation (illustrated in FIG. 2b for a chosen 30 percent draft) and (b) magnitude curves, wherein force for the chosen draft is plotted against the reciprocal of output thickness (as shown in FIG. 2c). Each of the shaping curves are normalized, i.e., intersect, at the chosen percentage of draft, and are considered to represent the non-linear characteristics of rolling force as a function of the amount of reduction taken. The shaping curves of FIG. 2b therefore can be considered to be stable during

rolling with only the magnitude curves of FIG. 2c possibly requiring adjustment in order to provide a means of adaptive feedback for the process representation.

The shaping and magnitude curves of FIGS. 2b and 2c may be derived from the overall process relationship shown in FIG. 2a, wherein the indicated point for normalization corresponds to a 30 percent draft condition. The elongation corresponding to the chosen per unit draft is calculated from the known relationships:

$$\text{p.u. draft} = H_{in} - H_{out}/H_{in}$$

wherein

p.u. draft is the per unit draft,

H_{in} is the input thickness of the bar, and

H_{out} is the output thickness of the bar, and

$$ELG = H_{in}/H_{out}$$

wherein

ELG is elongation.

At the elongation obtained from the foregoing equations, i.e., a 1.43 elongation for the chosen 30 percent draft, the shaping curves have a unitary ratio of actual force per unit width to force per unit width for the 30 percent draft condition, thereby providing the focal point F for the curves of FIG. 2b. The overall process relationship force curves of FIG. 2a then are entered at a value of 1.43 for elongation to determine the corresponding values on magnitude curve 2c for the diverse output thicknesses. For other elongations, the product of curves 2b and 2c provides the actual force value determined from FIG. 2a. Thus, for an elongation of 1.43 and a force ratio designated as 1.0, a force of 24 tons/inch is indicated by curve 32 as being required to reduce a bar (at the temperature of the curve) to an output thickness of 2 inches. This 2 inch output thickness corresponds to an inverse output thickness of 0.5 inches⁻¹, i.e., 1/(2.0 inches), and forms a point W for magnitude curve 34. Similarly, points X, Y and Z on magnitude curve 34 (corresponding to inverse output thickness of 1, 4 and 8 inches, respectively), are determined by observing on curves 32A, 32B and 32C, respectively, the forces (20 tons, 28 tons and 32 tons) required to effect a 1.43 elongation in bars having output gages of 1, 4 and 8 inches, respectively. Each point on curve 32 then is divided by the force, i.e., 24 tons, at the chosen per unit elongation to obtain curve 30 of FIG. 2b. Similarly, the force at each point on curve 32A is divided by 20 tons (i.e., the force required for a 1.43 elongation) to obtain curve 30A of FIG. 2b, while curves 30B and 30C are obtained by dividing curves 32B and 32C by 28 and 32 tons, respectively, i.e., the force per unit width for the curves at the chosen elongation. Because each of shaping curves 30-30C are brought to a force ratio of 1.0 at the chosen per unit draft in determining the configuration of the shaping curves, all the shaping curves necessarily intersect at the elongation corresponding to the chosen per unit draft. Each of shaping curves 30, 30A, 30B and 30C then are stored within computer C20 by coordinates representing points along each curve. Similarly, magnitude curve 34 is stored by the force magnitude, inverse thickness, and temperature corresponding to points W, X, Y and Z. It will be appreciated that in actual practice, each shaping and magnitude curve would typically be defined by approximately six to 10 points.

To determine predicted rolling force of roughing mill 10, the shaping and magnitude curves of FIGS. 2b and 2c are accessed to determine force ratio and force values for a desired elongation and inverse output thickness, respectively, whereafter the force ratio and force values are multiplied to produce predicted rolling force as illustrated in the flow chart of FIG. 3. Thus, the magnitude curve of FIG. 2c is entered utilizing magnitude curve subroutine 40 to obtain normalized force, i.e., the force required to produce a 30 percent draft for the desired output thickness at the known temperature, and the shaping curves of FIG. 2b are entered utilizing shaping curve subroutine 42 to obtain the force ratio, i.e., the ratio of actual force to force for the chosen draft, required to produce the desired elongation. The normalized force and force ratio then are multiplied in multiplier circuit 44 to obtain a calculated force for a given elongation and this calculated force is adjusted by empirically determined multiplication factors proportional to the known width and resistance to deformation of the bar to provide the predicted mill rolling force.

A magnitude curve subroutine suitable for determining the value of normalized force is illustrated in the flow chart of FIG. 4. The input data required for the subroutine is the desired output thickness H_{OUT} and the incoming temperature $TEMPR$ of the bar (as estimated by the computer utilizing either the known temperature of previously rolled bars, as measured by pyrometer P, or the temperature customarily produced in the bars during the most recent previous heats in the furnace (not shown) from which the bars enter the roughing mill). Because this subroutine can be employed both to determine either normalized force or normalized power dependent upon the operative mode of the subroutine, a mode indication normally is also supplied as part of the subroutine input data. The computer then checks the validity of the input information by observing that the desired output thickness is within the limits of the rolling mill, e.g., is between 0.5 and 15 inches, and that the temperature of the incoming bars is within a range suitable for rolling, e.g., between 1,500° F and 2,400° F. With the subroutine in a force mode, the model index is initialized for force and the force coefficients of curve 34 are utilized by the subroutine. The computer calculates the inverse thickness ER of the bar by taking the reciprocal of the known desired output thickness H_{out} whereafter the computer chooses the two stored points of magnitude curve 34 straddling (or otherwise nearest) the inverse thickness ER in question, e.g., 0.5 inch⁻¹ corresponding to point W and 0.25 inch⁻¹ corresponding to point Y (see enlarged FIG. 5). The temperature coefficient multiplier TCM for point W then is calculated in accordance with the formula:

$$TCM = 1 + KCM \cdot (T_W - T_{ER})$$

wherein

KCM is a temperature coefficient factor representing the partial derivative of per unit rolling force with respect to temperature of the bar,

T_{ER} is the temperature of the metal being rolled, and

T_W is the temperature value associated with point W. The force at point W then is denormalized for temperature effect to obtain point W' in accordance with the formula:

$$W' = TCM \cdot F_W$$

wherein

W' is the model quantity corrected for temperature, TCM is the temperature coefficient multiplier, and F_W is the force at point W before interpolation.

After the temperature coefficient multiplier for point Y is calculated and the force at point Y is denormalized for temperature effect to obtain point Y' (using the previously explained technique for obtaining point W'), the inverse thickness fraction IGF to be used in interpolation is determined in accordance with the formula:

$$IGF = ER - ER_Y / ER_W - ER_Y$$

wherein

ER is the inverse output thickness in point,

ER_Y is the smaller of the two stored inverse output thickness points straddling the inverse output thickness in point, i.e., 0.25 in FIG. 5, and

ER_W is the larger of the two stored inverse output thickness points straddling the inverse output thickness in point, i.e., 0.5 in FIG. 5. The force (or power, dependent on mode) $FNORM$ denormalized for the temperature and inverse output thickness in question then is determined by interpolation in accordance with the formula:

$$FNORM = F_{W'} + IGF \cdot (F_{W'} - F_{Y'})$$

wherein

$FNORM$ is the interpolated denormalized force for an inverse output thickness ER ,

$F_{W'}$ is the force for point W',

IGF is the inverse thickness fraction, and

$F_{Y'}$ is the force for point Y'.

This normalized force then is checked against force limits before being employed to calculate the actual rolling force in accordance with FIG. 3.

The operation of the subroutine of FIG. 4 can be understood from the following specific calculations of normalized force required to produce an output thickness of 3 inches in a bar having a temperature of 2,000° F. The computer initially checks the desired output thickness and temperature against known limits whereupon the inverse output thickness is calculated to be 0.333 inches⁻¹, i.e., the reciprocal of the desired output thickness. The computer then locates this inverse thickness as being between stored points W and Y having inverse output thickness of 0.5 inch⁻¹ and 0.25 inch⁻¹, respectively. The temperature coefficient multiplier for point W next is calculated by taking the difference in temperatures between the stored point and the temperature of the bar, e.g., 2,100° F - 2,000° F, and multiplying the answer by a temperature coefficient factor (KCM) of, for example, 10⁻³ p.u./°F, i.e., the empirically determined partial derivative of per unit rolling force with respect to temperature of the bar, to arrive at the per unit force correction, e.g., 0.1, required because of the temperature difference between the temperature corresponding to stored point W and the temperature of the bar. The force correction is added to 1.0 to obtain the temperature coefficient multiplier, i.e., 1.1, and the force at point W, e.g., 24 tons/inch, is multiplied by the temperature coefficient multiplier to obtain point W', i.e., 26.4 tons/inch. Similarly, point Y would be corrected for temperature

differences between stored point Y and the bar temperature to obtain point Y'. An interpolation fraction equal to D_1/D_2 , i.e., the quotient of (ER - 0.25) and (0.5 - 0.25), illustrated in FIG. 5 is calculated and the value of temperature normalized force $FNORM$ for the desired elongation is determined from curve Y' - W'.

A subroutine suitable for finding the force ratio $FRAT$ to be employed in the flow chart of FIG. 3 is illustrated in FIG. 6. The input information to the computer for the subroutine generally would include the entry thickness, H_{in} , and the desired exit thickness, H_{out} , of the bar as well as the desired mode of operation, i.e., a force mode, for the subroutine. After the routine has checked the validity of the input information to determine that the exit thickness is within a prescribed tolerance, e.g., between 0.5" and 15.0", two curves of FIG. 2b to be employed in determining the force ratio are chosen by identification of those curves bracketing (or otherwise nearest) the desired exit thickness. Thus, for an exit thickness of 1.5 inches, curves 30 and 30A would be employed for the subroutine while an exit thickness of 2.5 inches would require the utilization of curves 30A and 30B in the subroutine. The entry thickness then is compared to the exit thickness by the computer to check the validity of the information, i.e., that the entry thickness is greater than the exit thickness, and the elongation ELG is calculated as the quotient of the entry thickness and the exit thickness. The calculated elongation then is located on the stored ratio curves, i.e., as being a value between stored elongation points ELG_1 and ELG_2 along the curves, and the coordinates of the four stored points A, B, C and D (illustrated in FIG. 7) bracketing the ratio value are obtained. The elongation fraction $ELGF$ TO BE USED FOR HORIZONTAL INTERPOLATION THEN IS CALCULATED FROM THE FORMULA:

$$ELGF = ELG - ELG_1 / ELG_2 - ELG_1$$

wherein

ELG is the desired elongation for the bar,

ELG_1 is the elongation at the stored data point, i.e., point A, having an elongation immediately below the desired elongation, and

ELG_2 is the elongation at the stored data point, i.e., point B, having an elongation immediately above the desired elongation.

Assuming an output thickness between 2 inches and 4 inches, the force ratios $FRAT1$ and $FRAT2$ at elongation ELG then are determined from curves 30A and 30B using the formulas:

$$FRAT1 = FRATA + ELGF \cdot (FRATB - FRATA)$$

and

$$FRAT2 = FRATC + ELGF \cdot (FRATD - FRATC)$$

wherein

$FRAT1$ is the force ratio at point X on curve 30A,

$FRATA$ is the force ratio at point A on curve 30A,

$ELGF$ is the elongation fraction,

$FRATB$ is the force ratio at point B on curve 30A,

$FRAT2$ is the force ratio at point Y on curve 30B,

$FRATC$ is the force ratio at point C on curve 30B,

and

$FRATD$ is the force ratio at point D on curve 30B.

After determining the force ratios at points X and Y, vertical interpolation is made to find the force ratio for the thickness in question in accordance with the formula:

$$\text{FRAT} = \text{FRAT1} + \left[\frac{\text{HOUT} - \text{HOUT}(30\text{A})}{\text{HOUT}(30\text{B}) - \text{HOUT}(30\text{A})} \right] \cdot (\text{FRAT2} - \text{FRAT1})$$

wherein:

FRAT is the force ratio for the desired output thickness,

FRAT1 is the force ratio at point X on curve 30A,

HOUT is desired output thickness,

HOUT(30A) is the output thickness corresponding to curve 30A,

HOUT(30B) is the output thickness of curve 30B, and

FRAT2 is the force ratio at point Y on curve 30B.

Knowing the normal force as calculated by the magnitude curve subroutine of FIG. 4 and the force ratio as calculated by the shaping curve subroutine of FIG. 6, the force desired for rolling is predicted by multiplying these two quantities to obtain the force product as shown in FIG. 3. Before use of the force product for adjustment of the screwdowns, however, the force product normally is adjusted by multiplication factors corresponding to the resistance to deformation of the metal being rolled (dependent on the metallurgy of the rolled bars) and the width of the bars (as determined by the setting of vertical rollers VR1-VR3). Information concerning the metallurgy and desired width are provided for the computer C20 by the operator at the initiation of rolling and the computer chooses theoretically or empirically determined multiplication factors to be used in the force calculations from stored information associated with these inputs.

When curves 2b are the ratio of actual power to power required for 30 percent draft plotted against elongation and curve 2c defines the relationship between power required for 30 percent draft and inverse output thickness, the rolling power for each stand can be calculated utilizing the routines illustrated in FIGS. 3, 4 and 6. In these Figures, the required power routines are shown in brackets when differing from the heretofore explained force routines. To determine rolling power, the subroutine of FIG. 4 would be placed in a power mode by the calling sequence and the stored power curve coefficients (instead of the force curve coefficients) would be utilized by the subroutine. The subroutine otherwise functions identically to the previously described operation of the subroutine in the force mode. The output from the subroutine, however, is normalized power which is checked against power limits before using the normalized power for subsequent calculations. Similarly, the ratio curve subroutine of FIG. 6 is employed to determine power ratio by indexing data corresponding to the power ratio curves (instead of the force ratio curves), as a function of the mode indicator. The subroutine then functions identically to the previously described operation of the subroutine in the force mode with the ratio provided by the subroutine being a power ratio rather than a force ratio. The power ratio and the normalized power as determined by the subroutines of FIGS. 6 and 4, respectively, then are multiplied to provide the rolling power for the mill and this rolling power is adjusted by

empirically determined multiplication factors dependent upon the relative resistance to deformation and width of the bars and the speed of stands RS1-RS3 before being used to predict the power required by the drive motors forming the mill for the given rolling conditions.

Although desirably the curves of FIG. 2b are employed to determine force (or rolling power) ratio from known entry and exit thicknesses for the bars, the curves of FIG. 2b also can be accessed in opposite fashion to determine the required entry thickness of the bars knowing the specified exit thickness HOUT and the specified rolling force (or power) ratio by utilization of the routine shown in FIG. 8. The specified exit thickness provided for the subroutine is checked for validity and the force ratio curves of FIG. 2b having exit thicknesses immediately above and below (or otherwise nearest) the specified exit thickness are chosen for the calculations, e.g., curves 30A and 30B of FIG. 9. The stored force ratio data for these curves then is accessed by the computer and a thickness ratio fraction FRACT for use in vertical interpolation is determined in accordance with the formula:

$$\text{FRACT} = \frac{\text{HOUT} - \text{HOUT}(30\text{A})}{\text{HOUT}(30\text{B}) - \text{HOUT}(30\text{A})}$$

wherein

HOUT is the specified exit thickness for the bar in inches,

HOUT(30A) is the exit thickness of the stored data curve, i.e., curve 30A, immediately below the specified exit thickness, and

HOUT(30B) is the exit thickness of the stored data curve, i.e., curve 30B, immediately above the specified exit thickness. Knowing the thickness ratio fraction and the specified force ratio, a search is initiated to determine the coordinates of the four stored force ratio data points A', B', C' and D' encompassing the specified force ratio FRAT. In searching, the value of the force ratio FRAT initially is compared to 1.0 to determine the stored data points which need be considered, i.e., data points corresponding to an elongation between 0. and 1.43 or data points corresponding to an elongation above 1.43. The computer then chooses an elongation ELG2 on curve 30A having a corresponding force ratio immediately below the specified force ratio FRAT and the force ratio FRAT2 at the chosen elongation ELG2 is calculated using the formula:

$$\text{FRAT2} = \text{FRATB}' + \text{FRACT} \cdot (\text{FRATD}' - \text{FRATB}')$$

wherein

FRATB' is the force ratio of point B' of curve 30A of FIG. 9 corresponding to an elongation ELG2,

FRACT is the thickness ratio fraction, and

FRATD' is the force ratio at point D' of curve 30B corresponding to an elongation ELG2.

This calculated force ratio then is compared to the specified force ratio and if the specified ratio is more than the calculated ratio, the force ratio at the immediately lower stored elongation point ELG1 is calculated in an identical manner to find FRAT1. If the calculated force ratio FRAT1 is lower than the specified force ratio, FRAT, then points A', B', C' and D' are selected as the coordinates bracketing FRAT. Should the calculated force ratio at elongation ELG1 be larger than FRAT, the computer would successively calculate

the force ratio at each succeeding lower elongation to select the bracketing coordinates for the specified force ratio *FRAT*. Knowing the bracketing coordinates, the ratio fraction *RFRAC*T used for interpolation is calculated from the formula:

$$RFRAC = (FRAT - FRAT1 / FRAT2 - FRAT1)$$

wherein

FRAT is the specified force ratio (for the required elongation),

FRAT1 is the calculated force ratio at point X' of curve X'Y', and

FRAT2 is the calculated force ratio at point Y' of curve X'Y'.

The required elongation *ELG'* associated with the specified force ratio *FRAT* then is determined by interpolating between elongation points *ELG1* and *ELG2* and utilizing the formula:

$$ELG' = ELG1 + RFRAC \cdot (ELG2 - ELG1)$$

wherein

ELG1 is the elongation at point X' of curve X'Y',

ELG2 is the elongation at point Y' of curve X'Y', and

*RFRAC*T is the ratio fraction.

Knowing the required elongation and the specified exit thickness, the required thickness *HIN* is calculated as the product of these quantities, i.e.,

$$HIN = ELG' \cdot HOUT$$

wherein

ELG' is the calculated required elongation corresponding to the specified force ratio *FRAT*, and

HOUT is the specified exit thickness of the bar.

When the ratio curves and the magnitude curves are power curves, the subroutine of FIG. 8 also can be employed (in the manner described with reference to the force ratio curves) to determine entry thickness of the bars. The output thickness and power ratio would be provided for the subroutine and the data utilized during calculations would be power ratio curve data rather than force ratio curve data stored within the computer memory.

One of the major advantages of dual force (or power) curves in accordance with this invention resides in the fact that accurate on-line adaptive feedback can be achieved conveniently by updating only the magnitude curve of FIG. 2c in response to measured deviations between actual and anticipated force (or power) levels in the mill. One routine for achieving the desired adaptive feedback is illustrated in FIG. 10 wherein both the force and power feedbacks are depicted on the same routine. In a force feedback mode, a "measured model" magnitude curve is calculated, based on measured values. As will be seen, on-line feedback on the force model consists of modifying the force magnitude curve (in a vector sense) partially toward correspondence with the "measured model" curve. The measured model force is calculated based on the measured force, normalized for width, hardness, temperature and elongation in accordance with the formula:

$$FMMRI(I) = \frac{FMRI(I)}{DEN \cdot FMRAT(I) \cdot CFTRI(I)}$$

wherein

FMMRI(I) is the measured model force (magnitude) value for the measured rolling conditions during pass (I), but corresponding to actual model temperature,

FMRI(I) is the measured force for pass (I),

DEN is a calculated normalizing factor, the product of strip width and the hardness multiplier for the type of product rolled,

FMRAT(I) is the measured force ratio determined from the elongation associated with the measured input and output thicknesses for pass (I), and

CFTRI(I) is a force temperature coefficient multiplier corresponding to the difference between the actual model temperature and the estimated temperature for pass (I).

When the measured model force is zero (a dummied pass condition) and the dummied pass number is identified as between the delivery pass and the entry pass, the measured model inverse thickness *EMMRI(I)* (a supplied value) is calculated from the formula:

$$EMMRI(I) = \frac{EMMRI(J) + EMMRI(K)}{2}$$

wherein

EMMRI(J) is the measured model inverse thickness for the first active pass upstream of the pass in question,

EMMRI(K) is the measured model inverse thickness for the first active pass downstream of the pass in question.

This logic is included in order to provide measured model values for all passes, including possible dummied passes. Measured model values for dummied passes at either end of the mill (if any) are provided by extrapolation.

The measured model force calculation then is repeated for all passes.

Measured model force values for dummied passes (if any) then are calculated by interpolation between adjacent values for active passes. The interim force (or power) terms for the new model are calculated (based on temperature of the old model) using the formula:

$$FMODI(I) = FMODI(I) + KFBR \cdot (FMMRI(I) - FMODI(I)) \text{ wherein}$$

FMODI(I) is the force (magnitude) model term for pass (I),

KFBR is the adaptive feedback gain corresponding to the chosen fraction of the difference between measured force and stored force to be utilized in correcting the stored force representation,

FMMRI(I) is the measured model (force) value for pass (I). The inverse thickness for the new model next is determined using the formula:

$$EMODI(I) = EMODI(I) + KFBR \cdot (EMMRI(I) - EMODI(I))$$

wherein

EMODI(I) is the inverse thickness term for the force model for pass (I),

KFBR is the adaptive feedback gain for updating the force term, and

EMMRI(I) is the measured model inverse thickness for pass (I). After the inverse thickness for each pass is calculated, the temperature value of the old model is temporarily stored and the temperature term for the new model is calculated in accordance with the formula:

$$TMODI(I) = TMODI(I) + KTFBR \cdot (TMRI(I) - TMODI(I))$$

wherein

TMODI(I) is the temperature term for the force model for pass (I),

KTFBR is the adaptive feedback gain chosen as the desired fraction for updating the temperature term, and

TMRI(I) is the measured model temperature for pass (I). The interim force term next is normalized to correspond with the new temperature term in accordance with the formula:

$$FMODI(I) = FMODI(I) \cdot \left[\frac{1 + KFTR \cdot (TOLDR - TMRI(I))}{1 + KFTR \cdot (TMODI(I) - TMRI(I))} \right]$$

wherein

FMODI(I) is the force (magnitude) model term for pass (I),

KFTR is the temperature coefficient factor representing the partial derivative of per unit rolling force with respect to temperature of the bar,

TOLDR is the model temperature value for this pass prior to updating,

TMRI(I) is the measured model temperature for pass (I),

TMODI(I) is the model temperature value for this pass, after updating.

The adaptive force feedback is illustrated graphically in FIG. 11 wherein magnitude curve 34C is stored within the computer by points 50-54 corresponding to the average output thickness from each stand (or pass). The measured model points actually determined from measurements at each stand (by the load cells LC1-LC3 and screwdown position indicators ESP11-ESP13 during a pass of bars B1-B3 through mill 10) are identified by reference numerals 60-64 and form curve 68. The computer then calculates a weighted average of corresponding points along curves 34C and 68, i.e., point 50 is averaged with point 60, point 51 is averaged with point 61, etc., to obtain average points 70-74, the updated force model (magnitude) curve. This new curve is employed in the model calculations for the force setting for the next bar passing through the mill. Because a great deal of credibility can be given to existing model data points (i.e., points 50-54, already stored within the computer, which are based upon a number of previous passes) as compared with the measured model data points (i.e., points 60-64, measured during a single pass) the average between corresponding points desirably is weighted to shift the measured model data points only a small fraction, e.g., one-fourth, of the span between the stored and measured data points. This weighting is accomplished by the selected value of the feedback gains KFBR and KTFBR.

When the power magnitude curves are to be updated by adaptive feedback, the measured model power for the pass is calculated, based on the measured motor power corrected for power bias offset (to obtain rolling power) and normalized for width, hardness, temperature, elongation/power ration and speed in accordance with the formula:

$$PMMRI(I) = \frac{PMRI(I) - PBIASI(I)}{DEN \cdot VSLRI(I) \cdot PMRATI(I)} \cdot \frac{1}{CPTRI(I)}$$

wherein

PMMRI(I) is the measured model power (magnitude) value, corresponding to the measured rolling conditions for pass (I), but corresponding to actual model temperature,

PMRI(I) is the measured motor powers for pass I,

PBIASI(I) is the motor power bias value for stand (I), i.e., the motor power required to overcome windage and friction when there is no steel being rolled,

DEN is calculated normalizing factor, the product of strip width and the hardness multiplier for the type of product rolled,

VSLRI(I) is the strip speed out of pass (I),

PMRATI(I) is the measured power ratio determined from the elongation associated with the measured input and output thicknesses for pass (I), and

CPTRI(I) is Ppower temperature multiplier, based on the actual model temperature and the estimated temperature for pass (I). The measured model power calculation then is repeated for all passes and dummied values are supplied before interim power terms for the new model are calculated (based on temperature of the old model) using the formula:

$$PMODI(I) = PMODI(I) + KFBR \cdot (PMMRI(I) - PMODI(I)) \text{ wherein}$$

PMODI(I) is the power (magnitude) model term for pass (I),

K(FBR) is the chosen adaptive feedback gain, and

PMMRI(I) is the measured model (power) value for pass (I), whereafter the inverse thickness term for the new model is calculated. After calculating the temperature term for the new model, the power term is normalized to correspond to the new temperature term according to the formula:

$$PMODI(I) = PMODI(I) \cdot \frac{1 + KPTR \cdot (TOLDR - TMRI(I))}{1 + KPTR \cdot (TMODI(I) - TMRI(I))}$$

in a manner similar to that described for the corresponding force (magnitude) model terms. This new power term then is employed in the model calculations to predict the rolling power in the mill for the next bar passing therethrough.

While a specific embodiment of this invention as used in a tandem roughing mill has been described, it will be obvious that stored shaping and magnitude curves also can be employed in substantially identical fashion to control a finishing mill or a single-stand reversing hot mill without departing from the scope of this invention as described in the appended claims.

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

1. In a method of reducing the thickness of metal by rolling the metal between at least one set of rollers wherein rolling parameters for a rolling pass are determined in association with a digital computer system by access to stored information representing the variation of said rolling parameters as a function of diverse metal characteristics, the improvement comprising storing the magnitude of a rolling parameter selected from the group consisting of power and force as a function of the thickness of the metal for a chosen per unit draft taken by said rollers, storing the ratio of said selected parameter for an actual reduction to said selected parameter for the chosen per unit draft as a function of the deformation of the rolled metal, determining the value of said parameter at the chosen per unit draft for

a desired output thickness and the value of said parameter ratio for a desired deformation and setting said parameter for the succeeding rolling pass at the arithmetic product of said determined values.

2. A method of reducing the thickness of metal according to claim 1 wherein said selected parameter is force, said force being stored as a function of inverse output thickness for an associated temperature value and said force ratio being stored as a function of the elongation of the rolled metal.

3. A method of reducing the thickness of metal according to claim 2 further including modifying the arithmetic product of force at the chosen per unit draft and temperature for a desired inverse output thickness and force ratio for a desired elongation by factors proportional to the width, hardness and estimated temperature of the metal before setting the force for the succeeding rolling pass.

4. A method of reducing the thickness of metal according to claim 1 wherein said selected parameter is power, said power being stored as a function of inverse output thickness for an associated temperature value and said power ratio being stored as a function of the elongation of the rolled metal.

5. A method of reducing the thickness of metal according to claim 4 further including modifying the arithmetic product of said power ratio and said power for a chosen per unit draft and temperature by factors proportional to the width, hardness, estimated temperature and speed of the mill before setting the power for the succeeding rolling pass.

6. In a method of reducing the thickness of metal by rolling the metal between at least one set of rollers wherein predicted rolling parameters for a pass of the metal through the rollers are determined in association with a digital computer system by access of stored families of functions defining relationships between various rolling parameters as functions of metal characteristics, the improvement comprising defining a rolling parameter selected from the group consisting of power and force by a first family of functions describing the ratio of the value of the selected parameter for actually contemplated rolling conditions to the value of the selected parameter for a chosen per unit draft as a function of metal deformation for diverse output thicknesses, said family of functions being characterized by a common intersection at the chosen per unit draft, defining said selected parameter as a function of the magnitude of said selected parameter for said chosen per unit draft against the thickness of the metal from the stand for various associated temperatures, accessing said stored functions to determine the magnitude of said selected parameter at the chosen per unit draft for a desired output thickness and the ratio of the selected parameter for a desired deformation, and setting the selected parameter for the rolling pass at the arithmetic product of said magnitude and said ratio as determined from said functions.

7. A method of reducing the thickness of metal according to claim 6 further including measuring the actual parameter at the stand during rolling and adaptively updating only the stored curve defining the magnitude of said parameter for the chosen per unit draft as a function of the output thickness, said adaptive updating of said curve being an amount proportional to the difference between the actually measured parameter and the existing stored functions.

8. A method of reducing the thickness of metal according to claim 7 further including modifying the measured parameter by an amount proportional to the width, hardness and temperature of the metal being rolled, prior to updating of said functions.

9. A method of reducing the thickness of metal according to claim 7 wherein said selected parameter is power and further including measuring the actual power during rolling and adaptively updating only the stored curve defining the magnitude of power for the chosen per unit draft as a function of output thickness, said adaptive updating of said magnitude curve being an amount proportional to the difference between the actually measured parameter and the existing stored functions.

10. A method reducing the thickness of metal according to claim 9 further including modifying the measured power by an amount proportional to the width, hardness and temperature of the metal and speed of the stand prior to updating of said stored functions.

11. A computer controlled method of rolling metal by passing said metal between a pair of confronting rollers whereby the incoming thickness, and therefore the amount of reduction, of said metal required to achieve a desired magnitude of force for a given output thickness can be predicted, said method comprising determining the temperature of the metal being rolled, accessing stored data depicting the variation of force for a predetermined percentage draft as a function of output thickness to determine the normalized force required to obtain the desired output thickness, calculating the ratio of the actual force to be applied at said stand to the normalized force, accessing stored data depicting the relationship between the ratio of actual force to the normalized force as a function of a metal deformation factor selected from the group consisting essentially of elongation and per unit draft to determine the quantity of metal deformation produced by the calculated force ratio and determining the incoming thickness of said metal from said metal deformation and said output thickness.

12. A method of rolling metal according to claim 10 further including adjusting the normalized force by an amount dependent upon the width and hardness of the metal being rolled before calculating said force ratio.

13. A computer controlled method of rolling metal by passing said metal between a pair of confronting rollers whereby the incoming thickness, and therefore the amount of reduction, of said metal required to achieve a desired magnitude of power for a given output thickness can be predicted, said method comprising determining the temperature of the metal being rolled, accessing stored data depicting the variation of power for a predetermined percentage of draft as a function of output thickness to determine normalized power required to obtain the desired output thickness, calculating the ratio of the actual power to be applied at said stand to the normalized power, accessing stored data depicting the relationship between the ratio of actual power to the normalized power as a function of a metal deformation factor selected from the group consisting essentially of elongation and per unit draft to determine the quantity of metal deformation produced by the calculated power ratio and determining incoming thickness of said metal from said determined metal deformation and said output thickness.

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14. A method of rolling metal according to claim 13 further including adjusting the normalized power by an amount proportional to the width and resistance to deformation of the metal being rolled and the speed of the stand prior to calculating said power ratio.

15. An automated rolling mill comprising at least one rolling stand having a pair of confronting rollers, means for adjusting the openings between said rollers, and a computer control system having means defining a parameter selected from the group consisting of power and force by a first family of curves defining the ratio of the parameter magnitude for a chosen per unit draft as a function of elongation, said family of ratio curves being characterized by a common intersection at the chosen per unit draft, means defining said parameter for a chosen per unit draft as a function of the output thickness of metal passed through said stand, means for accessing said stored curves to determine both the

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value of the parameter for the chosen per unit draft required to produce a desired output thickness in metal passed through said rollers and the value of said ratio for a given elongation, means for calculating the arithmetic product for said values as determined from said curves, and means for predicting the selected parameter at said mill at the arithmetic product of said values.

16. An automated rolling mill according to claim 15 wherein said selected parameter is force and further including means for measuring the actual force at said stand during rolling and means for adaptively updating only said means defining force magnitude as a function of the output thickness, said adaptive updating being by an amount proportional to the difference between the representation for actually measured conditions and the existing representation.

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