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IRON AND STEEL ENGINEER, May, 1965. "Determination of a Mathematical Model for Rolling Mill Controls" by Dr. R. G. Schultz and A. W. Smith, Jr. pp. 127—133

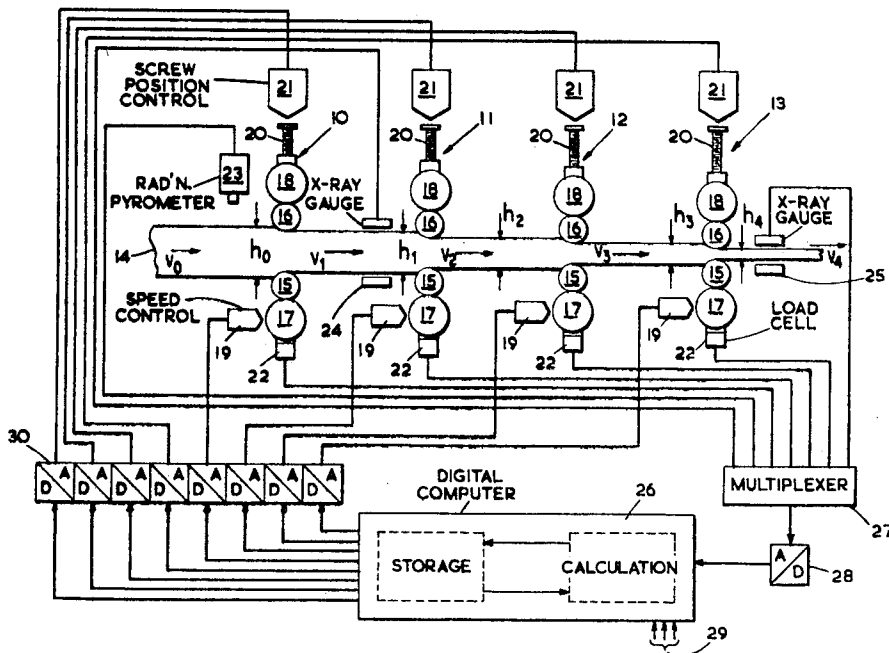
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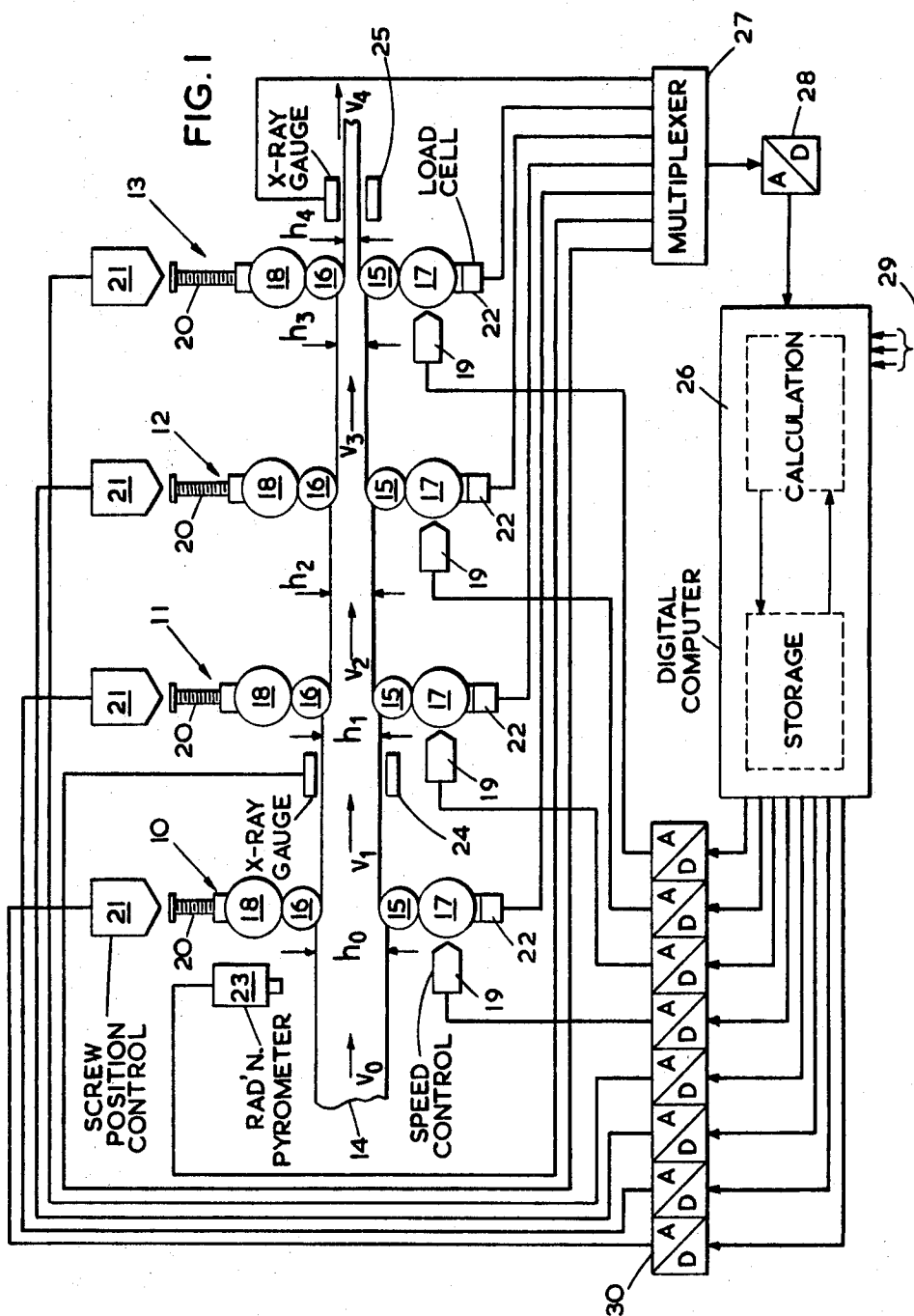
[54] **AUTOMATIC CONTROL OF ROLLING MILLS**  
**10 Claims, 7 Drawing Figs.**

[52] U.S. Cl. .... 72/8,  
 72/16  
 [51] Int. Cl. .... B21b 37/00  
 [50] Field of Search. .... 72/7, 8, 16,  
 17

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**ABSTRACT:** The specification describes a multistage rolling process which is controlled by a computer to reduce the thickness of a piece of deformable material from a known initial thickness to a desired final thickness. Using the terminal thicknesses and other known or assumed characteristics of the material, the computer derives values for the rolls separations in the stages for achieving an optimum value for a parameter such as maximum throughput or minimum power for the process as a whole.





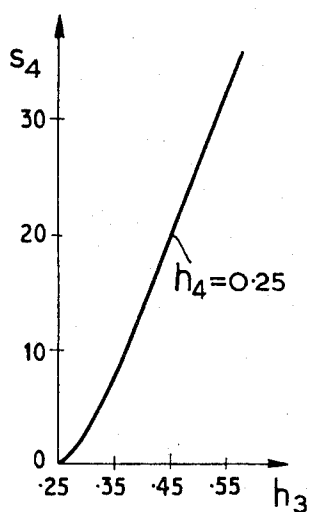


FIG. 2(a)

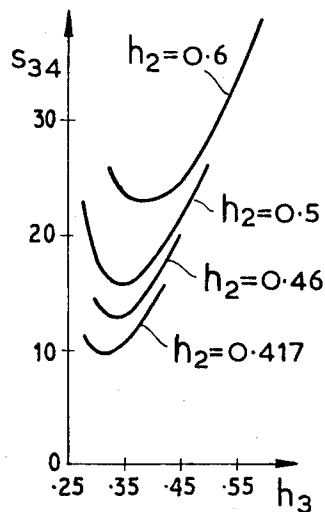


FIG. 2(b)

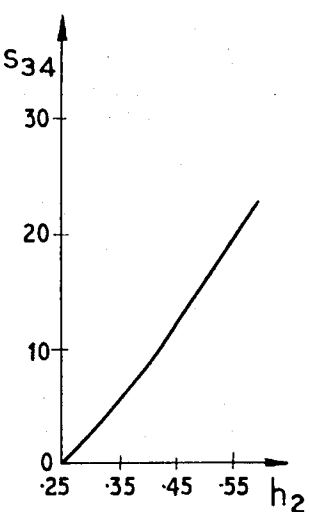


FIG. 2(c)

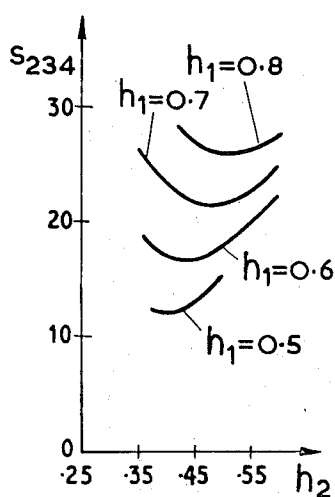


FIG. 2(d)

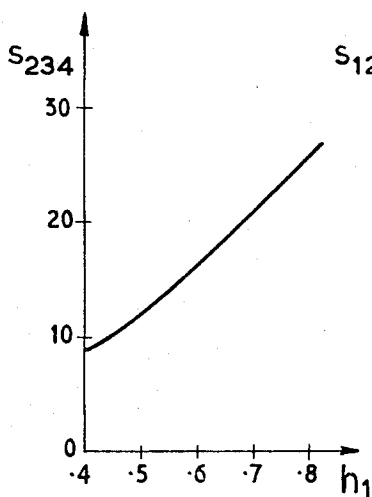


FIG. 2(e)

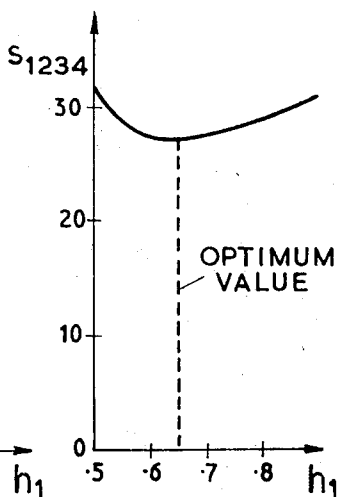


FIG. 2(f)

# AUTOMATIC CONTROL OF ROLLING MILLS

This invention relates to the automatic control of rolling mills for reducing deformable material such as steel from a known initial thickness to a desired final thickness; these two thicknesses may be referred to as the 'terminal thicknesses' of the rolling process.

In rolling mills to which this invention relates the reduction in thickness is effected by a multistage rolling process comprising a plurality of successive rolling stages in each of which the material is reduced by a desired amount.

The successive stages may be achieved by passing the material backwards and forwards in turn between a single pair of rolls in a single mill stand. Alternatively, the successive stages may be achieved by passing the material through successive pairs of rolls carried in successive separate mill stands, the material threading a plurality of stands simultaneously during a substantial part of the rolling process.

In recent years the enhanced automatic control of rolling mills has been the subject of various proposals in which the desired control has been effected by means of an electronic digital computer. In such proposals the computer has been provided with data specifying particulars as to the material to be rolled, and the mill, and other data fed back by monitoring devices of the mill so as to enable recomputation to correct errors which have arisen from the adoption initially of certain basic assumptions.

One such proposal for the automatic control of Rolling Mills is set out in U.S. Pat. No. 3,332,263 (Beadle et al.).

The present invention is directed at reducing the number of basic assumptions so that the computer may provide more accurate setting signals for setting the roll gap and speed for each rolling stage of a multistage rolling process. In such aforementioned prior proposals the distribution between the various rolling stages of the total reduction in material thickness to be achieved has been determined in quite arbitrary and empirical manners, on the basis of past experience of mill operators. No more scientific approach to this problem of distribution seems to have been attempted.

The present inventors have directed their attention to the problem of determining more scientifically the manner of distributing the total reduction between the successive rolling stages.

According to one feature of the present invention the distribution of the total reduction between the successive stages of a rolling process is computed in a control computer in such a manner as to optimize a rolling process parameter, such as the material throughput (maximized), the horsepower (minimized), or the horsepower per unit throughput (minimized). Preferably, operating constraints for the mill are used in computing the said distribution so that during no rolling stage is the mill caused to operate outside its constraints.

According to another feature of the present invention a method of setting up a rolling mill for rolling a material of known rolling characteristics in a series of successive rolling stages to reduce its thickness from a known initial value to a desired final value comprises the steps of:

- i. storing in a digital computer data specifying the characteristics of the mill for each stage, the material rolling characteristics, the initial thickness and the final thickness;
- ii. systematically computing in the digital computer from the stored data and in accordance with an expression specifying a process parameter in terms of the reduction in material thickness in a rolling stage and other parameter values of the mill relevant to the stage to determine for different combinations of reductions in the successive stages the values of the process parameter for the whole rolling process;
- iii. selecting the combination of successive stage reductions giving the optimum value for the process parameter for the whole rolling process;

- iv. determining in the computer the values of roll gap and speed for the respective stages using the selected combination of successive stage reductions; and
- v. setting roll gap and speed-controlling devices of the mill for the respective rolling stages in accordance with the values determined in the preceding step and with the mill stretch characteristics.

According to another feature of the present invention the method may also include the steps of:

- i. storing in the digital computer data specifying operation constraints for other process parameters within which the mill must operate during the respective stages so as not to damage the mill or material being rolled;
- ii. computing in the digital computer from the stored data and in accordance with expressions specifying the said other process parameters in terms of the reduction in material thickness in a stage and other parameter values of the mill relevant to the stage the values of the said other process parameters relevant to each rolling stage;
- iii. comparing in the computer the values of the said other process parameters relevant to each rolling stage with the stored constraint data for the respective stages, and
- iv. eliminating any of the said combinations of stage reductions which would cause the mill to operate during any stage outside the operating constraints for that stage.

The first-mentioned process parameter may comprise, for example, the mill throughput of rolled material, the selected combination of stage reductions being that giving maximum throughput for the whole rolling process.

Alternatively, the first-mentioned process parameter may comprise the mill horsepower, the selected combination of stage reductions being that giving the minimum horsepower required for the whole rolling process.

The said other process parameters may comprise, for example, the roll load in a rolling stage, or the roll horsepower in a rolling stage.

According to another feature of the present invention a method of setting up a rolling mill for rolling a material of known rolling characteristics in a series of successive rolling stages to reduce its thickness from a known initial value to a desired final value comprises the steps of:

- i. storing in a digital computer data specifying the characteristics of the mill for each stage, the material-rolling characteristics, the initial thickness and the final thickness;
- ii. computing (in the computer) for a pair of successive stages including one of the terminal stages an input/output characteristic (limited within the operating constraints of the mill) of an equivalent single rolling stage relating, for the predetermined terminal material thickness at the terminal stage, optimum values of a rolling process parameter to the value of the material thickness at the nonterminal side of the said equivalent single rolling stage;
- iii. computing (in the computer) for a second pair of successive rolling stages including the said equivalent single rolling stage an input/output characteristic (limited within the operating constraints of the mill) of a second equivalent single-rolling stage relating, for the said predetermined terminal material thickness, optimum values of the rolling process parameter to the value of the material thickness at the nonterminal side of the said second equivalent single rolling stage;
- iv. computing (in the computer) in turn for successive pairs of successive rolling stages each of which includes the equivalent single rolling stage deduced in the preceding step an input/output characteristic (limited within the operating constraints of the mill) of a next equivalent single-rolling stage relating, for the said predetermined terminal material thickness, optimum values of the rolling process parameter to the value of the material thickness at the nonterminal side of the said next equivalent single-rolling stage;

- v. selecting from data derived in producing an ultimate equivalent single rolling stage for the whole rolling process the value of the nonterminal thickness equal to the other of the two terminal material thicknesses of the rolling process;
- vi. computing (in the computer) from data representing the said input/output characteristics deduced and stored during the course of carrying out the earlier steps the values of the material thickness and speed in the respective stages of the rolling process; and
- vii. setting roll gap and speed-controlling devices in dependence upon the computed values of material thickness and speed determined in the preceding steps, and the mill stretch characteristics.

One automatic rolling mill installation embodying, and operating according to, the present invention will now be described by way of example and with reference to the accompanying drawings in which

FIG. 1 shows diagrammatically the mechanical arrangement of the rolling mill, and the apparatus for achieving the desired automatic control by digital control computer, and

FIGS. 2(a)—2(f) show a series of graphs which depict the manner, to be explained later, in which mill stand power  $S$  varies for various conditions of ingoing and outgoing slab thickness  $h$ .

Referring now to FIG. 1 only, the rolling mill has four stands 10 to 13 arranged for making successive reductions on a hot metal slab such as is indicated by the reference numeral 14 in its passage through the mill from left to right.

Each stand comprises lower and upper work rolls 15 and 16 and corresponding lower and upper backing rolls 17 and 18, the work rolls 15 and 16 being mechanically coupled to an associated electric motor (not shown) for driving the rolls in the required direction. Speed control devices 19 are associated with the driving motors and enable the motor speeds to be varied as is later to be described.

A screwdown motor (not shown) and associated screw 20 is provided for each stand so that the gap between the work rolls of the stand may be varied, in response to a signal from an associated screwdown control device 21.

A load cell 22 in each stand provides a signal indicative of the separating or roll force between the work rolls of the stand as a slab passes through it.

Other sensing devices provided are a radiation pyrometer 23 disposed at the entry end of the mill (i.e., before stand 10) for generating a signal indicative of the temperature of a slab passing beneath it, and two X-ray gauges 24 and 25 disposed respectively between stands 10 and 11 and at the outgoing end of the mill (i.e., beyond stand 13) for providing signals indicative of the thickness of the slab at those points.

A digital control computer 26 with storage and calculation capabilities receives, via a multiplexer 27 and an analogue-to-digital converter 28, the signals provided by the load cells 22, the radiation pyrometer 23 and the X-ray gauges 24 and 25. Further input signals may be passed to the computer in digital form via lines such as are indicated by the reference numeral 29.

Outputs from the computer are passed through respective digital-to-analogue converters such as are indicated by the reference numeral 30 to the speed control devices 19 and to the screwdown devices 21.

The computer operates under the control of a program which is constructed to achieve a rolling process as described later.

Let us assume that a slab of known thickness  $h_0$  is approaching the mill from, say, a roughing stand (not shown) to the left of the drawing and that it is required that the slab be reduced to a desired final thickness  $h_4$ . The thicknesses  $h_0$  and  $h_4$  may be referred to as the terminal thicknesses of the slab.

The mill shown in the drawing is first "set up" by the computer using the known input thickness  $h_0$  and desired output thickness  $h_4$  of the slab and the known grade of material of the slab. These three parameters are represented as signals

manually or automatically derived which are fed along one or more of the lines 29 to the computer. The computer accordingly holds them in storage.

The process of setting up of the mill is now to be described in detail. This process effects, inter alia, the setting of the roll gaps of individual stands of the mill in anticipation of the arrival of the slab. The criterion adopted is that the throughput of the mill (i.e., the rate of mass flow through the mill) in making the desired reduction is to be a maximum, subject of course to any constraints in horsepower, roll loads etc. of the rolling mill equipment.

For each stand the rolling process parameters, the power per unit throughput, the roll torque and the roll separating force (roll load) are each related to the work roll radius  $R$ , the outgoing thickness  $h$  of the slab as it leaves the stand and the reduction  $r$  performed on the slab by the stand, by an equation of the form:

$$\log_e X = A_0 + A_1 \log_e \frac{R}{h} + A_2 \log_e r + A_3 \log_e \frac{R}{h} \cdot \log_e r + A_4 (\log_e r)^2 \quad (1)$$

where  $X$  represents the parameter under consideration.

$A_0$ ,  $A_1$ ,  $A_2$ ,  $A_3$ , and  $A_4$  are generally given by the following expressions:

$$A_0 = p_1(T) + \left( \log_e \frac{2\pi N}{60} \right) p_2(T)$$

$$A_1 = p_3(T)$$

$$A_2 = p_4(T) + \left( \log_e \frac{2\pi N}{60} \right) p_5(T)$$

$$A_3 = p_6(T)$$

and

$$A_4 = p_7(T)$$

where  $N$  is the rotational speed of the stand rolls, and  $p_1(T)$ ,  $p_2(T)$ , etc. are power series in  $T$  (the slab temperature) of the form  $a_0 + a_1 T + a_2 T^2 - a_n T^n$ , where  $a_0$ ,  $a_1$ ,  $a_2$  etc. are constants of which the magnitude, particular to the parameter  $X$  and function  $A_0$ ,  $A_1$ , etc. being considered, is dependent upon such factors as the characteristics of the stand in question and the material specification of the slab involved.

In passing through the stands of the mill the rate of mass flow of the slab remains constant so that, assuming constant slab width, we have

$$v_0 h_0 = v_1 h_1 = \dots = v_n h_n = \dots$$

so that  $v_n = v_0 h_0 / h_n$  (2)

where  $v_0$  and  $h_0$  are the speed and thickness of the slab as it enters the mill and  $v_n$  and  $h_n$  are the speed and thickness of the slab as it leaves the  $n$ th stand.

The horsepower  $H_n$  of the  $n$ th stand is related to the stand torque  $G_n$  and rotational speed  $N_n$  by the equation:

$$\log_e H_n = \log_e G_n + \log_e N_n - k_1 \quad (3)$$

where  $k_1$  is a constant. Now  $N_n$  is proportional to  $v_n$  and is therefore also proportional to  $v_0 h_0 / h_n$  from equation (2) above.

Equation (3) therefore becomes:

$$\log_e H_n = \log_e G_n + \log_e k_2 v_0 h_0 / h_n \quad (4)$$

where  $k_2$  is a constant and the term  $\log_e G_n$  is given by equation (1) with the torque  $G_n$  as the parameter  $X$ . It will therefore be seen that equation (4) is a particular form of equation (1.)

Before the slab reaches the first stand, the computer is automatically caused to become active and compute the settings at which the rolls of the various stands are to be set in readiness for the arrival of the slab. In doing this, the computer behaves as follows.

The computer uses equations (1) and (4) as follows to determine the stand reductions required to satisfy the criterion of maximum throughput, in reducing a slab of known thickness  $h_0$  to a desired final thickness  $h_4$ .

For the particular rolling mill being described, in the power series  $p_1$ ,  $p_2$ ,  $p_4$  and  $p_5$  involved in equation (1), the terms involving powers of  $T$  greater than two are not significant and are ignored with little loss of accuracy; in the power series  $p_3$ ,  $p_6$  and  $p_7$ , the term involving  $T^2$  is also negligible.

For each stand the computer holds in storage empirically determined values of the constants  $a_0$ ,  $a_1$  and, where appropriate,  $a_2$  for each function  $A_0$ ,  $A$ , etc. of each parameter, these particular values being determined from the previous rolling of slabs of the same grade as the slab to be rolled.

Prior to the arrival of the slab at stand 10, the computer calculates the maximum permissible value of  $v_0$ , the slab speed into the mill as a whole, as follows.

The stand horsepower increases monotonically with  $v_0$ , and since stand 13 has a maximum permitted horsepower at any time, this particular value of horsepower can be used in equation (4), using the anticipated value of the slab temperature  $T$ , to enable the computer to determine, for each of a number of selected values of  $h_3$ , the maximum value of  $V_0$  allowed by the stand horsepower rating.

A further set of calculations is then made by the computer to ensure that the maximum allowable roll load will not be exceeded during rolling. To make this calculation, the computer solves equation (1) with the roll load of the last or terminal stand 13 as the parameter  $X$  and using the (stored) constants  $a_0$ ,  $a_1$  and  $a_2$  appropriate to stand 13 and to roll load. In an analogous manner to that previously described in connection with the rated horsepower, the maximum allowable value of roll load is substituted in the equation and the maximum values of  $v_0$  corresponding to the selected values of  $h_3$  are determined. The values of  $v_0$  thus calculated are then each compared with the corresponding values of  $v_0$  obtained from the maximum horsepower and the lesser of the two values for each value of  $h_3$  is taken and held in storage.

Another restriction to which  $v_0$  is subject is imposed by the operating speed,  $N_4$ , of stand 13, which must not exceed a known limiting speed value. To ensure that stand 13 will not be required to operate at a speed greater than this value, the computer calculates the value of  $v_0$  given by the relationship:

$$h_0 v_0 = h_4 v_4$$

where  $v_4$  has the limiting value corresponding to the limiting value of  $N_4$ . This value of  $v_0$  is compared with the values of  $v_0$  obtained from the previous comparison, and in each case the lesser of the values is taken and held in storage with the corresponding value of  $h_3$ .

There also exists a lower speed minimum below which the rotational speed of stand 13 cannot fall. Again using the relationship  $h_0 v_0 = h_4 v_4$ , the computer calculates the value of  $v_0$  appropriate to this limiting speed, compares this value with the values of  $v_0$  obtained from the previous comparisons and rejects any value of  $h_3$  for which the value of  $v_0$  determined from the minimum value of  $N_4$  exceeds the value of  $v_0$  determined from the comparisons.

From the above calculations there are therefore obtained (and held in storage) maximized values of  $v_0$  for a number of selected values of the interstand gauge  $h_3$  between stands 12 and 13.

Using each of the selected values of  $h_3$  in turn as the stand exit thickness, the computer then performs further calculations and comparisons identical to the above but in respect of stand 12 that is, for a number of selected values of entry thickness  $h_2$ . It will be appreciated that the sets of values of  $a_0$ ,  $a_1$  and  $a_2$  appropriate to stand 12 are used. The mass flow relationship  $h_0 v_0 = h_3 v_3$  is used for determining the limiting values of  $v_0$  so far as stand speed is concerned.

The resulting maximized values of  $v_0$  are then compared with the corresponding (in respect of  $h_3$ ) values of  $v_0$  derived as above from the consideration of stand 13, and for each value of  $h_2$  the lesser of the two values of  $v_0$  is taken for each value of  $h_3$ .

For each of the selected values of  $h_2$  the computer then takes the greatest (or greater, as the case may be) of the respective values of  $v_0$  for a given value of  $h_3$  and holds it in storage together with the associated value of  $h_3$ . This value of  $h_3$  is the optimum value of slab thickness between stands 13, so far as maximum throughput is concerned, that is, for the particular value of  $h_2$  being considered. Stands 12 and 13 in combination can therefore be considered as a single equivalent stand.

For each of a number of selected values of entry thickness  $h_1$  to the second mill stand 11, the computer then derives, for each of the selected values of  $h_2$ , values of  $v_0$  maximized as before.

These values of  $v_0$  are then compared with the corresponding values of  $v_0$  derived as described above from the combination of stands 12 and 13, and for each value of  $h_1$  the lesser value of  $v_0$  is taken for each value of  $h_2$ .

For each of the selected values of  $h_1$  the computer then takes the greatest of the respective values of  $v_0$  and holds it in storage together with the associated values of  $h_2$ . Stands 11, 12 and 13 can then be considered in combination to form a single equivalent stand.

Stand 10 is then considered. The entry thickness  $h_0$  is known, and using this value the computer derives a value of  $v_0$  maximized in accordance with the restrictions imposed by stand 10, for each selected value of  $h_1$ .

These maximized values are compared with the corresponding values of  $v_0$  derived from the combination of stands 11, 12 and 13, and for each value of  $h_1$  the lesser value of  $v_0$  is taken. The value of  $h_1$  giving the greatest value of  $v_0$  is then selected, and the associated values of  $h_2$  and  $h_3$  are selected in turn from the optimum values held in storage.

By the above calculations and comparisons there are therefore determined the values of the interstand gauges  $h_1$ ,  $h_2$  and  $h_3$  necessary for the mill to operate with maximum throughput. Also determined is the required entry speed to the mill and hence, by the mass flow relationship, the required interstand speeds.

Since only a number of discrete values of interstand thickness have been used, it will be appreciated that the values of  $h_1$ ,  $h_2$ ,  $h_3$  and  $v_0$  determined in this way are only approximate. In order to obtain more accurate values of  $h_1$ ,  $h_2$ ,  $h_3$  and  $v_0$  the calculations described above are made a second time using a smaller mesh (of suitably chosen values of interstand thickness) based on the interstand thicknesses already determined. The more accurate values obtained are then used to set the roll gap settings of the stands in anticipation of the arrival of the slab.

To give the actual roll gap setting required, that is, making the allowance for the amount that each stand will stretch when performing the reduction required of it, a function of the roll load to be expected and the stand stiffness is subtracted in the computer from the appropriate outgoing slab thickness calculated as described above. The roll load is calculated from equation (1).

Signals proportional to the roll gap settings thus predicted are then passed from the computer to the appropriate screwdown control devices 21 and these accordingly control their associated screwdown motors to move the work rolls 16 (and the backing rolls 19) until the roll gaps are at their predicted values.

The setting up of the mill described above occurs before the incoming slab reaches the pyrometer 23. As previously described, the value of the slab temperature  $T$  used in the calculation of the functions  $A_0$  to  $A_4$  is an anticipated value. If, when the slab reaches the pyrometer 23, the latter detects a slab temperature which is different from this anticipated temperature, then the computer recalculates the roll gap settings on the basis of the new temperature value. By using the same values of interstand thickness as were used in the second calculation (i.e., the finer mesh) the time required for this new calculation is kept sufficiently low for the roll gap settings of the stands to have been readjusted where necessary before the slab reaches stand 10.

The slab then reaches stand 10 and undergoes its first reduction in that stand. On emerging from stand 10 the actual thickness  $h_1$  of the slab is measured by the X-ray gauge 24 and a signal proportional to that thickness is passed to the computer. Alternatively, the thickness  $h_1$  of the slab emerging from the stand could be estimated by measuring the roll load and roll gap setting of the respective pair of rollers 15 and 16. If for any reason there is any discrepancy between the actual

and estimated (stored) values of  $h_1$ , the computer recalculates and readjusts where necessary the roll gap settings of stands 11, 12 and 13 on the basis of the actual value of  $h_1$ .

By thus using the actual temperature of the slab as it enters the mill and the actual thickness of the slab as it leaves stand 10, the mill control is provided with an adaptive feature in that the roll gap settings predicted before the slab enters the mill and set during the setting-up procedure are readjusted to take account of any errors between actual and assumed values of the slab parameters.

If the speed of the computer is sufficiently high, a further X-ray gauge may be positioned intermediate stands 11 and 12 for providing to the computer a further signal indicative of the actual slab thickness  $h_2$  at that point. This signal may then be used to readjust the roll gap settings of stands 12 and 13 in accordance with the actual thickness  $h_2$  so that even greater accuracy of outgoing thickness from the mill may be obtained. Ideally a further X-ray gauge is disposed between stands 12 and 13 for further extending the adaptive feature.

After stand 10 the slab undergoes further reductions in stands 11, 12 and 13. The actual thickness of the slab as it emerges from stand 13 is sensed by the X-ray gauge 25, and the signal produced by the gauge 25 and proportional to the outgoing slab thickness is used by the computer for readjusting the roll gap settings of all the stands in an error-reducing manner if, despite the adaptive feature described above, there is any error between the actual and desired outgoing slab thicknesses.

Although in the above description the calculation of the required interstand gauges is made beginning with the last stand (stand 13) and working back to the first stand, it will be appreciated that the calculation could alternatively be made involving the stands in the reverse order. Also, the mill exit speed  $v_4$  could be used instead of the entry speed  $v_0$  as the reference variable.

It will be realized that the time relation of the different calculations and comparisons need not be exactly as described, and any suitable order of computation and comparison may be used. Also, the reference variable ( $V_0$  or  $v_4$ ) may additionally or alternatively be maximized in respect of mill parameters other than stand horsepower, stand speed and roll load; it may, for example, be maximized in respect of strip tension and temperature.

Although in the specific description so far given the rolling process is such as to satisfy the criterion of maximum process throughput, it will be appreciated that other optimizing criteria may be used in a rolling process in accordance with the invention. In the description that now follows the rolling mill shown generally in FIG. 1 operates to provide settings for the roll gap and speed of the respective stands so as to obtain from the rolling process the minimum power consumption for a given throughput. To achieve this, the computer operates in the manner now to be described with reference to the FIGS. 2(a) to 2(f).

Using equation (4), the computer calculates the power  $S_4$  which it is anticipated will be needed of stand 13 in reducing the slab to the desired final thickness  $h_4$  from each of a number of selected values of ingoing thickness  $h_3$ , that is, for a particular mill throughput. Any value of  $h_3$  which gives excessive stand power is rejected.

For the purposes of the above calculation, the computer uses in equation (4) values of  $A_0$ ,  $A_1$ ,  $A_2$ ,  $A_3$  and  $A_4$  which are selected from storage in accordance with the known characteristics of stand 13 itself and the known grade and predicted temperature of the slab.

In order to make allowance for the speed limitations of the stand, the computer uses the known throughput in the mass flow relationship to derive the values of  $h_3$  which correspond to the maximum and minimum permissible entry speeds to the stand. Any one of the chosen values of  $h_3$  which lies outside these two limiting values is rejected.

The values of power  $S_4$  calculated as described above and the associated values of ingoing thickness  $h_3$  are passed to

storage and there held. The computer thus holds in storage a number of points defining the graph shown in FIG. 2(a).

For each of the selected values of thickness  $h_3$  the computer then uses equation (4) to determine the power required of stand 12 in reducing the slab to the thickness  $h_3$  from each of a number of selected values of the ingoing thickness  $h_2$  to stand 12 which lie within limits imposed by the speed of stand 12. The values of  $A_0$  to  $A_4$  appropriate to power and to stand 12, are, of course, used for these solutions. As for stand 13, the computer takes account of any limitations (horsepower and speed) there may be on stand 12 by rejecting impermissible values of  $h_2$ .

For each of the selected values of  $h_2$  the computer then adds to the values of power of stand 12 corresponding to the selected values of  $h_3$ , the appropriate values of power of stand 13. These values of the total power of stands 12 and 13,  $S_{34}$ , if plotted against  $h_3$  would form a family of curves, one curve for each value of  $h_2$ . As will be seen from the graph of FIG. 2(b) each curve has a minimum value. The computer determines the minimum value of the power  $S_{34}$  for each value of  $h_2$  and, together with the corresponding value of  $h_2$  and  $h_3$ , holds it in storage.

The computer thus holds in storage a number of points defining the graph shown in FIG. 2(c). This graph is similar in form to the graph shown in FIG. 2(a) so that stands 12 and 13 in combination can now be considered to form a single equivalent stand.

For each one of a number of selected (and confirmed) values of entry thickness  $h_1$  to stand 11, the computer then calculates the power required of stand 11 to reduce the slab to each of the values of thickness  $h_2$  used above. These values of power are then added to the corresponding (in respect of  $h_2$ ) values of power  $S_{34}$  to give the family of curves shown in FIG. 2(d). As for the curves of FIG. 2(b) the curves of the family each have a minimum value, and the computer likewise selects the minimum calculated values of the curves and, together with the corresponding values of  $h_1$  and  $h_2$ , holds them in storage. These points define the graph shown in FIG. 2(e). Stands 11, 12 and 13 in combination can now be considered to form a single equivalent stand.

For the known value of the thickness of the slab as it approaches the mill, the input thickness  $h_0$ , the computer then calculates the power required of stand 10 to reduce the slab to each of the values of  $h_1$  already used, and these values of power are added to the corresponding (in respect of  $h_1$ ) values of the power required of stands 11, 12 and 13 as determined above. This gives the single curve, as shown on FIG. 2(f), having a calculated minimum value which is selected and then, with its associated value of  $h_1$ , held in storage by the computer. This minimum value is the anticipated minimum value of the total power which will be required of the four stands of the mill (considered as a single equivalent stand) to reduce the slab from the known ingoing thickness to the desired outgoing thickness at the given throughput.

As has been particularly described for the calculations of power for stands 12 and 13, all values of the interstand thicknesses which give excessive power requirements on any of the stands are rejected so that this anticipated minimum value of the total power required of the mill does not require any overload of any of the stands. Also, all speed restrictions on the mill stands are taken into account during the calculation (as has been described) so no over or underspeeding of a mill stand is involved.

Further constraints may be imposed upon the interstand thicknesses by the rolls themselves. To take account of any restrictions in roll loadings, the roll loads for the values of the interstand thicknesses used in the calculation of specific power are calculated, separately from the calculation of power and using equation (1) (with the appropriate values of  $A_0$  to  $A_4$ ). Any value of interstand thickness which gives an excessive roll load is rejected.

In the above manner, any restrictions on stand horsepower, speed and roll load can readily be accommodated. In a similar

way, allowance can also be made for other parameters such as strip tension and temperature.

Using the data obtained as described above and held in storage, the computer then determines the values of interstand slab thickness as follows.

Using the minimum calculated value of  $h_1$  held in storage, the computer selects the value of  $h_2$  appropriate to that value of  $h_1$  as the required thickness between stands 11 and 12. This value of  $h_2$  is in its turn used in the selection of the required value for  $h_3$ .

As in the embodiment previously described, in order to obtain more accurate values of  $h_1$ ,  $h_2$  and  $h_3$ , the calculations described above are made a second time using a smaller mesh (of suitably chosen values of interstand thickness) based on the interstand thicknesses already determined.

The more accurate values of  $h_1$ ,  $h_2$  and  $h_3$  are then used in the setting of the roll separations of the stands in anticipation of the arrival of the slab. As before, allowance is made for the predicted stretching of the mill stands as the slab passes through them.

The slab then passes through the mill and in so doing is reduced to its required final thickness. Allowance is again made for any deviation of the slab temperature (on entry) from its predicted value, and for any deviation of the actual exit thickness from the first stand from the derived setting value. The negative feedback feature previously described is also provided, so that any deviation of the final strip thickness from its desired value is corrected by simultaneous control of all the stands.

The speed at which the slab passes through the mill affects the roll gap settings required to achieve the derived optimum interstand thicknesses, and account is made for the variation in speed of the slab (between threading speed and running speed) by predicting the roll loads at discrete intervals of speed as the strip accelerates and by using these values of roll load in the control of the roll gap settings. In this way the interstand thicknesses are maintained substantially at their optimum values throughout the strip acceleration. It will be appreciated that the values of the roll load are calculated using different sets of values of the functions  $A_0$  to  $A_4$  in equation (1). This technique is also available for the previously described rolling process using the criterion of maximum throughput.

The invention is not limited in scope to rolling processes such as have been specifically described above, nor is it limited in application to multistand hot steel rolling mills.

Thus, the invention may be applied to cold steel rolling mills, to single stand reversing steel mills, and to the rolling of materials other than steel. Where the invention is applied to a single stand reversing mill the computer sets up the mill initially for the first pass having calculated and stored the optimum roll gap settings required for each pass. The mill roll gap is then successively reset between passes in accordance with these settings. In an analogous manner to the two rolling processes described above, allowance may be made on entry and between passes (by modification of the roll gap settings) for any error between actual and assumed values of the slab parameters.

In applications of the invention to multistand rolling mills, it is not necessary for the roll separation to be set simultaneously for all the stands as has been described. The stands may thus be successively set in step with, (but in advance of), the material as it passes through the mill. Such an arrangement requires no readjustment of each roll separation after it has been initially set, whilst still enabling full allowance to be made for any deviation from the predicted values of the characteristics of the material when entering and passing through the mill.

Although equation (1) has a general form which is particularly suitable for solution by a digital computer, it will be appreciated that other forms of equation may be used. In addition, equation (1) need not be used in full; thus in some applications of the invention sufficient accuracy may be obtained even though the term  $A_4 (\log r)^2$ , for example, is omitted.

Equation (1) may be to any suitable logarithmic base, although  $e$ , the base of natural logarithms, is preferably used.

Although the invention has been particularly described with minimum power consumption and maximum throughput as the criteria used, other criteria may be used if desired.

Thus, in one rolling process in accordance with the invention, the criteria used is minimum power per unit throughput. By repeating a similar procedure to that previously described as many times as is necessary using the criterion of minimum power, the minimum power (and associated mill setup) is derived for each of a number of different throughputs. The mill setup selected is the one having the smallest ratio of minimum power consumption to throughput.

It will be appreciated that the invention is not limited to rolling processes having four successive rolling stages (as have been particularly described with reference to the drawings), but is applicable to rolling processes having two or more rolling stages.

Although in the rolling process described with reference to the drawings the computer is arranged to operate on line to make such calculation and comparison as is necessary to derive setting values required for the mill setup, (to achieve an optimum value of a predetermined parameter for the process as a whole), it will be appreciated that as an alternative the required setting values for various combinations of grade, terminal dimensions, temperature etc. may be calculated off line and held in storage. Mill setup as a workpiece is approaching the first stage, may then be achieved by selecting those setting values appropriate to the workpiece and by adjusting the roll separations accordingly.

However, if the passage of the slab through a stand shows the off-line computation to be based on incorrect data the process must be repeated online (in real time) in order to correct the settings for the subsequent rolling stages.

We claim:

1. The method of setting up a rolling mill for rolling a material of known rolling characteristics in a series of successive rolling stages to reduce its thickness from a known initial value to a desired final value comprising the steps of:

- i. storing in a digital computer data specifying the characteristics of the mill for each stage, the material-rolling characteristics, the initial thickness and final thickness;
- ii. systematically computing in the digital computer from the stored data and in accordance with an expression specifying a process parameter in terms of the reduction in material thickness in a rolling stage and other parameter values of the mill relevant to the stage to determine for different combinations of reductions in the successive stages the values of the process parameter for the whole rolling process;
- iii. selecting the combination of successive stage reductions giving the optimum value for the process parameter for the whole rolling process;
- iv. determining in the computer the values of roll gap and speed for the respective stages using the selected combination of successive stage reductions; and
- v. setting roll gap and speed-controlling devices of the mill for the respective rolling stages in accordance with the values determined in the preceding step and with the mill stretch characteristics.

2. The method according to claim 1 including the steps of:

- i. storing in the digital computer data specifying operating constraints for other process parameters within which the mill must operate during the respective stages so as not to damage the mill or material being rolled;
- ii. computing in the digital computer from the stored data and in accordance with expressions specifying the said other process parameters in terms of the reduction in material thickness in a stage and other parameter values of the mill relevant to the stage the values of the said other process parameters relevant to each rolling stage;
- iii. comparing in the computer the values of the said other process parameters relevant to each rolling stage with the stored constraint data for the respective stages, and

- iv. eliminating any of the said combinations of stage reductions which would cause the mill to operate during any stage outside the operating constraints for that stage.
- 3. The method according to claim 2, wherein the first-mentioned process parameter comprises the mill throughput of rolled material, and the selected combination of stage reductions is that giving maximum throughput for the whole rolling process.
- 4. The method according to claim 3, wherein the said other process parameters are selected from the group comprising:
  - i. the roll load in a rolling stage; and
  - ii. the roll horse power in a rolling stage.
- 5. The method according to claim 3, wherein the first-mentioned process parameter comprises the mill horsepower, and the selected combination of stage reductions is that giving the minimum horsepower required for the whole rolling process.
- 6. The method according to claim 5, wherein the said other process parameters are selected from the group comprising:
  - i. the roll load in a rolling stage; and
  - ii. the roll horsepower in a rolling stage.
- 7. The method according to claim 1, including the steps of
  - i. altering the stored data in accordance with data signals provided by the mill during any rolling stage; and
  - ii. repeating the steps specified in claim 1 so as to set the roll gap and speed-controlling devices for the remaining rolling stages of the rolling process so as to take account of the disparities between the initially stored data conditions and the relevant actual rolling conditions represented by the said data signals provided by the mill.
- 8. The method of setting up a rolling mill for rolling a material of known rolling characteristics in a series of successive rolling stages to reduce its thickness from a known initial value to a desired final value comprising the steps of:
  - i. storing in a digital computer data specifying the characteristics of the mill for each stage, the material rolling characteristics, the initial thickness and the final thickness;
  - ii. computing (in the computer) for a pair of successive stages including one of the terminal stages an input/output characteristic (limited within the operating constraints of the mill) of an equivalent single rolling stage relating, for the predetermined terminal material thickness at the terminal stage, optimum values of a rolling process parameter to the value of the material thickness at the nonterminal side of the said equivalent single rolling stage;
  - iii. computing (in the computer) for a second pair of successive rolling stages including the said equivalent single rolling stage an input/output characteristic (limited within the operating constraints of the mill) of a second equivalent single rolling stage relating, for the said predetermined terminal material thickness, optimum values of the rolling process parameter to the value of the material thickness at the nonterminal side of the said

- second equivalent single rolling stage;
- iv. computing (in the computer) in turn for successive pairs of successive rolling stages each of which includes the equivalent single rolling stage deduced in the preceding step an input/output characteristic (limited within the operating constraints of the mill) of a next equivalent single rolling stage relating, for the said predetermined terminal material thickness, optimum values of the rolling process parameter to the value of the material thickness at the nonterminal side of the said next equivalent single rolling stage;
- v. selecting from data derived in producing an ultimate equivalent single rolling stage for the whole rolling process the values of the nonterminal thickness equal to the other of the two terminal material thicknesses of the rolling process;
- vi. computing (in the computer) from data representing the said input/output characteristics deduced and stored during the course of carrying out the earlier steps the values of the material thickness and speed in the respective stages of the rolling process; and
- vii. setting roll gap and speed-controlling devices in dependence upon the computed values of material thickness and speed determined in the preceding step, and the mill stretch characteristics.
- 9. In combination:
  - a rolling mill for carrying out a multistage rolling process on material supplied to it and including roll gap and speed setting means for setting the roll gap and speed for each stage of the process in accordance with command signals received;
  - storage means for storing data signals specifying the characteristics of the mill for each stage, the material rolling characteristics, the initial thickness of the material at entry to the mill, and the desired final thickness at exit from the mill; and
  - digital computing means for computing in accordance with the stored data signals and an expression specifying a rolling process parameter the combination of material thickness reductions at each stage to give an optimum value over the whole rolling process of the rolling process parameter, and for supplying the said command signals in accordance with the said combination of material thickness reductions.
- 10. Apparatus according to claim 9, including process monitoring means for providing feedback data signals to the storage means whereby to alter the stored data in accordance with the actual rolling process conditions, and means for causing the digital computing means to compute a new combination of stage reductions which will provide an optimum value for the rolling process parameter for the stages of the process yet to be performed, and to provide appropriate new command signals for the stages yet to be performed.