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COMPLETE SPECIFICATION

Method and Apparatus for Rolling Metal Strip and Sheet

We, YOUNGSTOWN RESEARCH & DEVELOPMENT COMPANY, of Youngstown, Ohio, United States of America, a Corporation of the State of Ohio, United States of America, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

This invention relates to a method and apparatus for rolling metal strip and sheet, and more particularly to a method and apparatus for maintaining deflection of a single small diameter work roll of a roll stand substantially at a given position in the roll pass of the stand. The deflection to which this invention relates is in a direction with and opposite to travel of metal through the mill.

Generally, a single work roll is on a 5-high stand, a 3-high stand, or a 4-high stand where it is the smallest diameter roll of the stand. On the 5-high stand, it has an upper and a lower intermediate roll each of larger diameter and an upper and a lower backing roll each of greater diameter than the intermediate rolls and each each backing roll in frictional engagement with its intermediate roll. This work roll is in frictional engagement with the one intermediate roll and forms with the other intermediate roll a roll pass through which the metal travels and in which it is reduced in thickness.

On the 3-high mill, the roll is the smallest roll and is disposed between two backing rolls, each of which is driven by an electric motor.

Driving force for the work roll results from frictional engagement with at least one backing roll or intermediate roll and from application of forward tension to the metal by a winding reel or another stand on the exit side thereof.

In recent years, there has developed an increasing demand for wide metal strip and sheet, particularly in the very thin gauges such as 0.001″ to 0.007″ with a special emphasis upon flatness. Although it is recognized that small diameter work rolls readily bite into the metal being rolled, reduce screw pressures and make reductions in gauge of the metal which cannot be made with larger diameter rolls, efforts to use such small diameter rolls, especially those which are too small to be driven through their necks (those with diameters 1″ to 4″) have been unsuccessful. This has resulted from inability to control the deflection of these rolls in the plane of metal travel through the mill as a consequence of which it has been highly difficult to obtain a specified degree of flatness in the strip or sheet. The uncontrolled deflection of bowing of the small diameter work roll causes over-rolled edges or ripples and/or over-rolled centre portions or buckles in the strip. When this occurs in the thin gauges, it is costly and troublesome, if not impossible, to remove the buckles and riffles and off-gauge strip is produced, thereby rendering it unsatisfactory for specifications and orders.

Two factors can cause this deflection, the first being an unbalance of forces acting upon the small work roll and the second being a combination of forces generated by the screw-down mechanism of the stand acting upon the top backing roll and of the tolerances in the bearings and chocks for the backing rolls, intermediate rolls and the work roll. Considering first the deflection caused by the unbalance of forces acting upon the rolls and referring to Fig. 1 of the accompanying drawings which shows diagrammatically a 5-high mill, that mill comprises a top backing roll 1 and a bottom backing roll 2 with a top intermediate roll 3 and a lower intermediate

roll 4 disposed therebetween. The top intermediate roll is in frictional engagement with the top backing roll and the lower intermediate roll is in frictional engagement with the bottom backing roll with the backing rolls being driven by electric motors not shown. However, the intermediate rolls can also be driven. Disposed between the two intermediate rolls is a small diameter work roll 5 in frictional engagement with the lower intermediate roll 4 and forming a roll pass with the top intermediate roll 3. Extending through the roll pass is metal strip 6.

A combination of two resulting forces rotate the work roll 5. The first resulting force acts on the top side of the roll and comprises a portion of strip delivery tension T_d and a tangential force F_1 generated by the top backing roll 1 acting upon the top intermediate roll 3 and extending transversely through the strip thickness to the top part of the work roll 5. The sum of these two forces tends to move the roll 5 towards the delivery side of the mill as shown by arrow 7.

The second resulting force acts on the lower side of the work roll 5 and comprises a tangential force F_2 produced by rotation of the lower backing roll 2 in frictional engagement with the intermediate roll 4. The other component of this second resulting force is the entry tension T_e which, together with the tangential force F_2, acts to move the work roll 5 towards the entry side of the mill as shown by arrow 8. Consequently, for equilibrium conditions corresponding to a zero lateral deflection and zero bearing loads on the rolls, the following condition exists:

$$(T_e+F_2)=(T_d+F_1).$$

The second factor which causes the deflection results from a combination of forces generated by operation of a screwdown mechanism and of tolerances in the roll bearings and chocks. When the screwdown mechanism lowers the top backing roll and the top intermediate roll to establish a given roll pass to effect a particular reduction, the screwdown mechanism exerts a force on the rolls. This force, in combination with the tolerances between the roll necks, the bearings and/or the chocks and tolerances in the mill housing may cause the work roll to deflect in the direction with or opposite to travel of strip through the mill. Such deflection occurs because of the small amount of space between the bearings and the roll neck and between the chocks and the mill housings, thus enabling the roll necks and/or chocks to shift or move a small amount when subjected to the screwdown force.

Control over deflection of the small work roll to obtain a desired shape or flatness in the strip encounters further ~~complication~~ from a heat build-up in the rolls, especially during sustained rolling periods. This heat build-up cannot be completely dissipated by flood coolant and generally effects an expansion or swelling commonly called "crown" in a centre portion of the small roll. Presence of the crown causes over-rolling of the centre portion of the strip, thereby requiring compensation in the position of the small roll in the roll pass to minimize if not eliminate its effect upon the shape of the strip. Thus, regulation of deflection of the single small roll presents many problems which place severe requirements upon a control system therefor.

Full realization of advantages from use of the single small diameter work roll has been hampered by inability to very quickly effect a correction or compensation for deflection to maintain or return the roll at or to a given position in the roll pass. Since the metal is travelling through the mill at speeds from about 500 f.p.m. to about 6,000 f.p.m., a substantial amount of defectively shaped strip can result where even a 2—4 second period is consumed in returning the work roll to its given position. Production of defectively shaped strip is unwanted for it must either be cut out of the coil or the coil diverted to another order, thereby materially increasing costs of manufacture.

This invention permits full utilization of the advantages of the small diameter work roll by maintenance of deflection of the roll at a given position in the roll pass and by ability to effect an extremely fast correction for deviations in deflection from the given position.

The present invention is a method for rolling metal sheet or strip on a rolling mill having a small diameter work roll, at least one upper and at least one lower backing roll for said work roll, each of said backing rolls having a diameter greater than said work roll, said rolls being disposed substantially vertically of one another, said work roll and one of said upper and lower backing rolls forming a roll pass through which metal is reduced in thickness, and another of said packing rolls being in frictional engagement with said work roll, said work roll being subject to deflection in a direction substantially with or substantially opposite to travel of metal through said mill, the steps comprising driving an upper backing roll by at least a first motor operatively connected thereto, driving a lower backing roll by at least a second motor operatively connected thereto, controlling amount of said deflection of said work roll in said roll pass by effecting changes in apportionment of applied torque by said motors between said driven rolls through sensing amount and direction of deflection of said work roll from a given position, from said sensing generating a signal related to amount and direction of deflection, producing from said signal an error signal related to the difference between the sensed

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complications

position of said work roll and the given position of said work roll and related to the direction of said deflection, utilizing said error signal for increasing and decreasing output torque of one of said motors connected to one driven roll relative to output torque of said other motor connected to said other driven roll for effecting said changes in apportionment of applied torque to said driven rolls to control deflection of said work roll.

Embodiments of the invention will now be described by way of example, with reference to the accompanying drawings, in which:—

Fig. 1 shows schematically a 5-high mill in a section transverse to the axes of the rolls,

Fig. 2 is a schematic view of one device for detecting deflection of the single small roll of a 5-high mill;

Fig. 3 is a schematic view of a second sensing device;

Fig. 4 is a schematic view of third sensing device;

Fig. 5 is a schematic view of a fourth sensing device;

Fig. 6 is a schematic view of a fifth sensing device;

Fig. 7 is a schematic view of a sixth sensing device;

Fig. 8 is a schematic diagram showing the invention applied to a 2-stand, 5-high tandem mill;

Fig. 9 is a block diagram of apparatus for generating the signal which is used to maintain deflection of the roll at a given position;

Fig. 10 is a schematic wiring diagram of one embodiment of a slow acting regulating system and a fast acting regulating system which receives the signal and generates therefrom a reversible push-pull continuous current and reversible push-pull pulses of current for producing the regulating buck-boost output armature current;

Fig. 11 is a schematic wiring diagram showing a first modification of the embodiment of Fig. 10;

Fig. 12 is a schematic wiring diagram of a second modification of the embodiment of Fig. 10;

Fig. 13 is a schematic wiring diagram of a second fast regulating system for the embodiment of Fig. 10;

Fig. 14 is a schematic wiring diagram of a third fast regulating system for the embodiment of Fig. 10; and

Fig. 15 is a schematic wiring diagram of a third modification of the embodiment of Fig. 10.

Referring to Figs. 2, 9 and 10, the 5-high mill of Fig. 1 mounts apparatus 9 for detecting deflection of the single small diameter work roll 5 in a roll pass formed by the upper intermediate roll 3 and the small diameter roll itself. As shown, the lower backing roll 2 is driven by two motors 10 and 11 connected in tandem with motor 10 being shown in Fig. 2 and the top backing roll is driven by two motors 12 and 13 connected in tandem. The upper intermediate roll 3 is in frictional engagement with the upper backing roll 1 and the lower intermediate roll 4 is in frictional engagement with the lower backing roll 2. Although the roll drive is shown connected to the backing rolls, it may alternatively be joined to the intermediate rolls, one of which also functions as a backing roll for the work roll 5.

Connected to the sensing apparatus 9 is a signal generator 14 which produces from deflection a signal proportional in magnitude and directional as to direction of the deflection. This signal travels to a push-pull output amplifier 29 where a first portion continues to a push-pull driver amplifier 16 whose output is delivered to a slow acting regulating system 17 and a second portion advances to a bias and trigger generator combination 18 whose output is transmitted to a fast action regulating system 19. The slow regulating system produces a reversible push-pull substantially continuous current and the fast regulating system generates reversible push-pull pulses of current of short duration. These two currents are fed to a buck-boost generator 20 whose output is applied to the armatures of the motors for driving the backing rolls 1 and 2. By boosting the armature current of one roll drive motor combination and bucking the armature current of the other roll drive motor combination, a change is effected in the proportion of torque applied to the roll 5 to maintain it or return it to a given position in the roll pass.

Considering the sensing apparatus of Fig. 2, nozzles 21 and 21*a* connected to conduits 22 and 22*a* leading from a source of fluid under pressure such as air or liquid, straddle both sides of the roll 5, are substantially opposite the face 24 of the roll 5, and are substantially in alignment with the centre line of the roll and substantially midway between the ends of the face 24 thereof so that deflection of the roll 5 in the direction with or opposite to strip travel through the roll pass is toward one nozzle and simultaneously away from the other nozzle. Safety bars 25 and 25*a* mount and position the nozzles opposite the roll face.

These nozzles are located close to the roll face across gaps 26 and 26*a* between the ends ~~the ends~~ of the nozzles and the roll face so that deflection of the roll 5 produces a change in pressure of the fluid under pressure in the conduits. Preferably, the length of the gaps between the nozzle and the roll face is from about 0.005" to about 0.050" when the roll and its intermediate and backing rolls are in axial alignment as shown in Fig. 1.

Within the range of deflection of the roll 5, impingement of two jets of air or fluid against the roll face produces back pressure in the conduits 22 and 22*a* with this back pressure being less when the roll is deflected away from one nozzle to lengthen the gap and greater when the deflection is toward the nozzle to shorten the gap. When the rolls 5, 1, 2, 3 and 4 are in axial alignment, impingement of the two jets against the roll face produces equal amounts of back pressure in the conduits 22 and 22*a*. The back pressure effects the pressure of air or fluid forming the jet and as the gap shortens, the back pressure increases and as the gap lengthens, it decreases. Accordingly, as the work roll 5 deflects toward the nozzle 26, back pressure in the conduit 22 increases, thereby reducing the strength of the jet from the nozzle 26 and increasing pressure in the conduit 22. Simultaneously, the roll 5 deflects away from the nozzle 26*a* and decreases back pressure in conduit 22*a* accompanied by an increase in pressure of the jet from the nozzle 26*a* and a decrease in pressure in the conduit 22*a*. This change in strengths of the jets and the changes in pressures in the conduits are used for detection of roll deflection and the magnitude of the changes are proportional to the amount of deflection and the direction of change dependent upon an increase or decrease in pressure.

To convert changes in fluid pressure in the conduits into a signal for controlling operation of the mill, the conduits are connected to a signal generator 14 comprising a transducer 27 and a linear variable differential transformer (LVDT) 28 whose output is transmitted to an amplifier 29. The transducer 27 comprises a diaphragm 30 disposed in a casing 31 and forming therein two airtight chambers 32 and 33. This diaphragm 30 is sensitive to changes in pressure within both chambers 32 and 33. Connected to the chamber 32 is the conduit 22 and connected to the chamber 33 is the conduit 22*a* whereby the diaphragm detects changes in fluid pressure in the conduits and generates a signal in response to these changes. Seated between the diaphragm 30 and a cap 35 of the casing and in connection with the diaphragm 30 is an adjustable calibrated spring 36 which cooperates with a second spring 40 connected to a nonmagnetic rod 38 of the transformer 28 to maintain the diaphragm 30 in a neutral position. Thus, when the roll 5 is an axial alignment or in its given position in the roll pass and there is no deflection, the pressures exerted upon both sides of the diaphragm are equal and the two springs 36 and 40 assist to maintain the diaphragm 30 in its neutral position, i.e., that shown in Fig. 2. When the roll 5 deflects in a direction of strip travel indicated by arrow 37, pressure in the chamber 32 increases and that in the chamber 33 decreases, whereupon the diaphragm 30 moves upwardly and generates a signal proportional to the amount of roll deflection and directional with deflection of the roll. On the other hand, where the roll 5 deflects in the direction opposite to strip travel, the pressure in the chamber 32 decreases and that in the chamber 33 increases so that the diaphragm moves downwardly, thereby generating a signal proportional to the amount of roll deflection and indicating the direction of roll deflection. The two springs 36 and 41 also return the diaphragm to its neutral position upon removal of a pressure differential between the two chambers 32 and 33.

Movement of the diaphragm 30 operates the linear variable differential transformer 28 through the non-magnetic rod 38 carrying a magnetic core 39 thereon. A spring 40 at the opposite end of the rod 38 takes play out of the rod movement but the spring 36 joined to the diaphragm 30 in combination with the air pressure in the chamber 32 controls and effects movement of the diaphragm to determine directional movement of the core 39.

The linear variable transformer 28 comprises a primary coil 41 and two secondary coils 42 and 43 mounted in a hollow cylinder 44 of non-magnetic material. The magnetic core 39 and the non-magnetic rod 38 travel linearly between the primary coil and the two secondary coils in response to movement of the diaphragm 30 caused by roll deflection.

Energization of the primary coil by a power source 75, preferably one kilocycle or more, induces voltages in the two secondary coils in proportion to the magnetic couplings between the primary and the secondary coils through the magnetic core 39 which provides a path for magnetic flux linkages between the coils. When the magnetic core is in its control or neutral position between the primary and secondary coils in correspondence with the neutral position of the diaphragm, the voltages induced in the secondary windings are equal due to the symmetry of the physical location of the coils. The two secondary coils are connected series opposing so that the two voltages in the secondary circuit are opposite in phase and the net output of the transformer is the difference between these two voltages. Thus, when the magnetic core is in its neutral position, the output voltage from the secondary coils is zero but when the magnetic core is moved upwardly or downwardly, viewing Fig. 2, in response to movement of the diaphragm caused by roll deflection, there is a net voltage output.

When the diaphragm moves the core 39 from its neutral position, the voltage induced in the coil 42 towards which the core moves increases while the voltage induced in the other coil 43 decreases. Accordingly, a differential voltage output from the transformer results and this voltage is linearly propor-

tional to the amount of core movement and indicates the direction of roll deflection. Movement of the core in the opposite direction beyond this neutral position produces a similar voltage increase in coil 43 and a voltage dcrease in coil 42, but with the phase of the voltage output shifted 180°. It is this shift of 180° in the phase of the voltage output which represents the direction of roll deflection. The voltage output is the signal which is used to regulate the position of the roll 5 in the roll pass.

Figs. 3 and 4 show two other types of roll deflection sensing devices which utilize electromagnetic induction to induce eddy currents in the surface of the roll 5 where high frequencies such as 50 kilocycles and higher are used, or to effect changes in the inductive reactance in one or two electromagnetic inductors which changes correspond to shortening and lengthening of gaps between the inductors and the roll face. As shown in Fig. 3, two electromagnetic inductors 45 and 46 are located one on each side of the small roll 5 and connect each inductor into a bridge circuit 46*a* in which each inductor forms one arm of the reactance bridge. The other two arms of the bridge are resistors 45*a* and 45*b* of selected values. Two corners of the bridge formed by the junctions of the two resistors and the two inductors are connected to a high frequency source 47*a* of alternating current as provided by the driver oscillator 75. The other two corners of the bridge formed by the junctions of resistor 45*a* and inductor 45 and of resistor 45*b* and inductor 46 are the outputs of the reactance bridge and are connected to the amplifier 29. The reactance bridge circuit has a null balance RC network comprising a variable capacitor 45*c* and a variable resistor 45*d* connected in parallel and across one input corner 45*e* and one output corner 45*f*.

As to each inductor, changes in reactance as a result of roll deflection are non-linear. However, the two in combination, when disposed in the reactance bridge circuitry, will produce a linear output as a function of roll deflection.

Each inductor is spaced apart from the roll 5 to provide small gaps 48 and 49 between the roll face and the leading face of each inductor and each inductor generates magnetic lines of flux which travel from the inductor across the gaps to the roll face. When the small work roll 2 is in axial alignment with the backing rolls and when it has no lateral deflection, the gaps 48 and 49 between the roll face and each inductor are substantially equal in length. Thus, for substantially equal length air gaps, reactance of the two inductors is matched so that so long as the gaps between the roll face and each inductor are substantially equal in length, the bridge is in balance and either zero voltage output will result, or, it may be so calibrated by the null balance network that at this point the output voltage will be one-half or any desired value of that corresponding to a maximum gap. When the roll 5 is against one inductor, it is furthest away from the other inductor, resulting in a maximum output voltage. If on the other hand the maximum gap is reversed to the opposite side, then the bridge output voltage will be minimum but still in the same phase and above the null point. In other words, the system can be set up with a so-called null suppression which is desirable in a control or regulating circuitry since at equal gaps a definite bridge output voltage is present which after amplification can be matched to a reference voltage corresponding to a given gap set point. With any lateral roll deflection towards either inductor, the reactance bridge will further unbalance, resulting in an output voltage change proportional to the gap change as to both magnitude and direction.

If the bridge were null balanced with equal gaps, then a phase inversion would occur with alternate changes in the gaps which would then have to be detected and compensated for in the detection circuitry of the signal, complicating the circuitry; furthermore, a zero voltage bridge output would result at this point necessitating a zero reference voltage, which is not good practice.

For practical purposes it is better to move the roll against one inductor and the bridge null-balanced. The output voltage of the bridge will then be a function of the roll displacement away from that coil and will rise to a maximum value when the roll is against the opposite coil. At a ~~milway~~ gap point the out put voltage will then be substantially one-half of its maximum value which is conducive to good detection and regulating techniques as it can now be matched against an equal reference voltage. Any deviation from this reference is detected by a difference amplifier 78 (Fig. 9) which can now be further fed into the proper functional circuitry of a regulating system to restore balance.

It has been found that a gap between the roll face and the leading face to the inductor of about 0.005" to about 0.025" effects satisfactory detection of roll deflection.

Each inductor comprises a circular core 51 made of powdered iron with an exciting coil 52 located on the centre leg 53 of the core. Both the coil and core are sealed by suitable materials such as plastics resistant to oil and/or water, for example, epoxies, and the cores are disposed in bars located opposite the face of the roll 5.

The single inductor 51*a* of Fig. 4 operates similarly to those of Fig. 3 except that its output is non-linear and it requires additional compensation circuitry for the non-linearity output. In this regard, a reactance bridge

circuit 51*b*, similar to circuit 46*a* would have a variable inductance for one arm and a proper valued resistor associated with the variable inductance as another arm. The other half of the bridge comprises the inductor 51*a* and the resistor 45*b*.

Figs. 5 and 6 show two additional devices for detection of roll deflection which use the changes in reluctance of magnetic lines of flux which bridge one or two small gaps to detect the deflection. As shown in Fig. 4, two proximity transformers 54 and 55 are located one on each side of the single small diameter roll 5 and the primary winding of each transformer is connected to a source of A.C. power 47, as provided by an oscillator such as oscillator 75 of Fig. 9. Proximity transformer 54 has a primary winding 56 and a secondary winding 57 and proximity transformer 55 has a primary winding 58 and a secondary winding 59. Each transformer is spaced apart from the work roll 5 to form the small gaps 60 and 61 between the roll face and each transformer and each primary winding directs magnetic flux linkages to the roll 5 across the gaps and to its secondary winding. It has been found that a gap between the roll face and the proximity transformer of about 0.005" to about 0.025" effects satisfactory detection of roll deflection. The two primary windings are connected series aiding and the two secondary windings are connected in series bucking.

Connected to the two secondary windings 57 and 59 is an amplifier 50 so that output voltage of the two secondary coils travels thereto for production of a signal.

Because the two secondary windings are connected series bucking, the two output voltages in the secondary circuit are opposite in phase and the net output of the two proximity transformers is the difference between the two output voltages.

When the small work roll 5 is in axial alignment with the backing rolls and when it has no lateral deflection, the gaps 60 and 61 are equal in length. Thus, for equal length air gaps, the voltage output of the two secondary windings is equal and since the two secondary windings are connected series bucking, there is no transformer output voltage. However, when the roll 5 deflects towards a transformer, there is an increase in the strength of the magnetic flux linkages from the transformer towards the roll accompanied by a distortion of the transformer's flux pattern caused by a change in proximity of the roll having ferro-magnetic properties relative to the transformer. Accordingly, the increase in the strength of the magnetic flux linkages caused by deflection toward the transformer produces an increase in the voltage output of its secondary winding. Rolls made from steel and made from tungsten carbide have ferro-magnetic properties with the ferro-magnetic properties in tungsten carbide being in the cobalt binder. Correspondingly, there is a decrease in the strength of the magnetic flux linkages from the transformer away from which the roll deflects accompanied by a distortion of the transformer flux pattern caused by the change in proximity of the roll relative to the transformer. Thus, the decrease in the strength of the magnetic flux linkages caused by deflection away from the transformer produces a decrease in the voltage output of its secondary winding. Therefore, roll deflection effects a net output voltage of the two proximity transformers.

This net output voltage is proportional in amount to the magnitude of the deflection and is directional in accordance with the direction of deflection. An amplifier 50 generates from this net output voltage an impulse which is proportional to the amount of deflection and which has characteristics of direction of deflection.

Fig. 6 shows a single proximity transformer 62 positioned on one side of the single small diameter work roll 5 for detection of roll deflection. In using the single proximity transformer, its voltage output to the amplifier 50 when there is no deflection and the roll is in the given position and the roll pass is matched with a standard voltage in the amplifier. When there is roll deflection towards or away from the proximity transformer, there is a resulting increase or decrease in the voltage output of the transformer, thereby causing the amplifier to generate a signal of the same character as the signal produced when using two proximity transformers.

Fig. 7 shows another device for detection of roll deflection which comprises a tube 63 for delivering a fluid such as oil against the face of the roll 5 from a source of oil entering the tube through a flexible pipe 64. A nozzle 65 of the tube is opposite the face of the roll 5 and separated therefrom by a film of oil. The pressure of the oil issuing from the nozzle 65 in combination with the pressure of a spring 69*a*, to be described hereinafter, may be such that the nozzle backs away from the roll 0.0001" to about 0.001". Accordingly, the nozzle rides this film of oil and avoids a metal-to-metal contact with the roll to eliminate marking the roll face. The rear end 66 of the tube 63 engages an upper portion 67 of a pivoted arm 68 maintained in its neutral position corresponding to zero deflection of the roll from its given position in the roll pass by a spring actuated plunger 69 in contact with an upper portion of the arm. The lower end 70 of the arm 68 engages one end of a rod 71 which carries a magnetic core (not shown) corresponding to core 39. This core is disposed in a linear variable differential transformer 28*a* identical to the transformer 28. Consequently, deflection of

the roll toward and away from the nozzle 65 operates the linear variable transformer 28a in the same manner as transformer 28 to detect deflection of the roll.

A bar 72 extending substantially parallel to the longitudinal axis of the roll 5 carries the tube 63. Opposite the bar 72 on the other side of the roll 5 is a second bar 73 parallel thereto and having on its side opposite the other face of the roll 5 a cushion 74 made from a material which does not mark or mar the surface of the roll 5 should it contact same in deflection. This other bar assists to maintain the roll 5 within a given range of deflection so that should there be excessive deflection, the small roll will not break or fracture.

The roll deflection sensing devices disclosed herein have ability to detect very small amounts of roll deflection such as 0.001" from which a signal is produced for maintenance of the roll substantially at a given position in the roll pass. Additionally, these devices are such that use of a flood coolant on the mill does not affect their operation or reduce their ability to detect small amount of deflection.

Referring to Fig. 9, the linear variable differential transformer 28 has connected thereto an oscillator 75 which supplies A.C. power of high frequency therefor. The signal output of this linear variable differential transformer advances to an amplifier 29 where it is amplified and forwarded to a phase detector 76. This detector rectifies the A.C. roll position signal to provide a D.C. voltage proportional to the displacement of the roll from its given position in the roll pass with a polarity indicating the direction of the displacement.

A roll position selector 77 produces an adjustable reference D.C. voltage so that a position at which the roll is maintained can be selected by a mill operator. This reference D.C. voltage along with the output of the phase detector 76 is fed to a difference amplifier 78 which provides an output voltage signal proportional to the difference between the actual roll position and the desired position chosen on the selector 77. The output voltage signal for the amplifier 78 is proportional in magnitude to the amount of deflection and is directional relative to the direction of deflection.

The push-pull output amplifier 15 receives the output D.C. voltage signal from the difference amplifier 78 and provides sufficient power to drive two separate push-pull circuits which deliver portions of the output voltage signal of the amplifier 78 to the fast acting regulation system 19 and the slow acting regulation system 17. A first portion of the output of this push-pull amplifier 15 is transmitted to one separate push-pull circuit 79 comprising a rate generator 80 and an attenuator 81 connected in parallel with a frequency compensation network 82 and a second attenuator 83. This first portion, like the output voltage signal of the amplifier 78, has a magnitude proportional to the amount of deflection and is directional relative to the direction of deflection. The rate generator 80 is a differentiating circuit that gives an output signal proportional to the velocity of the deflection.

The frequency compensation network 82 controls the high frequency phase of the circuit and amplitude response of feedback circuits to be described hereinafter.

The attenuators 81 and 83 control the gain of feedback loop and the amount of dampening.

The output of this parallel circuitry advances to an adder 84 which combines the roll position error signal of the compensation network 82 and the rate signal of the rate generator 80 in the proper phases to produce an output signal. This signal is fed to the slow regulation system 17 through the push-pull driver amplifier 16, which is in circuit with two control fields 85 and 86 of a rotating amplifier 87 (Fig. 10) such as Amplidyne, Rototrol, Regulex regulators.

A second portion of the output of the push-pull amplifier is transmitted to a second separate push-pull circuit 88 identical to that circuit 79 comprising the rate generator 80, frequency compensation network 82, the two attenuators 81 and 83 and the adder 84. From the circuit 88 the resulting output signal is transmitted to the bias and trigger generator 18 connected to thyratrons which are a part of the fast acting regulating system 19.

The reference voltage produced by the roll position selector 77 is carefully regulated so that it does not fluctuate with line voltage, load or temperature changes. This reference voltage is derived from a calibrated roll position setting potentiometer located on the mill and convenient for the operator to select a given position. This reference voltage is then used to preselect the performance level required of the regulated quantity which is a current difference corresponding to torque differentials in the mill motor armatures.

Maintenance of the small roll in the given position requires that overall performance of the regulating system consisting of the fast and slow systems prevent over- or undershooting which can bring about oscillations of various frequencies in the roll. In this regard, various time constants of various elements of the mill, both electrical and mechanical, which add up to an overall time constant, must be taken into consideration and each individual time constant reckoned with in designing the regulating system to prevent oscillation.

It has been found that time constants in the various components of the electrical

system can be varied within reason by changes in $\frac{L}{R}$ ratios of each circuit. In this connection, the $\frac{L}{R}$ ratio can be shortened by increasing R through addition of external resistors which, of course, effect power losses and require an increase in size or capacity of components in the circuits.

The given position referred to in this application includes a small band of movement such as plus-minus 0.001" and on wide mills, may be plus-minus 0.0025". Within this small band of movement, regulation of deflection of the roll is achieved so that the deflection does not exceed on either side of a given line substantially parallel to the longitudinal axis of the roll plus-minus the ranges set forth above.

In order to achieve very fast and careful regulation of deflection of the roll it is mandatory that the driven mill rolls have separate motors to permit effecting a change in proportion of the division of torque between the two roll drives without affecting the total amount of torque imparted to the rolls themselves and without affecting the main generator's current output. Such a roll drive, in combination with out dual regulating system achieves correction for roll deflection in intervals such as 4 to 17 or 20 milliseconds.

Referring to Fig. 10, a main generator 89 driven by an A.C. motor 90 is connected to the mill motors 10, 11, 12 and 13 with mill motors 12 and 13 driving the top backing roll 1 mechanically coupled thereto and mill motors 10 and 11 driving the lower backing roll 2 and mechanically coupled thereto. Mill motor 10 is in series electrically with mill motor 12 as is mill motor 11 in series electrically with mill motor 13.

Connected across natural neutral points 91 and 92 on line 93 in the mill motors' power circuits is the buck-boost generator 20 driven by its A.C. motor 94.

The buck-boost generator has a main field 95 connected to the Amplidyne regulator 87 of the slow acting regulation system 17 and a fast field 96 is in circuit with the fast acting regulating system 19. The fast field is a relatively few-turn coil of heavy wire for current input from two back-to-back connected bridge rectifiers 97 and 98 so that the output from the bridges is transformed to field flux which adds to or subtracts from the flux of the main field 95. On the other hand, the main field 95 is a relatively high impedance winding having more turns per coil of small size wire.

Since the buck-boost generator experiences rapid changes in field flux, its field frame is preferably a laminated construction of good grade electrical sheet for fast response and low hysteresis and eddy current losses.

Through addition to or subtraction from the field flux of the main field 95 and the fast field 96 of the buck-boost generator 20 by operation of the fast and slow systems 17 and 19, a steep rise or fall in induced voltage of the armature 99 of the generator 20 is produced and provides a corresponding steep rise or fall buck-boost output armature current. Accordingly, the armature current of the generator 20 flows in either direction in line 93, as indicated by arrows 100 and 101 (Fig. 10) and increases the armature current in the upper roll drive motors in direction 100 while simultaneously decreasing armature current in the lower roll drive motors. This effects a change in the distribution of torque delivered by the two roll drives. Of course, flow of the armature current of the booster in the direction of arrows 101 has the opposite effect as to increasing armature current in the bottom roll drive and decreasing it in the top roll drive. Thus, the total amount of torque imparted to the driven rolls remains substantially the same but the proportion of torque delivered to one roll relative to the other is affected whereby correction for deflection in maintenance of the roll in a given position is achieved.

Forcing the fields 95 and 96 of the buck-boost generator 20 with higher than normal field supply voltage from the slow acting regulation system 17 and the fast acting regulation system 19 produces a fast response from the generator 20. Additionally, an external resistor 102 in series with the generator armature 99 reduces the time constant of the regulated power circuit, including the mill motors 10, 11, 12 and 13 by reducing the $\frac{L}{R}$ ratio. However, use of this resistor is not essential.

Considering the slow acting regulation system 17, the Amplidyne regulator 87 is driven by the A.C. motor 94e and has the two matched high impedance control fields 85 and 86 connected to the driver amplifier 16. One field's connection is reversed as to the other so that when each receives an equal amount of D.C. output voltage from the amplifier 16, the resultant magnetic field flux is zero for one cancels the other.

The driver amplifier 16 includes circuits which affect its time-rate output such as gain, rate feedback, bias and adjustable time constants, and additionally, has two output push-pull circuits which receive the push-pull signal from the adder 84. At zero signal the amplifier has equal D.C. output in both output circuits which voltage is negative when silicon transistors are used and positive when germanium transistors are used. When the push-

pull signal is received by the driver amplifier 16, one output voltage is raised an amount equal to that that the other output voltage is lowered but without a change in polarity. Which output circuit has its voltage raised is dependent upon the direction of deflection of the roll 5 and the amount of raise and of reduction is dependent upon the amount of deflection of the roll.

Application of this D.C. output voltage from the driver amplifier causes one control field 85 or 86 to drive to a higher excitation level while the other control field is driven to a lower excitation level to effect a net ampere turn current in one direction or the other to induce a voltage in the armature of the Amplidyne. Arrows 103 and 104 indicate the direction of voltage induced in the armature 105 of the Amplidyne 87 by control fields 85 and 86. Accordingly, the armature 105 of the Amplidyne delivers a variable and directional excitation current to the main field 95 of the buckboost generator 20 which current must have reversible polarity to effect maintenance of the roll 5 in the given position.

A negative feedback for the armature 105 of the Amplidyne comprises a differential field 106 connected across the armature 105 and a network of back-to-back connected zener diodes 107 and 108. This negative feedback improves transient performance and stability of the Amplidyne and reduces its residual voltage. Additionally, it serves as a voltage limiter for the output of the Amplidyne by shorting out a trimmer resistor 109 in the differential field circuit of the Amplidyne regulator 87 through the back-to-back connected zener diodes selected for a proper cut-off voltage.

A positive feedback circuit 110 coupled the output voltage of the booster generator 20 to the Amplidyne through a field 111 which is adjusted to hold the Amplidyne output and, in turn, the buck-boost generator's output voltage at any level up or down to which level the control fields have pushed the Amplidyne upon receipt of a signal. Additionally, the positive feedback circuit maintains the booster voltage at that level with a zero signal so that it performs substantially the same function as a servo motor driven potentiometer. Thus, if a correction signal is present, the slow system 17 is quickly driven to adjust operation of the roll drive motors to correct the error and the slow system is held at that correction level of operation so that no further operation of the Amplidyne occurs until receipt of a new correction signal. If this were not the case, then a continuous signal would be required for operation of the Amplidyne.

In actual operation of the mill, receipt of correction signals occurs at a rapid rate whereby a small level of output plus-minus from the driver amplifier 16 is generally present as the roll deviates from the given position in either direction.

Referring to the fast reaction regulating system 19, it comprises two pairs of back-to-back or cross-connected thyratron tubes 112 and 113 and 114 and 115 with the output of thyratrons 112 and 113 fed to the primary winding 116 of a first transformer 117 and the output of tubes 114 and 115 fed to the primary winding 118 of a second transformer 119. Joined to the grids 120 of each thyratron tube is the trigger generator 121 and to the filaments thereof the bias 122 of the combination 18 whereby upon receipt of a signal from the trigger generator, one of the two pairs of thyratrons is fired with the direction of deflection of the roll determining which pair.

The trigger generator includes adjustment circuits such as a proportional control and a rate control which singly or in combination effect firing of the thyratron and the conduction angle, thereby directly affecting output inasmuch as once a thyratron tube is fired, it conducts a half cycle A.C. wave only during the remainder of the wave. The output of the thyratron is dependent upon a time-degree relationship of triggering or firing and generally, output is less than a 180° conduction angle.

The secondary 123 of the first transformer 117 delivers its output to the first full wave bridge rectifier 97 and the secondary 124 of the second transformer 119 delivers its output to the second full wave bridge rectifier 98 connected together on the negative side with the first bridge rectifier. The positive terminals of the two bridges are joined to the fast field 96 of the buck-boost generator 20 and to even value loading resistors 125 and 126 disposed in series with an electrical connection 127 between the common negative line 128 and a midtap 129 between the two resistors.

As long as the push-pull signal from the trigger generator is present, the pair of thyratrons fired thereby are conducting and thereby energizing their transformer for the duration of the signal. The A.C. output of the transformer is converted to D.C. power by the bridge of its pair of thyratrons and this D.C. power is delivered to the fast field 96 of the buck-boost generator 20 where it is transformed to magnetic energy with a steep rise which adds to or subtracts from the main field flux of the generator and thus affects the output of the generator in a steep rise or fall pattern.

The output of the two full-wave bridge rectifiers 97 and 98 is push-pull and is reversible in that if bridge 97 is energized, current flows therefrom through field 96, then through resistor 126, back to the negative side of the bridge. At the same time, the bridge also self-loads through resistor 126

and the common connection 127. The output of the other bridge is the same except that the current through the fast field is reversed so that this fast field undergoes a magnetic polarity change with each change in firing of one of the pairs of thyratrons.

Where both thyratrons are overlapped on conduction, then at one instant and at some value depending on the degree of overlap, both bridges will have exactly the same voltage output in which event, the load current drops to zero for there are no potential differences thereacross. At this point, the bridges will both seld-load through their respective resistors 125 and 126.

The slow system 17 performs the major portion of the work for maintaining the roll at the given position and for returning the roll to the given position when it has moved away therefrom through delivery of a substantially continuous current. The amount of output current supplied by the slow system is dependent upon such factors as the difference between the amount of exit and entry tensions and the magnitude of the roll pressures' angular component which can be substantial especially when rolling thin gauges and which tends to force the roll 5 out of the given position, and also upon an unbalance in forces imposed upon the roll which unbalance requires compensation or correction by substantially steady or continuous output current. This slow system cannot effect all the regulation required because of its long time constants which may range up to about 20 seconds. If lower time constants are used in the range of from about 1 to 5 seconds, the slow system oscillates or hunts and is unable to effect correction for transient conditions in the strip such as a sudden change in gauge, a hardness area in the strip, etc. These transient conditions if not very quickly compensated for by the fast regulating system will quickly offset the small roll and then there is an unreasonably long time consumed to return it to the given position. During this time, a substantial amount of malshaped or defective strip results so that it is necessary to superimpose upon the slow system the fast system to take care of the transient conditions and to dampen the slow system as to oscillatory tendencies.

To avoid oscillation of the slow system, adjustable time constants are built into the driver amplifier 16 for the control fields 85 and 86 of the Amplidyne 87 with these time constants being in the range of about 1/2 to 5 seconds.

The two systems act independently and jointly to effect correction or compensation for maintenance of the roll at its given position. For example, when the buck-boost generator is driven towards a rising voltage left to right, viewing Fig. 10, to add to the top roll drive torque and bridge A is fired, it will be an addition to the buck-boost output from the fast field. In the event bridge B is fired due to a slight overcorrection of bridge A, the slow system cannot change the buck-boost generator armature polarity fast enough, but the output from the booster armature is reduced and overcorrection is avoided.

When the roll 5 deflects out of its given position, one bridge is cut off and the other bridge continually conducts until the slow system catches up and forces the roll back to the given position. When a transient condition occurs, the fast system operates very quickly in the order of 4—20 milliseconds to maintain the roll in substantially the given position and to prevent the slow system from oscillating and hunting in trying to correct for the transient condition. Thus, the slow system is the follower or slave of the fast system.

Fig. 11 shows a modification of the embodiment of Fig. 10 wherein the fast field 96 of the buck-boost generator is omitted and the resistors 125 and 126 connected to the bridges 97 and 98 are in series with the generator armature 99 and in the neutral circuit 93. In operation of this modification where bridge 98 aids the generator 20 from left to right, it self-loads through resistor 126 while bridge 97 subtracts from the generator's output through increased voltage drop in its loading resistor 125 which is a part of the generator's output circuit from 91 to 92.

In this modification, the thyratron, 112, 113, 114 and 115 are connected in the same way and operate in the same manner as described regarding the embodiments of Fig. 10. The bridge diodes of the bridges 97 and 98 must be of sufficient size or rating to conduct the entire generator's output current plus their self-loading current.

Fig. 12 shows a modification of the embodiment of Fig. 10 wherein a 3-wire generator 130, such as a Dobrowolsky machine, replaces the buck-boost generator 20. This generator has a main field 131 connected to the Amplidyne regulator 87 which has the same fields as those of the embodiment of Fig. 10, an armature 132 connected into the neutral line 93 between the motors 10 and 12 and 11 and 13 (not shown) of Fig. 10, and two derived external neutral points 133 and 134 into which the output of the thyratrons 112, 113, 114 and 115 (not shown) of Fig. 10 is fed through the back-to-back connected bridges 97 and 98. These neutral points are formed from A.C. outputs of the armature winding tapped at one-pole pitch intervals and brought to slip rings provided in addition to the normal commutators which are the D.C. output terminals of the machine.

As shown, two pairs of coils 135 and 136 and 135a and 136a of high reactance and low resistance are connected across two pairs

of slip rings 137 and 138 and 139 and 140, and are disposed upon cores 141 and 142, respectively. The voltage between slip rings 137 and 138 and 139 and 140 is alternating and a small A.C. current is always present in the reactance coils 135, 136, 135a and 136a when the bridges are not conducting. The midpoint of each reactance coil is tapped to form the neutral points 133 and 134 and the D.C. output of the bridges is fed into its coil where it divides at the midtap so that one-half of the total current flows in each direction around the core which has no resulting D.C. magnetization.

The two derived external neutral points 133 and 134 provide introduction of the current pulses from the bridges 97 and 98 into the armature circuit of the generator 130. This effects direct introduction of the current pulses into the armature circuit of the generator 130 and thereby eliminates a fast field in the generator 130 and, consequently, avoids interaction between the fast and main fields of the generator 130.

The main field 131 functions the same as the main field 95 of the buck-boost generator 20.

Fig. 13 shows electric circuitry which provides reversible D.C. pulses of the fast system 19 at a 1/4 cycle from a commercial frequency 3-phase A.C. power source. In this circuitry, a 3-wire, 3-phase A.C. power source 143 is converted to a 2-phase, 4-wire output in the transformer 144. The outputs of the isolated 2-phase side of the transformer 144 are isolated independent 1-phase voltages with 90° phase angle which are fed to the bridge transformers 117 and 119 of the bridges 97 and 98 by gang operated, individual ring core auto transformers 145 and 146 with sliding contacts.

In this arrangement, the bridges 97 and 98 supply 1/4 cycle D.C. push-pull pulses from 3-phase, 60-cycle power which on a 60-cycle per second basis is 4-1/6 milliseconds. These short pulses result from firing one thyratron only in each bridge for 1/2 cycle on the A.C. wave with the two firings overlapping each other by 90° to effect the 1/4 cycle D.C. output.

Fig. 14 shows a fast regulating system which uses two silicon controlled rectifiers 147 and 148 commonly referred to as SCRs in combination with solid state silicon rectifier devices in place of the two pairs of thyratrons.

As shown, SCRs 147 and 148 are connected across two corners of full-wave bridges 149 and 150, respectively, comprising silicon diodes which have adequate peak reverse voltage rating for the input A.C. supply voltage. Each full-wave bridge applies a full-wave rectified voltage to its SCR which will either absorb the voltage or apply it to the primary winding of the transformer in circuit therewith as determined by the phasing of the gate or triggering circuit, similar to the thyratron's triggering. Thus, one SCR will do the work of two thyratrons as it can be gated, fired or triggered every 1/2 cycle on the A.C. wave.

Where each roll drive has a single motor instead of two motors, the armatures of the two motors are connected in series across the main generator 89 with the series connection between the two motors forming one natural neutral point. To this arrangement is provided a balancer set comprising two motors series connected across the main generator and free to rotate without a mechanical load joined thereto. The series connection between the two balancers provides the other neutral point of a neutral line similar to that of Fig. 10 so that the buck-boost generator and the fast acting and slow acting ~~system~~ systems are similarly employed to effect correction and compensation for movement of the roll out of its given position.

One modification of this invention uses two roll drive motors connected in parallel across the main generator with a buck-boost generator in series connection through its armature with each mill motor. One buck-boost generator aids its motor while the other opposes its motor since the outputs of the two buck-boost generators are opposite in direction. The fast regulating system feeds the fast field of the two boosters connected in series therewith while the slow system feeds the main fields of the two boosters also connected in series therewith.

Fig. 15 shows a single mill motor 160 for driving the upper backing roll 1 and a second single mill motor 161 for driving the lower backing roll 2. These two motors 160 and 161 are connected in parallel across the main generator 89 with a first buck-boost generator 162 in series connection with the motor 160 through its armature 163 and with a second buck-boost generator 164 in series connection with the motor 161 through its armature 165. This series connection of the buck-boost generators with their motors is such that the output voltages of the two buck-boost generators are opposite in direction. Thus, one buck-boost generator aids its motor while the other buck-boost generator opposes its motor. Accordingly, the motor being aided takes a larger share of the main generator output current while the other motor takes a lesser share of this output current. Consequently, a torque difference is effected to maintain or return the roll 5 at or to its given position.

An A.C. motor 166 drives both buck-boost generators 162 and 164.

The buck-boost generators 162 and 164 have main fields 167 and 168 respectively which are joined to the armature 105 of the Amplidyne 87 in series. For one direction of Amplidyne output, arrows 169 and 170 indicate the direction of voltage induced in the

armatures 163 and 165 of the buck-boost generators 162 and 164. For the other direction of Amplidyne output, arrows 171 and 172 indicate the direction of voltage induced in the armatures 163 and 165.

Resistors 173 and 174 in series with motors 160 and 161 and the armatures of the buck-boost generators 162 and 164 respectively are not essential.

Output of the fast regulating system 19 of Fig. 15 is through an armature 175 of a buck generator 176 in series connection with resistors 125 and 126 in push-pull relation with the two bridges 97 and 98. The armature 175 and the resistors 125 and 126 are in circuit 177 which extends between neutral points 178 and 179 of the motors and buck-boost generators' circuits.

As shown, the buck generator 176 is driven by an A.C. motor 180 but it may be driven by the A.C. motor 166 joined to the buck-boost generators 162 and 164. Voltage for the field 181 of the buck generator 176 with parallel trimmer resistor 181*a* of the field 181 is supplied by the Amplidyne regulator 87. The fields 167, 168 of the buck-boost generators 162 and 164 and the field 181 of the buck generator 176 are connected in series.

The field parameter of the buck generator 176 is adjusted by its parallel trimmer resistor 181*a* so that its armature voltage matches and follows the voltage of the two buck-boost generators 162 and 164 which is across the neutral points 178 and 179 in either direction as determined by polarity reversal set by the slow system 17.

The armature polarity of the buck generator ~~175~~ 176 is opposite to that across the neutral points 178 and 179 in either direction so that the bridges 97 and 98 have zero voltage across their output connection points, namely, from point 182 to point 179 in the circuit 177.

In addition to the thyratrons and SCRs, ignitrons produce satisfactory results when connected in the same way as the thyratrons.

A substitute for the Amplidyne regulator is a static type regulator such as magnetic amplifiers with rectified D.C. outputs and silicon controlled rectifiers in combination with silicon diodes to provide a full-wave rectified D.C. output. These are arranged in push-pull circuitry with loading resistors to produce reversible output polarity or are used singly with two electrically isolated main fields of the buck-boost generator.

Fig. 8 shows application of the invention to a 2-stand tandem 5-high mill 151 on which the strip 6 travels from an unwind reel 152 to a first stand 153 where it advances between the upper intermediate roll 154 and the small diameter work roll 155. From the first stand, the strip then proceeds to the second stand 156 where it enters a roll pass formed by the lower intermediate roll 157 and the small diameter work roll 155 and then on to the winding reel 158. Such rolling practice presents both sides of the strip to a small diameter work roll so that each side receives a major portion of reduction in one roll pass and so that where the rolls are tungsten carbide, both sides of the strip have superior surface from the standpoint of smoothness, brightness and finish. This is important where the strip is to be plated or where plate or strip require a high, shiny finish.

Examples of 5-high mills on which this invention is useful include one mill with a 1" diameter small work roll, two 3" diameter ~~intermediae~~ intermediate rolls, and two 15" diameter backing rolls and a second mill has one 3-1/2" diameter work roll, two 12" diameter intermediate rolls and two 40—42" diameter backing rolls.

The present invention has important advantages which include:

(a) Ability to utilize a single small diameter work roll for rolling extremely thin gauge strip and sheet such as 0.001" to 0.007" in wide widths up to 50" and above while producing excellent flatness.

(b) Ability to maintain the single small diameter work roll in a given position in the roll pass and/or to purposely maintain the roll at a given position where there is a small amount of deflection therein either in the direction with or opposite to strip travel.

(c) Ability to effect excellent control over the shape of the very thin strip and sheet through extremely fast correction and compensation for deflection away from the roll's given position where the deflection is caused by transient conditions such as hard spots or areas, small off-gauge areas, etc., and/or from a deviation from equilibrium conditions between the forward and back tensions and that angular component of force of the roll pressure which tends to force the roll out of its given position.

(d) Ability to make use of tungsten carbide work rolls.

(e) Ability to control position of the single small work roll in the roll pass so as to compensate for heat build-up or crown while producing a high degree of flatness in extremely thin gauges.

WHAT WE CLAIM IS:—

1. In a method for rolling metal sheet or strip on a rolling mill having a small diameter work roll, at least one upper and at least one lower backing roll for said work roll, each of said backing rolls having a diameter greater than said work roll, said rolls being disposed substantially vertically of one another, said work roll and one of said upper and lower backing rolls forming a roll pass through which metal is reduced in thickness, and another of said backing rolls being in frictional engagement with said work roll, said work roll being subject to deflection in

armatures 163 and 165 of the buck-boost generators 162 and 164. For the other direction of Amplidyne output, arrows 171 and 172 indicate the direction of voltage induced in the armatures 163 and 165.

Resistors 173 and 174 in series with motors 160 and 161 and the armatures of the buck-boost generators 162 and 164 respectively are not essential.

Output of the fast regulating system 19 of Fig. 15 is through an armature 175 of a buck generator 176 in series connection with resistors 125 and 126 in push-pull relation with the two bridges 97 and 98. The armature 175 and the resistors 125 and 126 are in circuit 177 which extends between neutral points 178 and 179 of the motors and buck-boost generators' circuits.

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A substitute for the Amplidyne regulator is a static type regulator such as magnetic amplifiers with rectified D.C. outputs and silicon controlled rectifiers in combination with silicon diodes to provide a full-wave rectified D.C. output. These are arranged in push-pull circuitry with loading resistors to produce reversible output polarity or are used singly with two electrically isolated main fields of the buck-boost generator.

Fig. 8 shows application of the invention to a 2-stand tandem 5-high mill 151 on which the strip 6 travels from an unwind reel 152 to a first stand 153 where it advances between the upper intermediate roll 154 and the small diameter work roll 155. From the first stand, the strip then proceeds to the second stand 156 where it enters a roll pass formed by the lower intermediate roll 157 and the small diameter work roll 155 and then on to the winding reel 158. Such rolling practice presents both sides of the strip to a small diameter work roll so that each side receives a major portion of reduction in one roll pass and so that where the rolls are tungsten carbide, both sides of the strip have superior surface from the standpoint of smoothness, brightness and finish. This is important where the strip is to be plated or where plate or strip require a high, shiny finish.

Examples of 5-high mills on which this invention is useful include one mill with a 1" diameter small work roll, two 3" diameter ~~intermediae~~ intermediate rolls, and two 15" diameter backing rolls and a second mill has one 3-1/2" diameter work roll, two 12" diameter intermediate rolls and two 40—42" diameter backing rolls.

The present invention has important advantages which include:

(a) Ability to utilize a single small diameter work roll for rolling extremely thin gauge strip and sheet such as 0.001" to 0.007" in wide widths up to 50" and above while producing excellent flatness.

(b) Ability to maintain the single small diameter work roll in a given position in the roll pass and/or to purposely maintain the roll at a given position where there is a small amount of deflection therein either in the direction with or opposite to strip travel.

(c) Ability to effect excellent control over the shape of the very thin strip and sheet through extremely fast correction and compensation for deflection away from the roll's given position where the deflection is caused by transient conditions such as hard spots or areas, small off-gauge areas, etc., and/or from a deviation from equilibrium conditions between the forward and back tensions and that angular component of force of the roll pressure which tends to force the roll out of its given position.

(d) Ability to make use of tungsten carbide work rolls.

(e) Ability to control position of the single small work roll in the roll pass so as to compensate for heat build-up or crown while producing a high degree of flatness in extremely thin gauges.

WHAT WE CLAIM IS:—

1. In a method for rolling metal sheet or strip on a rolling mill having a small diameter work roll, at least one upper and at least one lower backing roll for said work roll, each of said backing rolls having a diameter greater than said work roll, said rolls being disposed substantially vertically of one another, said work roll and one of said upper and lower backing rolls forming a roll pass through which metal is reduced in thickness, and another of said backing rolls being in frictional engagement with said work roll, said work roll being subject to deflection in

a direction substantially with or substantially opposite to travel of metal through said mill, the steps comprising driving an upper backing roll by at least a first motor operatively connected thereto, driving a lower backing roll by at least a second motor operatively connected thereto, controlling amount of said deflection of said work roll in said roll pass by effecting changes in apportionment of applied torque by said motors between said driven rolls through sensing amount and direction of deflection of said work roll from a given position, from said sensing generating a signal related to amount and direction of deflection, producing from said signal an error signal related to the difference between the sensed position of said work roll and the given position of said work roll and related to the direction of said deflection, utilizing said error signal for increasing and decreasing output torque of one of said motors connected to one driven roll relative to output torque of said other motor connected to said other driven roll for effecting said changes in apportionment of applied torque to said driven rolls to control deflection of said work roll.

2. The method of Claim 1 in which a current is produced from said error signal, said current being related to the magnitude of said error signal and related to the direction of same and applying said current to said motors for effecting said changes in apportionment of applied torque to said driven rolls.

3. The method of Claim 2 in which said current is so produced that it comprises a first part which is substantially continuous and is proportional in magnitude and related in direction to direction of said deflection and comprises a second part which is pulses of short duration related in phase to the magnitude and direction of said deflection, applying said parts individually or jointly to said motors to effect said changes in apportionment of applied torque to said driven rolls.

4. The method of Claim 3 in which said continuous part effects control of the major part of said torque apportionment and requires a longer time interval to effect a change in said torque apportionment than said pulse part.

5. The method of Claims 1—4 wherein said signals are so modified that same are related to the velocity of said deflection.

6. The method of Claims 1—5 wherein said changes in apportionment of applied torque are effected without substantially affecting the amount of total torque delivered to said driven rolls.

7. A method of rolling sheet metal or strip from a rolling mill substantially as hereinbefore described with reference to Figs. 2—15 of the accompanying drawings.

8. In an apparatus for rolling metal sheet or strip on a rolling mill having a small diameter work roll at least one upper and at least one lower backing roll for said work roll, each of said backing rolls having a diameter greater than said work roll, said rolls being disposed substantially vertically of one another, said work roll and one of said upper and lower backing rolls forming a roll pass through which metal is reduced in thickness, and another of said backing rolls being in frictional engagement with said work roll, said work roll being subject to deflection from a given position in a direction substantially with or substantially opposite to travel of metal through said mill, wherein there is provided at least one electric motor drivingly connected to said upper backing roll, at least one electric motor drivingly connected to said lower backing roll, means for sensing amount and direction of said deflection, said sensing means being opposite a face of said roll so that deflection is toward and away therefrom, signal generating means connected to said sensing means for producing from said deflection a signal related to the amount of deflection and direction of said deflection, means coupled to said signal generating means for providing from said signal an error signal related to the difference between the sensed position of said work roll and the given position of said work roll and related to the direction of said deflection, and a regulating system connected to said error signal providing means and responsive to said error signal for increasing and decreasing the output torque of one of said motors connected to one driven roll relative to the output torque of said other motor connected to said other driven roll, whereby to effect changes in apportionment of applied torque to said driven rolls to control deflection of said work roll.

9. Apparatus according to Claim 8, wherein said error signal providing means includes rate means for imparting to at least a portion of said error signal a characteristic related to the velocity of said deflection.

10. The apparatus of Claim 8 wherein there is means coupled to said signal generating means for providing from said error signal a first portion and a second portion, each portion being proportional in magnitude and direction to said deflection and wherein said regulating system comprises a slow acting part connected to said portion providing means to receive said first portion of said signal and to produce therefrom a reversible push-pull substantially continuous current and a fast acting part connected to said portion providing means to receive said second portion of said signal and to produce therefrom variable phased pulses of current of short duration.

11. Apparatus for controlling deflection of a small diameter work roll of a mill for rolling metal substantially at a given position

* C L M S *

as hereinbefore described and as shown in Figs. 2—15 of the accompanying drawings.

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