March 8, 1966 L. F. COFFIN, JR 3,238,756

MATERIAL FORMING METHOD AND APPARATUS

Filed May 3, 1961 4 Sheets-Sheet 1

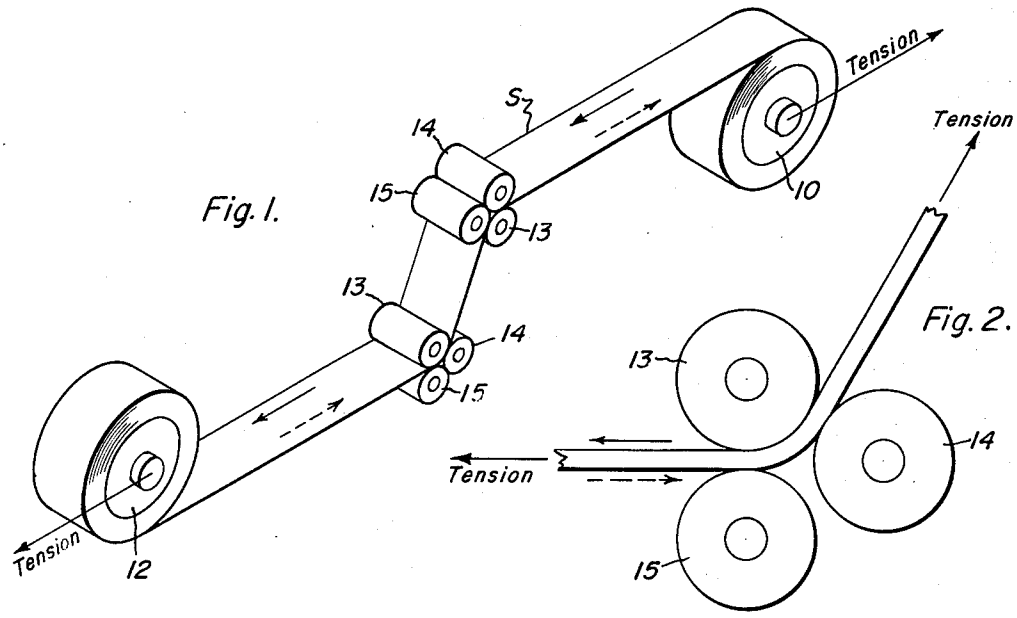


Fig. 1.

Fig. 2.

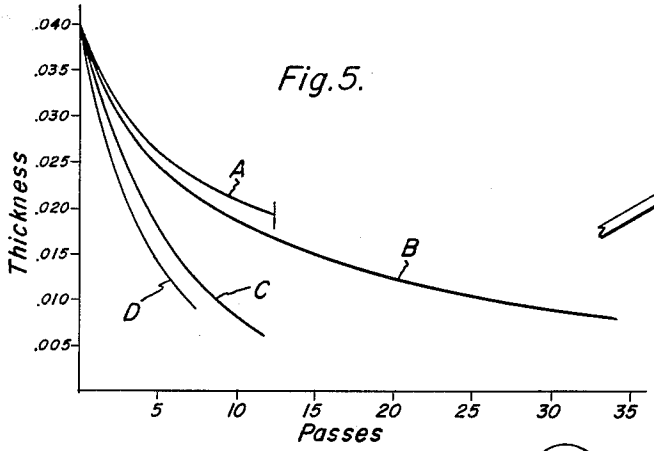


Fig. 5.

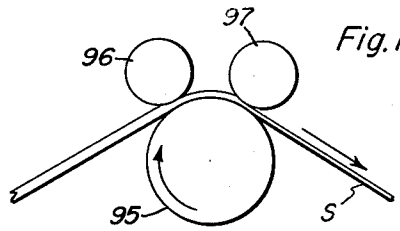


Fig. 16.

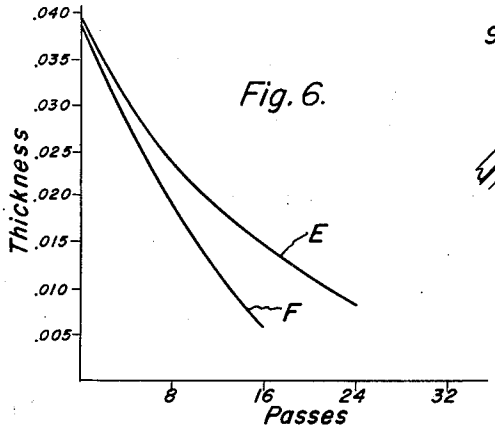
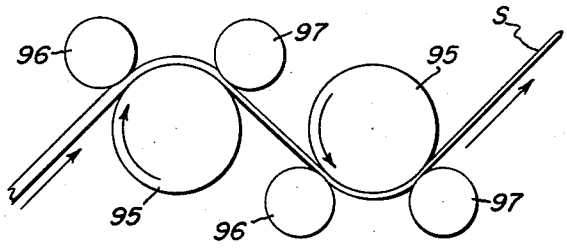


Fig. 6.

Fig. 17.



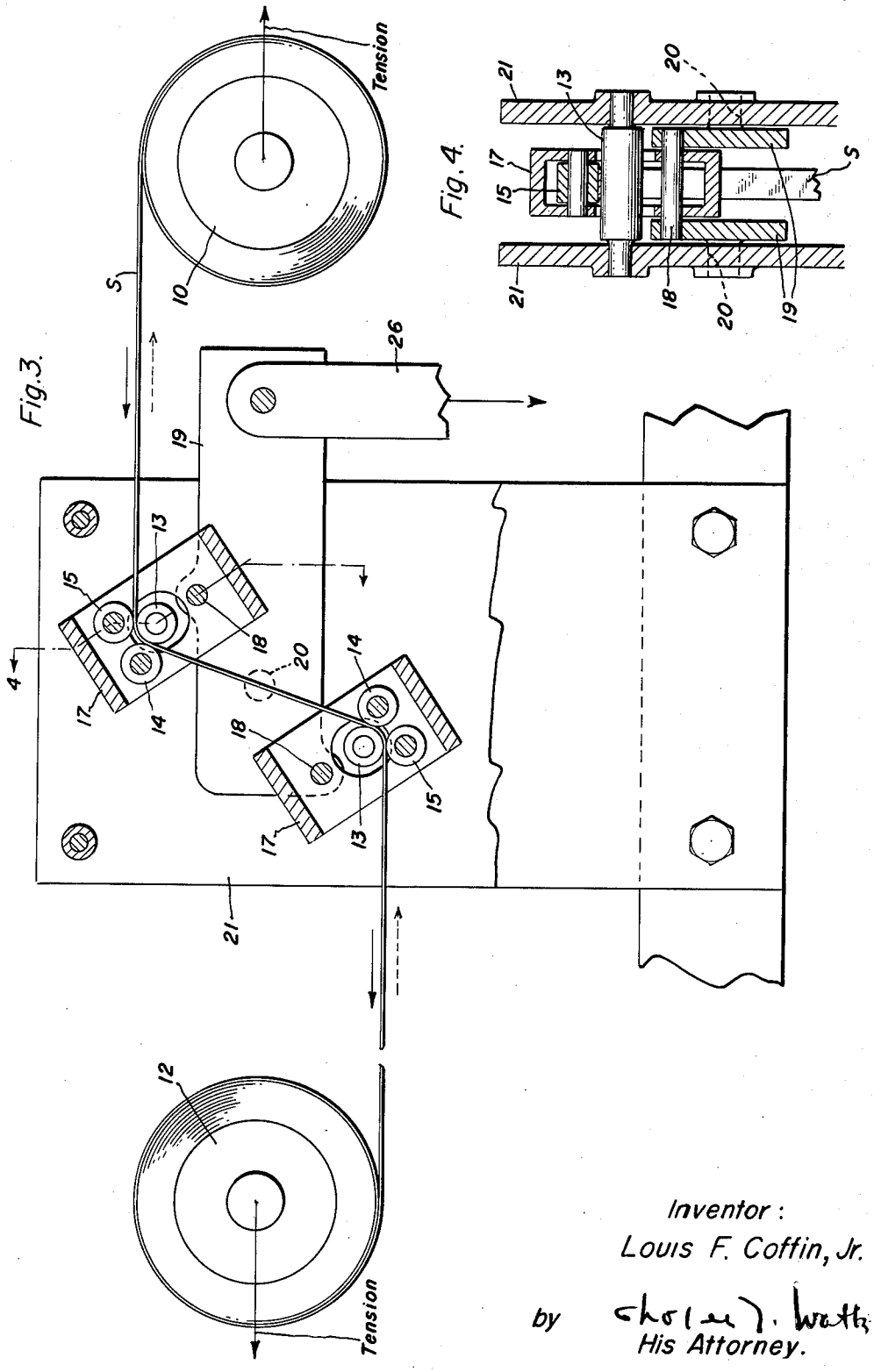
Inventor:
Louis F. Coffin, Jr.,

by Z L Smith
His Attorney.

March 8, 1966 L. F. COFFIN, JR 3,238,756

MATERIAL FORMING METHOD AND APPARATUS

Filed May 5, 1961 4 Sheets-Sheet 2



Inventor:
Louis F. Coffin, Jr.

by Charles J. Wirth
His Attorney.

March 8, 1966 L. F. COFFIN, JR 3,238,756

MATERIAL FORMING METHOD AND APPARATUS

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Fig. 7

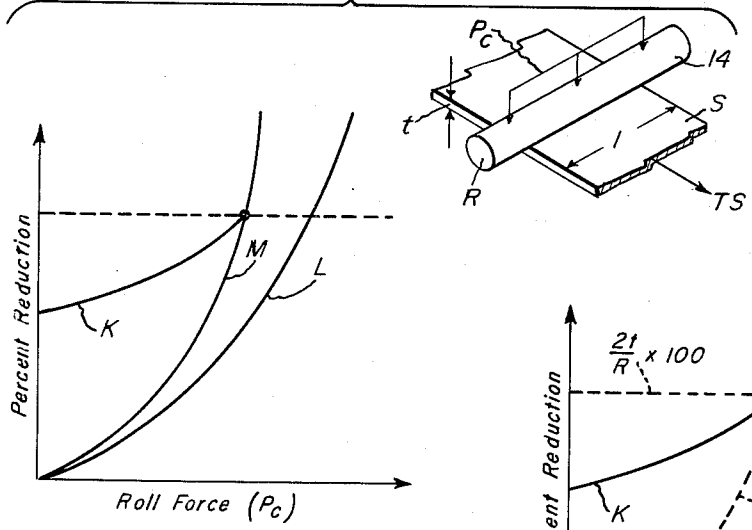
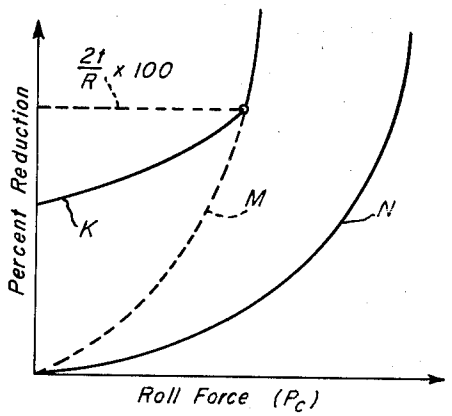


Fig. 8.



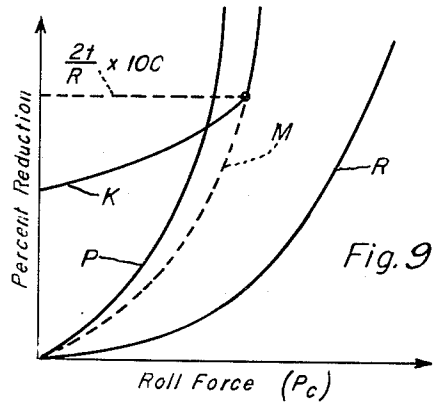


Fig. 9

Fig. 11

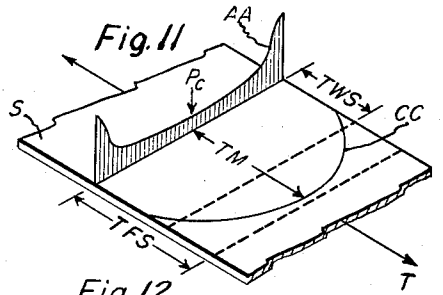


Fig. 10

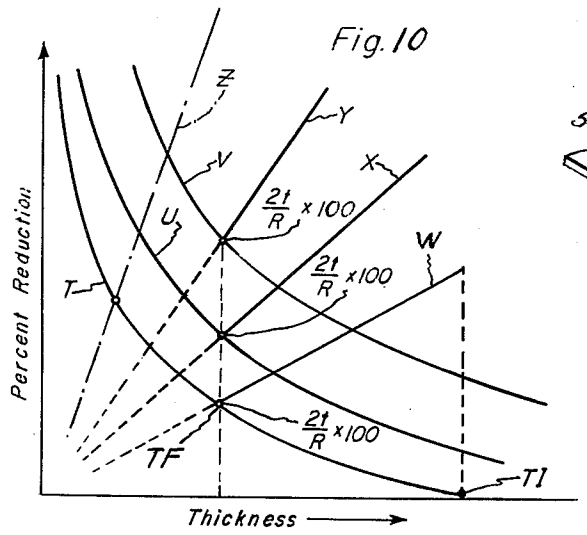
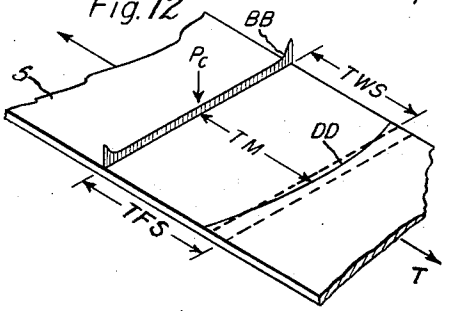


Fig. 12



Inventor:
Louis F. Coffin, Jr.,

by Thelen, Marth
His Attorney.

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MATERIAL FORMING METHOD AND APPARATUS

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Fig. 13

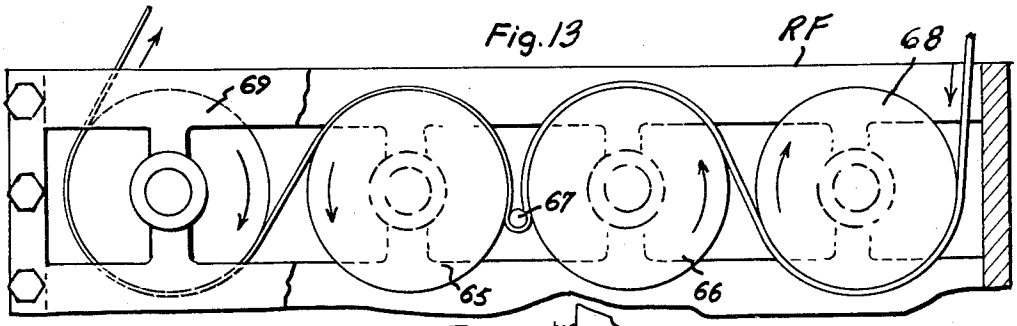


Fig. 14

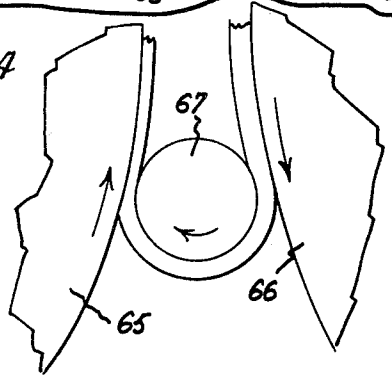
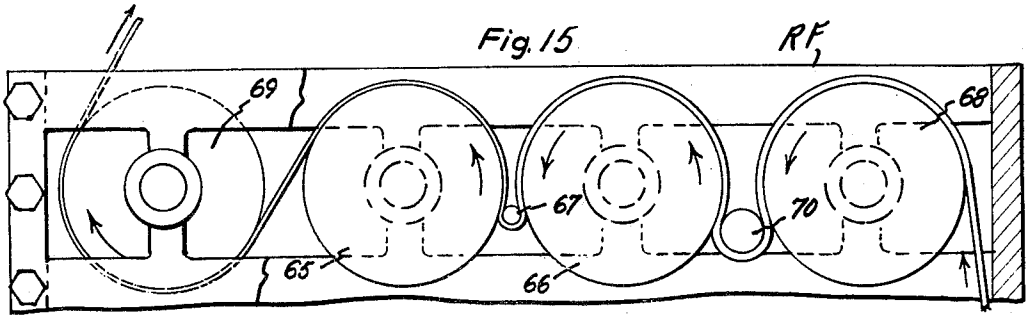


Fig. 15



Inventor:
Louis F. Coffin Jr.,
by Chas. D. Wrath
His Attorney.

United States Patent Office 3,238,756 Patented Mar. 8, 1966

3,238,756

MATERIAL FORMING METHOD AND APPARATUS

Louis F. Coffin, Jr., Schenectady, N.Y., assignor to General Electric Company, a corporation of New York

Filed May 3, 1961, Ser. No. 108,230
5 Claims. (Cl. 72—232)

This application is a continuation-in-part of my copending patent application, Serial No. 811,298, filed May 4, 1959, now abandoned.

The present invention relates generally to the art of shaping or deforming materials such as metals and is more particularly concerned with a novel method of changing the cross-sectional dimensions and increasing the length of a portion of an elongated metal body as, for instance, elongating and simultaneously reducing the thickness of a metal body such as a bar, a sheet, a strip or a thin foil. This invention is further concerned with a new apparatus implementing that novel method.

The excessive cost of conventional metal working machines and equipment such as mills for rolling iron and steel in thin gauges has long represented an important problem. Prior to the present invention, however, there has been no satisfactory answer to this problem and consequently capital expenditure requirements have limited the use of rolling techniques, particularly in the production of thin gauge material.

Over the whole gauge range of metal sheets and strips, rolling equipment presently in commercial use is uniformly massive and expensive and relatively unchanged at least in basic characteristics from that which was standard years ago.

By virtue of the present invention, which is predicated upon my surprising discoveries subsequently to be described, it is possible under certain conditions to accomplish metalworking results through the use of rolling forces substantially smaller than those required in presently conventional operations. This invention, therefore, opens the possibility of extending the use of certain types of methods and apparatus and also holds the possibility of making conventional metal products by new techniques and machines. It additionally accords new products having special physical characteristics and utility.

In addition to reducing very substantially the magnitude of the rolling forces required by heretofore conventional means, this invention has the unique advantage of affording much greater control over the tolerance in width during thickness reduction of very wide sheet or strip stock. The uniformity of stock thickness across the full width of the stock is maintained automatically or inherently in accordance with this invention, compensating thickness reductions occurring throughout the operation of this new method. This feature has special value and utility in the processing of sheet or strip stock which is so hard as not to be readily rolled for thickness reduction by prior methods.

Another novel feature and special advantage of this invention is that tension stress closely approaching the flow stress of the stock as a limit can be maintained during rolling with consistently satisfactory results. This contrasts with prior operations and especially tension rolling processes in which it is necessary to limit tension stress well below the optimum level to avoid excessive stock breakage.

A further advantage is that because of the compactness of the apparatus, rolling can, as a practical matter, be accomplished under controlled environmental conditions of temperature, atmosphere and the like.

It is contemplatetd, as set out in detail below, that this invention may be applied to the general procedure of rolling elongated metal stock to produce sheets, strips or foils of various types, wires, rods and tubes of various cross-sectional shapes, compositions and gauge thicknesses. In a typical operation of this kind, the rolling is accomplished under a continuously-applied, substantial, tension force which, however, is less than that required to plastically stretch the metal stock in the absence of a cyclic plastic strain, although it may approach that level, and involves repeated bending and unbending of the stock producing a cyclic plastic bending strain. Such a "contact-bend-stretch" ("CBS") rolling operation may advantageously be carried out by running metal stock between and contacting it with a pair of opposed rolls which exert a contact pressure at the places where cyclic plastic strain is taking place. This contact force is moderate at all times in the process and becomes increasingly effective in producing elongation of the metal stock as the thickness of said stock is diminished. By comparison with heretofore conventional rolling practices, the pressure or force exerted by the rolls on the stock is preferably quite small, the cyclic plastic strain again serving to magnify the effect of the contact force to the point that plastic deformation (elongation) is produced.

This rolling operation normally will involve either running the stock repeatedly back and forth through a processing line and thereby repeatedly bending and unbending the stock, or running the stock once straight through a processing line having a plurality of roll stands. In either instance the stock will repeatedly be simultaneously subjected to contact force, tension force and cyclic plastic strain and thereby elongated through successive increments of its length.

In another typical operation of this invention, rolling is conducted while the metal stock is under no significant tension stress, i.e., the tension force applied to the metal stock is zero or is so small as not to be a factor in the metal-working or the metal deformation process. This "contact-bend" rolling operation thus may be advantageously carried out as described above, contact pressure being exerted against the stock where cyclic plastic strain is taking place in the stock so as to preserve the stock surface against deterioration. Here, however, the objective of the operation may not be the elongation or the changing of the dimensions of the work piece, as it is in the case of contact-bend-stretch rolling, but instead it may be the significant alteration of the mechanical properties of the stock through the special combination of contact force and cyclic plastic strain. Where both new mechanical properties and substantial dimensional changes are desired, the stock may be contact-bend-stretch rolled, and depending upon the relative dimensional changes required, the tension or stretch to which the stock is subjected may be relatively great or may approach as a minimum a value above the upper limit of the tension force applied to the stock in the contact-bend rolling type of operation.

It is further contemplated that in operations which may resemble rolling only in terms of results, the present invention may be applied to advantage. Thus, for ex-

ample, in an operation similar to rolling in that the sheet stock is moved lengthwise through a processing station successive portions or segments of the length of the stock are subjected to cyclic shearing stresses which produce cyclic plastic shearing strain in the stock as it travels in either direction through the processing line. In this operation, as in the contact-bend-stretch rolling operation described above, the sheet stock is subjected to tension constantly and is drawn out or elongated and at the same time reduced in thickness usually but not necessarily without material reduction in its width by the combination of the cyclic plastic shearing strain, the contact force or pressure and the tension force. Again, the contact force is somewhat less than that required to produce generally the same elongation and thickness reduction results in the absence of the cyclic plastic shearing strain. The tension applied, however, may desirably approach a level at which the tension stress is just below the flow tension stress of the stock.

Those skilled in the art will understand that this invention centers to a large extent in a method concept since the procedures generally described above may be carried out in a variety of different apparatus or machines in addition to the novel apparatus of my present invention described below. They will also understand that broadly and generically described the method of this invention comprises the steps of subjecting an elongated body to cyclic plastic strain, simultaneously subjecting the body to tension stress insufficient of itself to produce plastic elongation of said body, and simultaneously also subjecting the said body to contact pressure sufficient in combination with the cyclic plastic strain and the tension stress to reduce the thickness of the body. More in detail, but still generically speaking, this method involves subjecting successive portions of the length of the body to the cyclic plastic strain, the tension force and the contact pressure simultaneously. Where metal strip employed in this method is of thickness greater than 0.001 inch, the thickness reduction and elongation may be accomplished without increasing the width of the strip or body, and this is in sharp contrast to the action and results of certain conventional rolling operations. It will be understood that this method is not limited to use on strip thicker than 0.001 inch but that it can be employed to obtain the foregoing new results where the strip thickness is of the order of 0.0001 or even thinner gauges.

Those skilled in the art will further understand that in one broad aspect the method of this invention is not mainly or only concerned with elongation, thinning or otherwise altering metal stock dimensions, but has as a principal objective endowing the stock or work piece with special mechanical properties and novel combinations of such properties. Since the application of tension force to the stock is not necessary and may even be detrimental in such operations, this form of the present method may be generally described as comprising the steps of subjecting the metal body to cyclic plastic strain in the range of from one percent to twenty percent or higher up to the point beyond which breakage would occur and simultaneously subjecting the body to lateral forces to preserve body surfaces of the body against degradation due to plastically straining. In this aspect of the method, the metal stock may be prepared in a particular manner for cyclic plastic straining operations and in this sense the method may be considered to include as a preliminary step or steps, one or another of several different types of cold working or annealing operations. Further, in a preferred embodiment of this aspect of the invention, the cyclic plastic strain will be produced by repeatedly bending and unbending the metal body, which is preferably in strip or sheet form, and the lateral forces preserving the surface quality of the metal stock will be applied by means of contact rollers located at points of bending and unbending as will subsequently be described in detail. Also, in accordance with this aspect of the present method, the dimensions of the work piece may actually by significantly changed as desired with or without imparting to or endowing in the resulting product certain special mechanical properties or characteristics.

One of my principal discoveries constituting the basis of this new general concept is that in the presence of a cyclic plastic strain of sufficient magnitude, a stress and particularly a steady stress, even of relatively low magnitude, can produce considerable deformation in a body of deformable material. More specifically, I have discovered that if a metal body such as a metal sheet is subjected to contact roll pressure and to a tension force less than that necessary to independently produce permanent elongation of the sheet and at the same time the sheet is repeatedly bent and unbent or otherwise subjected to stresses resulting in cyclic plastic strains applied time and again transversely of the sheet, the tension force and the contact pressure will produce a drawing-out effect on the sheet, reducing its thickness and increasing its length, while controlling its width and preserving or even improving the quality of its surface. This operation thus is carried out in such a manner that any tendency for the sheet to neck down in thickness at any particular point is avoided or prevented with resulting substantially uniform reduction in stock thickness and the production of a sheet product of practically any desired thickness down to the thinnest kind of tape or foil, i.e., 0.001 inch or less. Unlike a typical rolling operation, the width of the sheet may not be increased at any stage in the present process down to the point that the stock thickness is less than 0.001 inch, although its thickness may be decreased to a limited and not desirable extent during such working.

The apparatus of this invention, broadly described, comprises a set of three rolls including a bend roll and two contact rolls spaced from each other and opposed to the bend roll to bear against sheet or strip stock disposed in contact around a portion of the circumference of the bend roll. The first and second contact rolls, like the bend roll, each have a working surface for engagement with stock to be thinned and the several rolls are arranged with respect to each other so that the full width of such stock is engaged both by the bend roll and the contact rolls at the points at which the stock is bent and unbent in its travel in contact with the bend roll. The contact rolls are supported with their axes at a fixed distance from each other so that in one embodiment of the invention, the contact rolls may be moved together toward and away from the bend roll which is on a fixed center, while in another embodiment of the invention, the bend roll may be moved toward and away from the contact rolls which are on fixed centers. Further, while the various rolls may be on fixed centers, it is contemplated that they may be adjusted in position relative to the axes of the other rolls to accommodate varying operating circumstances.

In a preferred embodiment of this invention the bend roll will be a "floating" roll while the contact rolls will serve to back up or support the bend roll, being journalled in the rolling mill frame. By virtue of this arrangement very small diameter bend rolls can be employed without the necessity for providing special and additional bend roll support means. Then in a further modification of the apparatus of this invention the contact rolls or support rolls may both be driven, thereby eliminating the need to apply tension to pull the strip through the mill. The upper limit to the amount of deformation imposed by a pull-through system, which is governed by the maximum force that the outcoming material can withstand, thus can be avoided. By still further innovation, however, the capacity of the mills of this invention in respect to the reductions that can be accomplished on each pass can be substantially increased again. This modification consists generally in making the upstream supporting roll self-regulating in respect to its drive so that it ceases to drive the strip as effectively when the upstream tension

of the strip falls below certain limits, the downstream support roll being driven with a constant fixed rate at all times during passage of the strip through the mill. As a final alternative, the downstream support roll may likewise be arranged to drive strip in a tension-responsive manner.

The contact pressure in accordance with this invention is applied to the stock at the point where cyclic plastic strain is taking place. It is not normally essential, however, that the stock be subjected to contact pressure at every plastic bending location. The nature of the stock and the tendency for it to lose surface quality or to fracture, if of low ductility, under cyclic plastic strain processing will determine the necessity for such surface treatment. Compared to the pressure applied by rolls in heretofore conventional rolling operations, this surface treatment pressure is quite light and in fact can be insufficient of itself and the applied tension to produce plastic deformation of the stock of the desired magnitude. Rolls are preferred for delivering or applying this pressure to the stock but it will be understood by those skilled in the art that other means may satisfactorily be used. Die segments or jaws which are not rolls and do not rotate are exemplary as will subsequently be described.

Those skilled in the art will gain further and better understanding of this invention from the detailed description of several preferred embodiments of the method hereof, reference being had to the drawings accompanying and forming a part of this specification, in which

FIG. 1 is a perspective, somewhat diagrammatic view of apparatus for carrying out the method of this invention in one of its forms;

FIG. 2 is a fragmentary, longitudinal, sectional view of a part of the apparatus of FIG. 1, illustrating in exaggerated manner the action of the apparatus roller elements;

FIG. 3 is a fragmentary, side-elevational view of an apparatus for carrying out the operations indicated in FIGS. 1 and 2, parts being broken away for purposes of clarity;

FIG. 4 is a fragmentary, sectional view taken on line 4—4 of FIG. 3;

FIG. 5 is a chart bearing curves illustrating the effect of the combination of cyclic straining, contact roll pressure and tension stress applied simultaneously to sheet stock as will be described in detail below and also showing the necessity for contact pressure in this combination;

FIG. 6 is another chart bearing curves representing data showing the effect of the process of the present invention as carried out in a preferred manner, as described in detail below;

FIG. 7 is a chart bearing curves illustrating a comparison between the contact-bend-stretch rolling method of this invention and a heretofore conventional tension rolling mill operation, roll force being plotted against percent reduction and important parameters being represented by the fragmentary perspective sketch accompanying the chart;

FIG. 8 is a chart similar to FIG. 7 in which another heretofore conventional type of rolling process is compared with the said present invention rolling method;

FIG. 9 is a chart similar to that of FIG. 7, comparing the said present invention method with still another prior conventional rolling operation;

FIG. 10 is another chart bearing curves representing another comparison between the present novel contact-bend-stretch method and the conventional tension rolling operation concerned in FIG. 7, thickness being plotted against percent reduction;

FIG. 11 is a diagrammatic sketch illustrating both lateral non-uniformities in roll pressure and the lateral distribution of longitudinal tenison stress in heretofore conventional tension rolling methods;

FIG. 12 is a sketch like FIG. 11 illustrating both lateral non-uniformities in roll pressure and lateral distribution of longitudinal tension stress distribution in a typical contact-bend-stretch operation of the present invention;

FIG. 13 is a schematic, side-elevational view of a rolling mill embodying this invention in a preferred form;

FIG. 14 is an enlarged, fragmentary, side-elevational view of the apparatus of FIGURE 13 showing the bend roll in adjacent portions of the support rolls, strip stock in process being disposed around the bend roll and in engagement with the supporting rolls;

FIG. 15 is a view similar to FIGURE 14 showing still another rolling mill apparatus of this invention;

FIG. 16 is a fragmentary, side-elevational view of another embodiment of the apparatus of this invention designed for the purpose of processing ductile material where little or no tension is applied to the stock in process;

FIGURE 17 is a view similar to FIG. 16 wherein two driven bending roll units including floating contact roller pairs are provided after the manner of the apparatus of FIG. 1.

With reference to FIGS. 1, 2, 3 and 4, it is seen that apparatus comprising of relatively few parts will implement the embodiment of the method of this invention which involves contact-bend-stretch rolling. The roll elements of this apparatus and their arrangement with respect to each other are illustrated to best advantage in FIGS. 1 and 2, while in FIGS. 3 and 4 the means for supporting these elements and for applying tension to the sheet stock and adjusting the pressure between certain roller elements are illustrated. In this apparatus there are two sets of three rolls each, including in each instance a bending roll and two contact rolls with stock S disposed between the bending roll and the contact rolls opposed thereto. Thus, as shown in FIG. 1, sheet stock S to be processed in accordance with this invention is carried on a feed reel **10** and disposed through two sets of processing rolls and collected on pick-up reel **12**. Reels **10** and **12** may alternatively be regarded as supply or pickup rolls depending upon the direction of travel of this sheet stock through the apparatus at a given time. As indicated in FIGS. 1 and 3, reels **10** and **12** are maintained in position at all times during the operation of the apparatus and tension force is applied to stock S through the maintenance of differential torque or angular velocity of these reels to produce the thickness reduction results desired.

The cyclic plastic straining of the stock essential under the tension load and contact pressures applied in accordance with this invention to produce the desired elongation, is developed as the stock is passed between opposed rolls of each of the sets of three rolls. The action producing cyclic straining is best illustrated in FIG. 2. With stock S under tension and moving from right to left around bending roll **13**, it is first bent as it passes between roll **13** and contact roll **14** then it is unbent or straightened as it passes between contact roll **15** and bending roll **13**. Due to the arrangement of the rolls with respect to each other, a high degree of bending leverage is obtained so that comparatively small forces will produce plastic deformation, or in other words, the bending and unbending action illustrated in FIG. 2. Bending roll **13** is a fixed roll, while the contact rollers are floating.

The degree of reduction of the stock is a function of the strip tension, the amount of plastic strain produced in bending the strip over the bending roll, and the pressure or force between the contact roll in each instance and the bending roll. It is also a function of the instantaneous yield stress of the material of which the stock is composed.

In the machine shown in FIG. 3, the two sets of contact and bending rolls **13**, **14** and **15**, are arranged in the manner illustrated in FIG. 1, with the exception that bending rolls **13** are fixed in position, being journaled in the machine frame as shown in FIG. 4 and contact rollers **14** and **15** are floating since they are journaled in a roller frame **17**. The roller frame is disposed between and connected by means of a pivot pin **18** to a pair of

spaced members constituting lever **19** whereby lever **19** may be moved on its pivot **20** to adjust the force between contact rolls **14** and **15** and bending roll **13** simply by loading lever **26**.

A second set of rolls **13**, **14** and **15**, is similarly supported in operating relation to the machine frame and lever **19** so that the same action is obtained in this group of rolls as in the first group described just above. Thus, here again, bending roll **13** is journaled in the bifurcated frame **21** and contact rolls **14** and **15** are journaled in another roller frame **17**, which in turn is secured by means of another pivot pin **18** to a portion of lever **19** on the opposite side of pivot pin **20** from the point of connection of the first roll yoke assembly described above.

In the operation of the FIG. 3 apparatus as indicated in FIG. 1, the stock is wound and unwound from reels **10** and **12**, which also constantly supply the necessary tension in the stock. The stock is fed over the first bending roll and under the second one, contact being made with the two sets of contact rolls at the points of bending and unbending. The stock is progressively reduced by the unique action illustrated to best advantage in FIG. 2. Since, as stated above, the degree of reduction is a function of the instantaneous yield stress of the material, strip tension, force or pressure of contact rolls and amount of cyclic plastic strain or bending, the rate at which reduction is accomplished per pass through the mill can readily be adjusted within limits by regulation of tension in the stock through adjustment of the reel torque or the relative angular velocity between the two reels, to set the force applied to pull the stock back and forth. The reduction rate may also be regulated through adjustment of the pressure between the contact rollers and their respective bending rolls. This adjustment may be made by loading lever **26** to cause it to move downwardly as viewed in FIG. 3.

The following illustrative, but not limiting, example of the method of this invention as carried out on this apparatus is offered by way of further explanation of the essential features of the invention in terms of an actual specific application or use.

EXAMPLE 1

Metal strip stock having an initial thickness of 40 mils and a width of 1 inch was threaded through the FIG. 3 mill having two one-inch diameter bend rolls and contacting rolls of the same size. This continuous, reversible-type mill was operated, running the stock first in one direction almost its full length then in the other direction to the same extent, the stock being wound and unwound on the reels at the two ends of the machine. The supply and collection reels were run to establish the tensile forces desired in the strip. Relative speeds of each reel are adjustable over wide ranges for this purpose. Dead weights applied to the ends of lever **26** exerted a force between the contacting rollers and the bend rollers in accordance with predetermined desired results.

The strip stock was oxygen-free, high-conductivity copper in the as-received state and it was processed in the cold or room-temperature condition. The yield stress of this material normally would be about 50,000 p.s.i.

In the chart of FIG. 5 the results obtained in this operation and the repetitions of this operation with varying conditions of rolling are diagrammatically illustrated. Thus the data from which Curve A was plotted were gathered during an operation in which there was no contact pressure applied in the course of bending and unbending the stock repeatedly around one-inch diameter rolls as it was passed back and forth through the mill under 40,000 p.s.i. tension in the reduced end of the strip. This particular rolling test was conducted on the mill somewhat modified from that of FIG. 3 in not having contact rolls **13** and **14**. Progressive roughening of the surface of the stock became more and more pronounced until cracks developed which produced final severing of the strip at the point marking the lower end of Curve A. Just prior to the breakage of the stock, surface conditions were such that the product would be unsuitable for any manufacturing process and thus the necessity of the contacting rolls in this new process is demonstrated.

The data from which Curve B was plotted were collected in the course of a rolling operation differing only from the operation above described in that the mill of FIG. 3 was employed and contact roll pressure of 200 lbs. per inch (essentially line contact) was applied continuously by each one-inch-diameter roll. It may be noted that the actual reduction of the stock was not greatly altered over that obtained without the contacting force, but a surface of good quality was obtained in the sheet product although in the first stages it appeared to be rather rough. The strip did not break in this test, but a point of diminishing return was reached, as indicated by the asymptotic form of Curve B. When plastic reverse bending strains became too small to warrant continuation of the process as a practical matter, the test was stopped at the lower end point of Curve B.

The data represented by Curve C were collected in an operation the same as the operation of Curve B except that the contact force was 400 lbs. per inch of roll contact. As Curve C indicates, fairly uniform reduction per pass of about 17% is achieved with decreasing stock thickness.

Curve D depicts data gathered in an operation the same as that represented by Curve C except a one-half inch contact roller was used.

An increase of substantial proportions in the effectiveness or rate of reduction of the mill is indicated, particularly when the strip or sheet stock becomes relatively thin. In other words, as long as the strip or sheet stock is relatively thick, there appears to be little effect of the smaller diameter roll over the larger diameter roller, at least when the level of tensile stress is comparatively low. In the range below 10-mil thickness the small diameter contact roller plays a significant part in reducing the strip more rapidly and this is shown to best advantage in FIG. 6.

The data illustrated by Curve E of FIG. 6 were collected where the tension stress was 40,000 p.s.i. in the stock and the contact roll pressure of 200 lbs. per inch was applied. One-inch diameter contact rolls were used in producing the data of Curve E, while one-half inch diameter contact rolls were used in producing the data of Curve F. Thicknesses down to 3 mils have been produced in strip processed under the conditions of Curve F and the surface quality of this thin foil or tape is uniformly of the highest grade just as it is in the case of Curve E and Curves B, C, and D of FIG. 5 where contact rolls were also used.

In addition to the operation described in Example 1, the contact-bend-stretch method of this invention has been actually applied to other metals and to stock of initial widths up to 12 inches and initial thickness up to 100 mils (0.100 inch). Accounts of these operations are set forth in the following, non-limiting examples.

EXAMPLE II

By using the contact-bend-stretch strip mill apparatus illustrated in FIGS. 1 and 2 and described in detail above and equipped with bend rolls 12 inches long and one inch in diameter a mild steel strip of initial nominal size of 94-mils (.094 inch) thickness and 12-inch width was reduced in thickness in eleven passes to 6.2 mils, while the width was reduced to only 11.33 inch. The initial cross-sectional area of the strip was 1.130 square inches while the cross-sectional area of the final strip product was 0.0703 square inch. In the first pass a reduction in area of 20.5 percent was achieved as the thickness was reduced from 94 mils to 75 mils and the width was held constant. Strip tension stress upstream was 885 lbs. per

square inch and downstream it was 28,200 lbs. per square inch. Contact roll pressure upstream was 2900 lbs. per linear inch of contact and downstream it was 2820 lbs. per inch. The foregoing data and other significant information developed in the course of the run are set out in the following table.

Table 1

CBS ROLLING RECORD

Rolling mill: 12" CBS strip mill
Bend roll radius, r_b (in.): ½"
Material: Mild stee lstrip
Test No. 16
Date: 8/1/60
Nominal size: .094" thick x 12" wide

Pass	Strip tension stress (lbs./in.²)		Contact roll pressure		Strip geometry		Area red. f/preceding pass, percent
	In	Out	Lbs./in.	Cont.	Thick	Cross sec. area	
0					.0943	1.130	
1	885	28,200	2,900	2,820	.075	.900	20.5
2	3,890	35,300	3,210	3,190	.060	.715	20.5
3	4,200	56,500	3,165	3,180	.035	.416	41.6
4	0	51,000	2,700	2,700	.0247	.294	29.3
5	23,150	56,700	1,850	1,835	.019	.226	23.0
6	14,150	56,700	1,800	1,800	.0146	.1725	23.7
7	29,000	58,000	1,580	1,580	.0112	.1325	23.1
8	18,880	48,000	1,380	1,380	.010	.1183	10.5
9	29,560	53,500	1,200	1,200	.0089	.105	12.5
10	21,900	55,000	1,150	1,150	.0078	.092	12.7
11	38,050	55,000	1,080	1,080	.0062	.0703	23.5

The surface of the strip stock was initially good, this stock being obtained on the market under the commercial designation "annealed, hot-rolled, mild-steel band." The quality of the surface was maintained throughout the rolling operation and the final product had a good to excellent quality. This initial mild steel strip material and this final product made from the strip had the following physical characteristics.

	Initial	Final
Yield strength:		
Longitudinal	37,756	92,360
Transverse	38,275	104,640
Ultimate strength:		
Longitudinal	51,780	103,560
Transverse	51,225	108,560

EXAMPLE III

Dead soft 2–S aluminum strip 100 mils thick and12.00 inches wide was contact-bend-stretch rolled to 21 mils and a width of 11.5 inches, as described in Example II. The significant data gathered are set out in Table 2.

Table 2

CBS ROLLING RECORD

Rolling mill: 12" CBS strip mill
Bend roll radius, r_b (in.): ½"
Material: Dead soft 2–S Al strip
Test No. 25
Date: 10/20/60
Size: .100" thick x 12" wide

Pass	Strip tension stress (lbs./in.²)		Contact roll pressure		Strip geometry		Area red. f/preceding pass, percent
	In	Out	Lbs./in.	Cont.	Thick	Cross sec. area	
0					.100	1.200	
1	1,080	5,530	500	500	.087	1.040	13.3
2	5,660	10,370	500	500	.070	.830	20.2
3	5,780	11,590	500	500	.0575	.682	17.8
4	7,780	13,100	500	500	.0475	.557	18.3
5	8,800	16,780	500	500	.0363	.426	23.5
6	7,990	19,400	500	500	.0268	.3096	27.3
7	11,950	17,400	0	500	.021	.2420	21.8

Again, the quality of the surface of the aluminum strip stock was initially good and was maintained in the rolling operation so that the surface quality of the final product was satisfactory for all commercial purposes. Physical properties of this initial aluminum strip, this final product, and another final product obtained by rolling this initial strip in accordance with presently conventional practice to precisely the same final thickness, compared as follows:

	Initial	Conventional	Final
Yield strength:			
Longitudinal	7,163	23,313	22,200
Transverse	8,213	23,966	22,100
Ultimate strength:			
Longitudinal	12,700	26,750	26,200
Transverse	12,547	28,083	26,050
Vickers Hardness No. 27		54.5	50

EXAMPLE IV

In still another operation like that described in Example II, Type 302 stainless steel 100-mils thick and six inches wide was contact-bend-stretch rolled on a 12-inch mill under the circumstances and with the results set out in Table 3.

Table 3

CBS ROLLING RECORD

Rolling mill: 12" CBS strip mill
Bend roll radius, r_b (in.): ½"
Material: Type 302 Stainless Steel
Test No. 17
Date: 8/7/60 and 8/18/60
Nominal size: .100" thick x 6" wide

Pass	Strip tension stress (lbs./in.²)		Contact roll pressure		Strip geometry		Area red. f/preceding pass, percent
	In	Out	Lbs./in.	Cont.	Thick	Cross sec. area	
0					.099	.595	
1	16,800	46,200	3,000	3,000	.0822	.487	18.0
2	22,400	60,000	4,000	4,000	.072	.422	13.2
3	46,200	82,400	3,500/1,300	3,500/1,300	.0623	.364	13.8
4	61,000	98,100	4,000	1,300	.0542	.312	14.2
5	57,000	114,000	1,300	4,000	.0454	.260	17.0
6	53,800	122,000	4,000	4,000	.036	.204	21.5
7	46,000	128,000	4,000	4,000	.0272	.153	25.0
8	46,050	112,000	4,000	4,000	.0232	.130	15.0
9	50,000	140,000	4,000	4,000	.0169	.0944	27.5
10	54,700	122,000	3,400	3,400	.014	.077	17.5
11	78,000	115,000	3,060	3,060	.0122	.0675	12.5
12	81,500	110,000	2,840	2,840	.0115	.0635	6.0
13	74,000	108,000	2,840	2,840	.0112	.0618	2.7

The initial surface quality of this stainless steel strip was good and was maintained throughout the rolling operation and the final product therefore would meet the surface quality requirements for commercial use. Physical properties of this final product and a product obtained by rolling the same initial stainless steel strip material by presently conventional practice were as follows:

	Conventional	Final
Percent Reduction	80	90
Yield strength:		
Longitudinal	227,100	273,400
Transverse	223,900	285,500
Ultimate strength:		
Longitudinal	240,000	275,300
Transvrse	256,500	286,200
Vickers Hardness No	486	560

EXAMPLE V

Using the contact-bend-stretch strip mill of FIG. 1 as described above and in carrying out an operation after the manner set forth in Example 1, a commercial alloy known in the trade as René–41, which had been solution annealed, was contact-bend-stretch rolled in accordance with the method of this invention under the circumstances and with the results recorded in Table 4.

Table 4

CBS ROLLING RECORD

Rolling mill: 1" CBS strip mill
Bend roll radius, r_b (in.): ½"
Material: René 41—Solution annealed
Test No. 177
Date: 7/17/60

Pass	Strip tension stress (lbs./in.²)		Contact roll pressure		Strip geometry		Area red. f/preceding pass, percent
	In	Out	Lbs./in.	Cont.	Thick	Cross sec. area	
0					.0977	.04720	
1	41,300	87,600	7,000	7,000	.0717	.03422	26.6
2	36,500	115,000	7,000	7,000	.0551	.02605	23.2
3	50,800	109,000	7,000	7,000	.0456	.02155	17.3
4	37,800	111,000	7,000	7,000	.0372	.01744	18.4
5	32,700	110,000	7,000	7,000	.0305	.01430	18.0
6	30,800	112,000	7,000	7,000	.0246	.01152	19.35
7	25,200	109,800	6,000	6,000	.0203	.00948	17.47
8	30,100	111,000	6,000	6,000	.0166	.00775	18.20
9	19,350	113,000	5,000	5,000	.0134	.00619	19.30

The final rolled product had surface quality at least as good as that of the initial material and had physical properties comparing with the initial material and with this initial material conventionally rolled, as follows:

	Initial	Conventional	Final
Percent reduction	0	66	88
Yield strength:			
Longitudinal	65,100	200,000	254,200
Transverse	62,900	186,400	254,900
Ultimate strength:			
Longitudinal	131,700	233,000	264,300
Transverse	132,300	235,800	287,500
Vickers Hardness No.	249	477	523

EXAMPLE VI

In another operation like that described in Examples I and V, annealed 3¼ percent silicon-iron strip of initial thickness of 40 mils and width of 1 inch was rolled to a final thickness of 7.3 mils and 0.916 inch. In this case the contact roll radius was ⅛ inch whereas in all the prior rolling operations the contact roll radius was ¼ or ½ inch. The significant data in this run are set out in Table 5.

Table 5

CBS ROLLING RECORD

Rolling mill: 1" CBS strip mill
Bend roll radius, r_b (in.): ½"
Contact roll radius, r_c: ⅛"
Material: Annealed 3¼% silicon iron
Test No. 48
Date: 10/2/58

Pass	Strip tension stress (lbs./in.²)		Contact roll pressure		Strip geometry		Area red. f/preceding pass, percent
	In	Out	Lbs./in.	Cont.	Thick	Cross sec. area	
0					.0400	.0402	
1	31,080	42,500	830	830	.0374	.0376	6.54
10	61,150	82,400	1,066	1,066	.0215	.0206	9.92
11	63,000	87,700	1,079	1,079	.0192	.0182	11.58
19	53,100	86,500	1,118	1,118	.0088	.0081	10.74
20	55,350	89,800	1,119	1,119	.0073	.0067	17.10

The surface characteristics of this finished product were at least equal to those of the intial stock.

EXAMPLE VII

Again in an operation like that described in Examples I and IV commercial L-605 alloy was contact-bend-stretch rolled from an initial thickness of 43.6 mils and an intial width of 0.5 inch to 26 mils and a width of 0.462 inch, in an apparatus as described above, where ¼ inch radius contact rollers were employed in contrast to the ⅛ inch rollers of Example VI. Pertinent data on this operation are set out in Table 6.

Table 6

CBS ROLLING RECORD

Rolling mill: 1" CBS strip mill
Bend roll radius, r_b (in.): ½"
Contact roll radius, r_c: ¼"
Material: L-605 alloy
Test No. 28
Date: 6/15/58

Pass	Strip tension stress (lbs./in.²)		Contact roll pressure		Strip geometry		Area red. f/preceding pass, percent
	In	Out	Lbs./in.	Cont.	Thick	Cross sec. area	
0					.0436	.0218	
1	48,100	73,000	2,120	2,120	.0402	.0199	8.945
9	110,800	127,000	2,480	2,480	.0280	.0130	0.764
10	113,000	137,500	2,500	2,500	.0260	.0120	7.620

Strip surface quality was maintained throughout this operation.

EXAMPLE VIII

Again, using the 1 inch contact-bend-stretch strip mill of FIG. 1, as described in Example I, commercial Jetalloy 1650 which had been solution treated and wet blast cleaned was rolled from an initial thickness of 40.5 mils to 13 mils and from an initial width of 0.508 inch to the final width of 0.487 inch. The pertinent data concerning this operation appear in Table 7.

Table 7

CBS ROLLING RECORD

Rolling mill: 1" CBS strip mill
Bend roll radius, r_b (in.): ½"
Material: Jet Alloy 1650—solution treated—wet blast cleaned
Test No. 40
Date: 8/7/58

Pass	Strip tension stress (lbs./in.²)		Contact roll pressure		Strip geometry		Area red. f/preceding pass, percent
	In	Out	Lbs./in.	Cont.	Thick	Cross sec. area	
0					.0405	.0203	
1	25,600	76,000	3,500	3,500	.0342	.0171	15.5
7	58,900	151,000	4,110	4,110	.0150	.0073	14.0
8	59,000	143,000	4,150	4,150	.0130	.0063	13.6

Physical properties of the finished rolled product compared favorably with the initial material and the surface was apparently improved by the rolling operation.

As a further comparison of the novel rolling method of this invention with heretofore conventional rolling practice, annealed copper strip (OFHC) 12 inches wide and 100 mils thick had the yield strength and ultimate strength values at several stages of the two rolling operations as set out in Table 8.

Table 8

CONVENTIONAL ROLLING

Percent redn.	Yield strength		Ultimate strength	
	Long.	Trans.	Long.	Trans.
0		14,250		34,600
18	40,750	40,488	41,375	41,788
38	47,788	49,225	49,763	52,200
53	51,863	53,450	53,963	55,850
74	46,163	57,767	58,600	60,983
90	58,725	60,233	62,100	62,767

INVENTION ROLLING

0		14,250		34,600
19	31,117	32,823	42,517	43,327
38	36,200	35,917	46,367	49,133
53	26,717	26,667	48,900	50,867
74	39,383	43,067	51,333	56,233
90	51,100	48,400	55,950	56,067

As indicated hereinabove, one of the fundamental differences between the novel contact-bend-stretch rolling process of this invention and the rolling processes of the prior art, is the fact that in the present invention process, the roll force or roll contact pressure is small by comparison to all prior art rolling methods. Thus roll force in accordance with prior practice was always necessarily greater than the force necessary of itself to produce plastic deformation of the stock, but the roll force in accordance with this invention is considerably less than that required to so produce plastic elongation. By virtue of this difference it is possible for the first time in accordance with the present invention to subject stock during rolling to a tension stress which is relatively much greater than that which can be used under otherwise similar conditions in accordance with prior art practices. In accordance with this invention, in fact, the maximum tension stress to which the stock is subjected during roll may in some cases safely and very advantageously be maintained at a level approaching 95 percent of the flow stress of the stock.

Also, as indicated above and as will hereinafter be described in more detail, rates of reduction which are unique and heretofore unknown and unattainable in rolling operations can be achieved in the present process under certain conditions. This advantage over the prior art is of special importance in certain ranges of initial stock thickness and in certain types of materials.

These differences from and distinctions over the prior art are graphically illustrated in FIGS. 7 to 12 inclusive.

As the sketch accompanying the chart of FIG. 7 indicates, a wide strip S is subjected to contact roll force P_c per inch of width by roll **14** of radius R and is simultaneously subjected to a tensile stress TS as the stock is being plastically bent at the point of contact with roll **14** around a bend roller neither the bend roller nor the bend in the strip being shown. The strip is of thickness *t*, Curve K of FIG. 7 then represents a typical contact-bend-stretch operation of this invention, while Curve L represents a typical commercial tension mill operation in which the rolls are not driven and the stock is moved through the mill by tension force alone. Curve M represents a modification of the tension mill operation of Curve L wherein the tensile stress is maintained at a limit substantially higher than practical level of the Curve L operation. In the Curve K operation, tensile stress TS may advantageously be maintained at a value approaching 95% of TFS which represents the flow stress of the stock. In the operation of Curve M, the tensile stress TS is likewise maintained at a very high level, while in the case of the Curve L operation, tensile stress is limited to a level which is less than 50% of the TFS value of the stock.

The operations represented by the curves of FIG. 7 are all carried out under conditions of a fixed radius R and a fixed stock thickness *t*. The percent reduction per pass is indicated for various roll forces P_c. The intersection of Curves K and M represents the limit of effectiveness of the contact-bend-stretch method of this invention, the percent reduction for which is given by the expression

$$\frac{2t}{R}\times 100\%$$

Further processing of the stock in the contact-bend-stretch mill thus will not differ in terms of results or in actual process details from the tension mill operation represented by Curve M, the contact-bend-stretch mill in effect becoming a high-tension tension mill. To give this critical transition point a value for the sake of providing an illustrative example, assume an R of ½ inch, and a *t* of 1/10 inch. The dotted line paralleling the abscissa and passing through this transition point then will represent 40% reduction. The intersection point of Curves K and M represents for Curve K the reduction obtained in a single mill pass while that for Curve M represents the reduction obtained in four mill passes. Similarly Curve L represents four mill passes.

Curves K and M are shown again on the charts of FIGS. 8 and 9 along with the point of their intersection defined by the expression

$$\frac{2t}{R}\times 100\%$$

signifying the percentage reduction in a single pass in accordance with the method of this invention and in four passes in accordance with the conventional tension mill practice,

In FIG. 8 the method of the present invention and the tension mill method of Curve M are compared with another conventional operation in which the rolls are driven but strip S is not subjected to significant tensile stress. Curve N illustrates the typical performance of the latter type mill. From this chart it is seen then that it is not possible in Curve N type of rolling operation to produce the Curve K results of the present invention method and, in fact, it is not possible even to achieve the results of the conventional tension mill represented by Curve M or even the results of the typical tension mill operation represented by Curve L of FIG. 7.

In FIG. 9 Curves P and R represent driven-roll tension rolling operations in which, respectively, tensile stress TS closely approaches TFS, as in the Curve K method, and TS is maintained at less than 50% of TFS, as in the Curve L operation. Curve P thus represents a non-typical and wholly impractical operation in which the tensile stress in the stock is actually substantially greater even than that of the non-typical Curve L tension mill operation wherein the rolls are idlers and thus do not contribute to maintaining the tension stress in the strip constant through the mill. The Curve P operation accordingly represents maximum performance hitherto obtainable in terms of reduction rate, but because of excessive breakage of strip this operation has never been regarded as an answer to the problem of increasing tension rolling efficiency.

It will be understood by those skilled in the art that while all these operations are capable of producing the same total thickness reduction, the rate at which the reduction is accomplished varies and it is this difference which is illustrated by the curves of FIGS. 7, 8, and 9. In addition to this efficiency aspect these charts show that the contact-bend-stretch method of this invention is capable of producing results previously unattainable, through the use of any magnitude of tensile stress or roll force or any combination thereof.

To compare further the present invention method with the conventional tension rolling process represented by Curve L of FIG. 7 and also to illustrate the role of contact pressure or roll force, strip thickness is plotted against

percent reduction in FIG. 10. Two families of three curves each represent characteristic data for these two different kinds of operation wherein strip tension is the same but roll forces of three different magnitudes are applied for direct comparison of the two procedures. Actually, in this case one mill pass of this invention is compared with four mill passes of the conventional Steckel process. Thus, Curve T represents a tension rolling operation in which a relatively low roll force is applied to the strip, Curve U represents an operation which is the same except that the roll force is substantially greater and in the case of Curve V the difference consists again in the magnitude of the roll force which is still greater by a substantial amount. Curves W, X, and Y similarly represent contact-bend-stretch rolling operations of this invention wherein the roll forces correspond, respectively, to those in the cases of Curves T, U and V and the roll force magnitude, in each instance of comparison are exactly the same.

The points of intersection of the curves have the significance of the Curve K—Curve M intersection described above in reference to FIG. 7 and therefore define the operating limit of the present invention method in each case. This definition is in terms of a relationship between strip thickness and bending roll radius and stated mathematically is

$$\frac{2t}{R}\times 100\%$$

where, as before, t is the strip thickness and R is the roll radius expressed in the same dimensional unit. The dotted line extensions of Curves V, W and X do not represent real data or values but are merely used to indicate the symmetry of the roll force relationships in this present invention process.

As is evident, again, from FIG. 10, the contact-bend-stretch method is uniquely effective in certain ranges of strip thickness, assuming a constant bend roll diameter. In other words, so long as plastic bending of the strip occurs during the rolling operation, the rate of strip thickness reduction will be greater than that obtainable in a tension rolling operation in which the strip tension and the roll force are identical in the two operations. Curves X and U illustrate this fact and the other curve pairs of FIG. 10 repeat the demonstration. Thus it is seen that where the initial thickness of the strip to be rolled is TI, as designated by the dotted line connecting the ends of Curves W and T and intersecting the abscissa, a vastly greater thickness reduction rate is achieved by this invention method than by the tension mill operation. As the strip thickness is reduced, this rate differential between the two operations diminishes until finally at strip thickness TF, the two curves intersect, signifying that plastic bending is no longer occurring and that the contact-bend-stretch method has become simply a tension mill operation. By substituting a bending roll of somewhat smaller radius, however, the present invention method may be continued into still thinner strip thickness ranges, as indicated by Curve Z.

In addition to enabling the foregoing striking new results, the method of this invention permits the use of much greater tensile stress in rolling operations than has hitherto been possible. This means that rolling effectiveness may be substantially increased over the best previously known and means further that this may be done simply by increasing the tensile force applied to the strip as it is rolled. On the other hand, no modification of the prior rolling apparatus would enable such a result because the problem of strip breakage under excessive tension could not be solved.

To illustrate this tension problem graphically, two cases representing, respectively, conventional rolling practices and the contact-bend-stretch method of this invention are shown in FIGS. 11 and 12. In these views, strip S again is subjected to tension stress TS and to roll force P_c per unit width and in each instance the roll force non-uniformly applied across the width of the strip. This non-uniformity may be due to a number of factors such as lateral variations in strip thickness, roll crown, roll bending and thermal distortion of the rolls. Roll force seriously aggravates the tension problem attributable to any of these factors, as will be described, and consequently reducing that force materially in any rolling operation could hold an important advantage. This force has been minimized in accordance with this invention beyond anything heretofore known or believed possible by those skilled in the art.

The lateral non-uniformities in roll force are diagrammatically shown in FIGS. 11 and 12 by Curves AA and BB, respectively. Under the tensile force T normally applied in the rolling operation, lateral distribution of tension stress in strip S is digrammatically represented in FIG. 11 by Curve CC, while the flow stress of strip S is indicated by TFS and the working tension stress is represented by TWS. The expression for tension applied to the strip in this FIG. 11 case then is $T=TWS\times A$, where A is the cross-sectional area of stock S, the maximum tension stress represented by the TM line very closely approaching the TFS while the working stress is considerably less than TFS, say 0.5 TFS.

In the case of FIG. 12, where tensile force T is the same as in FIG. 11, strip S is again illustrated at the point where a contact roll bears against the strip as it is bent around a bend roller, the bend roller, however, not being shown, and also for purposes of clarity, the strip is shown unbent as in FIG. 11. Here again, the distribution of roll force across the strip is correlated with the distribution of longitudinal tensile stress across the strip in this new rolling process. Curve BB represents this roll force distribution, while Curve DD depicts the tensile stress distribution laterally of the strip. Again, TFS represents the flow stress of the stock, while TWS represents the working tension stress during the rolling process and TM represents the maximum tension stress applied to the strip in this operation. From FIG. 12, therefore, it is seen that while TM very closely approaches TFS as in FIG. 16, here TWS is much larger, approaching 0.95 TFS, resulting in greater reductions.

In these FIG. 11 and FIG. 12 operations, identical strips are involved and the tensile force and the roll force are the same in each case. Further, as the drawings show, Curves AA and BB are generally the same and those skilled in the art will understand that the differences in magnitude are due to the difference in roll forces in the two cases.

Curves CC and DD, however, are not the same shape nor do they depict proportional values because of the following relationship:

$$\text{Curve } CC=TFS-AA$$
$$\text{Curve } DD=TFS-BB$$

From these drawings, it will be understood that in a given case of equivalent reductions in a conventional mill of the prior art and in the new contact-bend-stretch method, the roll force is significantly less in the latter, although the relative variation in roll force is the same in the two situations. Consequently, in the conventional operation, the lateral variation of longitudinal tensile stress will be significantly greater, which imposes the necessity for limiting average tensile stress on the strip to values not exceeding about one-half the flow stress of the strip, to prevent its breakage. Because these lateral variations in tension may be relatively much smaller in the present process of rolling, tension (TWS) much greater than that permitted in prior rolling processes can consistently and safely be employed and substantially greater rolling effectiveness thereby can be realized.

The method described herein has been demonstrated to reduce effectively the thickness and increase the length of strip where the ratio of strip thickness to bending roll

diameter is initially 0.10 and decreases with reduction in thickness to 0.001. Larger initial ratios as, for example, 0.25 to as high as 0.5 in some instances with soft ductile metals such as aluminum or copper will be generally satisfactory, depending on the susceptibility to fracture of the material being rolled, and upon the preference of the operator.

Similarly, the ratio of the contact roller radius to the bend roll radius is not restricted but may be widely varied. The radius of the bend roll must, however, be related to the thickness of the strip stock and the nature of this stock to cause plastic deformation (bending) of the stock during the rolling operation.

As a practical matter, the initial thickness of strip material should probably not exceed three inches, and where the strip is of steel, it should preferably not be more than one inch thick. Such strip may be hot rolled in accordance with this invention to a thickness of about 0.1 inch, and then cold rolled to the final desired thickness in a continuation of the present method.

In accordance with the method of this invention, new products or materials having new combinations of physical characteristics can readily and consistently be produced. Thus, I have found that by running certain material through apparatus of this invention and either contact-bend-stretch rolling the material, or contact-bend rolling the material under certain special circumstances, unique mechanical properties can be imparted to it or produced in it. By way of example, a mild steel strip (SAE–1018 Steel) was run back and forth repeatedly through the apparatus of FIGS. 1 and 2 while the strip temperature was maintained between 100° C. and 300° C. Strengthening of the strip occurred very quickly until its yield stress approached 100,000 p.s.i. Then the cyclic-aged strip was cooled to room temperature and again run repeatedly back and forth through the apparatus and a progressive softening effect was observed. In this step of the operation, the cyclic strains were of the order of from two percent to ten percent strain range. In other similar operations, strains as high as fourteen percent uniform elongation can be obtained through subsequent mechanical cycling of cyclic-aged mild steel in strain range of four percent for ten cycles at room temperature.

In still another special application of the contact-bend method of this invention the apparatus of FIGS. 1 and 2 was used to improve the properties of low carbon sheet steel strip. While a substantial tensile force may be employed in this operation and relatively high tensile stresses may be set up in the strip, such is not essential to the desired results. In the actual operation the strip was not subjected to tension and a unique strip product was obtained, the yield point of this material actually being eliminated for a considerable length of time. In the first step in this operation the strip was annealed. Then it was run through the FIG. 1 mill so as to produce a plastic bending strain of from one to eight percent. The contact load was only sufficient to avoid surface marking associated with the yield point effect and was therefore of the order of 1000 pounds per linear inch for the one-inch contact roll. The rolling operation was carried out at room temperature and was followed by a straightening step.

In thus employing the cyclic bending action of this invention for initial yield point suppression, strain aged strengthening and improved ductility, the properties uniquely varied through the thickness of the strip material. Consequently, a strip can be produced which will not exhibit either an upper or lower yield point, sliplines or other characteristics of the strain-aging phenomenum. Further, a wide range of strength and ductility in mild steel can thus be obtained while keeping the percent reduction in area substantially constant.

These novel strip products and others like them that have been produced through this new procedure exhibit stability up to temperatures above where such material is of normal commercial interest. By way of example, a specimen of cyclic strain-aged, strain-softened material, produced in this manner was heated and held at a temperature of 250° C. for one-half hour. A subsequent tensile test of this strip indicated that it was essentially identical in stress-strain characteristics to the same material not so heated. Such apparent resistance to strain aging may have important technological interest in many metal forming processes where strain aging and Luder's band formation are a considerable problem.

Again, these unique materials and combinations of physical properties in various materials produced or processed in accordance with this invention are attributable to the present novel contact-bend-stretch or contact-bend operations. The metal or material, in other words is subjected in these operations to entirely different combinations of forces from those which it encounters in heretofore conventional rolling operations. The manner in which the plastic deformation, typically elongation, is accomplished is wholly unlike any of the prior procedures and the manner in which the material is caused to flow or deform in order to accomplish this result is likewise believed to be new and different. It is, in fact, believed that these new procedures and results and the new materials which this invention affords owe their existence to the novel way in which the metal or material of the body undergoing deformation is caused to flow under the applied forces.

Apparatus for carrying out the novel process of this invention which is alternative to the novel apparatus of FIGS. 1 and 2 but employs either the contact-bend-stretch or the contact-bend principle and involves cyclically and plastically bending sheet stock is shown in FIGS. 13–15. In the FIG. 13 apparatus strip S is disposed around two contact or supporting rolls **65** and **66** which define between their working surfaces a gap of width somewhat greater than twice the initial width of the strip. Strip S also is disposed around the bend roll **67** which is positioned with its axis parallel to the axes of rolls **65** and **66** and is situated so as to substantially close the gap between the contact rolls. An upstream bridle roll **68** and a downstream bridle roll **69** serve to deliver strip to the bending roll and contact roll assembly and to receive the strip therefrom and to maintain the strip under requisite tension both upstream and downstream from bend roll **67**. In this arrangement supporting rolls **65** and **66** are on fixed centers being suitably journalled in a rolling mill frame RF, while bend roll **67** is a floating element and is maintained in position in the gap between rolls **65** and **66** by strip S as illustrated to best advantage in FIG. 14. As described above in reference to FIGS. 1 and 2, it may be feasible or desirable to run strip S back and forth repeatedly through the bending station of this FIG. 13 apparatus, or it may be preferred to run it through this station only once and to have a series of such stations arranged for reduction of the strip thickness in separate steps. In the latter case, contact rolls **65** and **66** will suitably be driven at a predetermined peripheral velocity ratio to each other so that the assembly will accommodate the elongation resulting from the contact-bend-stretching action occurring at roll **67**.

In the apparatus of FIG. 15, rolls **65**, **66** and **67** again comprise the working part of the mill but in this case roll **66** is not directly driven. Instead, a second floating roll **70** is provided between upstream bridle roll **68** and roll **66**. By virtue of this arrangement very heavy reductions can be effected in the new apparatus without any tendency for bend roll **67** to be drawn too far into the gap between the rolls **65** and **66** with resulting excessive reductions and strip fracture. Roll **70** is of sufficient size that it otherwise is not plastically bent and thereby reduced as a result, of this arrangement, but this roll nevertheless acts as a means for transmitting

torque from bridle roll **68** to support roll **66**. In order for such torque transmission to occur, it is necessary that there be adequate tension in the strip in this region. Consequently, a decrease in upstream strip tension, which might lead to excessive reduction and strip fracture as stated above, results in decrease in the torque transmitted to the strip by roll **66**. In other words, torque transmitted to the strip by roll **66** is in this way related to upstream strip tension so that bend roll **67** does not tend to be drawn into the mill and the necessary control is maintained. Very heavy reductions up to fifty percent per pass in materials such as aluminum have been successfully accomplished over protracted periods of operation of this FIG. 15 apparatus. Again, as in the FIG. 19 apparatus, a rolling mill frame RF is provided and rolls **65**, **66**, **68** and **69** are journalled in and supported by this frame.

FIGURES 16 and 17 represent alternatives in some respects to the apparatus of FIGURES 1 and 2. However, the bend rolls of FIGS. 16 and 17 are driven so that in the event that tensile force applied to strip S is to be essentially zero, the strip may nevertheless be moved through the mill as rapidly as desired. This kind of operation is contemplated in accordance with one or another of the contact-bend methods of this invention subsequently to be described in detail. Accordingly, in FIGS. 16 and 17 bend rolls are represented by **95** and contact rolls are **96** and **97**, these being mounted as floating pairs for movement together relative to the associated bend roll **95**. Again, after the manner of FIG. 1, strip S is moved through the mill between bend roll **95** and the opposing contact rolls **96** and **97** which apply a contact pressure to the strip at the point of plastic bending and plastic unbending so as to preserve or even to improve the original surface quality of the strip.

Those skilled in the art will understand that instead of using in the novel apparatus of this invention bend rolls or contact rolls which are of uniform outside diameter, stepped rolls may be employed. Likewise, contact rolls or bend rolls of other working surface shapes may be employed. However, the same principles and parameters relative to cyclic plastic bend, tension and contact loads apply as in the foregoing detailed descriptions. By this means certain advantages may be achieved in rolling strip of uniform thickness and, in addition, lateral variations in strip thickness can be developed or produced for a variety of commercial applications.

To avoid possible lateral bending of the strip and tracking problems, the roll pattern should be symmetrical in respect to the center line of the strip. Since the rolling process of the present invention enhances uniformity in longitudinal strain because of the cyclic plastic bending action as previously described, variations in strip thickness which may be produced are a consequence of lateral flow. Accordingly, it would not be expected that very pronounced lateral variations in strip thickness can be produced when the strip is very wide and very thin because of severe lateral constraints to flow.

It is contemplated that such shaped roll elements may be used to advantage in the production of commutator segments, stator cores, blade and bucket materials and the like.

To illustrate the use of such contoured roll elements, two of the four contact rolls **14** and **15** of FIG. 1 may be shaped so that they engage strip S only in its center region, while the other two contact rolls of this mill engage the strip only at its edges. By virtue of this arrangement, excessive edge contact pressure which causes a redistribution of longitudinal stress due to strip tension and results in enhancing the tension in the central region of the strip, is avoided. Consequently, the tendency of the strip to undergo severe transverse checking and deterioration and possibly premature fracture is overcome because excessive tension coupled with reverse bending without adequate contact loading or roll force is prevented.

Those skilled in the art will understand that in general the present method is applicable to any elongated bodies which are deformable in the sense that strip or sheet metal is deformable at room temperature. Accordingly, it is contemplated that the present novel method may be applied to a wide variety of materials under a wide variety of environmental conditions to consistently produce or obtain the advantages stated above. Thus, for example, a body of a material which is not deformable at room temperature may successfully be subjected to this invention method at a temperature well below or well above room temperature, depending upon the relative plasticity or brittleness of the body at room temperature.

Having thus described this invention in such full, clear, concise and exact terms as to enable any person skilled in the art to which it pertains to make and use the same, and having set forth the best mode contemplated of carrying out this invention, I state that the subject matter which I regard as being my invention is particularly pointed out and distinctly claimed in what is claimed, it being understood that equivalents or modifications of, or substitutions for, parts of the specifically described embodiments of the invention may be made without departing from the scope of the invention as set forth in what is claimed.

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

1. Apparatus for increasing the length and uniformly reducing the thickness of metal strip, sheet or foil stock which comprises a frame, a first bending roll journaled in the frame, a first contact roll rotatably supported adjacent to the first bending roll for pressing engagement with the stock across its width as the stock first engages the said first bending roll, a second contact roll rotatably supported adjacent to the first bending roll and positioned for pressing engagement with the stock across the width of the stock as the stock leaves the first bending roll, a second bending roll journaled in the frame in radial spaced relation to the first bending roll, a third contact roll rotatably supported adjacent to the second bending roll for pressing engagement with the stock across its width as the stock first engages the second bending roll, a fourth contact roll rotatably supported adjacent to the second bending roll with its axis substantially paralleling that of said second bending roll and located to press the stock against the second bending roll at the point where the stock is having engagement with the said second bending roll, means including a lever movably supported by the frame and operably associated with the four contact rolls for simultaneously adjusting the portions of the contact rolls relative to the bending rolls to regulate the contact roll pressure applied to the stock, and means for running the stock back and forth around the bending rolls and maintaining the stock in tension in its travel around and between the bending rolls.

2. Apparatus for increasing the length of strip stock while subjecting the stock to tensile stress and to roll pressure which comprises a roll frame including journal means for rotatably supporting contact rolls on fixed centers, an upstream contact roll, a driven upstream bridle roll, and a driven downstream contact roll, said contact rolls being of relatively large diameter journalled in the roll frame on fixed centers and spaced apart to provide a gap, a floating undriven bend roll of relatively small diameter bearing against and being supported entirely by the contact rolls and substantially closing the gap therebetween, said bend roll being of diameter greater than the minimum width of the gap between the contact rolls and being small enough to cause plastic bending of the stock, and the contact rolls being of diameter such that the stock is not plastically bent in being disposed around said contact rolls as said stock is run through the roll assembly of the apparatus, and means for driving the

contact rolls at predetermined relative peripheral velocities to achieve said tensile stress and move the stock through the roll assembly.

3. Apparatus for increasing the length of strip stock which comprises a roll frame structure including journal means for rotatably supporting contact rolls on fixed centers, an undriven upstream contact roll, a driven downstream contact roll, said contact rolls being of relatively large diameter and disposed with their axes substantially parallel to each other and spaced apart to provide a gap as long as the opposed working surfaces of said rolls and of width greater than twice the initial thickness of the stock, a floating bend roll of relatively small diameter disposed to substantially close the gap between the contact rolls, said bend roll being of diameter greater than the minimum width of the gap between the contact rolls, and means for maintaining a predetermined peripheral velocity ratio between the said upstream and downstream contact rolls.

4. Apparatus for increasing the length of strip stock by plastically bending the stock while subjecting it to tensile stress and to roll pressure which comprises a roll frame including journal means for rotatably supporting contact rolls on fixed centers, an upstream contact roll, a driven upstream bridle roll, and a driven downstream contact roll, said contact rolls being of relatively large diameter and journalled in the roll frame on fixed centers and with their axes substantially parallel to each other and spaced apart to provide a gap as long as the opposed working surfaces of said contact rolls and of width permitting free passage of strip stock simultaneously in two directions through the gap, a floating undriven bend roll of relatively small diameter disposed to substantially close the gap between the contact rolls and to engage a strip stock loop leading through the contact roll gap and to grip strip stock loop leads against the contact rolls, said bend roll being of diameter greater than the minimum width of the gap between the contact rolls and small enough to produce plastic bending of strip stock, and means for driving the upstream bridle roll and the downstream contact roll at predetermined peripheral velocities relative to each other to achieve said tensile stress and move strip stock through the roll assembly.

5. The method of cold working a metal strip and thereby reducing the thickness and increasing the length of the strip which comprises the steps of advancing the strip along a travel course and overcoming the yield point of successive portions of the strip by plastically bending the strip at a first bending location, simultaneously subjecting the successive portions of the strip to tension stress and to compression force sufficient in combination with said plastic bending to reduce the thickness of the strip without degrading the surface quality of the strip, then transferring the resulting bent portions to a first unbending location spaced from the first bending location, then advancing the said bent portions of the strip through the first unbending location and overcoming the yield point of successive bent portions by plastically unbending said bent portions, simultaneously subjecting the successive bent portions of the strip to tension stress and to compressive force sufficient in combination with said plastic unbending to reduce the thickness of the strip without degrading the surface quality of the strip, then transferring the resulting successive plastically unbent portions of the strip through a distance at least as long as the distance between the first bending location and the first unbending location and thereby bringing the said unbent portions of the strip to a second bending location spaced from the first unbending location, then advancing the said unbent cold-worked portions of the strip through the second bending location and overcoming the yield point of successive cold-worked portions of the strip by plastically rebending the strip, simultaneously subjecting the strip to tension stress and compression force sufficient in combination with the plastic bending further to reduce the thickness of the strip without degrading the strip surface, then transferring the resulting plastically rebent cold-worked portions of the strip farther along the travel course to a second unbending location spaced from the second bending location, then advancing the said rebent portions of the strip through the second unbending location and overcoming the yield point of successive rebent portions of the strip by plastically unbending the said rebent portions, simultaneously subjecting the strip to tension stress and compression force sufficient in combination with plastic unbending to reduce still further the thickness of the strip without degrading the strip surface, and repeating the foregoing sequence of bending and transferring and unbending steps until the strip is of final desired thickness.

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CHARLES W. LANHAM, *Primary Examiner.*

LEON PEAR, WILLIAM J. STEPHENSON, *Examiners.*