CHAPTER XXV.

THE OPERATION OF ROLLING.

Historical.—To ensure the production of gold or silver coins of equal weights, the blanks from which they are pressed must be cut from sheets of metal of very regular thickness. To ensure this regularity Brulier, a Frenchman, in 1553, passed the sheet of metal between a pair of plain rolls. The invention of grooved rolls has usually been ascribed to the Englishman, Henry Cort, the inventor of the puddling process, who took out a patent for their use in the year 1783, but Mr. W. F. Durfee, in a most interesting account of early rolling mills,* states that in the *Transactions of the Académie des Sciences for 1728* is described a remarkable reversing rolling mill, for rolling lead into sheets. This mill had rolls 12 inches in diameter, by 5 feet long, the mill being moreover provided with roller tables 24 feet long, formed of rollers 4 inches diameter, set 12 inches apart, centre to centre. The plain rolls could be replaced by others, 16 inches diameter, provided with semi-circular grooves, varying from 4 inches to 2 inches diameter, in which lead ingots, cast hollow, were rolled on a mandril to form pipes. Mr. Durfee further quotes from a work by Christopher Polhem, who died in 1751, in which there is a description of the rolling of sections, as commonly practised in Sweden in his days, with the further assertion that the rolling mill could turn out 10 to 20 times more bars in a given time than could be tilted under a hammer. It also shows that Polhem was well aware of the fact that small rolls possessed much more power of stretching material than did large ones, and that he therefore employed for rolling sheets "slender" wrought-iron rolls, supported above and below by large cast-iron ones, which is the precise arrangement patented about 40 years ago by Lauth, and used in most of the American plate mills to-day, save that Lauth employed one and not two small rolls.

Nature of the Action of Rolls.—The end in view when rolling an ingot or bloom is to reduce its thickness, and so increase its superficial area to form a plate, or to reduce both its thickness and width, thus increasing its length, to form a bar of some desired cross section, the rolls doing, on a large scale and with greater rapidity and accuracy, the same work as the smith performs by hand, when he draws down a piece of iron into a small plate or bar on his anvil. In the early days of iron manufacture, before the method of using rolls for the purpose was devised, all plates and bars were thus shaped out by the hammer and anvil, hand hammers being first employed and then tilt hammers driven by water wheels. Indeed to this day, the best Sheffield tool steel is all drawn down into bars by steam hammers. A clear conception of the principles underlying the action of rolls will be facilitated by bearing in mind the essential similarity of the two operations of hammering and rolling.

If a smith wishes to draw down one end of a bar quickly, he puts in a socket in his anvil a tool called a "fuller," having a comparatively sharp rounded face, which crosses the bar at right angles to the direction in which he wishes to extend it. On the bar he then lays a corresponding tool, which his assistant strikes with his sledge (see fig. 368, A). By concentrating the work on only a small portion of the bar, he produces the maximum effect, and avoids expending so much power as would be needed were he to spread

* *Cassier's Magazine*, April, 1899.

his exertions over more surface. For instance, were he to employ at the drawing-out stage his "swages," which are 3 or 4 inches long, and have grooves in their faces, intended only for finishing the bar when it is nearly of the form desired, he would be spreading the work over so much ground that the pressure per unit of surface would be too slight to be effective, so that great force and several heats would be required to produce any appreciable result. The action of a pair of rolls (fig. 368, B) is analogous to the action of a pair of fullers, save that the pressure on, and travel of the bar is in that case continuous instead of intermittent.

The narrower the faces of the fullers and the smaller the diameters of the rolls, the deeper, with any given pressure, will they sink into the bar operated on. The sharper the fullers and the smaller the rolls, the greater is the horizontal component available for extending the bar in the direction of its length, and the smaller the proportion of the power expended in spreading the bar laterally in a direction at right angles to its length. Small rolls are, therefore, found to require less power to draw out a bar, doing so more quickly and causing less spreading in the operation than do large rolls, but questions of strength prevent full advantage being taken of this fact.

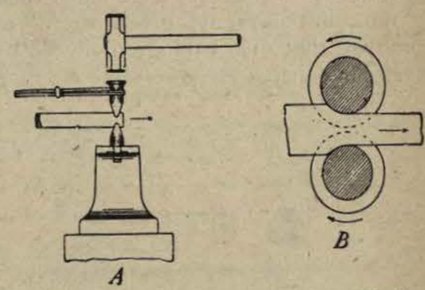


Fig. 368.—Drawing out Metal by Hand and by Rolls.

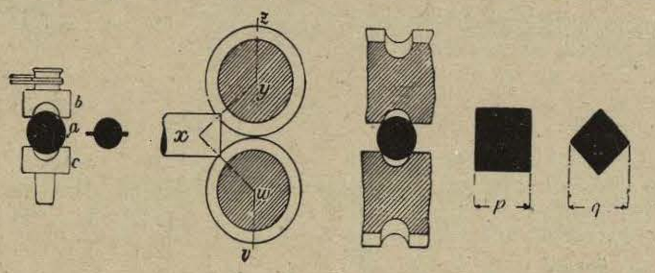
The extension of the bar is, moreover, assisted by the forward movement of the surfaces of the rolls, which drag forward the surface of the material in contact with them more rapidly than the interior.

The result of rolling is that the thickness of the piece is reduced and its length in the direction of its travel increased, with little increase in its width. When rolling plates, for instance, the piece is passed through the rolls a sufficient number of times to bring its length nearly up to the width required on completion. It is then turned at right angles, and one of the long edges of the partially-finished plate is presented to the rolls, and the rolling is continued in that direction until the plate is reduced to the thickness required, the spreading of the plate in a direction at right angles to that in which the piece travels being very small and depending on the thickness of the piece rather than on its width.

The form of rolls for producing plates is unaffected by this question of spreading, but when we come to rolling sections by means of grooved rolls this spreading action plays a very important part, and a thorough understanding of its nature and effects is essential for any one having to produce sections in grooved rolls.

Take the simplest possible case first, that of rolling a flat bar from an ingot. If the ingot were put in through a series of grooves cut in the body of a pair of rolls, the grooves continuously decreasing in depth and increasing in width to allow for the spread of the material, we should encounter the following difficulty. If too much allowance for the spread had been made by an undue width of groove, the bar would not fill the pass, and the edges, instead of being square and true, would be uneven and irregularly rounded, and though the central portion might be sound the edges of the bar would be ragged and insufficiently worked. If, on the other hand, an insufficient allowance had been made for the spreading, so that the material would more than fill the corners of the groove, the superfluous material would be squeezed out on each side between the collars of the rolls, forming thin "fins" on the sides of the bar exactly resembling the fins on fish, which would tend to increase at every pass and spoil the appearance of the finished bar, if they did not actually break the rolls. These "fins" are sometimes called "fens" by the workmen. As the amount of spread varies in every case with the natural hardness of the material and the temperature at the instant of rolling, it is found in actual practice to be generally impossible to hit off the precise allowance to be made for spread; and just as the smith occasionally turns upon its edge the bar he is drawing out in order to hammer it at right angles to the chief direction of working, so must the bar be turned on edge occasionally during rolling to avoid these defects and to ensure the sides being sound and true.

When round bars were required the question would be more complicated. It is not uncommonly imagined by those who have seen round bars rolled in a mill, but have not given careful attention to the precise form of the grooves, that such bars are produced by passing a piece of metal through a series of continually-decreasing circular holes cut in semi-circles in each roll,



A B C D E

Fig. 369.—Shaping a Bar in Cross-section by Hand and by Rolls.

forming a true circular opening on the centre line of the rolls when mounted one over the other, the circular openings being the exact size of the bar desired, and the requisite diameter of bar being obtained by stopping the operation when the bar has been passed through the opening of the size required. As a matter of fact, it would be quite impossible to produce round bars by such a method, the reason for this being perhaps best explained by comparing the action of the rolls with that of a pair of blacksmith's swages.

In fig. 369, A, if *a* is a circular bar which a smith desires to reduce to a smaller size, he cannot employ for that purpose a pair of swages with a semi-circular groove in each made to the radius of the bar he wishes to form, for if he used such swages, *b* and *c*, he would, by striking *b*, produce a bar of the section shown in B, with a fin on each side of it. If now we take a section through the semi-circular grooved rolls on the lines *v, w, x, y, z* (fig. 369, C), we get the same forming surface, for the grooved roll is merely the grooved plane of the swage bent round to form a grooved cylinder. The roll is really a die which impresses its form on the soft metal. But whereas the stamping action of a die in a falling stamp or a swage approaching the metal in a straight line is obvious to everyone, the similar action of the surface of the roll which approaches it in a curved path, is not so readily recognised as being essentially similar. Just as the swages reduce the section of the metal on which they operate only in that direction in which the pressure is applied, the plastic metal flowing away in a plane at right angles to the direction of pressure, so the rolls reduce the thickness of the piece put between them in the direction of a line joining the axes of the rolls, and spread it in a plane at right angles to that line.

It should be distinctly understood that in no possible case can any form of groove really reduce the overall width of the piece being rolled, measured in the direction parallel to the axes of the rolls, but on the contrary invariably increases this dimension by spreading the metal. When we hear of the "side pressure" exerted by any pass, its action in reality is essentially the reduction of such a section as D to E, fig. 369.

What has really occurred in the reduction of D to E, is that the inclined surfaces, in closing together vertically, have crushed the bar to a form determined by their own shapes; they have not caused the metal to flow laterally inwards towards the centre of the bar, but, on the contrary, any displacement which has not taken place in the direction of the travel of the bar through the rolls has been driven laterally outwards, not inwards. No form of groove can prevent the inevitable flow of the material at right angles to the direction of pressure; the width of the bar horizontally will always be appreciably greater after passing through the rolls than it was before, and to reduce the dimension, *p*, the bar must be turned on edge through an angle of 90°: *q* always is greater than *p*.

If the smith desires to bring down a bar of the section shown cross hatched and marked 1, in fig. 370, to the black section marked 3, by means

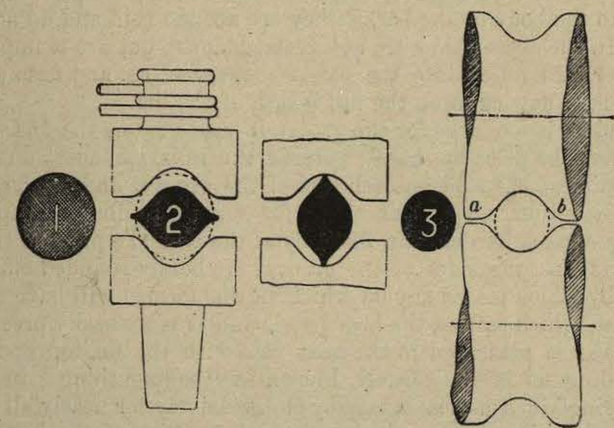


Fig. 370.—Method of avoiding the Formation of Fins.

of one pair of swages only, he uses a pair having the bottoms of the grooves formed to the circumference of the bar 3, which he wishes to produce, but their sides splayed out as shown, and so reduces the bar to the section 2. He then turns it on edge by revolving it on its axis through a quarter of a revolution, so that the sharp crests are top and bottom, and by again hammering the top swage he drives down the sharp crests, reducing the bar nearly to the section 3. The small amount of lateral bulging is removed by again turning the bar through an angle of 90° and rehammering. By repeating the operation a sufficient number of times a truly round bar can be produced. Note that the pressure is vertical, and that the metal has spread horizontally, so that section 2 is wider than the section 1 from which it has been produced, and to reduce its width it must be turned on edge.

The reduction of a bar in the rolls is effected in precisely the same way, the finishing groove being cut of the desired radius at the bottom, and splayed out at the sides to avoid the formation of thin fins. To get rid of the ridges formed on the sides, the bar is turned round through a quarter circle so that the ridges are top and bottom, and by passing the bar several times through the last groove which is not semi-circular, but is formed by a circular arc and two sloping sides, a truly round bar is formed.

Just as a smith would find, if he used swages to reduce his bar, that it would save time to employ in the earlier stages heavy blows on swages much splayed, and to finish it with light blows on another pair nearer the form of the finished bar required; so in the case of rolls it is usual first to employ grooves much splayed, or differing much in section from the preceding pair, so causing a heavy reduction in area at each squeeze, and to finish off in grooves more closely approximating to a half circle with less reduction in the final passes. It will not do to form even the last pass as a perfect half circle, for even if the bodies of the rolls were maintained in absolute contact, so as to form a true circular opening on the centre line of the rolls, the least surplus of material from the previous pass would cause a thin fin, which would break away the metal of the roll at the sharp edges on each side of the groove; the rolls are therefore kept a slight distance apart to permit of any trifling irregularity of this nature.

Fins.—Fins are not only unsightly but may be dangerous, causing a breakage of the rolls, and, when once formed, can only be got rid of by turning the bar through a quarter of a revolution, and passing it with the fins top and bottom through a pass in the rolls which will press them down smooth into the body of the bar, if they are not too thin and do not project too far. In such cases they are not pressed down, but are crumpled up or turned over and rolled into the bar, without welding, and form a "spill" or longitudinal flaw running the full length of the bar.

If the piece is too large for the groove it has to enter, the fins will begin to form when the piece has barely entered the rolls, spreading out between the flat bodies of the rolls on each side of the groove, and if the rolls are very close together, may break them, for such thin fins cool rapidly, and are therefore much harder than the body of the bar. To prevent the formation of thin fins, the sides of the grooves are boldly rounded off, as at *a b* (fig. 370), by which means any fin which may be formed will have an obtuse angled crest, which retains the heat better and is more easily pressed down when the bar is presented to the next pass with the fin top and bottom. This rounding off of the corners, known as "bellmouthing" in England and "tailoring" in America, is employed extensively for nearly all roughing passes, the finishing passes, which reduce the section of the bar to a less extent, having squarer edges.

The Size of the Rolls.—The diameter of the rolls used in mills for rolling steel varies from 6 inches to as much as 48 inches; rolls under 9 or 10 inches diameter are, however, very rarely used in steel works.

When a hot iron bar is struck with the flat face of a smith's sledge, the metal spreads out in all directions, but when it is struck instead with the narrow rounded pane of the hammer, the extension of the metal takes place almost entirely in the direction across the narrow face, comparatively little extension occurring in the direction of the axis of the face (see fig. 371). For the same reason large rolls cause more spreading in the piece rolled by them than do small rolls, when both effect the same reduction in thickness of the piece rolled.

Moreover, as with the same number of blows the bar is more rapidly drawn out by using the narrow pane than by using the flat face of the hammer, so small rolls require less power to produce a given result than do larger rolls, when both are employed on the same work.

There are usually, however, other considerations which have more influence in deciding the size of rolls than the amount of power consumed in the operation of rolling. The strength of an ungrooved roll to resist a

transverse stress is directly proportional to the cube of its diameter, and inversely proportional to the length of the body; therefore, pairs of rolls having the same length of body but a different diameter are able to safely exert a pressure, on a piece put between them, proportionate to the cube of their diameters; or if both pairs of rolls have lengths which are a similar multiple of their respective diameters, the strength of the two pairs is directly proportionate to the square of their diameters. When we come to groove the rolls, the strength of the rolls is reduced to that of the smallest part at the bottom of the grooves near the centre of the body, and if grooves of the *same* size and form are cut in both the large and small rolls, the smaller will evidently lose a much larger percentage of their strength than the larger pair, so that large rolls of this type are immensely stronger than small ones when employed to roll the same sections. There is accordingly always a great inducement for the sake of safety to use as large rolls as practicable, giving due consideration to the question of first cost.

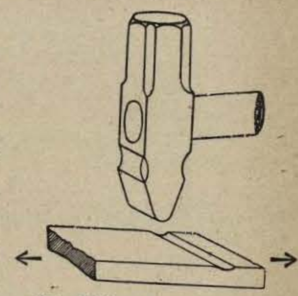


Fig. 371.—Producing considerable Longitudinal and slight Lateral Extension.

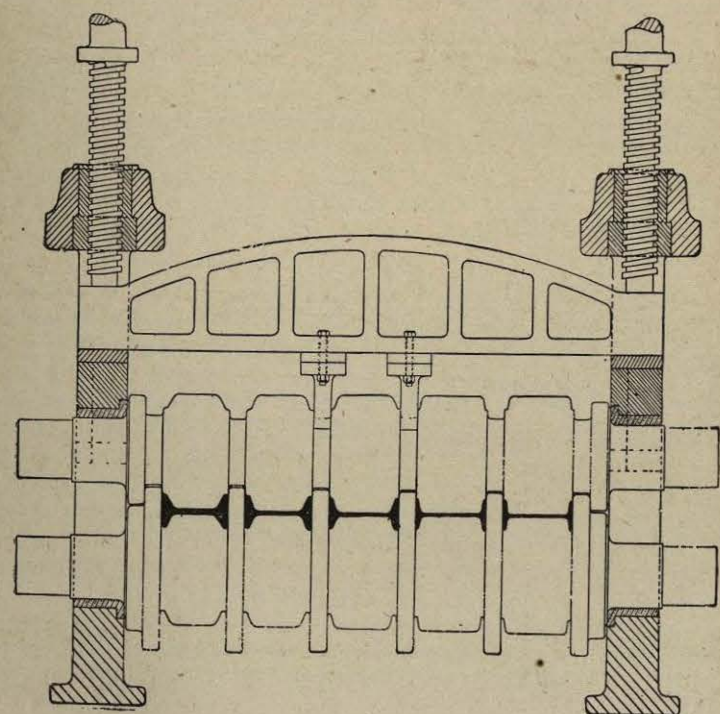


Fig. 372.—Stiffener for Strengthening a Deeply-cut Roll.

Occasionally sections must be rolled which are deeper than the mill is really suited to produce, necessitating the turning down of the barrel of the roll in some places to very small diameters. In such cases the upper roll, which is usually the one which must be most deeply cut into, may be supported at one or more points in its length by additional bearings, carried on a girder known as a stiffener, which is placed over the top chocks, the screws in the housings bearing on the ends of the girder (see fig. 372), and similar bearings may if necessary be laid on the bed plate to support the bottom roll. These, however, are not so satisfactory as the top ones, because the scale from the piece being rolled falls into these lower bearings.

Only when the rolls are large enough safely to withstand the pressure, can the maximum reduction be effected in every pass, and the number of passes be reduced to the minimum. Hence one or two stands of large rolls may turn out a greater quantity per hour of a given section, than two or three stands of smaller rolls, which yet require more men to work them.

There is a further consideration which helps to settle the minimum size of the roll apart from the question of strength, and that is the relative effect of large and small rolls on the piece they are intended to work upon. Roughing rolls will generally, under favourable conditions, grip the ingot presented to them without much roughing if the points of contact with the body of the rolls lie within angles of 30° from the vertical line joining the centres of the rolls (see fig. 373), and it is found that with rolls whose centres are fixed the thickness of piece which the rolls can deal with satisfactorily does not exceed one-half the distance that the centres of the rolls are apart, which in a box pass will effect a reduction of area of about 13 per cent. in the first pass. If a reduction of 25 per cent. is desired in the first pass, rolls having a diameter at least one-fourth greater must be employed. If the pass is of such a shape that the piece when put in is wedged in a taper groove, the thickness of piece may be somewhat increased. If thicker pieces are to be put in the mill, the rolls must be heavily "roughed" to make them bite, and even then the limit of capacity of the mill is nearly reached. The roughing is effected by cutting a series of indentations across the grooves with a round-nosed chisel, thus practically forming a series of small teeth on the surface of the rolls, and converting them into a species of cogged wheels, the teeth of which dig into and so firmly grip the piece to be rolled that they drag it bodily into the groove. Obviously such roughing is inadmissible in the finishing passes, as the surface of the bar would be spoiled by the traces of these indentations.

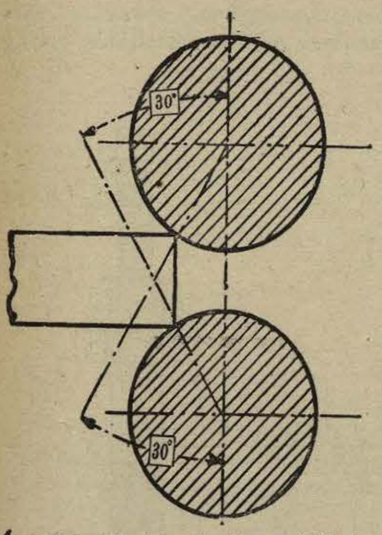


Fig. 373.—Limiting Angle at which the Rolls will Bite.

Seeing that the surface speed of the roll decreases the nearer we get towards the centre of the roll, the different parts of grooved rolls in contact with the piece being rolled travel at different speeds on different parts of the bar, producing a scraping action, the parts of the rolls travelling fastest tending to tear the portions of the bar in contact with them from the remainder of the section. If the steel is high in Sulphur, or is "hot short" from any other cause, this tearing occurs, and the pieces leave the rolls with deep cracks running across the bar and extending inwards for a considerable depth, or the edges are ragged and cracked, this trouble occurring more often the smaller the size of mill employed to produce a given section.

In bars of ⊥, ⊃, ✕, and I section one or more wings of the section must point directly inwards towards the axis of the roll, and must be tapered so as to allow them to clear out of the groove. If this part of the groove is shallow as compared with the diameter of the roll, so that the speeds at top and bottom of the groove do not vary greatly, a taper of 3° may suffice, but if the depth of the section is great as compared with the diameter of the roll, a taper of 5° to 7° must be allowed, or the material will be torn.

As previously explained, small rolls require less power to produce a given result than do large rolls, but the larger the roll the larger become the necks and wobblers, and the larger are all the surfaces over which the pressure due to rolling is spread. This reduction in the pressure per unit of surface much reduces wear and tear, which is generally a matter of much more importance than the use of a little more power.

The rolls are easily broken if too small for the work they are required to do, the delay and cost of replacing them causing serious increase in the running expenses of the works. On the other hand, large rolls mean heavy machinery throughout the mill, the first cost of which increases at least as much as the square of the diameter of the roll. To balance these conflicting considerations and to determine what is the best size of mill to employ for any particular purpose necessitates a knowledge of the material to be worked, the sections mostly required, and the output desired, and even then there is room still left for differences of opinion on the point.

The Speed of the Rolls.—The rolls must be run fast enough to finish the material while so hot as to be comparatively soft, or the power exerted and the wear and tear of the machinery will be greatly increased, while the desire to obtain larger outputs acts as a continual incentive to increase the speed.

There are, however, many considerations operating in the contrary direction. The power required to induce a flow in any solid is much reduced by extending the time during which the pressure can act, and there is no doubt that the resistance which material offers to deformation by the rolls rises considerably faster than the increase in speed of rolling, and adds materially to the pressure which forces the rolls apart. Further, the force of the blow caused by the piece entering the mill is proportional to the square of the speed at which the surfaces of the rolls are travelling, so that rolls strong enough to work safely at one speed may be readily broken by apparently moderate increases in their speeds of revolution.

In a hand-served mill the speed must not be too great to allow the workmen to catch the bar as it leaves the rolls, 600 feet per minute being usually considered the limit in this respect, though the author knows mills rolling short and light pieces which travel through the rolls at 800 feet per minute, and are handled with tongs in the ordinary way. At higher speeds than this, in the case of light material, and considerably less for even moderate weights, some mechanical means of handling becomes a necessity.

In continuous mills, where the piece once entered runs straight through the whole series of rolls until it emerges from the other end of the mill finished, the output is almost exactly determined by the rate of revolution of the finishing rolls, for the bar enters the first pair of rolls so deliberately that one piece can be fed in so close behind the preceding one as almost to touch it, whereby a practically continuous stream of finished material can be ejected from the finishing rolls; the same condition holds to a lesser extent in the case of a looping mill.

In ordinary mills, however, where the piece must pass to and fro to make several passes between the same rolls, so large a proportion of the time is consumed in handling the piece between one pass and the next, particularly when rolling short pieces, that the speed at which the rolls revolve plays a subsidiary part in the output. If the pace at which the piece travels through the rolls is measured, few pull-over mills will at their best be found to be turning out more than a third of the weight which the mill could produce, were the passes in the rolls always filled. In such cases, increasing the speed of the rolls adds largely to the risk of breakages, and does not give an increase in output at all proportionate to the increased speed. Cases are even known where less output has been got when the rolls were driven faster, because when more time had been afforded in which the material could flow, heavier reductions could be effected in each pass, and therefore fewer passes were necessary. Considerable experience is necessary to settle what is the best speed in each case, but the greater the length of the piece to be rolled, the greater is the advantage obtainable by increasing the speed.

Cogging mills dealing with short pieces make 30 to 50 revolutions per minute, plate mills 30 to 60 revolutions, small bar mills with rolls 12 to 9 inches diameter 150 to 250 revolutions, and wire-rod mills, which roll enormous lengths, and must finish the metal while it is hot, in rolls $10\frac{1}{2}$ to 8 inches diameter, run at speeds of 500 or 600, occasionally up to 1,200. At such speeds the material is not handled by the men, but is guided into the next pass by some mechanical contrivance, and is wound up on a reel as it leaves the last pass.

The Draught.—The difference in area between one pass and the next is termed "the draught." The greater the draught the more rapidly, of course, is the reduction performed, and the draught is consequently always made as heavy as it is possible to make it.

By examining the sections Nos. 1 and 3 in fig. 370, it will be seen that 3 is about one-half the area of section 1, and that the bar could not be reduced from 1 to 3 in less than two squeezes of the dies. Similarly with grooved rolls, except when rolling flats, the form of the grooves imposes limitations on the amount of reduction which can be effected in a single pass.

It is rarely that the piece can be reduced in sectional area more than 30 per cent. in one pass, and when nearing the finished shape 25 per cent. is about the maximum for sections, as beyond this bad fins are apt to form. The average practice in roughing down, which is usually done at a fairly high heat, is 20 to 22 per cent., falling to 15 per cent. or less in the finishing passes, while in the last pass of all the reduction is often very small indeed. This pass being merely intended to give an exact finish to gauge, it is important it should have as little to do as possible, so that frequent turning up of the rolls may be avoided, the wear on the other grooves being a matter of less importance than that of the finishing pass, where extreme accuracy is essential.

The heaviest draughts used are those in guide mills for rolling rounds, where draughts as high as 35 and 40 per cent. are common, running upon rare occasions to 45 and even 50 per cent. For heavy draughts of this kind, the sections which succeed each other are totally different, ovals passing into squares or squares into ovals, though for some small flats reductions of 50 per cent. are occasionally employed.

Reduction necessary for Steel.—The bar must be produced from an ingot of such size as to ensure sufficient "work" being put on the material to produce the requisite internal compression of the raw steel. No very precise rule can be laid down on this head, but, speaking generally, it may be said that a bar should never be rolled from an ingot which is less than

ten times its weight per lineal foot, while 20 to 30 times heavier is the proportion to be preferred. Generally the influence of working is more marked in the case of inferior material than in that of high quality. If possible, the work should not be put on the material so that the pressure is always in the same direction. Plates rolled from cast slabs which are not "edged"—that is, rolled with one edge upwards—are not so good as those rolled from ingots which have had first one and then another side upwards when being cogged. To give the requisite density to any ingot during cogging, it should, if possible, be given a quarter turn after every pass before rolling is continued in one plane only. Where fine sharp edges are required, or one portion of the section must have exceptional finish, the forms of the grooves in the rolls are cut so as to give a thorough kneading to that part which may be flattened down and forced out again several times before the finishing pass is reached.

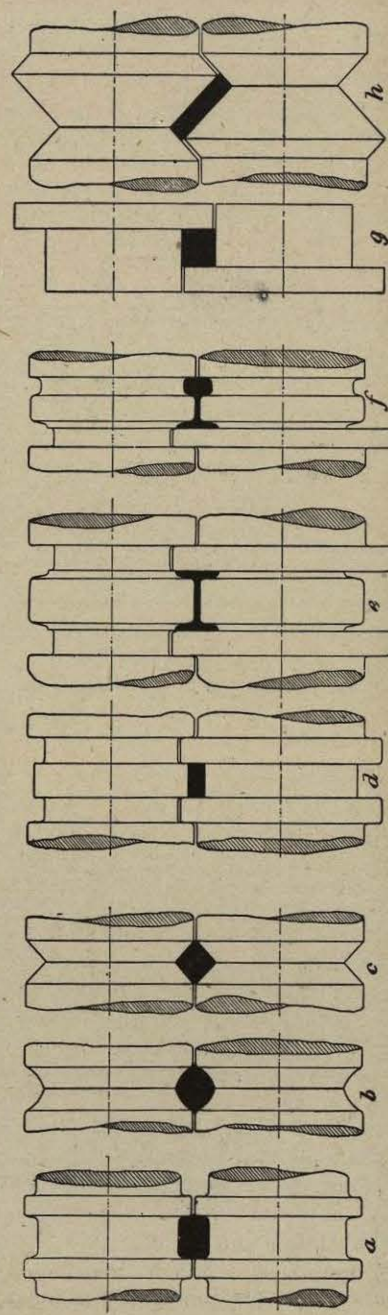


Fig. 374.—Various Forms of Grooves in Rolls.

Form of the Grooves.—The grooves in rolls are of two kinds, known as open and closed passes. In fig. 374, *a* is known as a box pass, *b* as a Gothic, and *c* as a diamond pass. These are the most common forms of open passes, so-called because the bodies of the rolls do not touch each other, and the pass not being closed in all round, metal can be squeezed out of the openings laterally. A closed pass consists of a groove cut in the lower roll, on each side of which is a collar of a diameter greater than the body of the roll, forming together the boundaries of the section on bottom and sides, the upper roll being recessed to admit the collars on the lower. The bar entering a closed pass must be appreciably narrower than the pass to allow for the spread. The upper boundary of the section is formed by that portion of the upper roll which projects downwards between the collars on the lower, and is known as the "former." This is not called a collar, because it does not project beyond the body of the roll as does a true collar. Sketches *d* and *e* show