CHAPTER XIV.—MEASURING MACHINES, TOOLS, AND DEVICES.

MEASUREMENTS are primarily derived in Great Britain and her colonies, and in the United States, from the English Imperial or standard yard. This yard is marked upon a bar of "Bailey's metal" (composed of 16 parts copper, 2½ parts tin, and 1 part zinc), an inch square and 38 inches long. One inch from each end is drilled a hole about three-quarters through the whole depth of the bar, into which are fitted gold plugs, whose upper end faces are level with the axis of the bar. Across each plug is marked a fine line, and the distance between these lines was finally made the standard English yard by an Act of Parliament passed in 1855. A copy of this bar is in the possession of the United States Government at Washington, and all the standard measuring tools for feet, inches, &c., are derived from subdivisions of this bar.

The standard of measurement in France and her colonies, Italy, Germany, Portugal, British India, Mexico, Roumania, Greece, Brazil, Peru, New Granada, Uruguay, Chili, Venezuela, and the Argentine Confederation, is the French mètre, which is also partially the standard in Austria, Bavaria, Wurtemberg, Baden, Hesse, Denmark, Turkey, and Switzerland. It consists of a platinum bar, called the "mètre des archives," whose end faces are parallel, and the length of this bar is the standard mètre. But as measuring from the ends of this bar would (from the wear) impair its accuracy, a second bar, composed of platinum and iridium, has been made from the "mètre des archives." This second bar has ruled upon it two lines whose distance apart corresponds to the length of the "mètre des archives," and from the distance between these lines the subdivisions of the mètre have been obtained.

As all metals expand or contract under variations of temperature, it is obvious that these standards of length can only be accurate when at some given temperature: thus the English bar gives a standard yard when it is at a temperature of 62° Fahr., while the French standard bar is standard at a temperature of 32° Fahr., which corresponds to 0 in the centigrade thermometer. But if a bar is copied from a standard, and is found to be too short, it is obvious that if its amount of expansion under an increase of temperature be accurately known, it will be an accurate standard at some higher temperature, or in other words, at a temperature sufficiently higher to cause it to expand enough to compensate for its error, and no more.

As all bars of metal deflect from their own weight, it is obvious that the bar must be supported at the same points at which it rested when the lines were marked, and it has been determined by Sir George Airy, that the best position for the points of support for any bar may be obtained as follows: Multiply the number of the points of support by itself (or, as it it is commonly called, "square it"), and from the sum so obtained subtract 1. Then subtract the square root of the remainder, which gives a sum that divided into the length of the bar will represent the distance apart for the points of support. It will be obvious that the points of support must be at an equal distance from each end of the bar.

Measurement may be compared in two ways, by sight and by the sense of feeling. Measurement by sight is made by comparing the coincidence of lines, and is called "line measurement." Measurement by feeling or touch is called "end measurement," because the measurement is taken at the ends. If, for example, we measure the diameter of a cylindrical bar, it is an end measurement, because the measurement is in a line at a right angle to the axis of the bar, and the points of touch on each side of the bar are the ends of the measurement, which is supposed to have no width.

In measuring by sight we may, for rude measurements, trust to the unaided eye, as in using the common foot rule, but for such minute comparisons as are necessary in subdividing or transferring a standard, we may call in the aid of the microscope.

The standard gauges, &c., in use in the United States have been obtained from Sir Joseph Whitworth, or duplicated from those made by him with the aid of measuring and comparing machines. It has been found, however, that different sets of these gauges did not measure alike, the variations being thus given by Mr. Stetson, superintendent of the Morse Twist Drill and Machine Co.

At the time the Government established the use of the standard system of screw threads in the navy yards, ten sets of gauges were ordered from a manufacturer. His firm procured a duplicate set of these and took them to the navy yard in Boston and found that they were practically interchangeable. He also took them to the Brooklyn Yard Navy. The following tabular statement shows the difference between them :—

Size.	Navy Yard Male Gauge.	Morse Twist Drill and Machine Co. Male Gauge.	Morse Twist Drill and Machine Co. Female Gauge.
$\frac{1}{4}$	0·25	0·25	Interchanged
$\frac{5}{16}$	·313	·313	"
$\frac{3}{8}$	·375	·3759	
$\frac{7}{16}$	·437	·437	Interchanged
$\frac{1}{2}$	·505	·505	"
$\frac{9}{16}$	·562	·564 (−)	"
$\frac{5}{8}$	Damaged	·626	"
$\frac{3}{4}$	·7505	·751	"
$\frac{7}{8}$	·876	·8758	"
1	1·00075	1·00075	"
1$\frac{1}{8}$	1·125 (+)	1·125 (−)	Navy Yard (+) M. T. D. & M. Co. (−)
1$\frac{1}{4}$	1·25	1·25	Interchanged
1$\frac{3}{8}$	1·375	1·375	"
1$\frac{1}{2}$	1·5	1·5 (−)	(−)
1$\frac{5}{8}$	1·6245	1·624	(−)
1$\frac{3}{4}$	1·749	1·749	Interchanged
1$\frac{7}{8}$	1·8745	1·874	(−)
2	1·999	1·999	

The sign (−) means that the piece is small, but not enough to measure.
The sign (+) means that the piece is large, but not enough to measure.

The advantages to be derived from having universally accepted standard subdivisions of the yard into inches and parts of an inch are as follows :—

When a number of pieces of work of the same shape and size are to be made to fit together, then, if their exact size is not known and there is no gauge or test piece to fit them to, each piece must be fitted by trial and correction to its place, with the probability that no two pieces will be of exactly the same size. As a result, each piece in a machine would have to be fitted to its place on that particular machine, hence each machine is made individually.

Furthermore, if another lot of machines are afterwards to be made, the work involved in fitting the parts together in the first lot of machines affords no guide or aid in fitting up the second lot. But suppose the measurements of all the parts of the first lot are known to within the one ten-thousandth part of an inch, which is sufficiently accurate for practical purposes, then the parts may be made to measurement, each part being made in quantities and kept together throughout the whole process of manufacture, so that when all the parts are finished they may go to the assembling or erecting room, and one piece of each part may be taken indiscriminately from each lot, and put together to make a complete machine. By this means the manufacture of the machine may be greatly simplified and cheapened, and the fit of any part may be known from its size, while at the same time a new part may be made at any time without reference to the machine or the part to which it is to fit.

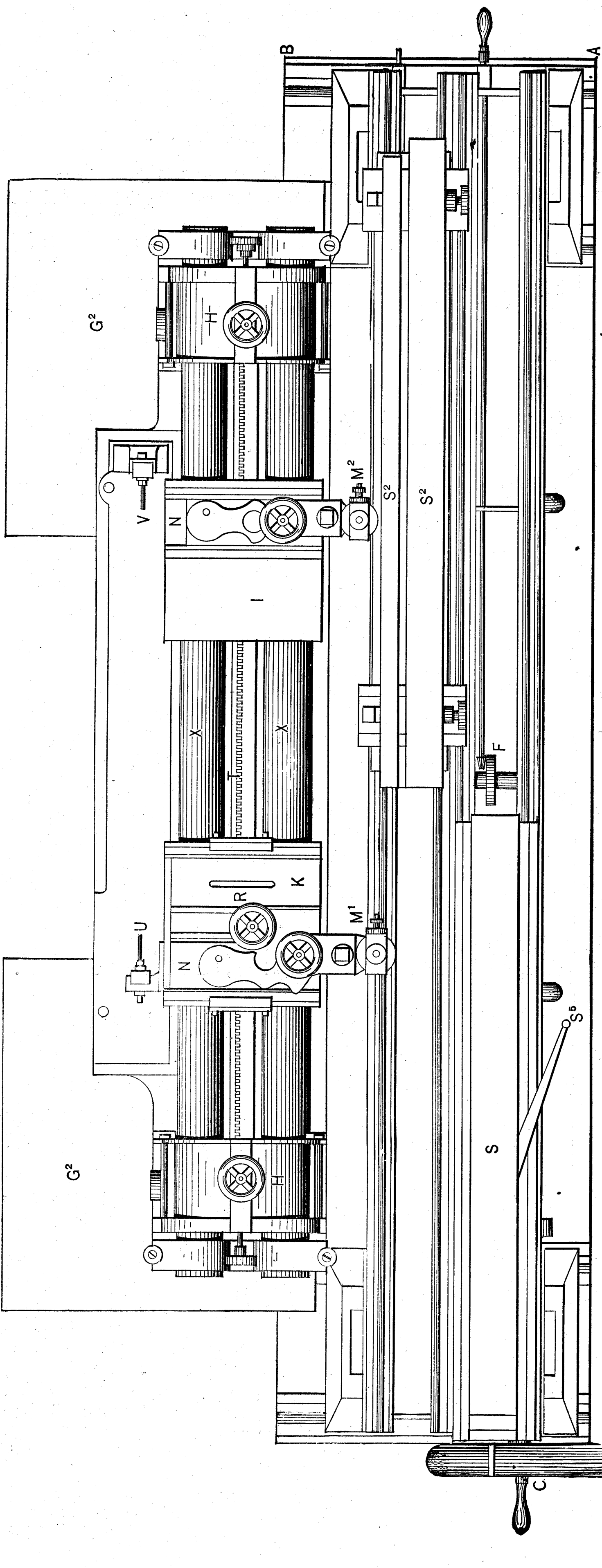

Fig. 1350.

Again, work made to standard size in one shop will fit to that made to standard size in another, providing the standard gauges agree.

The Pratt and Whitney Company, of Hartford, Connecticut, in union with Professor Rogers, of Cambridge University, in Massachusetts, determined to inspect the Imperial British yard, to obtain a copy of it, and to make a machine that would subdivide this copy into feet and inches, as well as transfer the line measurements employed in the subdivisions into end measures for use in the workshops, the degree of accuracy being greater than is necessary in making the most refined mechanism, made under the interchangeable or standard gauge system. The machine made under these auspices is the Rogers-Bond Universal Comparator; Mr. Bond having been engaged in conjunction with Professor Rogers in its construction.

The machine consists of two cylindrical guides, upon which are mounted two heads, carrying microscopes which may be reversed in the heads, so as to be used at the front of the machine for line measurements and on the back for end measurements.

Fig. 1348 is a front, and Fig. 1349 a rear view of the machine, whose details of construction are more clearly shown in the enlarged views, Fig. 1350 and 1352.

Fig. 1350 is a top view, and Fig. 1352 a front view, the upper part of the machine being lifted up for clearness of illustration. X, X, are the cylindrical guides, upon which are the carriages I, K, for the microscopes. The construction of these carriages is more fully seen in Fig. 1351, which represents carriage K. It is provided with a hand-wheel R, operating a pinion in a rack (shown at T in the plan view figure of the machine) and affording means to traverse the carriage along the cylindrical guides. The microscope may be adjusted virtually by the screw M^4. The base upon which the microscope stands is adjustable upon a plate N, by means of the two slots and binding screws shown, and the plate N fits in a slideway running across the carriage. U is one of the stops used in making end measurements, the other being fixed upon the frame of the machine at V in the plan view, Fig. 1350. The micrometric arrangement for the microscope is shown more clearly in Fig. 1353. The screw B holds the box in position, the edge of the circular base on which it sits being graduated, so that the position of M may be easily read. In the frame M is a piece of glass having ruled upon it the crossed lines, or in place of this a frame may be used, having in it crossed spider web lines. These lines are so arranged as to be exactly in focus of the upper glass of the microscope, this adjustment being made by means of the screw S. The lines upon the bar are in the focus of the lower glass; hence, both sets of lines can be seen

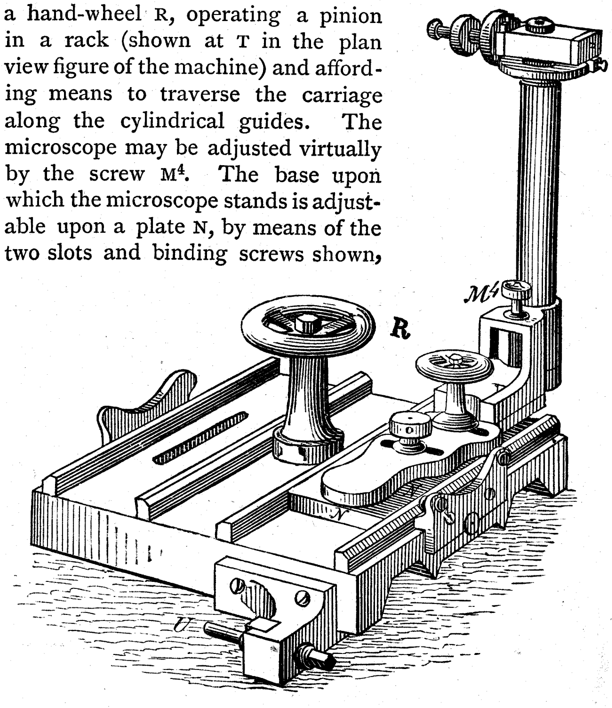

Fig. 1351.

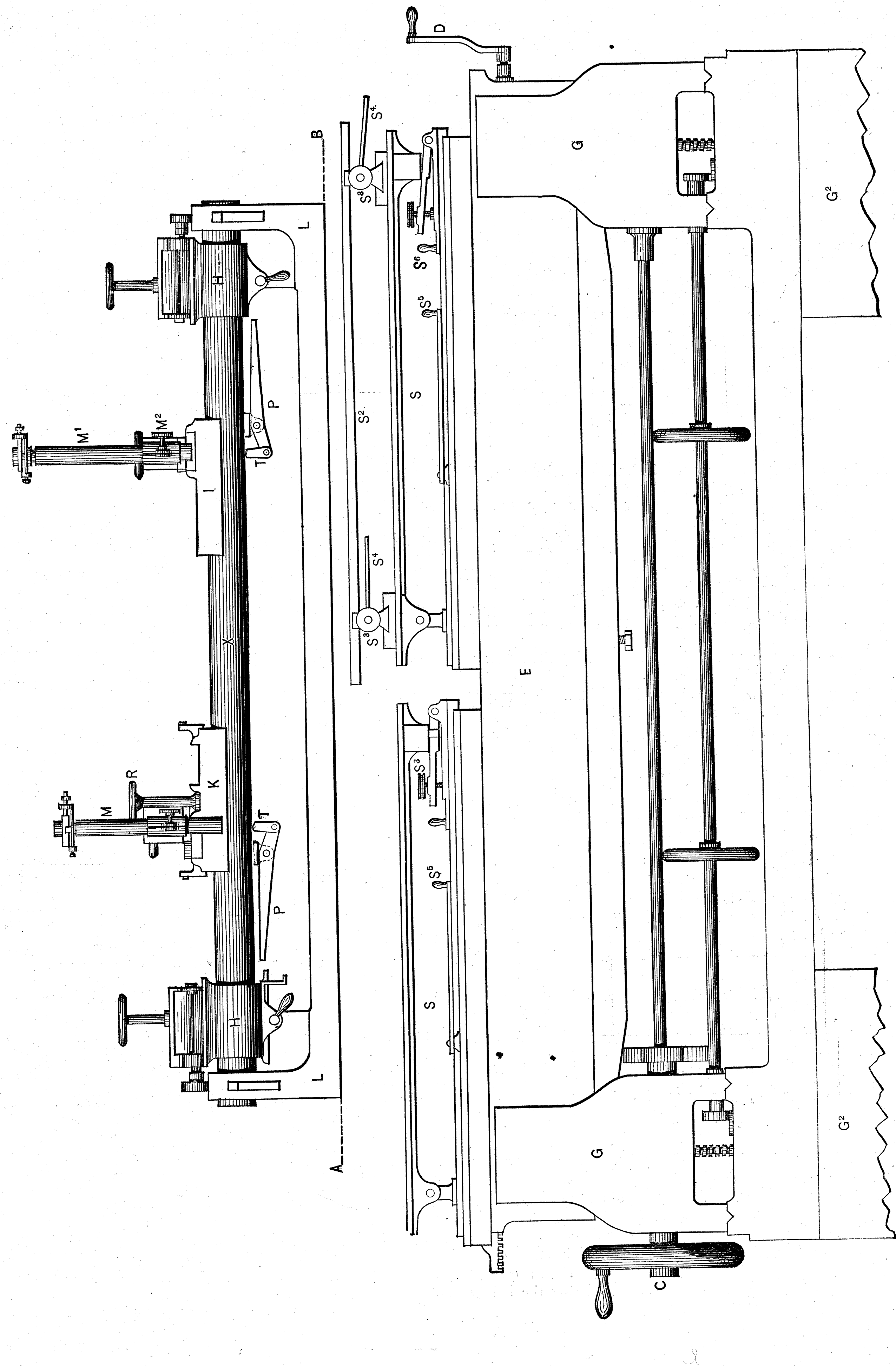

Fig. 1352.

simultaneously, and by suitable adjustment of the microscope can be brought to coincide.

Beneath the cylindrical guides, and supported by the rack T that runs between and beneath them, are the levers P, in Fig. 1352, upon which weights may be placed to take up the flexure or sag of the cylindrical guides.

In Fig. 1532, H, H, are heads that may be fixed to the cylindrical guides at any required point, and contain metallic stops, against which corresponding stops on the microscope carriages may abut, to limit and determine the amount to which these carriages may be moved along the cylindrical guides.

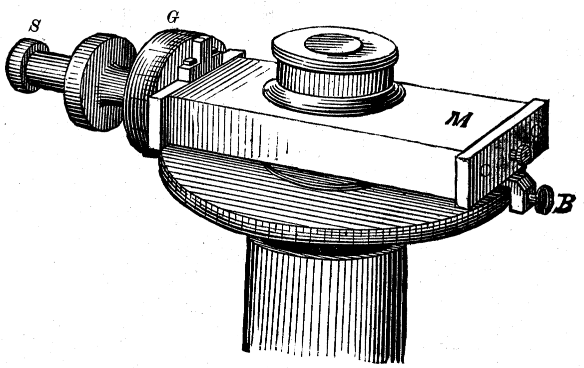

Fig. 1353.

The pressure of contact between the carriage and the fixed stops is found to be sufficiently uniform or constant if the carriage is brought up to the stops (by means of the hand-wheel R, Fig. 1351) several times, and a microscope reading taken for each time of contact. But this pressure of contact may be made uniform or constant for all readings by means of an electric current applied to the carriage through the metallic stops on heads H, H, and those on the carriage.

We have now to describe the devices for supporting the work and adjusting it beneath the microscopes.

Referring, then, to Fig. 1352, E is a bed or frame that may be raised or lowered by means of the hand-wheel C, so as to bring the plate S (on which rests the bar whose line measure is to be compared) within range of the microscopes. The upper face of E is provided with raised V slideways, which are more clearly seen in the end view of this part of the machine shown in Fig. 1354. Upon these raised Vs are the devices for adjusting the height of the eccentric rollers S^3, upon which the bars to be tested are laid, S^2 representing one of these bars. To adjust the bars in focus under the microscope, these eccentric rollers are revolved by means of levers S^4. At S^5 is a device for giving to the table a slight degree of longitudinal movement in the base plate that rests upon the raised Vs; on the upper face of E and at S^6 is a mechanism for adjusting the height of that end of the plate S. The base plate may be moved along the raised Vs of E by the hand-wheel D.

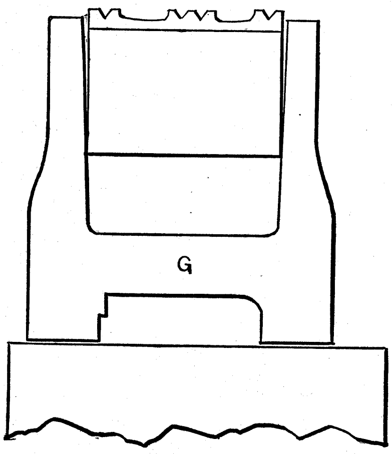

Fig. 1354.

To test whether the cylindrical guides are deflected by their own weight or are level, a trough of mercury may be set upon the eccentric rollers S^3, Fig. 1352, and the fine particles of dust on its surface may be brought into focus in the microscope, whose carriage may then be traversed to various positions along the cylindrical guides, and if these dust particles remain in focus it is proof that the guides are level with the mercury surface.

The methods of using the machine are as follows: The standard bar has marked upon its upper face (which is made as true as possible and highly polished) a line B (Fig. 1355), which is called the horizontal line, and is necessary in order to set the bar parallel to the cylindrical guides of the machine. The lines A, A, are those defining the measurement as a yard, a foot, or whatever the case may be, and these are called the vertical lines or lines of measurement.

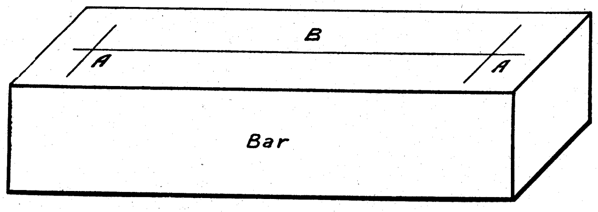

Fig. 1355.

Now, suppose we require to test a bar with the standard and the lines on its face are marked to correspond to those on the standard.

The first operation will be to set the standard bar on the eccentric rollers S^3 in Fig. 1352, and it and the microscopes are so adjusted that the spider web lines in the microscope exactly intersect the lines A and B on the standard, when the microscope carriage abuts against the heads H, Fig. 1352. The standard bar is then replaced by the bar to be tested, which is adjusted without altering the microscope adjustment or the heads H, and if the spider web lines in the microscope exactly coincide with and intersect the lines A and B, the copy corresponds to the standard. But if they do not coincide, then the amount of error may be found by the micrometer wheel G, Fig. 1353.

In this test the carriage is moved up against the stops H several times, and several readings or tests are made, so as to see that the force of the contact of the carriage against the stops H is uniform at each test, and if any variation is found, the average of a number of readings is taken. It is found, however, that with practice the carriage may be moved against the head H by means of the handwheel with such an equal degree of force that an error of not more than one fifty-thousandth of an inch is induced. It is found, however, that if too much time is occupied in this test, the heat of the operator's body will affect the temperature of the bars, and therefore expand them and vitiate the comparison. But in this connection it may be noted that if a bar is at a temperature of 40°, and is placed in an ice bath, it does not show any contraction in less than one minute, and that when it does so, the contraction is irregular, taking place in sudden movements or impulses.

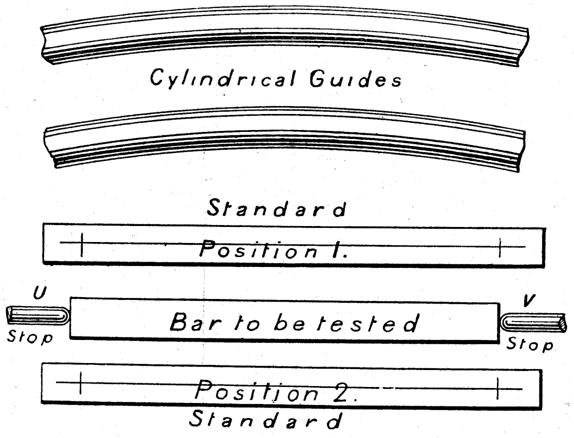

Fig. 1356.

Professor Rogers' methods of testing end measures are as follows: To compare a line with an end measure, a standard bar is set upon the machine, its horizontal and vertical lines being adjusted true to the cylindrical guides by the means already described, and the microscope carriage is so adjusted that the spider web lines of the microscope coincide with the horizontal and vertical lines marked on the standard, while at the same time the stop (U, Fig. 1350) on the carriage K has contact with the fixed stop (V, Fig. 1350.) Carriage K is then moved along the cylindrical guides so as to admit the bar (whose end measure is to be compared with the lines on the standard) between the two stops, and if, with the bar touched by both stops U and V, the microscope spider lines intersect the vertical and horizontal line on the standard bar, then the end measure corresponds to the line measure ; whereas, if such is not the case, the amount of error may be found by noting how much movement of the micrometer wheel of the microscope is required to cause the lines to intersect.

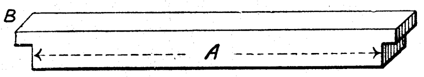

Fig. 1357.

It is obvious that in this test, if the cylindrical guides had a horizontal curvature, the test would not be perfect.

THE HORIZONTAL CURVATURE.—The copy or bar to be tested may be set between the stops, and the standard bar may be placed on one side of it, as in Fig. 1356, and the test be made as already described. It is then set the same distance from the bar to be tested, but on the other side of it, as in figure, and again adjusted for position and tested, and if the readings on the standard bar are the same in both tests, it is proof that the measurements are correct.

Suppose, for example, that the cylindrical guides were curved as in Fig. 1356, it is evident that the vertical lines would appear closer together on the standard bar when in the first position than when in the second position.

In the Rogers machine the amount of error due to curvature in the cylindrical guides in this direction is found to be about $\frac{1}{5000}$ part of an inch in 39 inches, corresponding to a radius of curvature of five miles.

Another method of testing an end with a line measure is as follows : The bar to be measured is shaped as in Fig. 1357, the end measurement being taken at A, and the projection B at each end serving to preserve the end surfaces A from damage. The standard bar is then set upon the machine and its horizontal and vertical lines adjusted in position as before described. In connection with this adjustment, however, the bar to be tested is set as in Fig. 1358; C being a block of metal (having marked centrally upon it horizontal and vertical lines), placed between the bar and the fixed stop U, its vertical line being in line with the vertical line on the standard. This adjustment being made, the block C is removed and placed at the other end of the bar, as shown in Fig. 1359, when, if the end measure on the bar corresponds with the line measure on the standard, the vertical line at the other end of the standard will correspond with the vertical line on block C.

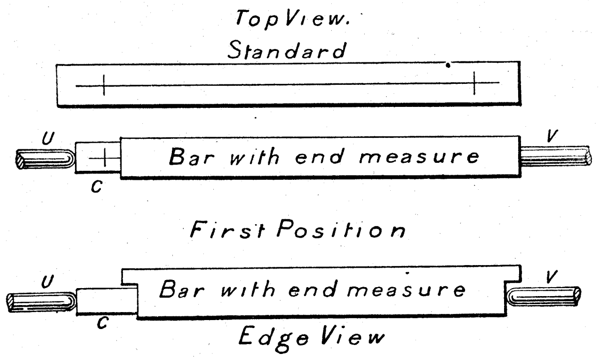

Fig. 1358.

To prove that the vertical line is exactly equidistant from each end of the block C, all that is necessary is to place it between the bar and the fixed stop U, Fig. 1350, adjust the microscope to it and then turn it end for end, and if its vertical line is still in line with the spider web of the microscope it is proof that it is central on the block, while if it is not central the necessary correction may be made. It is obvious that it is no matter what the length of C may be so long as its vertical line is central in its length.

In this process the coincidence of the vertical lines on the standard and on the piece C are employed to test the end measure on the bar with the line measure on the standard.

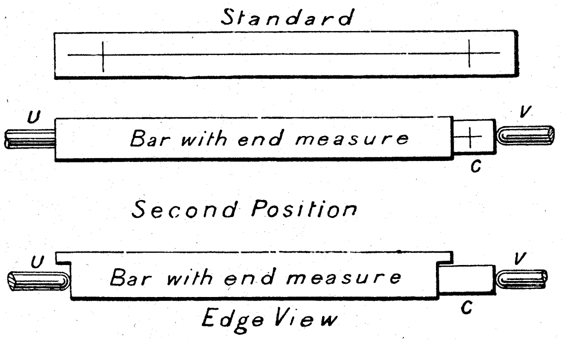

Fig. 1359.

Figs. 1360 and 1361 represent the Whitworth Millionth Measuring Machine, in which the measurement is taken by the readings of an index wheel, and the contact is determined from the sense of touch and the force of gravity.

It is obvious that in measuring very minute fractions of an inch one of the main difficulties that arise is that the pressure of contact between the measuring machine and the surfaces measured must be maintained constant in degree, because any difference in this pressure vitiates the accuracy of the measurement. This pressure should also be as small as is consistent with the assurance that contact actually exists, otherwise the parts will spring, and this would again impair the accuracy of the measurement.

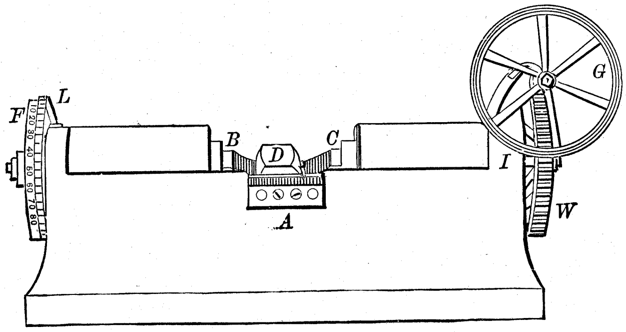

Fig. 1360.—General View.

If the degree of contact is regulated by devices connected with the moving mechanism of the machine it is indirect, and may vary from causes acting upon that mechanism. But if it is regulated between the work and the moving piece that measures it, nothing remains but to devise some means of making its degree or amount constant for all measurements ; so that if a duplicate requires to be compared with a standard, the latter may first be measured and the duplicate be afterwards measured for comparison.

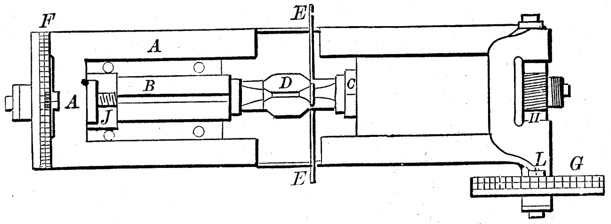

Fig. 1361 —Plan.

All that is essential is that the two be touched with an equal degree of contact, and the most ingenious and delicate method yet devised to accomplish this result is that in the Whitworth machine, whose construction is as follows :—

In a box frame A, is provided a slide-way for two square bars, B, C, which are operated by micrometer screws, one of which is shown at J (the cap over B being removed to expose B and J to view). The bars B, C, are made truly square, and each side a true plane. The groove or slide-way in which they traverse is made with its two sides true planes at a right angle to each other; so that the bars in approaching or receding from each other move with their axes in a straight line. At the two ends of the frame the micrometer screws are afforded journal bearings. The ends of the bars B, C, are true planes at a right angle to the axes of B, C. Bar B is operated as follows: Its operating screw J has a thread of $\frac{1}{20}$ inch pitch; or in other words, there are twenty threads in an inch of its length. It is rotated by the hand-wheel F, whose rim-face is graduated by 250 equidistant lines of division. Moving F through a distance equal to that between, or from centre to centre of its lines of division, moves B through a distance equal to one five-thousandth part of an inch.

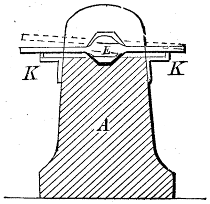

Fig. 1362.

The screw in head I for operating bar C also has a pitch of $\frac{1}{20}$ inch (or twenty threads in an inch of its length), and is driven by a worm-wheel W, having 200 teeth. This worm-wheel W is driven by a worm or tangent-screw H, having upon its stem a graduated wheel G, having 250 equidistant lines marked upon the face of its rim.

Suppose, then, that wheel G be moved through a distance equal to that between its lines of division, that is $\frac{1}{250}$th of a rotation, then the worm H will move through $\frac{1}{250}$th of a rotation, and the worm-wheel on the micrometer screw will be rotated $\frac{1}{250}$th part of its pitch expressed in inches; because a full rotation of G would move the worm one rotation, and thus would move the worm-wheel on the screw one tooth only, whereas it has 200 teeth in its circumference; hence it is obvious that moving graduated wheel G, through a distance equal to one of its rim divisions will move the bar C the one-millionth of an inch; because:

$$\underset{\frac{1}{20}\text{ inch}}{\text{Pitch of thread}} \times \underset{\frac{1}{200}}{\text{Rotation of worm-wheel}} \times \underset{\frac{1}{250}}{\text{Rotation of graduated wheel}} = \frac{1}{1000000}$$

Fixed pointers, as K, Fig. 1362, enable the amount of movement or rotation of the respective wheels F, G, to be read.

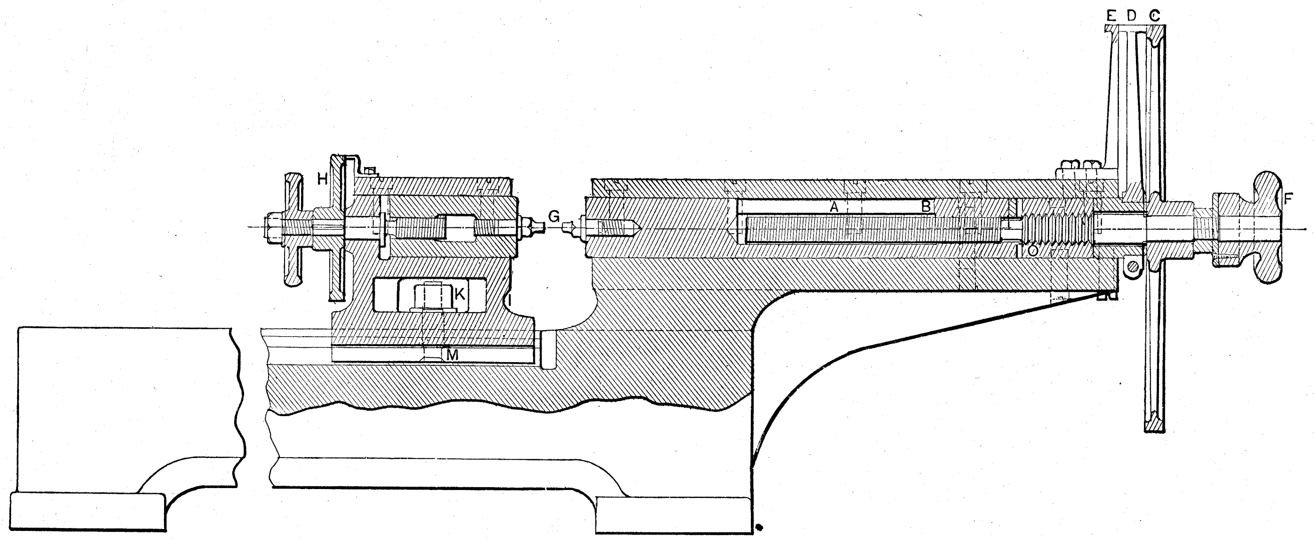

Fig. 1363.

A peculiarly valuable feature of this machine is the means by which it enables an equal pressure of contact to be had upon the standards, and the duplicates to be tested therewith. This feature is of great importance where fine and accurate measurements are to be taken. The means of accomplishing this end are as follows :—

In the figures, D is a piece in position to be measured, and between it and the bar C is a feeler consisting of a small flat strip of steel, E E, having parallel sides, which are true planes.

When the pressure of contact upon this piece E E is such that if one end be supported independently the other will just be supported by friction, and yet may be easily moved between D and C by a touch of the finger, the adjustment is complete. At the sides of the frame A are two small brackets, shown at K, in the end view, Fig. 1362, E E being shown in full lines resting upon them, and in dotted lines with one end suspended. The contact-adjustment may thus be made with much greater delicacy and accuracy than in those machines in which the friction is applied to the graduated wheel-rim, because in the latter case, whatever friction there may be is multiplied by the difference in the amount of movement of the graduated rim and that of the bar touching the work.

All that is necessary in the Whitworth machine is to let E E be easy of movement under a slight touch, though capable of suspending one end by friction, and to note the position of the lines of graduation on C with reference to its pointer. By reason of having two operative bars, B, C, that which can be most readily moved may be operated to admit the piece or to adjust the bars to suit the length of the work, while that having the finer adjustive motion, as C, may be used for the final measuring only, thus preserving it from use, and therefore from wear as much as possible; or coarser measurements may be made with one bar, and more minute ones with the other.

So delicate and accurate are the measurements taken with this machine, that it is stated by C. P. B. Shelley, C.E., in his "Workshop Appliances," that if well protected from changes of temperature and from dust, a momentary contact of the finger-nail will suffice to produce a measurable expansion by reason of the heat imparted to the metal. In an iron bar 36 inches long, a space equal to half a division on the wheel G having been rendered distinctly measurable by it, this space indicating an amount of expansion in the 36-inch bar equals the one two-millionth part of an inch!

The following figures, which are taken from *Mechanics*, represent a measuring machine made by the Betts Machine Company, of Wilmington, Delaware.

Fig. 1363 shows a vertical section through the length of the machine, which consists of a bed carrying a fixed and an adjustable head, the fixed head carrying the measuring screw and vernier while the adjustable one carries a screw for approximate adjustment in setting the points of the standard bars.

These screws have a pitch of ten threads per inch, and the range of the measuring screw has a range of 4 inches, and the machine is furnished with firm standard steel bars (4-inch, 6-inch, 18-inch, and 24-inch). The measuring points of the screws are of hardened steel, secured axially in line with the screws, and of two forms, with spherical and flat points, one set of each being used at a time. The larger wheel C is indexed to 1000 divisions, each division representing the ten-thousandth of an inch at the points; the smaller wheel has 100 divisions, each representing the one-thousandth part of an inch at the points. Beside, and almost in contact with, the larger wheel is a movable or adjustable pointer E, upon which the error of the screw is indexed for each inch of its length; the screw error is of the utmost importance when positive results are desired. The screw is immersed in oil to maintain a uniform temperature throughout its length, and to avoid particles of dust accumulating on its surface.

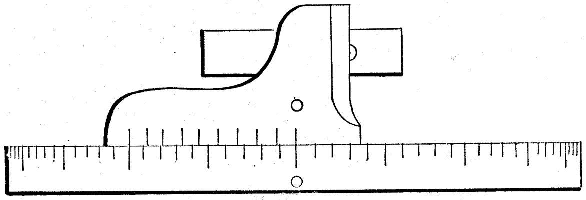
Fig. 1364.

As stated above, the readings are indexed to the ten-thousandth part of an inch, but variations to the hundred-thousandth part of an inch can be indicated. The machine will take in pieces to 24 inches in length, and to 4 inches in diameter. In measuring, the points are brought into easy contact and then expanded by turning the larger wheel, counting the revolutions or parts of revolutions to determine the distance between the points or the size of what is to be measured. The smaller machine is constructed so as to indicate by means of vernier attachment to the ten-thousandth part of an inch, and is of value in tool-rooms where standard and special tools are continually being prepared. By its use, gauges and other exact tools can be made, and at the same time keep gauges of all kinds to standard size by detecting wear or derangement. The machine consists of a frame with one fixed head; the other head is moved by a screw; on both heads are hardened steel points. As with the larger machine, the screw error is indicated in such a manner as to permit the operator to guard against reproducing its error in its work. These machines are used for making gauges, reamers, drills, mandrels, taps, and so on.

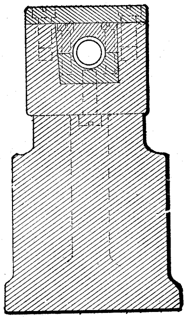
Fig. 1365.

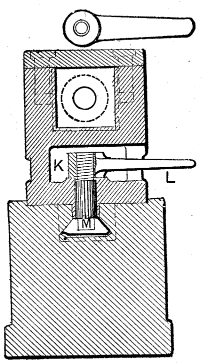

Fig. 1366.

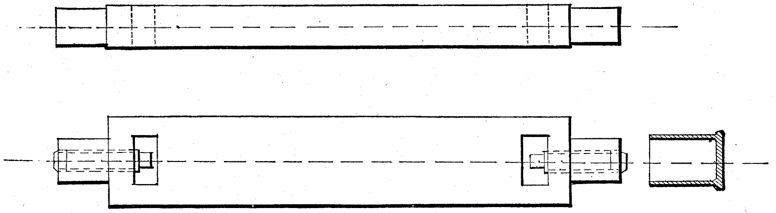
Fig. 1367.

The errors that may exist in the pitch of the measuring screw are taken into account as follows: The points of the measuring machine should be brought into light contact, the position of index-wheel, vernier, and the adjustable pointer which has the screw error indexed upon it should be as in Fig. 1364; that is, the zeros on index-wheel and vernier should be in exact line, the vernier covering half of the zero line on pointer. To measure $\frac{1}{2}$ inch, for illustration, five complete revolutions of index-wheel should produce $\frac{1}{2}$ inch, and would if we had a perfect screw, but the screw is not perfect, and we must add to the measurement already obtained one-half of the space, stamped upon corrective devise, 0—1. This space 0—1 represents the whole error in the screw from zero to 1 inch. The backlash of the screw should always be taken up.

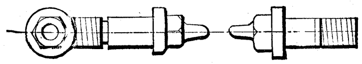
Fig. 1368.

The details of this machine are as follows:—

In Fig. 1363 the points G are those between which the measuring is done, and the slide held by the nut K in position is adjusted by means of inch bars to the distance to be measured; H, the hand-wheel for moving one point, and F the wheel which moves the other. Fig. 1366 is a cross section of the movable head through the nut K and stud M, by which the movable head is adjusted, and Fig. 1365 is a cross section through the fixed head. The bars used in setting the machine are shown in Fig. 1367, and in Fig. 1368 the points of the measuring screws are shown on a large scale. The other figures show various details of the machine and their method of construction. The vernier, it will be observed, is a double one. This is shown in Fig. 1364, and is so arranged that the zero is made movable in order to correct the errors of the screw itself. These errors are carefully investigated and a record made of each. Thus, in Fig. 1363 the arm E is graduated so as to show the true zero for different parts of the screw; D can then be adjusted to a correct reading, and the divisions on the large wheel will then be correct to an exceedingly small fraction. This method of construction enables the machine to be used for indicating very minute variations of length.

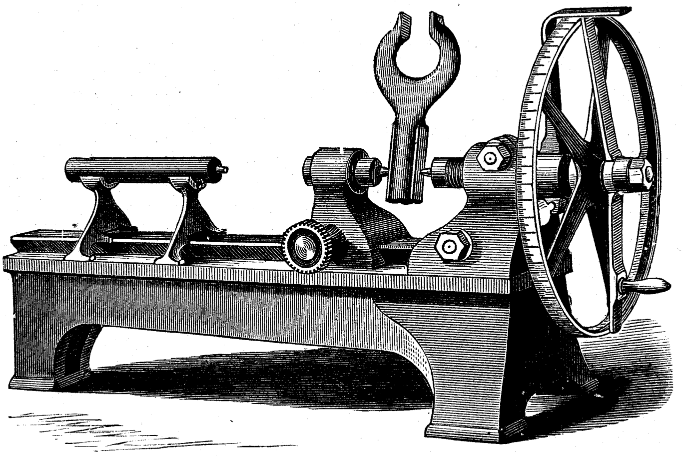
Fig. 1369.

In Fig. 1369 is shown a measuring machine designed by Professor John E. Sweet, late of Cornell University. The bed of the machine rests on three feet, so that the amount of support at each leg may remain the same, whether the surface upon which it rests be a true plane or otherwise. This bed carries a headstock and a tailstock similar to a lathe. The tailstock carries a stationary feeler, and the headstock a movable one, operated horizontally by a screw passing through a nut provided in the headstock, the axial lines of the two feelers being parallel and in the same plane. The diameters of the two feelers are equal at the ends, so that each feeler shall present the same amount of end area to the work. The nut for the screw operating the headstock feeler is of the same length as the screw itself, so that the wear of the screw shall be equalized as near as possible from end to end, and not be the most at and near the middle of its length, as occurs when the thread on the screw is longer than that in the nut.

The pitch of the thread on the screw is 16 threads in an inch of length, hence one revolution of the screw advances the feeler $\frac{1}{16}$ inch. The screw carries a wheel whose circumference is marked or graduated by 625 equidistant lines of division. If, therefore, this wheel be moved through a part of a rotation equal to one of these divisions, the feeler will move a distance equal to $\frac{1}{625}$ of the $\frac{1}{16}$th of an inch, which is the ten thousandth part of an inch, and as the bed of the machine is long enough to permit the feelers to be placed 12 inches apart, the machine will measure from zero to 12 inches by the ten-thousandth of an inch.

To assist the eye in reading the lines of division, each tenth line is marked longer than the rest, and every hundredth, still longer. The pitch of the screw being 16 threads to an inch enables the feeler to be advanced or retired (according to the direction of the rotation of the wheel) a sixteenth inch by a simple rotation of the wheel, an eighth inch by two wheel rotations, a thirty-second inch by a quarter rotation, and so on; and this renders the use of that machine very simple for testing the accuracy of caliper gauges, that are graduated to $\frac{1}{8}$, $\frac{1}{16}$, $\frac{1}{32}$, $\frac{1}{64}$th inch, and so on, such a gauge being shown (in the cut) between the feelers.

The bar or arm shown fixed to the headstock and passing over the circumference of the wheel at the top affords a fixed line or point wherefrom to note the motion of the wheel, or in other words, the number of graduations it moves through at each wheel movement. It is evident that in a machine of this kind it is essential that the work to be measured have contact with the feelers, but that it shall not be sufficient to cause a strain or force that will spring or deflect either the work itself (if it be slight) or the parts of the machine. It is also essential that at excessive measurements the feelers shall touch the work with the same amount of force. The manner of attaining this end in Professor Sweet's machine is as follows: Upon the same shaft as the wheel is an arm having contact at both ends with the edge of the wheel rim whose face is graduated. This arm is free to rotate upon the shaft carrying the graduated wheel, which it therefore drives by multiple friction on its edges at diametrically opposite points; by means of a nut the degree of this friction may be adjusted so as to be just sufficient to drive the wheel without slip when the wheel is moved slowly. So long, then, as the feelers have no contact with the piece to be measured, the arm will drive the graduated wheel, but when contact does take place the wheel will be arrested and the arm will slip. The greatest accuracy will therefore be obtained if the arm be moved at an equal speed for all measurements.

Fig. 1370 represents a Brown and Sharpe measuring machine for sheet metal. It consists of a stand A with a slotted upright having an adjusting screw C above, and a screw D, with a milled head and carrying a dial, passing through its lower part. One turn of the screw, whose threads are $\frac{1}{10}$th inch apart, causes one rotation of the dial, the edge of which is divided into one hundred parts, enabling measurements to be made to thousandths of an inch. The sheet-metal to be gauged is inserted in the slot of the upright. The adjusting-screw is set so that when the points of the two screws meet, the zero of the dial shall be opposite an index or pointer which shows the number of divisions passed over, and is firmly secured by a set-screw.

Next in importance to line and end measurements is the accurate division of the circle, to accomplish which the following means have been taken.

What is known as "Troughton's" method (which was invented by Edward Troughton about 1809) is as follows: A disk or circle of 4 feet radius was accurately turned, both on its face and its inner and outer edges. A roller was next provided of such diameter that it revolved sixteen times on its own axis, while rolling once round the outer edge of the circle. This roller was pivoted in a framework which could be slid freely, yet tightly, along the circle, the roller meanwhile revolving by frictional contact on the outer edge. The roller was also, after having been properly adjusted as to size, divided as accurately as possible into sixteen equal parts by lines parallel to its axis. While the frame carrying the roller was moved once round along the circle, the points of contact of the roller divisions with the circle were accurately observed by two microscopes attached to the frames, one of which commanded the ring on the circle near its edge, which was to receive the divisions, and the other viewed the roller divisions. The exact points of contact thus ascertained were marked with faint dots, and the meridian circle thereby divided into 256 very nearly equal parts.

The next part of the operation was to find out and tabulate the errors of these dots, which are called apparent errors, because the error of each dot was ascertained on the supposition that all its neighbors were correct. For this purpose two microscopes, which we shall call A and C, were taken with cross-wires and micrometer adjustments, consisting of a screw and head divided into 100 divisions, 50 of which read in the one and 50 in the opposite direction. These microscopes, A and B, were fixed so that their cross-wires respectively bisected the dots 0 and 128, which were supposed to be diametrically opposite. The circle was now turned half way round on its axis, so that dot 128 coincided with the wire of A, and should dot 0 be found to coincide with B, then the dots were sure to be 180° apart. If not, the cross-wire of B was moved till it coincided with the dot 0 and the number of divisions of micrometer head noted. Half this number gave clearly the error of dot 128 and was tabulated plus or minus according as the arcual distance between 0 and 128 was found to exceed or fall short of the removing part of the circumference. The microscope B was now shifted, A remaining opposite dot 0 as before, till its wire bisected dot 64, and by giving the circle one-quarter of a turn on its axis, the difference of the arcs between dots 0 and 64, and between 64 and 128 was obtained. The half of this distance gave the apparent error of dot 64, which was tabulated with its proper sign. With the microscope A still in the same position, the error of dot 192 was obtained, and in the same way, by shifting B to dot 32, the errors of dots 32, 96, 160 and 224 were successively ascertained. By proceeding in this way the apparent errors of all the 256 dots were tabulated.

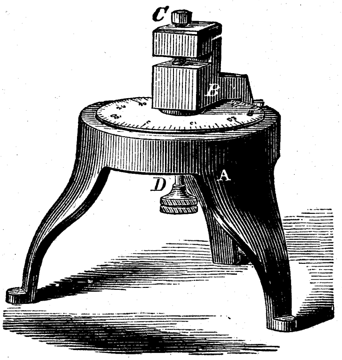

Fig. 1370.

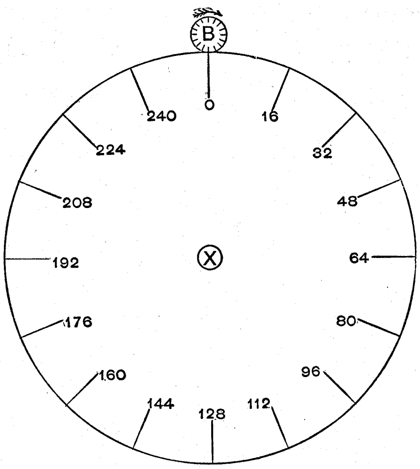

Fig. 1371.

In order to make this method fully understood, we have prepared the accompanying diagrams, which clearly show the plan pursued.

Fig. 1371 illustrates the plan of dividing the large circle by means of the roller B.

Fig. 1372 shows the general adjustment of the microscope for the purpose of proving the correctness of the divisions.

Fig. 1373 shows the location of the microscope over the points 0 and 128.

Fig. 1374 shows the circle turned half-way round, the points 0 and 128 coinciding with the cross threads of the microscope.

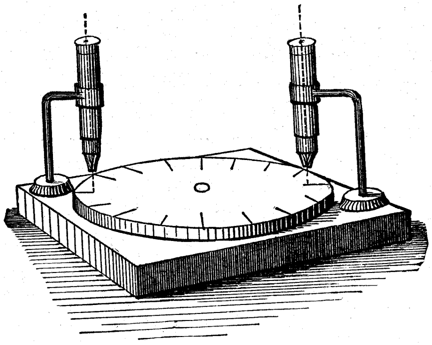

Fig. 1372.

Fig. 1375 shows a similar reading, in which the points do not coincide with the cross threads of the microscope.

Fig. 1376 shows the microscope adjusted for testing by turning the circle a quarter revolution.

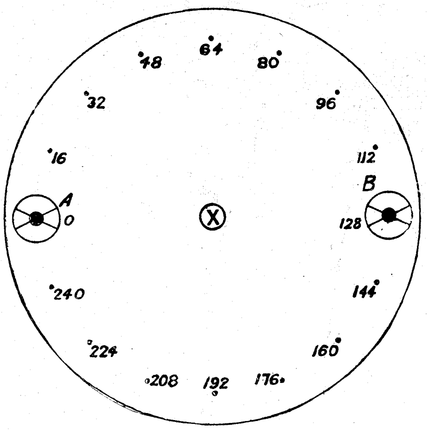

Fig. 1373.

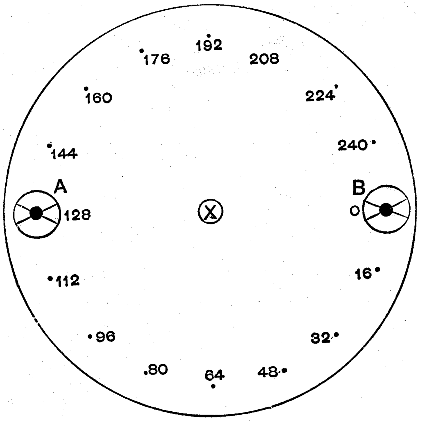

Fig. 1374.

Fig. 1377 represents one of the later forms of Ramsden's dividing engine.* It consists first of a three-legged table, braced so as to be exceedingly stiff. Upon this is placed a horizontal wheel with deep webs, and a flat rim. The webs stiffen the wheel as much as possible, and one of these webs, which runs round the wheel about half-way between the centre and the circumference, rests upon a series of rollers which support it, and prevent, as far as possible, the arms from being deflected by their own weight. An outer circle, which receives the graduation, is laid upon the rim of the wheel and secured in place. The edge of this circle is made concave. A very fine screw, mounted in boxes and supported independently, is then brought against this hollow edge, and, being pressed against it, the screw, when revolved, of course cuts a series of teeth in the circumference, and this tooth-cutting, facilitated by having the screw threads made with teeth, was continued until perfect **V**-shaped teeth were cut all around the edge of the wheel. This Mr. Ramsden calls ratching the wheel. The number of teeth, the circumference of the wheel, and the pitch of the screw were all carefully adjusted, so that by using 2160 teeth, six revolutions of the screw would move the wheel the space of 1°. When this work was finished, and the adjustment had been made as perfect as possible, a screw without teeth—that is, one in which the thread was perfect—was put in the place of that which had cut the teeth from the wheel, and the machine was perfected. The wheel A B C in the drawings is made of bell metal, and turns in a socket under the stand, which prevents the wheel from sliding from the supporting or friction rolls Z, Z. The centre R, working against the spindle M, is made so as to fit instruments of various sizes. The large wheel has a radius of 45 inches, and has 10 arms. The ring B is 24 inches in diameter by 3 inches deep. The ring C is of very fine brass, fitting exactly on the circumference of the wheel, and fastened by screws, which, after being screwed home, were well riveted. Great care was taken in making the centre on which the wheel worked exceedingly true and perfect, and in making the socket for the wheel fit as exactly as possible. The revolving mechanism is all carried on the pillar P, resting on the socket C′. We may state here that the machine, as shown in the engravings, now in the possession of the Stevens Institute, is in some respects slightly improved on that shown in the original drawings published in "Rees' Cyclopædia" in 1819. After the wheel was put on its stand, and the pulleys in place, the instrument was ready for the turning mechanism. The upper part of this pillar P carries the framework in which the traversing screw revolves.

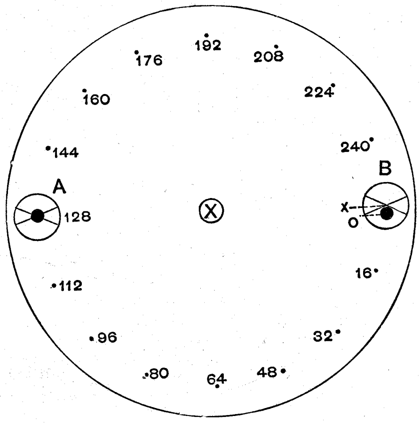

Fig. 1375.

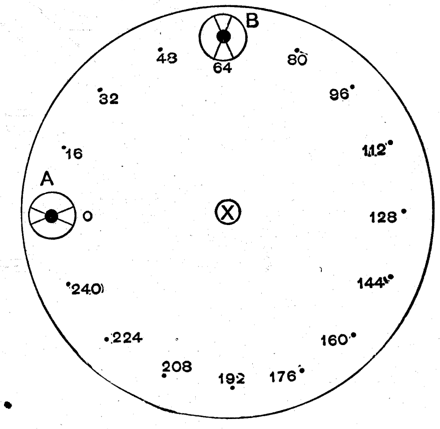

Fig. 1376.

In Fig. 1378 D is the head of this pillar, P the screw which turns the wheel. E^1 E^1 are the boxes, which are made conical so as to prevent any shake and to hold the screw firmly. Circles of brass, F and V, are placed on the arbor of the screw, and as their circumference is

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* From *Mechanics*.

divided into 60 parts, each division consequently amounts to a motion of the wheel of 10 seconds, and 60 of them will equal 1 minute. Revolution is given to the screw by means of the treadle B′ and the cord Y, which runs over the guiding screw W, Fig. 1379, and is finally attached to the box U. A spring enclosed in the box U causes it to revolve, and winds up the slack of the cord whenever the treadle is relieved. In the original drawing the head of the pillar P was carried in a parallel slip in the piece surrounding its head. The construction as shown in Fig. 1379 is somewhat different. The result attained, however, is identical, and the spindles and attachments are held so as to have no lateral motion. The wheels V and X have stops upon them, so arranged that the screw may be turned definitely to a given point and stopped. These wheels are at the opposite ends of the screw W. A detail of one of them is shown at V in Fig. 1380, where X is the ratchet-wheel. This figure also illustrates the construction of the bearings for the screw arbor. We have not space to explain the method by which the perfection of the screw was obtained, nor to discuss the means by which was obtained the success of so eliminating the errors as to make the division of the instrument more perfect than anything which had been attempted previously. Success, however, was obtained, and by means of the first or tooth-cutting screw the teeth were brought to such a considerable uniformity that, together with the fact that the screw took hold of a number of teeth at one time, most of the errors which would have been expected from this method of operation were eliminated. The method of ruling lines upon the instrument was most ingenious. The frame L L, is connected to the head D, of the pillar P in front, by the clamps I and K, and to the centre M by the block R. A frame N N stiffens the back. The blocks O, O on the frame Q′ are secured to the frame L L, by set-screws C, C.

Fig. 1381 shows a side view of the frame Q′, which it is seen carries a **V**-shaped piece Q, which in turn carries another **V**-shaped piece S, Fig. 1378. The piece Q is supported on pointed screws *d*, *d*, and the piece S is supported on two similar screws *f*, *f*. The point of this piece S carries the cutting tool E, Fig. 1378. Of course S can move only in a radial line from the centre M towards the circumference. If the sextant, octant, or other instrument be fastened to the large wheel A, with its centre at M, and the large wheel be rotated by the screw, all lines drawn upon it by E will be radial, and the distances apart will be governed by the number of turns made by the screw. This improvement, we think, was originated by Mr. Ramsden, and was a very great advance over the old method of the straight-edge, and has been used in some of the Government comparators and dividing engines. The following is Mr. Ramsden's own description of the graduation of the machine, and of his method of operating it. It shows the extreme care which he took in correcting the mechanical errors in the construction :—

"From a very exact centre a circle was described on the ring C, about $\frac{4}{10}$ inch within where the bottom of the teeth would come. This circle was divided with the greatest exactness I was capable of, first into five parts, and each of these into three. These parts were then bisected four times; that is to say, supposing the whole circumference of the wheel to contain 2160 teeth, this being divided into five parts, and these again divided into three parts, each third part would contain 144, and this space, bisected four times, would give 72, 36, 18, 9; therefore, each of the last divisions would contain 9 teeth. But, as I was apprehensive some error might arise from quinquesection and trisection, in order to examine the accuracy of the divisions, I described another circle on the ring C, Fig. 1378, $\frac{1}{10}$ inch within the first, and divided it by continual bisection, as 2160, 1080, 540, 270, 135, 67½, 33¾, and, as the fixed wire (to be described presently) crossed both the circles, I could examine their agreement at every 135 revolutions (after ratching could examine it at every 33¾); but not finding any sensible difference between the two sets of divisions, I, for ratching, made choice of the former, and, as the coincidence of the fixed wire with an intersection could be more exactly determined with a dot or division, I therefore made use of intersections on both sides, before described.

"The arms of the frame L, Fig. 1381, were connected by a thin

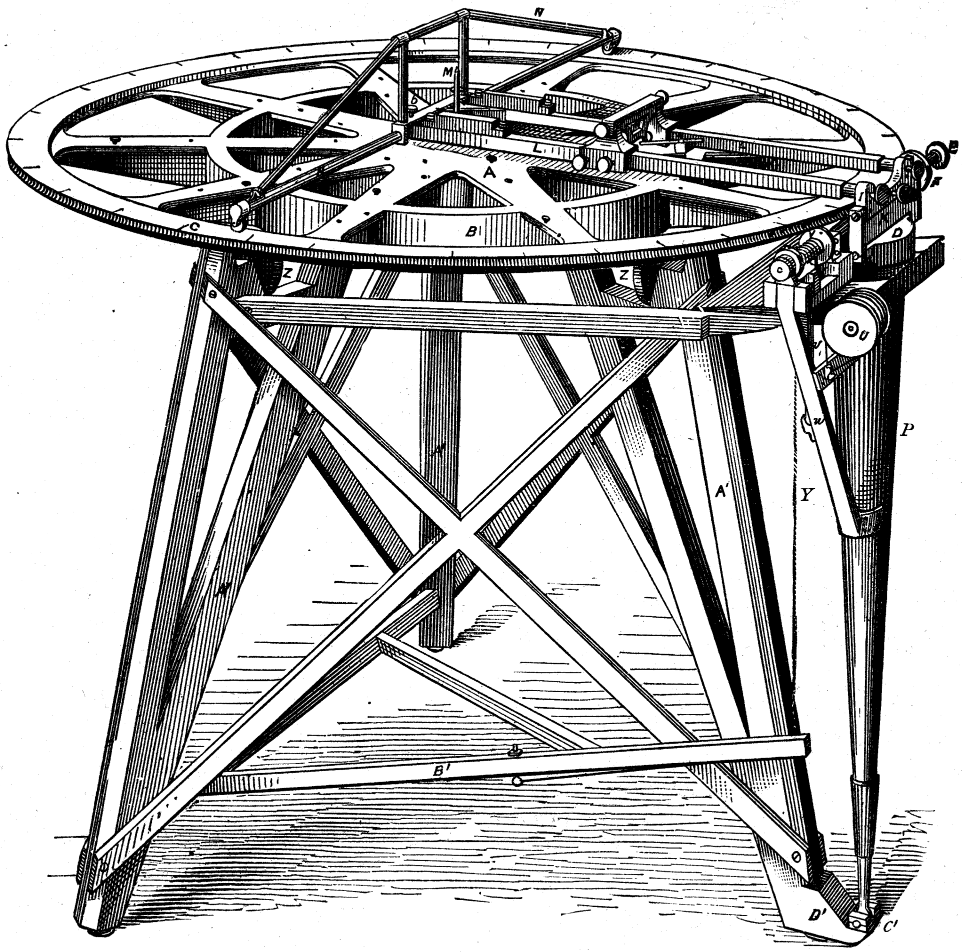

Fig. 1377.

piece of brass, $\frac{3}{4}$ inch broad, having a hole in the middle $\frac{4}{10}$ inch in diameter; across this hole a silver wire was fixed, exactly in a line to the centre of the wheel; the coincidence of this wire with the intersections was examined by a lens of $\frac{1}{10}$ inch focus, fixed in a tube which was attached to one of the arms L. Now (a handle or winch being fixed on the end of the screw) the division marked 10 on the circle F was set to its index, and, by means of a clamp and adjusting-screw for that purpose, the intersection marked 1 on the circle C′ was set exactly to coincide with the fixed wire. The screw was then carefully pressed against the circumference of the wheel by turning the finger-screw *h*; then, removing the clamp, I turned the screw by its handle nine revolutions, till the intersection marked 240 came nearly to the wire. Then, turning the finger-screw *h*, I released the screw from the wheel, and turned the wheel back till the intersection marked 2 exactly coincided with the wire, and by means of the clamp before mentioned, the division 10 on the circle being set to its index, the screw was pressed against the edges of the wheel by the finger-screw *h*, the clamps were removed, and the screw turned nine revolutions, till the intersection marked 1 nearly coincided with the fixed wire; the screw was released from the wheel by turning finger-screw *h* as before, the wheel was turned back till intersection marked 3 coincided with the fixed wire; the division 10 in the circle being set to its index, the screw was pressed against the wheel as before, and the screw turned nine revolutions, till intersection 2 was nearly coincident with the fixed wire, and the screw released, and I proceeded in this manner till the teeth were marked round the whole circumference of the wheel. This was repeated three times round to make the impressions deeper. I then ratched the wheel round continuously in the same direction, without ever disengaging the screw, and, in ratching the wheel about 300 times round, the teeth were finished.

"Now, it is evident that if the circumference of the wheel was even one tooth, or ten minutes, greater than the screw would require, this error would, in the first instance, be reduced by $\frac{1}{240}$ part of a revolution, or two seconds and a half, and these errors or inequalities of the teeth were equally distributed round the wheel at the distance of nine teeth from each other. Now, as the screw in ratching had continual hold of several teeth at the same time and thus constantly changing, the above-mentioned irregularities soon corrected themselves, and the teeth were reduced to a perfect equality. The piece of brass which carried the wire was now taken away, and the cutting-screw was also removed, and a plain one put in its place. At one end of the screw arbor, or mandrel was a small brass circle F, having its edge divided into 60 parts, numbered at every sixth division, as before mentioned. On the other end of the screw is a ratchet-wheel V (X, Fig. 1380) having 60 teeth, covered by the hollow circle (V, Fig. 1380), which carries two clicks that catch upon opposite sides of the ratchet-wheel. When the screw is to be moved forward, the cylinder W turns on a strong steel arbor E″, which passes through the piece X′; this piece, for greater firmness, is attached to the screw-frame by the braces *w*. A spiral groove or thread is cut upon the outside of the cylinder W, which serves both for holding the string and also giving motion to the lever I on its centre, by means of a

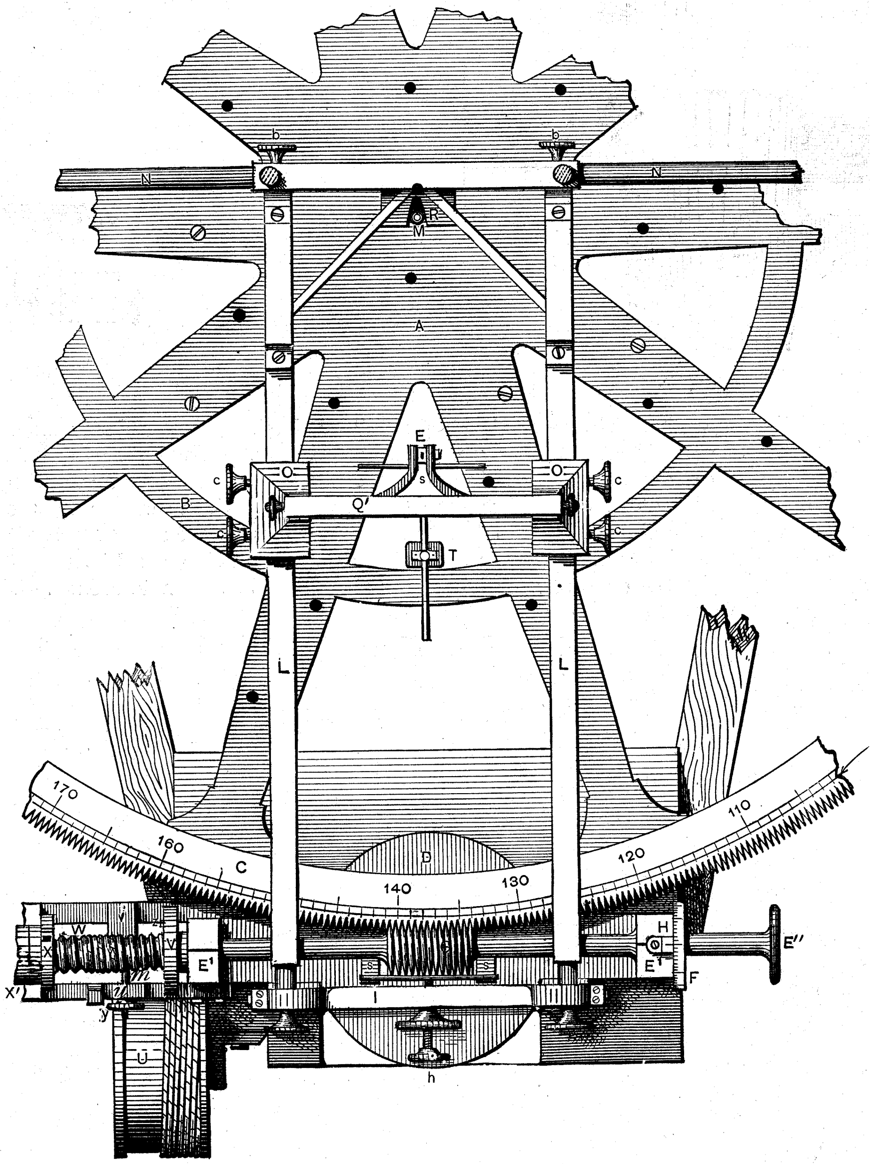

Fig. 1378.

steel tooth *v*, that works between the threads of the spiral. To the lever is attached a strong steel pin *m*, on which a brass socket turns; this socket passes through a slit in the piece *u*, and may be tightened in any part of the slit by the finger-nut *y*. This piece serves to regulate the number of revolutions of the screw for each tread of the treadle B'."

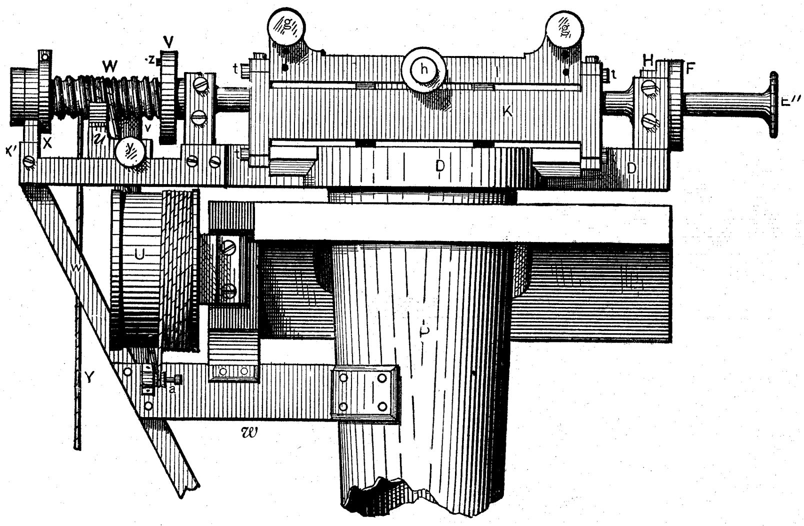

Fig. 1379.

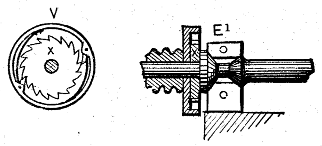

Fig. 1380.

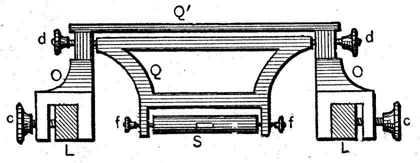

Fig. 1381.

Figs. 1382, 1383, and 1384 represent a method adopted to divide a circle by the Pratt and Whitney Company. The principle of the device is to enable the wheel to be marked, to be moved through a part of a revolution equal to the length of a division, and to test the accuracy of the divisions by the coincidence of the line first marked with that marked last when the wheel has been moved as many times as it is to contain divisions. By this means any error in the division multiplies, so that the last division marked will exhibit it multiplied by as many times as there are divisions in the whole wheel. The accuracy of this method, so long as variations of temperature are avoided, both in the marking and the drilling of the wheel, appears to be beyond question. In the figures, W represents a segment of the wheel to be divided, and C what may be termed a dividing chuck. The wheel is mounted on an arbor in a gear-cutting machine. On the hub of the wheel (which has been turned up for the purpose) there is fitted, to a close working fit, a bore at the end of an arm, the other end of the arm being denoted by A in the figures. The dividing chuck is fitted to the slide S of the gear-cutting machine, and is of the following construction.

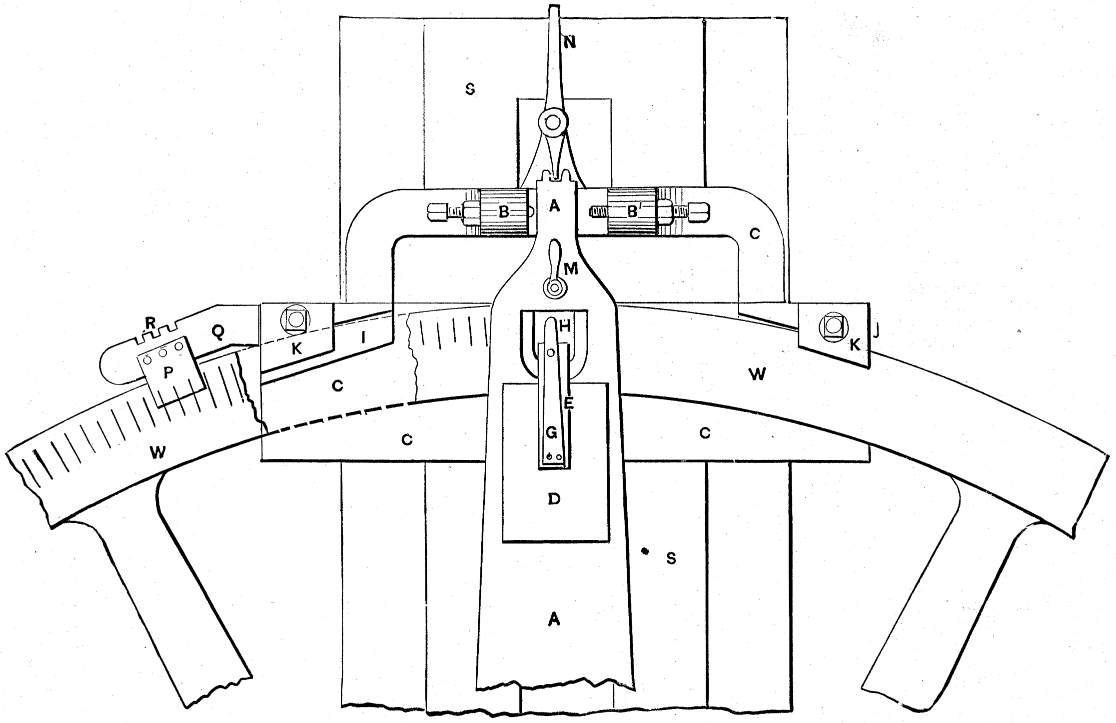

Fig. 1382.

Between two lugs, B and B', it receives the end of arm A. These lugs are provided with set-screws, the distance between the ends of which regulate the amount of movement of the end of arm A. Upon A is the slide D, carrying the piece E, in which is the marking tool F, the latter being lifted by a spring G, and, therefore, having no contact with the wheel surface until the spring is depressed. H is an opening through the arm A to permit the marking tool F to meet the wheel face, as shown in Fig. 1384, which is an end view of the slide showing the arm A in section. The face of the wheel rests upon the chuck on each side of the arm at the points I, J, and may be clamped thereto by the clamps K. The arm may be clamped to the wheel by the clamp shown dotted in at L, the bolt passing up and through the screw handle M. N is simply a lever with which to move the arm A, or arm A and the wheel. Suppose all the parts to be in the position shown in the cuts, the clamps being all tightened up, the slide D may be moved forward towards K, while the spring is depressed, and F will mark a line upon the wheel. The handle M may then be released and arm A moved until it touches the set-screw in B', when M may be tightened and another line marked. Clamps K are then tightened, and the wheel, with the arm A fast to it, moved back to the position shown in the cut, when the clamps may be tightened again and another line marked, the process being continued all round the wheel. To detect and enable the correction of any discoverable error in a division, there is provided the plate P, having upon it three lines of division (which have been marked simultaneously with three of the lines marked on the wheel). This plate is supported by an arm or bracket Q, on the rear edge of which are three notches R to hold a microscope, by means of which the lines on P may be compared with those on the wheel face, so that if any discrepancy should appear it may be determined which line is in error. The labor involved in the operation of marking a large wheel is very great. Suppose, for example, that a wheel has 200 lines of division, and that after going round the wheel as described it is found that the last division is 100th inch out; then in each division the error is the two-hundredth part of this 100th inch, and that is all the alteration that must be made in the distance between set-screws B and B'.

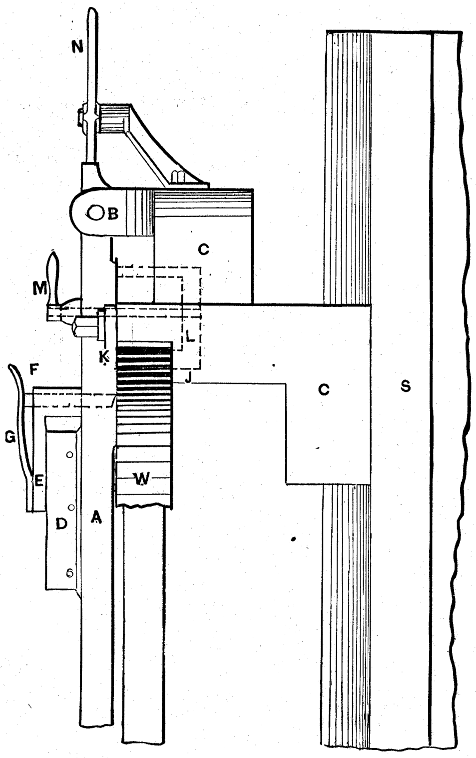

Fig. 1383.

Figs. 1385 and 1386 represent a method of originating an index wheel, adopted by R. Hoe and Co., of New York City.

In this method the plan was adopted of fitting round a wheel 180 tapering blocks, which should form a complete and perfect circle. These blocks were to serve the same purpose as is ordinarily accomplished by holes perforated on the face of an index wheel. In their construction, means of correcting any errors that might be found, without the necessity of throwing away any portion of the work done, would also be provided. Further, this means would provide for taking up wear, should any occur in the course of time, and thus restore the original truth of the wheel.

Fig. 1385 of the engravings shows the originating wheel mounted upon a machine or cutting engine. Upon the opposite end of the shaft is the worm-wheel in the process of cutting. After the master worm-wheel has been thus prepared by means of the originating wheel, it is used upon the front end of the shaft, in the position now occupied by the originating wheel, and operated by a worm in the usual manner. Subdivisions are made by change wheels. The construction of the originating wheel will be understood by the smaller engravings.

Fig. 1386 is an enlarged section of a segment of the wheel, while Fig. 1387 is an edge view of this segment. Fig. 1388 is a view of one of the blocks employed in the construction of the wheel, drawn to full size.

In the rim of the originating wheel there was turned a shoulder, C, Fig. 1387, 5 feet in diameter. Upon this shoulder there were clamped 180 blocks, of the character shown in Fig. 1386, as indicated by the section, Fig. 1387. These blocks were secured to the face of the wheel D by screws E, and were held down to the shoulder by the screw and clamp G F, shown in Fig. 1387. (They are omitted in Fig. 1385 for clearness of illustration.) In the preparation of these blocks each was fitted to a template T, in Fig. 1388, and was provided with a recess B, to save trouble in fitting and to insure each block seating firmly on the shoulder C. The shoulder, after successive trials, was finally reduced to such a diameter that the last block exactly filled the space left for it when it was fully seated on the shoulder C. The wheel thus prepared was mounted on a Whitworth cutting engine, as shown in Fig. 1385. The general process of using this wheel is as follows: The blocks forming the periphery of the originating wheel are used in place of the holes ordinarily seen in the index plates. One of them is removed to receive a tongue, shown in the centre of Fig. 1385, which, exactly filling the opening or notch thus made, holds the wheel firmly in place. After a tooth has been cut in the master worm-wheel, shown at the back of Fig. 1385, the block in the edge of the originating wheel corresponding to the next tooth to be cut is removed. The tongue is withdrawn from the first notch, the wheel is revolved, and the tongue is inserted in the second position. The block first removed is then replaced, and the cutting proceeds as before. This operation is repeated until all the teeth in the master wheel have been cut. The space being a taper, the tongue holds the originating wheel more firmly than is possible by means of cylindrical pins fitting into holes. The number of blocks in the originating wheel being 180, the teeth cut in the master wheel may be 180 or some exact divisor of this number.

The advantages of this method of origination are quite evident. Since 180 blocks were made to fill the circle, the edges of each had 2° taper. This taper enabled the blocks to be fitted perfectly to the template, because any error in fit would be remedied by letting the block farther down into the template. Hence, it was possible to correct any error that was discovered without throwing the block away. Further, as the blocks themselves are removed to form a recess for locking the originating wheel in position while cutting the worm-wheel, the truth of the work is not subject to the errors that creep in when holes or notches require to be pierced in the originating wheel. Such errors arise from the heating due to the drilling or cutting, from the wear of the tools or from their guides, from soft or hard spots in the metal and other similar causes. To avoid any error from the heating due to the cut on the worm-wheel, in producing master wheels, Messrs. Hoe and Co. allowed the wheel to cool after each cut. The teeth were cut in the following order: The first three were cut at equidistant points in the circumference of the wheel. The next three

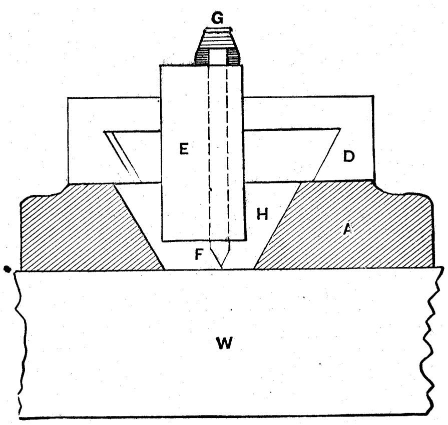

Fig. 1384.

also were at equidistant points, and midway between those first cut. This plan was continued until all the teeth were cut, thus making the expansion of the wheel from the heat as nearly equal as possible in all directions.

There is one feature in this plan that is of value. It is that a certain number of blocks, for example six, may be taken out at two or three different parts of the originating wheel and interchanged, thus affording a means of testing that does not exist in any other method of dividing.

The tools applied by the workmen to measure or to test work may be divided into classes.

1st. Those used to determine the actual size or dimension of the work, which may be properly termed measuring tools.

2nd. Those used as standards of a certain size, which may be termed gauges.

3rd. Those used to compare one dimension with another, as in the common calipers.

4th. Those used to transfer measurements or distances defined by lines.

5th. Those used to test the accuracy of plane or flat surfaces, or to test the alignment of one surface to another.

Referring to the first, their distinctive feature is that they give the actual dimensions of the piece, whether it be of the required dimension or not.

The second determine whether the piece tested is of correct size or not, but do not show what the amount of error is, if there be any.

The third show whatever error there may be, but do not define its amount; and the same is true of the fifth and sixth.

Fig. 1389 represents a micrometer caliper for taking minute end measurements. This instrument is capable of being set to a standard measurement or of giving the actual size of a piece, and is therefore strictly speaking a combined measuring tool and a gauge. The U-shaped body of the instrument is provided with a hub *a*, which is threaded to receive a screw C, the latter being in one piece with the stem D, which envelops for a certain distance the hub *a*. The thread of C has a pitch of 40 per inch; hence one revolution of D causes the screw to move endways $\frac{1}{40}$ of an inch.

The vertical lines of division shown on the hub *a* are also $\frac{1}{40}$ of an inch apart, hence the bevelled edge of the sleeve advances one of the divisions on *a* at each rotation.

This bevelled edge is divided into 25 equal divisions round its circumference, as denoted by the lines marked 5, 10, &c. If, then, D be rotated to an amount equal to one of its points of division, the screw will advance $\frac{1}{25}$ of $\frac{1}{40}$ of an inch. In the cut, for example, the line 5 on the sleeve coincides with the zero line which runs parallel to the axial line of the hub. Now suppose sleeve D to be rotated so that the next line of division on the bevelled edge of D comes opposite to the zero line, then $\frac{1}{25}$ part of a revolution of D will have been made, and as a full revolution of D would advance the screw $\frac{1}{40}$ of an inch, then $\frac{1}{25}$ of a revolution will advance it $\frac{1}{25}$ of $\frac{1}{40}$ inch, which is $\frac{1}{1000}$ inch.

The zero line being divided by lines of equal division into 40ths of an inch, then, as shown in the cut, the instrument is set to measure $\frac{3}{40}$ths and $\frac{5}{25}$ths of a fortieth.

It is to be observed that to obtain correct measurements the work must be held true with the face of the foot B, and the contact between the end of screw C and the work must be just barely perceptible, otherwise the pressure of the screw will cause the U-piece to bend and vitiate the accuracy of the measurement. Furthermore, if the screw be rotated under pressure upon the work, its end will wear and in time impair the accuracy of the instrument. To take up any wear that may occur, the foot-piece B is screwed through the hub, holding it so that it may be screwed through the hub to the amount of the wear.

To avoid wear as much as possible, the screws of instruments of this kind are sometimes hardened, and to correct the error of pitch induced in the hardening, each screw is carefully tested to find in what direction the pitch of the hardened thread has varied, and provision is made for the correction as follows:—

The zero line on the hub *a* stands, if the thread is true to pitch, parallel to the axis of the screw C, but if the pitch of the thread has become coarser from hardening, this zero line is marked at an angle, as shown in Fig. 1390, in which A A represents the axial line of the screw and B the zero line.

If the screw pitch becomes finer from hardening, the zero line is made at an angle in the opposite direction, as shown in Fig. 1391, the amount of the angle being that necessary to correct the error in the screw pitch. The philosophy of this is, that if the pitch has become coarser a less amount of movement of the screw is necessary, while if it has become finer an increased movement is necessary. It is obvious, also, that if the pitch of the thread should become coarser at one end and finer at the other the zero line may be curved to suit.

Fig. 1392 represents a vernier caliper, in which the measurement is read by the coincidence of ruled lines upon the following principle. The vernier is a device for subdividing the readings of any equidistant lines of division. Its principle of action may be explained as follows: Suppose in Fig. 1393 A to be a rule or scale divided into inches and tenths of an inch, and B a vernier so divided that its ten equidistant divisions are equal to nine of the divisions on A; then the distance apart of the lines of division on A will be $\frac{1}{10}$ inch; but, as the whole ten divisions on B measure less than an inch, by $\frac{1}{10}$ inch, then each line of division is a tenth part of the lacking tenth less than $\frac{1}{10}$ inch apart. Thus, were we to take a space equal to the $\frac{1}{10}$ inch between 9 and 10 on A, and divide it into 10 equal parts (which would give ten parts each measuring $\frac{1}{100}$th of an inch) and add one of said parts to each of the distances between the lines of division on B, then the whole of the lines on A would coincide with those on B. It becomes evident, then, that line 1 on B is $\frac{1}{100}$ inch below line 1 on A, that line 2 on B is $\frac{2}{100}$ inch below line 2 on A, line 3 on the vernier B is $\frac{3}{100}$ inch below line 3 on the rule A, and so on, until we arrive at line 10 on the vernier, which is $\frac{10}{100}$ or $\frac{1}{10}$ inch below line 10 on A. Suppose, then, the rule or scale to rest vertically on a truly surfaced plate, and a piece of metal be placed beneath B, the thickness of the piece will be shown by which of the lines on B coincides with a line on A. For more minute divisions it is simply necessary to have more lines of division in a given length on A and B. Thus, if the rule be divided into inches and fiftieths, and the vernier is so divided that it has 20 equidistant lines of division to 19 lines on

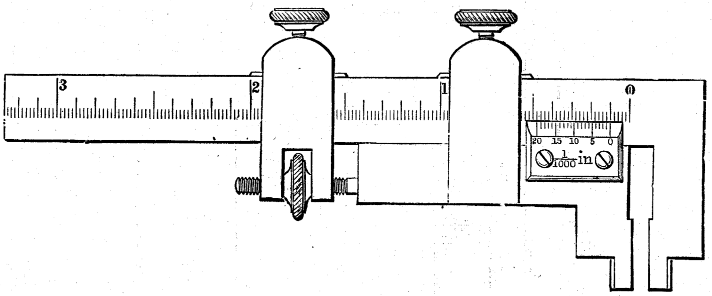

Fig. 1392.

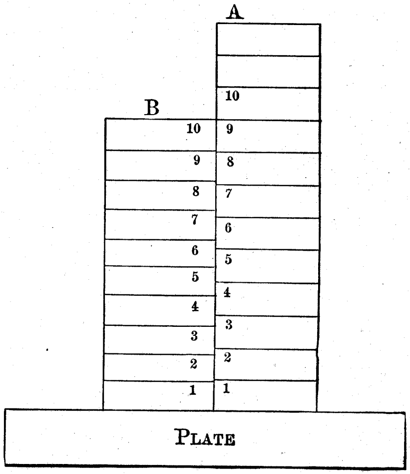

Fig. 1393.

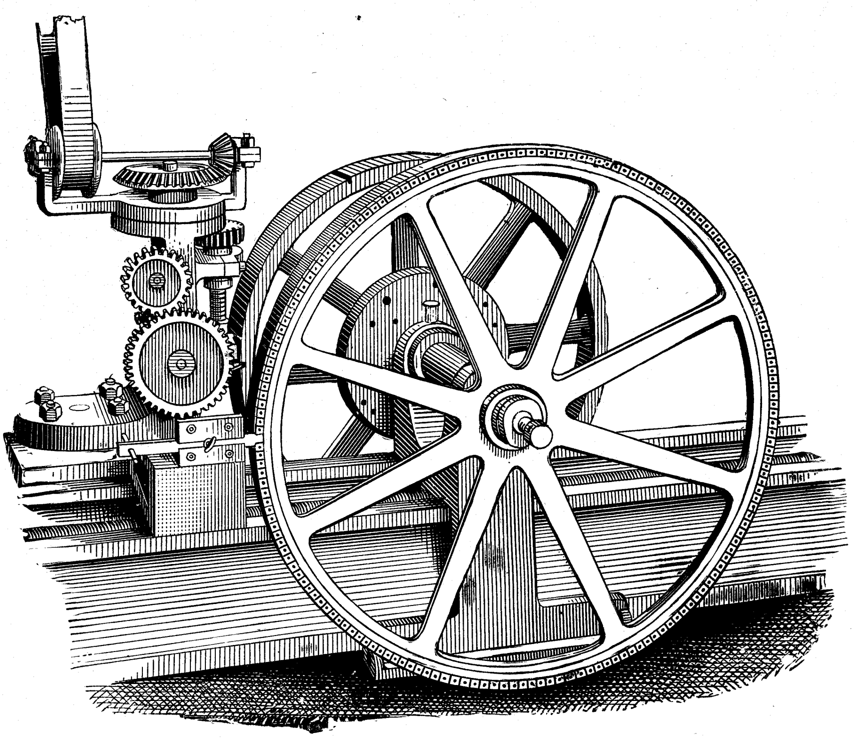

Fig. 1385.

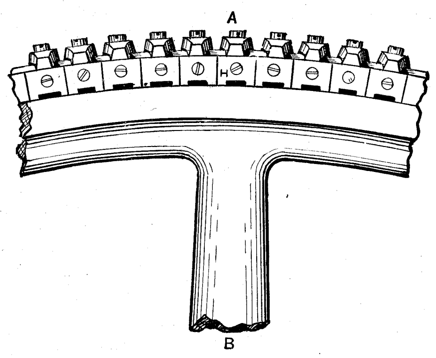

Fig. 1386.

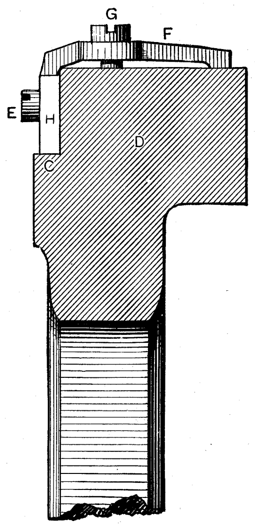

Fig. 1387.

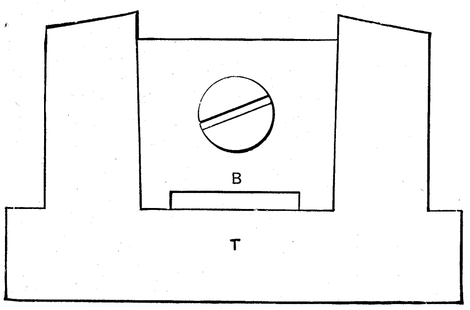

Fig. 1388.

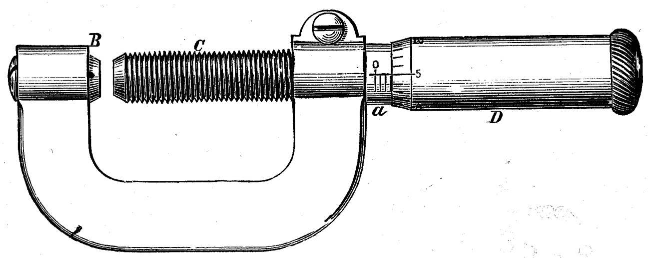

Fig. 1389.

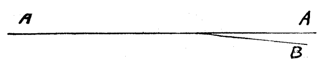

Fig. 1390.

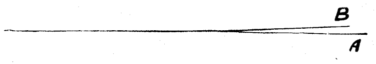

Fig. 1391.

the rule, it will then lack one division, or $\frac{1}{50}$ inch in $\frac{20}{50}$ inch, each division on the vernier will then be the one-twentieth of a fiftieth too short, and as $\frac{1}{20}$ of $\frac{1}{50}$ is $\frac{1}{1000}$, the instrument will read to one-thousandth of an inch.

Let it now be noted that, instead of making the lines of division closer together to obtain minute measurements, the same end may be obtained by making the vernier longer. For example, suppose it be required to measure to $\frac{1}{2000}$ part of an inch, then, if the rule or scale be graduated to inches and fiftieths, and the vernier be graduated to have 40 equidistant lines of division, and 39 of the lines on the scale, the reading will be to the $\frac{1}{2000}$ part of an inch. But, in any event, the whole of the readings on the vernier may be read, or will be passed through, while it is traversing a division equal to one of the divisions on the scale or rule.

In Fig. 1392 is shown a vernier caliper, in which the vernier is attached to and carried by a slide operating against the inside edge of the instrument. The bar is marked or graduated on one side by lines showing inches and fiftieths of an inch, with a vernier graduated to have 20 equidistant lines of division in 19 of the lines of division on the bar, and therefore measuring to the $\frac{1}{1000}$th of an inch, while the other side is marked in millimètres with a vernier reading to $\frac{1}{40}$th millimètre, there being also 20 lines of division on the vernier to 19 on the bar.

The inside surfaces of the feet or jaws are relieved from the bar to about the middle of their lengths, so as to confine the measuring surfaces to dimensions sufficiently small to insure accurate measurement, while large enough to provide a bearing area not subject to rapid wear. If the jaw surface had contact from the point to the bar, it would be impossible to employ the instrument upon a rectangular having a burr, or slight projection, on the edge. Again, by confining the bearing area to as small limits as consistent with the requirements of durability a smaller area of the measured work is covered, and the undulations of the same may be more minutely followed.

To maintain the surface of the movable jaw parallel with that of the bar-jaw, it is necessary that the edge of the slide carrying the vernier be maintained in proper contact with the edge of the instrument, which, while adjusting the vernier, should be accomplished as follows :—

The thumb-screw most distant from the vernier should be set up tight, so that that jaw is fixed in position. The other thumb-screw should be set so as to exert, on the small spring between its end and the edge of the bar, a pressure sufficient to bend that spring to almost its full limit, but not so as to let it grip the bar. The elasticity of the spring will then hold the edge of the vernier slide sufficiently firmly to the under edge of the bar to keep the jaw-surfaces parallel; to enable the correct adjustment of the vernier, and to permit the nut-wheel to move the slide without undue wear upon its thread, or undue wear between the edge of the slide and that of the bar, both of which evils will ensue if the thumb-screw nearest the vernier is screwed firmly home before the final measuring adjustment of the vernier is accomplished.

When the measurement is completed the second thumb-screw must be set home and the reading examined again, for correctness, to ascertain if tightening the screw has altered it, as it would be apt to do if the thumb-screw was adjusted too loose.

The jaws are tempered to resist wear, and are ground to a true plane surface, standing at a right angle to the body of the bar. The method of setting the instrument to a standard size is as follows :—

The zero line marked 0 on the vernier coincides with the line 0 on the bar when the jaws are close together; hence, when the 0 line on the vernier coincides with the inch line on the bar, the instrument is set to an inch between the jaws. When the line next to the 0 line on the vernier coincides with the line to the left of the inch line on the bar, the instrument is set to $1\frac{1}{1000}$ inches. If the vernier slide then be moved so that the second line on the vernier coincides with the second line on the left of the inch on the bar, the instrument is set to $1\frac{2}{1000}$ inches, and so on, the measurement of inches and fiftieths of an inch being obtained by the coincidence of the zero line on the vernier with the necessary line on the bar, and the measurements of one-thousands being taken as described.

But if it is required to measure, or find the diameter of an existing piece of work, the method of measuring is as follows :—

The thumb-screws must be so adjusted as to allow the slide to move easily or freely upon the work without there being any play or looseness between the slide and the bar. The slide should be moved up so as to very nearly touch the work when the latter is placed between the jaws. The thumb-screw farthest from the vernier should then be screwed home, and the other thumb-screw operated to further depress the spring without causing it to lock upon the bar. The nut-wheel is then operated so that the jaws, placed squarely across the work, shall just have perceptible contact with it. (If the jaws were set to grip the work tight they would spring from the pressure, and impair the accuracy of the measurements.) The thumb-screw over the vernier may then be screwed home, and the adjustment of the instrument to the work again tried. If a correction should be found necessary, it is better to ease the pressure of the thumb-screw over the vernier before making such correction, tightening it again afterwards. The reading of the measurement is taken as follows :—

If the 0 line on the vernier coincides with a line on the bar, the measurement will, of course, be shown by the distance of that line from the 0 line on the bar, the measurement being in fiftieths of inches, or inches and fiftieths (as the case may be), but if the 0 line on the vernier does not coincide with any line of division on the bar, then the measurement in inches and fiftieths will be from the next line (on the bar) to the right of the vernier, while the thousandths of an inch may be read by the line on the vernier which coincides with a line on the bar.

Suppose, for example, that the zero line of the vernier stands somewhere between the 1 inch and the $1\frac{1}{50}$ inch line of division on the bar, then the measurement must be more than an inch, but less than $1\frac{1}{50}$ inches. If the tenth or middle line on the vernier is the one that coincides with a line on the bar, the reading is $1\frac{10}{1000}$ inches. If the line marked 5 on the vernier is the one that coincides with a line on the bar, the measurement is an inch and $\frac{5}{1000}$, and so on.

For measuring the diameters of bores or holes, the external edges of the jaws are employed; the width of the jaw at the ends being reduced in diameter to enable the jaw ends to enter a small hole. These edges are formed to a circle, having a radius smaller than the smallest diameter of hole they will enter when the jaws are closed, which insures that the point of contact shall be in the middle of the thickness of each jaw. In this case the outside diameter of the jaws must be deducted from the measurement taken by the vernier, or if it be required to set the instrument to a standard diameter, the zero line on the vernier must be set to a distance on the bar less than that of the measurement required to an amount equal to the diameter of the jaw edges when the jaws are closed. This diameter is, as far as possible, made to correspond to the lines of division on the bar. Thus in the instrument shown in Fig. 1392, these lines of division are $\frac{1}{50}$ inch; hence the diameter across the closed bars should, to suit the reading (for internal measurements) on the bar, be measurable also in fiftieths of an inch; but the other side of the bar is divided into millimètres, hence to suit internal measurements (in millimètres or fractions thereof) the width of the jaws, when closed, should be measurable in millimètres; hence, it becomes apparent that the diameter of the jaws used for internal measurements can be made to suit the readings on one side only of the bar, unless the divisions on one side are divisible into those on the other side of the bar. When the diameter of the jaws is measurable in terms of the lines of division on the bar, the instrument may be set to a given diameter by placing the zero of the vernier as much towards the zero on the bar as the width of the jaws when closed. Thus, suppose that width (or diameter, as it may be termed) be $\frac{10}{50}$ of an inch, and it be required to set the instrument for an inch interval or bore measurement, then the zero on the vernier must be placed to coincide with the line on the bar which denotes $\frac{40}{50}$ of an inch, the lacking $\frac{10}{50}$ inch being accounted for in the diameter or width of the two jaws.

But when the width of the jaws when closed is not measurable in terms of the lines of division on the bar, the measurement shown by the vernier will, of course, be too small by the amount of the widths of the two jaws, and the measurement shown by the vernier must be reduced to the terms of measurement of the width of the jaws, or what is the same thing, the measurement of the diameter of the jaws must be reduced to the terms of measurement on the bar, in order to subtract one from the other, or add the two together, as the case may require.

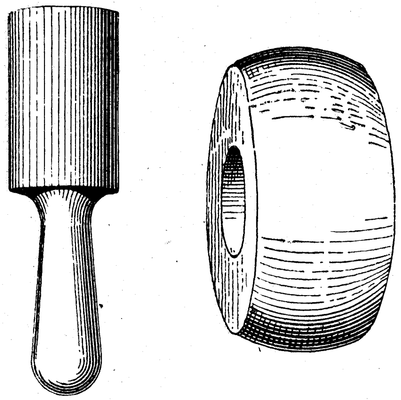

Fig. 1394.

For example: Suppose the diameter of the jaws to measure, when they are close together, $\frac{250}{1000}$ of an inch, and that the bar be divided into inches and fiftieths. Now set the zero of the vernier opposite to the line denoting $\frac{49}{50}$ inch on the bar. What, then, is the measurement between the outside edges of the jaws?

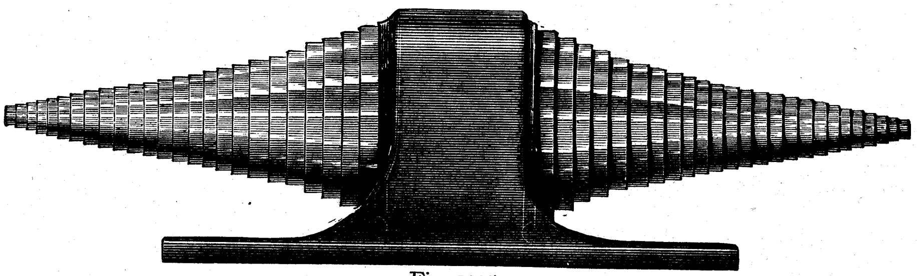

Fig. 1395.

In this case we require to add the $\frac{250}{1000}$ to the $\frac{49}{50}$ in order to read the measurement in terms of fiftieths and thousandths of an inch, or we may read the measurement to one hundredths of an inch, thus: $\frac{49}{50}$ equal $\frac{98}{100}$, and $\frac{250}{1000}$ equal $\frac{25}{100}$, and $\frac{98}{100}$ added to $\frac{25}{100}$ are $\frac{123}{100}$, or an inch and $\frac{23}{100}$. To read in $\frac{1}{1000}$ths of an inch, we have that $\frac{49}{50}$ of an inch are equal to $\frac{980}{1000}$, because each $\frac{1}{50}$ inch contains $\frac{20}{1000}$ inch, and this added to $\frac{250}{1000}$ makes $\frac{1230}{1000}$, that is $1\frac{230}{1000}$ inches.

The accuracy of the instrument may be maintained, notwithstanding any wear which may in the course of time take place on the inside faces of the jaws, by adjusting the zero line on the vernier to exactly coincide with the zero line on the bar, but the fineness of the lines renders this a difficult matter with the naked eye, hence it is desirable to read the instrument with the aid of a magnifying glass. If the outer edges of the jaws should wear, it is simply necessary to alter the allowance made for their widths.

Fig. 1394 represents standard plug and collar gauges. These tools are made to represent exact standard measurements, and obviously do no more than to disclose whether the piece measured is exactly to size or not. If the work is not to size they will not determine how much the error or difference is, hence they are gauges rather than measuring tools. It is obvious, however, that if the work is sufficiently near to size, the plug or male gauge may be forced in, or the collar or female gauge may be forced on, and in this case the tightness of the fit would indicate that the work was very near to standard size. But the use of such gauges in this way would rapidly wear them out, causing the plug gauge and also the collar to get smaller than its designated size, hence such gauges are intended to fit the work without friction, and at the same time without any play or looseness whatever. Probably the most accurate degree of fit would be indicated when the plug gauge would fit into the collar sufficiently to just hold its own weight when brought to rest while within the collar, and then slowly fall through if put in motion within the collar. It is obvious that both the plug and the collar cannot theoretically be of the same size or one would not pass within the other, but the difference that is sufficient to enable this to be done is so minute that it is practically too small to measure and of no importance.

When these gauges are used by the workmen, to fit the work to their wear is sufficient to render it necessary to have some other standard gauge to which they can be from time to time referred to test their accuracy, and for this purpose a standard such as in Fig. 1395 may be employed. It consists of a number of steel disks mounted on an arbor and carefully ground after hardening each to its standard size.

But a set of plug and collar gauges provide within themselves to a certain extent the means of testing them. Thus we may take a collar or female gauge of a certain size and place therein two or three plug gauges whose added diameters equal that of the female or collar gauge.

In Fig. 1396, for example, the size of the female gauge A being $1\frac{1}{2}$ inches, that of the male B may be one inch, and that of C $\frac{1}{2}$ an inch, and the two together should just fit the female. On the other hand, were we to use instead of B and C two males, $\frac{7}{8}$ and $\frac{5}{8}$ inches respectively, they should fit the female; or a $\frac{1}{2}$ inch, a $\frac{5}{8}$ inch and a $\frac{3}{8}$ inch male gauge together should fit the female. By a series of tests of this description, the accuracy of the whole set may be tested; and by judicious combinations, a defect in the size of any gauge in the set may be detected.

The wear of these gauges is the most at their ends, and the fit may be tested by placing the plug within the collar, as in Fig. 1397, and testing the same with the plug inserted various distances within the collar, exerting a slight pressure first in the direction of A and then of B, the amount of motion thus induced in the plug denoting the closeness of the fit.

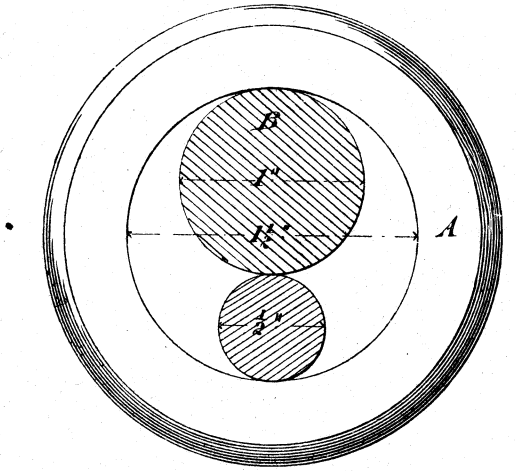

Fig. 1396.

In trying the fit of the plug by passing it well into or through the collar, the axis of the plug should be held true with that of the collar, and the plug while being pressed forward should be slightly rotated, which will cause the plug to enter more true and therefore more easily. The plug should be kept in motion and not allowed to come to rest while in the collar, because in that case the globules of the oil with which the surfaces are lubricated maintain a circular form and induce rolling friction so long as the plug is kept in motion, but flatten out, leaving sliding friction, so soon as the plug is at rest, the result being that the plug will become too tight in the collar to permit of its being removed by hand.

The surfaces of both the plug and the collar should be very carefully cleaned and oiled before being tried together, it being found that a film of oil will be interposed between the surfaces, notwithstanding the utmost accuracy of fit of the two, and this film of oil prevents undue abrasion or wear of the surfaces.

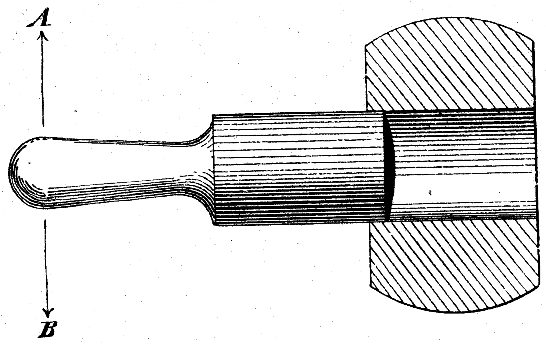

Fig. 1397.

When great refinement of gauge diameter is necessary, it is obvious that all the gauges in a set should be adjusted to diameter while under an equal temperature, because a plug measuring an inch in diameter when at a temperature of, say, 60° will be of more than an inch diameter when under a temperature of, say, 90°.

It follows also that to carry this refinement still farther, the work to be measured if of the same material as the standard gauge should be of the same temperature as the gauge, when it will fit the gauge if applied under varying temperatures; but if a piece of work composed, say, of copper, be made to true gauge diameter when both it and the gauge are at a temperature of, say, 60°, it will not be to gauge diameter, and will not fit the gauge, if both be raised to 90° of temperature, because copper expands more than steel.

To carry the refinement to its extreme limit then, the gauge should be of the same metal as the work it is applied to whenever the two fitting parts of the work are of the same material. But suppose a steel pin is to be fitted as accurately as possible to a brass bush, how is it to be done to secure as accurate a fit as possible under varying temperatures? The two must be fitted at some equal temperature; if this be the lowest they will be subject to, the fit will vary by getting looser, if the highest, by getting tighter; in either case all the variation will be in one direction. If the medium temperature be selected, the fit will get tighter or looser as the temperature falls or rises. Now in workshop practice, where fit is the object sought and not a theoretical standard of size, the range of variation due to temperature and, generally, that due to a difference between the metals, is too minute to be of practical importance. To the latter, however, attention must, in the case of work of large diameter, be paid: thus, a brass piston a free fit at a temperature of 100° to a 12-inch cast-iron cylinder, will seize fast when both are at a temperature of, say, 250°. In such cases an allowance is made in conformity with the co-efficients of expansion.

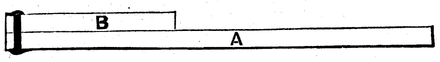

Fig. 1398.

In the case of the gauges, all that is practicable for ordinary work-shop variation of temperature is to make them of one kind and quality of material—as hard as possible and of standard diameter, when at about the mean temperature at which they will be when in use. In this case the limit of error, so far as variation from temperature is concerned, will be simply that due to the varying co-efficients of expansion of the metals of which the work is composed.

To provide a standard of lineal measurement which shall not vary under changes of temperature it has been proposed to construct a gauge such as shown in Fig. 1398, in which A and B are bars of different metals whose lengths are in the inverse ratio of their co-efficients of expansion. It is evident that the difference of their lengths will be a constant quantity, and that if the two bars be fastened together at one end, the distance from the free end of B to the free end of A will not vary with ordinary differences in temperature.

Plug and collar gauges may be used for taper as well as for parallel fits, the taper fit possessing the advantage that the bolt or pin may be let farther into its hole to take up the wear. In a report to the Master Mechanics Association upon the subject of the propriety of recommending a standard taper for bolts for locomotive work, Mr. Coleman Sellers says:—

"As the commission given to me calls for a decision as to the taper of bolts used in locomotive work, it presupposes that taper bolts are a necessity. In our own practice we divide bolts into several classes, and our rule is that in every case where a through bolt can be used it must be used. If we cannot use a through bolt we use a stud, and where a stud cannot be used we put in a tap bolt, and the reason why a tap bolt comes last is because it is part and parcel of the machine itself. There are also black bolts and body bound bolts, the former being put into holes $\frac{1}{16}$ inch larger than the bolt. It is possible in fastening a machine or locomotive together to use black bolts and body bound bolts. With body bound bolts it is customary for machine builders to use a straight reamer to true the hole, then turn the bolt and fit it into its place. It is held by many locomotive builders that the use of straight bolts is objectionable, on the score that if they are driven in tight there is much difficulty in getting them out, and where they are got out two or three times they become loose, and there is no means of making them tighter.

"There is no difficulty in making two bolts of commercially the same size. But there is a vast difference between absolute accuracy and commercial accuracy. Absolute accuracy is a thing that is not obtainable. What we have to strive for, then, is commercial accuracy. What system can we adopt that will enable workmen of limited capacity to do work that will be practically accurate? The taper bolt for certain purposes presents a very decided advantage. Bolts may be made practically of the same diameter, but holes cannot be made practically of the same diameter. Each one is only an approximation to correctness. We have here an ordinary fluted reamer (showing an excellent specimen of Betts Machine Company's make). That reamer is intended to produce a straight hole, but having once passed through a hole the reamer will be slightly worn. The next time you pass it through it is a little duller, and every time you pass it through the hole must become smaller. There have been many attempts made to produce a reamer that should be adjustable. That, thanks to the gentlemen who are making such tools a speciality, has added a very useful tool to the machine shop—a reamer where the cutters are put in tapered and can be set up and the reamer enlarged and made to suit the gauge. This will enable us to make and maintain a commercially uniform hole in our work. But the successful use of a reamer of this kind depends upon the drill that precedes this reamer being made as nearly right as possible, so that the reamer will have little work to do. The less you give a reamer to do the longer it will maintain its size.

"The question of tapered bolts involves at once this difficulty: that we have to drill a straight hole, then the tapered reamer must take out all the metal that must be removed in order to convert a straight into a tapered hole. The straight hole is maintained in its size by taking out the least amount of metal. It follows that the tapered reamer would be nearest right which would also take out the least amount of metal.

"Then you come to the question of the shape of the taper. When I was engaged building locomotives in Cincinnati, a great many years ago, we used bolts the taper of which was greater than I shall recommend to you. In regard to the compression that would take place in bolts, no piece of iron can go into another piece of iron without being smaller than the hole into which it is intended to go. If it is in any degree larger, it must compress the piece itself or stretch the material that is round it. So, if you adopt a tapered bolt, you cannot adopt a certain distance that it shall stand out before you begin to drive it, for there will be more material to compress in a large piece than in a small one. Metal is elastic. Within the elastic limit of the metal you may assume the compression to be a spring. In a large bolt you have a long spring, and in a short one you have a short spring. If you drive a half-inch bolt into a large piece of iron, it is the small bolt which you compress; therefore the larger the bolt the more pressure you can give to produce the same result. Hence, if you adopt the taper bolt, you will have to use your own discretion, unless you go into elaborate experiments to show how far the bolt head should be away from the metal when you begin to drive it.

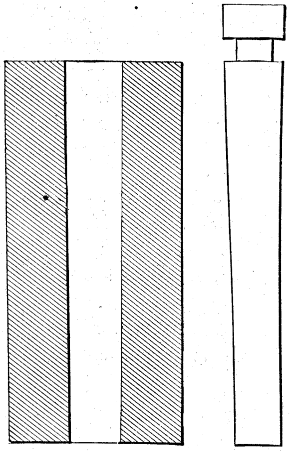

Fig. 1399.

"Certain builders of locomotives put their stub ends together with tapered bolts, but do not use tapered bolts in any other part of the structure. The Baldwin Works use tapered bolts wherever they are body bound bolts. They make a universal taper of $\frac{1}{16}$ inch to the foot. An inch bolt 12 inches long would be $1\frac{1}{16}$ inches diameter under the head. They make all their bolts under 9 inches long $\frac{1}{16}$ larger under the head than the name of the bolt implies. Thus a $\frac{3}{4}$ inch bolt would be $\frac{13}{16}$ inch under the head, provided it was 9 inches long or under. Anything over 9 inches long is made $\frac{1}{8}$ inch larger under the head, and still made a taper of $\frac{1}{16}$ inch to the foot. A locomotive builder informs me that a taper of $\frac{1}{8}$ inch to the foot is sometimes called for, and the Pennsylvania road calls for $\frac{3}{32}$ inch to the foot. But the majority of specifications call for $\frac{1}{16}$ inch to the foot. The advantage of $\frac{1}{16}$ inch taper lies in the fact that a bolt headed in the ordinary manner can be made to fill the requirements, provided it is made of iron. You may decide that bolts should be tapered, for the reason that when a tapered bolt is driven into its place it can be readily knocked loose, or if that bolt, when in its place, proves to be too loose, you have merely to drive it in a little farther: these are arguments in favor of tapered bolts, showing their advantage. It is easier to repair work that has tapered bolts than work that has straight bolts. If you adopt a tapered bolt, say, with a taper of $\frac{1}{16}$ inch to the foot, you are going to effect the making of those bolts and the boring of those holes in a commercially accurate manner, so that they can be brought into the interchangeable system. To carry this out, you require some standard to start with, and the simplest system that one can conceive is this: Let us imagine that we have a steel plug and grind it perfectly true. We have the means of determining whether that is a taper of $\frac{1}{16}$ inch, thanks to the gentlemen who are now making these admirable gauges. We have a lathe that can turn that taper. I think if you go into the manufacture of these bolts, you will be obliged to use a lathe which will always turn a uniform taper. Having made a female gauge, Fig. 1399, 8 inches long and $1\frac{1}{16}$ inches diameter with a taper of $\frac{1}{16}$ inch to the foot, this is the standard of what? The area of the bolt, not of the hole it goes into. We now make a plug, Fig. 1399. Taking that tapered plug we should be able to drop it into the hole. Your taper reamer is made to fit this, but you require to know how deep the hole should be. Remember, I said this is the gauge that the bolts are made by. Now let us suppose that we have this as a standard, and to that standard these reamers are made. We decide by practice how much compression we can put upon the metal. For inch bolts, and, say, all above $\frac{1}{2}$ inch, we might, say, allow the head to stand up $\frac{1}{8}$ of an inch. Let us make another female gauge like Fig. 1399, but turned down $\frac{1}{8}$ of an inch shorter. We then shall have the hole smaller than it was before. It is this degree smaller, ·0065 of an inch; that is a decimal representing how much smaller that hole is when you have gone down $\frac{1}{8}$ of an inch on a taper of $\frac{1}{16}$ inch to the foot.

"Having got this tapered plug, you then must have the means of making the bolts commercially accurate in the shop. For that purpose you must have some cast-iron plugs. Those are reamed with a reamer that has no guard on it, but is pushed into it until the plug—this standard plug—is flush with the end of it. If you go in a little too far it is no matter. Having produced that gauge, we gauge first the one that is used on the lathe for the workman to work by, and he will fit his bolt in until the head will be pushed up against it. If you have a bolt to make from a straight piece of iron, I should advise its being done in two lathes. Here are those beautiful gauges of the Pratt and Whitney Company, which will answer the present purpose; one of these gauges measuring what the outside of the bolt will be, the other gauge $\frac{1}{16}$ of an inch larger will mark the part under the head. Messrs. Baldwin have a very good system of gauges. All the cast-iron plugs which they use for this purpose are square. Holes are cut in the blocks the exact size of the bolts to be turned up, as shown in Fig. 1400. The object of this is that there shall be no mistake as to what the gauge is. These gauges can be readily maintained, because they have to go back into the room to the inspector. He puts this plug in. If it goes in and fits flush, it is all right. If the plug goes in too far, it is worn. He then turns a little off the end and adjusts it.

"Now practically through machine shops we find that we have to use cast-iron gauges. We take, for instance, 2-inch shafting. Shafting can only be commercially accurate. Therefore we make cast-iron rings and if those rings will go on the shafting it is near enough accurate for merchantable purposes. But this ring will wear in a certain time. Therefore it must not be used more than a certain number of days or hours. Here you have a system that is simple in the extreme. You have all this in two gauges, one gauge being made as a mere check on that tapered plug which is the origin of all things, the origin being $\frac{1}{8}$ or $\frac{1}{16}$, or $\frac{1}{4}$ of an inch shorter if the bolt is very large. There is where you have to use your own judgment. But having adopted something practical you then can use your reamer which is necessary to produce a hole of a given size. If this reamer wears, you then turn off this wrought-iron collar far enough back to let it go in that much farther. I know of no other way by which you can accomplish this result so well as by that in use at the Baldwin Locomotive Works. I think that the system originated with Mr. Baldwin himself.

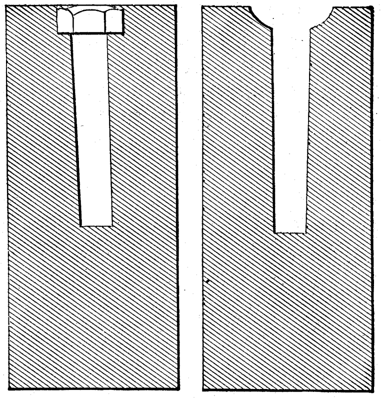

Fig. 1400.

"I do not feel disposed to recommend to you any particular taper to be adopted, because it is not a question like that of screw-threads. In screw-threads we throw away the dies that are used upon bolts, which are perishable articles. The taper that has once been adopted in locomotive establishments is a perpetual thing. If the Pennsylvania railroad and all its branches have adopted $\frac{3}{32}$, it is folly to ask them to change it to $\frac{1}{16}$ of an inch, because their own connections are large enough to make them independent of almost any other corporation, and the need of absolute uniformity in their work would cause them to stick to that particular thing. Any of you having five, six, seven, or two or three hundred engines, must make up your minds what you will do. When we adopt a standard for screw-threads, a screw-thread is adopted which has a manifest advantage. A bolt that has one screw thread can be used on any machine. But once having adopted a taper on a road, it is very difficult to make a change; and whether it is wisdom for this Association to say that thus-and-so shall be the standard taper, is a question I am unable to answer. Therefore I am unwilling to present any taper to you, and only present the facts, but will say that $\frac{1}{16}$ inch is enough. The less taper you have the less material you have to cut away. But to say that $\frac{1}{16}$ inch is preferable to $\frac{1}{32}$ inch is folly, because no human being could tell the difference. If a bolt has 5° taper on the side, it may set in place; if it has 7°, it may jump out. That is the angle of friction for iron or other metals. Five degrees would be an absurd angle for a taper bolt. Anything, then, that will hold; that is, if you drive the bolt it will set there.

"This presentation may enable you to arrive at some conclusion. Nothing is more desirable than an interchangeable system. In making turning lathes we try to make all parts interchangeable, and we so fit the sliding spindle. Every sliding spindle in the dead head of the lathe has to be fitted into its own place. We know of no method of making all holes of exactly the same size that shall be commercially profitable. The only way we could surmount that difficulty was to put two conical sleeves in that should compress. We have so solved the problem. We now make spindles that are interchangeable, and we do not fit one part to the other. But that is not the case with bolts. You cannot put the compressing thimbles on them, therefore, you have to consider the question, How can you make holes near enough, and how can you turn the bolts near enough alike?"

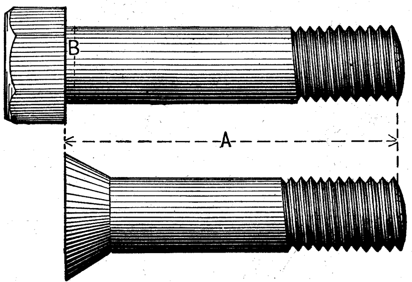

Fig. 1401.

Fig. 1401 represents, and the following table gives the taper adopted by the Baldwin Locomotive Works.

Bolt threads, American standard, except stay bolts and boiler studs, V-threads, 12 per inch; valves, cocks and plugs, V-threads, 14 per inch, and $\frac{1}{8}$ inch taper per 1 inch.

Standard bolt taper $\frac{1}{16}$ inch per foot.

Length of bolts from head to end of thread equals A.

Diameter of bolt under the head as follows:—

$\frac{3}{64}$	inch larger	at B	for 9 inch and under
$\frac{1}{16}$	,,	,,	over 9 inch to 12 inch
$\frac{3}{32}$	,,	,,	,, 12 ,, to 18 ,,
$\frac{1}{8}$	,,	,,	,, 18 ,, to 24 ,,
$\frac{5}{32}$	,,	,,	,, 24 ,, to 30 ,,
$\frac{3}{16}$	,,	,,	,, 30 ,, to 36 ,,

It is obvious that a plug or collar gauge simply determines what is the largest dimension of the work, and that although it will demonstrate that a piece of work is not true or round yet it will not measure the amount of the error. The work may be oval or elliptical, or of any other form, and yet fit the gauge so far as the fit can be determined by the sense of feeling. Or suppose there is a flat place upon the work, then except in so far as the bearing marks made upon the work by moving it within the gauge may indicate, there is no means of knowing whether the work is true or not. Furthermore, in the case of lathe work held between the lathe centres it is necessary to remove the work from the lathe before the collar gauge can be applied, and to obviate these difficulties we have the caliper gauge shown in Fig. 1402. The caliper end is here shown to be for $\frac{3}{4}$ inch, and the plug end for $\frac{13}{16}$ inch. If the two ends were for the same diameter one gauge only would be used for measuring external and internal work of the same diameter, but in this case the male cannot be tested with the female gauge; whereas if the two ends are for different diameters the end of one gauge may be tested with that of another, and their correctness tested, but the workman will require two gauges to measure an external and internal piece of the same diameter.

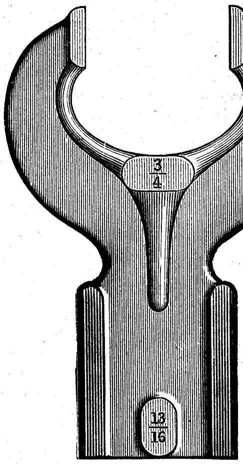

Fig. 1402.

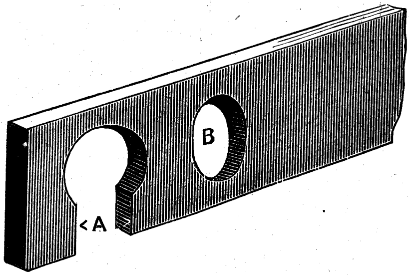

Fig. 1403.

For small lathe work of odd size as when it is required to turn work to fit holes reamed by a worn reamer that is below the standard size, a gauge such as in Fig. 1403, is sometimes used, the mouth A serving as a caliper and the hole B as a collar gauge for the same diameter of work. It is obvious that such a gauge may be applied to the work while it is running in the lathe, and that when the size at A wears too large the jaw may be closed to correct it; a plan that is also pursued to rectify the caliper gauge shown in Fig. 1402.

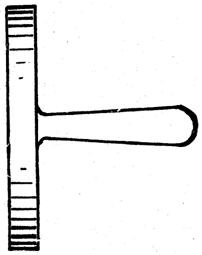

Fig. 1404.

On large work, as, say, of six inches in diameter, a gauge, such as in Fig. 1404, is used, being short so that it may be light enough to be conveniently handled; or sometimes a piece such as in Fig. 1405 is used as a gauge, the ends being fitted to the curvature of the bore to be tested. Gauges of these two kinds, however, are generally used more in the sense of being templates rather than measuring tools, since they determine whether a bore is of the required size rather than determine what that size is.

For gauging work of very large diameter, as, say, several feet, to minute fractions of an inch, as is necessary, for example, for a shrinkage fit on a locomotive tire, the following method is employed. In Fig. 1406 let A represent a ring, say, 5 feet bore, and requiring its bore to be gauged to within, say, $\frac{1}{100}$ inch. Then R represents a rod made, say, $\frac{1}{2}$ inch shorter than the required diameter of bore, and W, Fig. 1407, represents a wedge whose upper surface C D is curved, its lower surface being a true plane. The thickness at the end C is made, say, $\frac{51}{100}$ inch, while that at D is $\frac{48}{100}$ inch; or in other words, there is $\frac{3}{100}$ of an inch taper in the length of the wedge. Suppose then that the rod R is placed in the bore of A as in figure, and that the wedge just has contact with the work bore and with the end of the rod when it has entered as far as E in Fig. 1407, and that point E is one-third of the length of the wedge, then the bore of A will measure the length of the rod R plus $\frac{49}{100}$ of an inch. But if the wedge passed in to line F, the latter being two-thirds the length of the wedge from D, then the bore would be $\frac{50}{100}$ larger than the length of the rod R. It is obvious that with this method the work may be measured very minutely, and the amount of error, if there be any, may be measured.

Fig. 1405.

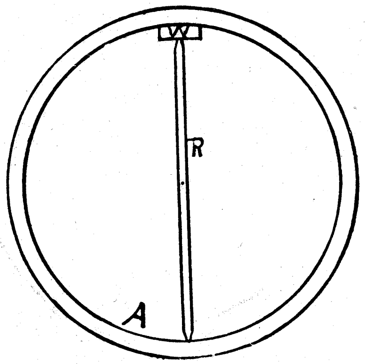

Fig. 1406.

The rod must be applied to the work in the same position in which its measurement was made, otherwise its deflection may vitiate the measurement. Thus, if the rod measures 4 feet 11½ inches when standing vertical, it must be applied to the work standing vertical; but if it was measured lying horizontal, it must be applied to the work lying horizontal, as there will be a difference in its length when measured in the two positions, which occurs on account of variations in its deflection from its own weight.

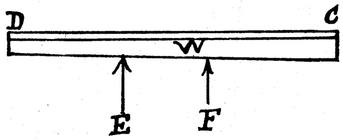

Fig. 1407.

For simply measuring a piece of work to fit it to another irrespective of its exact size as expressed in inches and parts of an inch the common calipers are used. Fig. 1408 represents a pair of spring calipers, the bow acting as a spring to keep the two legs apart, and the screw and nut being used to close them against the spring pressure. The slightness of the legs enables these calipers to be forced or to spring over the work, and thus indicate by the amount of pressure it requires to pass them over the work how much it is above size, and therefore how much it requires to be reduced. But, on the other hand, this slightness renders it somewhat difficult to measure with great correctness. A better form of outside calipers is shown in Fig. 1409, in which in addition to the stiffness of the pivoted joint a bow spring acts to close the caliper legs, which are operated, to open or close them, by operating the hand screw shown, the nuts in which the screw operates being pivoted to the caliper legs. The advantage of this form is that the calipers may be set very readily, while there is no danger of the set or adjustment of the calipers altering from any slight blow or jar received in laying them down upon the bench.

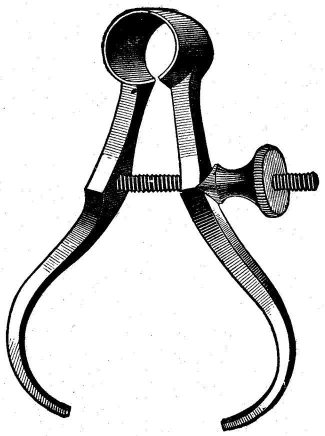

Fig. 1408.

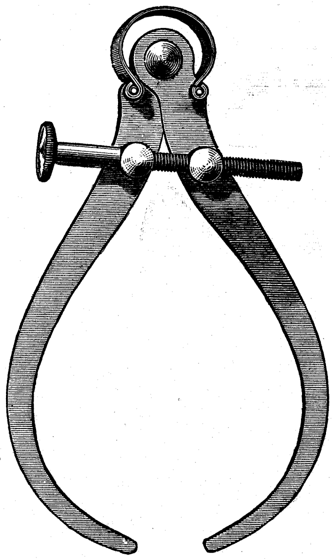

Fig. 1409.

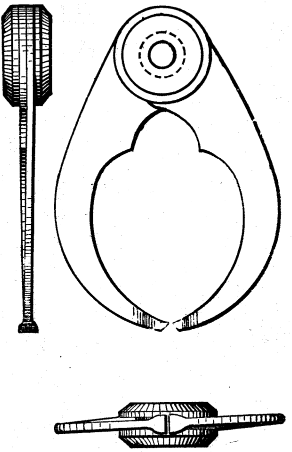

Fig. 1410.

Fig. 1410 gives views of a common pair of outside calipers such as the workman usually makes for himself. When this form is made with a sufficiently large joint, and with the legs broad and stiff as in the figure, they will serve for very fine and accurate adjustments.

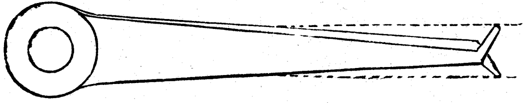

Fig. 1411.

Fig. 1411 represents a pair of inside calipers for measuring the diameters of holes or bores. The points of these calipers should be at an angle as shown in the Fig. 1412, which will enable the points to enter a long distance in a small hole, as is denoted by the dotted lines in the figure. This will also enable the extreme points to reach the end of a recess, as in Fig. 1413, which the rounded end calipers, such as in this figure, will not do.

Fig. 1414 represents a pair of inside calipers with an adjustment screw having a right-hand screw at A and a left-hand one at B, threaded into two nuts pivoted into the arms, so that by operating the screw the legs are opened or closed, and are locked in position, so that they cannot move from an accidental blow. But as the threads are apt to wear loose, it is preferable to provide a set screw to one of the nuts so as to take up the wear and produce sufficient friction to prevent looseness of the legs.

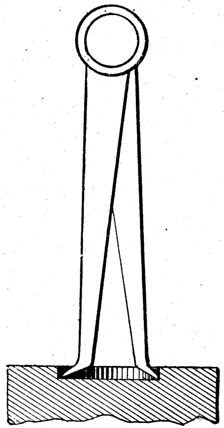
Fig. 1412.

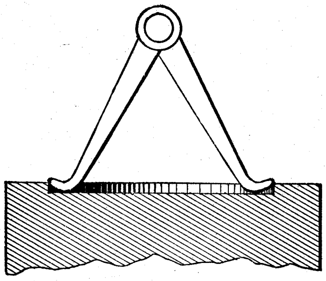
Fig. 1413.

Calipers are sometimes made double, that is to say, the inside and the outside calipers are provided in the one tool, as in Fig. 1415, which represents a pair of combined inside and outside calipers having a set screw at C to secure the legs together after the adjustment is made. The object of this form is to have the measuring points equidistant from the centre of the pivot A in Fig. 1416, so that when the outside legs are set to the diameter of the work as at B, the inside ones will be set to measure a hole or bore of the same diameter as at C.

This, however, is not a desirable form for several reasons, among which are the following:—

In the first place outside calipers are much more used than inside ones, hence the wear on the points are greatest. Again, the pivot is apt to wear, destroying the equality of length of the points from the centre of the pivot; and in the third place the shape of the points of calipers as usually made vitiates the correctness of the measurements.

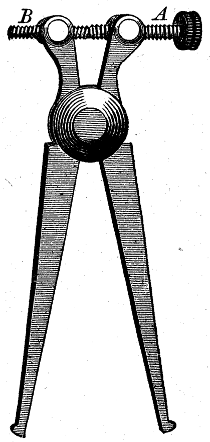

Fig. 1414.

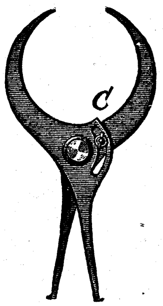

Fig. 1415.

Fig. 1417, for example, represents the ordinary form, the points being rounded; hence, when the legs are closed the point of contact between the inside and outside calipers will be at A, while when they are opened out to their fullest the points of contact will be at B. This may, however, be remedied to a great extent by bevelling off the ends from the outside as shown in Fig. 1416.

The end faces of outside calipers should be curved in their widths, as in Fig. 1418, so that contact shall occur at the middle, and it will then be known just where to apply the points of the inside calipers when testing them with the outside ones.

Inside and outside calipers are capable of adjustment for very fine measurements; indeed, from some tests made by the Pratt and Whitney Company among their workmen it was found that the average good workman could take a measurement with them to within the twenty-five thousandth part of an inch. But the workman of the general machine shop who has no experience in measuring by thousandths has no idea of the accuracy with which he sets two calipers in his ordinary practice. The great difference that the one-thousandth of an inch makes in the fit of two pieces may be shown as in Fig. 1419, which represents a collar gauge of $\frac{5}{8}$ inch in diameter, and a plug $\frac{1}{1000}$ inch less in diameter, and it was found that with the plug inserted $\frac{1}{8}$ inch in the collar it could be moved from A to B, a distance of about $\frac{5}{16}$ inch, which an ordinary workman would at once recognise as a very loose fit.

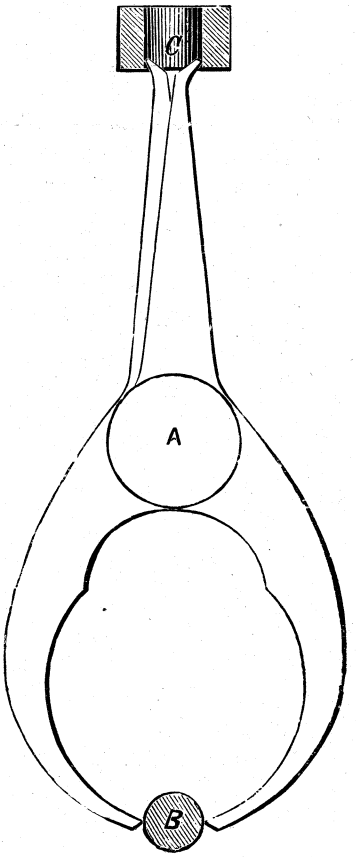

Fig. 1416.

If the joints of outside calipers are well made the calipers may upon small work be closed upon the work as in Fig. 1420, and the adjustment may be made without requiring to tap or lightly knock the caliper legs against the work as is usually done to set them. But to test the adjustment very finely the work should be held up to the light, as in Fig. 1421, the lower leg of the calipers rested against the little finger so as to steady it and prevent it from moving while the top leg is moved over the work, and at the same time moving it sideways to find when it is held

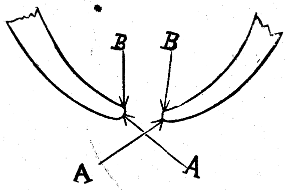

Fig. 1417.

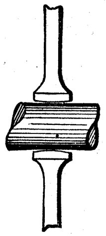
Fig. 1418.

directly across the work. For testing the inside and outside calipers together they should for small diameters be held as in Fig. 1422, the middle finger serving to steady one inside and one outside leg, while one leg only of either calipers is grasped in the fingers.

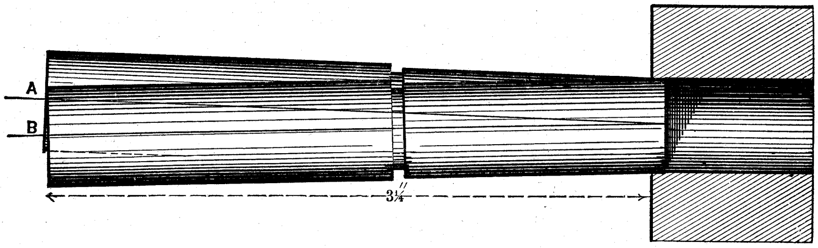

Fig. 1419.

For larger dimensions, as six or eight inches, it is better, however, to hold the calipers as in Fig. 1423, the forefinger of the left hand serving to rest one leg of each pair on the contact being thus tested between the legs that are nearest to the operator.

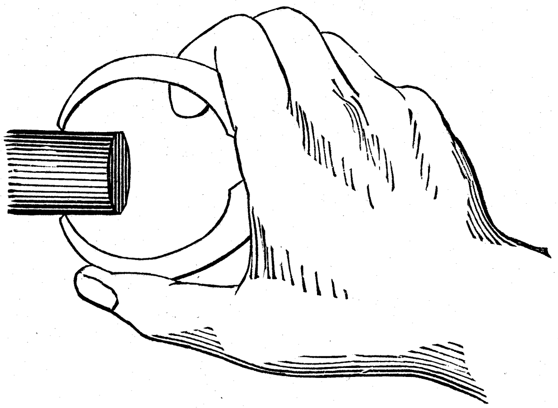

Fig. 1420.

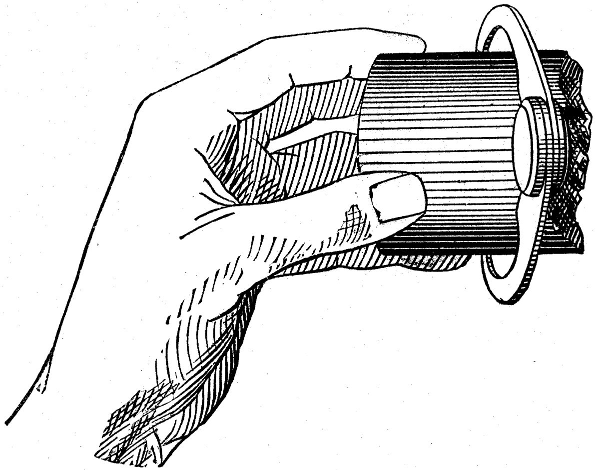

Fig. 1421.

The adjustment of caliper legs should be such that contact between the caliper points and the work is scarcely, if at all, perceptible. If with the closest of observation contact is plainly perceptible, the outside calipers will be set smaller than the work, while in the case of inside calipers, they would be set larger; and for this reason it follows that if a bore is to be measured to have a plug fitted to it, the inside calipers should have barely perceptible contact with the work bore, and the outside calipers should have the same degree of contact, or, if anything, a very minute degree of increased contact. On the other hand, if a bore is to be fitted to a cylindrical rod the outside calipers should be set to have the slightest possible contact with the rod, and the inside ones set to have as nearly as possible the same degree of contact with the outside ones, or, if anything, slightly less contact. For if in any case the calipers have forcible contact with the work the caliper legs will spring open and will therefore be improperly set.

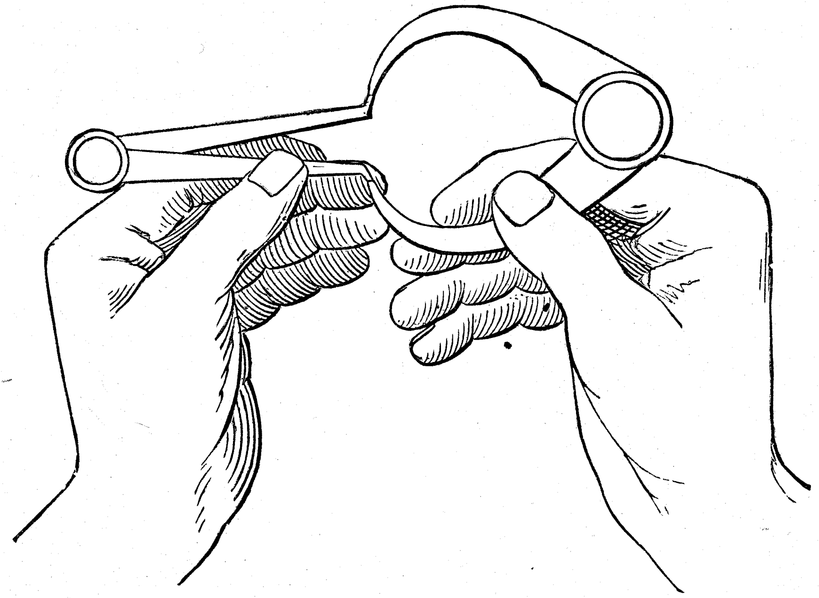

Fig. 1422.

Calipers should be set both to the gauge and to the work in the same relative position. Let it be required, for example, to set a pair of inside calipers to a bore, and a pair of outside calipers to the inside ones, and to then apply the latter to the work. If the legs of the inside calipers stand vertical to the bore for setting they should stand vertical while the outside calipers are set to them, and if the outside calipers are held horizontally while set to the inside ones they should be applied horizontally to the work, so as to eliminate any error due to the caliper legs deflecting from their own weight.

To adjust calipers so finely that a piece of work may be turned by caliper measurement to just fit a hole, a working or a driving fit without trying the pieces together, is a refinement of measurement requiring considerable experience and skill, because, as will be readily understood from the remarks made when referring to gauge measurements, there are certain minute allowances to be made in the set of the calipers to obtain the desired degree of fit.

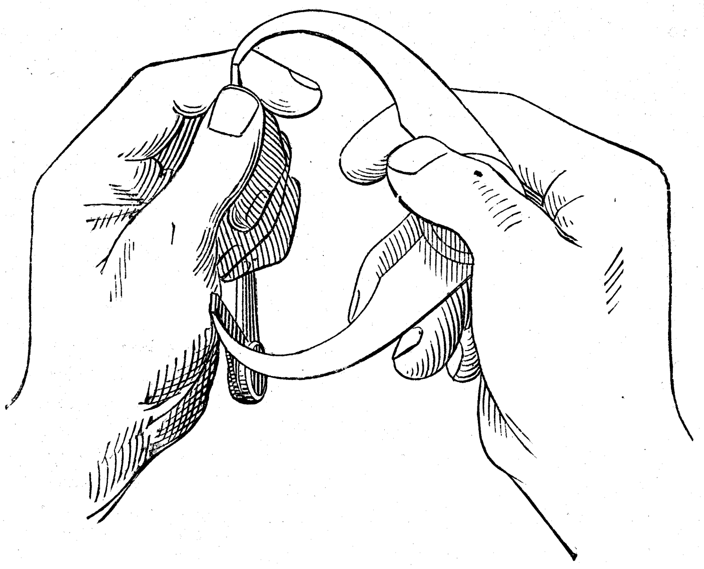

Fig. 1423.

In using inside calipers upon flat surfaces it will be found that they can be adjusted finer by trusting to the ear than the eye. Suppose, for example, we are measuring between the jaws of a pillow-block. We hold one point of the calipers stationary, as before, and adjust the other point, so that, by moving it very rapidly, we can just detect a scraping sound, giving evidence of contact between the calipers and the work. If, then, we move the calipers slowly, we shall be unable, with the closest scrutiny, to detect any contact between the two.

Calipers possess one great advantage over more rigid and solid gauges, in that the calipers may be forced over the work when the degree of force necessary to pass them on indicates how much the work is too large, and therefore how much it requires reducing. Thus, suppose a cylindrical piece of work requires to be turned to fit a hole, and the inside calipers are set to the bore of the latter, then the outside calipers may be set to the inside ones and applied to the work, and when the work is reduced to within, say, $\frac{1}{100}$ inch the calipers will spring open if pressed firmly to the work, and disclose to the workman that the work is reduced to nearly the required size. So accustomed do workmen become in estimating from this pressure of contact how nearly the work is reduced to the required diameter, that they are enabled to estimate, by forcing the calipers over the work, the depth of the cut required to be taken off the work, with great exactitude, whereas with solid gauges, or even caliper gauges of solid proportions, this cannot be done, because they will not spring open.

The amount to which a pair of calipers will spring open without altering their set depends upon the shape: thus, with a given joint they will do so to a greater extent in proportion as the legs are slight, whereas with a given strength of leg they will do so more as the diameter of the joint is large and the fit of the joint is a tight one. But if the joint is so weak as to move too easily, or the legs are so weak as to spring too easily, the calipers will be apt in one case to shift when applied to the work, and in the other to spring so easily that it will be difficult to tell by contact when the points just touch the work and yet are not sprung by the degree of contact. For these reasons the points of calipers should be made larger in diameter than they are usually made: thus, for a pair of calipers of the shape shown in Fig. 1410, the joint should be about 1¼ inches diameter to every 6 inches of length of leg. The joint should be sufficiently tight that the legs can just be moved when the two legs are taken in one hand and compressed under heavy hand pressure.

For measuring the distance of a slot or keyway from a surface, the form of calipers shown in Fig. 1424 is employed; the straight leg has its surface a true plane, and is held flat against the surface B of the slot or keyway, and the outside or curved leg is set to meet the distance of the work surface measuring the distance C. These are termed keyway calipers.

There are in general machine work four kinds of fit, as follow: The working or sliding fit; the driving fit; the hydraulic press fit; and the shrinkage fit. In the first of these a proper fit is obtained when the surfaces are in full contact, and the enveloped piece will move without undue friction or lost motion when the surfaces are oiled. In the second, third, and fourth, the enveloped piece is made larger than the enveloping piece, so that when the two pieces are put together they will be firmly locked.

It is obvious that in a working or sliding fit the enveloped piece must be smaller than that enveloping it, or one piece could not pass within the other. But the amount of difference, although too small to be of practical importance in pieces of an inch or two in diameter and but few inches in length, is appreciable in large work, as, say, of two or more feet in diameter. A journal, for example, of $\frac{1}{10}$ inch diameter, running in a bearing having a bore of $\frac{1}{1000}$ inch larger diameter, and being two diameters in length, would be instantly recognised as a bad fit; but a journal 6 inches in diameter and two diameters or 12 inches long would be a fair fit in a bearing having a bore of $6\frac{1}{1000}$ inches. In the one case the play would be equal to one one-hundredth of the shaft's diameter, while in the other case the play would equal but one six-thousandth part of the shaft's diameter. In small work the limit of wear is so small, and the length of the pieces so short, that the $\frac{1}{1000}$ of an inch assumes an importance that does not exist in larger work. Thus, in watch work, an error of $\frac{1}{1000}$ inch in diameter may render the piece useless; in sewing machine work it may be the limit to which the tools are allowed to wear; while in a steamship or locomotive engine it may be of no practical importance whatever.

A journal $\frac{1}{10}$ inch in diameter would require to run, under ordinary conditions, several years to become $\frac{1}{1000}$ inch loose in its bearing. Some of this looseness, and probably nearly one half of it, will occur from wear of the bearing bore; hence, if a new shaft of the original standard diameter be supplied the looseness will be reduced by one-half. But a 6-inch journal and bearing would probably wear nearly $\frac{1}{1000}$ inch loose in wearing down to a bearing which may take but a week or two, and for

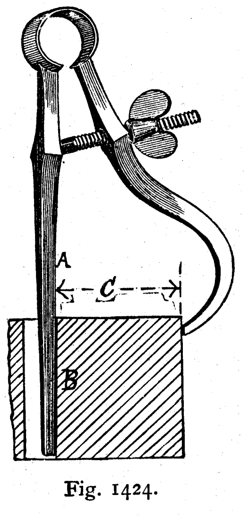

Fig. 1424.

these reasons among others, standard gauges and measuring tools are less applicable to large than to small work.

The great majority of fits made under the standard gauge system consist of cylindrical pieces fitting into holes or bores. Suppose then that we have a plug and a collar gauge each of an inch diameter, and a reamer to fit the collar gauge, and we commence to ream holes and to turn plugs to fit the collar gauge, then as our work proceeds we shall find that as the reamer wears, the holes it makes will get smaller, and that as the collar gauge wears, its bore gets larger, and it is obvious that the work will not go together. The wear of the gauge obviously proceeds slowly, but the wear of the reamer begins from the very first hole that it reams, although it may perform considerable duty before its wear sensibly affects the size of the hole. Theoretically, however, its size decreases from the moment it commences to perform cutting duty until it has worn out, and the point at which the wearing-out process may have proceeded to its greatest permissible limit is determined by its reduction of size rather than by the loss of its sharpness or cutting capacity. Obviously then either the reamer must be so made that its size may be constantly adjusted to take up the wear, as in the adjustable reamer, or else if solid reamers are used there must be a certain limit fixed upon as the utmost permissible amount of wear, and the reamer must be made above the standard size to an amount equal to the amount of this limit, so that when the reamer has worn down it will still bore a hole large enough to admit the plug gauge. To maintain the standard there should be in this case two sets of gauges, one representing the correct standard and the other the size to which the reamer is to be made when new or restored to its proper size.

The limit allowed for reamer wear varies in practice from $\frac{1}{1000}$ to $\frac{1}{10000}$ of an inch, according to the requirements of the work. As regards the wear of the standard gauges used by the workmen they are obviously subject to appreciable wear, and must be returned at intervals to the tool room to be corrected from gauges used for no other purpose.

To test if a hole is within the determined limit of size a limit gauge may be used. Suppose, for example, that the limit is $\frac{1}{1000}$ of an inch, then a plug gauge may be made that is $\frac{1}{1000}$ of an inch taper, and if the large end of this plug will enter the hole, the latter is too large, while if the small end will not enter, the hole is too small.

When only a single set of plug and collar gauges are at hand the plug or the collar gauge may be kept to maintain the standard, the other being used to work to, both for inside and outside work. Suppose, for example, that a plug and collar gauge are used for a certain piece of work and that both are new, then the reamer may be made from either of them, because their sizes agree, but after they have become worn either one or the other must be accepted as the standard of size to make the reamer to. If it be the collar gauge, then the plug gauge is virtually discarded as a standard, except in that if the plug gauge be not used at all it may be kept as a standard of the size to which the collar gauge must be restored when it has worn sufficiently to render restoration to size necessary. If this system be adopted the size of the reamer will be constantly varying to suit the wear of the collar gauge, and the difficulty is encountered that the standard lathe arbors or mandrels will not fit the holes produced, and it follows that if standard mandrels are to be used the reamers must when worn be restored to a standard size irrespective of the wear of the gauges, and that the standard mandrels must be made to have as much taper in their lengths as the limit of wear that is allowed to the reamers. Suppose, for example, that it is determined to permit the reamer to wear the $\frac{1}{2000}$ of an inch before restoring it to size, then in an inch mandrel the smallest end may be made an inch in diameter and the largest $1\frac{1}{2000}$ inch in diameter, so that however much the reamer may be worn within the limit allowed for wear the hole it produces will fit at some part in the length of the standard mandrel. But as the reamer wears smaller its size must be made as much above its designated standard size as the limit allowed for wear; hence, when new or when restored to size, the reamer would measure $1\frac{1}{2000}$ inches, and the hole it produced would fit the large end of the mandrel. But as the reamer wore, the hole would be reamed smaller and would not pass so far along the mandrel, until finally the limit of reamer wear being reached the work would fit the small end of the mandrel. The small end of the mandrel is thus the standard of its size, and the wear of the collar gauge is in the same direction as that of the reamer. Thus, so long as the collar gauge has not worn more than the $\frac{1}{2000}$ of an inch it will, if placed upon the mandrel, fit it at some part of its length.

Now suppose that the plug gauge be accepted as the standard to which the reamer is to be made, and that to allow for reamer wear the reamer is made, say, $\frac{1}{2000}$ inch larger than the plug gauge, the work being made to the collar gauge. Then with a new reamer and new or unworn gauges the hole will be reamed above the standard size to the $\frac{1}{2000}$ inch allowed for reamer wear. As the reamer wears, the hole it produces will become smaller, and as the collar gauge wears, the work turned to it will be larger, and the effect will be that, to whatever extent the collar gauge wears, it will reduce the permissible amount of reamer wear, so that when the collar gauge had worn the $\frac{1}{2000}$ inch the work would not go together unless the reamer was entirely new or unworn.

In a driving fit one piece is driven within the other by means of hammer blows, and it follows that one piece must be of larger diameter than the other, the amount of the difference depending largely upon the diameter and length of the work.

It is obvious, however, that the difference may be so great that with sufficiently forcible blows the enveloping piece may be burst open. When a number of pieces are to be made a driving fit, the two pieces may be made to fit correctly by trial and correction, and from these pieces gauges may be made so that subsequent pieces may be made correct by these gauges, thus avoiding the necessity to try them together.

In fitting the first two pieces by fit and trial, or rather by trial and correction, the workman is guided as to the correctness of the fit by the sound of the hammer blows, the rebound of the hammer, and the distance the piece moves at each blow. Thus the less the movement the more solid the blow sounds, and the greater the rebound of the hammer the tighter the fit, and from these elements the experienced workman is enabled to know how tightly the pieces may be driven together without danger of bursting the outer one.

What the actual difference in diameter between two pieces may require to be to make a driving fit is governed, as already said, to a great extent by the dimensions of the pieces, and also by the nature of the material and the amount of area in contact. Suppose, for example, that the plug is 6 inches long, and the amount of pressure required to force it within the collar will increase with the distance to which it is enveloped by the collar. Or suppose one plug to be 3 inches and another to be 6 inches in circumference, and each to have entered its collar to the depth of an inch, while the two inside or enveloped pieces are larger than the outside pieces by the same amount, the outside pieces being of equal strength in proportion to their plugs, so that all other elements are equal, and then it is self-evident that the largest plug will require twice as much power as the small one will to force it in another inch into the collar, because the area of contact is twice as great. It is usual, therefore, under definite conditions to find by experiment what allowance to make to obtain a driving or a forcing fit. Thus, Mr. Coleman Sellers, at a meeting of the Car Builders Association, referring to the proper amount of difference to be allowed between the diameters of car axles and wheel bores in order to obtain a proper forcing or hydraulic fit, said, "Several years ago some experiments were made to determine the difference which should be made between the size of the hole and that of the axle. The conclusion reached was that if the axle of standard size was turned 0·007 inch larger than the wheel was bored it would require a pressure of about 30 tons to press the axle into the wheel." The wheel seat on the axle here referred to was $4\frac{7}{8}$ inches in diameter and 7 inches long. It is to be remarked, however, that the wheel bore being of cast iron and the axle of wrought iron the friction between the surfaces was not the same as it would be were the two composed of the same metal. This brings us to a consideration of what difference in the forcing fit there will be in the case of different metals, the allowance for forcing being the same and the work being of the same dimensions.

Suppose, for example, that a wrought-iron plug of an inch in diameter is so fitted to a bore that when inserted therein to a distance of, say, 2 inches, it requires a pressure of 3 lbs. to cause it to enter farther, then how much pressure would it take if the bore was of cast iron, of yellow brass, or of steel, instead of wrought iron. This brings us to another consideration, inasmuch as the elasticity and the strength of the enveloping piece has great influence in determining how much to allow for a driving, forcing, or a shrinkage fit.

Obviously the allowance can be more if the enveloping piece be of wrought iron, copper, or brass, than for cast iron or steel, because of the greater elasticity of the former. Leaving the elasticity out of the question, it would appear a natural assumption that the pieces, being of the same dimensions, the amount of force necessary to force one piece within the other would increase in proportion as the equivalents of friction of the different metals increased.

This has an important bearing in practice, because the fit of pieces not made to standard gauge diameter is governed to a great extent by the pressure or power required to move the pieces. Thus, let a steel crosshead pin be required to be as tight a fit into the crosshead as is compatible with its extraction by hand, and its diameter in proportion to that of the bore into which it fits will not be the same if that bore be of wrought iron, as it would be were the bore of steel, because the coefficient of friction for cast steel on cast iron is not the same as that for steel on wrought iron. In other words, the lower the coefficient of friction on the two surfaces the less the power required to force one into the other, the gauge diameters being equal. In this connection it may be remarked that the amount of area in contact is of primary importance, because in ordinary practice the surfaces of work left as finished by the steel cutting tools are not sufficiently true and smooth to give a bearing over the full area of the surfaces.

This occurs for the following reasons. First, work to be bored must be held (by bolts, plates, chuck-jaws, or similar appliances) with sufficient force to withstand the pressure of the cut taken by the cutting tool, and this pressure exerts more or less influence to spring or deflect the work from its normal shape, so that a hole bored true while clamped will not be so true when released from the pressure of the holding clamps.

To obviate this as far as possible, expert workmen screw up the holding devices as tight as may be necessary for the heavy roughing cuts, and then slack them off before taking the finishing cuts.

Secondly, under ordinary conditions of workshop practice, the steel cutting tools do not leave a surface that is a true plane in the direction of the length of the work, but leave a spiral projection of more or less prominence and of greater or less height, according to the width of that part of the cutting edge which lies parallel to the line of motion of the tool feed, taken in proportion to the rate of feed per revolution of the work.

Let the distance, Fig. 1424A, A to B lie in the plane of motion of the tool feed, and measure, say, $\frac{1}{4}$ inch, the tool moving, say, $\frac{5}{16}$ inch along the cut per lathe revolution. Suppose the edge from B to D to lie at a minute angle to the line of tool traverse, and the depth of the cut to be such that the part from B to C performs a slight cutting or scraping duty, then the part from B to C will leave a slight ridge on the work plainly discernible to the naked eye in what are termed the tool marks.

The obvious means of correcting this is to have the part A B of greater width than the tool will feed along the cut, during one revolution of the work (or the cutter, as the case may be); but there are practicable obstacles to this, especially when applied to wrought iron, steel, or brass, because the broader the cutting edge of a tool the more liable it is to spring, as well as to jar or chatter, leaving a surface showing minute depressions lying parallel to the line of tool feed.

If the cutting tool be made parallel and cylindrical on its edges, and clearance be given on the front end of its diameter only, so as to cut along a certain distance only of its cylindrical edge, the rest being a close fit to the bore of the work, the part having no cutting edge, that is, the part without clearance, will be apt to cause friction by rubbing the bore of the work as the tool edge wears, and the friction will cause heat, which will increase as the cut proceeds, causing the hole to expand as the cut proceeds, and to be taper when cooled to an equal degree all over. This may be partly obviated by giving the tool a slow rate of cutting speed, and a quick rate of feed, which will greatly reduce the friction and consequently the heating of the tool and the work. On cast iron it is possible to have a much broader cutting edge to the tool, without inducing the chattering referred to, than is the case with wrought iron, steel, or brass, especially when the finishing cut is a very light one. If the finishing cut be too deep, the surface of the work, if of cast iron, will be pitted with numerous minute holes, which occur because the metal breaks out from the strain placed on it (and due to the cut) just before it meets the cutting edge of the tool. Especially is this the case if the tool be dull or be ground at an insufficiently acute angle.

When the work shows the tool marks very plainly, or if of cast iron shows the pitting referred to (instead of having a smooth and somewhat glossy appearance), there will be less of its surface in contact with the surface to which it fits, and the fit will soon become destroyed, because the wearing surface or the gripping surface, as the case may be, will the sooner become impaired, causing looseness of the fit. In the one case the abrasion which should be distributed over the whole area of the fitting parts is at first confined to the projections having contact, which, therefore, soon wear away. In the other case the projecting area in contact compresses, causing looseness of the fit.

Hydraulic press or forcing fits.—For securing pieces together by forcing one within the other by means of an hydraulic press, the plug piece is made a certain amount larger than the bore it is to enter, this amount being termed the allowance for forcing. What this allowance should be under any given conditions for a given metal, will depend upon the truth and smoothness of the surfaces, and on this account no universal rule obtains in general practice. From some experiments made by William Sellers & Co., it was determined that if a wheel seat (on an axle) measuring $4\frac{7}{8}$ inches in diameter and 7 inches long was turned $\frac{7}{1000}$ of an inch larger than the wheel bore, it would require a pressure of about thirty tons to force the wheel home on the axle.

At the Susquehanna shops of the Erie railroad the measurements are determined by judgment, the operatives using ordinary calipers. If an axle $3\frac{1}{2}$ diameter and 6 inches long requires less than 25 tons it is rejected, and if more than 35 tons it is corrected by reducing the axle.

In order to insure a proper fit of pieces to be a driven or forced fit it is sometimes the practice to make them taper, and there is a difference of opinion among practical mechanics as to whether taper or parallel fits are the best. Upon this point it may be remarked that it is much easier to measure the parts when they are parallel than when they are taper, and it is easier to make them parallel than taper.

On the elevated railroads in New York city, the wheel bores being $4\frac{1}{8}$ inches in diameter and 5 inches long, the measurements are taken by ordinary calipers, the workmen judging how much to allow, and the rule is to reject wheels requiring less than about 26 tons, or more than about 35 tons, to force them on. These wheels form excellent examples, because of the excessive duty to which they are subjected by reason of the frequency of their stoppage under the pressure of the vacuum brake. The practice with these wheels is to bore them parallel, finishing with a feed of $\frac{1}{4}$ inch per lathe revolution, and to turn the axle seats taper just discernible by calipers.

This may, at first sight, seem strange, but examination makes it reasonable and plain. Let a wheel having a parallel bore be forced upon a parallel axle, and then forced off again, and the bore of the wheel will be found taper to an appreciable amount, but increasing in proportion as the surface of the hole varied from a dead smoothness; in other words, varying with the depth of the tool marks in the bore and the smoothness of the cut.

Let the length of the wheel bore be 7 inches long, and the amount allowed for forcing be ·004 inch, and one end of the wheel bore will have been forced (by the time it is home on the axle) over the length of 7 inches of the axle-seat, whose diameter was ·004 larger than the bore: a condensation, abrasion, or smoothing of the metal must have ensued.

Now the other end of the same bore, when it takes its bearing on the shaft, is just iron, and iron without having suffered any condensation. If the tool marks be deep, those on one end will be smoothed down while those at the other remain practically intact. Clearly then, for a parallel hole, a shaft having as much taper as the wheel bore will get in being forced over the shaft best meets the requirements; or, for a parallel shaft or seat, and a taper hole (the taper being proportioned as before), the small end of the taper hole should be first entered on the shaft, and then when home both the axle and the wheel-bore will be parallel.

It may be remarked that the wheel seat on the axle will also be affected, which is quite true, but the axle is usually of the hardest metal and has the smoothest surface, hence it suffers but little; not an amount of any practical importance.

In an experiment upon this point made in the presence of the author by Mr. Howard Fry and the master mechanic of the Renovo shops of the Philadelphia and Erie railroad, an axle seat finished by a Whitney "doctor," and parallel in diameter, was forced into a wheel having a parallel bore, and removed immediately. On again measuring the axle, the wheel-seat was found to be $\frac{1}{1000}$ taper in its length.

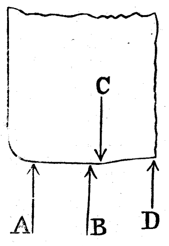

Fig. 1424A.

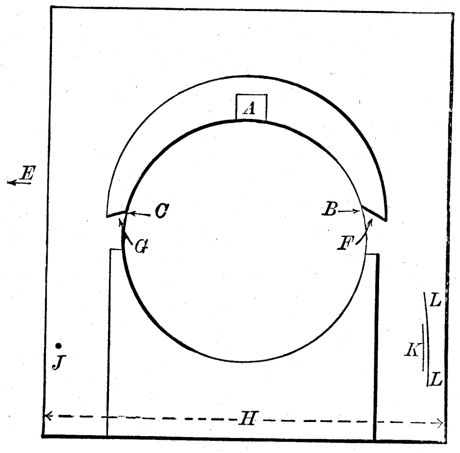

Fig. 1425.

The wheel-bore was found to be but slightly affected in its diameter, which is explained because it being very smooth, while the turning marks in the axle were plainly visible, the abrasion fell mainly upon the latter.

When the enveloping piece or bore is not solid or continuous, but is open on one side, the degree of the fit may be judged from the amount that it opens under the pressure of the plug piece.

Thus the axle brasses of American locomotives are often made circular at the back, as shown in Fig. 1425, and are forced in endways by hydraulic pressure. The degree of tightness of the brass within the box may, of course, be determined by the amount of pressure it requires to force it in, but another method is to mark a centre punch dot as at J, and before the brass is put in mark from this dot as a centre an arc of a circle as L L. When the brass is home in the box a second arc K is marked, the distance between L and K showing how much the brass has sprung the box open widening at H. In an axle box whose bore is about 4 inches to 5 inches in diameter, and 6 inches long, $\frac{1}{32}$ inch is the allowance usually made.

Shrinkage fits are employed when a hole or bore requires to be very firmly and permanently fastened to a cylindrical piece as a shaft. The bore is turned of smaller diameter than its shaft, and the amount of difference is termed the allowance for shrinkage. The enveloping piece is heated so as to expand its bore; the shaft is then inserted and the cooling of the bore causes it to close or contract upon the shaft with an amount of force varying of course with the amount allowed for contraction. If this allowance is excessive, sufficient strain will be generated to burst the enveloping piece asunder, while if the allowance for shrinking is insufficient the enveloping piece may become loose.

The amount of allowance for shrinkage varies with the diameter thickness, and kind of the material; but more may be allowed for wrought iron, brass, and copper, than for cast iron or steel.

Again, the smoothness and truth of the surfaces is an important element, because the measurement of a bore will naturally be taken at the tops of the tool marks, and these will compress under the shrinkage strain, hence less allowance for contraction is required in proportion as the bore is smoother.

In ordinary workshop practice, therefore, no special rule for the amount of allowance for shrinkage obtains, the amount for a desultory piece of work generally being left to the judgment of the workman, while in cases where such work is often performed on particular pieces, the amount of allowance is governed by experience, increasing it if the pieces are found in time to become loose, and decreasing it if it is found possible to get the parts together without making the enveloping piece too hot, or if it is found to be liable to split from the strain.

The strength of the enveloping piece is again an element to be considered in determining the amount to be allowed for shrinkage. It is obvious, for example, that a ring of 8 inches thick, and having a bore of, say, 6 inches diameter, would be less liable to crack from the strain due to an allowance of $\frac{1}{50}$ inch for contraction, than would a ring of equal bore and one inch thick having the same allowance. The strength or resistance to compression of the piece enveloped in proportion to that enveloping it, is yet another consideration.

The tires for railway wheels are usually contracted on, and Herr Krupp states the allowance for contraction to be for steel tires $\frac{1}{100}$ inch for every foot of diameter; in American practice, however, a greater amount is often employed. Thus upon the Erie railroad a 5 foot tire is given $\frac{1}{16}$ inch contraction. The allowance for wrought iron or brass should be slightly more than it is for steel or cast iron, on account of the greater elasticity of those metals.

Examples of the practice at the Renovo shops of the Pennsylvania road are as follows:

Class E, diameter of wheel centre, 44 inches; bore of steel tire, $43\frac{15}{16}$ inches.

Class D, diameter of wheel, 50 inches; bore of tire, $49\frac{9}{16}$ inches.

It is found that the shrinkage of the tire springs or distorts the wheel centre, hence the tires are always shrunk on before the crank-pin holes are bored.

Much of the work formerly shrunk on is now forced on by an hydraulic press. But in many cases the work cannot be taken to an hydraulic press, and shrinkage becomes the best means. Thus, a new crank pin may be required to be shrunk in while the crank is on the engine shaft, the method of procedure being as follows: In heating the crank, it is necessary to heat it as equally as possible all round the bore, and not to heat it above a *very dark* red. In heating it some dirt will necessarily get into the hole, and this is best cleaned out with a piece of emery paper, wrapped round a half-round file, carefully blowing out the hole after using the emery paper. Waste or rag, whether oiled or not, is not proper to clean the hole with, as the fibres may burn and lodge in the hole; indeed, nothing is so good as emery paper.

It is desirable to heat the crank as little as will serve the purpose, and it is usual to heat it enough to allow the pin to push home by hand. It is better, however, to overheat the crank than to underheat it, providing that the heat in no case exceeds a barely perceptible red heat. If, however, the crank once grips the pin before it is home, in a few seconds the pin will be held so fast that no sledge hammer will move it. It is well, therefore, to have a man stationed on each side of the crank, each with a sledge hammer, and to push the crank pin in with a slam, giving the man in front orders to strike it as quickly as possible at a given signal; but if the pin does not move home so rapidly at each blow as to make it appear certain that it will go home, the man at the rear, who should have a ten-pound sledge, should be signalled to drive out the crank pin as quickly as he possibly can, for every second is of consequence. All this should be done so quickly that the pin has not had time to get heated to say 100° at the part within the crank.

So soon as the pin is home, a large piece of wetted cotton waste should be wrapped round its journal, and a stream of water kept running on it, to keep the crank pin cold. At the other end water should be poured on the pin end in a fine stream, but in neither case should the water run on the crank more than can be avoided. Of course, if the crank is off the shaft, the pin may be turned downward, and let project into water.

The reasons for cooling the pin and not the crank are as follows: If the crank be of cast iron, sudden cooling it would be liable to cause it to split or crack. If the crank pin is allowed to cool of itself, the pin will get as hot as the crank itself, and in so doing will expend, placing a strain on the crank that will to some extent stretch it. Indeed, when the pin has become equally hot with the crank it is as tight a fit as it will ever be, because after that point both pieces will cool together, and shrink or contract together, and hence the fit will be a looser or less tight one to the amount that the pin expanded in heating up to an equal temperature with the crank.

The correct process of shrinking is to keep the plug piece as cold as possible, while the outside is cooled as rapidly as can be without danger of cracking or splitting.

The ends of crank pins are often riveted after being shrunk in, in which case it is best to recess the end, which makes the riveting easier, and causes the water poured upon its face to be thrown outward, thus keeping it from running down the crank face and causing the crank to crack or split.

It sometimes becomes necessary and difficult to take out a piece that has been shrunk in, and in this event, as also in the case of a piece that has become locked before getting fully home in the shrinking process, there is no alternative but to reheat the enveloping piece while keeping the enveloped piece as cold as can be by an application of water.

The whole aim in this case is to heat the enveloping piece as quickly as possible, so that there shall be but little time for its heat to be transmitted to the piece enveloped. To accomplish this end melted metal, as cast iron, is probably the most efficient agent; indeed it has been found to answer when all other means failed.

The fine measurements necessary for shrinkage purposes render it necessary, where pieces of the same form and kind are shrunk on, to provide the workmen with standard gauges with which the work may be correctly gauged. These often consist of simple rods or pieces of iron wire of the required length. Figs. 1426 and 1427, however, represent an adjustable shrinkage gauge designed by H. S. Brown, of Hartford, Connecticut. Fig. 1427 is a sectional, and Fig. 1426 a plan side view of the gauge. A is a frame, containing at its lower end a fixed measuring piece B, and provided at its upper end with a threaded and taper split hub to receive externally the taper-threaded screw cap C, and threaded internally to receive a tube E, which is plugged at the bottom by the fixed plug F. The adjustable measuring leg G is threaded with the tube E, so as to be adjustable for various diameters of boxes, but it is locked when adjusted by the jamb-nut H. The operation is as follows: The cap-nut C and jamb-nut H are loosened and screwed back, allowing stem G and tube E to be adjusted to the exact size of the shaft for which a shrinkage fit is to be bored, as, say, in an engine crank. In setting the gauge to the diameter of the shaft, the cap end C and jamb-nut H are screwed home, so as to obtain a correct measurement while all parts are locked secure. The cap-nut C draws the split hub upon the tube E, and the jamb-nut H locks up G to E, so that the shaft measurement is taken with all lost motion, play and spring of the mechanism taken into account, so that they shall not vitiate the measurement. This being done, C is loosened so that E can be rotated, and raised up (by rotating) to admit the shrinkage gauge-piece J, whose thickness equals the amount to be allowed for the size of borer to be shrunk on the shaft. J being inserted, E is rotated back so as to bind J between the end of E and the foot piece B, when C is screwed down, clamping E again. Thus the measuring diameter of the gauge is increased to an amount due to the thickness of the gauge-piece J. At the right of Fig. 1426 an edge and side elevation of J is shown, the $\frac{12}{1000}$ indicating its thickness, which is the amount allowed for shrinkage, and the 6-inch indicating that this gauge-piece is to be used for bores of 6 inches in diameter. The dotted circle K K L L represents a bore to which the gauge is shown applied.

The system of shrinking employed at the Royal Gun Factory at Woolwich, England, is thus described by Colonel Maitland, superintendent of that factory:—

"The inside diameter of the outer tube, when cold, must be rather smaller than the outside diameter of the inner tube: this difference in the diameter is called the 'shrinkage.' While the outer coil is cooling and contracting it compresses the inner one: the amount by which the diameter of the inner coil is decreased is termed the 'compression.' Again, the outer coil itself is stretched on account of the resistance of the inner one, and its diameter is increased; this increase in the diameter of an outer coil is called 'extension.' The shrinkage is equal to compression plus the extension, and the amount must be regulated by the known extension and compression under certain stresses and given circumstances. The compression varies inversely as the density and rigidity of the interior mass; the first layer of coils will therefore undergo more compression than the second, and the second more than the third, and so on.

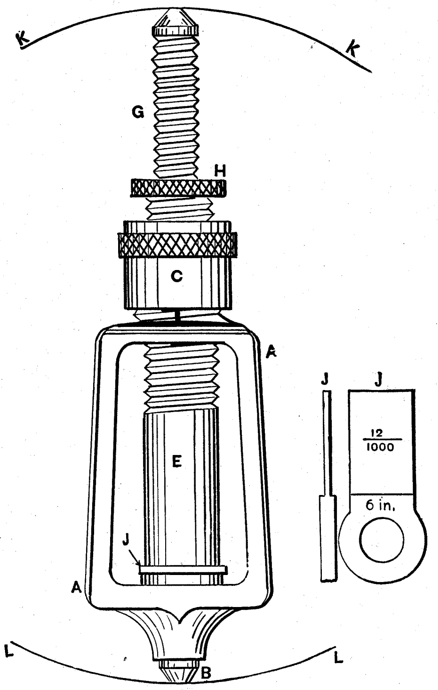

Fig. 1426.

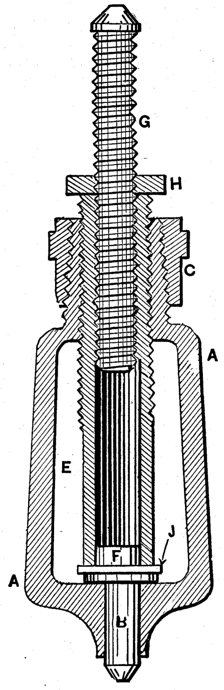

Fig. 1427.

"Shrinking is employed not only as an easy and efficient mode of binding the successive coils of a built-up gun firmly together, but also for regulating as far as possible the tension of the several layers, so that each and all may contribute fairly to the strength of the gun.

"The operation of shrinking is very simple; the outer coil is expanded by heat until it is sufficiently large to fit easily over the inner coil or tube (if a large mass, such as the jacket of a Fraser gun, by means of a wood fire, for which the tube itself forms a flue; if a small mass, such as a coil, in a reverberatory furnace at a low temperature, or by means of gas). It is then raised up by a travelling crane overhead and dropped over the part on to which it is to be shrunk, which is placed vertically in a pit ready to receive it.

"The heat required in shrinking is not very great. Wrought iron, on being heated from 62° Fahr. (the ordinary temperature) to 212°, expands linearly about 1-1000th part of its length; that is to say, if a ring of iron 1000 inches in circumference were put into a vat of boiling water, it would increase to 1001 inches, and according to Dulong and Petit the coefficient of expansion, which is constant up to 212°, increases more and more from that point upward, so that if the iron ring were raised 150° higher still (*i.e.* to 362°) its circumference would be more than 1002 inches. No coil is ever shrunk on with so great a shrinkage as the 2-1000th part of its circumference or diameter, for it would be strained beyond its elastic limit. Allowing, therefore, a good working margin, it is only necessary to raise a coil to about 500° Fahr.,* though in point of fact coils are often raised to a higher degree of temperature than this in some parts, on account of the mode of heating employed. Were a coil plunged in molten lead or boiling oil (600° Fahr.) it would be uniformly and sufficiently expanded for all the practical purposes of shrinking, but as shrinkings do not take place in large numbers or at regular times, the improvised fire or ordinary furnace is the more economical mode, and answers the purpose very well.

"Heating a coil beyond the required amount is of no consequence, provided it is not raised to such a degree of temperature that scales would form; and in all cases the interior must be swept clean of ashes, &c., when it is withdrawn from the fire. With respect to the modes of cooling during the process of shrinking, care must be taken to prevent a long coil or tube cooling simultaneously at both ends, for this would cause the middle portion to be drawn out to an undue state of longitudinal tension. In some cases, therefore, water is projected on one side of a coil so as to cool it first. In the case of a long tube of different thickness, like the tube of a R. M. L. gun, water is not only used at the thick end, but a ring of gas or a heated iron cylinder is applied at the thin or muzzle end, and when the thick end cools the gas or cylinder is withdrawn from the muzzle, and the ring of water raised upward slowly to cool the remainder of the tube gradually.

"As a rule, the water is supplied whenever there is a shoulder, so that that portion may be cooled first and a close joint secured there; and water is invariably allowed to circulate through the interior of the mass to prevent its expanding and obstructing or delaying the operation; for example, when a tube is to be shrunk on a steel barrel, the latter is placed upright on its breech end, and when the tube is dropped down on it, a continual flow of cold water is kept up in the barrel by means of a pipe and syphon at the muzzle. The same effect is produced by a water jet underneath, when it is necessary to place the steel tube muzzle downward for the reception of a breech coil. As to the absolute amount of shrinkage given when building up our guns, let us take the 12½-inch muzzle-loading gun of 38 tons as an example.

SHRINKAGES OF COILS OF 12·5 INCH R. M. L. GUNS.

Coils.	Shrinkages.				Remarks.
	In Inches.		In terms of diameter.		
	Rear.	Front.	Rear.	Front.	
Breech-piece .	·022	·026	$\frac{D}{857}$	$\frac{D}{807}$	Shrunk on A tube.
B coil . . .	·055	·01	$\frac{D}{561}$	$\frac{D}{190}$	„ „
B tube . . .	·035	nil.	$\frac{D}{668}$	nil.	„ „
C coil . . .	·03	·06	$\frac{D}{1134}$	$\frac{D}{729}$	Shrunk on to breech piece and rear end of 1 B coil."

The objections to fitting work by contraction where accuracy is required in the work are, that if the enveloping piece is of cast iron its form is apt to change from being heated. Furthermore, if the enveloping piece, which is always the piece to be heated, is of unequal thickness all round the bore, the thin parts are apt to become heated the most, and to therefore give way to the strain induced by contraction when cooling, which, while not, perhaps, impairing the fit, may vitiate the alignment of parts attached to it. Thus, a crank pin may be thrown out of true by the alteration of form induced first by unequal heating of the metal round the crank eye, enveloping the shaft; and secondly, because of the weakest side of the eye giving way, to some extent, to the pressure of the contracting strain. To counteract this, the strongest part of the enveloping piece should be heated the most, or if the enveloping piece be of equal strength all round its bore, it should be heated equally all round. To effect this object heated liquids, as boiling water, or heated fluids, as melted lead, may advantageously be employed.

In some practice, locomotive wheel tires are heated for shrinking in boiling water. The allowance for shrinkage is from ·075 millimètre to every mètre in diameter, which is ·02952 inch to every 39·37079 inches of diameter.

The employment of hot water, however, necessitates that the tires be bored very smoothly and truly, and that the wheel rim be similarly true and smooth, otherwise the amount of expansion thus obtained will be insufficient to maintain a permanent fit under the duty to which a wheel tire is submitted.

Shrinking is often employed to strengthen a weak place or part, or one that has cracked. The required size is, in this case, a cylindrical surface that is not a true cylinder, obtained by a rolling wheel rotated by friction over the surface to be enveloped by the band. Or if the surface is of a nature not to admit of this, a strip of lead or piece of lead wire may be lapped round it to get the necessary measurements.

The bands for this purpose are usually of wrought iron, and require in the case of irregular surfaces to be driven on by hammer blows, so that the fit may be correct. As the band is forced on a heavy hammer is held against it, to prevent its moving back and off the work as the other parts are forced on.

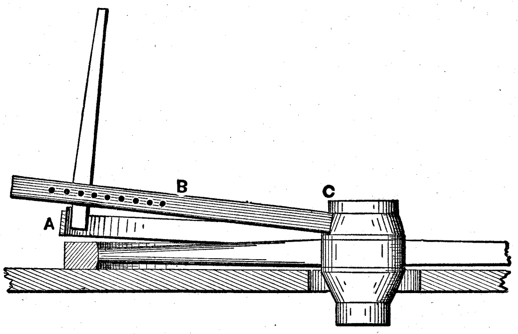

Fig. 1428.

Very slight bands may be forced on by levers: thus, wagon makers use a lever or jack, such as in Fig. 1428, for forcing the tires on their wheels. The wheel is laid horizontally on a table as shown, and the tire A forced out by the vertical lever, the arm B affording a fulcrum for the lever, and itself resting against the hub C of the wheel.

The following extracts are from a paper read by Thomas Wrightson, before the Iron and Steel Institute of Great Britain.

"The large amount of attention bestowed upon the chemical properties of metals, and the scientific methods adopted for their investigation, have led to the most brilliant results in the history of iron and steel industries. It must not, however, be overlooked that iron and steel have highly important properties other than those which can be examined by chemical methods. The cause for so little having been done in accurate observation of the physical properties of iron is twofold: 1. The molecular changes of the metals are so slow, when at ordinary temperatures and when under ordinary conditions of strain, that reliable observations, necessarily extending over long periods, are difficult to obtain: 2. When the temperatures are high—at which times the greatest and most rapid molecular changes are occurring—the difficulties of observation are multiplied to such an extent that the results have not the scientific accuracy which characterizes the knowledge we have of the chemical properties of metals.

"The object of the present paper is to draw attention to some

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* The temperature may be judged by color; at 500° F. iron has a blackish appearance; at 575° it is blue; at 775° red in the dark; at 1,500° cherry red, and so on, getting lighter in color, until it becomes white, or fit for welding, at about 3,000°.

phenomena connected with the physical properties of iron and steel, and to record some experiments showing the behavior of these metals under certain conditions.

"In experimenting the author has endeavored to adopt methods which would, as far as possible, eliminate the two great difficulties mentioned.

"It is obvious that the possible conditions under which experiments may be made are so numerous that all which any one experimenter can do is to record faithfully and accurately his observations, carefully specifying the exact conditions of each observation, and this must eventually lead to a more complete knowledge of the physical properties of the metals.

"The author's observations have been led in the following directions:—

"1. The changes in wrought and cast iron when subjected to repeated heatings and coolings.

"2. The effect upon bars and rings when different parts are cooled at different rates.

"3. These changes occurring in molten iron when passing from the solid to the liquid state, and *vice versâ*.

PART I.

"To illustrate the practical importance of knowing the effects of reiterated heating and cooling on iron plates, one of the most obvious examples is the action of heat upon the plates of boilers which are alternately heated and cooled, as in use or otherwise. When in use, the plates above the fire are subjected to the fierce flame of the furnace on one side, and on the other side to a temperature approximating to that of the steam and water in the boiler. Where the conducting surfaces of the metal are thickened at the riveted seams, a source of danger is frequently revealed in the appearance of what are known as 'seam-rips.'

"The long egg-ended boilers, much used in the North of England, are very subject to this breaking away of the seams. From some tests made by the writer on iron cut from the plates of two different boilers which had ripped at the seams, and one of which seam-rips had led to an explosion resulting in the destruction of much property, though happily of no lives, it was found that the heat acting on the bottom of the boiler had, through time, so affected the iron at the seam as to make it brittle, apparently crystalline in fracture, and of small tensile strength. Farther from the seam the iron appeared in both cases less injuriously affected. But although the alternate heating and cooling of the plates over a long period had produced this change in the molecular condition of the iron, a method of restoration presents itself in the process of annealing. In subjecting the pieces cut from the seam-rips to a dull red heat, and then allowing them to cool slowly in sawdust, the writer found that the fibrous character of the iron appeared again, and renewed testing showed that the ductility and tensile strength were restored.

"The same process of annealing is equally effectual in restoring the tenacity of iron in chains rendered brittle, and apparently crystalline, by long use, and is periodically applied where safety depends upon material in this form. Thus the heating and cooling of iron may be looked upon as the bane or the antidote according to the conditions under which the process is carried out. This affords an example of the importance of the physical effects produced by repeated changes of temperature. The change effected by one heating and cooling is so small that a cumulative method of experiment is the only one by which an observable result can be obtained, and this is the method adopted by the writer in the investigation now to be described.

"It is well known that if a wrought-iron bar be heated to redness, a certain expansion takes place, which is most distinctly observed in the direction of its length. It is also known, although not generally so, that if a bar be thus heated and then suddenly cooled in water, a contraction in length takes place, the amount of this contraction exceeding that of the previous expansion, insomuch that the bar when cooled is permanently shorter than it originally was. If this process of heating and cooling be repeated, a further amount of contraction is found to follow for many successive operations.

"Experiments Nos. 1 and 2 were made to verify this, and to show the increment of contraction after each operation.

"EXPERIMENTS ON WROUGHT-IRON BARS $1\frac{1}{8}$ IN. SQUARE BY 30·05 IN. LONG, HEATED TO A DULL RED, THEN COOLED SUDDENLY IN WATER.

	Experiment No. 1. Common Iron.		Experiment No. 2. Best Iron.	
	Contraction.	Percentage on original length.	Contraction.	Percentage on original length.
	Inches.		Inches.	
After 1st cooling	·04	·13	·04	·13
,, 2nd ,,	·10	·33	·10	·33
,, 3rd ,,	·16	·53	·14	·46
,, 4th ,,	·17	·56	·16	·53
,, 5th ,,	·23	·76	·20	·66
,, 6th ,,	·28	·93	·24	·80
,, 7th ,,	·31	1·03	·27	·89
,, 8th ,,	·33	1·10	·30	1·00
,, 9th ,,	·40	1·33	·33	1·10
,, 10th ,,	·47	1·56	·39	1·30
,, 11th ,,	·52	1·73	·42	1·40
,, 12th ,,	·54	1·80	·47	1·56
,, 13th ,,	·58	1·93	·51	1·70
,, 14th ,,	·62	2·06	·54	1·80
,, 15th ,,	·68	2·26	·56	1·86

"The Table of Experiment No. 5 shows that at the twenty-fifth cooling a contraction of 3·05 per cent. had taken place, or an average of ·122 per cent. after each cooling. This is almost identically the same average result as shown in Experiment No. 1 with straight bars.

"The above experiments only having reference to the permanent contraction of the iron in the direction of its length, the author made the following experiments to ascertain the effect in the other dimensions, and to see whether the specific gravity of the iron was affected in the reduction of dimensions.

"*Experiment No.* 6.—Wrought-iron plate, ·74 inch thick, planed on both surfaces and all edges to a form nearly rectangular, and of the dimensions given in Fig. 1429.

"*Specific Gravity.*—Two small samples were cut out of different parts of the same piece of plate from which the experimental piece was planed, and the specific gravity determined as follows:—

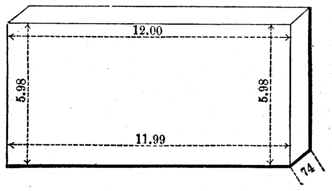


Fig. 1429.

No. 1 piece	7·629	Mean, 7·64.
No. 2 piece	7·651	

"*Quality.*—Subjecting a piece to tensile strain in the direction of the grain, it broke at 21·2 tons per square inch of section, the ductility being such that an elongation of 8·3 per cent. occurred before fracture, with a reduction of 9·6 per cent. of the area of fracture. This may be looked upon as representing a fairly good quality of iron.

"A bar of wrought iron, $1\frac{1}{8}$ inches square and 30·00 inches long, was heated to redness, and then allowed to cool gradually in air. Measurements after each of five coolings showed no perceptible change of length.

"*Experiment No.* 4.—Wrought-iron bar, $1\frac{1}{8}$ inches square by 30 inches long, heated to a white heat and cooling gradually in air.

	Contraction.	Percentage on original length.	Remarks.
	Inches.		
After 1st cooling	No change.		—
,, 2nd ,,	,,		—
,, 3rd ,,	·02	·07	—
,, 4th ,,	·05	·17	—
,, 5th ,,	·05	·17	—

"It may be remarked, that if the bars be heated to white heat a slight contraction does occur, as shown by Experiment No. 4, where a bar of the same dimensions as No. 3 contracted ·17 per cent. after the fifth cooling. As, however, the further remarks on this subject have only reference to bars heated to redness and then cooled, the writer would summarize the results of Experiments Nos. 1, 2, and 3, by stating that wrought-iron bars heated to redness permanently contract in their length along the fibre when cooled in water of ordinary temperature; but when cooled in air, they remain unchanged in length.

"To show that this is true as applied to circular hoops, Experiment No. 5 was made upon a wrought-iron bar of 1⅛ inches square in section, welded into a circular hoop, 57·7 inches outside circumference.

"*Experiment No.* 5.—Wrought-iron hoop, 1⅛ inches square by 57·7 inches outside circumference, heated to a dull red, then cooled suddenly in water.

	Contraction.	Percentage of original circumference.	Remarks.
	Inches.		
After 1st cooling	·06	·10	Red heat.
,, 2nd ,,	·06	·10	This was nearly white, but before cooling red hot.
,, 3rd ,,	·16	·28	
,, 4th ,,	·26	·45	
,, 5th ,,	·35	61	
,, 6th ,,	·46	·80	
,, 7th ,,	·54	·93	
,, 8th ,,	·60	1·04	
,, 9th ,,	·68	1·18	
,, 10th ,,	·76	1·32	
,, 11th ,,	·80	1·38	
,, 12th ,,	·87	1·51	
,, 13th ,,	·94	1·63	
,, 14th ,,	1·00	1·73	
,, 15th ,,	1·08	1·90	
,, 20th ,,	1·30	2·25	On opposite edge 1·66; hoop splitting.
,, 25th ,,	1·76	3·05	

"This hoop was heated to redness and cooled in water twenty-five times, the circumference of the hoop being accurately measured after each cooling.*

"Two wrought-iron bars, 1⅛ inches square and 30·05 inches long, were selected.† No. 1 was of common "Crown" quality; No. 2 of a superior quality known as "Tudhoe Crown." These bars were heated to redness in a furnace and then plunged into water of ordinary temperature, the length being accurately measured after each cooling. After fifteen heatings and coolings the permanent contraction on No. 1 bar was 2·26 per cent. of the original length, and that on No. 2 bar 1·86 per cent., or an average on the two bars of about ·13 per cent. after each cooling, the increment of contraction being nearly equal after each successive operation. It is noticeable that after the first two coolings the better quality of iron did not contract quite so much as the common quality, and that in the latter the contraction was going on as vigorously at the fifteenth as at the first cooling.

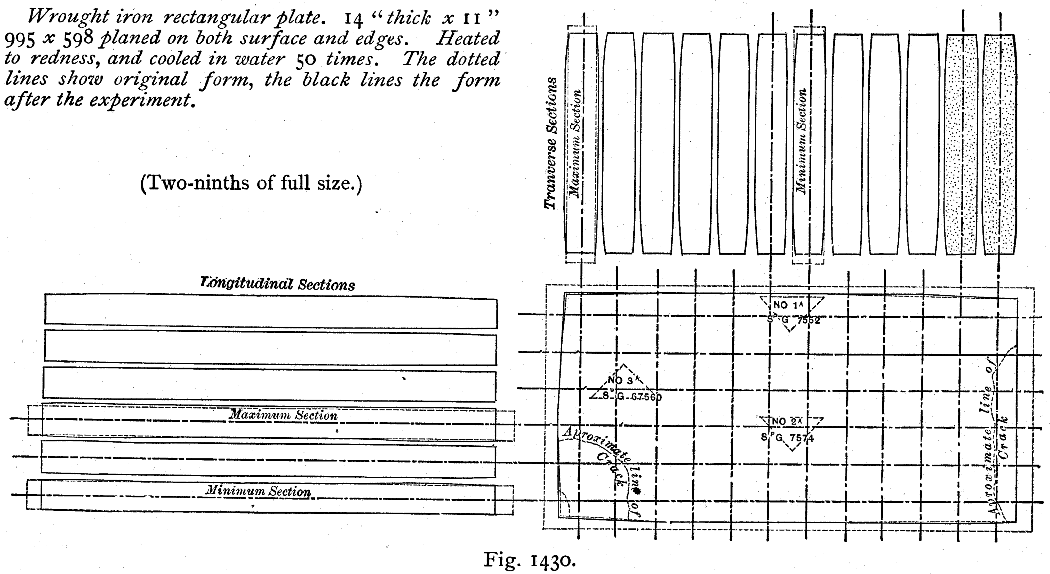
"Similar bars of wrought iron, heated to redness and then allowed to cool in air at ordinary temperature, do not appear to suffer any permanent change in their length.

"Experiment No. 3 was made to verify this.

"*Experiment No.* 3.—Wrought-iron bar, 1⅛ inches square by 30 inches long heated to a dull red and cooled gradually in air.

	Contraction.	Percentage on original length.	Remarks.
After 1st cooling	No change.	——	——
,, 2nd ,,	,,	——	——
,, 3rd ,,	,,	——	——
,, 4th ,,	,,	——	——
,, 5th ,,	,,	——	——

The plate was subjected to fifty heatings to redness and subsequent coolings in water of ordinary temperature. At every tenth cooling accurate measurements were taken of the contraction in superficial dimensions, and Fig. 1430 shows the final form after fifty coolings. The intermediate measurements at every tenth cooling showed a uniform and gradual decrease in the superficial dimensions, but the thicknesses were only measured after the fifty coolings had been completed. The thickness appears to have varied considerably; in some places, notably towards the centre and outside edges, being much reduced. Between the centre and outside edges the thickness appears to have increased, and in some few places the plate has been split open. The average dimensions in inches before and after the experiment were as follows (dimensions of cracks being allowed for):—


Wrought iron rectangular plate. 14 "*thick x* 11 " 995 *x* 598 *planed on both surface and edges. Heated to redness, and cooled in water* 50 *times. The dotted lines show original form, the black lines the form after the experiment.*

(Two-ninths of full size.)

Fig. 1430.

	Average length.	Average breadth.	Average thickness.	Cubic inches capacity.
	Inches.	Inches.	Inches.	
Original	11 995	5·98	·74	53·08
After 50 coolings . .	11·25	5·59	·774	48·72
Per cent. variation from original . .	Decrease of 6·2 p. c.	Decrease of 6·52 p. c.	Increase of 4·6 p. c.	Decrease of 8·2 p. c.

* The lengths of circumference were taken, in this and other hoops, after each cooling, by encircling the periphery with a very fine piece of "crinoline" steel, the ends of which were made just to meet round the original hoop. By again encircling the hoop with the same piece of steel the expansion was shown by a gap between the ends, and a contraction by an overlap, either of which was measured with great accuracy by means of a finely divided scale.

† In some of these experiments the original sizes of the iron were only measured with an ordinary foot-rule, in which case the dimensions are given in the ordinary fraction used in expressing the mercantile sizes of iron. When accurate measurement was taken decimals are invariably used both in this paper and the Tables of Experiment.

"Three triangular pieces of iron were then cut out of the plate from positions indicated on the diagram; No. 1A from the part most reduced in thickness, No. 3A from the part most increased in thickness, and No. 2A from a part where the thickness was a mean between the thickest and thinnest part. The specific gravities were accurately determined as follows :—

No. 1A	7·552 thinnest part.
No. 2A	7·574 average thickness.
No. 3A	7·560 thickest part.

"The average of these specific gravities is 7·562.

"The average before experiment was 7·64. Hence the average loss in specific gravity has been 1·02 per cent.

"The small triangular piece No. 1A, specific gravity 7·552 (already subjected to fifty heatings when forming part of the solid plate), was next heated and cooled fifty times more. The specific gravity at the end of the one hundred total coolings was 7·52, being ·43 per cent. lower than after fifty heatings in plate, and 1·57 per cent. lower than 7·64, the original mean specific gravity of the plate.

"The same piece, 1A, was then heated twenty-five times more, making 125 in all. On taking the specific gravity it was found to be 7·526, or practically the same as after 100 total heatings and coolings.

"It thus appears that there is an undoubted decrease in specific gravity on repeated heating and cooling as described up to one hundred coolings, the specific gravity decreasing as much as 1·57 per cent.; that this percentage appears to be less when the pieces of iron operated upon are very small; that while there is a decrease of specific gravity there is also a decrease of total volume.

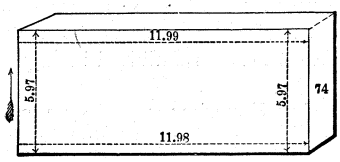


Fig. 1431.

"From the above it was evident that the volume was affected by several causes :—

"1. By the permanent contraction of the outer skin, either the volume would be lessened, or relief by bulging out the sides must occur.

"2. By the decrease of specific gravity an increase of volume must occur, which could also find relief in bulging.

"3. A diminution of the whole mass must occur through scaling of the surface.

"Having determined the change in specific gravity by Experiment 6, we only now want to determine the loss of volume due to surface scaling, and we can then infer the actual contraction of the outer skin.

"*Experiment No.* 7.—To ascertain the amount of scaling which took place in heating and cooling under same conditions as Experiment No. 6, a wrought-iron plate was cut from the same piece as No. 6, thickness ·74 in., planed on both surfaces and all edges to a form nearly rectangular, and to the dimensions given in Fig. 1431.

"The only difference (except the very small difference in the dimensions) between this and 1430, was that the principal grain of the iron was in 1431 in the direction of the arrow, whereas in the other it was lengthwise of the plate.

"This piece was subjected to fifty heatings to redness and sudden coolings in water of ordinary temperature, as in the case of No. 6. The change in form was exactly the same in general character, but the contraction was not quite so great either in length or breadth; the increase in thickness, however, was proportionately greater, the volume (measured by displacement of water) after fifty heatings being 48·6 cubic inches, which is nearly the same as in No. 6 after the same number of heatings. The weight of the piece :—

	Avoirdupois. lbs.	 oz.	 dr.
Before heating	14	10	15
After fifty heatings	13	5	10
Difference	1	5	5

"This represents a loss of 9·07 per cent. of the original weight by scaling, and upon the whole original surface (sides and edges) represents a thickness of ·0284 of an inch for the fifty immersions, or ·00057 of an inch for the thickness of the film lost at each immersion over the whole surface.

"Calculating the weight of No. 6 before and after experiment from the volumes and specific gravities, we find the following :—

	Volume.		Mean specific gravity.		Weight of cubic inch water.		Pounds.
Weight before heating should be	53·08	×	7·64	×	·036	=	14·599
„ after „ „	48·72	×	7·562	×	·036	=	13·262
Difference in weight							1·337

the ascertained difference in the case of No. 7 being 1·332, thus sufficiently accounting for the discrepancy between specific gravity and change of volume by the scaling.

"By Experiment 7 it has been shown that the loss of thickness due to scaling after fifty immersions was ·0284 inch over the whole surface (sides and edges.) Therefore, assuming this scaling as uniform over the surface, the girth, whether measured lengthwise or breadthwise, should be eight times ·0284, or ·23 inch less after immersion than before. Now the gross loss of girth is :—

	Lengthwise.	Breadthwise.
	Inches.	Inches.
In No. 6	1·38	·86
In No. 7	1·2	·52
Or for both experiments a mean of . .	1·29	·69
Deducting from them the loss of girth due to scaling	·23	·23
Net contraction after fifty immersions . .	1·06	·46
Or in percentage of original girths, which were	25·46 per cent.	13·43 per cent.
We have a percentage of	4·16	3·42
Or for each immersion an average of . .	·083	·07

"Comparing these results with those of Experiments Nos. 1, 2, and 5, we find that the contraction of the skin of the plate is less for each immersion than that of a bar or hoop, in the proportion of ·125 to ·083. This is what might be expected, as the contraction of the plate is resisted by the volume of heated matter inside, which is eventually displaced by bulging, while the bar finds relief endwise without having to displace the interior.

"We have now before us the following facts, substantiated by the experiments described :—

"1. That in heating to redness, and then cooling suddenly in water at ordinary temperatures, bars and plates of wrought iron, a reduction of specific gravity takes place, the amount being about 1 per cent. after fifty immersions, and 1·57 per cent. after one hundred immersions, further heatings and coolings not appearing to produce further change.

"2. That a reduction of the surface takes place after each heating and cooling, this being due to two causes :—

"*a.* The scaling of the surface, which is shown to amount to a film over the (sides and edges) entire area of ·00057 inch in thickness for each immersion, or 0·284 inch for fifty immersions (Experiment 7).

"*b.* A persistent contraction, which takes place after each immersion. This varies according to the form of the iron, being in plates from ·07 per cent. to 0·83 per cent (Experiment 6), while in long bars it varies from ·122 to ·15 per cent. (Experiments 1, 2, and 5). This contraction continues vigorously up to fifty immersions, and probably much farther.

"3. That in the case of plates a bulging takes place on the largest surfaces, increasing the thickness towards the centres, although the edges diminish in thickness.

"4. That wrought-iron bars heated to redness, and allowed to cool slowly in air, do not show any change in dimensions (Experiment 3).

"The reduction of specific gravity, and the bulging out of the sides, have been explained as follows by the learned Secretary of the Royal Society, Professor Stokes, who has taken considerable interest in these experiments, and who has kindly allowed the author to publish the explanation:

"'When the heated iron is plunged into water, the skin tends everywhere to contract. It cannot, however, do so to any significant extent by a contraction which would leave it similar to itself, because that would imply a squeezing in of the interior metal, which is still expanded by heat, and is almost incompressible. The endeavor, then, of the skin to contract is best satisfied, consistently with the retention of volume of the interior, by a contraction of the skin in the two longish lateral directions, combined with a bulging out in the short direction. The still plastic state of the interior permits of this change.

"'Conceive an india-rubber skin of the form of the plate in its first state, the skin being free from tension, and having its interior filled with water, treacle, or pitch. I make abstraction of gravity. It would retain its shape. But suppose, now, the india-rubber to be endowed with a tension the same everywhere similar to that of india-rubber that has been pulled out, what would take place? Why, the flat faces of considerable area, being comparatively weak to resist the interior pressure, would be bulged out, and the vessel would contract considerably in the long directions, increasing in thickness. This is just what takes place with the iron in the first instance. But when the cooling has made further progress, and the solidified skin has become comparatively thick and strong, the further cooling of the interior tends to make it contract. But this it cannot well do, being encased in a strong hide, and accordingly the interior tends to be left in a porous condition.'

"The reduction by scaling does not require any explanation. The only fact which appears unaccounted for is this persistent contraction of the cooled iron skin, which does not appear to be explicable on any mechanical grounds; and we are, therefore, obliged to look upon it as the result of a change in the distance of the molecules of the iron, caused by the sudden change of temperature in the successive coolings.

"Our next subject is the curious effect of cooling bars or rings by partial immersion in water. Bearing in mind the results at which we have arrived, viz., that wrought iron contracts when immersed in water after heating, and that when allowed to cool in air it remains of the same dimensions, let us ask what would be the behavior of a bar or circular hoop of iron cooled half in water and half in air, the surface of the water being parallel to the fibre and at right angles to the axis of the hoop?

"Arguing from the results of Experiments 1, 2, and 5, it might be expected that the lower portion cooled in water would suffer permanent contraction; and, arguing from Experiment 3, that the upper or air-cooled edge would not alter. This apparently legitimate conclusion is completely disproved by experiments. This will be seen by a reference to Experiments 8, 9, and 10.

"In No. 8 a circular hoop of wrought iron was forged out of a 3½-inch by ½-inch bar, the external diameter being about 18 inches, the breadth, ½ inch, being parallel to the axis of the hoop. This hoop, Fig. 1432, was heated to redness, then plunged into cold water half its depth, the upper half cooling in air. The changes in the external circumference of the hoop were accurately measured after each of twenty successive coolings, at the end of which the external circumference of the water-cooled edge had increased 1·24 inches, or 2·14 per cent. of its original length, and the air-cooled edge had contracted 7·9 inches, or 13·65 per cent.

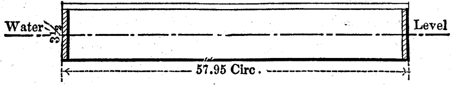


Fig. 1432.—Experiments with a circular hoop of wrought iron. Appearance of the hoop at the beginning.

"*Experiment No.* 8.—Wrought-iron hoop, 3½ inches by ½ inch by about 18 inches in diameter, or exactly 57·85 inches in circumference at top, and 57·95 inches at bottom edge.

	Top Edge.		Bottom Edge.		Remarks.
	Contraction.	Percentage of original circumference.	Expansion.	Percentage of original circumference.	
	Ins.		Ins.		
After 1st dip .	·50	·86	·08	·14	
,, 2nd ,, .	·99	1·71	·08	·14	
,, 3rd ,, .	1·47	2·54	·26	·45	
,, 4th ,, .	1·92	3·32	·30	·52	
,, 5th ,, .	2·30	3·97	·34	·59	
,, 6th ,, .	2·60	4·49	·40	·70	Slight crack in expanded edge.
,, 7th ,, .	2·94	5·25	·44	·76	
,, 8th ,, .	3·40	5·98	·50	·86	
,, 9th ,, .	3·70	6·39	·56	·96	
,, 10th ,, .	4·40	7·60	·62	1·07	
,, 11th ,, .	4·42	7·64	·66	1·14	
,, 12th ,, .	4·85	8·40	·70	1·22	
,, 13th ,, .	5·24	9·02	·78	1·34	
,, 14th ,, .	5·74	9·92	·80	1·39	
,, 15th ,, .	6·00	10·37	·86	1·49	
,, 20th ,, .	7·90	13·65	1·24	2·14	After deducting for a crack ·06 inch wide which appeared at sixth dip.

"It will be observed that we have here two remarkable phenomena: 1. The reversal of the expansion and contraction as described. 2. The very large amount of contraction on the upper edge compared with what was exhibited in Experiment 5 of entire submersion.

"The table showing Experiment 5 gives a contraction of 2·25 per cent. after the twentieth cooling, whereas the contraction on the air-cooled edge of Experiment 8 is 13·65 per cent., or six times the contraction of an entirely submerged hoop.

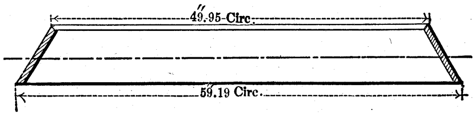


Fig. 1433.—Condition of the hoop after the twentieth cooling.

"To ascertain whether these unexpected phenomena had any connection with the circular form of the hoop, Experiment 9 was made with a straight bar of iron 3½ inches deep by ½ inch thick by 28·4 inches long.

"*Experiment No.* 9.—Wrought-iron bar, 3½ inches by ½ inch by 28·4 inches long, heated to a dull red, then quenched half its depth in water.

	Bottom Edge.		Top Edge.	
	Expansion.	Percentage on original length.	Contraction.	Percentage on original length.
	Inches.		Inches.	
After 1st cooling .	·05	·18	·26	·91
,, 2nd ,, . .	·10	·35	·43	1·51
,, 3rd ,, . .	·10	·35	·54	1·90
,, 4th ,, . .	·14	·49	·75	2·64
,, 5th ,, . .	·20	·70	·92	3·24
,, 6th , . .	·30	1·05	1·25	4·40
,, 7th ,, . .	·34	1·20	1·50	5·28
,, 8th ,, . .	·38	1·34	1·56	5·53
,, 9th ,, . .	·39	1·37	1·66	5·84
,, 10th ,, . .	·40	1·40	1·76	6·19
,, 11th ,, . .	·41	1·43	1·84	6·48
,, 12th ,, . .	·44	1·55	1·96	6·90

"This was cooled half in air and half in water, and the length of the two edges measured accurately after each of twelve coolings. At the end of this experiment the air-cooled edge had contracted 6·9 per cent., while the water-cooled edge had expanded 1·55 per cent. of the original length. The effect on the bar was to make it gradually curve, the water-cooled or extended edge becoming convex, the air-cooled or contracted edge concave.

"Experiment No. 10 was made in order to show the effect of reversing this cooling process. After five coolings, a bar of iron, 28 inches long, $3\frac{1}{2}$ inches deep, and $\frac{1}{2}$ inch thick, was curved so that the versed sine of its air-cooled edge was $1\frac{1}{2}$ inches. The coolings were then reversed, what was the air-cooled edge being then immersed in water. After five more coolings the bar was restored to within $\frac{1}{8}$ inch of being straight, and the eleventh cooling threw the concavity on the other side of the bar.

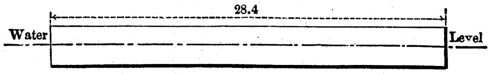


Fig. 1434.—Experiments with a wrought-iron bar. Appearance of the piece before heating.

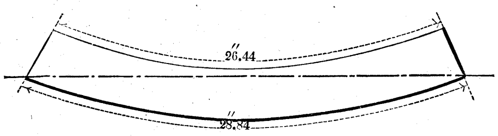


Fig. 1435.—Appearance of the bar after the twelfth cooling.

"*Experiment No.* 10.—Wrought-iron flat bar, 28 inches long by $3\frac{1}{2}$ inches by $\frac{1}{2}$ inch, heated to dull red, then quenched half its depth in water, up to five heats, then the opposite edge dipped.

	Versed sine of concave, *i.e.* air-cooled edge.		Reversed Cooling. Versed sine of concave, *i.e.* now water-cooled edge.
	Inches.		Inches.
1st cooling	$\frac{5}{16}$	6th cooling	$1\frac{3}{16}$
2nd "	$\frac{9}{16}$	7th "	$\frac{7}{8}$
3rd "	$\frac{13}{16}$	8th "	$\frac{3}{4}$ scant.
4th "	$1\frac{3}{8}$	9th "	$\frac{3}{8}$ full.
5th "	$1\frac{1}{2}$	10th "	$\frac{1}{8}$
		11th "	Brought concavity $\frac{1}{8}$ in. on other side.

"When the author had proceeded thus far, these curious results were shown to several leading scientific men, who expressed interest in the subject, which encouraged the author to extend his experiments under varied conditions with a view of ascertaining the cause for these anomalous effects. These experiments (Nos. 11 to 17) are fully recorded, and the results shown on the diagrams; the actual rings are also on the table before you.

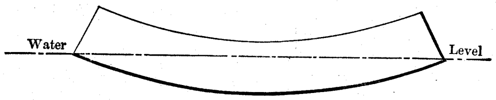


Fig. 1436.—After the preceding experiment the same bar was reheated and reversed in the water, the eleventh cooling resulting in the above form, the bar bending in the opposite direction from that previously shown.

"*Experiment No.* 11.—Wrought-iron hoop, turned and bored, 37·1 inches, outside circumference, by 2·95 inches deep by ·44 inch thick, the grain of the iron running the short way of the bar from which the hoop was made, heated to redness, then cooled half its depth in water (see Fig. 1437 at A for final form of hoop after ten heatings and coolings).

	Top Edge.		Bottom Edge.	
	Contraction.	Percentage on original length.	Expansion.	Percentage on original length.
	Inches.		Inches.	
After 1st cooling . . .	·3	·83	·05	·13
" 2nd " . . .	·64	1·72	·12	·32
" 3rd " . . .	1·02	2·75	·22	·60
" 4th " . .	1·38	3·72	·30	·80
" 5th " . . .	1·62	4·37	·37	1·00
" 10th " . . .	3·14	8·46	·76	2·05

"*Experiment No.* 12.—Wrought-iron hoop, turned and bored, 6 inches diameter (18·85 inches circumference) outside, by 2 inches deep by ·375 inch thick, heated to redness, then cooled, with lower edge barely touching the water (see Fig. 1437 at B for final form of hoop after twenty heatings and coolings).

	Top Edge.		Bottom Edge.	
	Contraction. Outside circumference.	Percentage of original circumference.	Contraction. Outside circumference.	Percentage of original circumference.
	Inches.		Inches.	
After 5th cooling . .	·10	·53	·16	·85
" 10th " . . .	·22	1·17	·34	1·80
" 15th " . . .	·32	1·70	·48	2·54
" 20th " . . .	·48	2·54	·62	3·30

"*Experiment No.* 13.—Wrought-iron hoop, turned and bored, 6 inches diameter (18·85 inches circumference) outside by 2 inches deep by ·375 inch thick, heated to redness, then cooled one-fourth its depth in water (see Fig. 1437 at C for final form of hoop after twenty heatings and coolings).

	Top Edge.		Bottom Edge.	
	Contraction.	Percentage of original circumference.	Extension.	Percentage of original circumference.
	Inches.		Inches.	
After 1st cooling .	·06	·32	·02	·10
" 5th " .	·28	1·50	A hair's-breadth contraction.	
" 10th " .	·56	3·00	Returned to original circumference.	
" 15th " .	·78	4·14	0·2 contraction.	·10
" 20th " .	1·12	6·00	0·2 contraction.	·10

Experiment No. 14.—Wrought-iron hoop, turned and bored. 6 inches diameter (18·85 inches circumference) outside by 2 inches deep by ·375 inch thick, heated to redness, then cooled one-half its depth in water (see Fig. 1437 at D for final form of hoop after twenty heatings and coolings).

	Top Edge.		Bottom Edge.	
	Contraction. Outside circumference.	Percentage of original circumference.	Expansion. Outside circumference.	Percentage of original circumference.
	Inches.		Inches.	
After 5th cooling .	·46	2·44	·06	·32
" 10th " . .	·96	5·00	·09	·48
" 15th " . .	1·34	7·10	·18	·96
" 20th " . .	1·80	9·10	·26	1·38

Experiment No. 15.—Wrought-iron hoop turned and bored, 6 inches in diameter (18·85 inches circumference) outside by 2 inches deep by ·375 inch thick, heated to redness, then cooled three-fourths its depth in water (see Fig. 1437 at E for final form of hoop after twenty heatings and coolings).

	Top Edge.		Bottom Edge.	
	Contraction.	Percentage of original circumference.	Expansion.	Percentage of original circumference.
	Inches.		Inches.	
After 1st cooling .	·05	·26	·015	08
" 5th " .	·30	1·60	·02	·10
" 10th ., .	·56	3·00	A hair's-breadth contraction.	
" 15th " .	·74	3·92	·02 contraction.	·10
" 20th " .	1·02	5·40	·03 contraction.	·10

Experiment No. 16.—Cast-copper ring, turned and bored to same dimensions as Nos. 12, 13, 14, and 15, heated to redness, then cooled half its depth in water (see Fig. 1437 at F for final form of hoop after twenty heatings and coolings).

	Top Edge.		Bottom Edge.	
	Contraction.	Percentage of original circumference.	Expansion.	Percentage of original circumference.
	Inches.		Inches.	
After 1st cooling . .	·01	·05	·05	·26
,, 2nd ,, . .	·01	·05	·08	·42
,, 3rd ,, . .	·02	·10	·14	·75
,, 4th ,, . .	·02	·10	·17	·90
,, 5th ,, . .	No change from original size from 5th to 20th cooling.		·22	1·17
,, 10th ,, . .			·40	2·13
,, 15th ,, . .			·56	3·00
,, 20th ,, . .			·70	3·70

"It will be unnecessary to occupy much time in analyzing the experiments, as any one who takes a practical interest in the subject will have full information in the diagrams and tables.

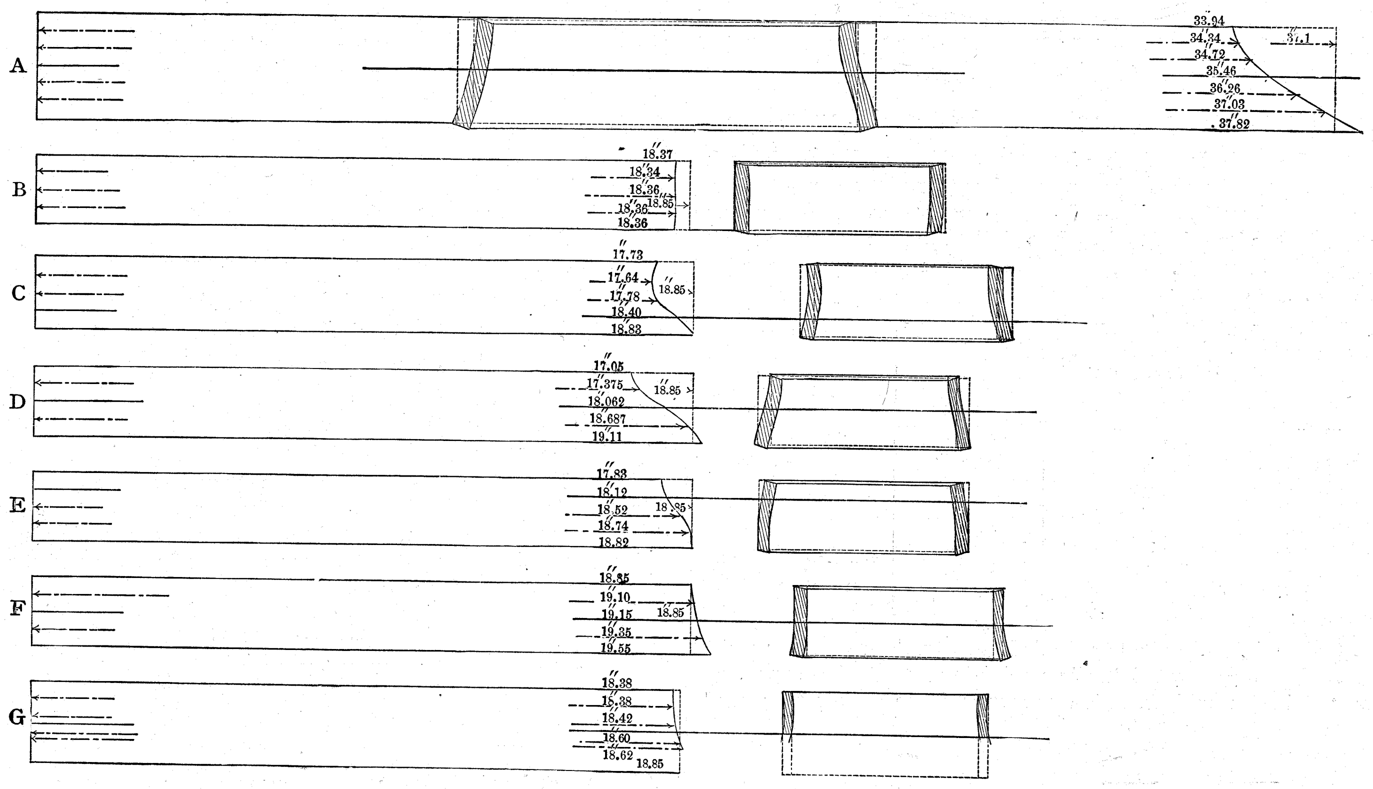


Fig. 1437.

Professor Stokes drew attention to the fact that, in 1863, similar phenomena had been noticed by Colonel Clark, of the Royal Engineers. His experiments, made at the Royal Arsenal, Woolwich, were published in the 'Proceedings of the Royal Society,' and Professor Stokes had himself attached an explanatory note, the outline of which was as follows:—

"Imagine a cylinder divided into two parts by a horizontal plane at the water-line, and in this state immersed after heating. The under part, being in contact with water, would rapidly cool and contract, while the upper part would cool but slowly. Consequently by the time the under part had pretty well cooled, the upper part would be left jutting out; but when both parts had cooled their diameters would again agree. Now in the actual experiments the independent motion of the two parts is impossible on account of the continuity of the metal; the under part tends to pull in the upper, and the upper to pull out the under. In this contest the cooler metal, being the stronger, prevails, and so the upper part gets pulled in a little above the water-line while still hot. But it has still to contract in cooling, and this it will do to the full extent due to its temperature, except in so far as it may be prevented by its connection with the rest. Hence, on the whole, the effect of this cause is to leave a permanent contraction a little above the water-line, and it is easy to see that the contraction must be so much nearer to the water-line as the thickness of the metal is less, the other dimensions of the hollow cylinder and the nature of the metal being given. When the hollow cylinder is very short, so as to be reduced to a mere hoop, the same cause operates, but there is not room for more than a general inclination of the surface, leaving the hoop bevelled.

"The expansion of the bottom edge was not noticed in Colonel Clark's paper, perhaps owing to the much smaller hoops which he used in experimenting. Accepting Professor Stokes' explanation of the top contraction, it appears that expansion of the bottom may be accounted for by the reacting strain put on the cooled edge when forcing in the top edge, acting in such a way as to prevent the cooled edge coming quite to its natural contraction, and this, when sufficiently great, expresses itself in the form of a slight expansion.

"*Experiment No.* 14.—Forged steel hoop, turned and bored, 18·53 inches in circumference outside by 2·375 inches deep by ·27 inch thick, heated to redness, then cooled one-half its depth in water (see Fig. 1437 at G for final form of hoop after three heatings and coolings).

	Top Edge.		Bottom Edge.		
	Contraction.	Percentage of original length.	Expansion.	Percentage of original length.	
	Inches.		Inches.		
After 1st cooling	06	·32	—	—	Cracked at water-cooled edge one-third depth of ring.
,, 2nd ,,	·12	·64	—	—	
,, 3rd ,,	·20	1·08	·05	·27	After allowing for three small cracks in bottom edge."

The shrinkage of iron and steel by cooling rapidly is sometimes taken advantage of by workmen to refit work, the principles involved in the process being as follows:—

Suppose in Fig. 1438 *a a* represents a piece of wrought-iron tube that has been heated to a bright red and immersed in cold water *c c* from the end B to D, *until that end is cold.* The part submerged and cold will be contracted to its normal diameter and have regained its normal strength, while the part above the water, remaining red-hot, will be expanded and weak. There will be, then, a narrow section of the tube, joining the heated and expanded part to the cooled and contracted part, and its form will be conical, as shown at D D. Now, suppose the tube to be slowly lowered in the water, the cold metal below will compress the heated metal immediately above the water-line, the cone section D being carried up into the metal before it has had time to cool; and the tube removed from the water when cold will be as shown in Fig. 1438, from *c* to D, representing the part first immersed and cooled. To complete the operation the tube must be heated again from the end *c* to a short distance past D, and then immersed from E nearly to D, and held still until the submerged part is cold, when the tube must be slowly lowered to compress the end *c* D, making the tube parallel, but smaller in diameter and in bore, while leaving it of its original length, but thickening its wall.

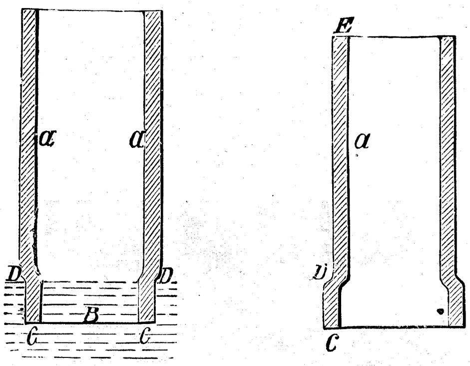


Fig. 1438.

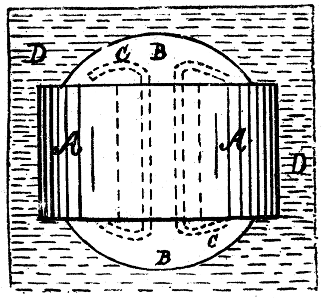


Fig. 1439.

This process may, in many cases, be artificially assisted. Suppose, for example, a washer is too large in its bore; it should have its hole and part of its radial faces filled with fire-clay, as shown in Fig. 1439, in which A is the washer and B B the clay, *c c* being pieces of wire to hold the fire-clay and prevent its falling off. The washer should be heated to a clear red and plunged in the water D D, which will cool and shrink the exterior and exposed metal in advance of the interior, which will compress to accommodate the contraction of the outer metal, hence the hole will be reduced. This operation may be repeated until the hole be entirely closed.

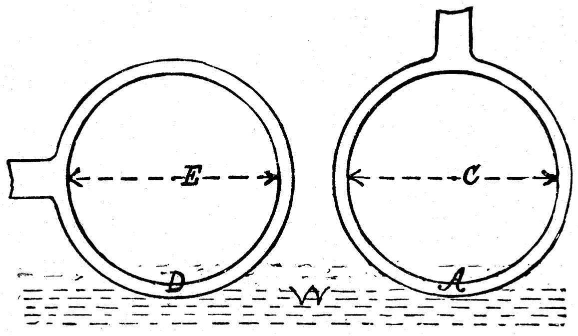


Fig. 1440.

Another method of closing such a piece as an eye of large diameter compared to its section, is shown in Fig. 1440; first dipping the heated eye at A and holding it there till cold and then slowly lowering it into the water, which would close the diameter across C, and, after reheating, dipping at D till cold, and then slowly immersing, which would close the eye across E. To shrink a square ring, the whole ring would require to be heated and a side of the square dipped, as shown in Fig. 1441, until quite cold, and then immersed slowly for about an inch, the operation being performed with a separate heating for each side. Connecting rod straps, wheel-tires, and a large variety of work may be refitted by this process, but in each case the outside diameter will be reduced.

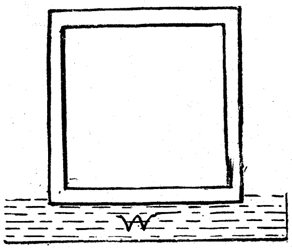


Fig. 1441.