GEAR CUTTING METHODS.

In the Papers on Engineering Subjects, No. 3, the Mechanism of Toothed gearing is discussed, and a brief outline of various methods of tooth cutting is given. The object of this present paper is to indicate in greater detail the methods of cutting the helical gearing as used in H.M. Ships; also to draw attention to the various possibilities of inaccuracy in cutting such gears, and to describe briefly some of the methods used for detecting such errors as may arise.

Modern methods of cutting helical gears for turbine reduction gearing may be divided into two classes, viz., (*a*) Planing or Shaping, and (*b*) Hobbing.

Up to the date of writing no gears made by any process other than that of Hobbing are running in H.M. Service. A spare set of planed gears has been constructed, however, but no opportunity has yet arisen to use it. The facilities existing for cutting large gears by the planing process are at present small, and this reason is mainly contributory to the non-employment of such units in H.M. Service. A further reason exists in the fact that although the planing process probably produces a tooth contour of more truly involute form than does the hobbing process, yet at the same time the profile of the teeth produced in the former manner tends to consist of a number of facets running longitudinally along the tooth face, and it is conjectured that such facets may not be conducive to good running. The hobbing process also produces facets on the tooth profile, but their location is more uniformly distributed along the line of contact than those produced by planing, and hence they are less likely to lead to noisy gears. Trials alone can determine their relative merits in this respect.

The main body of this paper therefore deals principally with the hobbing process, but brief descriptions of two planing machines are given.

Planing Processes.

I. The Sunderland Gear Cutter employed by David Brown and Sons of Huddersfield may be cited as an example of this process.

Here the Cutters are in the form of a rack. The involute teeth of the rack being straight sided, it is a simple manufacturing proposition to produce such a cutter with little possibility of error. The cutters, after being hardened, are ground to accurate form.

Figure 6, page 26 (of Papers No. 3), indicates the method of forming gear teeth by use of such a cutter. The cutter is a rack and during the process of generation is moved longitudinally, while the blank with which it engages is rotated by suitable gearing at the correct speed relative to the cutter.

In order to cut the teeth the tool is caused to reciprocate transversely at a rapid rate, being set at an angle equal to the lead angle with the axis of the blank.

A complication is necessary in order to limit the length of cutter employed, otherwise this latter would need to be longer than the circumference of the wheel being cut. Hence, after the cutter has travelled a distance equal to one pitch, the blank is disengaged from the cutter and its rotary motion checked, while the cutter is returned to its original position; the motion of the gear then starts as before. Thus at the end of each such cycle of operations the blank advances one tooth ahead of the cutter.

To avoid needless wear of the mechanism the dividing wheel and worm are at rest during the cutting stroke, and only operate the feeding gear during the return stroke of the cutter.

The action, referred to above, of returning the cutter for each tooth cut, is a possible source of inaccuracy though probably little, if any, worse than that due to the " whip " in the three or more comparatively thin shafts used in the hobbing process for driving the indexing and dividing mechanism.

Such a system may be employed to cut double helical gears without any gap between the right and left-handed portions. This is effected by arranging two cutters, one for each helix, and causing these to reciprocate towards each other, cutting to the apex at the centre of the gear.

The teeth are cut directly from the blank without any preliminary roughing cut. The front teeth of the cutter are arranged to take the heaviest cuts, while the back teeth only have to deal with light cuts, this being specially arranged for by the method of indexing; by this means a roughing and a finishing cut is taken in one operation.

The possibility of omitting the gap between the two halves of the gear is one advantage of the planing over the hobbing process, as applied to gears of such dimensions that a centre bearing is not called for on the pinion shaft, since on this account the gears may be made somewhat shorter and therefore lighter, and also the adjacent ends of the teeth of the two halves of the gears are mutually supported.

It is incidentally easier to do away with the centre pinion bearing if no " gap " is necessary, as in this latter case the distance between the centres of the pinion bearings is somewhat reduced.

The above advantages are, however, considerably discounted when very large gear wheels have to be cut, since it would not generally be possible to make the blank, on which the teeth are to be cut, in one piece if of large diameter and width; in such cases therefore considerations of ingot sizes, etc., make it necessary to cut the two halves of the gear on separate rims which are afterwards shrunk and pinned to the respective wheel centres.

II. Another type of gear cutting machine which is now finding increasing use is the Sykes' Planer, as developed by the Power Plant Co.

The principle of action of this machine is shown in Figure 1., and the leading particulars in Figure 2. The cutter is to all intents and purposes a helical pinion of narrow width. The teeth of this cutter are generated to accurate shape in a special machine, the final operation after hardening being a grinding one—this being also a generating process.

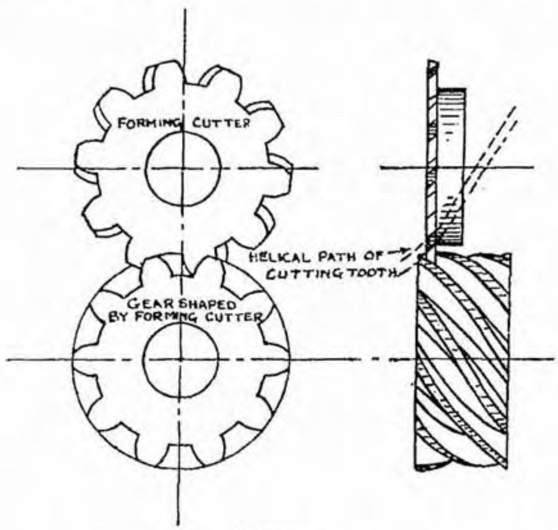


FIGURE 1.

The cutter and the blank are rolled together as if they were mating gears, while the cutter is reciprocated axially to plane the metal. In addition to these two movements the cutter has a third motion, viz., a rocking motion about its axis, so that its teeth follow the helical path of the tooth which has to be cut.

In practice two cutters are used, one of each hand to suit the two helices on the wheel being cut; each cutter is reciprocated inwards to the point where the two halves of the gear meet, it being a special feature of the machine that the "gap" between the right and left-hand helices can be entirely eliminated.

The blank is mounted with its axis horizontal and the cutters are attached to a shaft which is carried on the slide of the machine, this slide being reciprocated in line with the axis of the blank. The cutter operating shaft has a helical groove of suitable angle and lead cut upon it, and passes through the boss of the index worm-wheel (A). A stop is fitted in the boss of (A) to engage with the helical groove, hence, as the cutter is reciprocated to and fro, the action of the stop in the groove suffices to impart the rock-motion previously referred to.

The index worm-wheel is driven by a worm and suitable gearing from the main driving motor, as is also the main dividing

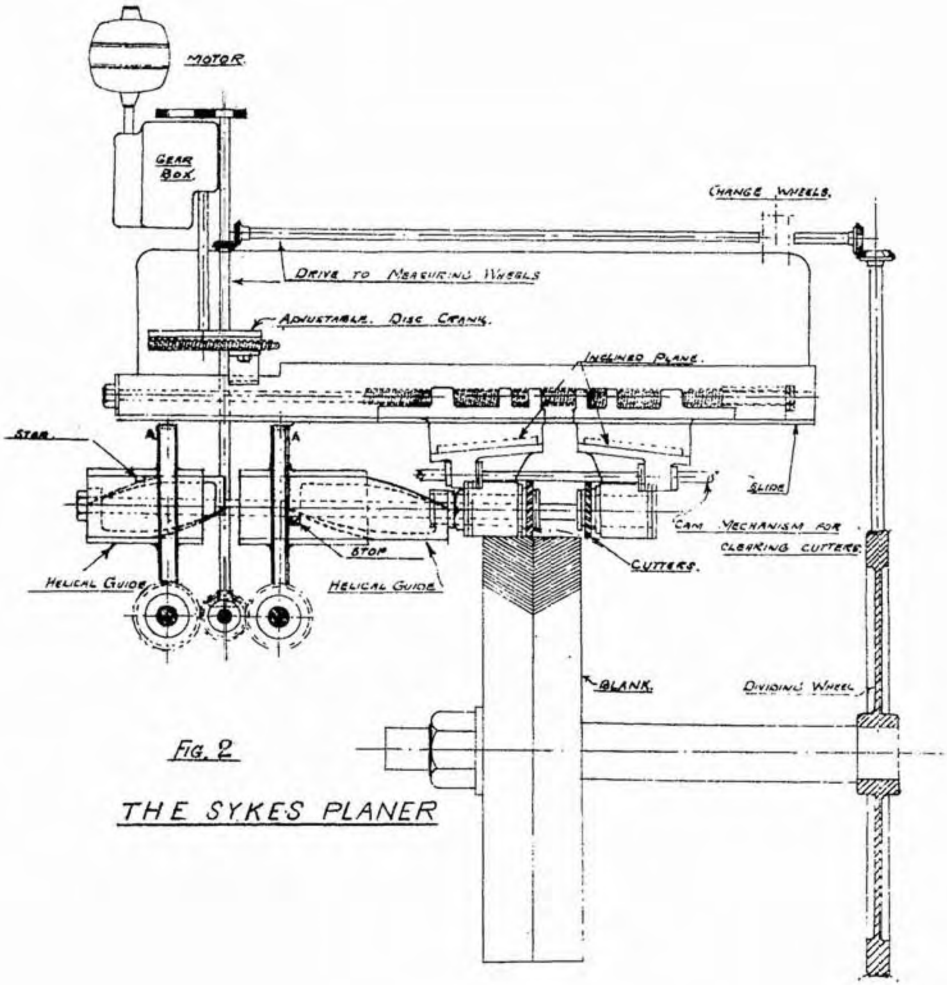


FIG. 2

THE SYKES PLANER

worm-wheel on the shaft carrying the blank. The change gears in these two driving shafts are such as to cause the correct rolling motion between cutter and blank. For compactness, the cutter operating shafts are mounted one inside the other, the two indexing worm-wheels for driving the cutters being at the same end of the machine.

A further complication is introduced owing to the necessity for clearing the cutters from the work on the return stroke. The method of doing this "relieving," as it is termed, is both simple and ingenious: the journal adjacent to the cutter is connected to the slide of the machine through the medium of an inclined plane, so arranged that when the journal is forced (by suitable cam mechanism) in one direction parallel to the axis of the cutter shaft, the cutter will be at its cutting depth, while when the journal is forced hard over in the opposite direction the cutter will be relieved from its work. This longitudinal motion is only about $\frac{1}{16}$th an inch, while the amount of "relief" given is a few thousandths of an inch. The cutter index worm-wheels are mounted on slides and a similar type of inclined plane action is employed to move these through the same distances as the cutter heads are moved, thus keeping the cutter shafts parallel to the main slide.

In such a machine, although there is a considerable number of working parts, they are compactly arranged and are of ample stiffness; the cutting action appears more smooth and regular than that of a hobbing machine while the quality of the work produced is excellent.

The accuracy depends first and foremost on the accuracy of the cutter, but given accurate design there appears little, if any, source of error to fear in this direction when the method of manufacture and finish by a generating process is followed. The helical angle generated depends for its accuracy on the helical groove actuating the cutter shafts; hence these grooves require checking from time to time, particularly as they are subjected to considerable wear.

Other than the above, the remaining probable cause of inaccuracy lies in the worms driving the indexing worm-wheels or in these latter themselves. The remarks to be made later on a similar subject as regards hobbing machines are equally applicable here.

Two or more cuts are usually taken when producing gears in this machine, the initial cuts being taken with well backed off cutters, and the final one being a light finishing cut, using very accurately ground cutters.

After the pinions and gear-wheel are completed they are erected in the gear case and run light with a grinding compound, which consists of fine glass powder of the consistency of flour and light oil, instead of the usual lubricating supply to the tooth surfaces. This grinding-in is considered by the Makers to be most beneficial in smoothing down minute high places, etc., unavoidable in any tooling process; it certainly gives a very fine finish to the gears. In theory it is to be noted that the grinding process is not calculated to improve the accuracy of the contour of the teeth.

The Hobbing Process.

Consider first of all the method employed for hobbing spur gears. The principle of this method is shown in Figure 3.

This shows an imaginary rack meshing with a gear and moulding its teeth. The teeth of this rack (shown dotted) coincide with the outline of a hob, which has been set at an angle which will make the teeth on its cutting or front side parallel with the axis of the gear; that is, it has been set at its helical angle, measured at the pitch line.

If the hob and the gear blank be now rotated at a speed ratio equivalent to that between the number of threads in the hob and the number of teeth in the gear, the resulting movement will be exactly the same as if the blank were meshing with the imaginary rack referred to.

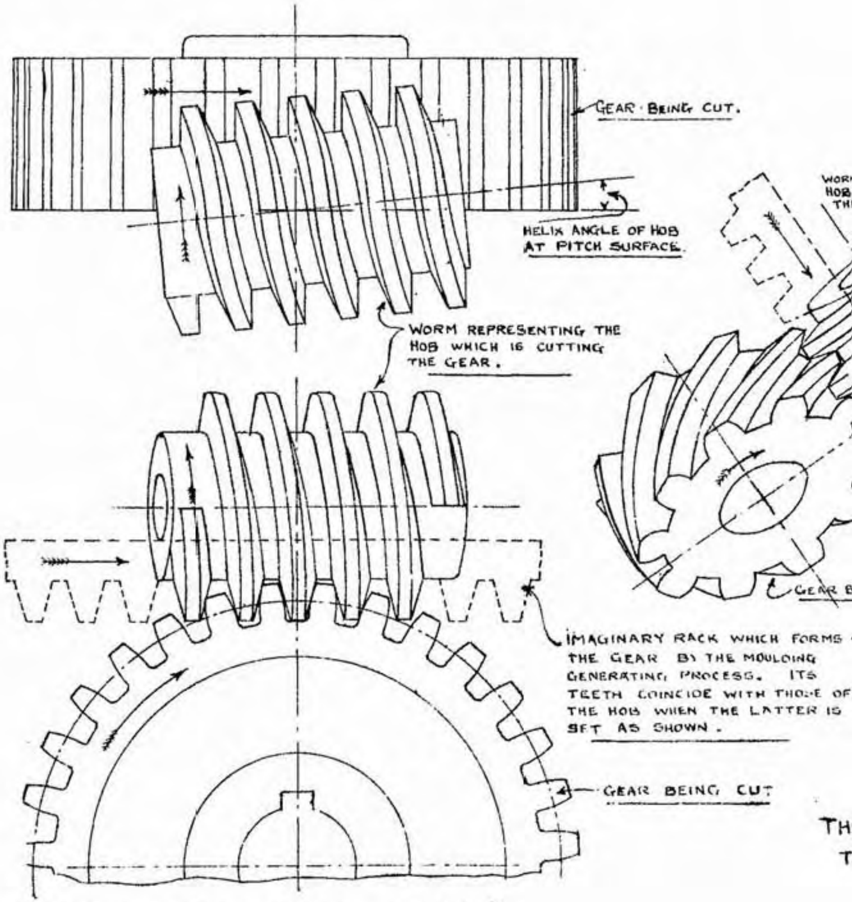
In the case of hobbing helical gears the arrangement is as shown in Figure 4.

The hob is set at an angle with the line of movement of the imaginary rack, equal to its own helical angle, as for spur gears. The blank is set at an angle with this same line equal to its own helical angle, so that in the case shown (hob and gear with right hand helices) the tool and work are set at an angle equal to the difference between their respective helical angles. If the hob and blank be revolved at the proper speed ratio, the former will cut teeth in the latter in the same way that the imaginary rack would, provided it is fed progressively through the work in the direction of the line XX.

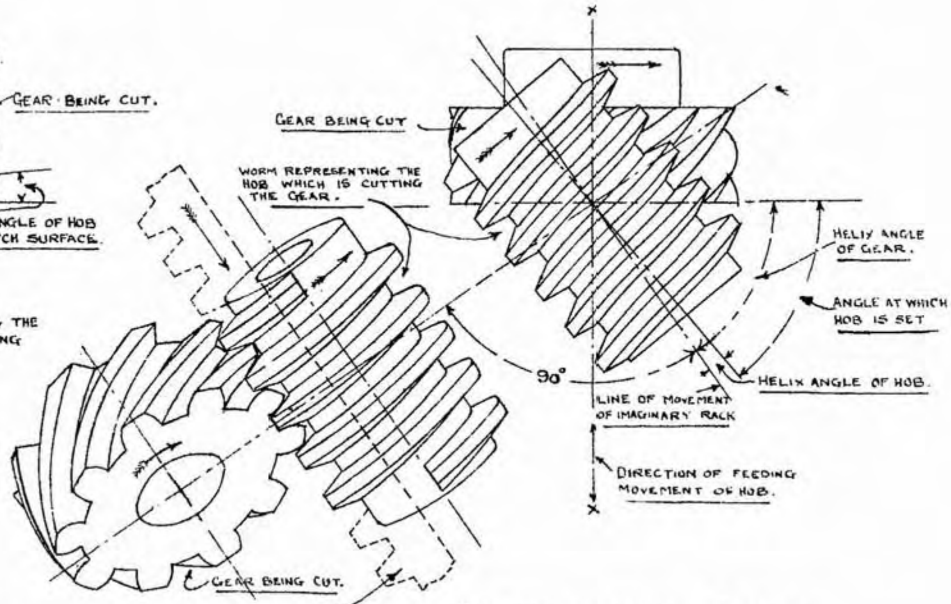
This latter requirement introduces further complexity in the machine, and its necessity is best understood from the following:—
Imagine the work to be stationary; then, in order that the hob may be fed in direction XX without the teeth of the hob and the gear fouling each other, it is necessary to revolve either the work or the hob. Suppose the work to be connected by change gearing to the feed screw of the cutter slide so that it is revolved as the hob is fed up and down; this will permit the cutter to pass freely through the work.

Summing up, therefore, not only must the work revolve in unison with the hob, so as to generate the correct number of teeth, but also it must revolve in a definite relation with the feed of the cutter slide in order to produce the correct helix. The work must then be so connected to the cutter and to the cutter feed screw, that it will be under the influence of either or both of them, without any interference of the two movements with each other. This is usually effected by means of differential gearing.

It is evident from consideration of what has been said above that the circumferential velocity of the pitch circle of the blank and the velocity in an axial direction of the teeth of the hob must



HOBBING OF SPUR GEARING. FIGURE 3.



HOBBING OF HELICAL GEARING.

FIGURE 4.

THE PRINCIPLE OF THE HOBBING PROCESS FOR CUTTING THE TEETH OF GEARING.

be the same at all parts of each successive revolution; if this is not so the blank may accelerate or retard an infinitesimal amount during a portion of a revolution, causing the hob to generate teeth which vary in thickness.

The relative velocity of hob and work are produced by means of suitable mechanisms of the type shown in Fig. 5, and it can be readily imagined that slight errors are difficult to avoid in the erection of such devices, while their detection calls for special instruments. The hobs themselves are supplied as nearly correct as is commercially possible, and may be eliminated from the problem if checked by suitable means.

Methods have been recently developed whereby any variation in the relative angular velocities of the hob and work spindles may be detected, and use is made of these by at least one well known firm of gear cutters, enabling errors of the type mentioned to be eliminated. Since however, these devices are designed for use when the machine is running idle, their employment will not necessarily remove errors due to the indexing mechanism when cutting is in progress, owing to the deformation of such mechanism when under load.

In order to ensure that mating gears have the same helical angle, it is extremely desirable (and is in fact specified as such for all Admiralty turbine reduction gears) that both gear wheel and pinion should be cut on the same machine. Even this will not, however, ensure the same helical angle unless the feed mechanism of the machine is suitably arranged for the purpose.

The diagram in Figure 5 shows the elements of a typical high-class mechanism suitable for producing gears of identical helical angle.

The Hob (*A.*) is driven through the shaft D by change-wheels E from the motor.

The Table is driven by the dividing worm-wheel B through the worm C and shaft R by change-wheels G from the motor.

The cutter slide.—The feed screw is controlled by shaft R through feed gears H, worm and worm-wheel J and compensating gears K through shaft S.

The shaft S further controls the helical angle by accelerating or retarding the hob through change gears M and differential N.

As pointed out previously the helical angle can be obtained by causing the work to revolve in a definite relation to the cutter slide, which in the case of the mechanism now being described would entail placing the differential gear in the table motion, shaft R. Such an arrangement has, however, the disadvantage that change wheels have to be introduced, sometimes precluding identical helical angles being obtained in mating gears; on the other hand, with the shaft S controlling the cutter slide and the hob (instead of the table) an identical effect is obtained and angle variations do not arise when the feed is changed.

Referring to Figure 6 it will be seen that the hob will cut either right- or left-hand helical gears or straight cut spur gears, depending on its setting relative to the wheel axis. It has been found as a result of experience that if a helix is cut with the hob of opposite hand (*i.e.,* say, a right-hand helix with a left-hand hob) the work tends to "float" thus causing any backlash between dividing worm and wheel to become apparent, with consequent variable errors. It is therefore desirable to cut a right-hand helix with a right-hand hob, and a left-hand helix with a hob of similar hand.

When hobbing straight cut spur gears the hob makes one revolution per tooth cut, but in hobbing helical gears as the hob travels down it must be retarded, making a fraction under one revolution per tooth. This fact often necessitates awkward change gears for feed variation, hence the introduction of the differential control.

It is readily apparent that the use of the differential mechanism referred to may be avoided if the hob is fed in the direction of the helix as indicated in Figure 7.

Machines have been designed to achieve this, but their use is entirely out of the question with gears having wide faces, such as are necessary for turbine reduction gearing, as the length of the hob will be altogether prohibitive.

The principal requirements for a successful hobbing machine are :—

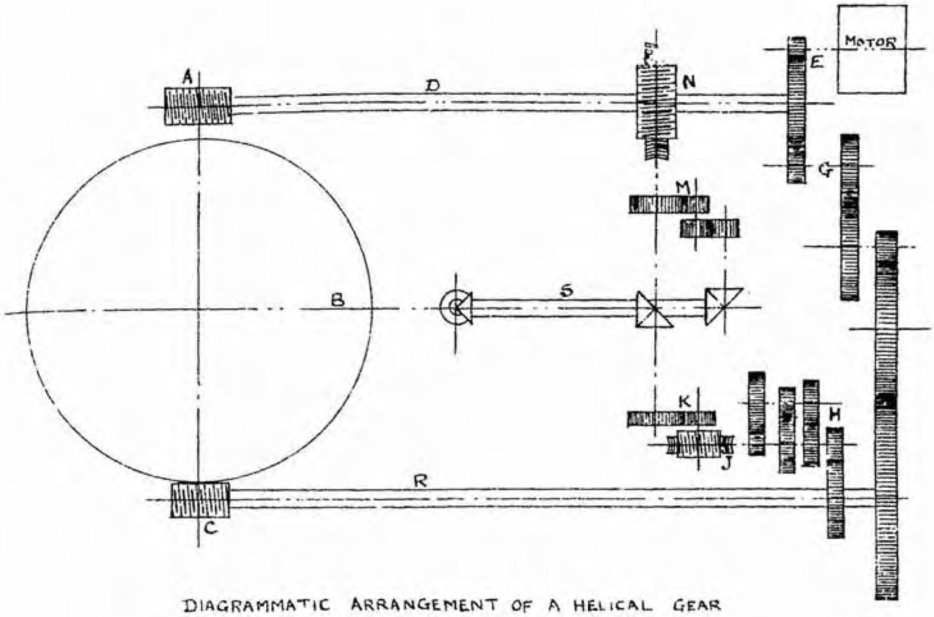
(1) **Frame and Mechanism of Great Rigidity.**—In this connection it is pointed out that the complexity of the feed mechanism tends to limit the capacity of the machine in taking heavy cuts, the effect of which is to produce torsional and other strains in the mechanism, thus prejudicing its accuracy.

(2) **Durable and Powerful Driving Mechanism.**—The drive is invariably by a separate electric motor embodied in the machine, while the lubricating arrangements are extremely thorough, since the machine may have to run for several days without stopping.

(3) **Accurate Indexing Mechanism.**—The dividing wheel should be the maximum diameter possible in order to control the work properly.

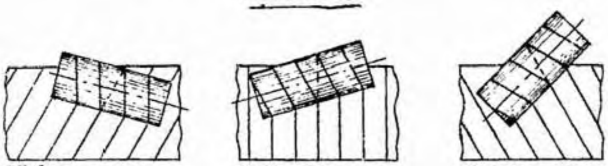
A highly accurate dividing worm-wheel is imperative. Mathematical accuracy is of course impossible, but a very close approximation thereto can be assured by Engineering methods. In such gears there need be no practically measurable tooth-to-tooth error, while the accumulated error in groups of, say, 20 teeth should be well distributed round the circumference. Homogeneity of the material of which the wheel is made is of prime importance, so that there are no soft spots which will wear more quickly than the remainder of the wheel.

The importance of the accuracy of the dividing wheel cannot be overestimated, for the work in no case can be better than the dividing wheel producing it.



DIAGRAMMATIC ARRANGEMENT OF A HELICAL GEAR HOBBING MACHINE.

FIGURE 5

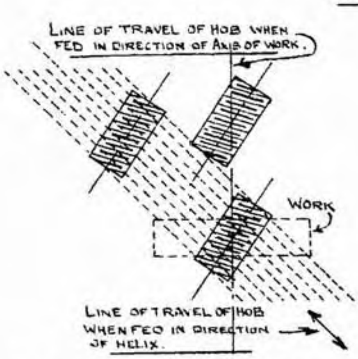


R^T. H^O. HOB CUTTING R^T H^O. HELIX.

R^T. H^O. HOB CUTTING SPUR WHEEL.

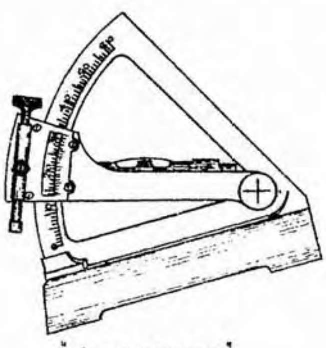
R^T. H^O. HOB CUTTING LEFT HAND HELIX.

FIGURE 6.



HOB BEING FED IN DIRECTION OF HELIX.

FIGURE 7.



"CLINOMETER"

FIGURE 8.

The dividing wheel requires testing about once every six months if the machine is in regular operation. A simple method of carrying out this test is as follows :—

A straight edge is clamped to the machine with its edge radial, and a horizontal surface is set up so that on rotation of the table a point on the straight edge will describe an arc on the surface. An arc is actually scribed in this way at some suitable radius from the centre of the table. Having selected any suitable train of wheels for the dividing gear, one of these wheels is rotated through a given number of turns, and the length of arc due to this movement is marked on the surface. The same number of turns is again given to the same wheel and the length of arc described is again marked.

The process is repeated till the dividing wheel has made one complete revolution; the errors, of course, are estimated from the variation of the chordal distances thus marked, these being accurately measured and compared with the calculated length for all parts of the wheel.

It is essential, before commencing cutting with a new machine, to run the table in each direction for a period of about three days in order to bed in the worm and worm-wheel thoroughly.

It is preferable that the worm should wear rather than the worm-wheel, for a worm is easily replaced without affecting the accuracy of dividing, while errors introduced into the worm-wheel are always present and can only be cured by the costly replacement of the wheel itself. In practice the actual wear, after the initial running in, is small, and the worms run for periods of two or three years before replacement is necessary. The actual amount of wear on some worms has been about ·002 inches after two years use.

In the earlier gears, where periodic errors crept in, these were traced to the dividing wheel. Sir Chas. Parsons therefore introduced his " creep " mechanism, which essentially consists in mounting the work on a secondary table carried on the main table, which latter is turned by the dividing wheel. The secondary table is caused to rotate, by suitable gearing, at a slow speed relative to the main table, the combined speeds being, of course, adjusted to give the correct speed ratio between work and hob. This angular advance of the work relative to the dividing wheel causes the errors due to the latter to be developed on spiral paths around the gear rather than on planes parallel to the axis of the gear as in the case without " creep "—thus, instead of a series of inaccurate zones being in gear at definite intervals, the errors are very uniformly spread over the whole surface of the teeth.

The creeping table if used with standard hobs produces increased tooth spaces, since if any error is " crept " it must appear as an increase in the space, hence hobs for use with this device are made with a thinner tooth to compensate for this action. Originally gears were cut by hobs having equal tooth and space widths, but the modern gear hobs have increased "spaces," thus improving the conditions for the formation of the lubricating film, which reduces the "singing" noise: in other words it has been found necessary to increase the oil clearance between the teeth. The creeping table gives this action automatically, and has thus been responsible for reducing noise in this manner as well as by spacing out the errors.

The creep gear in its original form is now largely being given up, as, however well the mechanism is made originally, it is bound to wear in course of time and produce unknown errors in the work, such errors attaining dimensions greater than those in the main dividing wheels; further, worm-wheels can now be cut with such a high degree of accuracy as to render unnecessary the employment of such a device as the creeping-table.

(4) **Means of taking Weight of Work.**—It should be appreciated that the accuracy of the finished product will be affected by the torsional deflection of the indexing and dividing mechanisms. These devices, if of reasonable design and carefully constructed and erected, will produce accurate "tracking" of cutter and blank when not under load, but will not necessarily do so when cutting is in progress.

If, however, the machine can be adjusted so that its driving parts are subjected to an approximately constant torque under all conditions, then all gears produced by it should have a similar degree of accuracy, in so far as this is affected by the above considerations.

As the work dealt with by any one machine varies in weight it has therefore been found desirable to counter-balance a portion of the weight of the blank in order that the machine may work against constant frictional resistance, whatever the weight of the work.

To achieve this, suitable arrangements are made so that any desired proportion of the weight can be counterpoised, it being usual to adjust the counterpoise so that the current taken by the motor is a constant figure, determined by experience, whatever the load on the table.

(5) **Position of Driving Worm.**—As regards the position of the worm controlling the dividing wheel, it has been found that if this is placed diametrally opposite to the hob, distortion is liable to be set up, and that it is best located immediately below the hob. Some makers drive the wheel by two worms placed diametrally opposite each other, but it is very questionable whether they can both function simultaneously, and in any case the danger of distortion still exists.

(6) **The Cutter Slide Feed Screw.**—The accuracy of this screw is a factor equally important as that of the dividing wheel, since the helical angle depends on the combination of the two.

(7) **Cutter Slide.**—Since the thread of the hob must be exactly on the line of the helix, the cutter slide must be capable of being

set at any angle with the vertical. This is a most important setting and any inaccuracy affects the width of the tooth space.

One method of setting the angle of the cutter slide is by means of a Clinometer (Figure 8). This may consist of a graduated arc of a circle with an arm, carrying a spirit level, pivotted at the centre of the arc. The instrument is first levelled on the work, or on the bed of the machine, to give its zero. The pivotted arm is now moved through the required angle and the instrument then placed on the cutter slide which is rotated till the spirit level is horizontal. The arc is very accurately graduated and is fitted with a vernier after the fashion of a sextant.

A further point in connection with the mounting of the hob is that it should have no side play and no axial freedom. This should be checked before cutting is commenced.

(8) **Setting Up.**—This is most important and cutting should not be started till the work is mounted truly concentric with the axis of the table. It is considered preferable by some makers to mount the work on a cradle, because bolts, cramps, etc., passing directly to the table are liable to induce distortion.

The cradle is generally skimmed up true to the axis of rotation by a tool carried on the cutter slide. The blank is also skimmed true to its axis at a convenient part, the cradle being turned to fit this trued portion of the blank—the latter can then be placed in the cradle with certainty.

Heavy gears upset the alignment of the machine by causing the foundation to sink, and therefore this should be tested after the blank has been placed in position, and if necessary the table relevelled.

One method of attaining this is as follows :—

When installing the machine, before levelling, the bed-plate is balanced with its centre of gravity over a flat bar of suitable dimensions; wedges are then adjusted all round the bed to level it up.

If the weight of the blank causes distortion, the wedges are knocked out, leaving the bed balanced on the bar. The wedges are now re-adjusted to level the table again and the whole is grouted in concrete.

(9) **Depth of Cut., &c.**—This is adjusted by moving the upright carrying the cutter-slide towards the work. A micrometer device is fitted to enable the depth of feed to be gauged; the zero position of the micrometer is set before cutting by bringing the hob in contact with the work and then setting the micrometer—from this setting the depth of cut at any time can be gauged.

The alignment of the table of the upright may be affected by strain after heavy work or by settlement of the foundations of the machine. Fig. 9 indicates a method of checking this alignment. Any error in this may possibly cause rubbing of the points of the gear teeth in working.

Some gear-cutting firms maintain that the top of the upright should lean slightly towards the centre of the table in order to allow for "spring" when cutting, but this device appears open to question.

It would appear at first sight that greater accuracy might be attained by taking a series of cuts rather than by cutting to the full depth at one operation. It should be appreciated that the dividing mechanism is necessarily based on the pitch circle diameter of the hob and that of the completed gear. If therefore a half depth cut is taken, the hob is attempting to produce a number of teeth in the blank not in accordance with the setting given by the dividing mechanism. This strain plays on the soft and hard places in the blank, which can never be entirely homogeneous, and thus errors creep in, accentuated as they are by backlash in the dividing gear.

Obviously, the deeper the cut taken the more nearly are the hob and dividing gear in accord, and hence the less strain on the mechanism, with consequent lessened liability to error.

It is therefore on this account to be recommended that only one cut should be taken, and that where a finishing cut is desired this should be of the order of, say, not more than $\frac{1}{100}$th of an inch.

It is pointed out that owing to the hob receiving a certain feed for each revolution of the work, the face of the tooth is necessarily composed of a number of small facets; on this score a light finishing cut appears very desirable, followed, possibly, by running the hob through again in a slightly different relative position to that in which the main cut was taken, thus tending to remove the high points of the facets.

Experience goes to show that in any case the greater part of the errors in a gear are introduced during the initial cut and are not removed by subsequent ones, but rather tend to reproduce themselves.

Another consideration affecting the rate of feed given to the hob is that if this is too fast, excessive torsional strain of the blank or hob is likely to occur, thus introducing possibilities of considerable error—this is particularly the case in cutting the teeth of pinions which necessarily have not the rigidity of gear wheels.

Finally, this question is further complicated by wear of the hob. It has been found that the amount of wear of a hob is a function of the length of time it is in contact with its work, and is largely independent of the cut taken. On this account when cutting wheels over, say, 6 feet in diameter the wear of the hob becomes a serious matter. Gears of large diameter and width of face should preferably have the spaces cleared by a "stocking" cutter and then be finished by a well backed-off hob run through at as high a speed as is consistent with a good finish. The stocking cutter used for this purpose may consist of a serrated worm thread, with teeth formed similarly to those of a stocking milling cutter. These cutters are often built up of helicoidal sections to permit of more easy sharpening.

Hobs are usually removed from the machine for regrinding, etc., after they have cut so many feet round the circumference of the work. It must be appreciated, of course, that a hob cannot be changed while a cut is being taken, and for this reason the teeth of the work are always thicker at the region where the hob leaves than at that at which it starts the cut.

In this connection it is of interest to note that completed gears after running generally show " hard bearing " marks at the outer ends of the two helices. It will be found in such cases that the blank was reversed end for end between the cutting of the two halves of the gear, thus leading to the hob leaving its work at the position where the hard places are subsequently observed.

Hobs.

The question of hobs is a most important one, though the limitation imposed by the machine and the type of tooth do not permit of wide variation in the design of these tools.

The hob itself resembles a large tap, and, like these latter, is tapered to distribute the cut, since it enters its work endwise.

Hobs may be single or multiple threaded, the main object in using the latter form being that the wear is distributed over several threads instead of over only one, as in the former type, thus leading to reduction of the actual wear.

On the other hand, experience goes to show that for extreme accuracy the slower the lead of the hob thread the better; hence multiple threaded hobs tend to give less accurate results than single threaded, since the lead of the former type is of course rapid.

A modern type of hob has been developed in which the alternate teeth have been removed; this feature enables the teeth to be more easily ground, and, further, it provides better clearance for freeing the chips. In addition, the leading teeth can be given front rake so as to rout freely, enabling a deeper cut to be taken and so reducing the strain previously referred to. It is considered by some authorities that a lesser number of teeth than the normal is an advantage in that it gives freer cutting, whereas the more usual type of hob with many teeth tends to give a burnishing action rather than a cutting one. Experience with this type of hob, however, appears to indicate that in practical work it gives no better results than the ordinary type.

These tools are made by " specialist " manufacturers and it is not possible to check their accuracy completely without the use of special instruments, such as are described later. Individual teeth can, however, be accurately gauged by the instrument used in most machine shops for measuring the thickness of a tooth at any given distance from its point. Such dimensions are given on the standard hob drawing, and should be checked before and after each occasion on which the hob is used, and also after grinding. This checking of the hob is most important, since the product is dependent on the hob no less than on the remaining elements of the producing machine for its freedom from error.

Hobs are now produced commercially which are accurate within a maximum cumulative pitch error of $\frac{2}{1000}$ in., that is, the sum of the maximum positive and negative variations from the designed pitch does not exceed the figure given. It may be pointed out that this degree of accuracy is far from general, since it can only be checked by very special apparatus, the necessity for which is only now beginning to be appreciated in circles outside the highly specialised gear cutters.

Checking of Gears.

The best instrument at present available for checking the accuracy of the thickness of gear teeth isthe Sykes' Comparator.

This consists of a pair of suitable shaped jaws, representing the adjacent profiles of two teeth, with a plunger working between them. This plunger is attached to a dial gauge arranged to give readings to the desired degree of accuracy, say to $\frac{1}{10000}$ in.

In operation a pair of jaws are fitted to the comparator, these jaws being chosen to suit the pitch and form of the teeth of the gears.

The comparator is then applied to one tooth of the gear and the plunger of the dial gauge set to give zero reading. If the comparator is now tried all over the gear it will give errors $+^{ve}$ and $-^{ve}$ as compared with the tooth for which it is set.

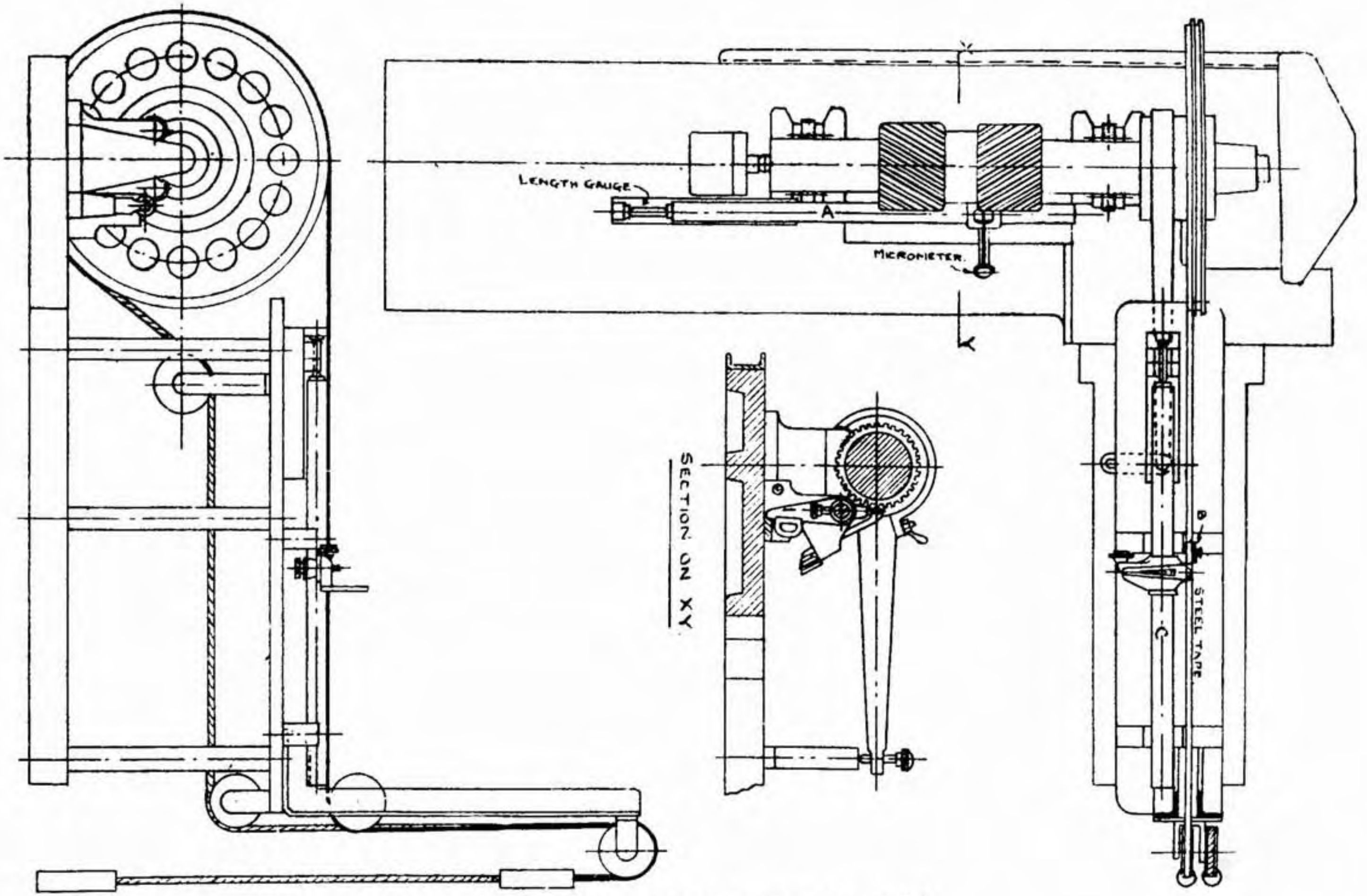
In lieu of setting the instrument on any one tooth it may be set to a standard tooth form as supplied in various sizes with it.

This instrument indicates therefore any variation in the thickness of the teeth at the pitch line (or elsewhere), and such indications are of considerable value. It does not, however, show up errors in pitch or in helical angle, the measurement of which necessitates instruments of considerable precision and of some complication.

Machines for Measuring Pitch of Gear Teeth.

I. The Metropolitan-Vickers Co. have recently produced a machine for measuring completed gear teeth and hobs which is illustrated in figure 10; in this device the circumferential and axial pitches of the teeth are both measured. The pinion is mounted on rollers in a horizontal position, with a straight cylindrical shaft arranged truly parallel to the axis of the pinion on vee-blocks alongside the latter.

This shaft (A in figure) carries a measuring device, consisting of a multiplying lever, the short arm of which is fitted with a spherical head while the long arm is attached to the micrometer device, which comprises a dial gauge. The end of the shaft (A) is placed against a stop fitted on the end V-block; the spherical head is now brought into contact with a tooth of the pinion, this being done by rotating the pinion by means of a lever clamped to its shaft; the dial gauge is now set to zero.



METROPOLITAN VICKERS GEAR TESTER. FIGURE 10.

A number of very accurately made length gauges are supplied, each differing in length by an amount equal to the axial pitch of the pinion teeth. One of these gauges is inserted between the stop and the end of the shaft A, thus transferring the spherical head of the measuring device an amount equal to one axial pitch. The dial gauge should, of course, now show zero; its actual reading will indicate any error in axial pitch.

A longer gauge is now inserted and the process repeated; it is necessary, of course, that the shaft (A) be kept from rotating while being moved axially, and a special device, consisting of a finger bearing on a shaft parallel to (A), is fitted for this purpose. After a whole series of such measurements, *i.e.*, when the spherical head has travelled the full width of the pinion face, the pinion is rotated on its axis through an angle corresponding to one circumferential pitch, similar length gauges being employed, and a new set of readings taken in the axial direction.

These operations are repeated till the whole circumference of the pinion has been traversed.

The method of rotating the pinion through the correct angle is somewhat similar to that employed in advancing the measuring device through an exact multiple of the axial pitch. On the pinion shaft is mounted a wheel, the attachment being by means of a split cone in order to ensure exact concentricity. A flat steel tape is attached to the circumference of this wheel and after passing round the wheel it is led off in a horizontal direction over suitable pulleys, being kept in constant tension by means of a weight. The pull of this weight is balanced by another which is attached to a cord wound round the wheel in opposition to the tape.

A horizontal steel bar is arranged parallel with the tape and carries upon it a steel slider (B) which can be clamped to the tape as desired.

Parallel with the tape and the bar is fixed a shaft (C), also on V-blocks, and carrying a second dial micrometer gauge with a multiplying lever. The short arm of the multiplying lever ends in a spherical head as before, and this head can be brought in contact with a prepared surface on the slider (B).

The end of shaft (C) bears against a micrometer head, and a series of "length" gauges, each differing in length by a distance equal to one circumferential pitch of the pinion teeth, are provided for adjusting the axial position of this shaft.

Initially the pinion is adjusted as previously described, so that the axial pitch micrometer reads zero when in contact with a tooth of the pinion.

Having made this setting, the slide (B) is clamped to the tape and the circumferential pitch micrometer is adjusted to read zero, with a gauge of convenient length in use. After the first set of axial readings have been taken the next gauge in the series is fitted at the end of shaft (C) and the pinion is rotated till the micrometer attached to the former reads zero, *i.e.*, till the pinion has turned through one circumferential pitch. The axial readings are now continued and the process is repeated till the working face has been covered. Both dial gauges read to $\frac{1}{1000}$ of an inch.

The instrument is admirably adapted for use in checking pinions and hobs as previously stated, but would need to be of considerable dimensions to enable it to be used for gear wheels. Its principal practical value undoubtedly lies in checking the accuracy of the hobs.

II. A simple type of instrument recently invented merits a short description, if only on account of its simplicity and portability. The device can be used with the gears in place and is arranged to measure the axial pitch of the teeth.

The instrument is shown in Figure 11. It consists of a round bar (A) and a square bar (B), which is fixed in a groove in (A) parallel to the axis of the latter; this bar (B) forms a bed on which the measuring devices can be moved.

Assuming that the pinion and gear wheel are in true alignment and are cylindrical, then if (A) be placed in contact with them both, as indicated, the bar (B) will be truly parallel to the axes of pinion and wheel.

The bar (A) is magnetised and thus holds itself fairly in position, with no risk of distortion.

On the square bar slides a block (C) carrying two fingers (D) and (E) on a small bar (F), which is secured to (C) by a clamp. Of these two fingers (E) can be clamped in any desired position on (F), while (D) is connected to a micrometer dial gauge of the usual type.

The bar (A) having then been placed in position as shown, the two fingers (D) and (E) are adjusted a suitable distance apart, approximately equal to one pitch of the gear teeth. The whole apparatus is now pressed in an axial direction, thus causing the fingers to make contact with the flanks of two consecutive teeth; a reading of the dial gauge is now taken.

The apparatus as a whole is now advanced one pitch in the axial direction and a new set of readings taken; these operations are repeated till a complete record is made.

The accuracy of the teeth may be tested before the gears are erected, by employing an angle plate in the manner indicated in Figure 11 (*a*), the pinion being placed upon a surface table for the purpose.

The alignment of gears can also be simply tested by placing the apparatus as indicated in Fig. 11 (*b*), it being so arranged that one edge of the square bar touches the point of the teeth. The errors in alignment can then be found by inserting feelers between the bars and the points of the teeth. It should be noted that the two fingers can be rotated round or with the rod (F), and, further, that rotation of (A) towards the pinion is prevented by a small rod (G) clamped to the square bar, and butting against the pinion shaft. By means of these adjustments the axial pitch may be measured at any position on the tooth profile.

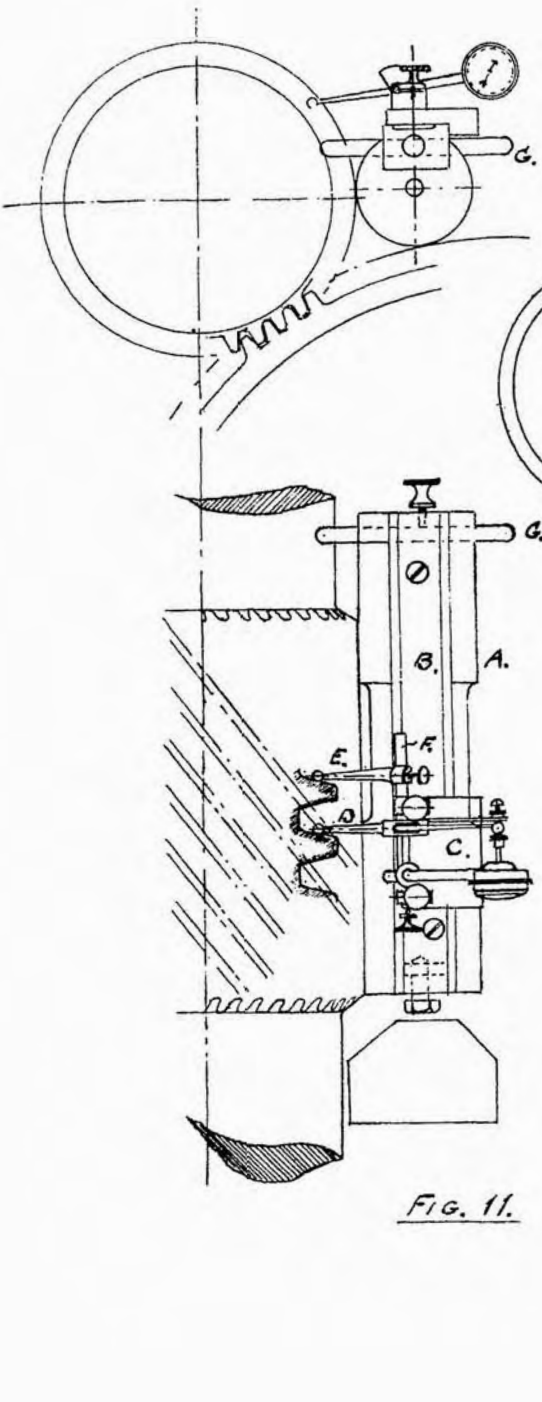


FIG. 11.

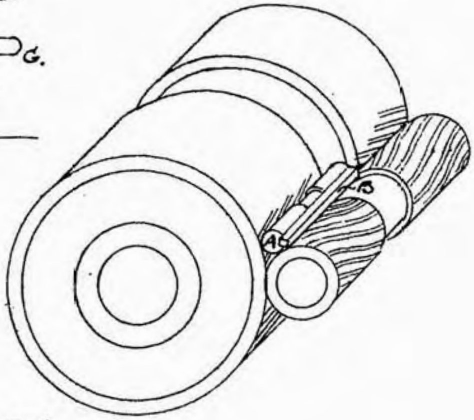


FIG. 11 b

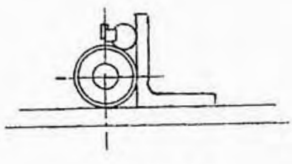


FIG. 11 a

All gears used for turbine reduction in H.M. Navy are "run-in" in the erecting shop, but necessarily under "light" conditions. This test serves to bed them in to some extent, but it must be appreciated that when under load such gears are subject to torsional deflection which will modify the contact of the teeth from that obtaining when run light. On this account the practice, previously mentioned, of grinding gears together is likely to be of less value than would otherwise be thought.

It must be appreciated that once a gear has been cut very little can be done to improve its accuracy, while the checking of such accuracy is a matter of considerable difficulty. Despite the extreme care taken in modern high-class gear cutting and the accuracy of the tools employed, periodic errors traceable to the cutting process are found to creep in occasionally in gears cut by the best makers. This emphasises the need for the exercise of the utmost care at all stages of the cutting process, and indicates that the degree of accuracy required in large high-speed gears can only be assured by close attention to the finer details of the processes employed and an intelligent appreciation of their significance by the inspector no less than by the makers.