MODERN CUTTING TOOLS AND MACHINE TOOL DESIGN

by

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The carbide tipped tools mentioned herein are undoubtedly excellent for the purpose for which they were developed, e.g., "mass production," but it has limitations when applied to the general type of repair work encountered on board most of H.M. ships. Carbide tipped tools are, however, being provided in some repair ships where the type of work approaches "mass production."

Cutting tool research has for its object the reduction of the cost of production and accordingly the problems are to a great extent economic.

Rate of production is determined by the rate of feed and high cutting speeds have been developed in order to allow rapid feeding. As so many difficulties are associated with high speed machining, it might well be asked why rapid feeds were not used in conjunction with low cutting speeds. Heavy feeds at low speeds give rise to thick chips and heavy cutting loads. Frequently the rigidity of the work limits the permissible cutting load and heavy chip formation is always combined with poor surface finish quality.

Heavy cutting loads necessitate heavy machines and recent cutting tool research has tended to the development of the light machine running fast as distinct from the heavy slow speed machine. Great accuracy of the product with good surface finishes are now required and both of these demand high speeds with relatively light cuts.

The history of machine tools shows that they have not created a demand but have been originated to meet a demand. Of late years there has been a large increase in the lighter production industries catering for the automobile, electrical, and domestic appliance trades and the calls of these industries for machine tools have contributed greatly to the growth of the light high-speed machine tool.

It is a large step from the realm of laboratory research to the application of the results to production, and this is true of recent work on cutting tools. Much investigatory work has been done both in this country and in America on the phenomena concerning the cutting of metals, and although considerable advance has been made in knowledge of the subject, many problems await solution before the full benefits can be handed on to the machine user. Good cutting performances are all very well in their way, but many machine tools are occupied in cutting for a surprisingly small proportion of the 24-hour day, and the benefits of enhanced cutting efficiency can easily be overwhelmed by the time required for tool setting, handling, loading, and machine maintenance. The machine designer must take account of these aspects of the problem as well as the cutting efficiency, if a satisfactory overall efficiency is to be obtained.

The story of the development of cutting tools is marked by several well-defined steps which have each shown the necessity of improving the available machine tools to enable them to be used with the new types of cutting tools.

High-speed Cutting Steels

One of these steps was the introduction of high-speed steel which, in a very short time, rendered obsolete most of the chip forming types of machine tools then in use, and revolutionized machine tool design. It is usual in such circumstances for the machine designer to make the new machine capable of complete mastery over the cutting tool, and in response to this new challenge still further improvements in cutting materials resulted. Subsequent development made slow but steady progress over a number of years until in 1927 the introduction of tungsten carbide tools caused another upheaval and once more placed the cutting material ahead of the machine.

Although tungsten carbide tools raised cutting speeds to figures thought unattainable, the change was not so sweeping as when high-speed steel was first made, since the inherent brittleness of the new material prohibited its use for certain operations which required a tool combining toughness with good cutting qualities.

Chip-producing machine-operations fall into two classes : roughing and finishing. The roughing operations essentially cover work concerned with the economical removal of relatively large amounts of material with little importance attached to dimensional accuracy of the product. Finishing operations are concerned principally with the economic attainment of dimensional accuracy with the removal of small amounts of material.

Roughing tools must be sufficiently robust to allow heavy cutting and to this end hardness may be sacrificed to obtain toughness, since slight tool wear—which would cause minor changes in surface finish or of size of the component—is not of importance. On the other hand, finishing tools must maintain both surface finish and size so that tool wear must be kept as low as possible to prevent change in the shape of the cutting edge.

On introduction, tungsten carbide was most used on cast iron and non-ferrous materials, and the brittleness of the new cutting tools restricted their use to light finishing operations as they were thought to be unsuitable for heavy roughing work.

Subsequent improvements in the quality of the cutting tools widened the range of application, but the brittle nature of the material still caused considerable trouble in an industry educated to the use of high-speed steel.

The provision of large section tool shanks and more rigid machines did much to overcome the early troubles and eventually it became general knowledge that high cutting speed was an essential condition for the successful use of the new material. The full significance of this fact seems not to have been appreciated for some considerable time. Tool troubles with high-speed steel were usually obviated by the use of reduced cutting speeds, but with the new material the opposite applied and increases in speed frequently gave better performances.

The question of cutting-tool life is intimately connected with the machinability of the material to be cut. With the tungsten carbide tools it was possible to cut at considerably higher speeds than had been practicable when using high-speed steel. The speed range had been lifted to such an extent as to give an altered set of conditions obtaining at the tool nose.

With the new conditions, the temperature reached by the work and by the chips adjacent to the tool nose was very high indeed, so that local softening both of the work and the chips resulted. The softening gave the material the property of being machined more readily so long as the heating conditions were maintained. Very high speed cutting with high-speed steel tools soon gives rise to tool failure caused by local softening of the tool by heat, but carbide tools maintain their hardness at much higher temperatures and so can be run at correspondingly higher speeds. Unfortunately the property of maintaining hardness at high temperatures is always associated with lack of toughness.

Tool Performance

The separation of a chip by a cutting tool takes place in two stages ; first the chip is sheared from the parent body and then it passes across the face of the cutting tool to escape, in the form of a completely separated piece of material.

Heat is generated by the initial rupture which takes place ahead of the tool nose and also by the friction of the passage of the chip across the tool face.

The higher the cutting speed, the greater the softening tendency and the more readily the material machines, if the tool edge maintains its hardness and shape.

Apart from breakages, tool failure usually takes two forms : wear on the nose clearance angle caused by the tool tip scraping on the machined surface below the chip, and wear on the tool face caused by the passage of the chip across it. High-speed cutting tends to aggravate both types of wear but attempts to increase resistance to wear usually lead to increased brittleness and make tools more prone to breakage.

The obvious development of using wear resisting but brittle material for the tips, and increasing the mechanical strength by change in design, led to low positive rake tools and eventually to negative rake tools.

Negative rake tools have been much to the fore in recent years, and it is unfortunate that such tools have been so named. No sudden change in cutting conditions occurs as the top rake of a positive rake tool is gradually reduced through zero top rake to negative top rake, although the use of the terms " positive rake " and " negative rake " tends to imply some radical change. There is very little connexion between the wedge type of cutting tools, of which the pen-knife is a good example, and the shearing type of tool which is used almost universally for metal machining operations. Even high positive rake tools used for metal cutting operate principally by shearing, as also do the so-called negative rake tools. This is a point which should receive attention when tool nomenclature is being considered, with the object of emphasizing that there is no essential difference in operation.

The use of low top rake appears to encourage local softening of the work and of the chip adjacent to the tool nose, and so improves the machinability of the material if this can be softened readily by heat.

The impact of the new technique of cutting with low rake tools has been far reaching in its effects on machine design and operation.

Before examining the modifications in machine design following the introduction of tools with small positive and negative rake, it is advisable to appreciate the limitations governing the use of the new system of machining.

For all practical purposes, apart from diamond tools, the use of tungsten carbide is essential in order to handle the wear resulting from the high-speed rubbing of the tool nose on the work and the passage of the chips across the tool face.

Carbide tips restrict the design of cutters due to the difficulty of securing tips of large size. Brazing is the most commonly used method of securing the tips to the shanks and cutter bodies, as not only does this give a strong joint but the junction has good heat transmission qualities. As the coefficient of thermal expansion of tungsten carbide is roughly half that of steel, it is inevitable that a state of stress occurs on cooling after brazing. Careful design of the tip seatings can do much to obviate trouble arising from the differential expansion, but the size of tips used has a direct bearing on the problem. It is for this reason that so much negative-rake milling has been carried out with facing cutters, as, in such tools, the size of the tips bears little relation to the size of the cutter.

Mechanical methods of securing tips by clamps and wedges usually impede free chip flow or, alternatively, are suitable only for light cutting. They have not been used to anything like the same extent as brazing.

Another limitation which has caused much difficulty is the necessity of cutting at high speeds with a proportional increase in power necessary to drive the machine. The importance of this will be realized when it is appreciated that speeds of cutting of from six to eight times those used with high-speed steel tools are common practice when using carbide tools.

The success of high-speed cutting of any material depends to a great extent on the facility with which the chips can escape from the cutting tool edge after they have been separated from the mass being machined. For this reason, simple forms of chips must be produced, the ideal being a simple ribbon chip. The greater the departure from this simple shape the greater the resistance to free chip flow. Chips from form tools, in which different portions of the same chip are flowing in different directions, create exceedingly high pressures on the cutting edge and, if sufficient time is not given for the chips to escape, the pressures may rise to dangerous proportions leading to tool failure. Time for the chips to flow is a most important requirement for any form cutting operation and is the reason why slow speeds are necessary for this work.

Consideration has to be given to this point in the design of machines on which straightforward turning has to be combined on one machine with the ability to carry out form cutting.

Simple tool shapes with carbide tools demand high operational speeds, but when form cutting such as threading has to be carried out on the same components, the speed has to be reduced to suit the more complicated form of chip produced by the threading dies. In threading work, high-speed cutting cannot be attempted, owing to the time required for the chips to flow in the multi-directional paths. Pressures are high and the utmost toughness is called for in the dies if breakage is to be avoided. Carbides of the harder varieties are most difficult to form grind to a high degree of accuracy, and although tungsten carbide screwing dies have been made experimentally they are not an economical proposition and usually fail by breakage. It will be seen that in spite of the introduction of carbides for tools for general machining, the higher grades of steel tools have to be relied on for threading. The effect of this on machine design is that whilst there has been a great increase in the higher speeds used for turning, the lower speeds have not been raised to correspond. In fact there has been a steady call for several years for lower and still lower screwing speeds to suit the demands of the aircraft industry for the use of higher quality steels for screwed components.

Machine Design

There are already indications that great machine design difficulties are approaching due to efforts to increase the speed of machining, and as a direct result of this, methods of production are introduced which minimize the number of chip forming operations required ; die casting, plastic moulding, powder metallurgy, pressing, and thread rolling are obvious examples.

Machine tool users operating in a competitive market naturally want tools which are as versatile as possible so as to extend their range of usefulness and to give efficient cutting conditions even for the production of small quantities of components.

In designing a lathe for use with high-speed steel, a range of spindle speeds has to be provided which is capable of giving efficient cutting speeds on work differing in diameter from the maximum which the lathe will swing down to the smallest size of bar to be turned. In addition, a range of low speeds has to be provided for screwing and forming.

The introduction of carbide turning tools necessitates the raising of the turning speeds by from six to eight times as much as before. If this has to be combined with a reduction in screwing speeds to suit the new alloy steels, the overall speed range of the spindle drive unit becomes very great indeed.

For cutting with carbide tools, the requirement of high power is associated with high speed and thus the stresses on the various machine elements need not be unduly high if the high speed characteristics are maintained throughout the driving train from motor to tool. In practice it usually happens that stresses in a machine using carbide tools are appreciably lower than those encountered in the same machine engaged on conventional high-speed steel cutting, and this in spite of the fact that the output obtained from the machine when using carbide tools may be two or three times as much as the output when using high-speed steel. The new technique throws more emphasis on the ability of a machine to run fast than on the strength—as distinct from rigidity—of the machine elements.

Wide-range multi-speed gearboxes are costly to make and difficult to operate for rapid speed changing other than by friction clutches. Multi-speed motors simplify the gearbox problem by reducing the overall speed range of the gears, but such motors cannot operate at maximum efficiency and lose power appreciably at the lower speeds. Operational control of multi-speed reversing motors is very easy but frequency of speed changing and of reversing has to be considered if overheating of the motor is to be avoided. Certain classes of machines can operate efficiently with less power as the spindle speed is reduced, but others require full power over a wide range of speeds. An example of the latter class is the combination turret lathe which may be used at maximum power with carbide tools on small diameter work running at the top spindle speed whilst other work may necessitate maximum power for high-speed steel cutting at slow speed on work of large diameter.

Stepless speed control by electric, hydraulic, or mechanical means is very attractive at first sight, but for main drives on chip forming machines it is doubtful if such controls are of much practical advantage. The speeds of cutting tools are rarely critical and if speed control is by manual operation it is difficult to persuade operators to take the trouble to effect speed changes for short traverses unless a large variation is required.

Equipment with electronic control for use with large powers is costly and in any event gives only a partial solution of the machine tool drive problem of to-day.

Electronic control of direct current main-drive motors permits of stepless speed variation over a very wide range but constant power is usually available over a comparatively narrow range of about 4/1 at the higher speeds, after which the power falls on the basis of constant torque. Thus at the low speeds little power is available. Low power at low speeds is suitable for many feed drives and electronic control in its present form is well adapted for this work.

On special purpose machines and machines running on restricted ranges of operations, the gearbox design problem can be simplified by the use of slip gears. Such designs give a wide overall speed range with a narrow choice of speeds for operational use at each set-up ; the limited speeds available being changed electrically by multi-speed motors which may be combined with friction clutch changes of constant mesh gears.

At high speeds, crash gearboxes used in conjunction with a friction drive clutch have to be used with a fair degree of skill if heavy maintenance costs are to be avoided. Time has to be allowed for the gear speeds to fall before speed changes are effected, but for easy changing the gears must not come to rest.

Speed changing by the use of friction clutches in conjunction with constant mesh gears, permits unskilled and rapid operation, and in a still more advanced form pre-selection of speeds and electric operation by push button are possible.

The "Preoptive" headstock (Fig. 1) is controlled by four electric push-buttons, a speed selecting dial, and a plunger. The four push-buttons are used for motor control "stop," "forward," "reverse," and "inch." The speed selecting dial is engraved with the available speeds but the dialled speeds are not brought into operation until the centre plunger is pressed, when the appropriate friction clutches are engaged by using the stored energy in a flywheel keyed to the spindle of a small electric motor which runs constantly. The final drive clutches transmitting the power of the main motor to the spindle are of the self-adjusting type arranged to transmit predetermined torques in order to permit a certain amount of slip when the speed changes are made. By this means the power transmission details are insulated from severe shocks arising from the changes of velocity of members having much stored energy.

The various speed changes are normally made under full cut even when using carbide tools and it is rarely possible to detect the point of change from an inspection of the finished component.

The design of such a gearbox to meet the demands for more and more power brings to light several conflicting issues. The friction clutches have to be run at high speeds in order to enable them to transmit the required power, and this in turn implies high gear speeds for the gears on the variable speed shafts. As the rotational velocity of these shafts is much higher than the spindle speeds, a final gear reduction is necessary.

High clutch speeds enable large powers to be transmitted but the clutches have to be engaged at fast speeds and must be designed to handle severe loading conditions resulting from the inertia of fast running rotating masses.

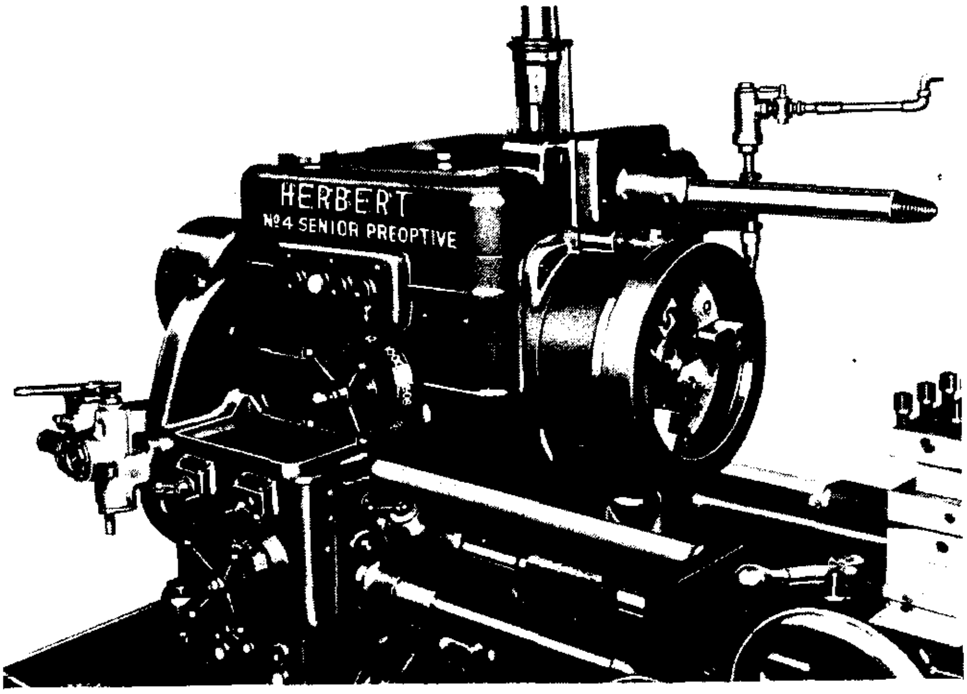

FIG. 1.—PREOPTIVE GEAR BOX

The machine tool drive problem to-day has not been completely solved and the best service which the tool research engineer could render to the machine tool designer would be to concentrate on work which would lead to permitting increases in the operational speeds of the low-speed tools such as drills, taps, dies, reamers, and form tools to bring them into line with the carbide turning tools. An increase in the cutting speed of the low-speed tools would reduce the speed range of the main drive gearbox and so give more flexibility in design.

High cutting speeds are desirable as they permit rapid feeds and thus give increased production but of late years there has been a tendency to expect high rates of production combined with greater dimensional accuracy and improved surface finishes from chip forming operations of all types.

Carbide tools have helped appreciably in giving better finishes on the work and in increased production, but special precautions may have to be taken to maintain dimensional accuracy.

The mechanical efficiency of the modern machine tool drive gearbox is determined by gear losses, bearing losses, clutch friction losses, and oil churning losses.

Fast running multi-speed gearboxes are of necessity complicated, and a considerable proportion on small machines—frequently as high as 40 per cent—of the input power is lost in the form of heat. As compared with the average industrial reduction gearbox, the power loss is very high but a large proportion is due to heat arising from large diameter anti-friction bearings running in multiple at high speeds, and another source of loss is represented by the price paid to obtain quick and easy gear changing by means of multi-plate friction clutches—the slipping of the disengaged plates creating power loss by friction.

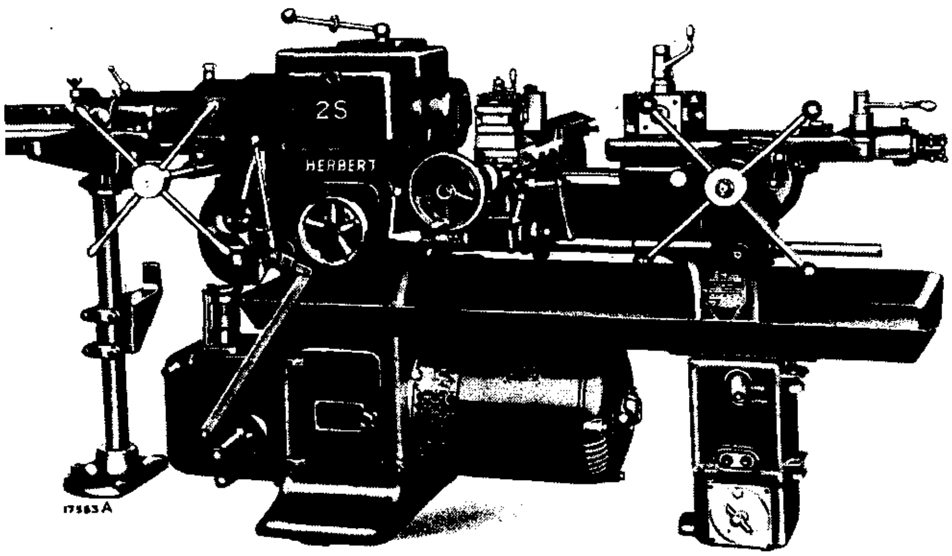

FIG. 2.—CAPSTAN LATHE

The most important bearings are those on which the spindle is mounted and their size is determined not so much from the load they have to carry as from the size of the hole through the spindle which, in the case of lathes, may be very large.

The dissipation of heat by radiation and convection enables equilibrium to be attained, but until equilibrium is reached dimensional changes which may affect the accuracy of the work are inevitable.

The increase in centre height of a lathe, due to expansion resulting from heat generated in the headstock, makes the choice of tool position important. Tools set at the side of the work on the horizontal plane containing the work axis should be used for finishing diameters which have to be held to close tolerances. Using such tools, variations in centre height of the work axis relative to the bed, have little effect on the diameter of the finished work.

Variations in the height of centres due to temperature rise are not so great in the simpler types of machines, an example being the capstan lathe (Fig. 2). The final drive to the spindle is by belt. The spindle drive box attached to the left hand leg does not affect the spindle alignment by heat arising from power transmission losses.

This design has very obvious advantages for fast running machines, as the heat generating elements which can affect the spindle alignment have been restricted to the spindle bearings only. The machine shown in Fig. 2 has a maximum spindle speed of 3,090 r.p.m.

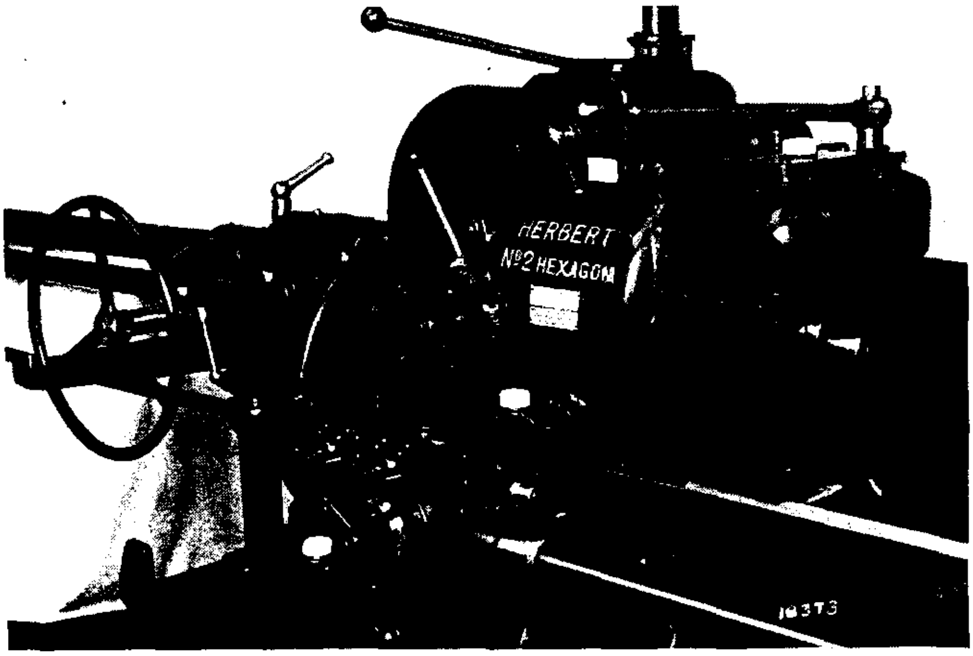

FIG. 3.—HEXAGON TURRET LATHE

Machines for producing components from bar stock have been affected greatly by recent developments in cutting tools. The material usually lends itself to high turning speeds, but threading and forming operations are often required. It follows that a very wide range of spindle speeds is necessary, but high power is not always called for at the low speeds. This is an application which can well be met by the use of a two-speed motor. The hexagon turret lathe (Fig. 3) has a top speed range of 1,520 r.p.m. to 80 r.p.m., over which 7½ h.p. is available. The two-speed motor gives 2 h.p. at the low speed range 70 r.p.m. to 20 r.p.m.

Bar lathes rely on roller steady turning box tools for most parallel turning operations and such tools have been completely redesigned to take advantage of carbide tools. A box tool of 2-inch capacity is shown in Fig. 4. The rollers, which run at the same peripheral speed as the bar, are mounted on grease lubricated needle roller bearings. The tipped tool is presented tangentially to the work and so is given maximum rigidity. As the bar machined is supported by the rollers in very close proximity to the tool, heavy cutting is possible without bending the bar.

Provision is made for retracting the cutting tool on the return stroke to prevent rubbing of the cutting edge on the finished work and at the same time avoid damage by the draw-back mark.

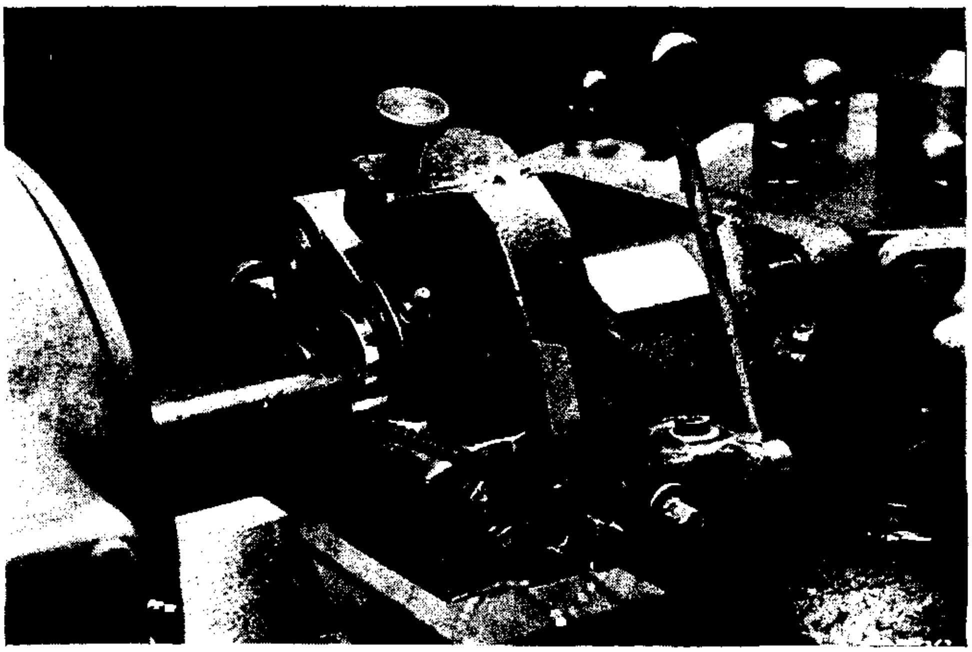

FIG. 4.—BOX TOOL—2-INCH CAPACITY

Cratering and Tool Design

Tools for bar turning are best arranged with the cutting edge at right-angles to the bar axis so as to produce a square face at the end of the cut. A flat topped tool with the cutting edge placed in this manner directs the chips on to the completed part of the work and so damages the finish.

The grooved tool rolls the chip into corkscrew formation which flows away from the work, the direction of flow being nearly perpendicular to the work axis. The tool thus has the advantage of producing square shoulders of minimum length of active cutting edge and of promoting chip flow away from the finished work surface.

The cutting action of the tool is most efficient and this is reflected in long tool life between grinds and in low power consumption per cubic inch of material removed per minute.

The reason for the high cutting efficiency of the tool is that as little work as possible is done on the chips after they have been sheared from the parent metal. The chips take up a natural spiral formation, the shape of the coils depending on the difference of the diameter of the bar before and after turning. The angular groove in the top face of the tool acts as a chip curler and is so dimensioned that the coils fit into the groove and are supported until they are well clear of the work, tool, and rollers.

There is still much doubt as to what happens at the edge of a cutting tool when in use at high speed, but it would appear that the working conditions adjacent to the edge of most turning tools used on soft steels are less severe than they are farther away from the edge.

A flat-topped straight-edged tool of conventional shape begins to show signs of cratering almost as soon as it is put into use.

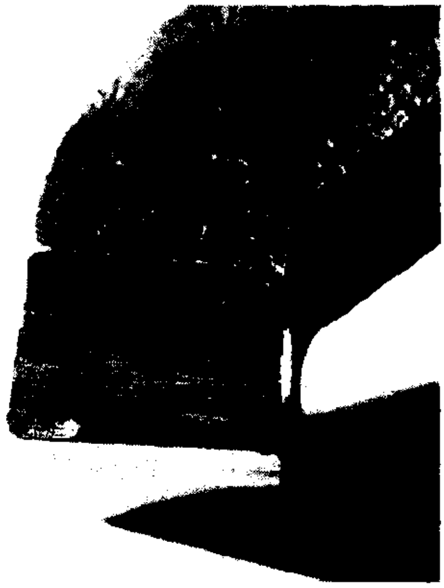

Fig. 5

Typical Crater on Top Face of Turning Tool

Fig. 5 shows a typical crater formed on the top face of a turning tool ; the familiar " D " shape will be noticed, this being formed due to the uniform load and speed conditions, which obtain in the centre of the cutting edge, being altered at the ends. At the end adjacent to the finished bar surface the crater shape is affected by the chip flow from the tool nose radius, and at the other end of the cutting edge the chip pressure is relieved by the possibility of the chip being able to flow sideways for a small distance.

The formation of a crater is shown by Fig. 6, 7, and 8. These are enlargements of the top surface of a lathe tool and represent sections at right-angles to the cutting edge, the latter being the dark horizontal line at the bottom of each section.

The tool of 45 deg approach angle, and 10 deg negative top rake at right-angles to the cutting edge, was used for machining a 0.40 per cent carbon steel bar at 800 ft/min. cutting speed with a feed of 40 cuts per inch. The tool, with a tip of a hard grade of carbide suitable for steel cutting, was carefully lapped on both top face and front clearance face with a 400-grit bakelite impregnated diamond wheel.

The typical outline of a crater is apparent after a very short run and at first takes the form of the crater area slightly pitted all over ; the spaces between the pits being practically undamaged tool surface. Further running increases the severity of the pitting and eventually the pits unite to form a complete crater which enlarges as further cutting takes place.

It will be seen that between the cutting edge and the crater is an area of the tool top surface which is almost undamaged.

Fig. 6 was taken after 50 peripheral feet of material had been machined. On the tool the outline of the crater was clearly visible to the naked eye. The enlargement which represents about $\frac{1}{16}$ inch of the cutting edge, shows that pitting has started, but the scores which run vertically upwards on the picture are restricted to the portion of the tool top surface where the chip commences to curl away from the tool in order to escape.

Fig. 7 shows the same tool after a total of 100 peripheral feet of machining. The scores are still more pronounced and are beginning to join into large grooves which are still mainly concentrated on the outgoing edge.

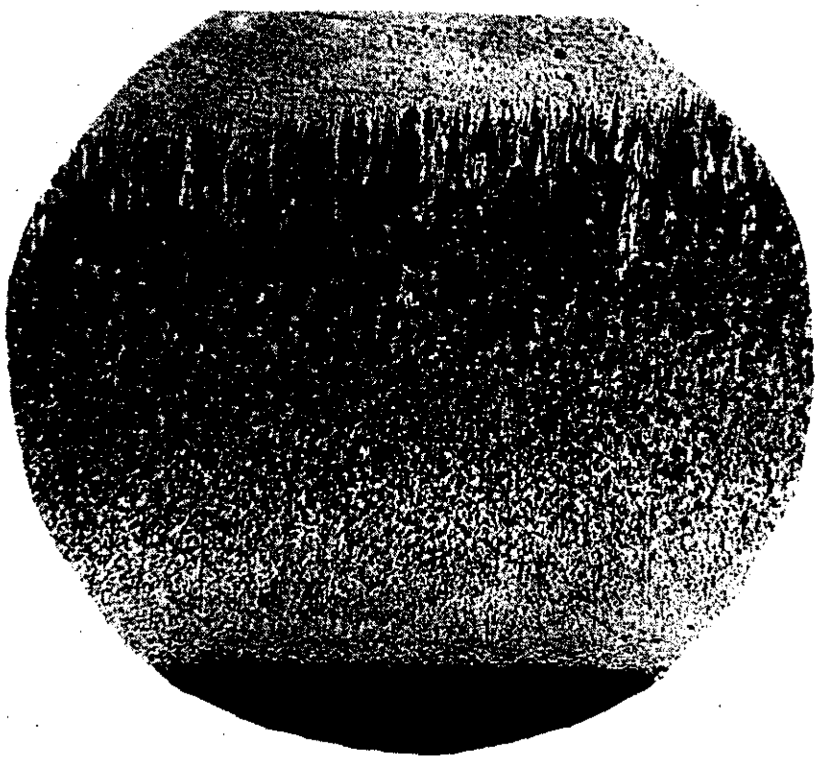

Fig. 6

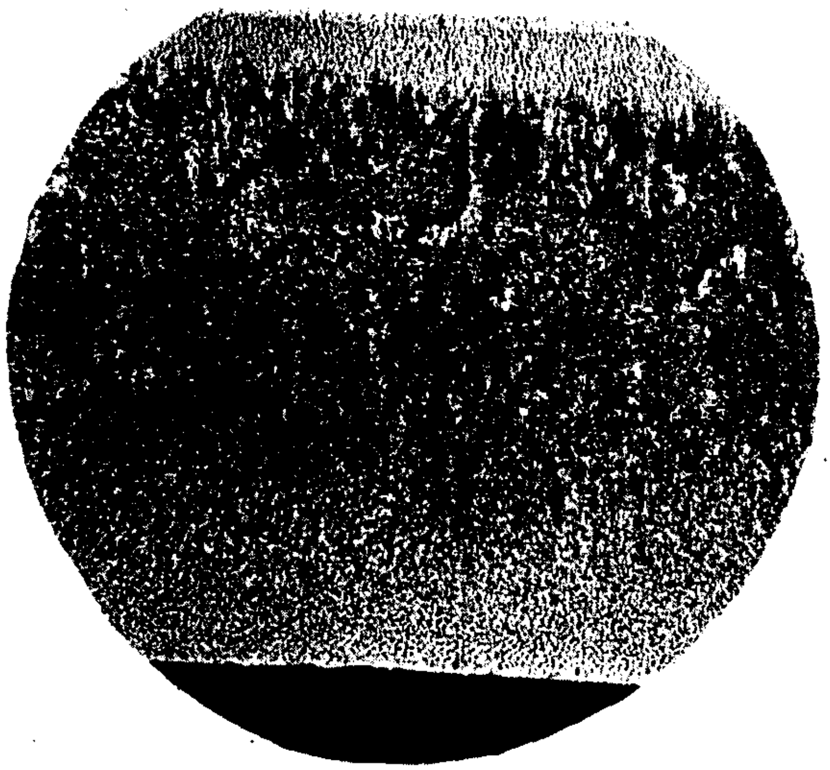

Fig. 7

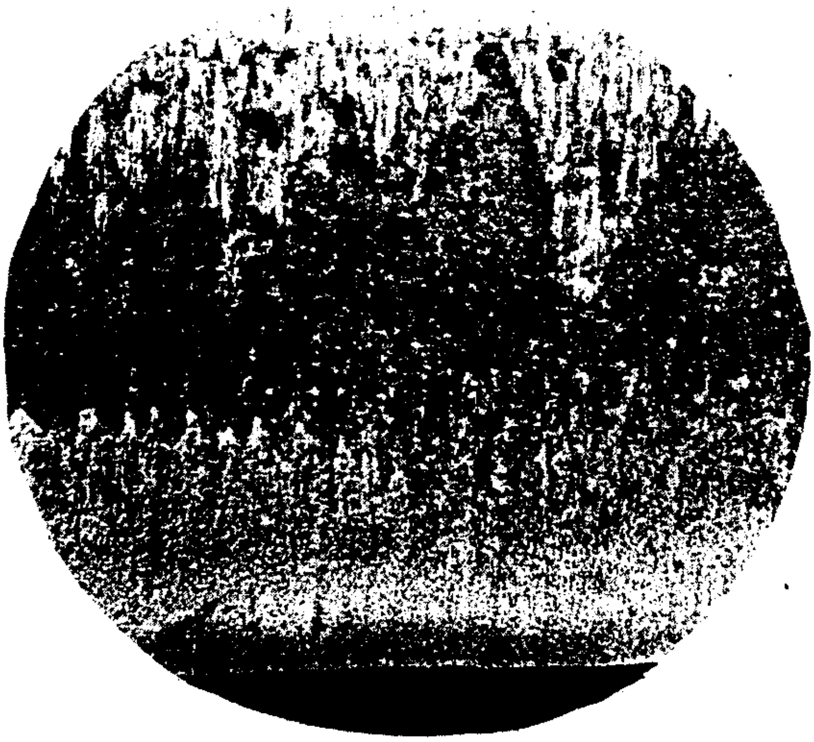

FIG. 8

Fig. 8, to the same magnification as the previous two figures, shows the complete failure of a well-defined area, with a little scoring on the ingoing edge and heavy scoring on the outgoing edge. The tool shown in Fig. 8 had completed a total turning distance of 150 peripheral feet. The good condition of the land adjacent to the cutting edge is in striking contrast to the conditions farther back.

When a definite crater has formed, the rate of failure of the tool appears to diminish. The crater gradually increases in size, the outgoing side wearing at a greater rate than the ingoing side. This is fortunate as it means that the diminution in width of the area with little damage adjacent to the cutting edge, is not rapid. If this land becomes too small, the crater breaks through to the cutting edge and causes complete failure of the tool edge.

Fig. 9 shows the results, on size of crater and width of land behind the cutting edge, of cutting 0.40 per cent carbon steel at 800 ft/min. with varying feeds. Hard-steel-grade carbide tools were used. These had 45 deg approach angle and 10 deg negative top rake at right-angles to the cutting edge.

In all tests a uniform distance of 1,320 peripheral feet was cut. The speed chosen was higher than usually used in production but was in line with other work which had been done in connexion with machinability tests, where accelerated failure was used as a measure of machinability of different materials.

It will be noted that higher feeds give larger land widths but proportionally greater craters.

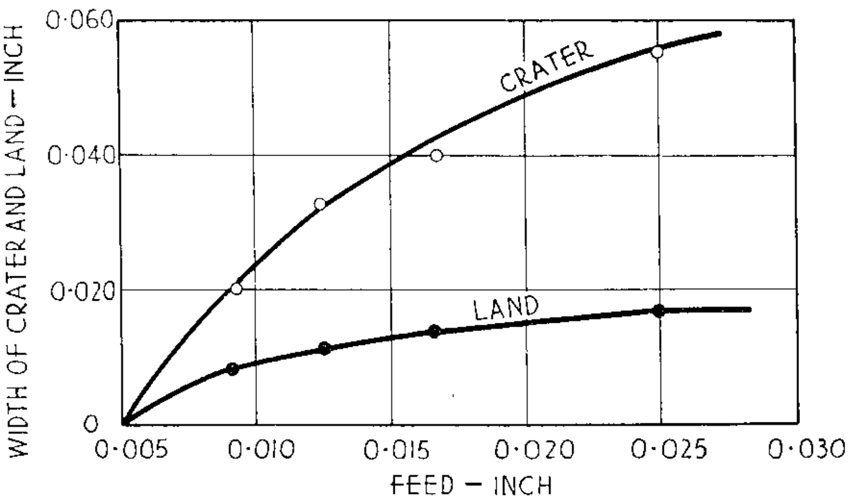

Fig. 9

Fig. 10 shows the corresponding relationship between crater and land for similar conditions but using constant feed of 40 cuts per inch and variable speeds.

Low speed and high feeds clearly indicate maximum tool life and it is interesting to compare this with results from high-speed steel tools, where the same obtains but much farther down the speed scale.

In originating cutting data for application to production, the cost of tools and of reconditioning them must be considered.

Conditions vary in each machine shop and with each type of tool, but experience with carbide tools of the type tested, when operating on unscaled 0.40 per cent carbon steel, has established 550 to 600 ft/min. as an economic speed. The determination of the ideal speed is more important than feed, since the rate of increase of crater width with respect to speed is greater than with respect to feed, and in any event the maximum feed which can be used is often determined by the rigidity of the work.

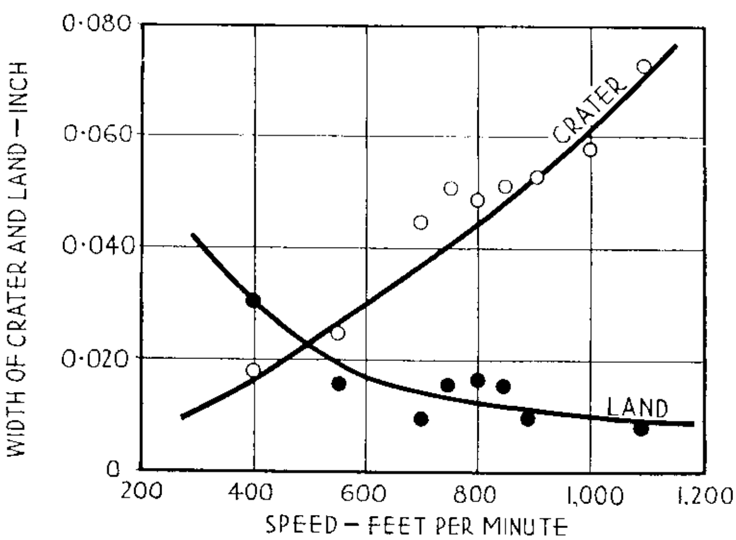

Fig. 10

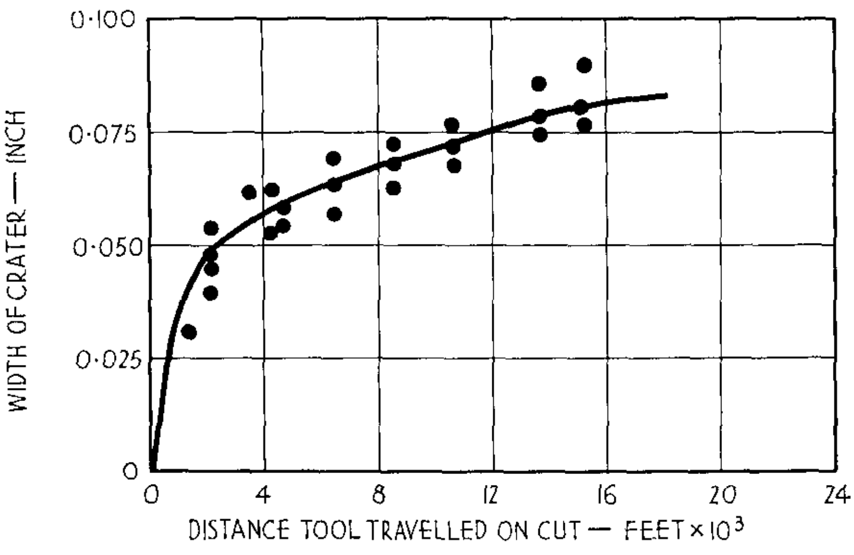

FIG. 11

At 600 ft/min. with a feed of 40 cuts per inch, the rate of crater growth with respect to the total distance travelled in the cut is as shown in Fig. 11.

The crater increases in size very quickly at the start but the rate of growth decreases with greater distances cut.

On the 0.4 per cent carbon steel tested, 20,000 peripheral feet is about the most which can be expected to be cut per tool grind as, at this distance, the crater growth begins to cause weakness of the tool edge and the point of breakage is near.

The crater width of 0.080 inch which can be expected at this point of 20,000 feet travelled, corresponds to a depth of about 0.016 inch and this represents the minimum amount of carbide which has to be ground off the tool top face before it can be put back into service.

The cutting land on the top face of a cutting tool is reduced as the crater increases in size, and it is also reduced by wear on the clearance angle face below the cutting edge.

Wear on the clearance face is affected very much by lack of rigidity of either tool or work and is subject to most erratic variations. It is difficult to measure with accuracy and forms a very unsatisfactory means of judging tool performance when cutting steel.

If the cratered area performed some useful service in supporting the chip during its passage across the tool face, it would be reasonable to assume that the crater is formed by abrasion, but the natural tendency of a chip is to curl upwards away from the tool face and this curling tendency still persists even when the portion of the top face of the tool, which would normally be cratered, is cut away as it is with the grooved type of tool, Fig. 12.

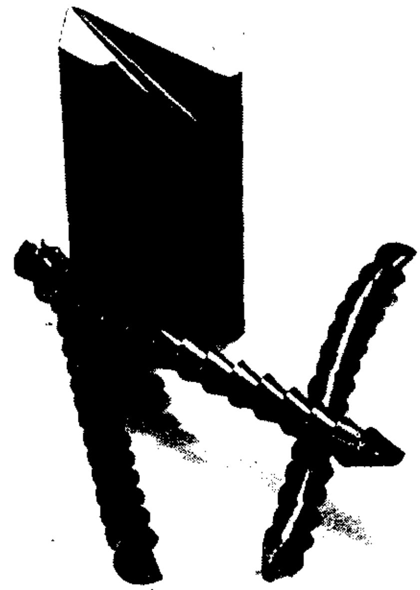

FIG. 12

FIG. 13

The grooved type of tool is essentially a flat-topped negative-rake tool with a V-groove so positioned as to leave a narrow land parallel to the cutting edge.

The groove runs out on the cutting face, leaving the nose radius intact and removing the area which would normally become cratered in use. The chips still curl upwards without causing much sign of heavy pressure on the back edge of the groove.

The main portion of the chip does not flow down to the bottom of the groove but slides across it by resting on each edge. Near the nose radius the groove becomes very shallow, and at the nose radius there is no groove at all. As would be expected, cratering does occur about this portion of the tool face, as seen in Fig. 13, but as the groove becomes deeper and wider farther back from the nose, the chip eventually bridges the gap.

The tool shown in the figure has a groove worn in the cutting edge : this represents the part of the tool edge in contact with the scale on the outside diameter of the bar being turned and indicates the cutting depth.

The absence of the crated area on a grooved tool appears to have a bearing on the tool efficiency and it may well be that the friction induced by a chip passing at high speed over a rough crated area causes a complete change in the cutting conditions and so affects the power required and also the formation of the chip. As the chip normally curls upwards, the initial formation of a crater is more likely to be due to chemical attack and welding than by heavy mechanical abrasion.

It might be expected that the rollers of a roller steady box tool operating on the finished machined surface would cause work hardening, but this effect is very slight indeed and, under workshop conditions, practically immeasurable. The usual method of testing is to prepare specimens of about $1\frac{1}{2}$-inch diameter : one end is then machined with a positive rake high-speed steel turning tool at about 60 to 70 ft per min. cutting speed, with a fine feed of about 240 cuts per inch. The other end is then machined with a box tool operating at the

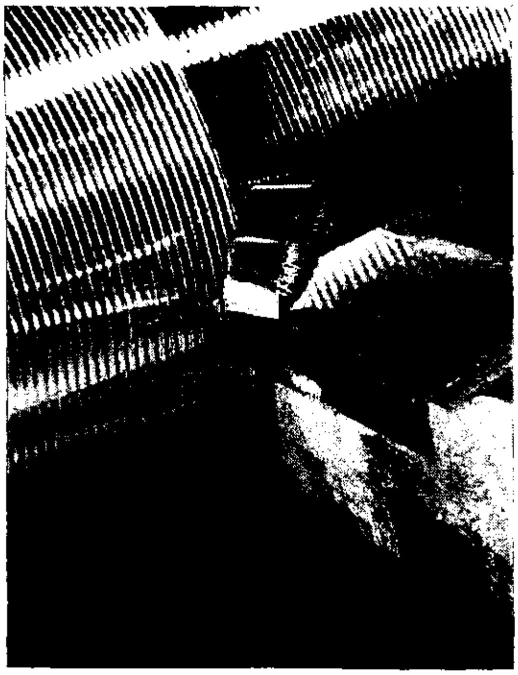

FIG. 14

required production cutting speed and feed. The two machined surfaces so produced are tested for hardness under various loads, and the readings compared. Even with a steel such as nickel-chromium air hardening steel, which is prone to work hardening, it is rarely possible to detect the difference by means of a diamond hardness test.

Grooved tools of the type mentioned are not used for general turning work. The characteristic coiled chip depends for its formation on the ratio of the maximum and minimum diameters of the cut surface. If this ratio is small, satisfactory tight coils are not produced and a chip formation results which is difficult to handle.

Conventional turning tools can often be arranged to break chips into short curls, Fig. 14, by directing the chip flow either against the tool tip or against the work.

The grooved tool encourages chip continuity and so enables the chips to be directed clear of the rollers. The tool is weaker than a conventional tool, but being well supported against the work—which is itself restrained by rollers—excellent tool life can be obtained.

The worst operating condition for a grooved tool is facing, as on such work the lengths of the chip on both edges are practically the same and the chip does not coil into a corkscrew formation, but tends to roll up somewhat like a clock spring, which subsequently tangles round an obstruction and so causes trouble.

The high production capabilities of carbide tools, and the difficulties of handling and breaking the chips, are responsible to some extent for the present tendencies to simplify tooling and even to revert to single tool cutting.

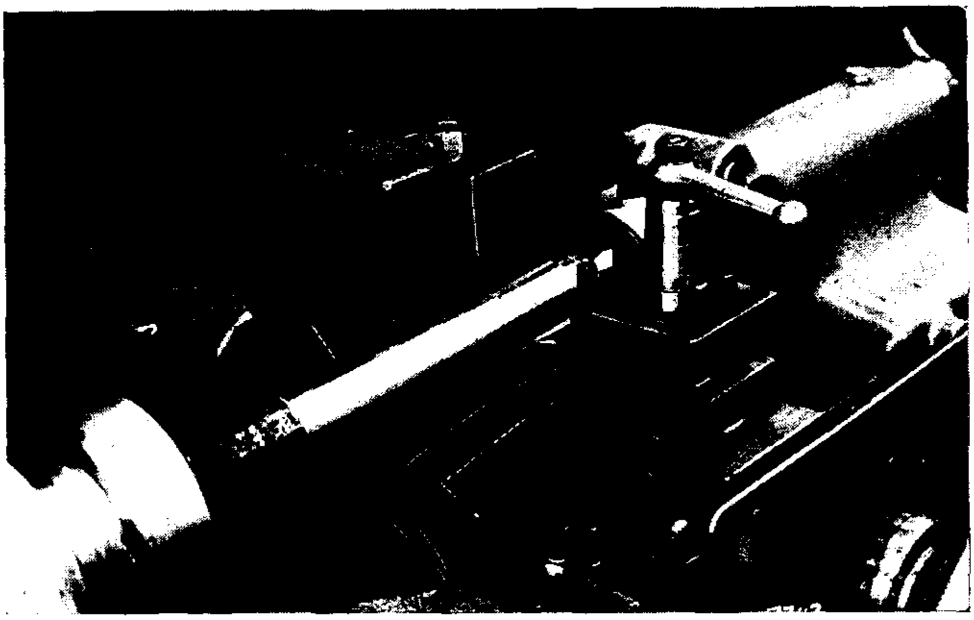

FIG. 15

The high production centre lathe as exemplified by the machine shown in Fig. 15 is essentially a single tool machine, as nearly all the work is carried out by the rear tool : a square turret is provided at the front for tools for recessing, undercutting, ending, and similar operations. By restricting the main turning to the rear tool, chip disposal is simplified as the turnings are directed to the rear, clear of the operator.

The spindle is belt driven from a two-speed motor driving through a gearbox with slip gears ; the two-speed motor gives the choice of two speeds instantly available under finger tip control.

Recent developments in cutting tools have produced tools which are very brittle and capable of carrying little tensile loading. One result of this is that the failure of a carbide tool by breakage is likely to be disastrous, and a mishap which, with a high-speed steel tool would necessitate a regrind, may well scrap a carbide tool completely. Less liberties can be taken with modern cutting tools, and the speeds and feeds under which they are to work have to be more rigidly controlled.

The shortcomings of carbide, from the point of view of tensile strength, are responsible for the lack of progress which has been made in the application of carbide to drills.

Some progress has been made with two-blade carbide-tipped drills for use on cast iron and brass, but drills for steel are rarely satisfactory.

The centre of the drill point is subjected to combined crushing and torsional stresses, and usually fails by breakage. The essential condition of high-speed cutting is impossible as the centre is approached, and this increases the probability of failure.

Attempts have been made to improve the cutting conditions by replacing the usual blunt point at the drill centre by a narrow slot, with the intention of leaving a small diameter core intact at the centre of the hole, in the hope that

FIG. 16

the core would repeatedly break off as drilling proceeded. The drills were not satisfactory and considerable difficulty was experienced in keeping the centre slot clear of the pieces of broken core. The provision of the slot, whilst removing the absolute centre, exposed two additional cutting points which had to operate at low speed, and failure by breakage occurred in every case. Conditions can be improved by allowing for a core of relatively large diameter and passing this through a hollow drill, so making the operation one of trepanning. Such a drill is restricted for use with through holes, otherwise the core cannot be removed.

Bar machines present special problems in the application of modern cutting tools ; cutting speeds are high and work diameters are small so that fast rotational speeds are necessary. The requirement for a wide speed range for screwing and forming has already been mentioned but another major problem remains, due to the difficulties resulting from rotating long bars at high speeds. Special precautions have to be taken in centralizing the tail ends of the bars and heavy chucking is necessary if the chuck grip is not to be loosened by the whirling of the bar when running. The rapid operational cycle makes it advisable to provide power operation of the chuck and of the feeding of the bar stock.

Cutting tool development has always been concerned with increasing the rate of metal removal without sacrificing tool life through wear. High rates of metal removal can be carried out with almost any tool for a longer or shorter period, but in general it can be taken that with a particular tool the higher cutting speeds are associated with increased rates of tool wear.

Tool wear effects a change in the machining process, since the cutting tool takes up a different shape from the original and this influences the cutting action as far as the type of chip flow is concerned, and it also alters the size of the machined component as well as the quality of the surface finish.

A negative rake turning tool gradually takes up the characteristics of a tool with positive rake as the cutting face craters in use, and as the change takes place the chips coil to smaller and smaller radii and in doing so create greater pressures on the face of the tool. The rate of deterioration gradually increases until failure results by breakage of the edge.

Fig. 16 shows the two different types of chips produced by a lathe tool before and after cratering occurs. The freer cutting characteristics of a freshly ground tool are indicated by the chips which are curved to a large radius. The radius of curvature of the crater affects the chip shape to an appreciable degree.

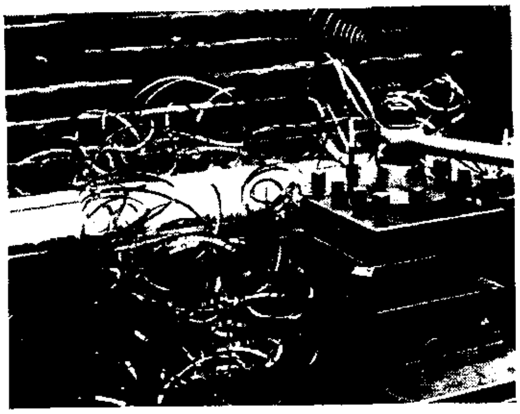

FIG. 17

FIG. 18

Difficulties due to Chip Formation

One of the main difficulties of rapid machining processes is to handle the chips so as to avoid danger to the operator and at the same time ensure that the chips do not interfere with the action of the machine. On complicated multi-tool set-ups the chips cannot be allowed to take up the ideal form of straight ribbons, as such chips rapidly wind themselves round various projections, Fig. 17. The problem on milling is much simplified as the cutting is automatically interrupted and continuous chips are never produced.

On turning work the chips must be broken in some manner unless the tool shape is such that they break themselves as they leave the tool nose. The usual method of breaking the chips is to present an obstacle in their path which causes them to undertake a sudden change of direction sufficient to cause them to fracture. The provision of a step immediately behind the cutting edge will, if suitably proportioned, break the chips into short pieces but this can only be done at the expense of reduced tool life. Another method with the corkscrew type of chip is to guide the coiled chip into an abutment placed some little distance from the cutting edge so as to break the coils into short lengths which fall into the tray of the machine, Fig. 18.

The heat resisting qualities of carbide tools enables coolants to be eliminated on many operations. There is a little advantage to be gained in cutting efficiency from the use of coolants but the advantage is often negatived by the attendant troubles resulting from excessive spray and splash caused by rapidly rotating masses in contact with the coolant.

On straightforward turning operations, perhaps the chief advantage resulting from the use of suds is that the chips are cooled and there is less likelihood of burns to the operator being caused by accidental contact with the chips.

Milling Cutters

There is very little fundamental difference between cutting with a lathe tool and with a milling cutter, and the drive to the cutter spindle of a milling machine can be compared with the spindle drive of a lathe, since the operating conditions are very similar.

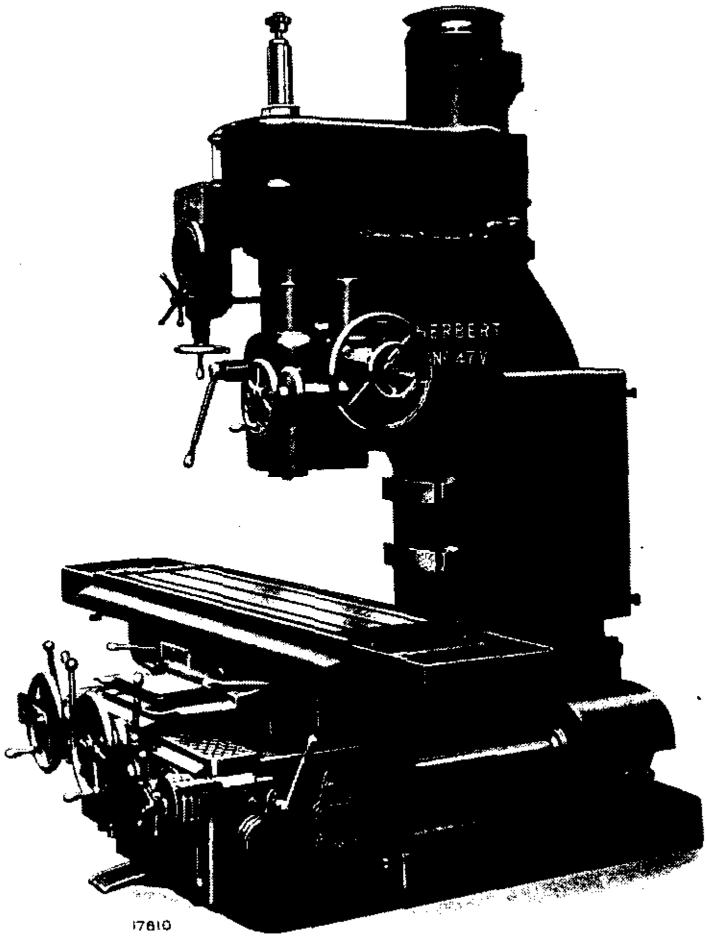

Fig. 19

As with turning, the introduction of cutting carbides has necessitated an increase in the speed range of general purpose milling machines. The spindle speed range must be wide enough to handle efficiently small diameter carbide cutters and also large diameter high-speed steel cutters.

The cutting speeds for carbide tipped milling cutters may be about the same as for turning tools, but in milling it is usual to reduce the cutting speed a little in order to conserve the life of the more expensive type of cutter.

Not only is the milling cutter expensive in first cost, but the cost of regrinding after use is very high when compared with the cost of reconditioning a lathe tool.

In one respect the milling machine has an advantage over the lathe. On a lathe the correct cutting speed has to be obtained with different diameters of work, and this must be done by adjusting the work rotational speed to suit.

The milling machine has a little more flexibility, as the cutting speed is determined not by the size of the work but by the rotational speed of the spindle and the diameter of the cutter. The diameter of the cutter, on many classes of work, is not fixed.

The intermittent nature of a milling cut imposes a fluctuating torsional load on a milling machine spindle, and the provision of a heavy rotating mass on the spindle is useful in maintaining uniform velocity of this member. The rotating mass may take the form of a heavy final drive gear which can be assisted by the provision of auxiliary flywheels mounted on the spindle nose and on the arbor.

The full advantage of flywheels on milling machine cutter spindles can only be obtained at high speeds, and for this reason it is better to use small diameter cutters at high rotational speeds in preference to large diameter cutters running slowly.

The chip load which may be imposed on a milling cutter tooth is almost independent of the diameter of the cutter, and the feed rate is determined by the permissible chip load per tooth and the number of teeth brought into operation per minute.

Fig. 19 shows a vertical milling machine having a wide speed range. The two-speed motor gives 15 h.p. over a speed range of 43 to 1,525 r.p.m. and $7\frac{1}{2}$ h.p. at speeds of 21 to 750 r.p.m. Feeds of $\frac{3}{4}$ inch to 60 inches per minute are available.

Rapid speed changing is rarely necessary on a milling machine, and the drive to the spindle can be simplified on this account. The machine shown has no clutch on the spindle drive train, and the crash gears are changed after the motor has been stopped. The use of a vertical motor obviates the provision of a right-angle drive to the spindle and enables ground spur gears to be used throughout the main drive.

The operating conditions of a milling cutter are very similar to those of a lathe tool as far as concerns the cutting action at the tool nose. One practical difference is that, in milling, cutting is always intermittent, and chip disposal problems may be better or worse on this account, depending on the particular circumstances.

Another essential difference is that the chip load on each individual milling cutter tooth varies throughout the cycle and is not of constant value as it is with a lathe tool running under steady conditions.

In face milling, the size and position of the cut area relative to the diameter and position of the cutter determines the chip loading on each tooth and, taken in conjunction with the cutter lead angle, give the actual chip thickness normal to the cutting edge ; this varies throughout the cut. The maintenance of a satisfactory chip thickness is an important factor which affects the life of the cutter between grinds.

As with lathe tools, the simpler the form of cutting edge the better are the cutting conditions, and tool shapes—which on a lathe would produce dangerous ribbon-like chips—may be used with advantage since the chips are automatically broken at each interruption of the cut.

The surface finish of work, after being milled with carbide tools running at high speed, is usually much better than that obtained from high-speed steel tools, and advantage has been taken of this to eliminate grinding operations on some components. This technique must not be used to the extreme for, although under good conditions exceptionally good surface finishes can be produced, this is at the cost of reduced cutter life.

Both on turning and milling, high cutting speeds give less cutter life but give reduced labour cost by saving production time. An economic balance must be struck between the relative costs and the cutting speed to be used, chosen to suit these conditions.

So many factors are involved that a true analysis becomes exceedingly complicated, and unless large quantity production is anticipated it is rarely worth while.

Conclusion

It is practically impossible to forecast the results which might be expected from a long production run by testing a few samples.

Much experimental work has been done on cutting tools by taking repeated tests on bars and flat test blocks. This is a very different condition from the usual production work where surface scale and imperfections are encountered on every component.

The true value of the performance of a cutting tool must take into account the cost of regrinding the tool after use, and with carbide tools the cost of sharpening may well be considerable. This is particularly so with milling cutters. Much can be done to cheapen the cost of tool sharpening if the tools are designed in such a way that the minimum amount of carbide has to be removed when sharpening is necessary.

Many tools are badly designed from the point of view of economy of carbide and of subsequent regrinding. There is rarely much virtue in large tips ; they are high in first cost, difficult to braze without cracking and have to be handled with great care when grinding.

Carbide tools are difficult to grind and there is room for much work in this field. The cost of tool grinding is an essential part of the cost of production, and excessive grinding cost frequently precludes the full application of modern cutting tools. A certain amount of success has resulted from the use of coarse grit diamond impregnated grinding wheels running at peripheral speed as high as 10,000 ft/min., but the rate of carbide removal is still very low compared with what can be expected from high-speed steel grinding.

Unbalanced progress in the development of cutting tools has left the production engineer and the machine tool designer in a somewhat difficult position.

Economic speeds for some tools have advanced tremendously but the operational speeds of other tools have made little progress. What is now most urgently needed is tools of the carbide type but with greatly increased toughness, heat resistance, and abrasion resistance. Given these qualities, the most difficult problems would approach solution.