British Machine Tools During the War*

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In giving my lecture its title, I do so with the acknowledgement that I cannot hope to deal adequately with the war effort of the British machine tool trade. Still less is it possible to describe the invaluable contribution of America by purchase and under the Lease-Lend agreement.

British machine tool makers were able to produce a very fine and wide range of types and sizes, but there were certain highly specialized machines developed for the American automobile and aircraft industries, for which we were entirely dependent on America, and there were no British equivalents. It is indeed a matter for thankfulness that the supply did not fail.

Recently a Government White Paper gave some information about the country's war effort in providing the munitions and supplies on which mechanized warfare depends, but this White Paper made no reference to the machine tool effort, without which none of the achievements named would have been possible. Great plans for increasing the output of aircraft, tanks, weapons and munitions of all kinds could not have born fruit until the factories were equipped with the machine tools, which are the basis of all engineering production—in fact, production of almost all kinds. The machine tool industry must be content with the knowledge that the deficiency in Machine Tools which at one time threatened the most serious consequences was, by its exertions, overcome. It is within my knowledge that one firm, between 3rd September 1939 and 30th November 1944, was responsible for the production in its own shops and directly working subcontractors of 35,000 machine tools.

The present, therefore, does not seem an inopportune time to look at the general picture, and to record what, during the war period, has been the state of progress of British machine tool engineering.

In the years immediately preceding the war, the activities of the machine tool maker had been intense; and considerable progress in design was being made under the demands of the re-armament programme. When war came, however, development work was very largely stopped, and the machine tool trade rationalized itself and reduced "over laps" in design between different makers. This resulted in a considerable simplification of programme and more economical manufacture. The rationalization did not, however, stop the demand for special single-purpose machines which were designed and made straight from the drawing board; and there were indeed many brilliantly successful examples.

Despite the standstill order on new designs, important detail improvements were forced on designers and makers by the hard and intensive school of experience of war conditions.

In the light of experience of the last few years, we can examine the mechanical requirements and attainments of some British machine tools used during the war years.

First, in considering machine tool drives and speed variations, we know that the self-contained completely motorized machine is now almost universally manufactured, and exceptions are confined to such as embody starting clutches in the machine itself, thus preserving the ability to be adapted to lineshaft drive.

The simplest form of machine tool drive of this type is by single-speed squirrel-cage alternating-current motor, Figs. 1*a* and 1*b*, Plate 1, operating through gearbox incorporating clutches for starting, stopping, and reversing. The alternating-current motor requires only simple switchgear for starting once or twice per day. The speed ratios between the fast and slow extremes in an eight-speed box may be anything up to 25/1, and in a sixteen-speed box 50/1. A further development where line-shaft drive need not be considered is to eliminate the clutches, and to start, stop, and reverse by the motor. If quick stopping is required, this may be effected by a plugging relay operated by push button (Fig. 2, Plate 1) or by throwing the switch over into reverse by hand until the machine spindle comes to rest. Obviously, for such applications, the switchgear must be robustly built for heavy duty, whilst the motor must embody special insulation and rotor bars of high conductivity to prevent breakdown of windings when reversals are frequent.

On manufacturing machines where speed changes are not required during a run on a number of work pieces (horizontal milling machines are a good example) "pick-off" gears may be used instead of gearboxes, with a limit of ratio of 9/1 for simple pick-off gears and 20/1 for compound gears (Fig. 3, Plate 1).

Multi speed pole-changing alternating-current motors are frequently used to advantage, since they enable gear changes to be eliminated; but multi-speed motors have limitations as they develop horse-powers varying approximately with the speed of the motor. Despite this, on small machines they provide a very satisfactory form of drive and speed change, as the maximum powers are only required when operating machines at the higher speeds (Fig. 4, Plate 1).

Multi-speed alternating-current motors giving two, three, or four speeds can be used with or without gear changes, depending on the total range of speeds required. On relatively large machines, such as combination turret lathes, the maximum power may be required throughout a wide range of speeds to suit the varying diameters of work being machined. As such machines frequently require a range of slow speeds for screwing high-tensile alloy steels, this can ideally be met by having a two-speed motor giving, for instance, 15 h.p. at 1,430 r.p.m. and 7½ h.p. at 720 r.p.m.

It may be mentioned here that cutting speeds are constantly increasing; and a speed up to 1,000 ft. per min. is now common on steels with negative-rake carbide cutters, to which I shall refer later. This can be catered for without losing the ability to deal with high-speed steel cutters. For instance, a vertical milling machine can be provided with a two-speed motor giving 15 h.p. at 2,800 r.p.m. and 7½ h.p. at 1,430 r.p.m. (Fig. 5, Plate 1).

An interesting development in machine tool driving, which is rapidly coming into prominence, is the use of direct-current motors with electronic control, by which infinitely variable speeds are available with constant horse-power. The speed range is about 4/1, whilst further ranges up to 15/1 are available with constant torque. As an example the machine shown in Fig. 6, Plate 2, requires 50 h.p. at speeds from 3,000 to 750 r.p.m., and varying horse-powers from 50 down to 3½ at speeds from 750 to 50 r.p.m. The constant horse-power is obtained by field control, and constant torque by armature control. The control gear consists of electronic valves, the main source of supply being alternating current.

The feeding of machine tool slides is mostly effected through gears operating finally through rack and pinion or screw and nut. The screw and nut ensures the more steady feed. Cam feeds are usually associated with automatic lathes and are a variant of screw feeds.

Feeding by hydraulic cylinders was growing very rapidly about ten years ago, but the fashion is now finding its true level, and is very largely confined to grinding machines where the loads are practically constant (Fig. 7, Plate 2).

Quick power traverses are necessary as a means of reducing fatigue of operators. Handwheels should always be automatically

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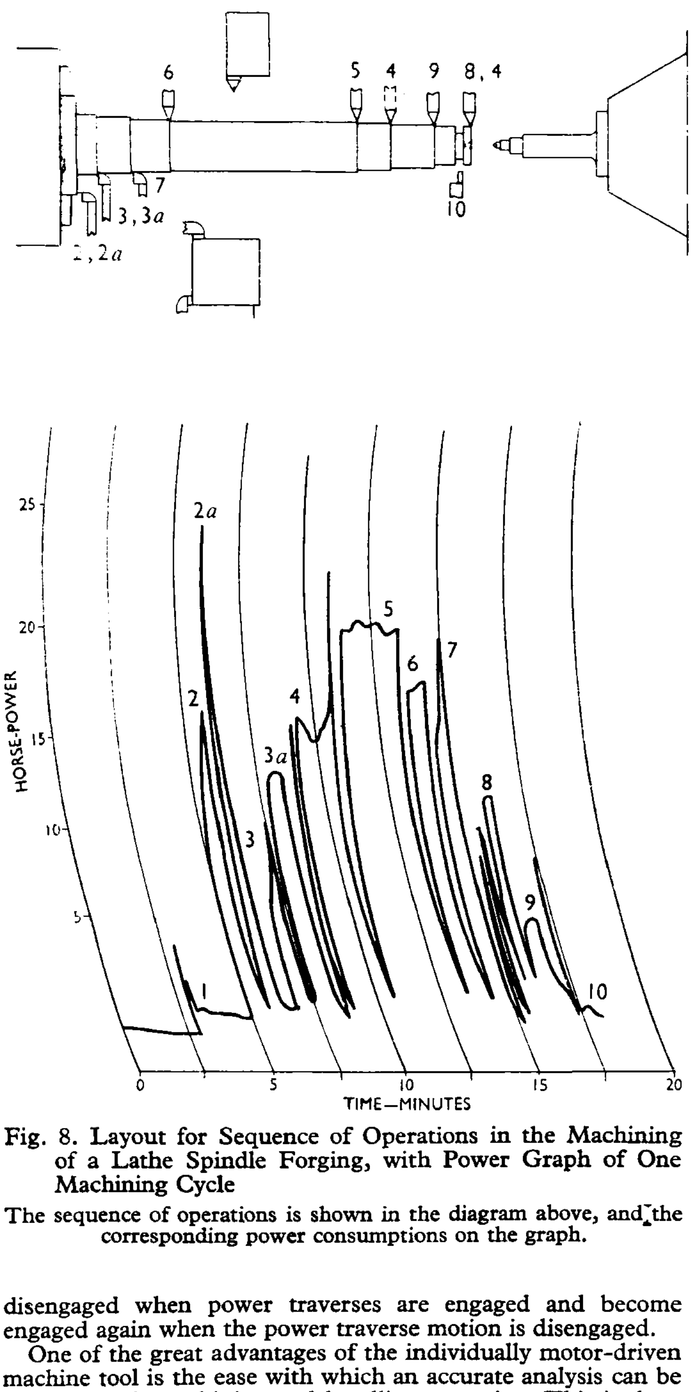


Fig. 8. Layout for Sequence of Operations in the Machining of a Lathe Spindle Forging, with Power Graph of One Machining Cycle

The sequence of operations is shown in the diagram above, and the corresponding power consumptions on the graph.

disengaged when power traverses are engaged and become engaged again when the power traverse motion is disengaged.

One of the great advantages of the individually motor-driven machine tool is the ease with which an accurate analysis can be made of each machining and handling operation. This is done by connecting an automatic power recording meter into circuit with the motor driving the machine tool, the power consumed being continuously recorded on a slowly moving chart.

Fig. 8 shows at the top a workpiece consisting of a fairly heavy forging for a lathe spindle being machined with a simple tool layout, and below it is shown the complete power consumption for the machining of one forging. The sequence of the machining operations is:—

1.	Centre.
2 and 2*a*. . .	Heavy facing of spindle flange in two cuts.
3 and 3*a*. . .	Turning in two cuts.
4.	Turning of right end of spindle up to point 5.
5, 6, 7, 8, and 9.	Turning of spindle surface in this sequence.
10.	Turning groove.

The numbers on the graph indicate the corresponding machining operations.

The following characteristics will be noted on the graph:—

(*a*) The violently fluctuating nature of the load on the motor.
(*b*) The large overload capacity required for a short duration compared with the average load. In the example shown the maximum is nearly 25 h.p., whereas the average power is only approximately $7\frac{1}{2}$ h.p.
(*c*) The variations in the heavy peak loads, due to irregularities in the forging. The motor must necessarily be powerful enough not to stall on these momentary loads, otherwise the cutting tools (if of tungsten carbide) will most certainly be damaged.
(*d*) The heaviest continuous load in the plain turning at point 5 is nearly 20 h.p.

The careful examination of these curves where multiple cutting tools are used, as on an automatic lathe, often enables the tools to be regrouped so as to avoid excessive peak loads and consequent strain to the motor or machine tool.

Fig. 9 shows a part of a series of curves of the same machining operation taken during a test run. It should be appreciated that where a test of machining is made with the operator under observation, it is in general not a representative performance. But if a recording meter is used, the average performance throughout the day can be obtained, and—what is also important—the amount of idle or non-cutting time.

From Fig. 9 it can be seen at a glance that the floor-to-floor times are approximately 16 minutes, the loading time is 6 minutes, and that the maximum power steadily increases as the tools begin to wear. Further points which can be examined are:—

(i) The falling-off in production due to fatigue of the operator, if any.
(ii) Any possible gain in efficient production by equalizing the load of the various machining operations and the possible elimination of idle time.
(iii) The most suitable size of motor for the job and hence a high load factor for the total electrical plant.

Whilst the designer seeks by provision of adequate and easily changed speeds and feeds to reduce cutting times to the minimum, the non-cutting period becomes increasingly important as it assumes a growing proportion of the time cycle. Further the physical contribution of the operator must be drawn upon to the smallest degree as the time cycle reduces, and the number of cycles in the day tends to increase. The extended employment of women in the engineering shops during the war has drawn attention to this point. Power-operated chucks, fixtures, and clamping devices have therefore figured prominently in the equipment on war-time machine tools (Fig. 10, Plate 2). Notable designs include chucks operated by compressed air, or hydraulically, or electrically. The usual type of air chuck has radially movable jaws which are operated through bell crank levers connected to a retractable draw-rod passing through the spindle. At the rear end of the spindle there is a cylinder with a piston, on either side of which compressed air can be applied through a valve. As an alternative to the piston-operated draw-rod, the latter may be threaded and have on it a nut which can be rotated in either direction by a reversible electric motor mounted on the back end of the spindle. One further design, quite commonly used, employs hydraulic pressure in place of the air in a cylinder similar to that of the air chuck. Clamping fixtures for milling machines, grinding machines, etc., in which there are multiple clamping points are operated from a single control by compressed air or hydraulically.

The conditions of the war period have demanded that machine tools should be able to withstand almost continuous duty, alternating between heavy roughing cuts and fine precision finish cuts. It speaks much for the robustness and precision of the immediate pre-war designs that this condition is so successfully met. Contributing factors are the liberal use of high-tensile steels, anti-friction bearings, covered slides, and hardened slideways. It has long been accepted that safe working conditions for the operators are not merely humane but profitable in production. The British machine tool was notably good in this

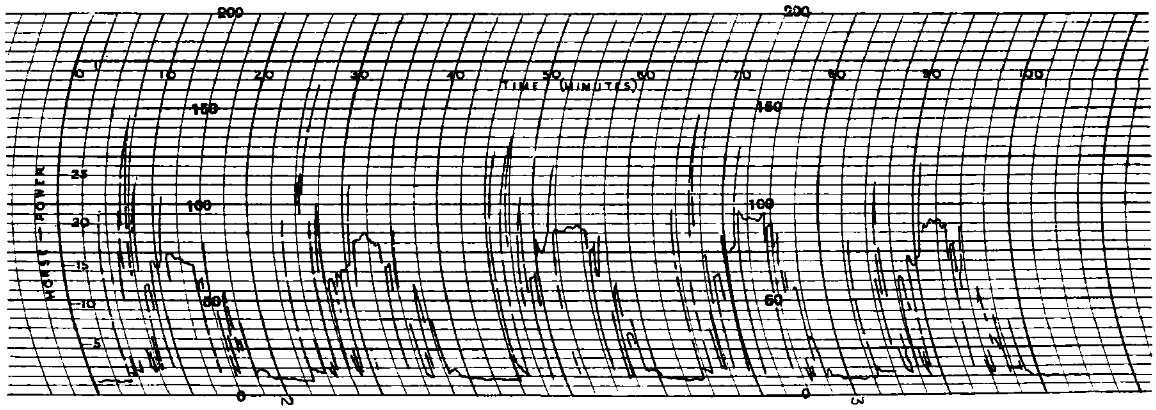


Fig. 9. Series of Power Graphs for Machining of Lathe Spindles during Part of a Working Shift

respect, although it certainly profited by the experience of conditions under which thousands of unskilled people came into contact with power-driven machine tools for the first time in their lives (Fig. 11, Plate 2). Not the least important lesson which has been learned during the last few years is the desirability of assisting the operator to work in cleaner conditions. This has led to marked improvement in guards, giving freedom from splash. The extended use of carbide cutters, which, in the machining of steel, now allows of the complete elimination of coolant, leads one to look forward to the day when coolants will be associated only with slow-moving machines such as are used for screwing or tapping when centrifugal force is low and the coolant more tractable.

Whilst the importance of continuous lubrication is fully realized, conditions under which machine tools have operated in recent years have called particular attention to this feature in design. Time was when operators took a pride in their machines and lovingly attended to every lubricating point. To-day, in most factories, the reverse is the case, due to systems of payment by results, multiple shift work, and changes of operators on machines. Designers therefore have looked upon the matter of lubrication as a major feature of design; and grouped oiling, with filters suitable for a routine "valet" service, are the general rule. It is too much to hope that machine tools will ever be built which never require adjustment and never break down. Accessibility of adjustment and ease of replacement of wearing parts are therefore as desirable as ever.

I have already referred to the new technique of cutting with carbide tools having negative rake, which I will now deal with more fully.

Throughout the development of metal-cutting tools there has been a constant striving to obtain the best combination of keenness, hardness, and mechanical strength. A great step forward has been taken in the combination of hard carbides with more obtuse cutting edges in tool noses.

Fig. 12, which is much out of scale, shows how negative rake tools differ from positive rake tools in two important points:—

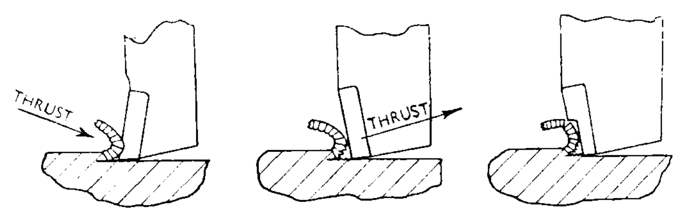
(1) The direction of the thrust from the chip, and
(2) The strength of the tool nose.

The chip thrust on the positive-rake tool tends to break away the relatively weak tool nose, and, as this part of the tool is in tension, the cutting portion has to be made of material capable of carrying tensile loading. Toughness can only be obtained by sacrificing hardness, and, if this is done, the scouring action of the chip across the tool face eventually causes "cratering" which weakens still further the already weak tip and thus accelerates failure.

With the negative-rake tool the thrust loading places the tip of the tool in compression—a stress which the hardest of carbides are capable of withstanding. As hard carbides can be used, the liability of the tool face to "crater" is much reduced.

In both positive- and negative-rake tools the actual point of the tool is concerned with scraping the roughness from the cracked surface which precedes the cutting tool. With positive-rake tools the fine particles scraped away become welded on to the tool nose and cause the built-up edge. The built-up edge has a highly positive rake in itself, and not only causes roughness on the work being machined, but subjects the tool nose to an additional stress. The built-up edge never occurs on a negative-rake tool if it is operating at the correct speed.

The right-hand tool in Fig. 12 shows, diagrammatically, a



Positive rake. Weak tip in tension. | Negative rake. Strong tip in compression. | Tool with chip-breaker. Chips broken by stop on tool face.

Fig. 12. Difference between Positive- and Negative-Rake Tools together with Diagram showing Action of Chip-Breaker Stop

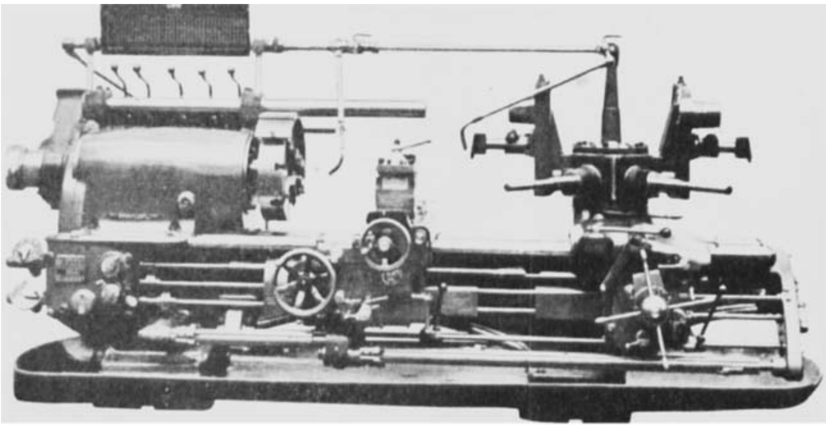
chip-breaker. Negative-rake tools are capable of removing metal very rapidly, and the chips have to be broken so that they may be handled without danger to the operator. There are several methods of breaking chips, and all depend on the fast-flowing chip meeting an obstruction in its path which causes an abrupt change of direction sufficient to break the long chips into short pieces. Fig. 13, Plate 2, was taken during the test of a tool without a chip-breaker and clearly shows the necessity for chip-breaking.

At first sight, negative-rake tools appear to be most inefficient cutting instruments, and it is surprising to find a tool with up to 40 deg. negative rake (Fig. 14, Plate 2), capable of cutting. The expected result on using such tools would be excessive chip pressure followed by increased abrasive wear. This actually happens if the tools are run slowly, but by running fast the chips, torn away from the metal being cut, are partly plasticized by the heat generated.

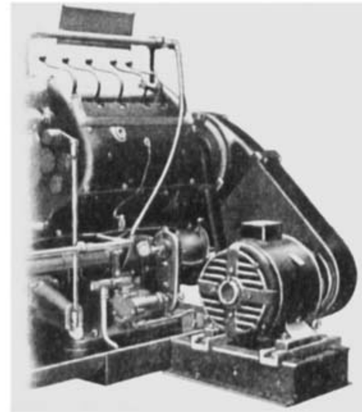
This softening of the chips by heat reduces the coefficient of friction at the tool-chip interface and so facilitates the free flow and escape of the chips with the minimum abrasive wear on the tool face.

Cast iron is abrasive even when hot, and, whilst it can be cut with negative-rake tools, it is generally better to use positive-rake tools operating at medium cutting speeds. The positive-rake tools, having reduced chip load, reduce the effects of the abrasive nature of the cast iron.

For a given cutting depth, high-speed cutting results in a thin chip flowing fast, and slow-speed cutting produces a thick chip flowing slowly. The two conditions are shown in Fig. 15, and the areas of parent metal to be sheared are roughly represented by the lengths of the lines AB. The shorter length AB for the fast-cutting tool gives a measure of the relatively lighter load



a Drive from lineshaft.



b Motor drive from single-speed alternating-current motor.

Fig. 1. Combination Turret Lathe

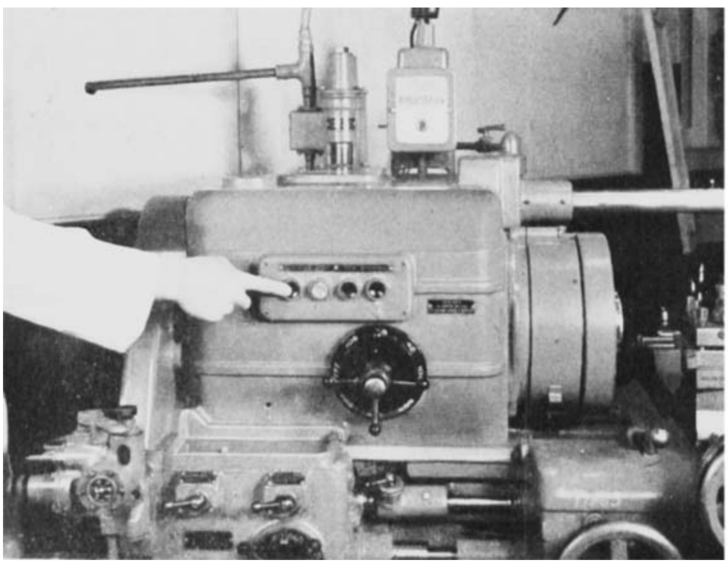


Fig. 2. Headstock for Capstan Lathe started, stopped, and reversed by Push Buttons through Plugging Relay

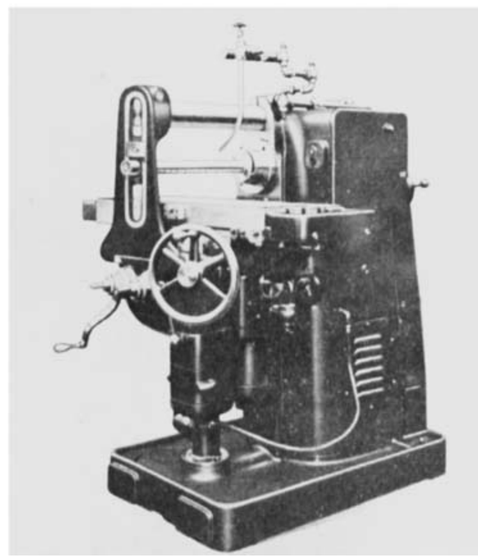


Fig. 3. Horizontal Milling Machine with Speed and Feed Changes effected by Pick-Off Gears

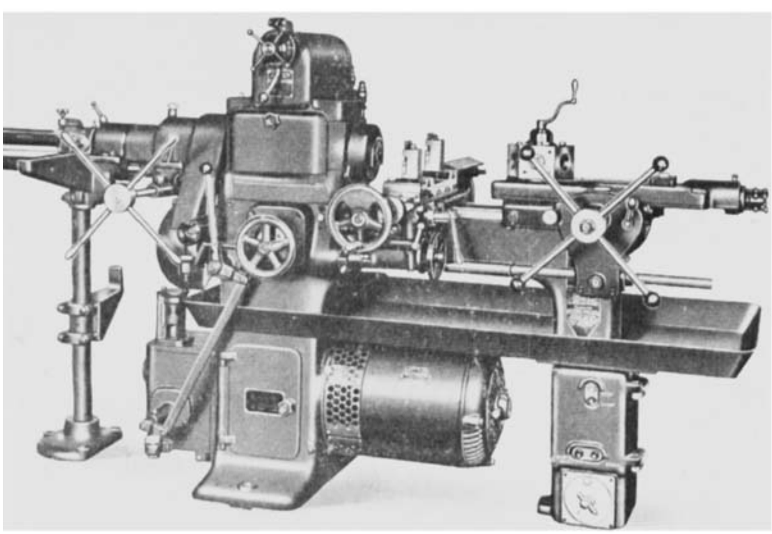


Fig. 4. Capstan Lathe with Eight Speeds

Both forward and reverse speeds are obtained from four-speed pole-changing motor doubled by clutch change in driving gearbox, giving the eight speeds, reversible by the motor, all without stopping the spindle.

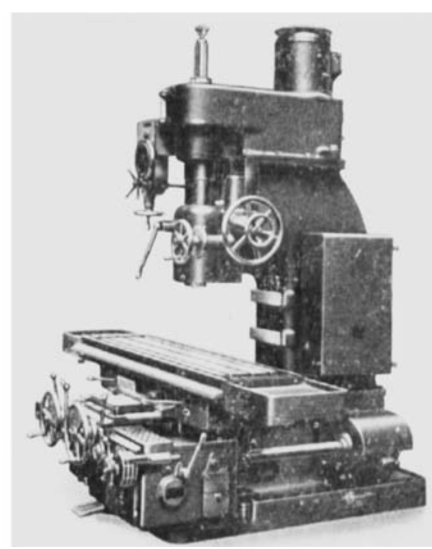


Fig. 5. Vertical Mill driven by Two-Speed Motor

Power, 15 h.p. at 2,800 r.p.m. and $7\frac{1}{2}$ h.p. at 1,430 r.p.m.

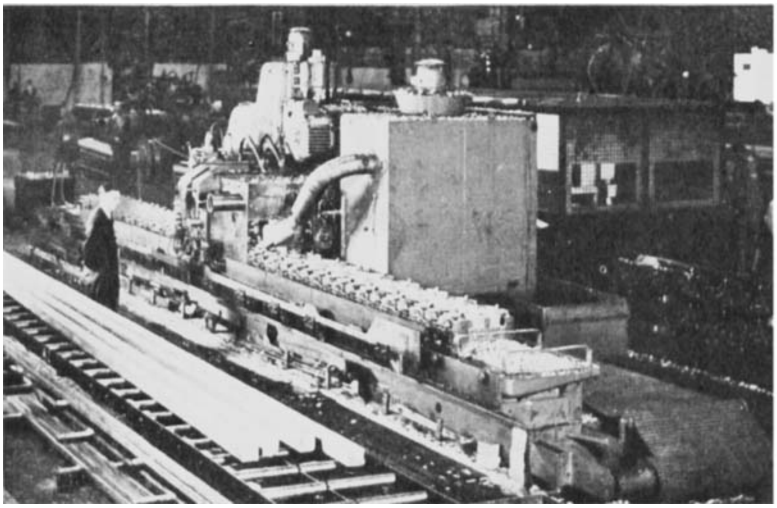


Fig. 6. Profile-Milling Machine for Aeroplane Spars, with Electronic Control to Speed and Feed Changes

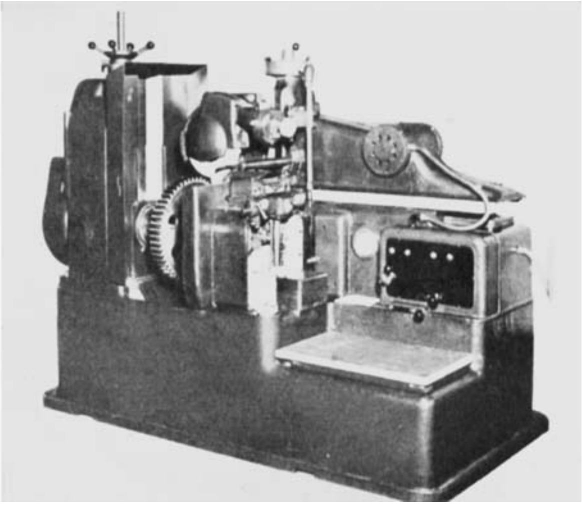


Fig. 7. Gear Grinder with Wheelhead Slide Reciprocated Hydraulically

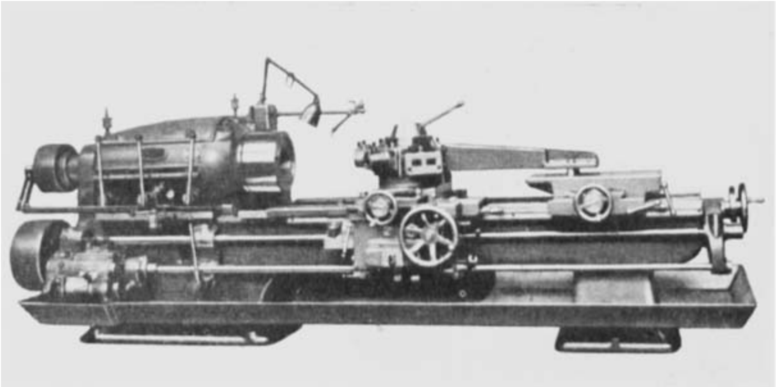


Fig. 10. Shell-Boring Lathe with Air-Operated Chuck

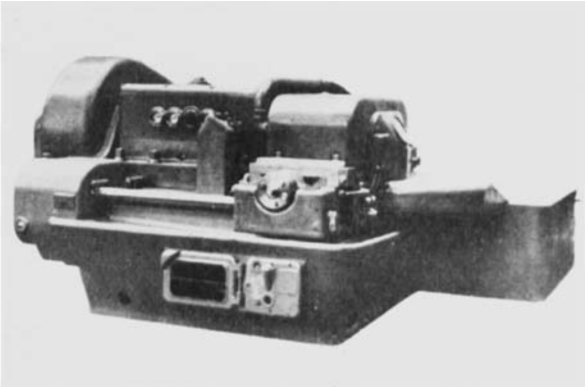


Fig. 11. Aero-Engine Cylinder Finning Machine

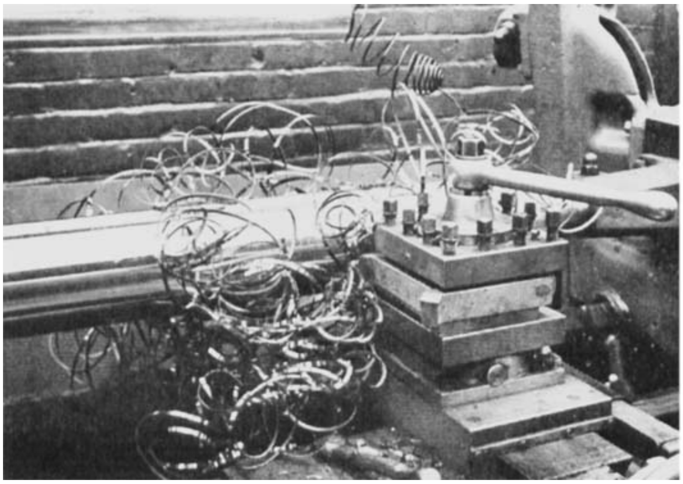


Fig. 13. Dangerous Chip Formation from Lathe Tool without a Chip-Breaker

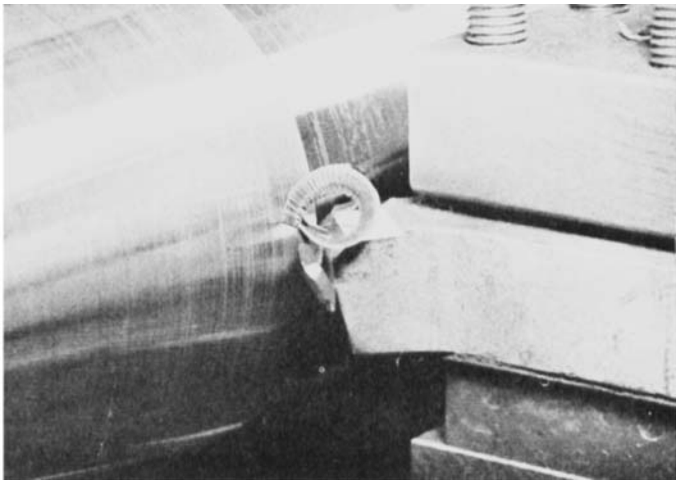


Fig. 14. Tool with 40 deg. Negative Rake

on this tool compared with the load on the slower tool operating at the same cutting depth.

Negative-rake machining requires more power (about 25 per cent more) than positive-rake work, but machines using negative-rake tools are not stressed to the same degree, since the loads on the machine details are reduced on account of the power

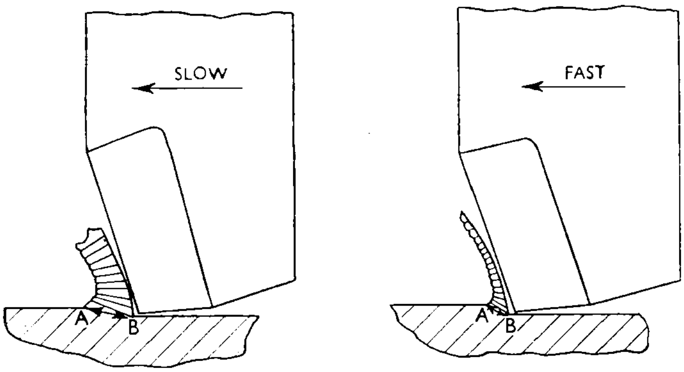


Fig. 15. Diagram showing Difference, in Chip Formation, between High and Low Cutting Speeds

being transmitted at higher speed. The increase in speed is usually greater than the increase in horse-power.

If it is assumed that an operation using carbide negative-rake tools is completed in half the time taken by a positive-rake high-speed steel tool, the increase in horse power using negative rake would be about 2½ times that using positive rake.

The increase in speed would probably be of the order of 500 ft. per min., as compared with 100 ft. per min. On account of the horse-power being increased 2½ times and the speed five times, the net result is that the machine elements are subjected to reduced loading represented by

$$\frac{2\frac{1}{2}}{1} \times \frac{1}{5} = \frac{1}{2}$$

It will be noted that, whilst the power transmission members of the machine are carrying only half the torque, they have to be capable of running satisfactorily at five times the speed; so the designing of suitable machines for negative-rake cutting resolves itself into providing for faster-moving parts less heavily loaded.

I have to thank the many British machine tool makers for their generous assistance in providing the material for this lecture, and to express regret that only a small number of the sixty illustrations originally shown could be reproduced in the printed version, due to considerations of space.