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Development of Metalworking Industries in Developing Countries

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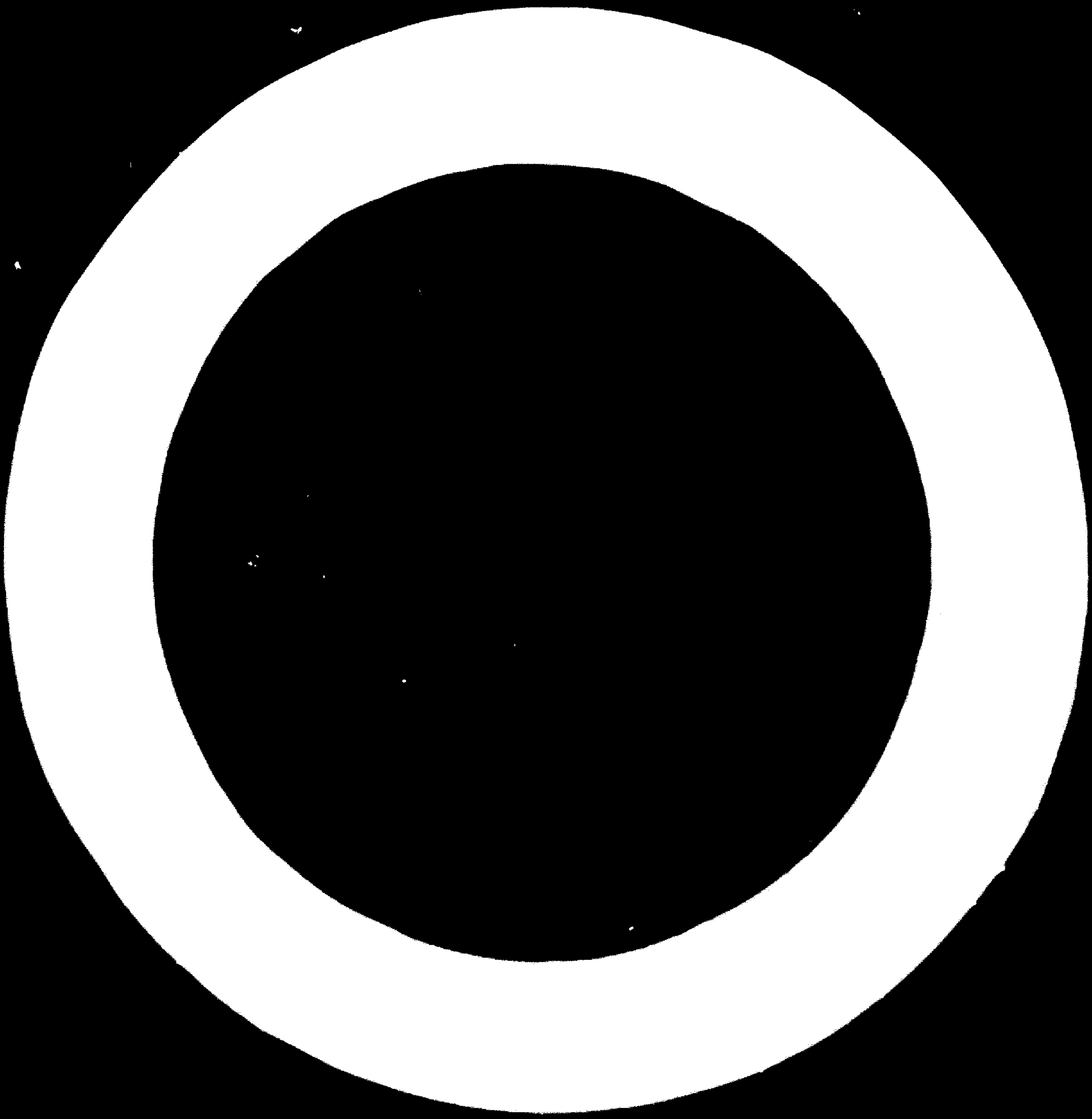

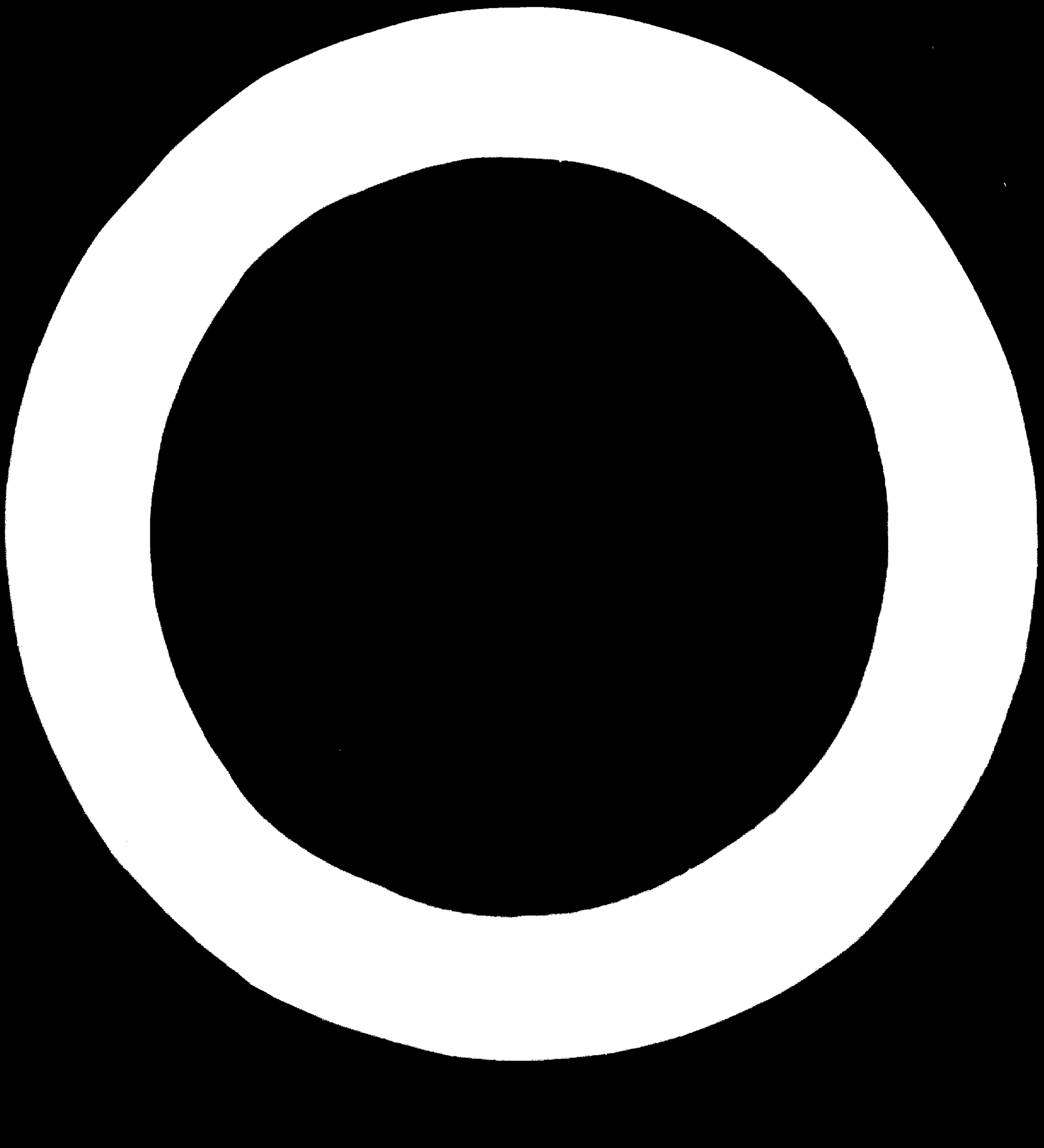

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RESEARCH FOR THE MACHINE-TOOL INDUSTRY

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INTRODUCTION

The business of the machine-tool industry is to make machine tools, and research for the machine-tool industry must, therefore, have two main objectives: (*a*) to facilitate the design and manufacture of machine tools; and (*b*) to improve existing machine tools and develop new ones.

But machine tools are not manufactured as ends in themselves; they are essentially means to a wide variety of ends. Machine tools are made in order to make possible the manufacture of other machinery power-stations, rolling-mills, typewriters, motor-cars etc. and the design of machine tools, must be determined largely by the requirements of the production engineers responsible for their use. Thus, the scope of research for the machine-tool industry is ultimately determined by the manufacturing requirements of modern industry. It includes problems associated not only with metal-cutting machine tools, such as lathes and drills, but with metal-forming machines, such as presses and forging machines and with new types of machine tool, such as electrochemical machines. It probably should also include work on some types of casting machines and machines for powder metallurgy, all of which can be regarded as possible alternative manufacturing machines. The aim of research for the machine-tool industry can, therefore, be stated as being to help the designer of manufacturing machines to meet the manufacturing requirements of his customers.

Even if the customers' needs could be completely satisfied and were to remain unchanged, research would still have a part to play in making it easier and cheaper for these needs to be met. New materials, new techniques and new methods of design can all be used by the machine-tool designer in his efforts to meet his customers' requirements. Thus even though many of the basic types of machine tool used today were already in existence 100 years ago, research on their performance and construction can still be justified in terms of the contribution it can make to reducing the resources required for their design and manufacture.

Of course, the needs of users of machine tools do not remain unchanged. Today's machine tools must be more accurate, more versatile and more economical to use than their predecessors were, while, at the same time, they are required to work at higher speeds and on a wider variety of materials. The improvements have been achieved by the development of greatly improved structures, mechanisms, control systems and machining techniques, and it is to further improvements of the same kind that much current machine-tool research is directed. Although the older types of machine tool are continually being improved, they are still unable to meet all the needs of the modern production engineer. New machining processes are necessary to meet the requirements of technologically advanced industries, such as the aerospace and nuclear power industries, which base their designs on the use of materials which are difficult, if not impossible, to machine in the conventional way. And even in the mass production industries, economic considerations emphasize the need for manufacturing processes which do not involve the wastage, as swarf or scrap, of large proportions of the raw material purchased. Improved versions of the older types of machine tool have, therefore, been supplemented by entirely new machine tools electrochemical machines, high-energy forging machines and even, for some purposes, electron-beam and laser machines.

Conventional metal-cutting processes, which depend upon plastic deformation and shearing of the workpiece material, have been studied for many years and, although they are not yet fully understood, a considerable body of data is available on which to base the design of machine tools. Little information is yet available, however, about the mechanism of machining by lasers, for example. Thus, although the successful design and operation of these newer types of machine tools still depends upon basic research on structures and mechanisms, it requires, in addition, the backing of considerable research into the fundamentals of the processes themselves.

Nevertheless, whether it is intended to facilitate the design of a conventional machine tool or to develop a new machining process, the results of research must eventually be incorporated into a machine tool. And the research is successful only if the machine tool is itself successful in production conditions. Much, but not all, of the research and development required for the production of a new machine tool can be done by the machine-tool maker, or in government and other laboratories. But the successful development of a new machine tool requires also a substantial contribution from users and, indeed, the rate at which new machine tools and processes can be developed and applied probably depends more upon users than upon the manufacturer. Machine-tool research, if it is to be fruitful, must be accompanied by equally basic studies in production engineering. The quality and quantity of production engineering research must keep pace with the considerable recent growth of research for the machine-tool industry, and the economics and organization of manufacturing must, therefore, be added to the list of topics for study.

In practice, the way in which a machine tool is used can be as important a factor in determining whether or not it is successful as the quality of the engineering that has gone into its design. Thus, studies of all aspects of machine-tool utilization, including ergonomics, also form a vital part of machine-tool research.

It is obviously impossible, in a single paper, to describe completely all the problems and procedures of machine-tool research. In this paper, therefore, some of the main problems of current interest will be described in relation to their background, and an indication will be given of the way in which the problems are being tackled and of some of the results obtained.

The work described is based mainly on that of the Machine-Tool Industry Research Association (MTIRA), a co-operative research association working for the machine-tool industry in the United Kingdom of Great Britain and Northern Ireland.

I. MACHINE-TOOL STRUCTURES

The functions of the structure of a machine tool are, first, to support the workpiece and cutting tool; and, secondly, to allow relative motion of prescribed kinds between the tool and the workpiece. Furthermore, accuracy must be maintained even when the structure is subjected to the forces required to machine the workpiece. Thus, the structure must not only be geometrically accurate, it must also have high stiffness to permit it to resist deformation by cutting forces. A structure which is stiff enough for this purpose will, almost invariably, also be strong enough to support the workpiece.

It is convenient to discuss separately the problems of geometrical accuracy and stiffness, and although the examples quoted in this section refer mainly to metal-cutting machine tools, the principles discussed apply also to all other types of machine tool.

A. *Accuracy*

Fundamentally, accuracy must be built into a machine tool; surfaces must be flat and perpendicular or parallel to each other, slides must move along straight lines and spindles must rotate about defined axes. All this must be achieved by accurate manufacture, and the main contribution of research has been to the techniques of measurement.

As standards of accuracy of machine tools have increased, particularly on larger machines, with the spread of numerical-control systems, it has become increasingly difficult to measure the performance of the completed machine tool with an accuracy comparable with the resolution of the measuring scales on the machine. This problem has recently been eased considerably by the development of portable laser interferometers, and this instrument is a good example of the way in which research in fields which are apparently remote from machine-tool technology can be applied to the benefit of the machine-tool industry. (Reference has already been made to the use of solid-state lasers for machining operations; a further development of laser research is discussed in a subsequent section.) The high degree of coherence in the light emitted by a single-mode gas laser permits fringes to be formed between two beams of light even when their optical-path lengths differ considerably. With suitable corrections for temperature and atmospheric pressure, therefore, lengths of up to 5 metres can now be measured to an accuracy better than 1 part in 10^6.

Thus lasers, discovered only in 1961, are already in routine use for calibrating machine tools that could not be checked to the required accuracy in any other way (see figure 1).

The availability of this instrument makes possible the calibration, under workshop conditions, of both large and small machine tools with an accuracy hitherto attainable only under standards-room conditions. Although much remains to be learned about the practical application of machine tools of laser interferometry, it seems likely that this new technique will have an immediate beneficial effect on the performance of the more accurate machine tools and, at the same time, will stimulate research into methods of achieving still greater accuracies.

As mentioned above, it is the application of numerical-control systems to large machine tools that has been mainly responsible for the growing need for more accurate calibration of the linear displacements of the moving parts of machine tools. With manual operation, small adjustments to correct residual inaccuracies can always be made by the operator but, as yet, these same adjustments cannot be carried out automatically, although the development of adaptive control systems for machine tools (which are discussed later) may eventually make this possible. At the current time, however, although numerically controlled machine tools are capable of a higher degree of repeatability than are manually operated machines, they can achieve the same absolute accuracy in practice only if they are inherently more accurate or if they are controlled from the actual machined dimensions of the workpiece, rather than from the relative positions of tool-holder and work-table, as is more usual. This requires some form of "in-process" gauging to measure workpiece dimensions immediately behind the cutting tool. Pneumatic gauging systems are already being applied in this way for the control of cylindrical- and disc-grinding machines, and versions suitable for use on lathes are now being developed. Mechanical systems for measuring the diameter of large bores by rolling a disc around the periphery are also used. Other methods of in-process gauging which are currently being developed include the electronic measurement of the dimensions of an image of the workpiece projected on to a television camera tube, and the optical straight-edge system shown in figure 2, which illustrates yet another possible application of lasers to machine tools.

Until quite recently, one could not expect a machine tool to machine to an accuracy better than that of the machined surfaces in the machine tool itself—slideways,

Figure 1

LASER INTERFEROMETER CALIBRATOR USED BY MACHINE-TOOL INDUSTRY RESEARCH ASSOCIATES FOR CHECKING THE ACCURACY OF A MACHINE TOOL

bearings etc. However, the growing use of hydrostatic bearings for slideways and spindles means that this is no longer true. A slide supported on a film of oil under pressure will, because of the integrating effect of the oil film, move along a line which deviates from the straight appreciably less than the actual slideway surface. Similarly, a spindle supported on hydrostatic journal bearings can rotate with less eccentricity than is present in the bores of the journal bearings. Research on hydrostatic bearings (which are discussed more fully below) has thus led to the possibility of using a machine tool to produce a series of further machines, each of which is more accurate than the last.

It is also possible, using a recently developed type of hydrostatic bearing pad (see figure 3) to correct automatically for gross errors in the straightness of slideways by causing the slide to follow a path defined by a beam of light. An arrangements of photocells detects any deviation of the slide from the desired path and corrections are effected by increasing or decreasing the thickness of the oil film between the slide and slideway. The stiffness of the system normal to the plane of sliding is now determined by the gain in the error-control system. Although research on this subject is continuing, the system would currently appear to be practicable only in special circumstances. However, the possibility of obviating all need for accurate machining of machine tool surfaces by using optical means of guidance and servo systems to provide the required structural stiffness is an attractive one.

Hydrostatic slideway bearings have the additional advantage that, as there is no metal-to-metal contact during sliding, there is no wear. Moreover, as explained above, a small amount of wear does not necessarily affect the accuracy with which the slide moves. With adequate lubrication and properly fitted slideway covers, wear can often be reduced to negligible proportions. It is still sometimes necessary, however, to operate slideways without protection and, in general, it is necessary to take account of the possibility of wear of slideways

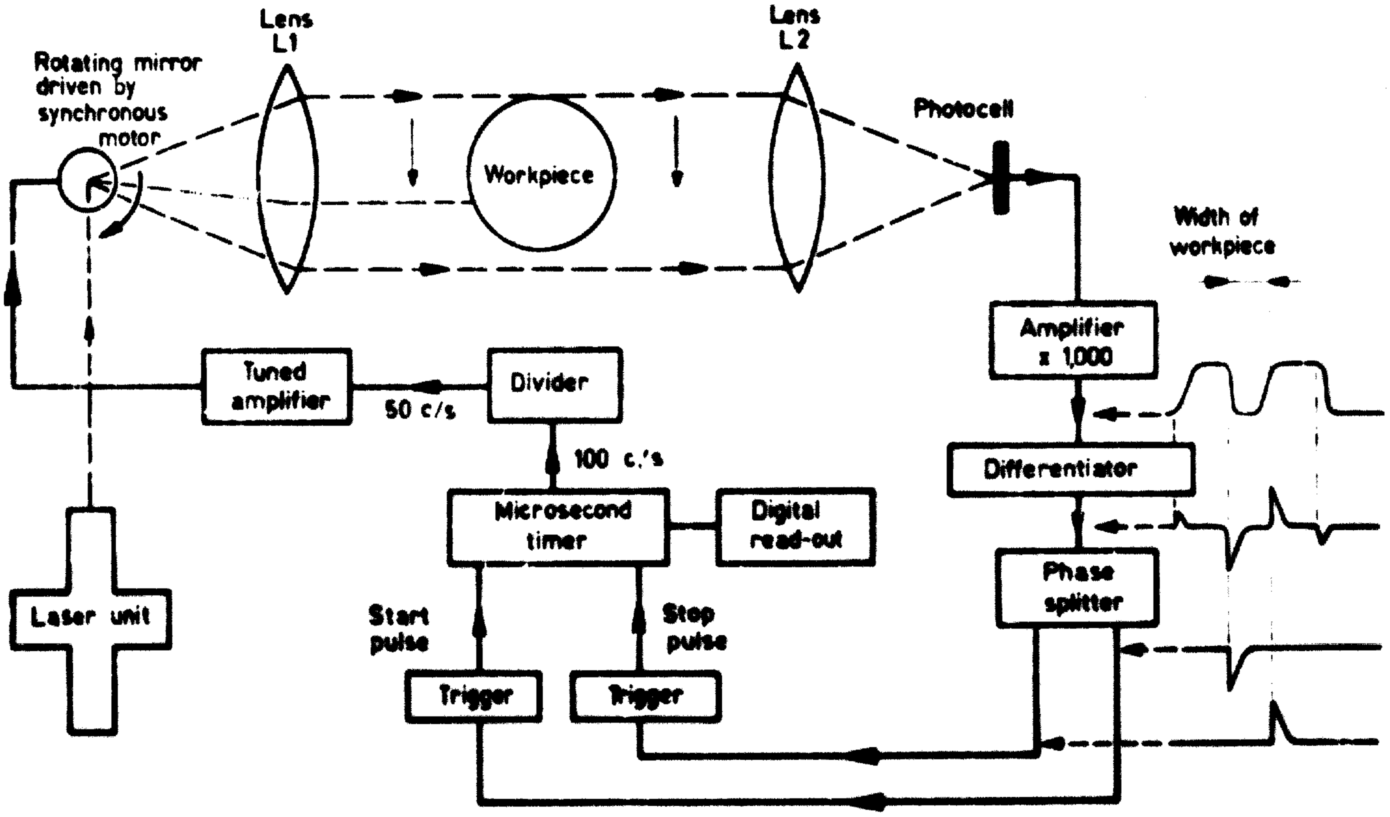

Figure 2

USE OF A LASER FOR IN-PROCESS MEASUREMENT OF WORKPIECE SIZE

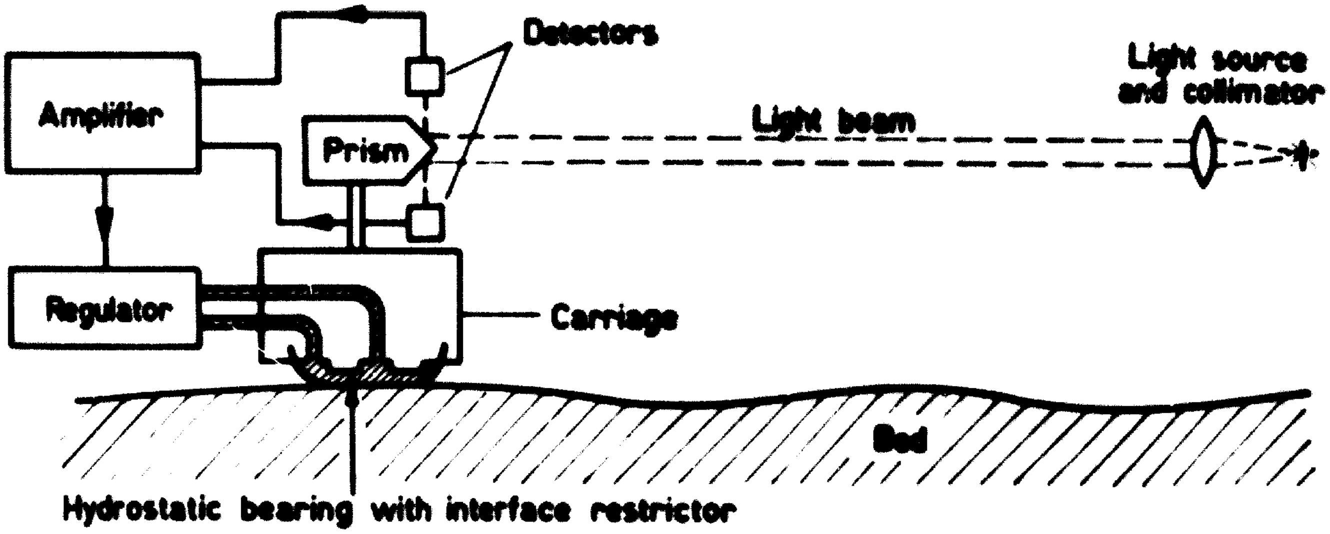

Figure 3

AUTOMATIC CORRECTION OF ERRORS IN MACHINE-TOOL SLIDEWAYS BY VARYING THE THICKNESS OF THE OIL FILM IN A HYDROSTATIC BEARING which operate under conditions of boundary or hydrodynamic lubrication. If wear of slideways is likely to be experienced, care should be taken to position the slideways in such a way that wear has the least effect on the accuracy of machining. For example, by supporting a machine tool slide on three sliding surfaces arranged so that the normals to the surfaces interesect at a point, any rotation of the slide as a result of wear of the surfaces is minimized. Figure 4 shows a practicable arrangement of three surfaces which approximately meets this condition.

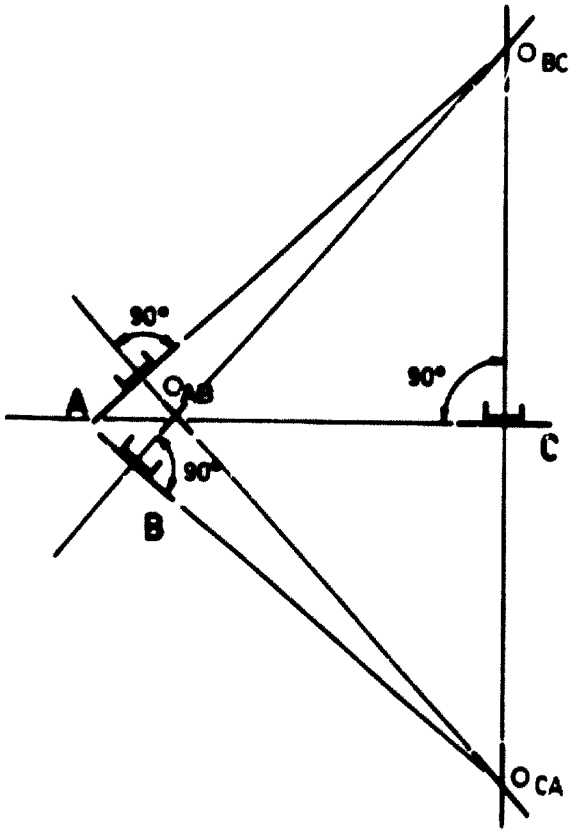

Figure 4

A PRACTICABLE ARRANGEMENT OF SLIDING SURFACES WHICH APPROXIMATELY SATISFIES THE RULE FOR THE MINIMUM EFFECT OF WEAR

Such an arrangement might be used to support the saddle of a lathe and if, in addition, the axis of the lathe spindle passes through the point of intersection of the normals, then wear will produce only a tangential displacement of the cutting tool, which will have little effect on the accuracy of the machine tool. In practice, it would probably be sufficient to arrange that the lathe spindle was on a line joining the point of intersection of the normals and the point of the cutting tool.

Similar considerations can be applied to determine the best geometrical arrangement of slideways for other kinds of machine tool.

B. *Stiffness*

The cutting forces which tend to distort a machine tool structure do not remain constant, even under nominally uniform cutting conditions. Interrupted cutting conditions or variations in workpiece properties can give rise to alternating components of cutting force superimposed on the steady forces, and the alternating forces will produce forced vibrations of the structure which may result in a wavy surface on the workpiece. A machine-tool structure must, therefore, be not only statically stiff so as to resist deformation by steady forces, but also dynamically stiff in order to prevent alternating components of cutting force from giving rise to large amplitudes of vibration. Since it is impossible to know the frequencies of all the alternating components of force (although there will usually be components at the frequency of revolution of the spindle and at cutter tooth frequencies), it is usually desirable to make the natural frequencies of vibration of machine-tool structures as high as possible so as to minimize the chances of excitation of vibrations of large amplitude. In general, therefore, the objective of a high dynamic stiffness is usually interpreted as meaning a high natural frequency. Damping is also important, however, and at resonance the effective stiffness is determined mainly by the damping in the structure.

In some circumstances, when the damping in the structure is small, energy can be fed back from the main drive to build up and sustain vibrations of the structure at a frequency approximately equal to the natural frequency of vibration. Such "regenerative chatter" vibrations can be of large amplitude and, in addition to leading to poor surface finish, may even lead to actual damage to the workpiece, cutting tool or machine structure. The theory of chatter vibrations, has been extensively discussed in the literature, but although the phenomenon is reasonably well understood, it is still not easy to design from first principles a structure that can be guaranteed not to chatter.

The accuracy of movement of a machine tool is normally assured by some form of acceptance test, and it would be useful for both makers and users if the actual machining performance of a machine tool could be tested in a similar way. Dynamic acceptance tests would include noise level, power available at the spindle etc., but they would be really useful only if they provided a measure of the inherent resistance of the machine tool to chatter. The difficulty is to devise an objective and meaningful test, as small differences in stiffness and damping can have a great effect on performance. A machine tool may perform satisfactorily with one workpiece and cutting tool, but unsatisfactorily with other workpieces and tools, even though these may be essentially similar to the first.

Even when a machine tool is known to be unsatisfactory in respect of chatter behaviour, it is not always easy to say just how it can be improved. Increasing the static stiffness may help, but this could have the opposite effect by bringing the natural frequency of the structure into near coincidence with an exciting frequency. Indeed, it is often possible to improve the machining capabilities of a machine tool by reducing its stiffness in a particular direction. In general, however, the best way of reducing liability to chatter would undoubtedly be to increase the damping in the structure, although this is not easily achieved since the sources of damping in machine structures are not yet fully understood.

The inherent damping in cast-iron or steel structural members is only a small proportion of the total damping, although it is possible to increase the damping in welded-steel structures by the use of a laminar construction, in which there is a relative movement at the interface when the structure deflects. Sand or concrete filling can also increase the damping of a structure, although there is little quantitative information available. Joints certainly contribute a large proportion of the damping, presumably by friction when the joint surfaces move in relation to each other. Increasing the relative movement will increase the damping, but only at the expense of reducing the static stiffness. Oil films, such as those which are formed in hydrostatic slideways, are capable of dissipating energy as the thickness of the film varies cyclically and are thus potential sources of damping. The damping effect increases rapidly as the frequency increases, but, unfortunately, so does the stiffness of the oil film (see figure 5). At frequencies greater than a few cycles per second, therefore, the oil film is probably as stiff or as stiffer than the rest of the structure, so that alternating forces will produce little variation in thickness of the film and there will be little contribution to the damping. The problem of finding effective ways of increasing the damping in machine-tool structures therefore remains to be solved.

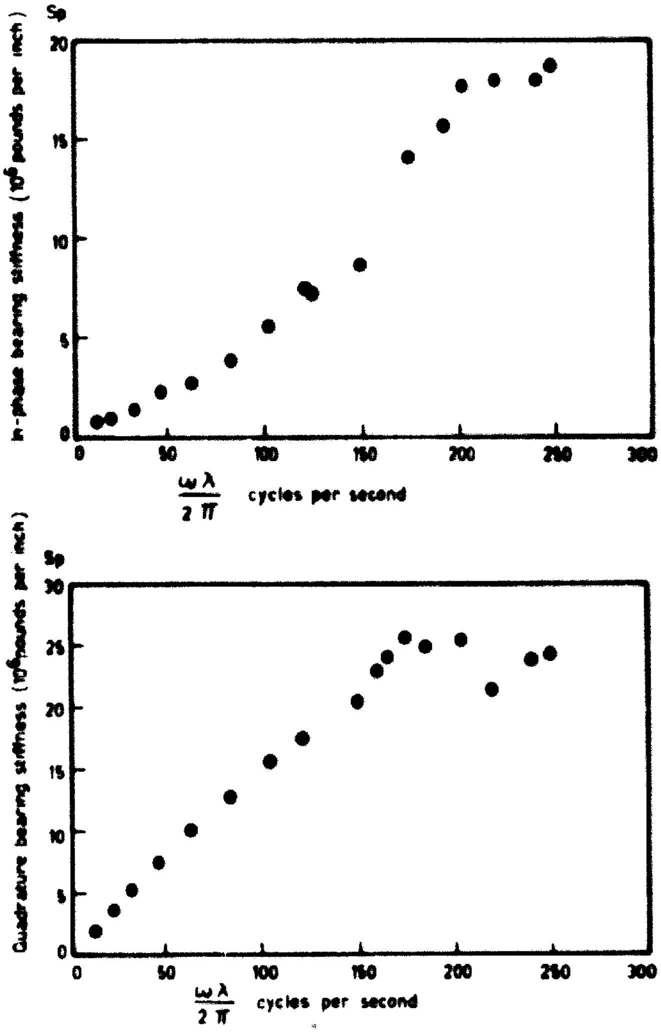

Figure 5

IN-PHASE AND QUADRATURE STIFFNESS OF A HYDROSTATIC THRUST BEARING WITH AN 0.04-MILLIMETRE OIL FILM

Until more is known about the dynamic behaviour of machine-tool structure, it is probably best for the designer to aim at producing structure with high static stiffness and high natural frequencies of vibration. This means, in practice, that the stiffness has to be achieved using as little structural material as possible. Michell structures—orthogonal pin-jointed frame structures so proportioned that the stress is constant everywhere—can be shown to have the maximum stiffness to a given set of forces for a given weight of material. The saving in weight can be appreciable (see figure 6) and these structures would seem to be a good approximation to structures of high natural frequency. Unfortunately, Michell structures can, as yet, be specified only for simple two-dimensional sets of forces, although research to extend their range of application is continuing. Moreover, practical continuous structures can only be approximate to true Michell structures.

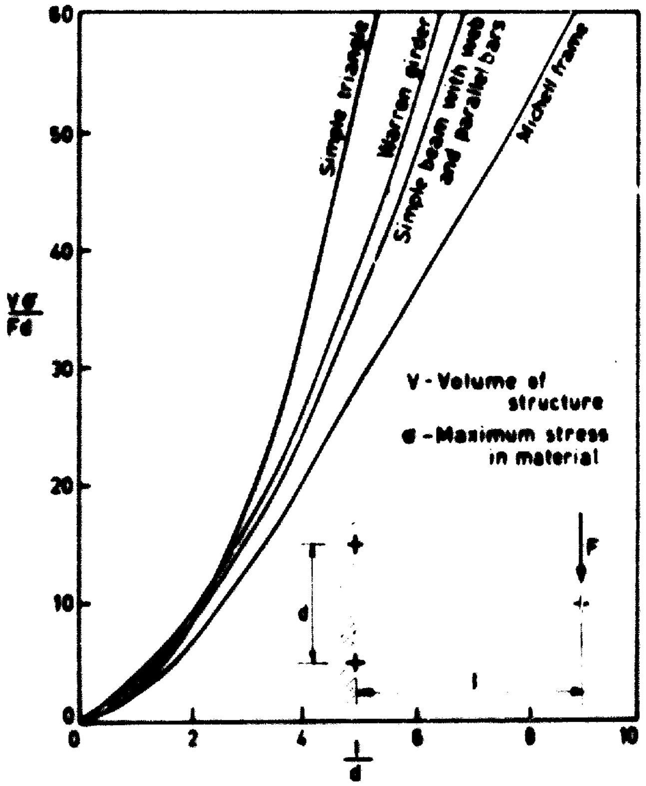

Figure 6

COMPARISON OF THE VOLUMES OF DIFFERENT TYPES OF CANTILEVER STRUCTURE

For the time being, therefore, machine-tool structures must be designed using more empirical methods. Structures which are stiff to bending, torsional and shear forces are required (the need for shear stiffness is often overlooked, but deflections due to shear can represent a large proportion of the total deflection of some structures), although the relative magnitudes of these forces will vary from one machine tool to another. In general, it is best to base the design on a structure which has maximum torsional stiffness since such a structure usually has good bending and shear stiffness also (see figure 7).

A major problem is the need to prevent local distortion and to ensure that the material of the structure is, as far as possible, uniformly stressed. Simple structural models are often useful for showing up weaknesses and for suggesting ways of stiffening a structure. Weak regions, such as can be caused by holes, must be stiffened by properly placed ribbing, and arrangements must be made for spreading point loads.

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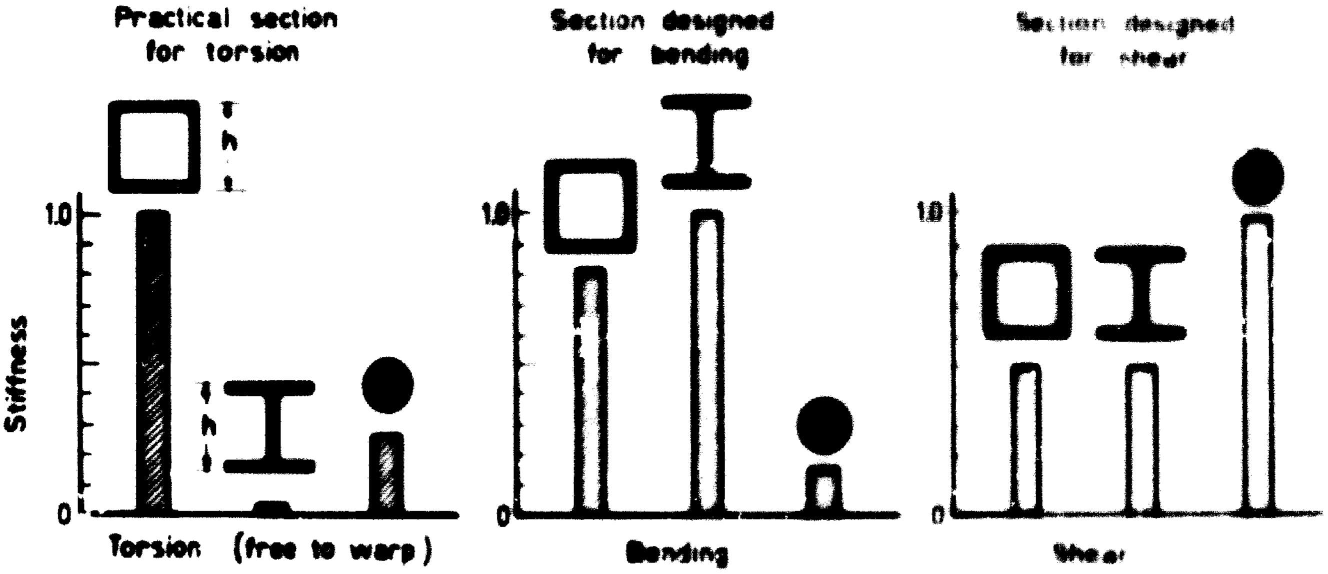


Figure

RELATIVE STIFFNESS OF VARIOUS SECTIONS IN TORSION, BENDING AND SHEAR

Tests on models are also often used for predicting the stiffness of full-scale structures. More recently, however, as a result of research, it has become possible to use computing techniques for predicting the static and dynamic stiffnesses and modes of vibration of proposed structures. It is necessary to represent the proposed structure by a lumped-parameter model and to describe in reasonable detail the shapes and sizes of the various structural elements. Once this has been done, however, stiffnesses, mode shapes and natural frequencies of vibration can be determined by using the programme prepared for this purpose. The effects of proposed modifications to the structure are easily calculated also. It seems likely that the use of computer techniques in this way will gradually replace model tests for the study of the dynamic behaviour of structures.

Joints can contribute a large part of the total compliance of a machine-tool structure and their effect must be taken into account in any consideration of structural stiffness. Studies of joint behaviour have shown the importance of interface pressure and surface finish of the joint surfaces, and it is now possible to predict the effective stiffnesses of simple joints. This information can

it is not economical to make the bed of the machine stiff enough to allow the machine to be used without attaching it to a foundation. It is then necessary to ensure that the machine tool is attached to its foundation in such a way that the stiffness of the foundation block is fully utilized. Since it is usually necessary also to allow for differential settlement of the foundation and for changes in its shape and size with temperature and humidity, the choice of the method of attachment of the machine tool to the foundation requires some care.

H. MATERIALS OF CONSTRUCTION

If, however, the foundation has to be regarded as an integral part of the machine-tool structure (and this is usually the case where static or dynamic stiffness is involved), it is reasonable to consider integrating the design of machine tool and foundation by making the machining bed in concrete. A few machine tools with concrete structural members have already been produced, but doubts about the long-term stability of the material have tended to inhibit the acceptance of this method of construction. Recent measurements indicate, however, that if proper precautions are taken it should be possible to achieve the necessary stability. The possible advantages of concrete as a structural material for machine tools include reduced cost, reduced transport charges because large structural elements can be cast on site, and, possibly, increased damping. A full assessment of the use of concrete in this way cannot be made, however, until more data are available on stability and damping capacity.

Although cast iron is still the most commonly used material for machine-tool structures, fabricated structures are being used to an increasing extent and offer economic advantages in some circumstances, particularly when the shape can be chosen to take advantage of the increased modulus of elasticity of steel, as compared with that of cast-iron. The possibility of introducing additional damping into fabricated structures has already been mentioned and the ease with which modifications can be made to fabricated structures is also relevant. Modular (s.g.) cast-iron, whose properties are intermediate between those of steel and ordinary grey cast-iron, is also worth studying as a possible structural material.

For obvious reasons, plastic materials are not frequently used for the structural members of machine tools, but are increasingly used for non-load-bearing components. Laminated plastic inserts impregnated with PTFE are used as slideway materials, as are various soft non-ferrous alloys.

III. MECHANISMS

Although stiffness is the main criterion in the design of the structural elements of machine tools, relative movement of structural members—slides on slideways or spindles in journal bearings—is often necessary and bearings, both plain and journal, are important elements of machine tools. The usual requirements are for stiffness perpendicular to the direction in which movement is to be permitted and little resistance to movement in the desired direction.

The simplest and cheapest slideway bearings are plain lubricated bearings, and much effort has been devoted to examining lubricants and the shape and finish of sliding surfaces in attempts to reduce wear, reduce friction and eliminate stick-slip effects. Reproducible and relevant results are not easily obtained in tests of this kind but special oils and laminated plastic impregnated with PTFE, or soft metal surfaces sliding on hardened-steel or cast-iron surfaces have permitted the manufacture of low-friction, wear-resistant slides and slideways, with controllable friction characteristics. The advent of numerically controlled machine tools has, however, accentuated the need for slideway bearings requiring even lower forces to move the slides, and rolling-element bearings of various types have been developed to meet this need. But the stiffness normal to the plane of sliding is not easily obtained without pre-loading, which increases the effective frictional force opposing movement.

Hydrostatic slideways, in which the sliding surfaces are supported by a film of fluid—oil or air—under pressure, offer many advantages. The film of fluid can be made very stiff to forces normal to its plane, but it offers little resistance to sliding motion and the effective frictional force (viscous) increases with velocity so that there is no danger of stick-slip effects. Moreover, the integrating effect of the film of fluid means that the slide moves along a line which can be more nearly straight than the slideway itself.

The fluid used may be gas (usually air) or oil. Air has the advantage of not requiring collection after use, but is expensive to supply at the pressures and volumes required and has little damping capacity. Oil is cheaper to supply and it can provide damping of motion in and normal to the plane of sliding; furthermore, hydrostatic slideways using oil are easier to design than those using gas. The main disadvantage of oil is the need to collect it after use and to keep it free from contamination with cutting or other fluids.

Hydrostatic slideways are made stiff normal to the plane of sliding by supplying oil to the slideway pockets (see figure 8) *via* some form of restriction. Any tendency for the thickness of the oil film to decrease, say, when the load changes is opposed by the resultant increase of pressure in the oil film, the thickness of which thus tends to stay constant. The simplest forms of hydrostatic slideway use capillary restrictors, but more elaborate diaphragm-controlled restrictors have been developed. With the latter, the pressure in the oil film varies the resistance of the restrictor in such a way that even greater stiffness can be obtained. Single-sided hydrostatic slideway bearings often suffice, but there are many advantages in using opposed pairs of pads. These will not only support loads in both directions, but can be made with greater stiffness than can single-sided bearings. Moreover, their stiffness is less dependent upon the load carried.

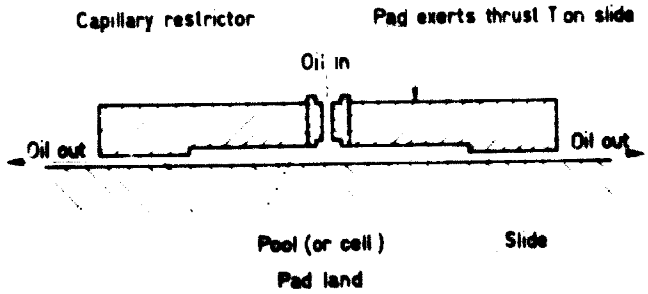


Figure 8

CROSS-SECTION OF HYDROSTATIC THRUST PAD

Hydrostatic slideway bearings are relatively easy to design and make. There are, however, many variables involved and the development of procedures for optimizing the design has involved much research. The relations between stiffness (and load) and restrictor resistance and oil-film thickness are complex (see figure 9); it is also necessary to consider the area available for the bearing pads, the oil-supply pressure and the minimum allowable gap (oil-film thickness). Account must also be taken of the heat generated and the pumping power required; and, in general, it is not possible to minimize both these quantities simultaneously. Therefore, the final design must always be some kind of

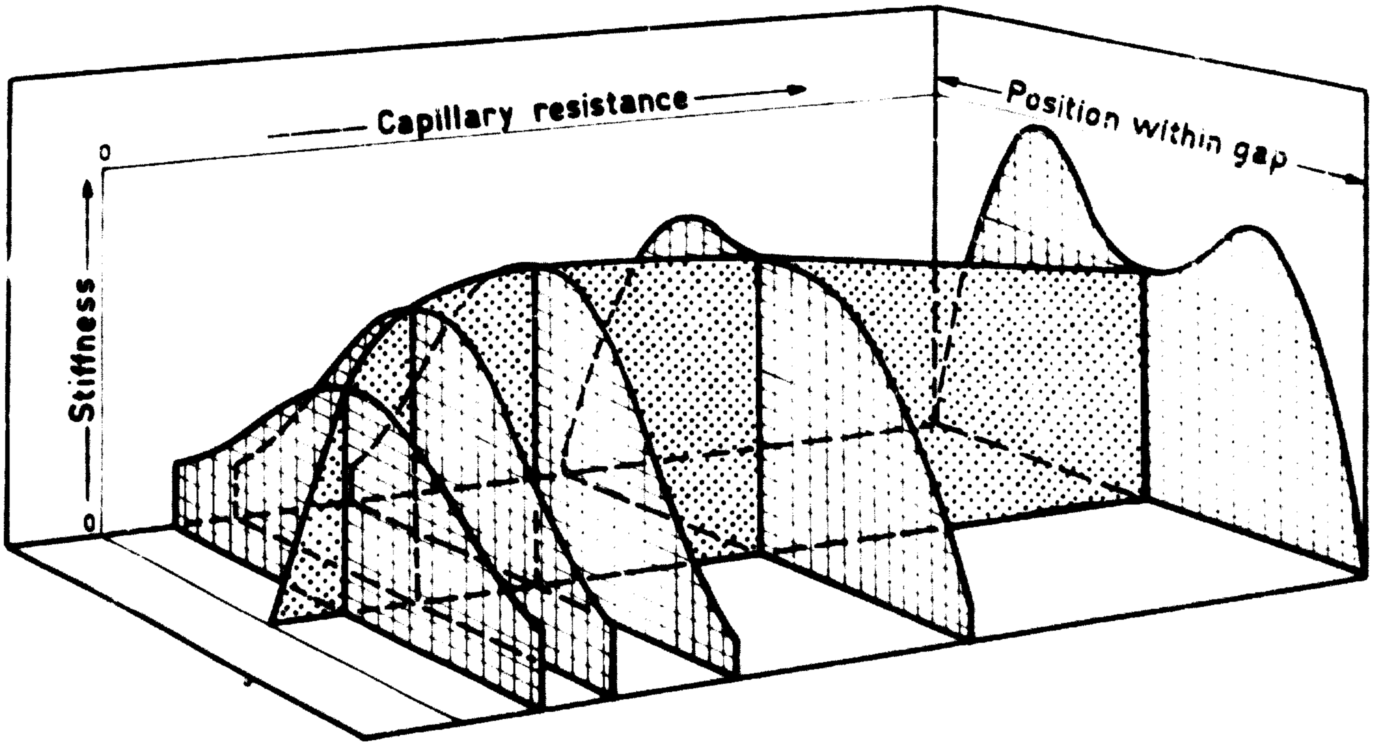


Figure 9

STIFFNESS CONTOURS FOR A TYPICAL HYDROSTATIC PAD-PAIR

compromise, but with all the data available in a readily usable form, the designer can easily choose a design which best suits his conditions. The preparation of design data of this kind for hydrostatic bearings and other mechanisms and structures is an important objective of research for the machine-tool industry. In the United Kingdom, the Machine Tool Industry Research Association prepares "MTIRA notes for designers", which present in analogue (graphical) form the results of extensive computations to permit designs to be optimized for any given conditions.

A similar approach is adapted to the design of hydrostatic journal and thrust bearings, although the number of variables involved is even greater than for plain sliding bearings and the problems are correspondingly more complex. However, studies of the phenomena involved have led to an understanding of the behaviour of these bearings (see figures 10 and 11) and to the development of design procedures which permit optimization for any given conditions. Conventional rolling-element journal bearings can be pre-loaded to give the required radial stiffness at low speeds, but pre-loaded bearings cannot be run at high speeds because the heat generated in the bearings would cause seizure. Unless, therefore, arrangements are made to remove the pre-load as the speed increases, it is not possible to achieve uniform stiffness over a wide speed range. This is, however, easily achieved with hydrostatic journal bearings. Moreover, accurate, stiff bearings of large diameter can be operated up to speeds which present considerable difficulties for conventional rolling-element bearings.

Nevertheless, most machine-tool spindles still rotate in rolling-element bearings and research has led to the development of highly accurate bearings of this type. The performance, in respect of accuracy of rotation and stiffness, of machine-tool spindles with rolling-element bearings depends not only upon the bearings themselves, but also upon the way in which they are mounted in the machine tool. An inaccurately machined bearing housing can cause loss of stiffness, overheating and inaccurate relation. Furthermore, the design of the housing and the way in which it is attached to the rest of the machine-tool structure play a large part in determining the effective stiffness of the bearing.

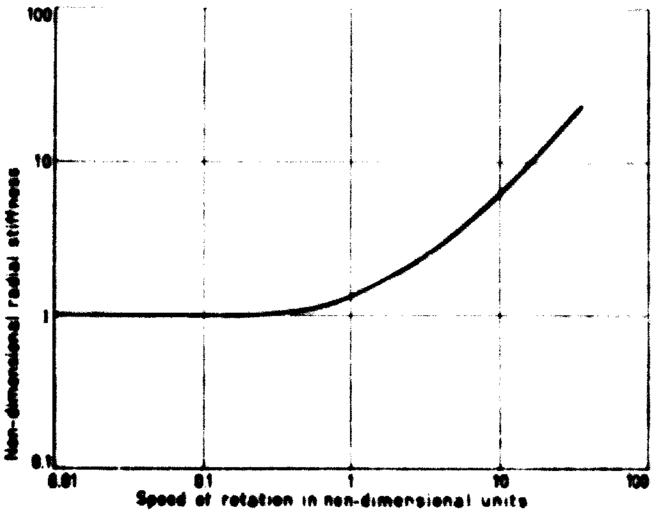


Figure 10

EFFECT OF ROTATIONAL SPEED ON THE RADIAL STIFFNESS OF A HYDROSTATIC JOURNAL BEARING

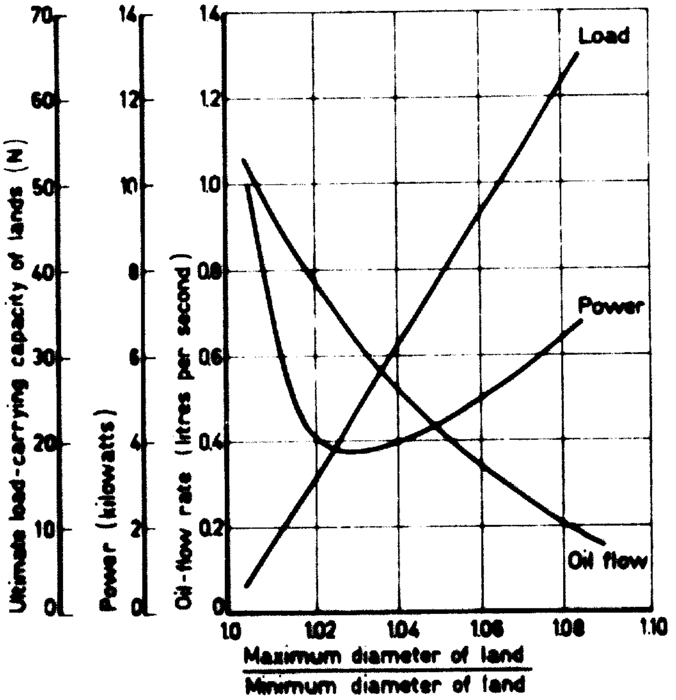


Figure 11

EFFECT OF WIDTH OF LAND ON THE ULTIMATE LOAD CAPACITY, OIL-FLOW RATE AND TOTAL POWER REQUIREMENTS OF A HYDROSTATIC THRUST BEARING

Whatever the type of bearing used, the stiffness of the bearings must be properly matched to that of the spindle if full advantage is to be taken of both. Before the optimum design can be produced, it is necessary to have full knowledge of the stiffness of bearings and spindles. Here again, the use of a computer to calculate the necessary relationships (which can then be presented in graphical form) makes it possible to present the designer with all the information necessary to enable him to produce the optimum design. Occasionally, however, it may not be possible to achieve the optimum design in practice because of lack of space or other practical considerations, but if the designer knows just how much he is sacrificing by not having optimum conditions, he is in a better position to make the necessary decision.

IV. DRIVES

A. *Spindle drives*

For a given input power, high spindle speeds mean low torques and therefore small forces, whereas low spindle speeds involve large forces and high torques. At low speeds, therefore, the power that can be utilized by a machine-tool spindle is limited by the stiffness of the size of the driving motor. The ideal power speed characteristic for a machine-tool drive is, therefore, of the form shown in figure 12, i.e. a constant torque at low speeds and a constant horsepower at high speeds.

For small variations of speed about a given speed, however, it is not always clear whether a constant-torque or a constant-power characteristic is to be preferred. Direct drive by a variable-speed hydraulic or electric motor usually gives the first type of characteristic, while the conventional gear drive is of the second type. With the first type of drive, if the resistance experienced by the tool-point varies, e.g., with interrupted cuts or because of variations in workpiece properties, the cutting speed will decrease so as to keep the cutting force constant, whereas with the second type of drive, the speed will tend to remain constant and the cutting force will increase correspondingly. Under these conditions, the effects of the characteristics of the spindle drive on surface finish and tool wear do not seem to have been investigated. The constant-torque drive would seem to be less hard on the cutting tool, although most designers and users of machine tools think that they need a constant-horsepower drive.

Although there is ample evidence (see figure 13) that most users of machine tools do not make full use of the spindle speeds available, the economic advantages of being able to choose the correct speed for each application can be considerable. Continuously variable-speed drives tend to be more expensive than gear drives, but when allowance is made for all the savings associated with the omission of a gear-box and for the added convenience afforded both the designer and the user, the extra cost may not be very great. For some operations, e.g., facing operations on a lathe, the extra cost can certainly be justified.

At the current time, most machine-tool spindles are driven, *via* systems of gears or belts, from a constant speed alternating-current electric motor. It is usual for the spindle speeds available to cover a wide range—100:1 is not uncommon in very small steps, in order that the correct cutting speed may be available for any tool and workpiece combination. Thus, spindle drives may involve several gear trains and sometimes a belt drive also. Both the total compliance and the total inertia of the drive can, therefore, be high and its torsional natural frequency low, so that torsional vibrations of relatively large amplitude can easily be set up if the cutter-tooth frequency happens to correspond to a harmonic of the resonant frequency. Torsional vibration in a spindle drive will

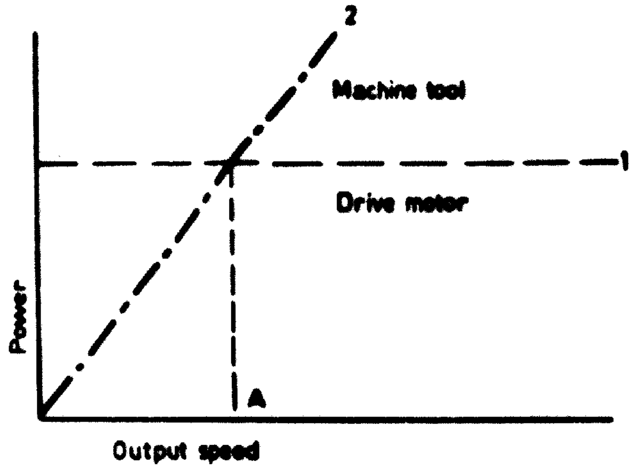


Figure 12

IDEAL POWER SPEED CHARACTERISTIC FOR MACHINE-TOOL DRIVE

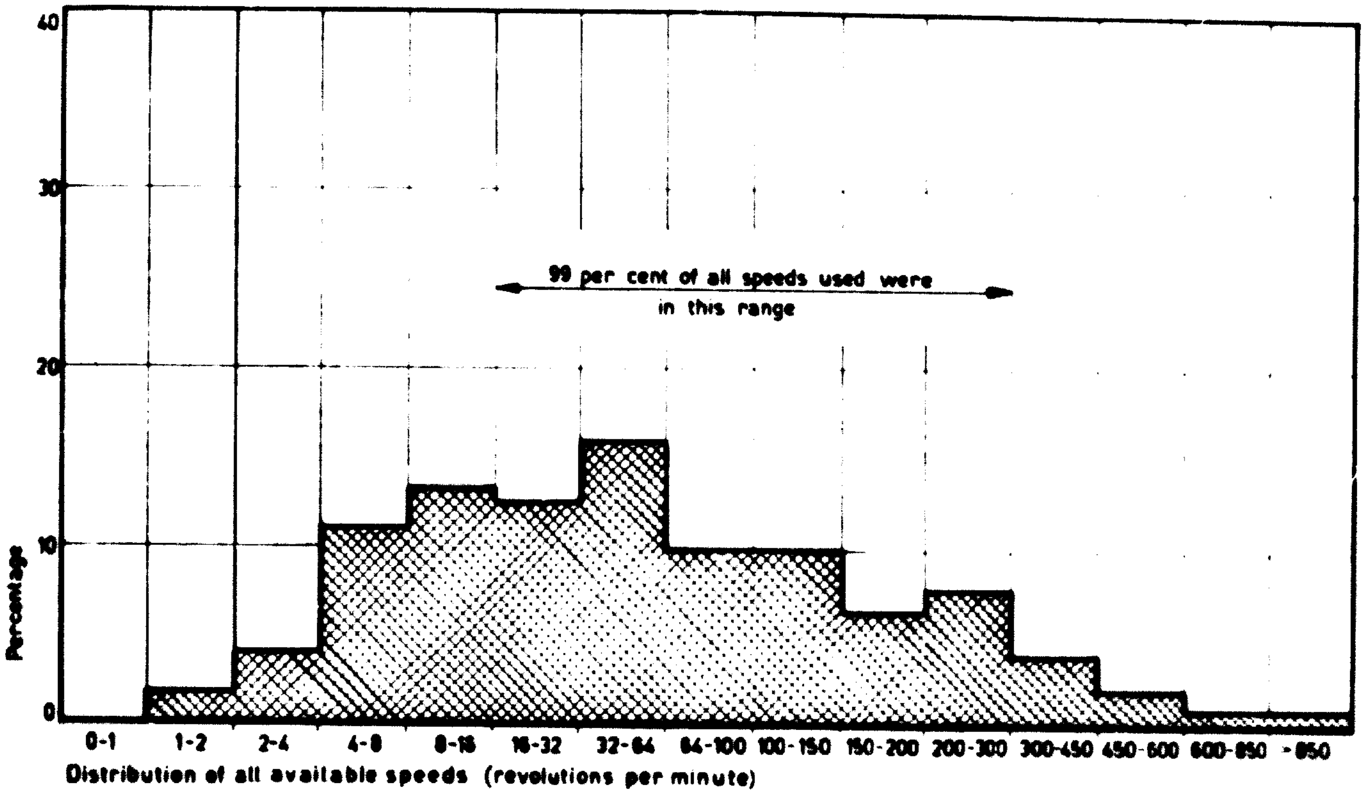


Figure 13

DISTRIBUTION OF AVAILABLE SPINDLE SPEEDS ON A GROUP OF HORIZONTAL BORING MACHINES

cause the cutting speed to vary cyclically, but it may or may not affect the surface finish of the workpiece. It is possible, however, for coupling to occur between torsional vibrations of the drive and vibrations of the machine tool structure. In those circumstances, torsional vibrations can contribute to machine-tool chatter. Knowledge of the torsional characteristics of spindle drives, gear and belt is therefore important to permit the design of drives with the desired characteristics.

These are only a few of the problems concerning the choice of spindle drives and spindle speeds. The full answer requires the development and use of adaptive-control systems which will optimize cutting conditions continuously. The criterion for optimization may be productivity, surface finish or minimum cost. Experimental adaptive-control systems with provision for the continuous measurement of cutting force, tool temperature, tool wear etc., and with a computer which continuously optimizes feeds and speeds, have already been built. Adaptive-control systems of this kind are currently uneconomic for general use, but the time may soon come when they control the operation not only of individual machine tools, but also of complete manufacturing units.

In the meantime, however, there is considerable interest in continuously variable-speed drives for machine tools. Hydraulic motors and direct-current electric motors are often used, and the growing use of silicon-controlled rectifiers for speed control of electric motors should increase the use of continuously variable-speed drives for machine tools. In particular, frequency-changing circuits using silicon-controlled rectifiers should make possible the use of induction motors for a wide range of speeds.

Power-dividing transmissions, in which differential gears are used to extend the range of a small-ratio variable-speed unit (see figure 14) are of interest for machine-tool spindle drives because, depending upon the actual arrangements adopted, almost any desired power speed characteristics can be obtained. In the particular version shown in the figure, the variable-speed unit operates in the usual way in the low-speed range, but at higher speeds only part of the input power flows through the variable-speed unit, the remainder being transmitted by the high-efficiency differential gear. The transition from one stage to the other is effected by means of a two-way clutch operated when there is no speed difference between the output shafts of the two stages.

A. *Feed drives*

The major problem with feed drives is not their power-handling capacity, but the natural frequency of the table drive system. This presents little difficulty on manually operated machine tools, but it can be a source of trouble on numerically controlled machine tools where the speed with which a slide or table can be positioned or made to follow a given path is limited by the band width of the servo-system. If the natural frequency of the table drive system lies within the band-width of the servo-system, errors can arise as a result of the phase changes associated with resonance and in extreme cases, the system can become unstable. If, therefore, numerically controlled

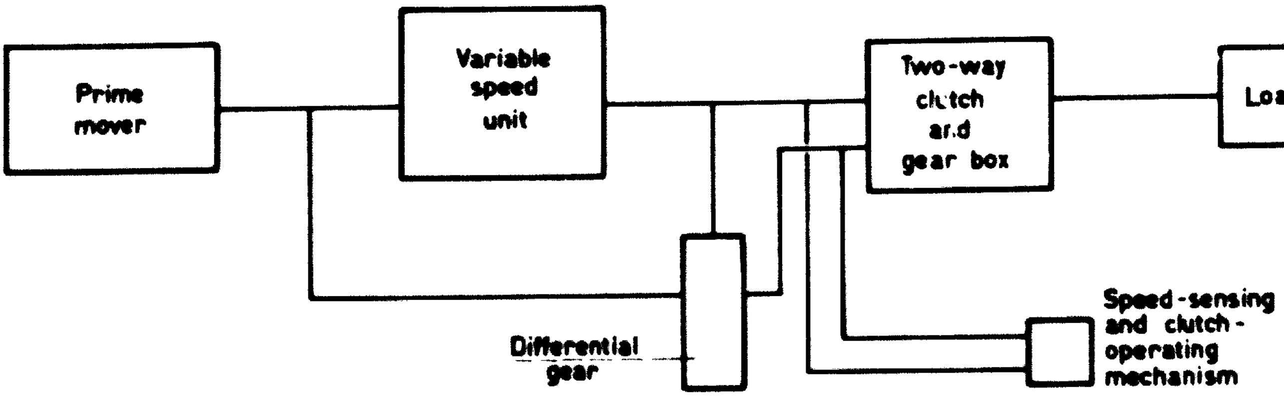


Figure 14

COMBINED SERIES: SHUNT DRIVE

machine tools are to be capable of following or of being positioned at high speed, the natural frequency of the table drive system must be made as high as possible.

In the case of ram drives, the natural frequency is essentially that of the mass of the table and workpiece, together with the spring formed by the column of oil in the ram. Clearly, when the product of the mass and the length of the ram is large, a high natural frequency can be obtained only with a ram of large diameter. The larger the diameter of the ram, however, the greater the required flow of oil into the ram for a given rate of linear movement and, thus, the larger the valve required to control the oil flow. As the diameter of the ram is increased, therefore, a point is reached at which the speed of response of the system is determined by the response time of the valve.

Attempts to overcome this difficulty have included the development of a drive in which a short-stroke ram for rapid, short displacements is combined with a rack-and-pinion drive for larger, slower movements—i.e. a system of two short-stroke rams acting in a step-by-step fashion; a system of short rams acting on a series of inclined planes; and the efflux drive (see figure 15) in which oil supplied under pressure to one of two pairs of pockets produces a force on the slide.

In the case of lead screw drives, the lead screw itself forms the spring and, by increasing the diameter of the lead screw sufficiently, the natural frequency of the table on the lead screw can be made as high as is desired. Although practicable, lead screw drives can be made for greater values of the mass stroke product than is possible with ram drives. There comes a point, however, as the diameter of the lead screw is increased, at which the effective inertia of the lead screw itself exceeds that of the table and workpiece so that the response time tends to be limited by the inertia of the lead screw.

It might be mentioned in passing that it is not only structural resonances within the control loop (such as that of the table and its drive) that restrict the band-width of the servo. Resonances outside the loop, for example, that of a counterbalance weight or, more significantly, of the machine tool and its foundation block on the "springy" soil (which may occur at a frequency as low as 10c/s), must also be considered. The difficulty of raising these resonant frequencies has already been mentioned and alternative methods of permitting greater servo band-width have to be considered. The inclusion of compensating elements and subsidiary control loops allows some increase of band-width without instability in the presence of structural resonances (see figure 16), but more elaborate types of control system are probably required to eliminate this problem entirely.

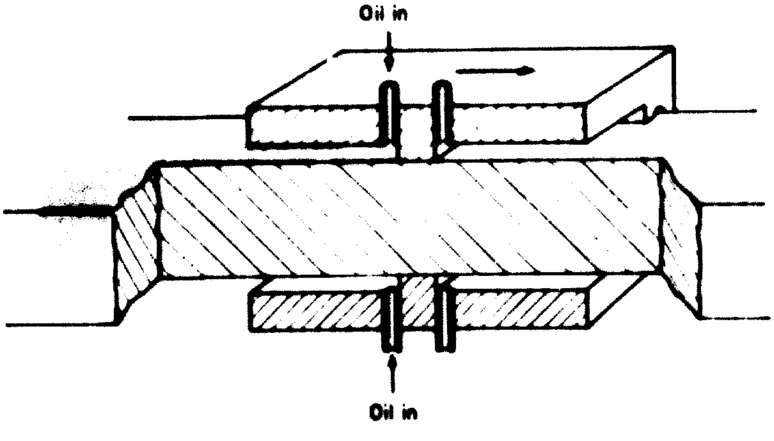


Figure 15

EFFLUX DRIVE

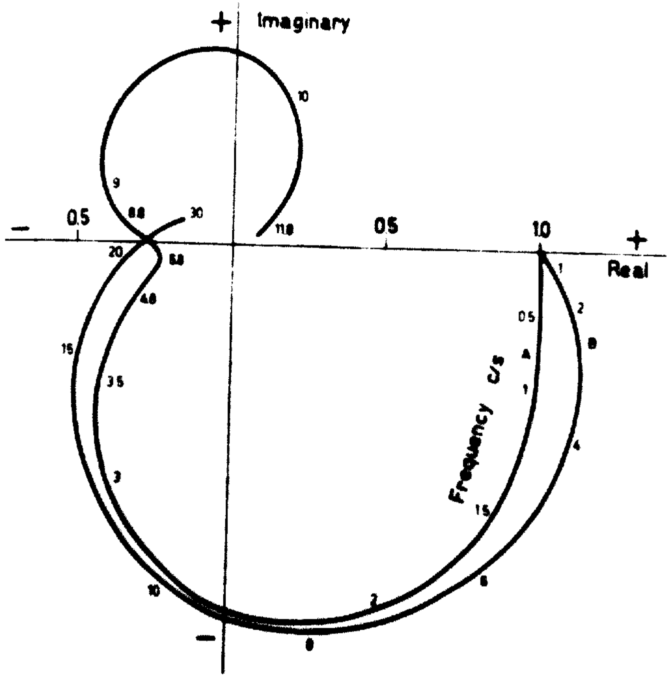


Figure 16

FREQUENCY RESPONSE OF CONTROL LOOP INCLUDING POORLY DAMPED STRUCTURAL RESONANCE AT 10c/s

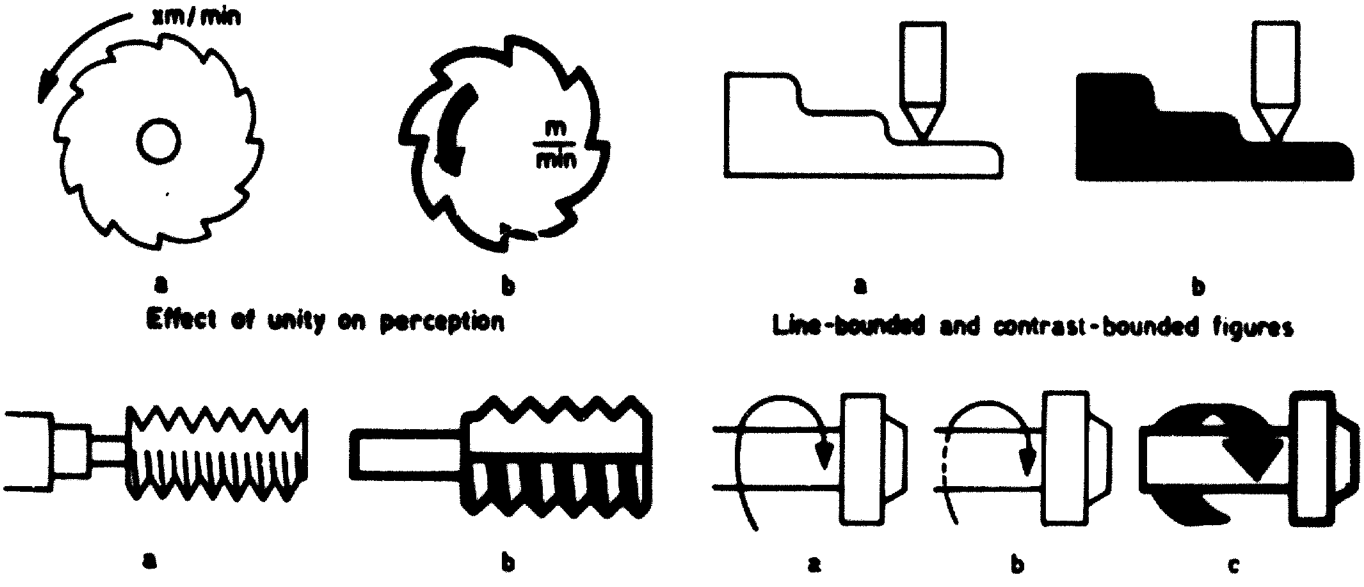
A high natural frequency is not, of course, the only requirement of a feed drive; stiffness, absence of backlash and low friction are important also. For lead screw drives, the recirculating ball nut has proved a useful way of meeting these requirements, which are particularly important on numerically controlled machine tools. However, backlash can be eliminated only by increasing the pre-load and thereby, at the same time, increasing frictional resistance. The answer would seem to lie in the application of hydrostatic lubrication to lead screw nut. A film of oil under pressure between the mating surfaces of lead screw and nut virtually eliminates friction and, properly designed, is stiff and exhibits no backlash. Design data are available, but the problem of manufacturing the nut to the tolerances required still presents difficulties.

V. ERGONOMICS

Even numerically controlled machine tools have to be set up manually, although, of course, the extent to which the operator participates in the operation of the machine is very much greater in the case of manually operated machine tools. Aspects of the design of machine tools to which the science of man-machine relationships ergonomics—can contribute include the positioning, shape and characteristics of control levers and knobs, the design of control panels, the design of scales and scale readers and the layout of legend plates and the design of symbols (see figure 17). Figure 18 shows the difference, in terms of the speed of operation and the ease of learning, between a conventional legend plate and a plate designed for the same purpose but based on ergonomic principles.

VI. THE UTILIZATION OF MACHINE TOOLS

Although research to provide designers with the data they need for the layout of machine tools and for the design of structures, mechanisms and control systems is undoubtedly important, the design of a machine tool really begins one stage farther back. It is first necessary to know what function the machine tool is required to perform. For special-purpose machine tools, such as those incorporated in transfer lines, the question is relatively easy to answer (although even with this kind of machine tool it is not always clear just what feeds and



a b
Effect of unity on perception

a b
Line-bounded and contrast-bounded figures

a b
Effect of simplicity on perception

a b c
Effect of figure on perceptual stability

Figure 17

PRINCIPLES UNDERLYING THE DESIGN OF SYMBOLS FOR MACHINE TOOLS

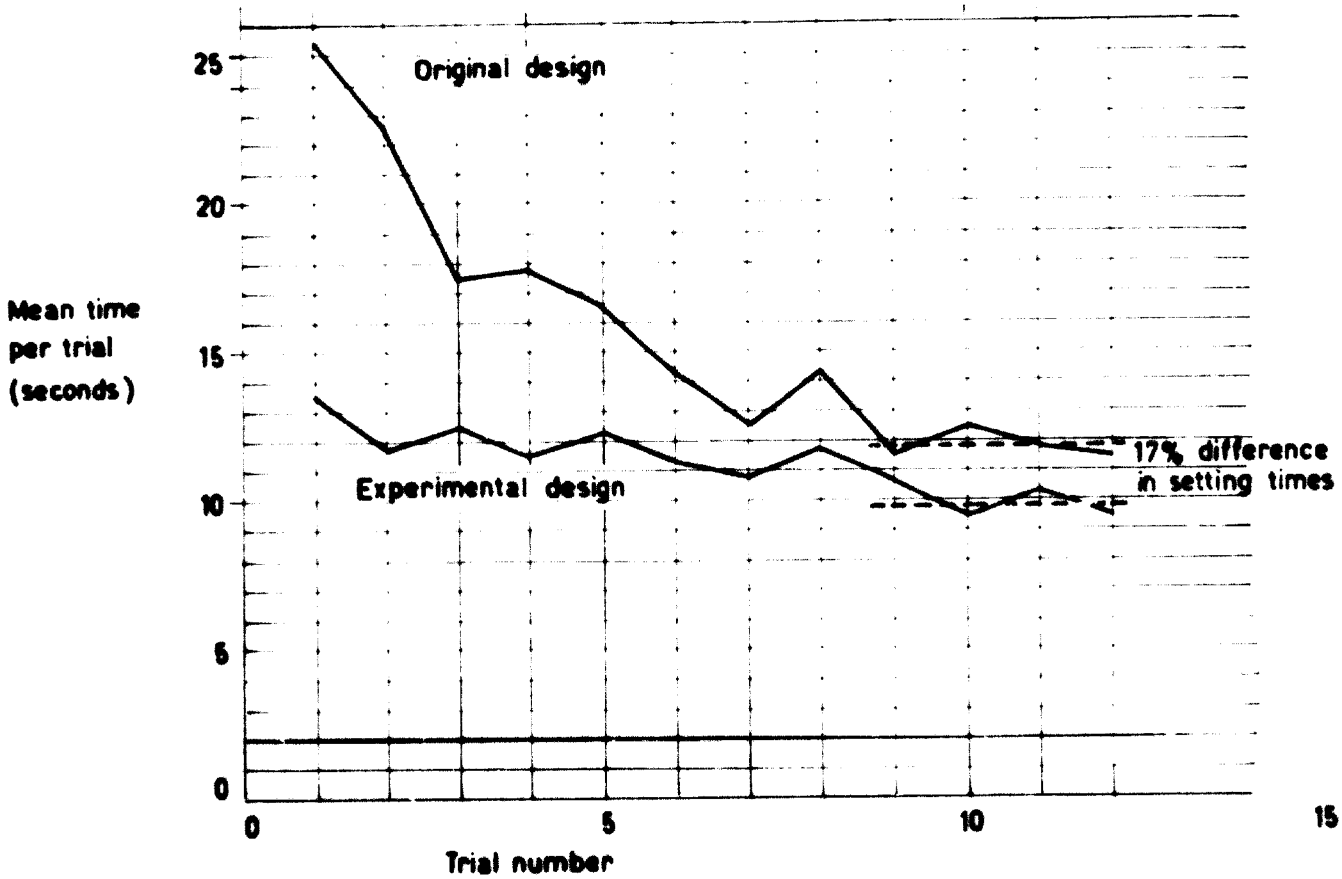


Figure 18

TIME REQUIRED FOR SETTING UP A LATHE GEAR-BOX, USING TWO DIFFERENT DESIGNS OF LEGEND PLATES

speeds will be required). But general-purpose machine tools are used for such a wide variety of work that they have to be designed so that all the facilities that users may require can be incorporated. There is, however, a growing body of evidence that general-purpose machine tools are ill-matched to the purposes for which they are used. Figure 19, for example, compares the facilities available on a large number of machine tools in a number of workshops with those actually used. It is probable from these and many similar results that if machine tools could be properly matched to the real requirements of users, the equivalent capital value of the plant required for machining (taking account of the reduction in complexity and size of the machine tools, of the reduced workshop area and of the reduced costs of heating etc.) could be reduced by about 30 per cent. In the United Kingdom alone, the sum involved would be more than £250,000. In practice, of course, not all of this saving could be realized, but even a 5 per cent saving would be well worth while.

This problem, like so many others, requires full co-operation between users and makers of machine tools. Users should analyse their requirements carefully, on the basis of studies of the actual components to be manufactured, and should not over-specify their requirements. It might then be possible for machine-tool makers, knowing that all the facilities ordered would actually be required, to produce a small range of standard machines which would meet most requirements, so that the current need for extra equipment on nearly all machines could be greatly reduced. The problem requires research into the pattern of shapes and sizes of components and study of the way in which they should be manufactured, i.e. into the optimum machining conditions. Such studies could also lead to even greater standardization through the introduction of machining on the family-group system, whereby different components of essentially similar shapes are machined together. The fact that components can thus be machined in larger batches greatly facilitates their manufacture.

Studies of the way in which machine tools are actually used can also point to other ways of increasing their effectiveness. For example, figure 20 suggests that the provision of better measuring and handling facilities could greatly increase the utilization of centre lathes.

Any work on the economics of metalworking processes must obviously include studies of the use of numerical control and similar automatic systems. Although the greatly increased capital cost of numerically controlled machine tools can be justified when they are properly used, the techniques currently available for deciding when the capital expenditure would be justified are often inadequate. Research for the machine-tool industry must, therefore, include studies of the economics of manufacture and must include co-operation with management and accountants.

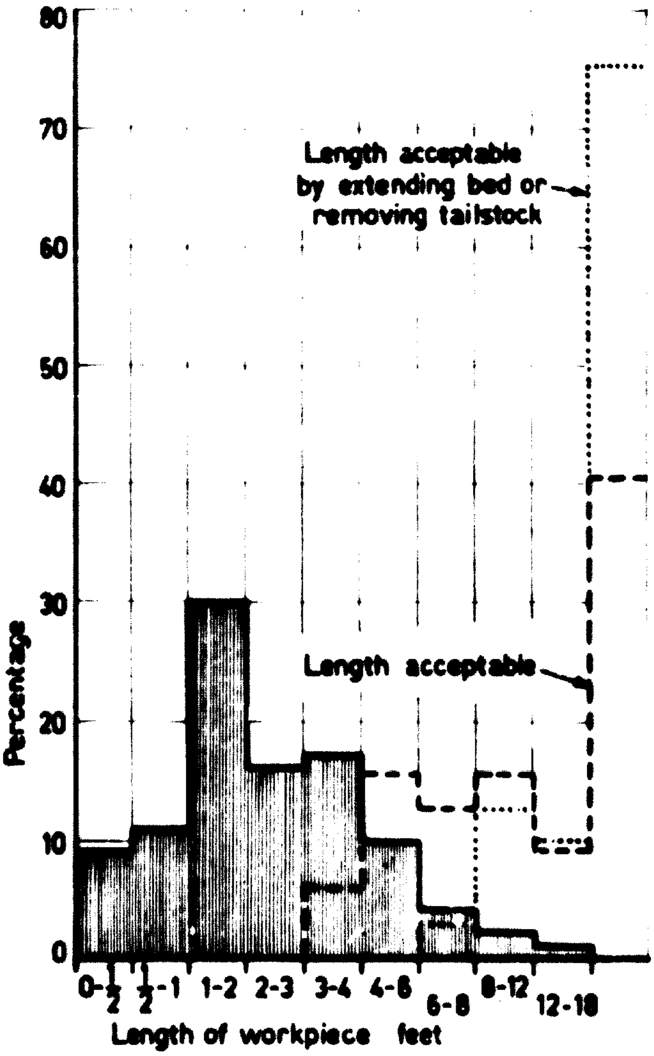


Figure 19

HORIZONTAL BORING MACHINES: COMPARISON OF ACTUAL LENGTHS OF WORKPIECES WITH THOSE ACCEPTABLE

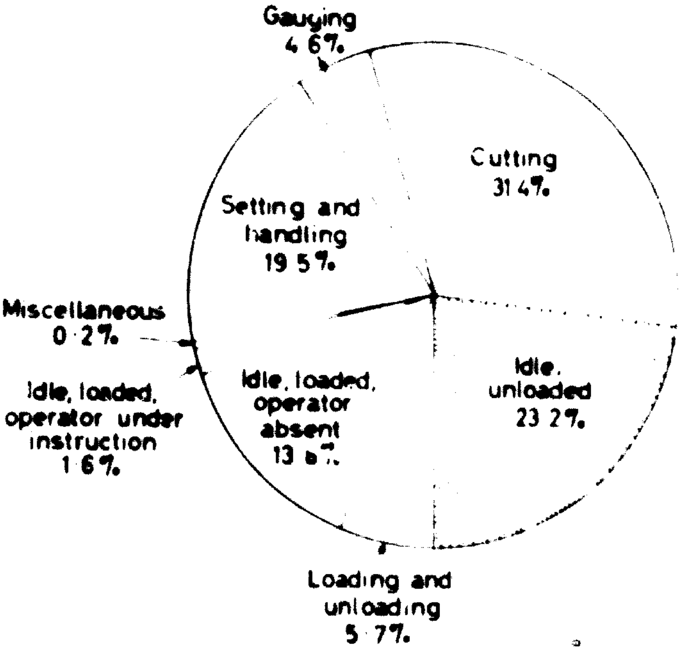


Figure 20

CENTRE LATHES: PROPORTION OF TIME SPENT IN DIFFERENT OPERATIONS (PERCENTAGE)

VII. AUTOMATIC CONTROL

In order to increase productivity faster than the rate at which the amount of skilled labour available will increase and in order to make the best use of skilled labour of all kinds, there must be greatly increased use in future of automatic controls of all kinds. Although, in the context of machine tools, automatic control is coming increasingly to mean numerical control, it must be realized that numerical control, as it is currently understood, is neither the beginning nor the end of automatic control of machine tools. Mechanically operated automatic machine tools and auxiliary equipment have been used for many years, and such recent developments as static switching, electric, hydraulic and pneumatic logic units etc. have greatly increased their flexibility. The current trend is exemplified by the programme-sequence controlled lathes of the capstan and automatic type, although essentially similar, but simpler, systems are in use on transfer lines, conveyor systems and on other machine tools. Information about the operations to be carried out and the sequence in which they are to be performed is fed to the control system by punched paper tape or punch cards, or by setting up electrical connexions by switches or plugs. Switches on the machine signal the completion of each operation, and the resulting electrical signals from the input system and the machine are interpreted by the logic units which control the operation of the machine. Control systems of this kind were originally based on electromagnetic units, but continuing research has led to the emergence of systems based on cold-cathode tubes, solid-state semi-conductor devices and, more recently, fluid-logic elements of hydraulic or pneumatic nature.

Programme-sequence control systems differ from numerical-control systems in that they select only discrete functions — particular feeds, speeds or tools; they do not control the dimensions of the workpiece, which are determined in the usual way by fixed stops on the machine. With numerical-control systems, however, the dimensions of the workpiece are determined by numerical information fed to the machine together with the required process information, the position of the moving parts of the machine tool being measured continuously by suitable transducers. Research for numerically controlled machine tools can be considered under three headings.

A. *Control systems*

In addition to the development and improvement of transducers — optical gratings, inductosyns and resolvers, digitizers etc., there is scope for the development of control systems with improved characteristics in respect of ease of programming. The problem of improving following speeds and response times has already been mentioned.

B. *Mechanical design*

The absence of a human operator to make correcting adjustments imposes special design requirements on numerically controlled machine tools. Most of these—high stiffness, low friction etc.—have already been mentioned and it is worth noting that many of the design features that have been developed to meet those special needs (hydrostatic slideways, recirculating-ball lead screws etc.) have also been incorporated in conventional machine tools. In general, too, there is a higher degree of reproducibility of numerically controlled machine tools and this also involves greater care in design. Satisfactory results can be assured currently only by more or less individual fitting of the control system to the machine tool. It should, however, ultimately become possible to make both machine tools and control systems to specifications which will ensure their mutual compatibility. Accuracy, inertias, natural frequencies and frictional characteristics of the machine-tool structure could be specified and controlled to agreed limits. At the same time, the accuracy of measuring transducers, the gain and phase characteristics of the control loop and other features of the control system could also be specified. It should then be possible to ensure that any control system meeting the specification would function satisfactorily on any machine tool which also met the appropriate specification. Much research is needed, however, before this desirable end can be achieved.

The possibility of using an automatic-control system to correct errors in straightness or alignment has already been mentioned. In a rather similar way, the use of in-process measuring systems for actual measurement and control of workpiece dimensions during machining is now being developed. At the current time, deflections of the machine tool or workpiece during machining are outside the feedback control loop and cannot, therefore, be corrected. Good mechanical design of the machine tool and care in setting up the workpiece can minimize, but cannot eliminate, these errors. Particularly when high standards of accuracy are required, therefore, there is a need for in-process measurement of actual workpiece dimensions.

C. *Part programming*

The problems of part programming—the preparation of instructions for numerically controlled machine tools—are too complex to discuss at length here, but the facility with which machining instructions can be programmed will influence very considerably the extent to which numerically controlled machine tools are used.

In some parts of the world at least, numerical control is now well-established, and although its future development requires research into programming languages and techniques and also into the way in which numerically controlled machine tools should be used, the improvement of the machine tools themselves probably depends more upon machine development than upon research. Likely directions for the future development of numerically controlled machine tools include:

(*a*) The development of multiple-axis machines and suitable programming languages and techniques to facilitate their use for die-sinking and similar operations;

(*b*) The development of photogrammetry as a means of supplying to the machine tool the information about a prototype component;

(*c*) Extension of programme-sequence controlled machine tools to full numerical control, the development of simplified systems for straight-line machining and the development of systems to permit one numerical-control system to operate a number of machine tools;

(*d*) Combination of numerical control with electro-erosion or electro-chemical machining for dealing with difficult-to-machine alloys.

There are, however, other types of automatic-control systems demanding the attention of the scientists and engineers in machine-tool research. At the current time, cutting conditions, such as feeds and speeds on numerically controlled machine tools, have to be determined in advance. They must, therefore, be chosen conservatively and unless the programme is intended for one machine tool only, they must take account of any variations which may exist between machine tools. With a manually operated machine tool, on the other hand, the operator can, if necessary, make continual adjustments to ensure accuracy, surface finish or maximum productivity. There is, however, no reason why the machine tool itself should not perform the same function and, by occasional or continuous monitoring of its performance, keep itself adjusted in the optimum manner. This is adaptive control which, in its most complete form, involves the continual making of small variations in one or more of the quantities to be controlled, noting the result on the chosen criterion—surface finish, productivity etc.—and continually optimizing the values of the controlled quantities (see figure 21). Systems of this kind could be applied to individual machine tools in order to minimize costs or to maintain accuracy or surface finish; they could also be applied to control an entire workshop or manufacturing process. Adaptive control can be considered quite independently of numerical control but the fact that, with a numerically controlled machine tool, the exact state of the machining operation is known at any instant greatly facilitates the application of adaptive control.

Simpler forms of adaptive-control systems are also possible and have already been applied to some machine tools. One of the simplest merely involves measuring the machined dimension and then making, automatically, a second operation to correct any error that may be detected. Such a system could, until systems of in-process measurement have been fully developed, be applied with advantage to the machining of workpieces which deflect appreciably under the cutting forces imposed on them. Adaptive-control systems could also be used to ensure that the feeds and speeds used for machining are correctly chosen to optimize productivity or surface finish. As with in-process measurement, however, the successful application of adaptive control requires the development of measuring techniques for the continuous measurement of workpiece dimensions, surface finish, cutting forces, tool wear etc.

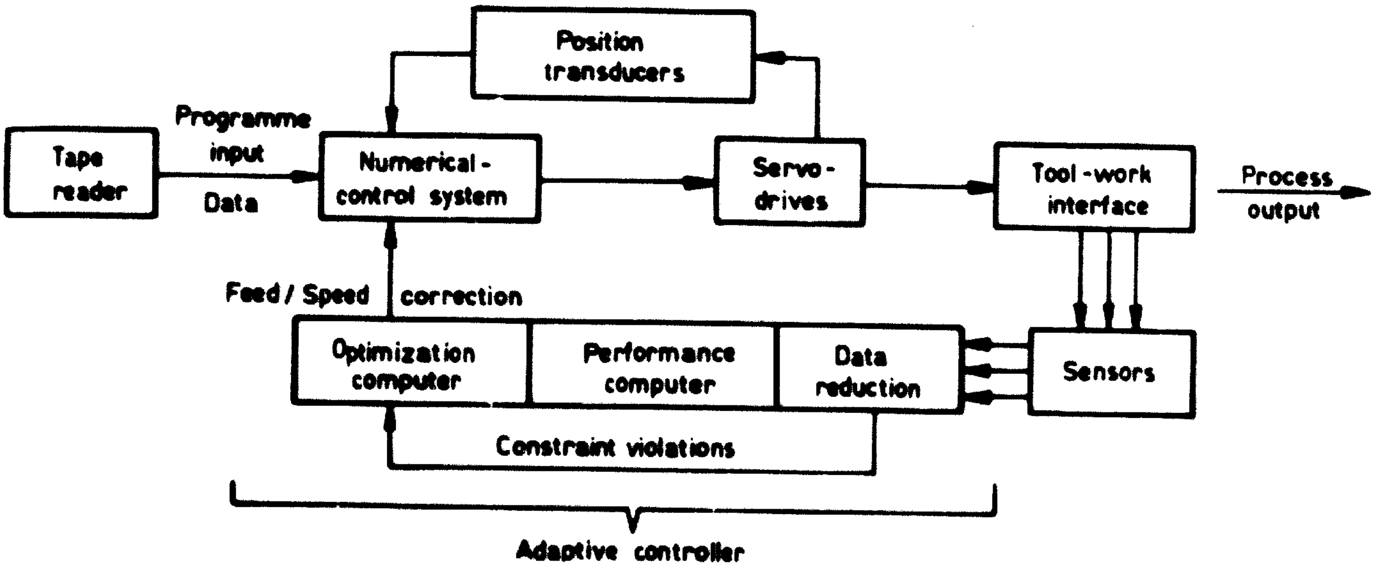


Figure 21

ADAPTIVE CONTROL SYSTEM

The use of computers and other numerical aids to engineering design, although not a problem peculiar to the machine-tool industry, is, nevertheless, closely associated with the use of numerically controlled machine tools. Examples have already been given of ways in which computers have been and can be used by or for the machine tool designer, but there remain many directions in which further research into their application is required. Numerically controlled drawing machines and computer-aided design systems of the "sketch-pad" type (in which the designer is in full and continuous communication with a computer *via* an electronic sketch-pad) represent the two extremes and there are many intermediate possibilities.

VII. MANUFACTURING PROCESSES

Although a distinction can always be drawn between the machine tool and the tool which actually changes the shape of the workpiece, it will be clear that the design of a machine tool must be considerably influenced by the characteristics of the cutting tools with which it will be used. The study of metalworking processes of all kinds must, therefore, be considered when discussing research for the machine tool.

There is a long history of research into the mechanism of metal-cutting and the subject was being studied long before research, as distinct from development, was begun on machine tools. In the course of this work, much has been learned about the mechanism of chip formation and tool wear although practical machining has benefited very little from it, the considerable advances in metal cutting that have been made during the last years—increased speeds, improved cutting-tool materials and design, better cutting fluids etc.—having been made on a mainly empirical basis. Although work on cutting forces, tool temperatures, frictional phenomena and deformation processes in the cutting zone still continues in many centres, it now seems unlikely that work on the current lines will contribute significantly to the development of metalworking processes, and a new and more fruitful approach is urgently needed.

Measurements of cutting forces under steady conditions have provided a picture of the effects of tool geometry, cutting speed etc. on the forces required in various machining processes, and this provides a basis for the mechanical specification of a machine tool. The dynamic characteristics of the cutting process, as affected by cutting speed, depth of cut, tool geometry etc. are just as important as the dynamic characteristics of the machine-tool structure in determining the performance of the machine tool. Relatively little detailed information is available, however, about cutting forces under the more usual non-steady conditions, i.e. when the chip thickness is varying continuously either because of the geometry of the workpiece itself or because the machine tool is vibrating.

But even if basic research in metal cutting seems unlikely to produce useful results, there is considerable scope for making better use of the large amount of empirical data that now exist on cutting forces and conditions. Not only are the optimum feeds, speeds and depths of cut for different machining operations and materials rarely used because of lack of information or lack of attention to the economics of machining, but considerable experimenting with tool geometry is often required, even when machining conventional materials, before acceptable conditions can be obtained. And with the increasing use of harder and tougher alloys the problem is continually increasing.

The pioneer work of Taylor on wear of cutting tools led to the development of a relationship between speed and tool wear which, although still not fully understood, has proved very useful and could, with advantage, be more widely used for determining optimum machining conditions—feeds, speeds etc. More recently, work on the physical and chemical reactions in the high-temperature region near the tool-point and on the effect of inclusions in the workpiece materials, has suggested the possibility of considerable improvements in tool life.

Perhaps not surprisingly, still less is known about the mechanism of the grinding process although recent work has made significant contributions. As with metal-cutting, however, grinding processes (including lapping and honing) have been developed empirically and recent developments high-speed grinding and the use of grinding for stock removal (abrasive machining) have been made in the same way.

Of metal-forming processes, forging is perhaps the oldest, but it has recently been shown that greatly improved results can often be obtained by forcing the metal to deform rapidly. Under these conditions, plastic deformation takes place simultaneously in most regions of the workpiece and cracks are less likely to develop than when the deformation takes place slowly. High-energy forging is, therefore, a possible method of making components that could not be successfully forged in the normal way. Extrusion processes (forward, backward or combined) have long been used for shaping light-alloy parts, but, recently, extensive research has permitted the process to be used to produce steel components also.

The advantages of forming as opposed to machining are: (*a*) less wastage of material as swarf, chips etc.; (*b*) reduced production time; and (*c*) better mechanical properties as a result of the way the material has flowed during forming (see figure 22).

Of course, not all components can be produced by forming, but if the problems of die life could be solved and more was known of the economics of the processes, it seems likely that many components now produced by machining could be made by a forming process. An even more recent development is the use of investment casting for producing components in steels and other metals. Cast components usually require even less finish-machining then do formed components; and, of course, both processes produce components with much less wastage of material than is involved in machining. As yet, however, neither process is used on a really large scale and there are many technical problems to be solved before this is possible. But even more important, perhaps, is the need for studies of the economics of these and other manufacturing processes to establish the conditions in which each should be used.

There is an increasing trend towards the wider use of materials which are tougher and harder than the conventional mild steels and non-ferrous alloys, and which retain their hardness and toughness at high temperatures. All conventional metal-cutting, grinding, forming, forging etc. processes rely essentially on plastic deformation of the workpiece material caused by pressure against a harder tool. The harder the workpiece material, the more difficult it becomes to find tools that will behave satisfactorily. These new materials are, therefore, difficult to machine by conventional methods and it is not possible to cut them at the rates which were possible with the materials that they have replaced (see figure 23). The search has begun for new methods of machining and particularly for methods that are independent of the hardness or toughness of the workpiece material.

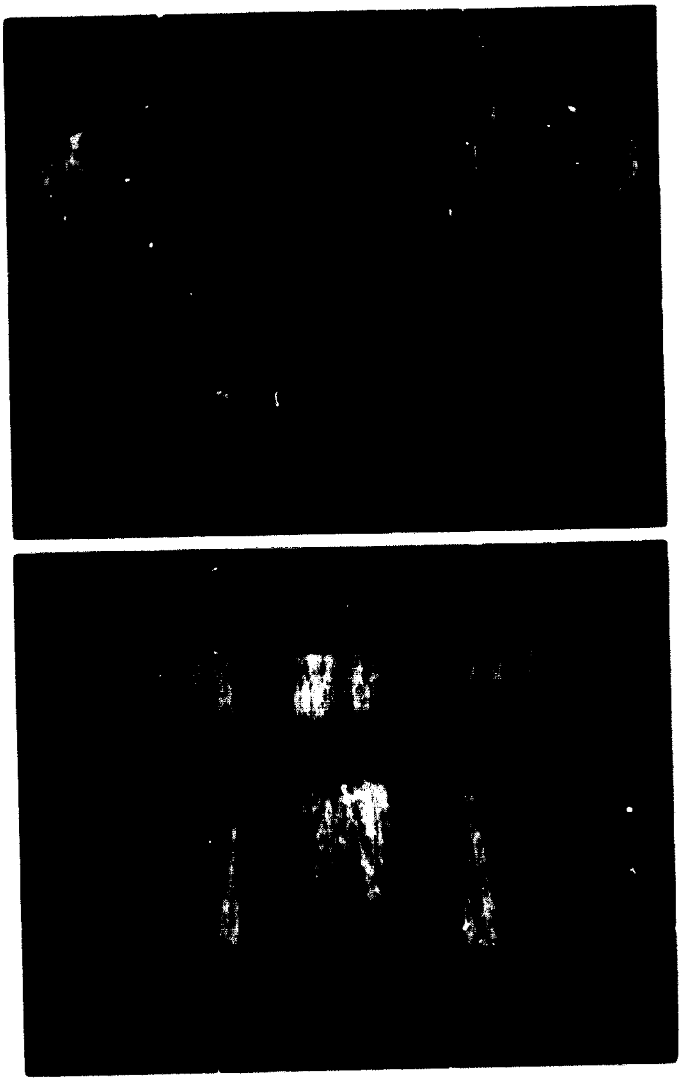


Figure 22

GRAIN STRUCTURE IN COMPONENTS PRODUCED BY TURNING AND BY FORMING

The traditional way of machining hard materials is, of course, to use an abrasive process since the form of the tool used in such processes permits much greater wear rates to be tolerated without loss of accuracy. Special abrasive methods have also been developed for making fine cuts in very hard and brittle materials, particularly glass and semi-conductors. These include:

(*a*) Abrasive jet machining in which a fine high-velocity jet of air carries fine abrasive particles which, on impinging on the workpiece, cause material to be removed;

(*b*) Ultrasonic machining in which a shaped tool is vibrated rapidly against the surface of the workpiece, a slurry of fine abrasive particles flowing between the tool and the workpiece. The impact of the tool causes small particles to be chipped off the workpiece.

Even abrasive machining, however, is much slower with harder materials and the high rate of tool wear limits its application. The newer methods of machining that are now being developed avoid this difficulty by

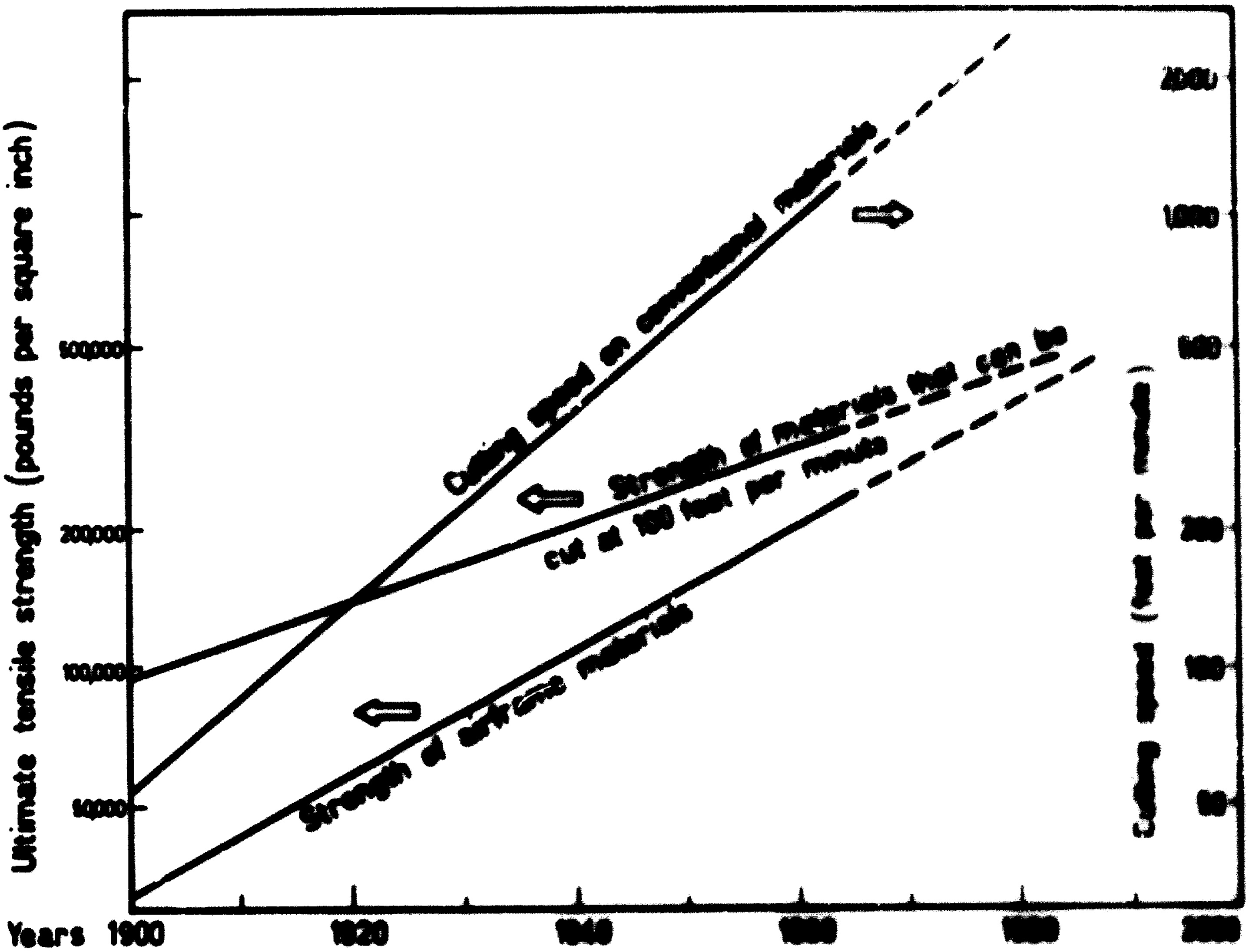


Figure 23

DEVELOPMENT OF NEW MATERIALS LEADING TO SLOWING DOWN OF RATE OF METALWORKING

NEW METHODS OF MACHINING

	Maximum rate of metal removal (cubic inches per minute)	Power consumption (horsepower per cubic inch per minute)	Cutting speed (feet per minute)	Penetration rate (inches per minute)	[illegible]	[illegible]	[illegible]	[illegible]
Turning	100	1	200		[illegible]	[illegible]	[illegible]	[illegible]
Grinding	50	10	10		[illegible]	[illegible]	[illegible]	[illegible]
Plasma jet	10	20	90	10	[illegible]	[illegible]	[illegible]	[illegible]
Spark-erosion	0.5	40		0.5	[illegible]	[illegible]	[illegible]	[illegible]
Electrochemical	1	160		0.5	[illegible]	[illegible]	[illegible]	[illegible]
Ultrasonic	0.05	200		0.02	[illegible]	[illegible]	[illegible]	[illegible]
Electron beam	0.0005	10,000	200	6	[illegible]	[illegible]	[illegible]	[illegible]
Laser	0.0003	60,000		4	[illegible]	[illegible]	[illegible]	[illegible]

[a] Source only.

relying on quite different processes for shaping the workpiece. Two main processes are involved—chemical processes, in which the material of the workpiece is removed atom by atom by chemical action; and thermal processes, in which the material of the workpiece is melted and vaporized. A summary of the characteristics of the principal methods available is given in the table on page 541.

A. *Thermal methods*

Thermal processes depend essentially upon achieving a high concentration of energy on a small area of the workpiece so that the temperature of a small volume of the material is raised sufficiently high for that small volume to be melted and vaporized while leaving the remainder of the workpiece relatively unaffected. Power densities in the range 10^4–10^{12} watt cm^{-2} can be achieved. (A power density of 10^{12} watt cm^{-2} is equivalent to putting the output of several large power-stations through an area of 1 square centimetre.) Even though these power densities are achieved for only a small fraction of a second, the local temperature of the workpiece is thereby raised to 10–20,000 K. The main forms in which thermal methods of machining are practised are:

1. Plasma torch

The use of an oxygen-hydrocarbon flame for metal cutting is not new, but the development of plasma torches, in which the temperature of the flame is increased by electrical energy, has greatly extended the applicability of the technique. Materials which could not be cut economically with conventional flames can now be cut and, furthermore, the increased power densities obtainable with plasma torches permit rough turning and gouging operations to be carried out also. The accuracy currently obtainable is not high, but it can be expected to increase.

2. *Electro-erosion*

Electro-erosion is currently the most widely used of the new methods of machining. The energy necessary to raise the local temperature of the workpiece is supplied electrically by passing electric sparks or arcs through a dielectric fluid between a shaped tool and the workpiece. Material is removed from both anode and cathode but, for reasons which are not yet fully understood, it is possible to arrange for most of the material to be removed from one or other, and thus to arrange for a cavity complementary to the shape of the tool to be formed in the workpiece (see figure 24). Although each pulse of current may produce only one spark and, therefore, remove metal from one small region to the workpiece only, succeeding sparks will pass at other parts of the workpiece. A typical pulse rate is 400–200,000 c/s, so that over a period of a few minutes, metal is removed more or less uniformly from all parts of the workpiece close to the tool. As machining proceeds the tool is fed towards the workpiece, the distance of closest approach being maintained at about 0.01 mm, so that eventually material is being removed over the whole area of the workpiece exposed to the tool.

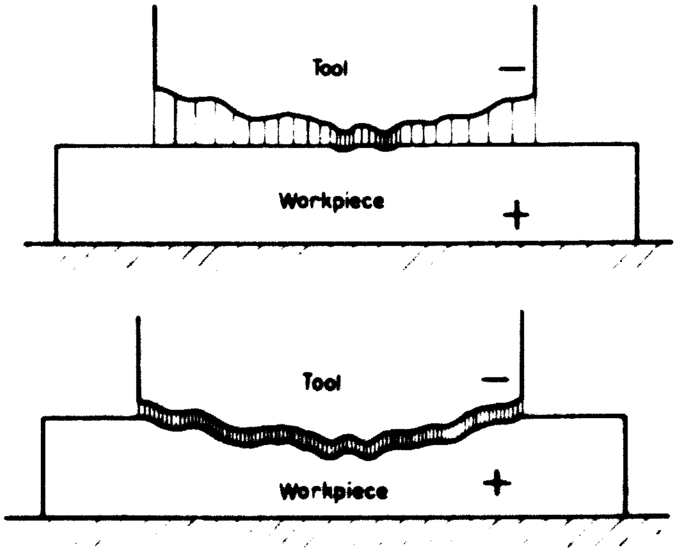


Figure 24

CAVITY FORMATION BY ELECTROCHEMICAL AND ELECTRO-EROSION MACHINING

Problems requiring solution are:

(*a*) A full understanding of the mechanisms of electro-erosion;

(*b*) Choice of tool material for minimum wear;

(*c*) Choice of circuit conditions—amplitude, shape and frequency of current pulses—for optimum metal-removal rate and tool wear;

(*d*) Reduction of damage to the workpiece surface and improvement of surface finish;

(*e*) Development of scanning systems, perhaps with numerical control, for generating three-dimensional cavities with a small electrode.

3. *Electron beams*

The energy of a beam of high-velocity electrons is converted into heat when they impinge on a solid target and, since the beam can be focused on to a very small spot (diameter less than 5μ), very high power densities can be obtained. The position of the beam can be controlled electrically by means of deflecting coils so that fine intricate shapes can be machined automatically by suitably deflecting the beam.

The advantages of electron-beam machining are that fine intricate cuts can even be made in materials like evaporated metal films which are less than 250 Å thick. The disadvantages are that the workpiece must, at the current time, be enclosed within the vacuum of the electron-beam tube and the fact that the relatively high capital cost and the limited power available make the method unsuitable for bulk removal of metal.

An electron-beam machine for machining purposes may have a total beam power of only a few hundred watts, but much larger machines, with powers up to 10^4 watts, are used for welding. Very clean, reliable narrow welds can be made in material up to 10 cm thick, including materials which are difficult to weld in the normal way. Although it is usually necessary to enclose the workpiece within a vacuum chamber, even this is unnecessary on the latest machines.

4. *Lasers*

The characteristics of the light emitted by lasers are such that it can be focused on to a spot of very small diameter and, as high-energy pulses of short duration can be produced, very high power densities can be obtained on small areas for short periods of time. As with an electron beam, machining to the desired shape is achieved by moving the focused beam in relation to the workpiece.

Current applications of lasers for machining are rather similar to those of electron beams, the main differences being that with a laser the workpiece does not need to be in a vacuum chamber and that the position of the electron beam can be controlled electrically. Progress in the development of lasers is, however, so rapid that it is difficult even to speculate on the future of laser machining techniques. Until very recently, the necessary high-output energies could be obtained only by the use of "giant-pulse" techniques with solid-state lasers, the mean output power being limited mainly by the low efficiency of the laser. The recent development of high-output gas lasers of high efficiency have materially changed the picture, but as yet little information is available on the machining capabilities of this type of laser.

B. *Chemical methods*

Chemical methods of metal removal have been practised for a long time, e.g., pickling of metal sheets, but chemical etching (sometimes called chemical milling) has recently been developed as a selective metal-removal process for reducing weight or for producing complex shapes in thin materials. Regions where chemical attack is not desired are protected by a suitable coating, which may be applied only where it is required, or applied overall and then selectively removed by manual or photo-exposure techniques to expose the appropriate regions of the sheet.

Electrolytic action as a means of removing metal was first proposed more than thirty years ago and was developed at about that time for removing asperities and thus producing a flat polished surface — electropolishing. It has since been applied to assist the removal of metal in grinding and honing, and also for bulk metal-removal. The rate at which metal is removed by electrolytic processes is independent of the hardness or other physical properties of the workpiece and depends only, according to Faraday's laws, upon its chemical composition and the quantity of electricity passed. For the most usual workpiece materials, the rate at which metal is removed is about 1 mm^3 per minute per ampere of current flowing.

In electrolytic honing, the normal mechanical honing action (which, by virtue of the rotating and reciprocating motions involved, is intermittent on any portion of the workpiece) is augmented by electrolytic action on those portions of the workpiece not in contact with the abrasive stones. If desired, the final cuts can be purely mechanical to give the characteristic honed surface. In electrolytic grinding, however, the electrolytic action takes place parallel with and at the same time as the normal grinding action. An electrically conducting grinding-wheel is used, current being passed from the wheel as cathode to the workpiece as anode.

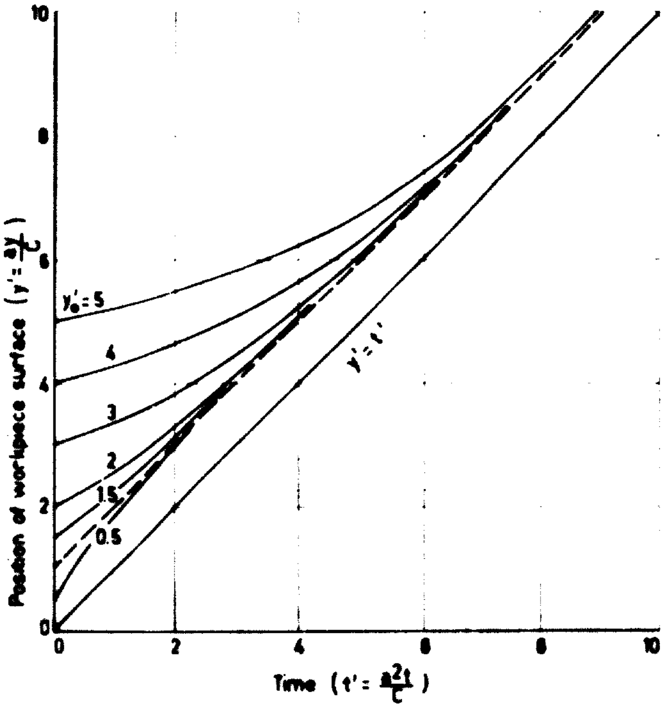
In both processes, electrolyte — usually a salt solution — is fed to the gap between anode and cathode, which is maintained at the desired value either by control of the surface of the grinding wheel (the amount by which abrasive particles protrude above the conducting matrix, or, in the case of graphite-bonded wheels, the structure and composition of the wheel), or, in honing, by the position of the electrodes with respect to the surface of the honing stones. In both electrolytic honing and electrolytic grinding, however, most of the metal is removed electrolytically, thus giving increased production rates and less wear of the abrasive, while the geometry of the finished surface is controlled essentially by the mechanical dimensions and characteristics of the abrasive stones or wheels. Electrolytic action can also be used to augment ultrasonic machining in a similar way.

In electrochemical machining proper, however, all the metal is removed electrolytically. Current passed through an electrolyte between a shaped tool and a workpiece will concentrate in the region of closest approach (see figure 24) so that, in time, the surface of the workpiece will become approximately complementary to that of the tool. The distance of closest approach is kept approximately constant, either by actual control of the gap or by keeping constant the potential applied across it. In these latter circumstances, the gap tends to a constant value, any deviation leading to an increase or decrease in current, which quickly restores the gap to the equilibrium value (see figure 25). If conditions (electrolyte, tool material) are properly chosen, there need be no wear of the tool.

Some of the possible ways of applying electrochemical machining are shown in figure 26. Most of the current applications are for shaping or deep-hole drilling operations on gas-turbine blades. The process is, however, also being used for a wide variety of miscellaneous applications, again mostly with high-temperature alloys, and there would seem to be some scope for a numerically controlled electrochemical cavity-sinking machine for machining complex shapes in tough materials.

To summarize, the new methods of machining that seem to offer most promise for the future are electrochemical machining and the use of lasers. As far as lasers are concerned, it is too early to say much about the research that is needed for their application since there is still so much to be done to develop lasers which have the required output powers and which are both cheaper and more efficient than those currently available. But it is possible to discuss briefly the research problems associated with electrochemical machining:

(a) *Electrochemistry.* Little is known of the nature of electrolytic phenomena when the current densities are as large as those normally used in electrochemical machining (200–300 amp cm^{-2}). More knowledge of the mechanisms involved would help in the solution of all the following problems;



Note: With a constant applied potential and a constant feed rate, the gap between tool and workpiece in electrochemical machining always tends toward the equilibrium value, whatever the initial gap may be. In the units used, the equilibrium gap is 1.

Figure 25

TENDENCY OF GAP BETWEEN TOOL AND WORKPIECE IN ELECTROCHEMICAL MACHINING, WITH A CONSTANT APPLIED POTENTIAL AND A CONSTANT FEED RATE

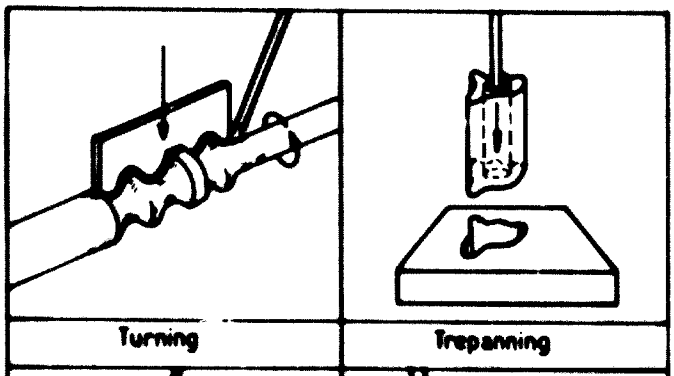


Figure 26

APPLICATIONS OF ELECTROCHEMICAL MACHINING

(b) *Tool design.* Even under ideal conditions, the workpiece shape is not exactly complementary to that of the tool. To produce a given workpiece shape, the required tool shape is that equipotential which, at the appropriate distance from the workpiece, produces a current density which is uniform over the surface of the workpiece. The problems of determining the desired equipotential line, which is probably the most important outstanding problem of electrochemical machining, can be tackled by analogue methods, digitial computation or by trial-and-error methods;

(c) *Gap control.* Closely associated with the problem of tool design is that of control of the size of the gap between tool and workpiece, both having a direct influence on the accuracy of machining. Although control of the potential across the gap will always maintain an equilibrium gap, this remains constant only if the conductivity of the electrolyte does not vary. In practice, changes in the temperature and composition of the electrolyte cause its conductivity to vary, and alternative approaches to the problem of gap control are now being considered. These include direct control and also indirect control by measurement of electrolyte conductivity;

(d) *Electrolyte flow.* In order that it shall continue to be possible to pass large currents through the electrolyte in the narrow (0.05 1 mm) gap between tool and workpiece, the electrolyte in this region must be continually replenished. In practice, this usually means that electrolyte must be made to flow rapidly between the electrodes, and the need for this rapid flow of electrolyte brings several problems:

- (i) Large pressures are required to force the electrolyte through the gap and these produce large forces tending to separate the electrodes. A pressure of 60 N cm^{-2} acting on an area of, say, 100 cm^2 produces a separating force of 6,000 N, and if the machine structure is not stiff, the resultant deflections will, as with conventional machine tools, influence the accuracy of machining by causing the gap between the electrodes to vary;
- (ii) Tools must be designed in such a way that the electrolyte can be pumped through the gap, but also so that the holes necessary for this purpose produce the minimum of interference with the required surface;
- (iii) The Joule heating associated with the passage of electric current through an electrolyte causes the temperature of the electrolyte to rise. The temperature of the electrolyte will increase from inlet to outlet (see figure 27), and the resultant variation in conductivity complicates the problem of tool design;
- (iv) Turbulent flow of the electrolyte is necessary if large currents are to be passed, but persistent eddies tend to cause machining marks on the surface of the workpiece;

(e) *Electrolyte.* Although, in principle, any ionic solution will serve as the electrolyte for electrochemical machining, in practice, the following considerations are involved:

(i) cost;

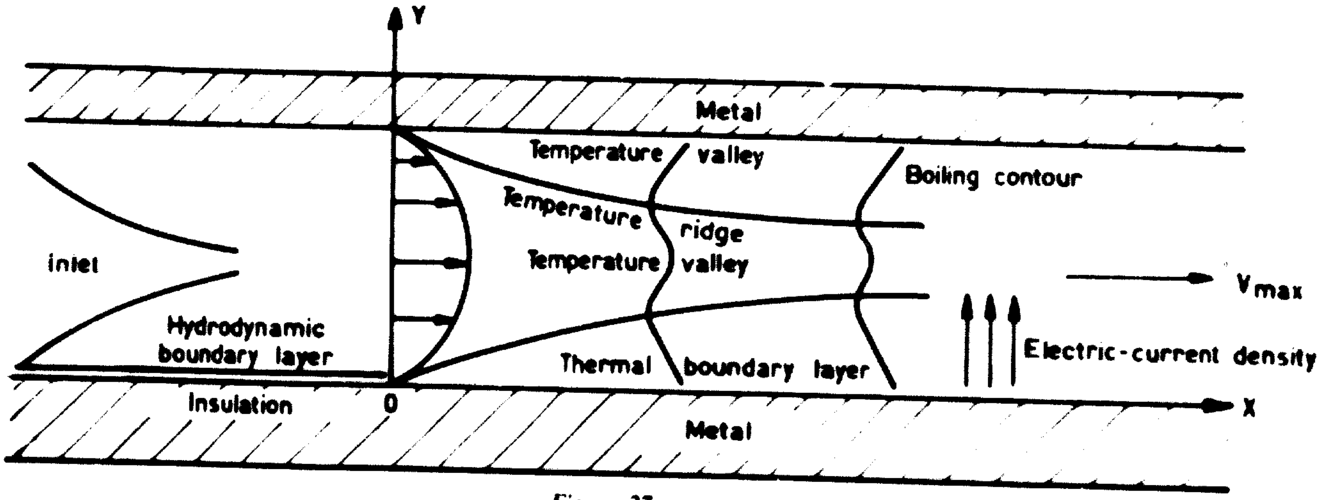


Figure 27

THEORETICAL TEMPERATURE AND FLOW CONDITIONS IN THE GAP BETWEEN TOOL AND WORKPIECE

(ii) Conductivity: most of the electrical power required for electrochemical machining is dissipated as heat in the electrolyte;

(iii) Corrosion: the electrolyte should not corrode the workpiece or material of the machine;

(iv) Surface finish: although the reasons are not fully understood, the surface finish obtained by electrochemical machining varies greatly with the electrolyte used;

(v) Filtration: both the form in which the material removed from the workpiece exists in the electrolyte and the effect that it has on its properties are important.

VIII. THE ORGANIZATION OF MACHINE-TOOL RESEARCH

It may be useful to conclude this review of some of the research problems of the machine-tool industry with a short discussion of the way in which research is organized.

The border line between research and development is never clearly defined and is probably even more indistinct than usual when machine-tool research is involved. The improvements that took place in machine tools between 1850 and 1950, say, obviously involved considerable effort, but since, with a few notable exceptions, little of this led to any systematic collection of information of general applicability, it can perhaps be best regarded as development rather than research. This distinction between research and development is a useful one to bear in mind even if it is not universally applicable.

This paper has not been concerned with development work, important though that may be, but with the wider and more general problems of research which, if the information gained is to be really useful, must be tackled at a fundamental level. Only the very largest individual manufacturers of machine tools can afford the necessary effort to basic research, which must, therefore, usually be carried out in co-operative, educational or state laboratories.

Prior to 1950, the amount of real research of interest to the machine-tool designer was very small. In the United States of America valuable work was done on the metal-cutting process, and in Germany, the foundation for more subsequent work on machine-tool structures was laid. Since 1950, however, interest in machine-tool research has increased rapidly and an appreciable proportion of the research effort of most industrial countries is now devoted to machine-tool problems.

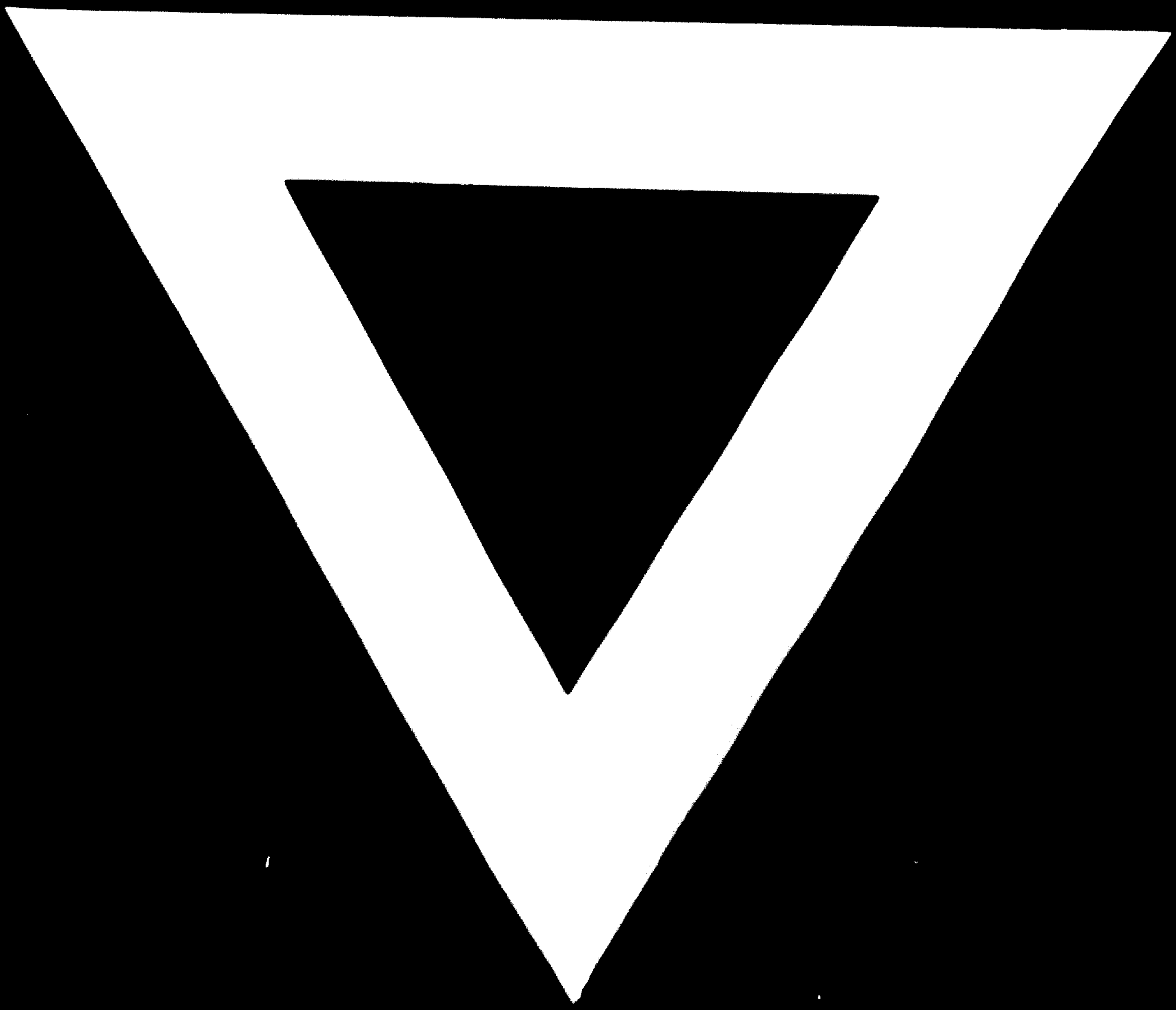
The pattern varies from one country to another. In the United States of America most of the research is done privately by machine-tool manufacturers, often with support from the state for specific projects. In addition, some universities have always shown an interest in the subject and the amount of university research is now increasing. In Eastern European countries and the Union of Soviet Socialist Republics, machine-tool research tends to be concentrated into one or a small number of large state-supported institutes whereas in the United Kingdom and in Western Europe, private research by machine-tool manufacturers is combined with co-operative research in research associations, state laboratories and educational establishments.

As the amount of machine-tool research increases, there is a danger that too large a proportion of the effort available will be devoted to empirical problems and not enough to fundamental studies. The mathematics involved in the analysis of real situations such as are found in machine-tool problems can be difficult, but the rapid spread of electronic computing techniques is doing much to alleviate the difficulties.

In general, a theoretical analysis of the physical phenomena involved, augmented by experiments to determine numeric values or to check conclusions, is likely to be of far more use in the long run than attempts to draw general conclusions from a large number of *ad hoc* experiments, although the latter approach is usually much easier. Isolated measurements of various phenomena can, of course, be very useful in the development of a particular machine. Unless, however, they are made systematically, i.e. with proper control of all the variables and on a sufficiently wide basis for the results to be generally applicable, taking account of all or most of the variables involved, they are unlikely to be generally useful and may, indeed, be misleading.

This point is conveniently illustrated by reference to work on slideway lubrication. There are innumerable references in the literature to measurements of coefficients of friction between slides and slideways, account being taken of lubricant properties, sliding speed, method of preparation of the surfaces etc. Some of the measurements were made on actual machine tools, and these undoubtedly helped in determining and specifying operating conditions for those machines. Other measurements were made on specially constructed rigs, but although a small amount of useful information was obtained in this way, the results have not been found to be generally applicable and it remains impossible to predict with any certainty just how any particular machine-tool slide will behave under given conditions. The reason for this became clear when it was realized that the frictional behaviour of the slide depends upon the shape of, and pressure in, large numbers of small wedge-shaped oil films which form between the sliding surfaces. The shapes and other properties of these wedges obviously depend upon the character of the surfaces, but they depend also upon the constraints applied to the sliding members. For example, the frictional behaviour when the surfaces are constrained so as always to remain exactly parallel can be expected to be different from that observed if a small amount of tilting is possible.

There is no substitute for real understanding of the physical phenomena involved and although, as this paper has tried to illustrate, the range of problems facing those engaged in research for the machine-tool industry is very wide indeed, the benefits to be gained from such an understanding can also be very great.



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