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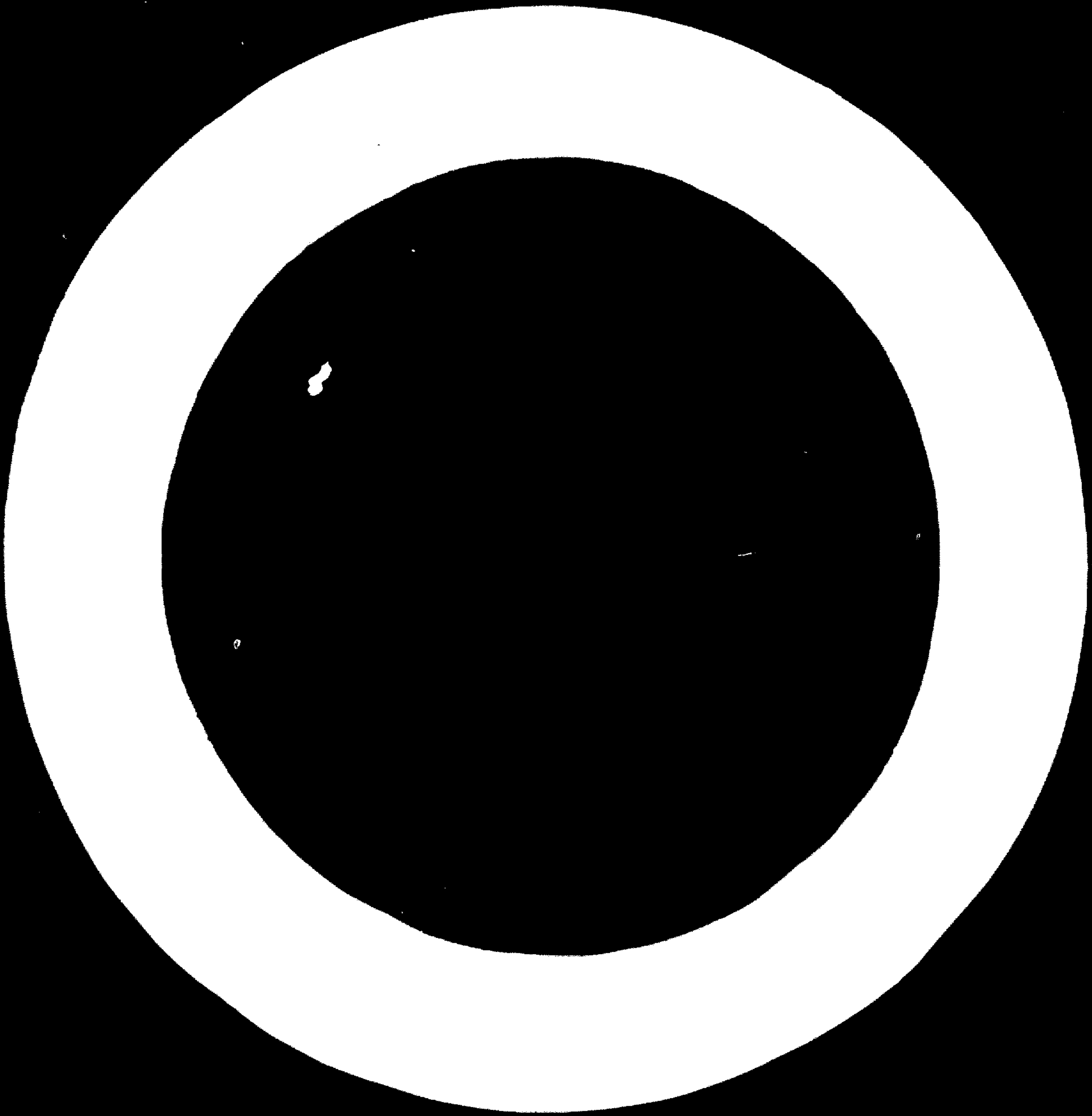

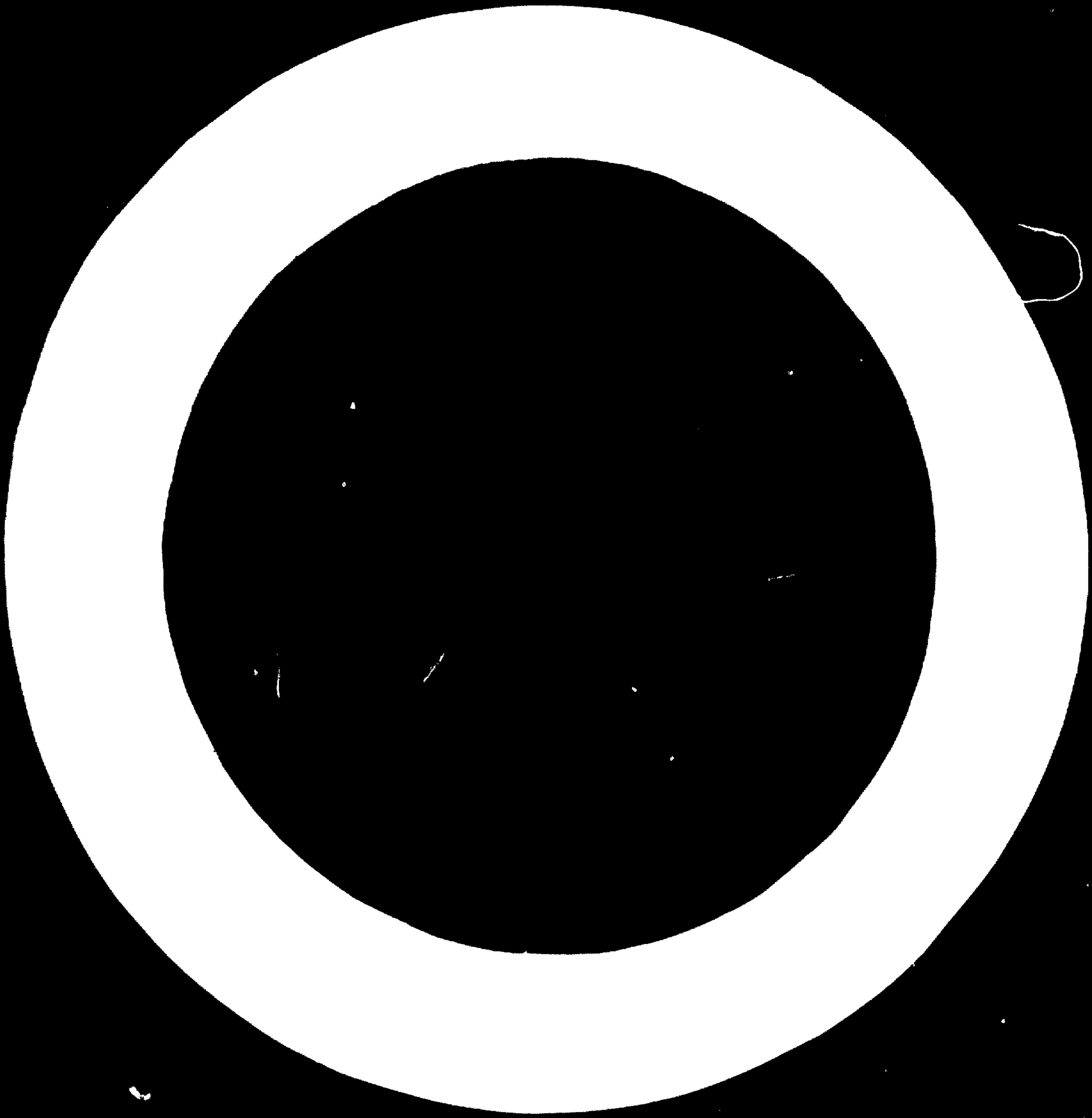

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TRENDS IN THE DESIGN OF METALWORKING MACHINERY AND IN PRODUCTION METHODS

Max Kronenberg, Consulting Engineer, United States of America

INTRODUCTION

For every nation, the world of tomorrow depends upon the metalworking machinery of today and the development of such machinery in the years ahead. Nations with highly developed metalworking industries enjoy the highest standards of living. The industrially developing countries are striving to follow this pattern.

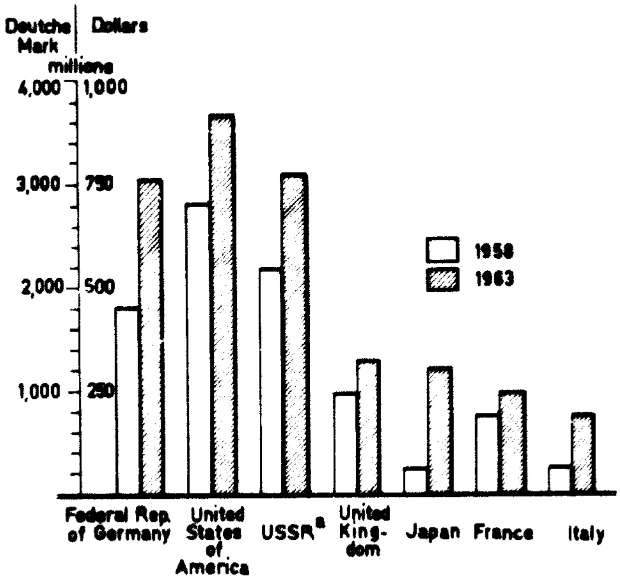
All modern products, whether large or small, are manufactured on machine tools or on machinery that has been produced on them. Machine tools are power-driven machines, not portable by hand, which are used to shape or form metal, primarily by cutting, but also by impact, pressure or electrical techniques, or by a combination of these processes.

Estimates of the magnitude of chip-producing operations illustrate the significance of machine tools for the general economy. In the first edition (1927) of a book by the present author, it was estimated that approximately 1.5 million machine tools of all types were in operation in German machine shops (1). About 1 million of those tools could be classified as metal-cutting machines. On the basis of one eight-hour shift per day and 300 days per annum, there was a total of 2,400 million working hours on machine tools per annum. Thus, at a charge of $2 per hour (in 1927), it was estimated that $4,800 million was spent annually in Germany for metal-removing operations. This author subsequently estimated that about $10,000 million was spent in the United States of America for these purposes (2). In a similar estimate of metal-cutting operations in that country, H. Ernst arrived at the same figure (3).

In an estimate prepared for the United States Air Force, Metcut Research Associates came to the conclusion that $3,000 million was spent in chip-making on machine tools for aircraft parts alone and $34,000 million for all the metalworking industries in the United States of America.

According to shipment data for 1963 (see figure 1), collected by the machine-tool industry in the Federal Republic of Germany, the industry in the United States of America was leading with $925 million, followed by the Union of Soviet Socialist Republics (estimate of $770 million) and the Federal Republic ($750 million). Other countries of significance in machine-tool production include the United Kingdom of Great Britain and Northern Ireland ($325 million), Japan ($300 million), France ($225 million) and Italy ($190 million). No data are available for Austria, Eastern Germany and Switzerland.

With regard to technological developments in the industry, there has been much progress. In the past forty years, the horsepower available in machine tools has increased tenfold and the accuracy, fiftyfold. It is, therefore, possible to remove ten times as much metal per minute (in cubic inches) at the current time as it was in the 1920's. High-precision workpieces for the aircraft and spacecraft industries can now be produced. Forty years ago, there was neither the need for, nor the ability to produce such workpieces.



Source: Amtliche Statistiken der Länder.
^a Estimated.

Figure 1

DATA ON SHIPMENTS BY MACHINE-TOOL INDUSTRY, SELECTED COUNTRIES, 1958 AND 1963

Technological developments also have an important bearing on the human side of production. The strenuous physical effort formerly associated with operating a machine tool, such as cranking a lathe carriage or milling-machine table, has been reduced to pushing buttons or loading the machine with stock, or to supervising a numerically controlled (NC) machine tool. The workers are, therefore, less fatigued. Furthermore, less scrap is produced.

It should be noted, however, that there is no indication that metalworking plants will become so completely automated that workers will not be needed. On the contrary, in its report to the National Commission on Technology, Automation and Economic Progress, the National Machine Tool Builders Association stated that by 1975 the number of workers in metalworking industries could be expected to increase by 15 per cent (1). Numerical control will create many new jobs requiring high skills and technical training—for example, programmers, electronic-maintenance men, systems analysts and machine-tool control service technicians.

The programmer for numerically controlled machine tools must be familiar with the relationships between cutting speed, cutting force, tool life, horsepower, depth of cut, feed, geometry of the cutting edge, vibration, production time, etc., in order to obtain optimum results. Numerically controlled machine tools may be doing up to 80 per cent of the work handled by general-purpose machines in modern small- and medium-sized machine shops, when their owners can realize corresponding profits.

With technological progress, there is an increased need for research. Forty years ago, the number of engineers engaged in machine-tool research and metal-cutting science was very small; today, thousands of engineers are working in this area of ever-increasing significance to industrial production. This increase has been greatly fostered by the progress in NC machine tools and by the new metals coming into application.

The increase in metal-removing capacity—as indicated by the increase in horsepower—and the great improvements in accuracy require the elimination or reduction of the vibration and deflection of machine tools. This depends, in turn, upon the reduction of cutting forces, an increase in the rigidity and related problems which are discussed in this paper. The need for research in regard to vibration was expressed in 1927 by the present author:

> "The development in machine tools will correspond to that of other branches of engineering, particularly aircraft development, namely, building for high speeds, low forces, increased rigidity—which is not identical with increased weight—and absence of vibration.
>
> "More research should be devoted to vibration problems in machine tools, because high speeds to be expected will come into resonance with the neutral frequencies of the structural design of machine tools" (1).

The trend towards high speeds has increased, due to the advent of carbide and ceramic tools, and vibration research is being conducted at many places.

As noted above, the new metals, among them the high-temperature alloys and the refractory metals, are another reason for the increase in metal-cutting research. These metals are often difficult to machine; and, in some instances, the cutting speeds have had to be reduced so much—in comparison with the machining of conventional materials—as to require more machine tools, more floor space and higher investment in order to produce the same number of units.

Therefore, alternative machining methods have been and are being developed. Many of these methods are still in the experimental stage and may develop slowly, while others may be expected to influence production methods in the near future. Among the latter group are the electrical machining methods, hot machining, laser cutting and measuring, and high-energy forming. These methods, as well as others, are discussed in the present paper.

I. NUMERICAL CONTROL

Metalworking by numerical control will grow rapidly in application and will have a great influence on trends in the design and production of machine tools. This is not an evolutionary development, but a complete change in the operation of a factory and of the machine tools in it. At the current time, numerical control is still limited to a relatively small number of machine tools which are in operation in the industrialized countries. In the United States of America, for example, of a total of 2.1 million machine tools currently installed in industry, 7,000 are numerically controlled. It is anticipated, however, that by 1975 the production of NC machine tools may well amount to 40 per cent, in monetary terms, of the machine-tool industry in the United States of America.

With numerical control, operation of the machine tools in the shop is the responsibility of the methods department and the control engineer rather than of the operator. Time studies in the shop will gradually become superfluous, as the tape will control both the handling and the cutting time. The operator is thus elevated to being a supervisor of the machines, requiring greater skill in that he must be able to service the machines should trouble develop.

In early 1963, about 150,000 tool and die makers were employed in the United States of America (4,5) in addition to 360,000 machinists, layout men and instrument makers, and 40,000 set-up men. During the 1960s 35,000 workers will be needed to replace those who die or retire. An adequate labour supply is not expected to qualify unless company training programmes are established to teach workers in a brief time to do new jobs; such upgrading then opens vacancies further down the line.

There is no place for NC machine tools in mass-production industries, where automated transfer lines and similar large-scale production equipment, e.g., automatic machine tools, will continue to prevail. Rather, NC machine tools are intended for the shop in which the usual lot size is one to ten or twenty pieces of a kind.

The skilled operator of conventional general-purpose machines manually arranges such elements as speed levers and feed-changing levers, and dials the depth of cut, etc., according to instructions he receives from reading blue prints or from consulting routing cards delivered to him with the workpieces to be machined. In the case of the automatic machine, however, instructions on tool travel, positioning etc. are built into the machine by the operator himself, who manually adjusts cams, bars, cycle times and other mechanical and electrical devices. In automatic screw machines, automatic single- or multiple-spindle bar machines and others, the operator's activity is thus limited to the set-up of the machines.

With NC machines, the set-up time is considerably reduced, due to the elimination of cams and levers. Such machines do not even have hand-wheels, levers, dials and similar elements for operating them. The ratio of machining (i.e., productive) time to set-up and handling time is substantially increased by numerical control. A punched tape is virtually free of inertia, in comparison with a heavy drum for cams, and thus permits a more rapid travel and the shortening of idle time. Electronic controls work more accurately and also more rapidly than mechanical devices, which need often complex linkages. The tape takes over the set-up procedure, which is expensive in time and quality of labour because it must be repeated each time an operation is changed. In the case of NC machine tools, it is only necessary to replace one tape with another.

Research on numerical control began in 1947 and was accelerated by the needs of the aircraft industry for new techniques that could produce intricate parts more rapidly and more accurately than conventional manufacturing methods.

In 1952, this writer had the opportunity of observing the performance of the first NC machine tool at the research laboratory of the Massachusetts Institute of Technology (United States of America). At that time, numerical control was, in many quarters, considered impractical, and relatively few engineers expected a development of such magnitude as that which has occurred during the past decade. Numerical control became practical as a result of advances in machining research and electronics used in other fields of engineering, such as radar, teletype and communications.

A. *Economy of numerical control*

The first question that arises when considering the application of NC machine tools is that of economy. In general, the initial investment is higher than that for manually controlled machine tools. It is, therefore, advisable to quote a few case histories which show the actual savings obtained (and also sometimes not obtained) when installing NC machinery.

Brown & Sharpe, who operate NC boring mills made by Giddings & Lewis, realized the following savings several years ago: 40 per cent in the machining of turret heads for boring machines; 28 per cent in the machining of columns; 42 per cent in machining milling-machine tables, mostly owing to reducing down-time; and 50 per cent in the milling, fine boring and thread cutting of milling-machine housings. A total of $47,000 was saved during one year; 80 per cent of this sum was due to the elimination of jigs and fixtures, and the reduction of set-up and handling times. The NC machine paid for itself in four years. The deciding factor was the elimination of fixtures that would have had to be built for the production of a new line of machinery. Furthermore, they gained additional freedom in the design of machine parts because changes in some dimensions only required changing the tape, rather than rebuilding a fixture.

In an aircraft factory, it was found that the set-up time for an average operation was 2 hours on a manually operated machine tool and only 15 minutes on one which was numerically controlled. The number of pieces that could be machined during one shift rose from two or three on the manual machine tool to ten and more on the NC machine. In this case also, the elimination of fixtures and jigs played a major role in reducing costs and increasing production.

At the Miehle-Goss-Dexter plant, presses for the graphic industries are manufactured on many horizontal boring mills of the Giddings & Lewis type. Several years ago, management decided that it would be best to begin with one machine in order to get experience with NC boring mills. The intention was to reduce the number of machines so as to save space in the shops and to cut the cost of fixtures, which often required considerable investment, particularly when only one machine was on order, as is frequently the case in this type of manufacturing. Formerly, it was necessary to design and build new fixtures for almost every customer because the presses had to be adapted to the special requirements of each order. Through the introduction of NC machine tools, it was possible to eliminate 750 fixtures and to save large areas of floor space which had been required for storing the fixtures. More productive space thus became available. The company is currently storing more than 15,000 punched tapes in a small space. Many of them can only be used for a special part, but such tape is economical, particularly when high accuracy is required. A punched tape is always made when six to eight holes are to be drilled in a workpiece. It is up to the programmer to decide whether to manufacture on a numerically controlled or a manually operated machine tool when less than six holes occur.

The preparation of punched tapes is a new field for many plant divisions where NC machine tools are being introduced for the first time. The designer will learn without difficulty to enter dimensions in co-ordinates from a reference point on the drawing. Recently, method has been developed which even permits programming directly from a dimensionless drawing.

Operation scheduling begins with the drawings and entails the use of standard form sheets containing columns for the position of work and tool, their size, cutting speed, spindle rpm, type of tool, feed, depth of bore etc. These data, retyped on a special typewriter, are deposited in duplicate in a fireproof box. Simultaneously with the retyping, the punched tape is produced on the typewriter. It is often possible to save tape preparation time when different workpieces have, in part, the same dimensions. One tape can be used for them, with additions to or removal of a part of the tape. Scribing of heavy workpieces can often be entirely eliminated when punched tapes are used. After about three months' training, an engineer will even be able to programme complicated processes.

The cases discussed so far refer only to positioning operations by numerical control. Economic considerations will be different in cases where fixtures do not exist and, hence the cost in this regard cannot be saved,

Table 1

TRACER CONTROL VERSUS NUMERICAL CONTROL: LOT SIZE, SIX PIECES[a]

Operation	Operating time (minutes)			
	Tracer lathe		Numerically controlled lathe	
	Total	Per piece	Total	Per piece
Drawing of template	90.0	15.0	—	—
Programming	—	—	496.00	82.60
Production of template	1,500.0	250.0	—	—
Punching of tape	—	—	124.00	20.60
Set-up time	90.0	15.0	15.00	2.50
Floor-to-floor time	112.8	18.8	125.52	20.92
Total time per lot	1,763.70	—	759.60	—
Total time per piece	—	298.80	—	126.60

Savings in time: 57.7%

[a] See figure 2 for illustration of workpieces.

as, for instance, in turning operations. The R. K. LeBlond Machine Tool Co. has given attention to this fact and has run comparative turning operations on tape-controlled and numerically controlled lathes. The latter produce workpieces with cylindrical as well as sloped and curved portions in continuous operation. Figure 2 shows a workpiece, and comparative data are given in table 1.

It will be seen from table 1 that the floor-to-floor time was slightly less on the tracer lathe (18.3 minutes) than on the NC lathe (20.92 minutes). In spite of this, the total time per piece was 57.7 per cent less on the NC lathe than on the tracer lathe. This result is mainly due to the fact that the production time per piece for the manufacturing of the template is as high as 250 minutes, while the corresponding time for the NC machine, namely, the tape-punching time, is only 20.6 minutes. If the lot size had been considerably larger than six pieces, say, 600 pieces, the floor-to-floor time per piece would have been the same as indicated in table 1, while the handling and preparation times would have been reduced to one-hundredth of the indicated time per piece.

The break-even point, that is, the lot size for which the

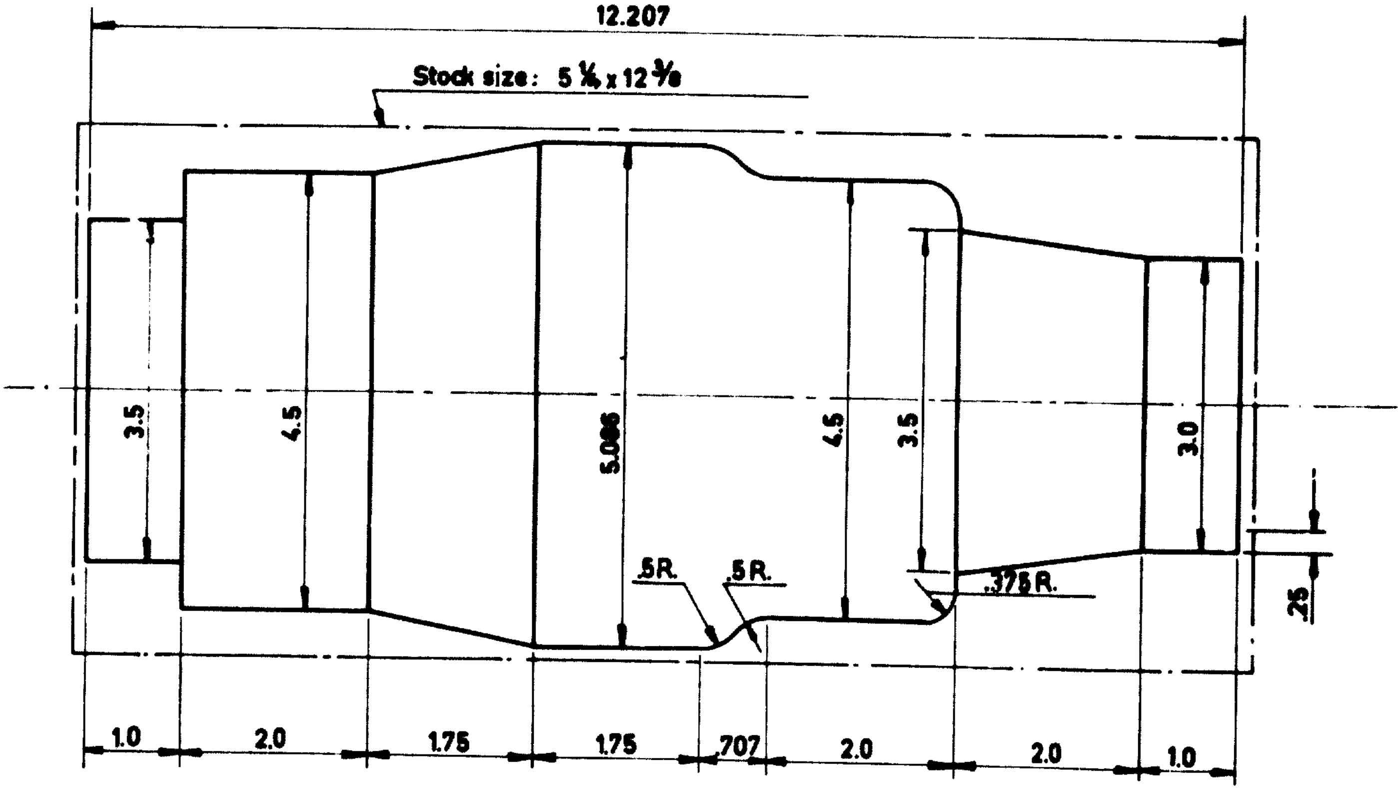


Figure 2

WORKPIECE USED FOR COMPARATIVE TESTS ON TRACER LATHE AND NUMERICALLY CONTROLLED LATHE total time per piece is the same for NC and tracer-controlled machine tools, can be computed in the following way for the workpiece illustrated above in figure 2. Let:

H_t handling + preparation time for tracer lathe
H_n same for NC lathe
F_t floor-to-floor time for tracer lathe
F_n same for NC lathe

The total time would be the same for the two types of machines when:

$$H_t + F_t = H_n + F_n \quad \text{total time per piece} \qquad \text{(Equation I-1)}$$

Assuming that the floor-to-floor times would remain unaffected when increasing the lot size, one finds from table 1 that the difference between them, namely, $F_n - F_t$, is 2.12 minutes. Hence, from equation 1:

$$F_n - F_t = H_t - H_n = 2.12 \text{ minutes} \qquad \text{(Equation I-2)}$$

The lot size (L) times 2.12 minutes must equal the known lot size (six pieces) times the difference between the sum of the handling times; hence:

$$2.12\,L = 6\,(280 - 105.7) = 1{,}045.8 \qquad \text{(Equation I-3)}$$

Thus the "break-even" lot size:

$$L = 1{,}045.8/2.12 = 495 \text{ pieces.} \qquad \text{(Equation I-4)}$$

Details of this analysis are given in table 2.

Table 2

TRACER CONTROL VERSUS NUMERICAL CONTROL: LOT SIZES, SIX PIECES AND 495 PIECES[a]

Operation		*Operating time (minutes)*			
		Tracer lathe		*Numerically controlled lathe*	
	Lot size	6	495	6	495
Preparation and handling time per piece		280.0	3.39	105.70	1.27
Floor-to-floor time per piece		18.8	18.80	20.92	20.92
Total time per piece		298.8	22.19	126.62	22.19
Savings in time (percentage)				57.7	0

[a] See figure 2 for illustration of workpiece.

It is evident from these figures that the NC machine tool has a considerable advantage over the tracer-controlled machine tool as long as the lot size does not approach mass-production quantities. The advantage of the NC machine is particularly great in the case of the small lot sizes. This confirms the claim that NC machine tools are intended for the job shop and other plants in which the production of a few pieces is predominant.

B. *Reduction of prices for numerically controlled machine tools*

The technological advantages of NC machine tools for the small and medium-sized machine shops cannot be denied. Their problem is the cost of initial investment. The trend in the prices for NC machine tools supports the general trend towards the increasing application of numerically controlled machines. Although the prices for a number of NC machine tools has gone up during the past five years, the prices have been reduced in many more cases, resulting in an over-all reduction of about 15 per cent during the period from 1960 to 1964. This figure applies, as an average, to all types of machine tools. The picture is different when the price changes are itemized for various types of machines and types of controls.

In 1964, about four times as many NC machine tools were shipped as in 1960. Positioning controls increased somewhat more than four times and contouring-path controls about five times, while the straight-cut systems increased only twofold. Technological differences between the various numerical controls are discussed in the following section.

Eight times as many NC drilling machines were delivered in 1964 as in 1960 and 60 per cent more NC horizontal boring mills.

The price of machine tools equipped with positioning-control systems dropped about 31 per cent from 1960 to 1964 and that of the positioning systems themselves, by 45 per cent. The same percentages apply approximately to the straight-cut systems, that is, to systems where the cutting tool stays in the cut during the tape-control travel. In the case of point-to-point control, the tool is not in engagement during travel. Contouring-control systems have been considerably improved and their prices have risen about 21 per cent, causing a price increase of 40 per cent for the machine tools equipped with this type of numerical control. The difference reflects the cost of changes in the design of these machines.

Comparing the prices by types of NC machine tool yields significant information. In the case of horizontal boring mills, the price rose about 8 per cent from 1960 to 1964. This applies to both the control systems themselves and the machine tools equipped with them, indicating that no substantial price changes were necessary, due to improvements in the design of horizontal boring mills.

The prices for drilling machines equipped with numerical control dropped about 60 per cent, which is the same percentage as the price drop in the control systems alone. Hence, the price reduction in the NC systems was passed on to the user of these machines. On the other hand, from 1960 to 1964, the price for lathes with numerical control was reduced by 43 per cent, although the price for the control systems dropped 64 per cent. The difference reflects again the cost increase caused by substantial changes in the design of the machines themselves. Data for milling machines with numerical control do not permit a clear analysis and conclusions.

The cost of the NC equipment averages about 30 per cent of the total cost of a machine tool. This figure has not changed substantially during the period 1960–1964, even within the different categories considered above, as is shown in table 3.

Table 3

PROPORTION OF COST OF NUMERICAL CONTROL IN TOTAL MACHINE PRICE

(Percentage)

Category	*1960*	*1964*
Point-to-point control	37	29
Straight-cut positioning	?	20
Contouring control	37	32
Boring mills	31[a]	31
Drilling machines	30	34
Milling machines	34	?
Lathes	41	25
Over-all average (approx.)	30	30

[a] 1961.

C. *Types of numerical control*

Three types of numerical control are usually considered. First, there is the so-called "positioning control", also known as point-to-point control, where the tool is not in engagement with the workpiece during positioning. Either the tool or the workpiece is moved by NC in order to position a drill or milling-cutter over several holes. The second is the straight-cut control, where the tool performs a machining operation, such as cutting a groove in a workpiece, while travelling under numerical control. These two types of NC are often combined, for instance, when drilling holes. The positioning is effected by NC when the tool is not cutting, while the straight cut—in this case, drilling the hole—is carried out under NC after positioning. In the third type, contouring control, the cutter follows a predetermined path consisting of straight lines, tapers, and simple or complex curves, as required by the contour of the workpiece to be machined.

In 1960, only 15 per cent of NC machine tools were designed for contouring and 85 per cent for positioning and straight-cut control. Since then, the trend has changed considerably. The application of contouring control has risen to 30 per cent, and that of the two other types has fallen to 70 per cent of all NC machine tools built in the United States of America. The trend in other countries is similar.

In contouring control, two subgroups can be differentiated, namely, point-to-point and continuous-path control. The latter system makes use of the fact that most contours of workpieces are composed of simple slopes, circular curves and ellipses. When the lengths and slopes of the straight lines and the arc lengths are known, the continuous-path contouring system converts the data into continuous movements of the machine. Control sheets are developed directly from the engineering drawings and the punched tapes on a typewriter.

Figure 3 shows the difference between the two subgroups of contouring control. At the left are shown three cases for the point-to-point contouring method, also called "step contouring", while the corresponding continuous-path method is shown at the right. In the top row, slopes are considered. In the case of step contouring, the steps represent the actual path of the tool, requiring many separate commands to approximate the straight line of the slope.

Circular arcs are compared in row "B". Again, the steps at the left represent the actual path of the tool for producing an arc of radius "R". At the right, it is shown that the arc can be produced by one command. In the case of ellipses, many commands are required for contouring them by the step method, while with the continuous-path method, only two commands (marked c_1 and c_2) and two repeat commands (marked d_1 and d_2) are necessary. The numerous computations required for the steps are reduced to a few in the case of continuous-path contouring systems.

D. *Co-ordinate systems: machine axis designations*

The designation of the axes of NC machine tools began with the drilling machine, where the customary co-ordinate system applies, namely, that x is the axis to the right in a horizontal plane, y is the axis going north to the x axis and z is the axis vertical to the $x-y$ plane. Although this principle is still used, it was found necessary to adapt the co-ordinates to the requirements of programming for numerical control.

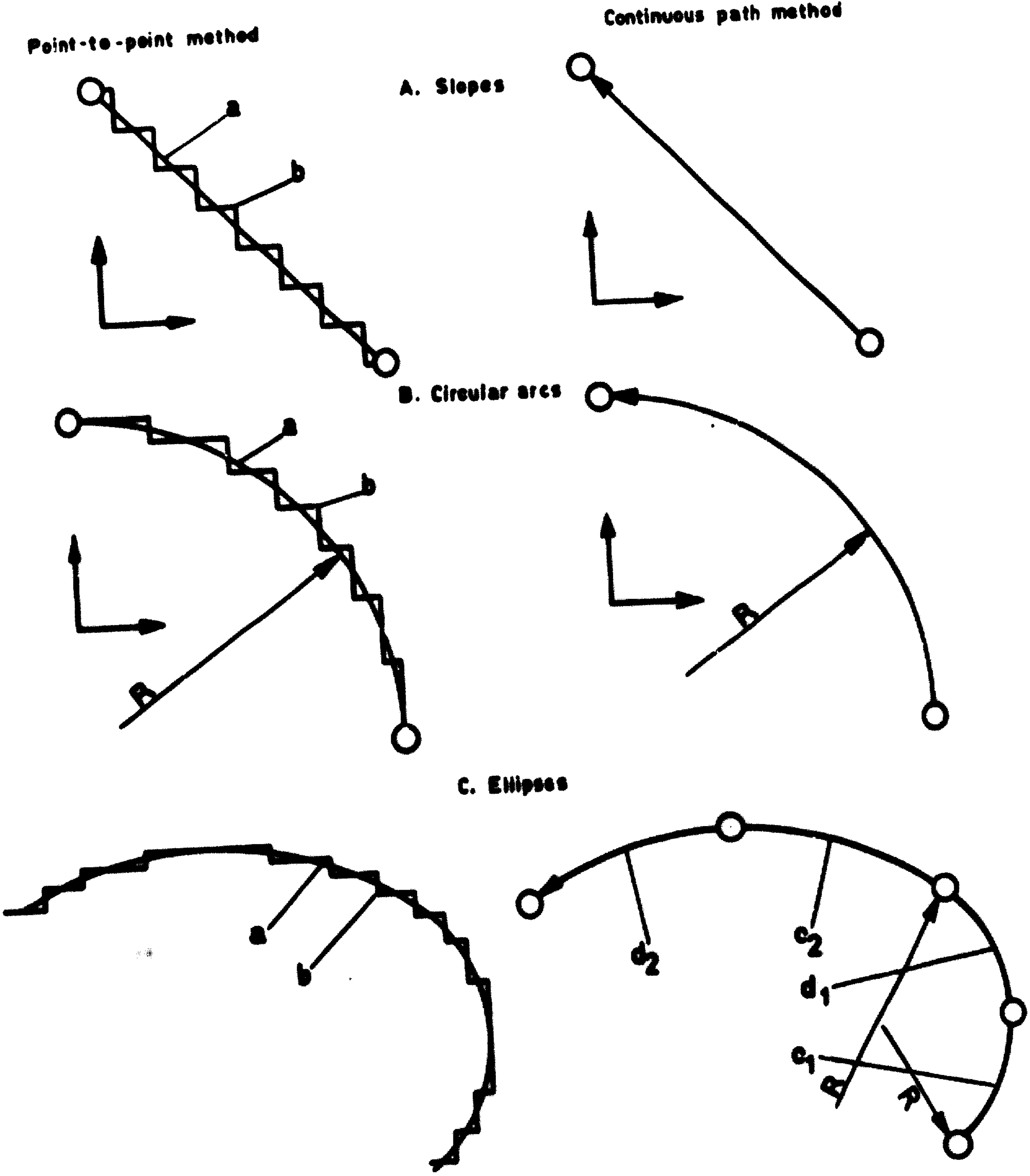
Numerical control can be simplified if the z axis is not always vertical (as is customary and in use for drilling and other machines), but if z is taken either as the axis of rotation of the tool (fig. 4) or as the axis of rotation of the workpiece (fig. 5).

As is shown in figure 4, z is vertical in the case of the single-spindle drilling machine, but horizontal for the knee type of milling machine and for horizontal boring mills. In the case of a skin mill, the z axis may even be inclined.

Correspondingly, the z axis is horizontal for workpieces with horizontal work rotation, as on lathes, grinding machines or turret lathes, as is shown in figure 5.

When more complex machine tools are considered, e.g., milling machines for profiling and contouring (see fig. 6), the z axis, taken in the traditional way, is vertical when the cross-rail movement is tape-controlled, but it becomes the sloped axis of tool rotation if the vertical movement is not tape-controlled. In the case of shaping machines and planers, z is again the vertical co-ordinate.

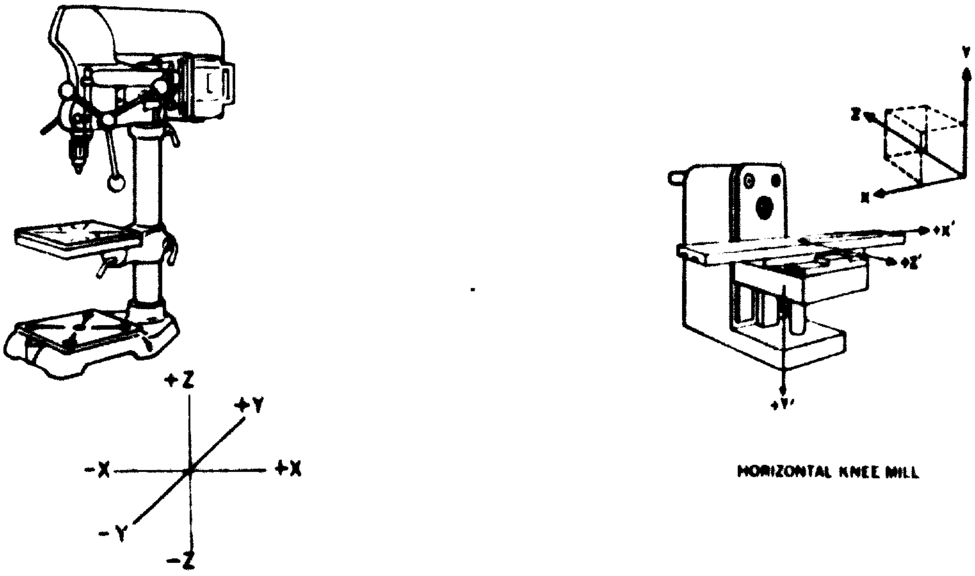
These axis designations have not been universally



a — line to be produced; b — actual path of tool; R — radius of arc; c_1, c_2 — commands; d_1, d_2 — repeat commands.

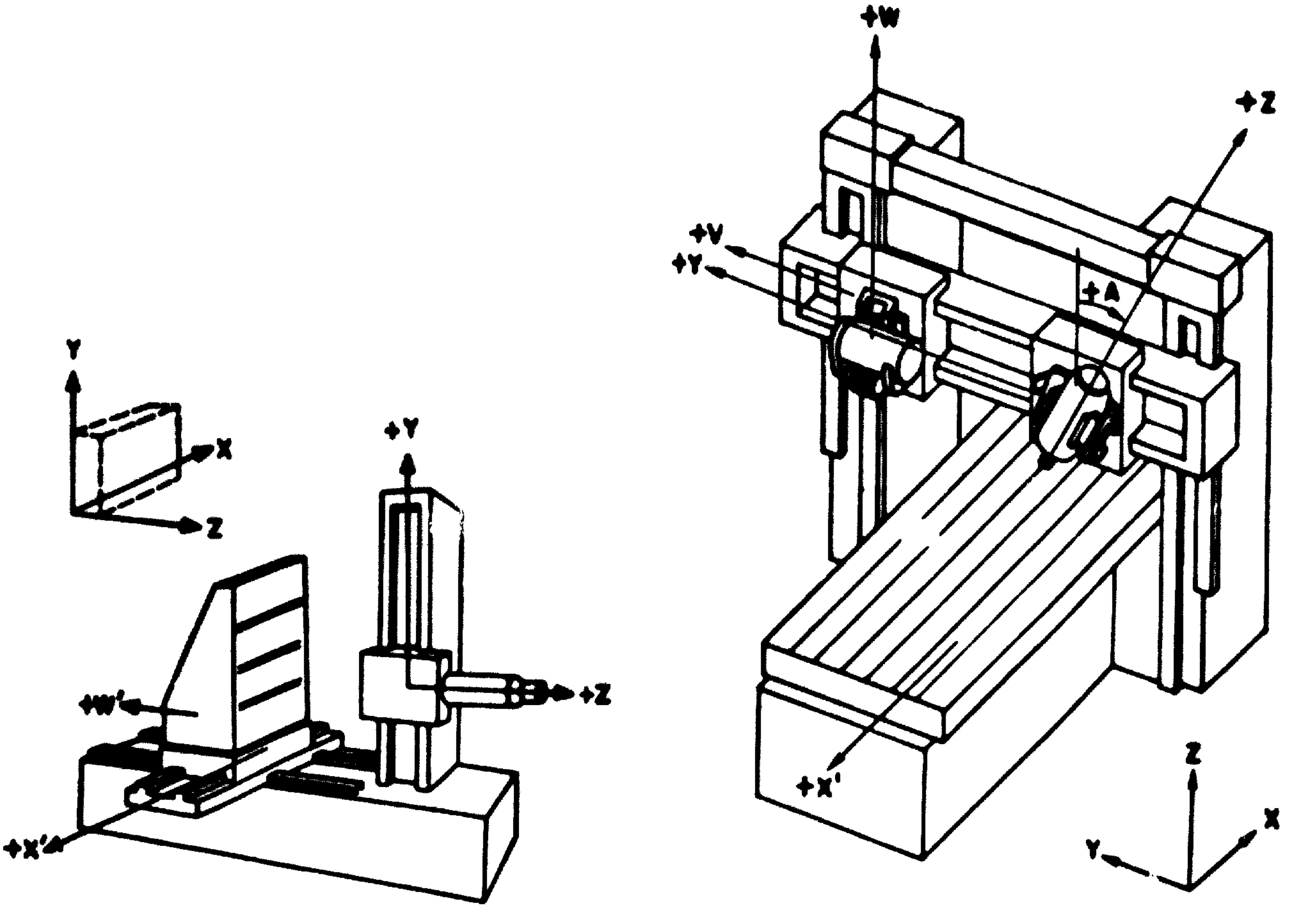
Figure 3

COMPARISON OF POINT-TO-POINT AND CONTINUOUS-PATH METHODS OF CONTOURING



SINGLE SPINDLE DRILLING MACHINE

HORIZONTAL KNEE MILL

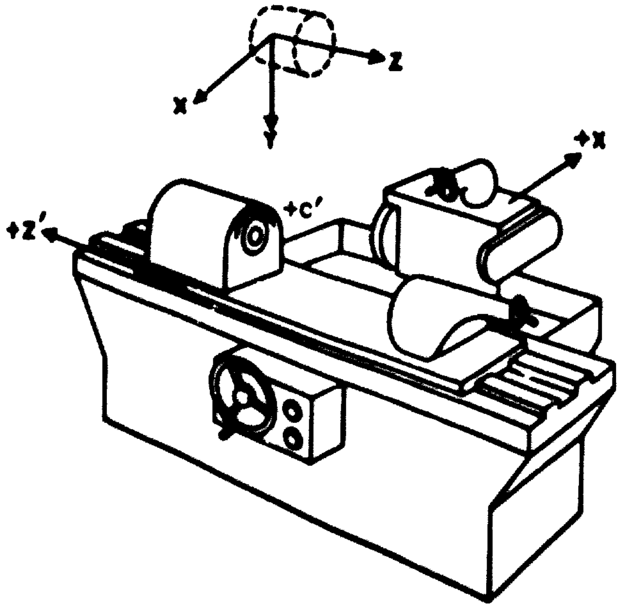


HORIZONTAL BORING MILL

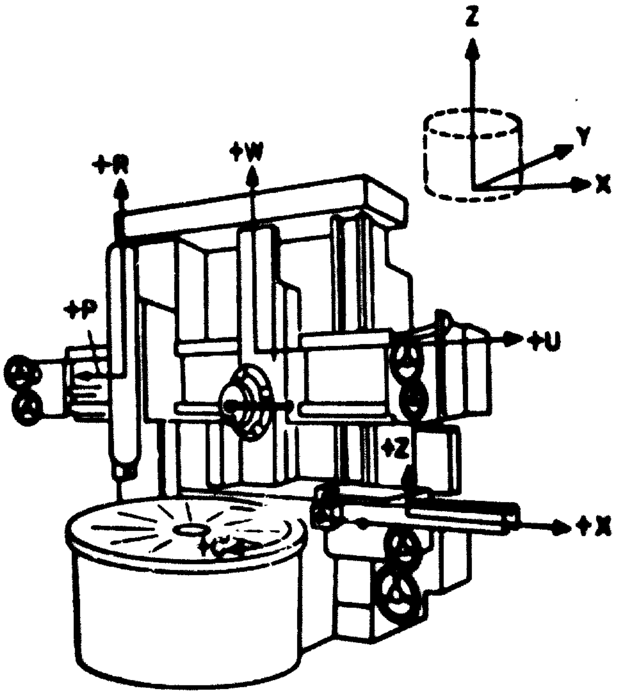
SKIN MILL

Figure 4

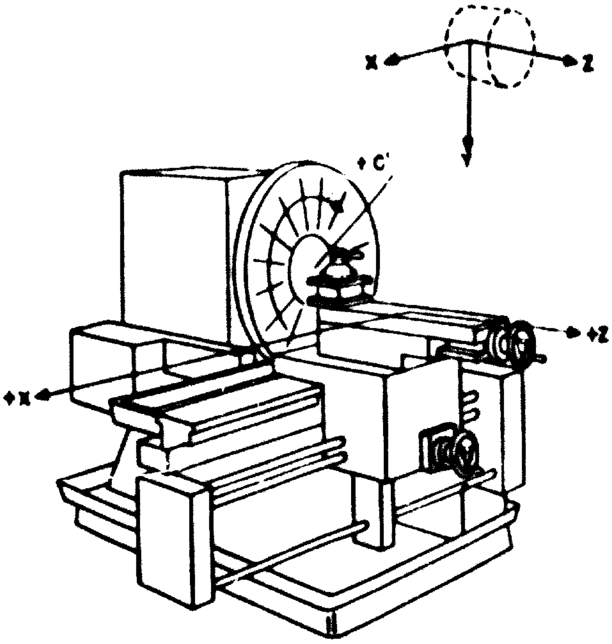
Co-ordinate systems with Z taken as axis of rotation of the tool



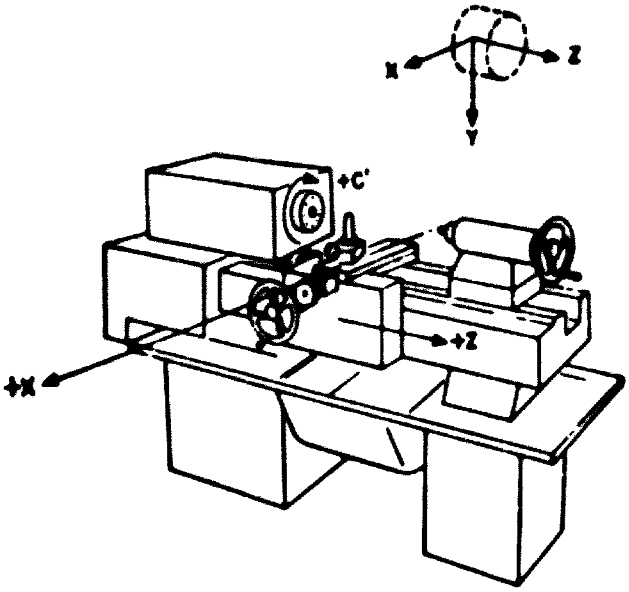
UNIVERSAL GRINDER



VERTICAL TURRET LATHE
VERTICAL BORING MILL



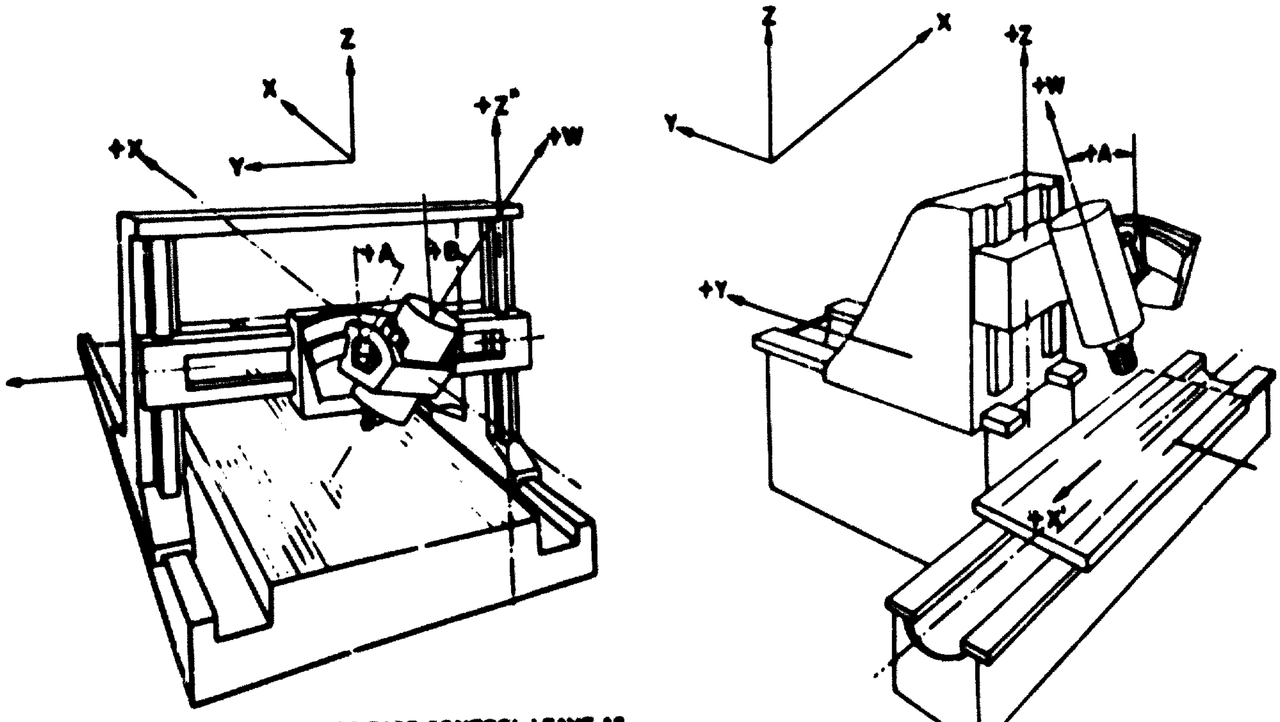
RIGHT ANGLE LATHE



ENGINE LATHE

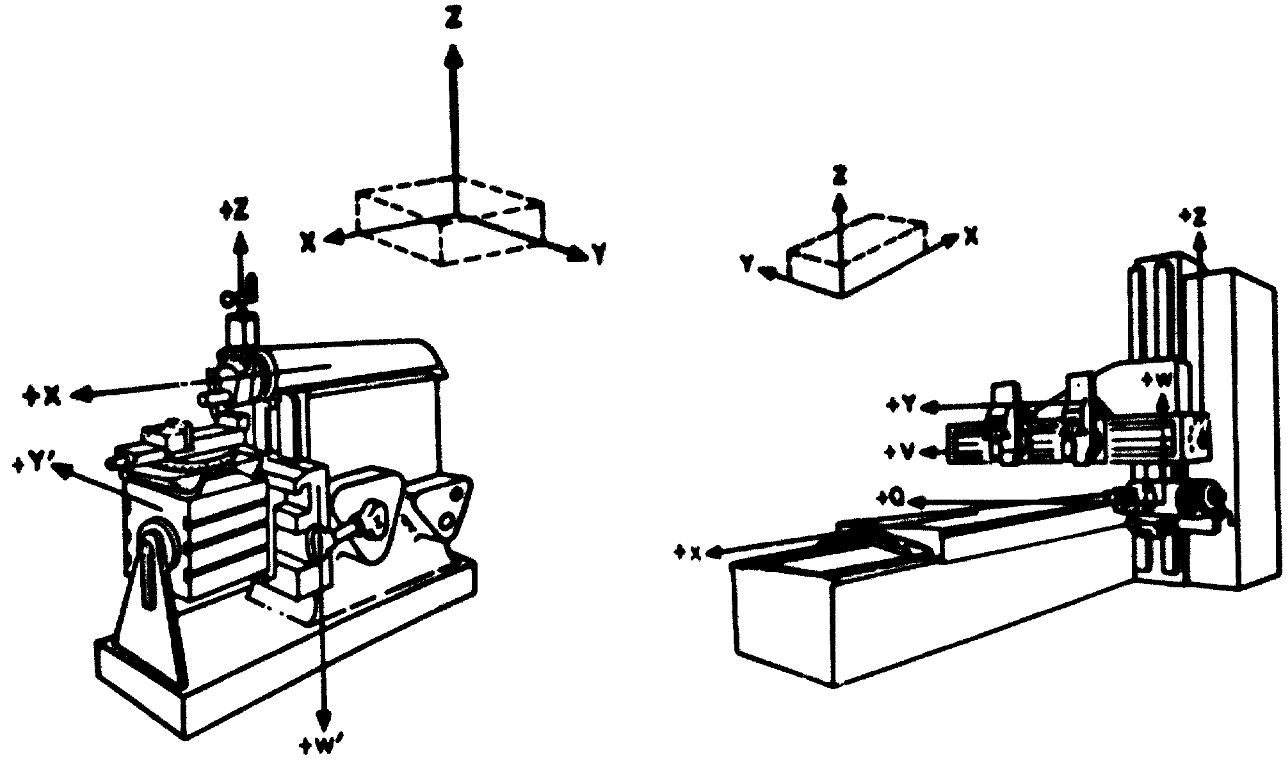
Figure 5

CO-ORDINATE SYSTEMS WITH Z TAKEN AS AXIS OF ROTATION OF THE WORKPIECE



*IF Z IS UNDER TAPE CONTROL LEAVE AS IS, IF NOT, +W BECOMES +Z.

MILLING MACHINE, PROFILING AND CONTOURING



SHAPER

OPENSIDE PLANER

Figure 6

Co-ordinate systems for milling machines used for profiling and contouring, and for shaping machines and planers

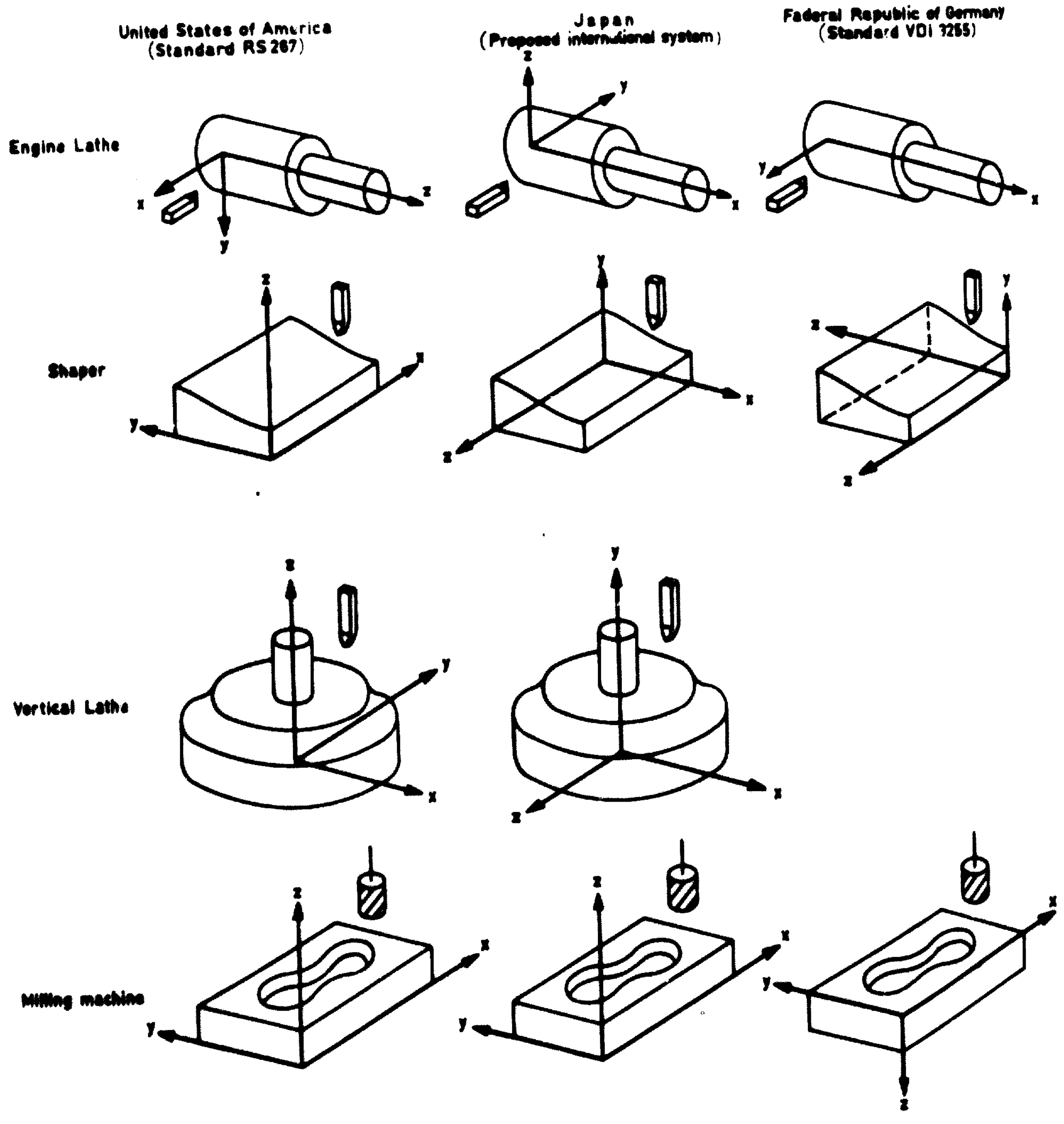


Figure 7

COMPARISON OF TWO STANDARD CO-ORDINATE SYSTEMS FOR NUMERICALLY CONTROLLED MACHINE TOOLS AND INTERNATIONAL SYSTEM PROPOSED BY THE PROGRAMMING COMMITTEE OF THE JAPANESE ELECTRONICS INDUSTRY

adopted, however, and this situation prompted the Programming Committee of the Japanese Electronics Industry to prepare suggestions for an international standardization of co-ordinate systems for NC machine tools. Figure 7 shows a comparison of Standard RS 267 of the United States of America with Standard VDI 3255 of the Federal Republic of Germany and with the Japanese compromise solution. The standard used in the United States of America is based on a right-hand co-ordinate system and that of the Federal Republic on a left-hand system.

This is particularly evident from the sketch of the vertical milling machine shown in figure 7. Looking at the workpiece in the direction of the *z* axes shown there, it will be realized that the *x* axis turns the workpiece to the right in the co-ordinate system used in the United States of America and to the left in the system used in the Federal Republic of Germany. In the case of the vertical milling machine, the Japanese Committee has suggested the adoption of the method used in the United States, while in other cases, new designations have been submitted. The following definitions for the z axis have been suggested by the Committee:

(*a*) For machine tools with rotating tools (milling machines, horizontal boring mills, drilling machines), the z axis is that which is parallel to the axis of tool rotation;

(*b*) for machine tools with rotating workpieces (lathes, turret lathes) and for machine tools with rotating tools and workpieces (grinding machines), the z axis is that which is parallel to the direction of the main cutting force;

(*c*) For machine tools with straight-line motion of non-rotating tools or workpieces (shaping machines, planers), the z axis is that which is parallel to the direction of the stroke of tool or workpiece.

In a number of cases, definitions used in the United States of America agree with the Japanese suggestions, while in others, they do not. In the United States, Standard RS 273 lists fourteen different motions and designations for NC machine tools. Obviously, no one machine tool will have all fourteen; in fact, only the more complex machines have four or, occasionally, five or six axes. The additional axes are the axes of swing (designated by a, b, c) around the basic x, y and z axes.

In the United States of America, the trend in NC machine tools is towards the utilization of simultaneous multiple movements. Such a method will permit simultaneous machining in various directions, as is desirable for the machining of complex contours. This will free the designer from the limitations imposed by production problems, so that he will be able to use special contours on vehicles and machine parts, such as helicopter rotor blades or impellers, which give optimum performance.

Although industries in the United States of America are the most advanced in the development and application of NC machine tools, other industrialized countries have also entered the field.

In the Federal Republic of Germany, numerous machine-tool companies are beginning to produce NC machine tools. The Automation Committee has, among its eighteen subcommittees, a group concerned with numerical control. Items handled by this subcommittee include electrical control, hydraulic control, tools, machine-tool standards and training.

A few years ago, programming work in the United Kingdom was at a relatively low level. The machine-tool manufacturers had been taken by surprise, but they changed their policy upon realizing that NC machine tools would be used in factories everywhere. Research facilities were established to investigate such design problems as deflections, vibration and thermal expansion. At the current time, sixteen companies in the United Kingdom are building NC machine tools.

In the USSR, numerical control began with a milling machine and a turret lathe with punch-card control. The machining cycle included speed and feed change, work stroke adjustment, rapid traverse, positioning, dwelling, spindle reverse for tapping etc. Seventy-seven horizontal and twenty-two vertical columns were punched. The punched cards were mounted on a silver-plated brass drum. The Soviet Union is currently producing seven types of NC machine tools, and programming involving the machining of three-dimensional workpieces with curved surfaces is also being developed.

Other countries in which NC machine tools are being produced include Austria, Czechoslovakia, Eastern Germany, France, Italy, Japan, Sweden and Switzerland.

E. *Standardization of punched tapes*

Punch cards are no longer so significant, having been replaced by the eight-channel punched tape, which is 1 inch in width. The binary system is mainly used because it requires only "On" and "Off" positions. In practice, however, it is often difficult to read binary numbers, which are, of course, based on the numerical 2. Table 4 provides useful data for conversion from the binary to the decimal system.

Table 4

BINARY/DECIMAL CONVERSION

(Read from right to left)

Place in binary figure	6	5	4	3	2	1
Exponential value	2^5	2^4	2^3	2^2	2^1	2^0
Decimal value	32	16	8	4	2	1

In order to convert the binary number 1100 into decimals, one must read "1100" from right to left, remembering that "0" means "off" and "1" means "On". The two zeros at the right end of 1100 indicate "Off" and do not appear in the decimal equivalent. Numerical "1" in the third place from the right in 1100 has a value of 4, according to table 4; the next "1" taking the fourth place from the right in 1100 has, correspondingly, a decimal value of 8. The sum of the valid numbers is therefore: 4 + 8 = 12. Hence, the binary number 1100 is represented by 12 in the decimal system. After some practice, it will be found that the conversion offers no great difficulties. Table 4 can be extended to the seventh place, which has a decimal value of 2^6 = 64 etc.

The disadvantage of binary numbers is their length. For example, fourteen digits are required to represent the decimal number 10.256. On the punched tape, therefore, a combination of horizontal and vertical binary numbers is used. Most of the standard tapes have channels 2^0, 2^1, 2^2 and 2^3. Each of these numbers (1, 2, 4, 8) thus has one channel, resulting in the following arrangement for 10.256:

First channel 2^0 1 10.010 (each 1 means 1)
Second channel: 2^1 2 00.101 (each 1 means 2)
Third channel: 2^2 4 00.011 (each 1 means 4)
Fourth channel: 2^3 8 00.000 (each 1 means 8)

Sum 10.256

Although the figure 10.256 is now represented by twenty digits, the optical reader can process five short numbers faster when they are arranged in four channels than it can handle one long figure in one channel. The holes, representing the "1" and the blank spaces, representing the "0", are compressed into a shorter length.

In RS 244, which is the *de facto* standard used in the United States of America for the eight-channel, 1-inch wide tape, the code requirements are spelled out for designating numbers, letters and symbols to be placed on the tape. Other standards include the following: RS 227, which specifies the tolerances of the medium and the holes punched therein for the 1-inch perforated paper tape, RS 267, which applies to interchangeable perforated tape for positioning and straight-cut NC machine tools, and RS 274, which deals with the interchangeable perforated tape for contouring and contouring positioning NC machine tools.

The rise of the computer and, with it, the increase in codes, created an economic problem, due to the cost of the computers. As a result, a new code, known as ASC-II, was developed. This trend in the development of NC machine tools, however, has resulted in a controversy, which is going on at the current time. Opposing the new code are many engineering organizations, including among others, the American Society of Mechanical Engineers, the American Society of Tool and Manufacturing Engineers, the Society of Automotive Engineers, and the National Machine Tool Builders Association.

An argument presented by the proponents of the new code—which has, thus far, been suggested only—is that information will, in increasing volume, be sent *via* teletype to programming centres from a machine shop many hundreds of miles away and that this can be done faster with the proposed code. Those opposed to the new code claim that this is also possible with the existing codes, although at somewhat reduced speed. The main objection centres about the increased cost for the conversion of existing tapes into tapes adapted to the proposed code. It is, furthermore, pointed out that the proposed code requires twice as many holes as the codes currently used and that the punching errors will, therefore, considerably increase. Figure 8 shows a comparison of the two codes. At the right is the standard code, which is used to a proportion of 98 per cent in the United States of America; at the left is the proposed code, ASC-II. The short horizontal lines in the figure refer to the right-hand (standard) code; they separate commands as indicated by the hole punched in the eighth channel, counting the channels, as always, from right to left. In the new code, shown at the left in figure 8 four holes are required for the same purpose.

In the Federal Republic of Germany, the preliminary standards for numerical control (series VDI 3250) cover nomenclature, programming and tapes. Programming should be based on fourteen letters, ten numerals and the plus and minus signs. Most of the standards refer to the five-channel tape, which is more widely used in Europe than in the United States of America, where the eight-channel tape is nearly 100 per cent in use. The European five-channel tape was developed in conjunction with the teletypes used abroad to a considerable extent. Repair parts available for teletype machines can thus be utilized in the devices for numerical control.

The eight-channel system, however, permits 255 punch combinations, while the European five-channel tapes allow only 31 combinations. There are tapes that can be used for both five- and eight-channel programming. Companies in the United States of America have developed typewriters that are mainly used for eight channels; but there are adapters which translate automatically from the eight-channel system to the five-channel system used in Europe, thus making it possible to convert methods used in the United States into European methods of programming and coding. It should be noted that in Czechoslovakia, 35-mm film is used in NC machine tools.

F. *Recent trends in programming*

During the past few years, newer systems have been developed in the United States of America, primarily for programming contours, namely, the so-called "ADAPT", "APT" and "APT III" systems. ADAPT and APT III can also be used for positioning purposes. With the ADAPT system, the complete NC processing of a workpiece can be described by "English-like" sentences, which represent the information on the drawing and the

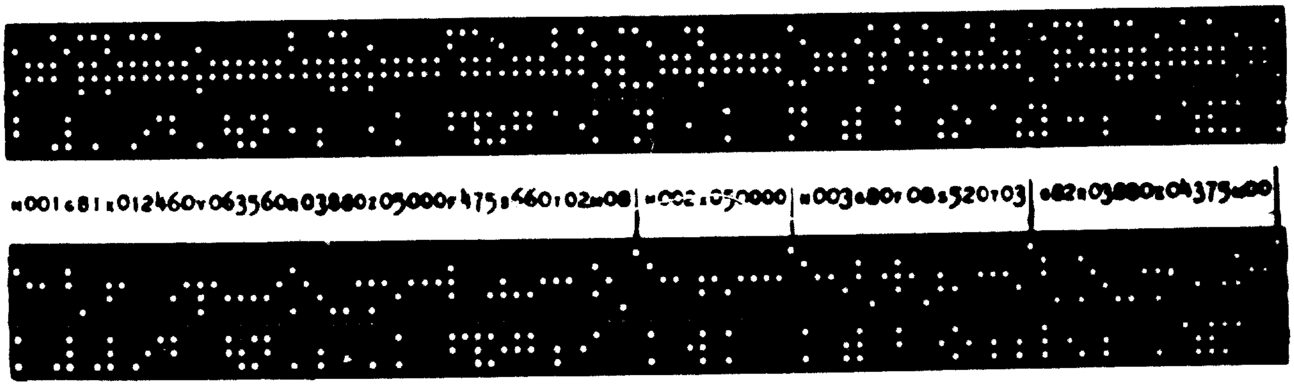


Figure 8

COMPARISON OF NEW ASC-II CODE WITH STANDARD EIGHT-CHANNEL CODE USED IN UNITED STATES OF AMERICA actions necessary to manufacture the part. It consists of the main processor, which translates the part programme to computer "language", and the post processor, which converts the output of the main processor into a control tape. With these systems, the user can employ any computer or have his programme prepared outside. APT III is available at outside data-processing centres for participating companies. ADAPT is simpler, but it can handle 75 per cent of the requirements of the average shop. These systems can also detect punching errors, such as punching I instead of 1. The computer cannot handle a dimension, such as 5.125 instead of 5.125.

Another step in the direction of saving time in the preparation of the tape is the development by the General Electric Company (United States of America) of the "Autoprogrammer". This machine makes it possible to prepare a punched tape from a drawing without dimensions on it. It eliminates the typing of programme manuscripts and the dimensioning of drawings. A stylus is placed over the drawing on the layout table and scans the dimensionless drawing, automatically punching the x and y co-ordinates into the tape. As soon as all information from the drawing has been entered, the tape is ready for use. The operator can give auxiliary commands, such as spindle speed, feed etc., by depressing the appropriate letters on the console.

G. *Design features of numerically controlled machine tools*

The advent of NC machine tools has influenced the design of not only this important portion of machine tools, but also all or many other types of conventionally controlled machine tools, as is discussed in detail in a subsequent section of this report.

As far as NC machine tools are concerned, some companies deemed it necessary to make such machine tools heavier than the corresponding manually controlled machine tools. The guideways were widened and anti-friction bearings and rollers were incorporated. These changes were necessary because of the so-called "stick-slip" effect of slowly moving tables, carriages and saddles before coming to an accurate stop at a predetermined position. Motors must be dimensioned to avoid overheating, and the lubricating systems must be well designed. Lead screws must have a good fit, and carriages must be able to travel to within fractions of a thousandth of an inch. The design of the machines not only requires good machine-tool practice, but also good theoretical knowledge of the deflections, thermal expansion and vibration of machine tools and of their elements. Research into the structure and the distribution of the masses for minimizing or eliminating these disturbances is playing an increasing role in the design of all machine tools.

Engineers in the Soviet Union challenge the theory that friction, reduced by increasing speed or increased by reducing speed, is mainly responsible for the phenomenon of stick-slip. They claim that the design of guideways and drives has a major effect on friction and that it is not sufficient to consider only the lubrication and the material of the gliding surfaces. They consider also the surface finish, the guideway design and the inertias of the travelling machine elements.

At least two degrees of freedom of vibration must be considered, one in the direction of motion and the other, perpendicular thereto. Adding weight to a machine tool does not necessarily reduce vibration. This conclusion was reached by machine tool experts in both the Soviet Union and the United States of America. The floating of a table depends upon the oil film, tilting the table at stroke reversal in various ways, depending upon the velocity. The leading edge of a table rises at slow speed but drops at higher speeds. Between these speeds, the table remains stable.

Similar investigations carried out in the Federal Republic of Germany, where lead screw drives were tested at various speeds and with different masses, resulted in the following formula for the optimum table speed to minimize over- or undershooting of the positioning location:

$$v = \left(\frac{v_o \cdot s_r}{1.6\,c}\right)^{3.8} \qquad \text{(Equation 1-5)}$$

where v_o = coasting velocity while approaching the desired position, s_r = distance travelled and c = constant involving mass and friction. It will be noted that the effect of these quantities is very large, due to the exponent 3.8.

In the United Kingdom, NC machines with conventional cast-iron beds and slides were compared with combinations of cast-iron beds with bronze-impregnated bearings and hydrostatic bearings, as well as with other combinations. In the case of cast-iron on cast-iron, it is necessary to take the microasperities into account, in addition to the surface shape and flatness. The combination of cast-iron *versus* impregnated bronze seems to have a substantial advantage because the coefficient of friction remains constant as the slide approaches its final position, while the coefficient of friction increases in the case of the conventional combination of cast-iron on cast-iron. Hydrostatic bearings can be adapted to maintaining a thin oil film, as is desirable for continuous-path contouring.

In Switzerland, the effects of NC requirements on machine-tool design are likewise closely examined. Good results have been obtained with regard to the stick-slip problem by coating the guideways with a molybdenum compound.

In the present paper it is possible to describe only a few of the many NC machine tools which have recently been designed. The trend is towards the so-called "machining centre". Machines of this type are multiple-purpose NC machine tools permitting milling, drilling, boring, tapping etc. in one or a few set-ups. The workpieces may have several surfaces. Considerable savings are realized, particularly in handling and set-up time. On a workpiece with four sides, one top and one bottom surface, only three changes in the set-up are required when using a machining centre, as against thirty-two set-up changes in the case of conventional methods. Hence [illegible] 0.94, or 94 per cent of the set-up time is saved, which may amount to $100 per workpiece, assuming a cost of $20 per hour and 10 minutes per change.

Numerically controlled machine tools usually do not have hand-wheels or levers, as is made evident in figure 9, which shows lathe model 1025 of the American Tool Works. This machine is equipped with the Mark Century 102 C numerical control made by the General Electric Company. The tool can stay in the cut when the spindle speed is changed by numerical control.

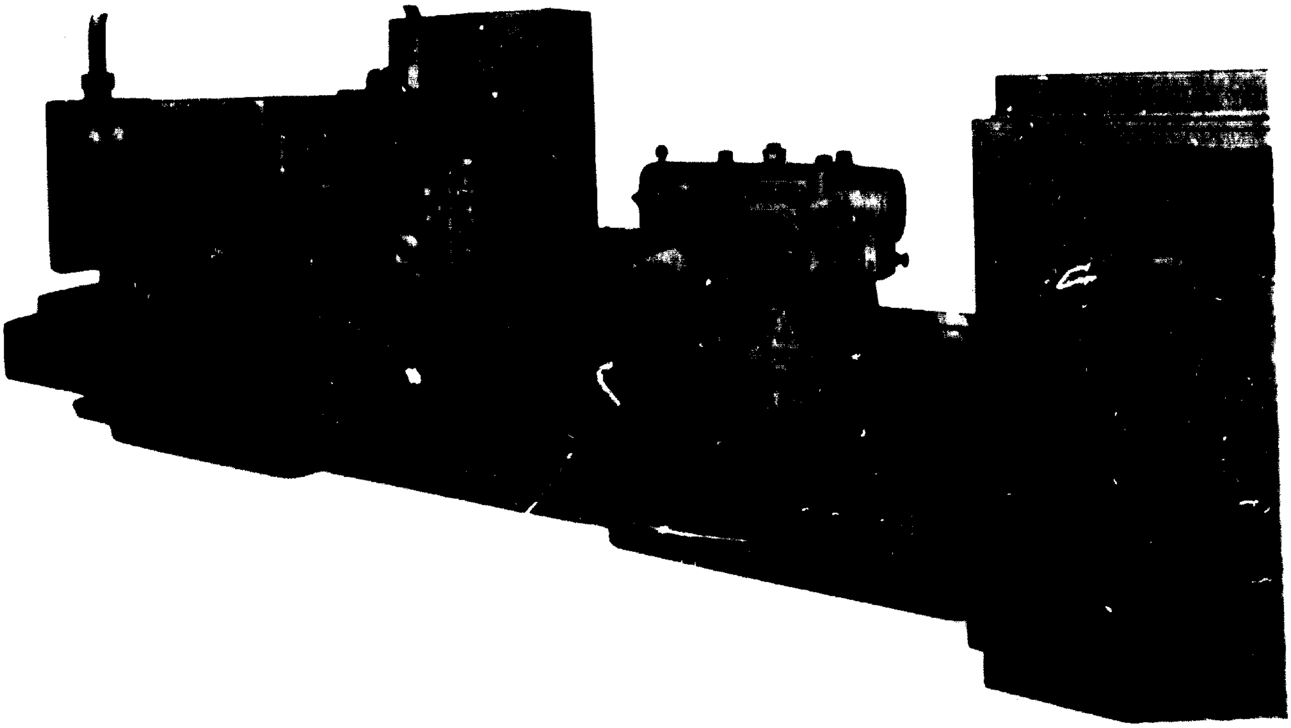


Figure 9

NUMERICALLY CONTROLLED LATHE, MODEL 1025, AMERICAN TOOL WORKS

Figure 10 shows a new model of the turret lathe with inclined bed, which is being built by Warner & Swasey (United States of America). This machine, in the design of which the present author participated, offers several innovations. The bed is slanted at 20° to the vertical. Research had shown that the cutting forces could be well distributed over the guideways and other elements of the machine. The width of the ways with regard to least wear and minimum cost was also investigated. The machine is equipped with the Mark Century No. 100 NC model. The sequence of operations can be programmed by the operator himself. If a change in feed, cutting speed or depth of cut should be necessary during the automatic cycle, the operator can override the tape commands without affecting the remaining commands. In this way, optimum metal-removal rates and accuracy can be obtained. The operator can also correct the command when the tools begin to wear or when the stock of material on the rough workpieces varies. The slides are moved by ball screw feed shafts.

The new Milwaukee-matic (see fig. 11), which is built by Kearney & Trecker (United States of America) is designed for multiple machining operations. It is a point-to-point straight-line system that handles milling, drilling, reaming, tapping and boring in a single set-up. It changes the tools automatically, selecting the proper one from an indexed rotary magazine which is capable of storing fifteen tools and which can be seen at the top of figure 11. The tool changes are co-ordinated with the positioning of the workpiece for the next operation. The four-position indexing table permits the machining of four sides of a workpiece in a single set-up. The machine can also be equipped with two-axis contouring control.

II. PRODUCTIVITY

The increase in metal-removal rates required by modern manufacturing methods is well reflected by the increase in the horsepower currently available at the cutting edge and in the motors of machine tools, in comparison with those in use only ten years ago. The metal-removal rate, measured in cubic inches per minute, depends upon the hp of the machine tool, according to the following equation:

$$\text{cu. in./min.} = \frac{396{,}000 \cdot \text{hp}}{k_s} \qquad \text{(Equation II-1)}$$

where k_s = unit cutting force (lb/sq. in.) of the material being cut. It follows from equation II-1 that more metal can be removed per minute when the horsepower of the machine is increased. Limits for this general equation for the metal-removal rate are discussed below; they are due to tool wear, feed, speed and other qualities.

Figure 10

NUMERICALLY CONTROLLED TURRET LATHE WITH INCLINED BED, PRODUCED BY WARNER & SWASEY

Dividing both sides of equation II-1 by the horsepower results in:

$$\frac{\text{cu. in./min.}}{\text{hp}} = \frac{396{,}000}{k_s} \qquad \text{(Equation II-2)}$$

Equation II-2 indicates that the metal removal rate per horsepower of the machine is nothing but the reciprocal of the unit cutting force, multiplied by 396,000. Hence, trying to establish a trend based on cu. in./min./hp cannot give the desired information. Such information pertains only to the unit cutting force required for machining the respective materials. This is often not realized by many engineers and salesmen for machine tools.

It is, rather, the horsepower of the machine tools that may serve, within its limits, as a fair criterion for the trend in productivity and in the metal-removal rates.

Productivity, as expressed by the metal-removal rates and the horsepower of the machine tools, has increased more than 100 per cent during the period from 1953 to 1963. A few typical examples of this trend are listed in table 5.

These increases in productivity, together with the increased demand for higher accuracy, have been made

Table 5

SURVEY OF INCREASE IN PRODUCTIVITY AS EXPRESSED BY INCREASE IN HORSEPOWER OF MACHINE TOOLS

	Horsepower		*Increase*	*Spindle speed (maximum rpm)*		
Machine-tool group	1953	1963	*(percentage)*	1953	1963	*Make*
Lathes (engine)	10	20	100	700	1,750	Monarch
Lathes (tool room)	1	2	100	1,200	2,500	Monarch
Lathes (turret)	10	25	150	730	2,000	Gisholt
Horizontal boring mill	25	60	140		—	Giddings & Lewis
Grinders (small)	15	30	100			Mattison
Grinders (large)	30	70	133			Mattison
Grinders (rotary)	150	250	67			Mattison
				Feed (inches per minute)		
Milling machine (knee)	10	18	80	40	90	Cinti Mill.
Milling machine (bed)	15	55	268	30	150	Cinti Mill.

Over-all average 125

possible by changes in the design of the machine tools, often based on scientific and applied research into rigidity, deflection, thermal expansion and vibration.

A. *Productivity charts*

The utilization of the horsepower available at the cutting edge of the tool has been made possible by metal-cutting research and application of results to practice. The man in the shop used to rely upon data collected from observed experience: these data often had such wide tolerances that it was nearly impossible to determine optimum values for a specific job with sufficient accuracy. In an effort to improve this situation, the significant metal-cutting data collected in the United States of America and in numerous European countries have been investigated and brought into a logical system.[1] Numerous tests have been conducted, and many of the formulae and data discovered in this way have proved useful in practice.

To get the message through to those who need it, these data and findings should be presented in ways best suited to the eventual user, i.e., the tool engineers, time-study men, supervisors, managers and operators. The means may be charts, tabulations or instruction sheets. Charts give a survey and permit realization of the effect of change from one quantity to another. Intermediate values are more readily found from charts than from

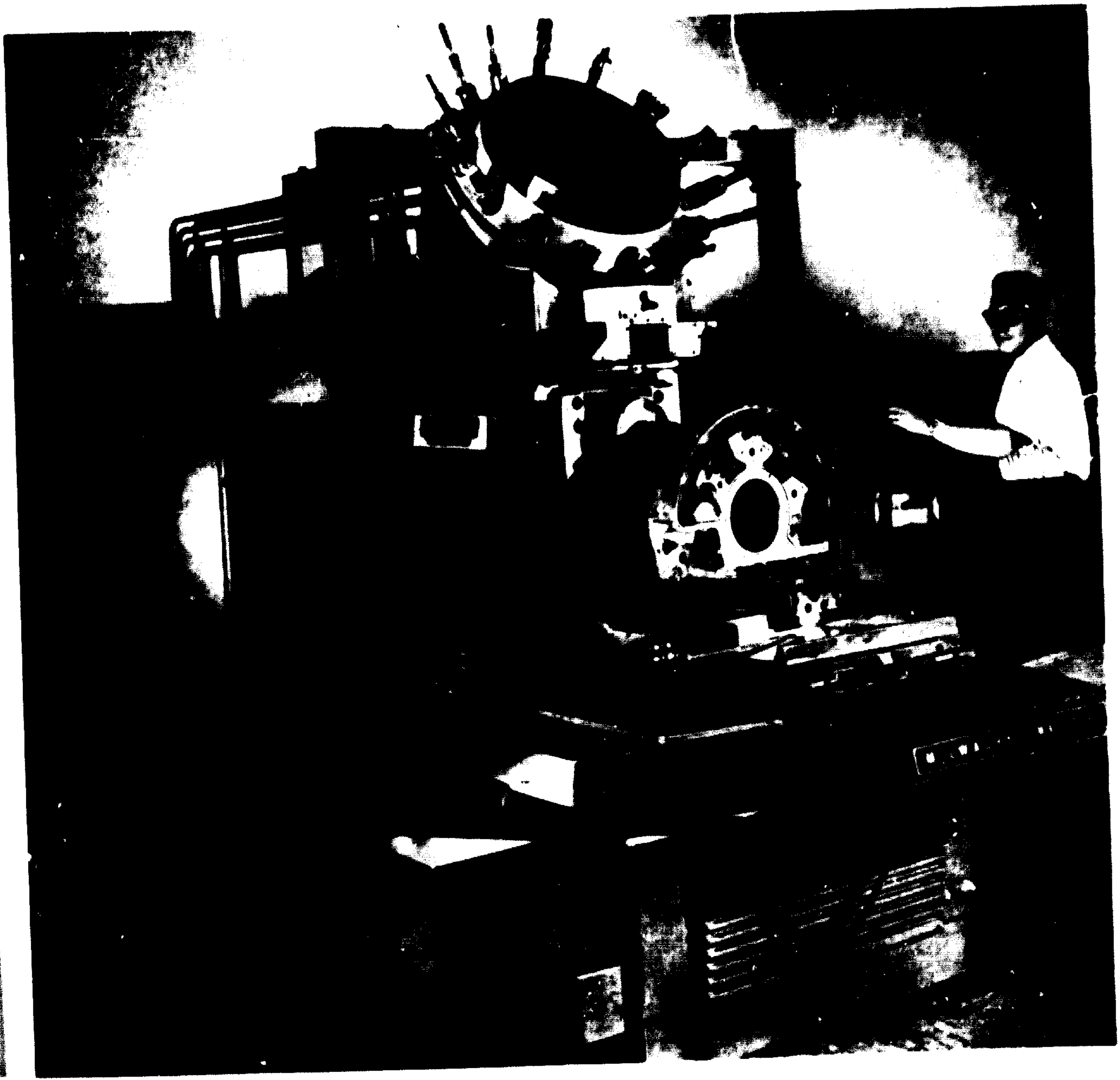


Figure 11

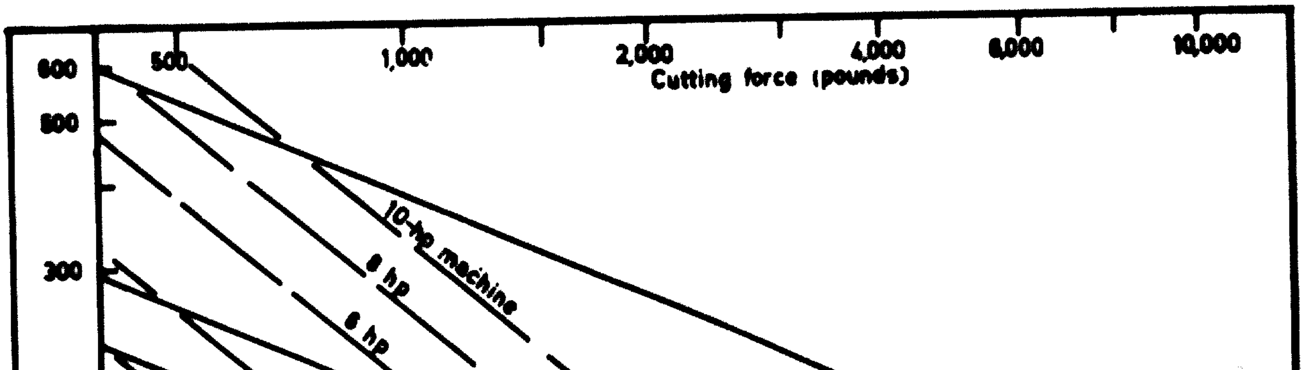
MILWAUKEE-MATIC MULTIPLE-PURPOSE MACHINE TOOL, PRODUCED BY KEARNEY & TRECKER tables. On the other hand, tables are more useful than charts when the user is not sufficiently familiar with the reading of charts (as may be the case in the industries of developing countries) or when a reading must be duplicated exactly.

Productivity charts convey basic information to the eventual users, including programmers for NC machines. In making up the productivity chart shown in figure 12 (in this case, for SAE 1035), the lower horizontal axis is plotted in terms of chip areas (feed × depth of cut) in values of 0.002 to 0.050 square inches. The cutting speed is plotted on the vertical axis for a range from 30 to 600 ft/min. At the top of the chart, a scale for cutting forces ranging from 500 to 10,000 pounds is plotted. Cutting force is a very important quantity in metal cutting and is required for determining deflections and whether the machine or the workpiece is rigid enough with respect to the accuracy desired.

In the centre field of figure 12, two series of lines descend from left to right at different slopes. The lines with the smaller slope (those going to points 1 and 2) are the result of tool-life investigations, while those with the larger slope (those going to points 3 and 4) are derived from horsepower and cutting-force investigations. The limits qualifying the application of the general formula for the metal-removal rate (equation II-1) are incorporated in the productivity chart, as will become evident hereafter. For example, assume an 8-hp machine, a high-speed steel tool and a tool life of 60 minutes for the removal of a chip of 0.013 sq. in. (¼-inch depth of cut by 0.050-inch feed/rev). The circle at the intersection of these quantities shows that these conditions will be satisfield when the cutting speed is set to 80 ft/min.

It is now desired to investigate the changes that occur in the metal-removal rates if speed, feed, horsepower or tool life are changed.

Following the 60-minute tool-life line in direction of the arrow leading to point 1 results in an increase in cutting speed and a reduction in feed. In this way, the 6-hp line is approached. Hence, an 8-hp machine cannot be fully utilized if the feed is reduced and the speed is increased in such a manner that the tool life of 60 minutes is maintained. The metal-removal rate, or, in other words, the productivity, would be reduced, as can be determined



Note HSS = high-speed steel

Figure 12

PRODUCTIVITY CHART FOR SAE 1035 (20° TRUE RAKE ANGLE) from the chart. At the circle, the metal-removal rate is 0.013 × 80 × 12 = 12.5 cu. in./min. At point 1, with a cutting speed of 105 ft/min and a chip cross-section of 0.0065 sq. in., the metal-removal rate has dropped to 0.0065 × 105 × 12 = 8.2 cu. in./min. This is a loss of 35 per cent.

Following the 60-minute tool-life line in the opposite direction, namely, along the arrow leading to point 2, results in an increase in feed and a decrease in cutting speed. Here, the 10-hp line is approached, indicating that the 8-hp machine would be overloaded.

A third possibility is indicated by the arrow leading to point 3. Again, the speed is increased, but even more so, and the feed is reduced. In this case, one leaves the 60-minute tool-life line and approaches the 10-minute line. Because such a short tool life will often be undesirable, one changes from high-speed steel to carbide tools and thereby increases the tool life to more than 1,000 minutes, as indicated by the fact that one is below the carbide line for 1,000 minutes. The metal-removal rate at point 3 is somewhat less than at the circle, namely, 0.0065 × 144 × 12 = 11.2 cu. in./min. This is a loss of only 10 per cent, as against the loss of 35 per cent when maintaining a tool life of 60 minutes for high-speed steel. The loss in the metal-removal rate is compensated by the gain in tool life and, hence, by a reduction in down-time for tool changes, as well as by improvement in the surface finish, due to the disappearance of the built-up edge at higher speeds. The accuracy will also be improved, as indicated by the reduction in the cutting force which drops from 3,200 lb at the circle to 1,800 lb at point 3. (The same drop applies also to point 1, without, however, the benefits in tool life, surface finish etc.)

In spite of the loss in the metal-removal rate, which is always the result of feed reduction and speed increase, it is often desirable to reduce the feed and increase the speed according to the line to point 3, that is, by fully utilizing the horsepower of the machine. This procedure is recommended whenever the workpiece is unstable and/or when a high surface finish is required. The trend in production methods follows this combination of speed and feed, and will do so in the future to an increasing extent when the metal-cutting relationships disclosed by research are more fully understood in the shops.

Another possibility remains, as indicated by arrow leading to point 4. Here, the feed is increased, the speed is reduced and the horsepower is again kept constant. Tool life of high-speed steel is improved, and the metal-removal rate increases to 15.3 cu. in./min. at point 4. This is a gain of 22 per cent. However, the cutting force increases considerably; namely, from 3,200 lb at the circle to 8,000 lb at point 4. The workpiece and machine would, therefore, be considerably more deflected than they are at the circle, resulting in a poorer finish and reduced accuracy. This type of change is therefore recommended only in the case of roughing heavy workpieces on powerful and rigid machines.

B. *Time-studies of production methods*

Although numerical control is going to reduce the significance of time-studies—because handling time depends upon the commands given the machine by the tape—such studies will be required for many years to come in a great number of machine shops.

Productivity charts are also useful for time-studies, as in the case of mass production on a 2.5-hp automatic screw machine (see fig. 13), turning 1-inch brass bar stock. By following the 2.5-hp line from right to left, one obtains, for each point, a different combination of feed, speed, cutting time etc. The cutting speed increases, while the chip area (and therefore the feed) decreases, as is indicated in table 6.

Table 6

MACHINING DATA FROM PRODUCTIVITY CHART FOR MACHINING BRASS: SCREW MACHINE[a]

Point on chart	*Chip area (square inches)*	*Cutting speed (feet per minute)*	*Tool life (minutes)*	*Tool*
a	0.0040	225	60	High-speed steel
b	0.0020	375	2,000	Carbide
c	0.00064	900	1,000	Carbide

[a] See figure 13.

Which combination of feed and speed will be the most favourable in practice? Note point "c" and the two arrows shown. One arrow is placed horizontally on the 900 ft/min cutting-speed line, the other one vertically on the 0.0064 chip-area line.

The time-study engineer usually assumes a feed rate that he thinks will produce a satisfactory surface finish. The assumption is 0.0051 in./rev and ⅛-inch depth of cut, giving a chip area of 0.00064. Point "c" in figure 13 shows that a tool life of 1,000 minutes would be obtained, which is not sufficient, in view of the considerable down-time involved in changing tools, particularly, as here, in the case of mass production and short runs per piece.

The time-study engineer decides that 3,000 minutes of tool life are desirable for optimum manufacturing conditions. He consults the chart and sees that at least two answers exist for obtaining 3,000 minutes of tool life. By following the horizontal arrow at point "c", he finds that the desired tool life of 3,000 minutes can be obtained by reducing the chip area to 0.00047 square inches, which corresponds to a feed of 0.0038 in./rev and a depth of cut of ⅛ inch. The cutting time for a 1-inch length of cut would be 4.6 seconds, as against 3.42 seconds, for point "c" and 1,000 minutes of tool life.

By following the vertical arrow from point "c" down to the 3,000-minute tool-life line, the time-study engineer finds that the desired tool life can also be obtained by reducing the speed to 740 ft/min. This value is adopted because the cutting time is 4.15 seconds per 1-inch length; hence, it is less than the 4.6 seconds for 3,000 minutes of tool life, although more than the 3.42 seconds for 1,000 minutes of tool life. The cutting times are computed from:

$$t = \frac{L \,.\, t \,.\, D \,.\, \pi \,.\, 60}{12 \,.\, A \,.\, v} \text{ sec} \qquad \text{(Equation II-3)}$$

where L = length of cut (1 inch); t = depth of cut (= ⅛ inch); D = diameter (= 1 inch); A = chip area (variable); and v = cutting speed (variable).

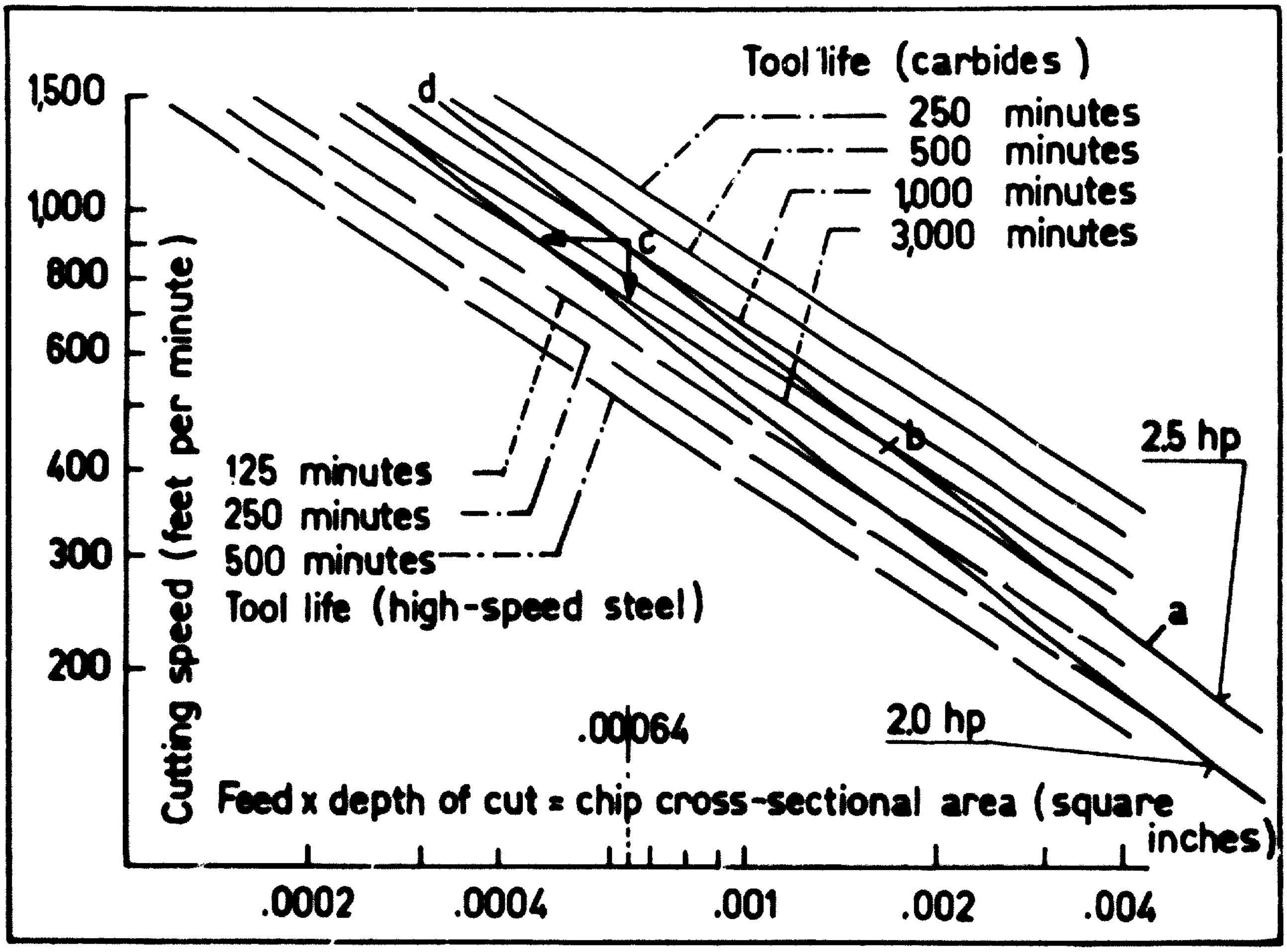


Figure 13

PRODUCTIVITY CHART FOR MACHINING BRASS: SCREW MACHINE

Charts like those discussed above can also be used by a skilled machine operator. If the operator is not able to read a technical chart, he can be furnished with tables prepared from the charts.

C. *Service life*

The design trend in machine tools is not only affected by the increase in productivity, horsepower and metal-removal rates, but also by the service life of new machines in comparison with older designs.

The service life often influences management decisions as to whether to buy a new machine or to replace an older one. Service life is, on the one hand, tied to such design features as rigidity, wear resistance and absence of vibration; and, on the other, to financial considerations. For many years, industry has been using the MAPI formulae for determining whether a new design of machine tool would improve production. The following somewhat simplified equation shows the adverse minimum (d), acquisition cost of a new machine (c) and interest rate (i) in relation to the service life of a new machine (n). The adverse minimum is the time-adjusted annual average of operating inferiority and capital cost obtainable from the equipment in question:

$$d = c\left(\frac{i}{1.4} + \frac{2n - 1}{n^2}\right) \qquad \text{(Equation II–4)}$$

It will be seen that the service life (n) is a dominant factor for comparing two machine tools with regard to their economical productivity and profitability.

Assuming the same acquisition cost of $33,000 for two new machines and service lives of fifteen years and nine years, respectively, the cost of running the machines, when the interest rate is 5 per cent, would be:

Fifteen years' service life: $d_1 = 33{,}000\ (0.05/1.4 + 29/225) = \$5{,}478$

Nine years' service life: $d_2 = 33{,}000\ (0.05/1.4 + 17/81) = \$8{,}118$

Hence, purely as a result of the difference in service life of six years, the annual savings would be $8,118 − $5,478 = $2,640, when the machine with the better service life is purchased. Over a period of nine years, the savings would be nearly $23,000. The better quality machine could even cost more and still be more profitable than the one with the shorter service life. At a cost of $40,000 for the machine with the long service life, the savings would amount to $13,250 over a period of nine years. The trend towards improving the quality is thus not only justified by engineering considerations of increased production, but also by economics.

D. *Deflection under load*

Deflection of a machine tool under load is a measure of the rigidity of the machine. This deflection, however, is much more complex than the deflection of a bar on a test stand. Deflection in a machine tool is complex because an assembled machine is composed of many parts with different fits. It is the deflection between the workpiece and the tool that is of prime importance because of its effect on the geometrical accuracy and on the surface finish of the workpiece, as well as on vibration and thus on service life and tool wear.

On a lathe, this deflection is a composite of the deflections of bed, headstock, carriage etc. With radial drills, lifting of the arm is caused by the cutting force and may lead to broken drills, inaccurate holes and uneconomical down-time.

On a horizontal milling machine, the most important deflection occurs between table and arbor. As a result of numerous tests to determine the relationship between load and deflection, it has been found that a hysteresis curve applies, as is shown in figure 14.

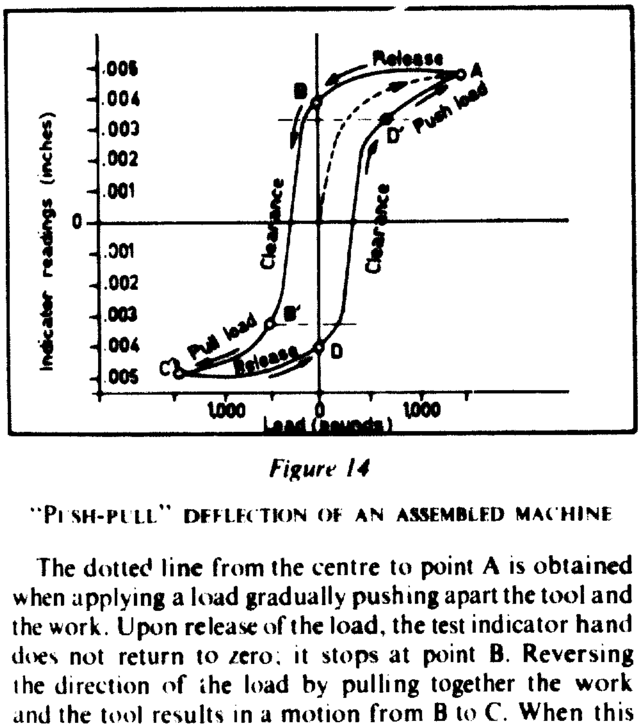


Figure 14

"PUSH-PULL" DEFLECTION OF AN ASSEMBLED MACHINE

The dotted line from the centre to point A is obtained when applying a load gradually pushing apart the tool and the work. Upon release of the load, the test indicator hand does not return to zero; it stops at point B. Reversing the direction of the load by pulling together the work and the tool results in a motion from B to C. When this load is released, the indicator hand does not go back to zero deflection, but stops at point D. If the tool and workpiece are again pushed apart with the same amount of applied load, the load-deflection curve will go again to point A, but it will travel by the D-D'-A path. This cycle can be repeated many times.

On the hysteresis loop, the straight portions B-B' and D-D' are of particular interest. They indicate the motion of assembled parts, not deflection. A load of only a few pounds is sufficient to impart a sizeable motion to the parts of the machine. This load need only be large enough to overcome friction between the assembled parts. This friction must be overcome by a load in the reverse direction so that the displacement of the parts becomes zero and the indicator hand thus stops at zero deflection. Backlash in gearings accounts for a large part of the motion between assembled parts as the load direction changes, indicated by the straight portions, B-B' and D-D'.

In the case of true deflection, energy is stored in the deflected part. This energy returns a deflected part to its original state upon release of the load, without any additional outside load, except an insignificant loss caused by internal friction. It is sometimes difficult to determine which portion of a loop is due to deflection and which to motion, since the straight portions of the loop, which are not always as distinct as those shown on figure 14, may be slightly curved.

The hysteresis loop is also a measure of damping in the assembled machine parts. In the case of vibration, such load cycles occur, but at rates that cannot be simulated by push-pull tests.

E. *Rigidity*

Rigidity of a machine tool may be defined as the ratio of load to deflection. It is easiest to use 1/1,000 of an inch as the reference deflection in determining rigidity. Hence, the load in pounds that deflects a machine part 1/1,000 of an inch represents its rigidity.

On a broaching machine, the rigidity between the column face and the broach tool was found to be 1,000 lb per 0.025 inch of deflection, which is equivalent to a rigidity factor of 1,000/2.5 400 lb/0.001 in. The load was applied parallel to the column face in order to simulate the vertical cutting-force component on a broaching tool with a shear. The rigidity of the work-table in relation to the tool was substantially less, namely, 212 lb/0.001 in. The desirable rigidity depends, of course, upon the type of work being broached. When broaching a complex contour, such as those on some vending-machine parts, a higher rigidity is required than is the case when broaching flat surfaces.

The effect of milling-machine gib tightness on rigidity can also be seen from test data. With tight gibs the hysteresis loop does not have any straight portions and the branches curved to the right and the left join each other. Deflection under load was 0.0003 inches per 1,000-lb load, corresponding to a rigidity factor of about 3,300 lb/0.001 in. Turning the set screws loose by two turns, as recommended by the manufacturer, reduced the rigidity to about one-fourth, namely, to 835 lb/0.001 in. Loosening another turn reduced the rigidity to 330 lb/0.001 in.

On a horizontal milling machine, the knee deflection was 0.0037 inch when a load of 1,000 lb was applied. The rigidity was thus 270 lb/0.001 in. when feeding to the left. When feeding to the right, however, the rigidity was only 90 lb/0.001 in. Inspection of the machine showed that when feeding to the left the load was directed against a solid dovetail. When feeding to the right, it acted against an inserted dovetail. By replacing the screws of the inserted dovetail with tightly fitted dowel pins, the rigidity was increased to about 200 lb/0.001 in.

Figure 15 shows the increase in rigidity of vertical boring mills. By changing the moments of inertia and, hence, the mass distribution (see figs. 16 and 17) of the cross-rail and of other members of the machines, it was possible to strengthen the new design considerably.

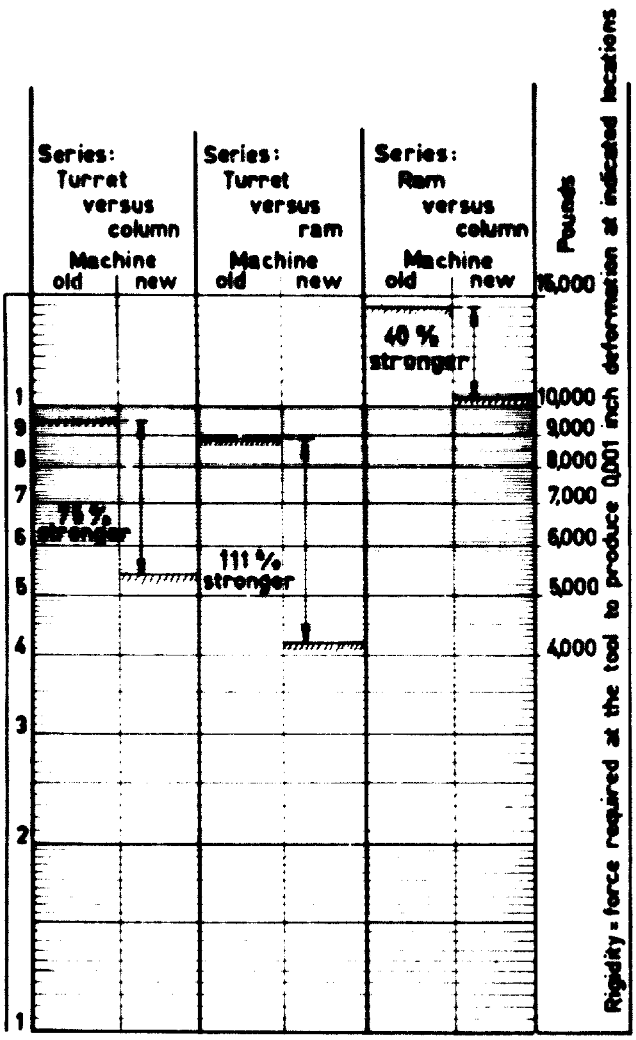


Figure 15

PRELIMINARY RESULTS OF COMPARATIVE RIGIDITY TESTS: NEW *versus* OLD 36-INCH VERTICAL BORING MILLS

Measuring the rigidity of the turret *versus* the column showed that the new machine was 75 per cent stronger. The rigidity of the turret *versus* the ram increased 111 per cent and that of the ram *versus* the column, 40 per cent.

Recently, in a similar investigation in France, the rigidity of a vertical boring mill was increased by changing the design and using a J-shaped arm, rather than modifying the mass distribution.

In precision lathes for the aircraft and space industries, very close tolerances must be met for the crosswise slope of the carriage when travelling on the bed. This requires great care in the design and production of such lathes. A combination of a cast-iron bed and a welded-steel base brought satisfactory results after several modifications of the original concept were made. These modifications were based on the results of a series of tests. Figure 18 shows this combination of bed and base, and the instruments which were used in the initial stage of investigation of the torsional rigidity. More elaborate equipment was subsequently used, after the range of measurements had been determined from the preliminary data obtained with the inexpensive set-up shown. The torque was simulated by placing varying weights on the long arms, and it considerably exceeded the torque actually expected.

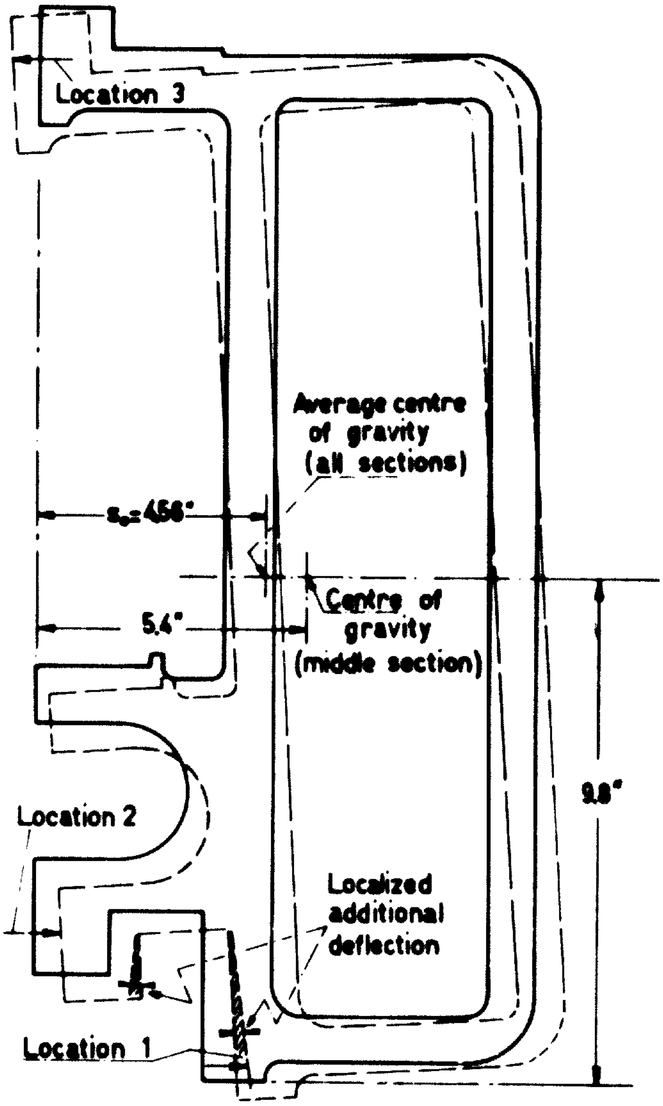


Figure 16

DEFLECTION OF OLD TYPE OF CROSS-RAIL: 36-INCH VTL

Angular displacement of bed and tool causes oversized workpieces like those illustrated by the sketches in figure 19. Horizontal displacement is considerably more severe than vertical displacement, as is indicated by the two formulae shown in figure 19. Their ratio follows:

$$\frac{u_1}{u_2} = \frac{2h \, . \, 2d}{h^2} = \frac{4d}{h} \qquad \text{(Equation II-5)}$$

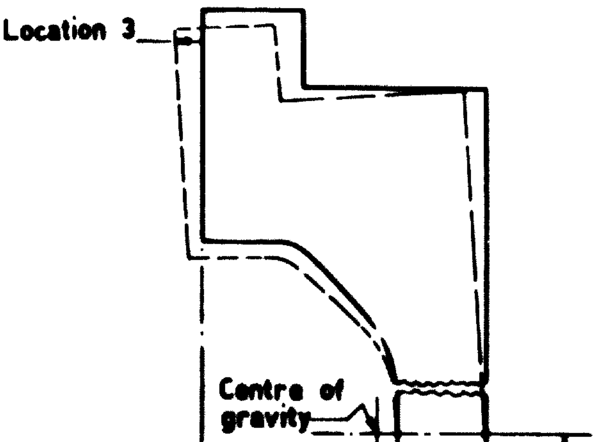


Figure 17

DEFLECTION OF NEW TYPE OF CROSS-RAIL: 36-INCH VTL

Hence, for a work diameter of 1 inch and a permissible displacement of $h = 0.0001$ inch:

$$u_1/u_2 = 10{,}000 : 1 \qquad \text{(Equation II–6)}$$

That is, a horizontal displacement between tool and work has 10,000 times more effect on the oversize of the workpiece than does a vertical displacement of the same amount. This ratio increases with increasing diameter and decreasing displacement (h).

The example indicates, furthermore, that a vertical bow in the bed is less significant in its effect on the oversize of the workpiece than is a horizontal bow. Hence, the straightness of a lathe bed in the horizontal plane is important.

Measurements of angular deflections of the bed and the base, and of the bed bolted to the base, are listed in table 7. The results are expressed in the degree of twist per 10-inch length and for a torque of 10,000 in.-lb. The torsional rigidity ratio in column 3 of table 7 is obtained by assigning a value of unity (1.0) to the bed and base combination and dividing the corresponding angular deflections.

Table 7

COMPARISON OF ANGULAR RIGIDITY

Structure	*Degree of twist per 10-inch length for 10,000 inch-pounds*	*Relative rigidity*
Bed + base	0.00253	1.00
Base only	0.00600	0.42
Bed only	0.02180	0.116

It will be seen from table 7 that the steel base is torsionally more than 3.5 times as strong as the cast-iron bed (0.42/0.116 = 3.6). The base strengthens the bed considerably, increasing the torsional rigidity by a ratio of 1.0/0.116 = 8.6. The bed, on the other hand, strengthens the base also, although to a lesser degree, namely, at a ratio of 1.0/0.42 = 2.4.

The great strengthening effect of the steel base is due to the fact that the material could be so distributed as to give a high moment of inertia. This is not as easily achieved with cast-iron designs, due to the core openings which reduce torsional rigidity considerably, while welded designs permit closed-box sections. The trend is, therefore, in the direction of increasing application of welded designs, often combined with cast-iron parts where desirable.

Figure 20 shows the deflection of heavy lathes when under axial loads, and figure 21 shows the deflection for radial loads. Axial deflections occur on lathes when the centres, holding the workpiece, are too tight and also when the heat causes elongation of the workpiece. In tropical countries, such deformation may also occur when a lathe is too much exposed to the sun. The beds warp upwards, and headstock and tailstock get out of alignment. The beds return to the original alignment upon release of the centre load and upon cooling. They may even take the shape shown in the lower part of figure 20 (pull load) when the workpieces or the cutting forces are too large and the rigidity is too low.

The radial cutting force may deform a weak bed, as is shown on figure 21. This is particularly undesirable because this type of deflection and the corresponding vibration causes oversize of the workpiece and undulated surfaces.

Another example of the trend towards finding the weak spots in machine tools and improving their rigidity is given in figure 22. Applying a vertical load at point "a" over the front wings of a lathe carriage or at point "b", outside the guideway of the front wings, it was found that the rear wings bulged upwards, as sketched in the lower part of figure 22. The design was subsequently changed, strengthening the cross-section of the wings at the centre line of the bridge.

In another series of tests, strain gauges were attached at the four radii marked a, b, c, and d on figure 22 and also shown at "A" on figure 23. Moving the carriage to the left (i.e., towards the tailstock) showed that the rear wings were trailing the front wings, deflecting the bridge, as sketched, and hence the tool also. Under oscillating cutting forces, the bridge would swing in this way and would produce the well-known vibration patterns on the workpieces. This type of vibration has received little attention so far.

The rigidity of machine-tool spindles has been investigated in the Federal Republic of Germany, where attention is being given to the behaviour of spindles supported in two bearings. Upon converting these rigidity data from the metric system, it may be seen that rigidities as high as 4,000 lb per 0.001 inch can be obtained on a test stand, i.e., when the spindle is tested outside the lathe and is supported on wedges. In view of the fact that bearings do not act like wedges, the rigidity of spindles built into the machine is less than those outside. Satisfactory rigidity values lie between 1,500 and 2,500 lb per 0.001 inch for a lathe of 10-inch swing.

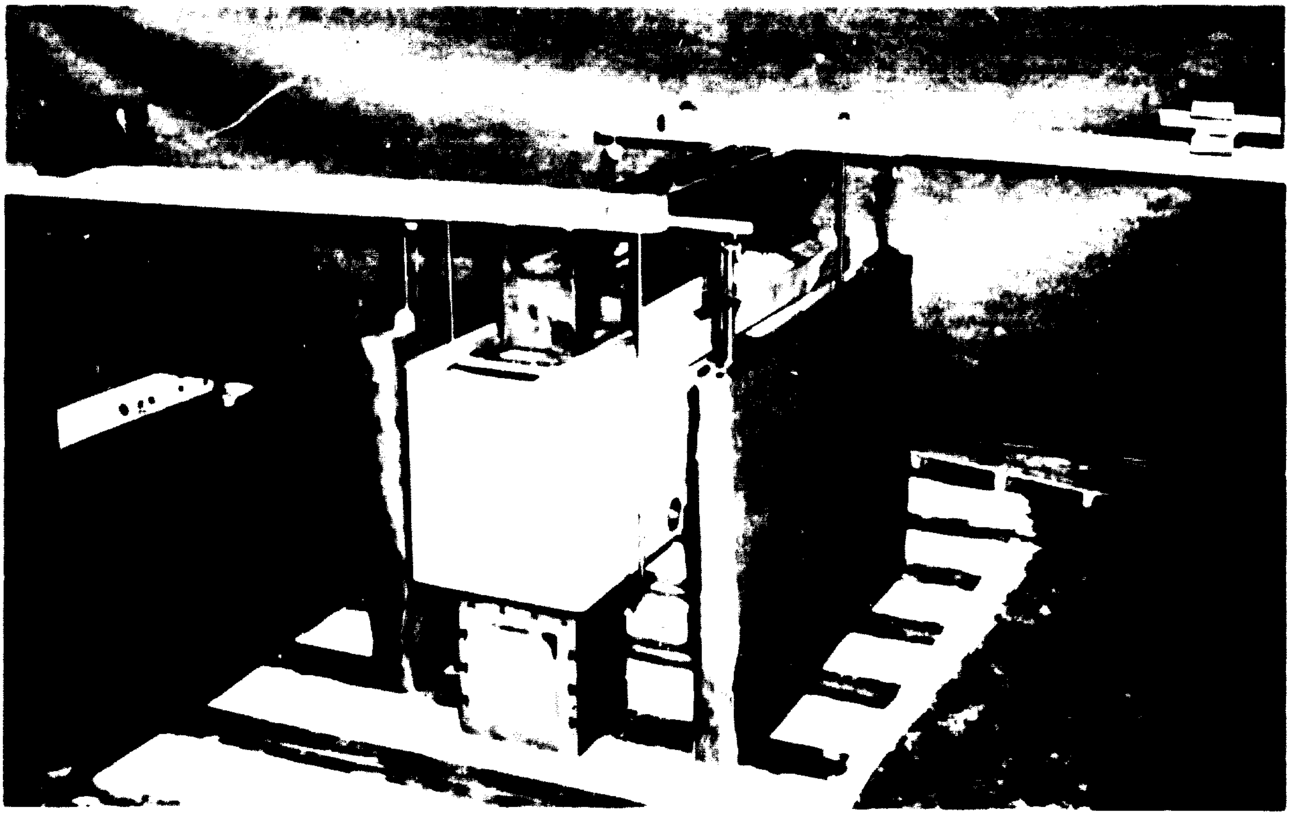


Figure 18

CAST-IRON BED AND WELDED-STEEL BASE, AND INSTRUMENTS USED IN INITIAL TESTS OF TORSIONAL RIGIDITY OF PRECISION LATHES

In the United States of America, machine-tool spindles are often supported in three bearings, and the trend is in this direction in order to increase the spindle rigidity. Three-bearing support requires, of course, a careful alignment in order to avoid permanent deformation of the spindle. The alignment depends upon the bores in the headstock; they must be machined with care on a precision lathe or horizontal boring mill. Details of the present author's investigations of the rigidity of spindles with three supports have been published previously (6). The rigidity of jog borers and other precision machine tools depends upon the number and location of the points of support. In the USSR, the angle of deflection of a jog borer supported at three points was taken as reference (7). Through the addition of four support points, the rigidity of the machine could be increased by 67 per cent. Best results, however, were obtained when a jig borer was supported at two points at the front of the base and at one point at the rear. With this set-up, the rigidity increased 180 per cent. More than three points make a rigid system statically indeterminate.

As an example of a method for obtaining high rigidity of the frame of multiple-spindle automatics, figure 24 shows a unit built by the New Britain Machine Tool Company. Headstock, base and pan are cast integrally.

The trend towards increasing the rigidity of machine tools is further indicated by the advent of hydrostatic and hydrodynamic bearings, by duplex walls, by mounts and by similar advances in the design.

F. *Vibration*

Attempts to combat vibration are closely linked to the efforts to increase the rigidity of machine tools. In the case of vibration, however, consideration must be given

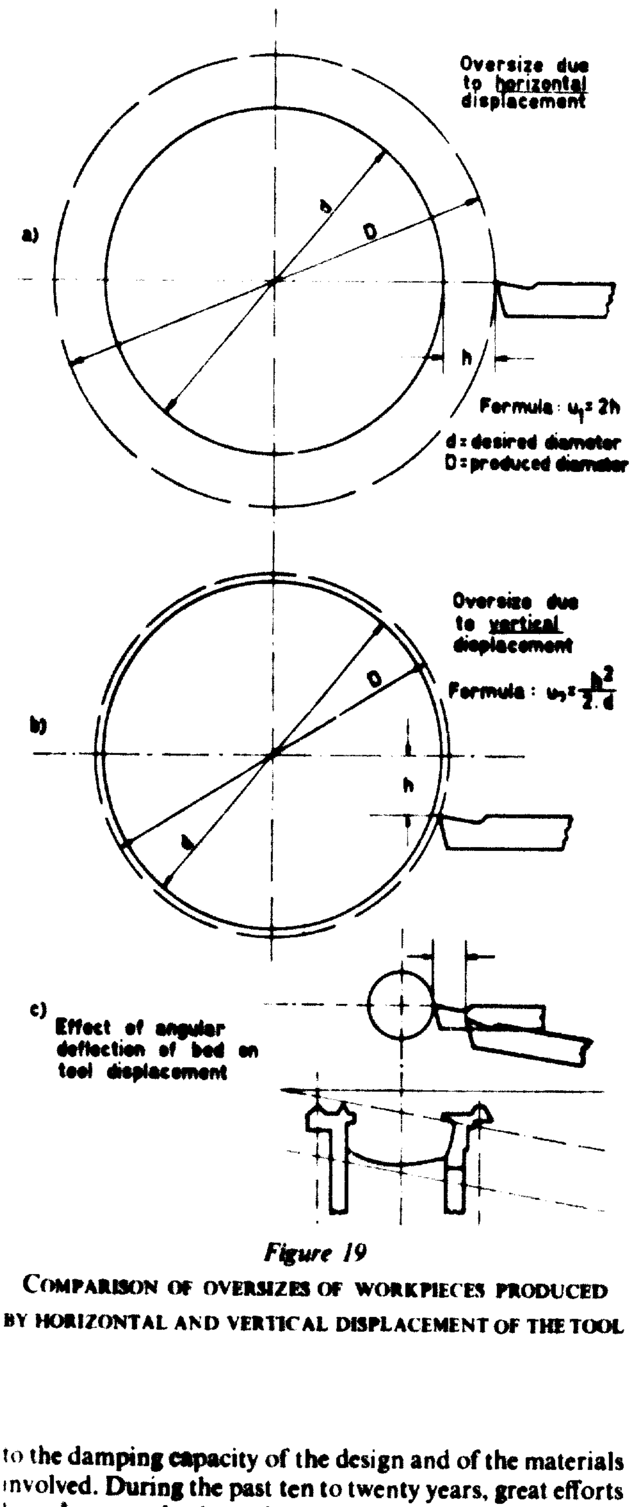
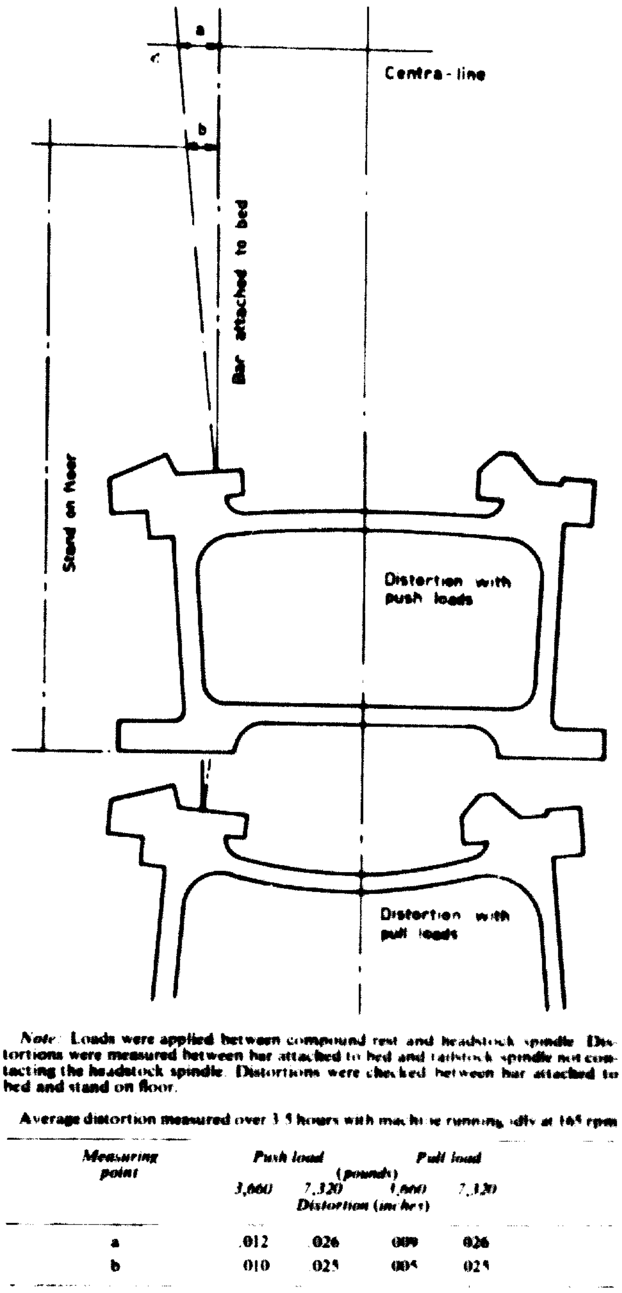


Figure 19

COMPARISON OF OVERSIZES OF WORKPIECES PRODUCED BY HORIZONTAL AND VERTICAL DISPLACEMENT OF THE TOOL



Note: Loads were applied between compound rest and headstock spindle. Distortions were measured between bar attached to bed and tailstock spindle not contacting the headstock spindle. Distortions were checked between bar attached to bed and stand on floor.

Average distortion measured over 3.5 hours with machine running idly at 165 rpm

Measuring point	*Push load* (pounds) 3,660	*Push load* 7,320	*Pull load* 3,660	*Pull load* 7,320
	Distortion (inches)			
a	.012	.026	.009	.026
b	.010	.025	.005	.025

Figure 21

DISTORTION OF BED SECTION UNDER RADIAL LOADS: 50-INCH HEAVY-DUTY LATHE

to the damping capacity of the design and of the materials involved. During the past ten to twenty years, great efforts have been made throughout the world to find the relationships between the numerous factors that affect vibra- n in machine tools, although the significance of the blems had been recognized for many more years (6). order to reduce the number of factors, a serrated bar s used as a vibration exciter, thus eliminating the ffects of dulling of the tools, chip formation, hard spots n the material and the like, which are difficult to control nd to evaluate in the case of exciting vibration under ctual cutting conditions. Subsequently, other exciters, such as electric and magnetic fields, were used. In the case of the serrated bar, the direction of the exciting force could be so directed as to simulate the direction of the main cutting force.

In this way, the effect of mounting a carriage on two different designs of lathe beds could be studied, and improvements in vibration performance could be obtained. Figure 25 shows the results. The shaded areas indicate the improvement obtained by the new design. It will be seen that the intensity of vibration, measured with strain gauges, exceeded the admissible value of 40-millionth of an inch per inch for almost all spindle

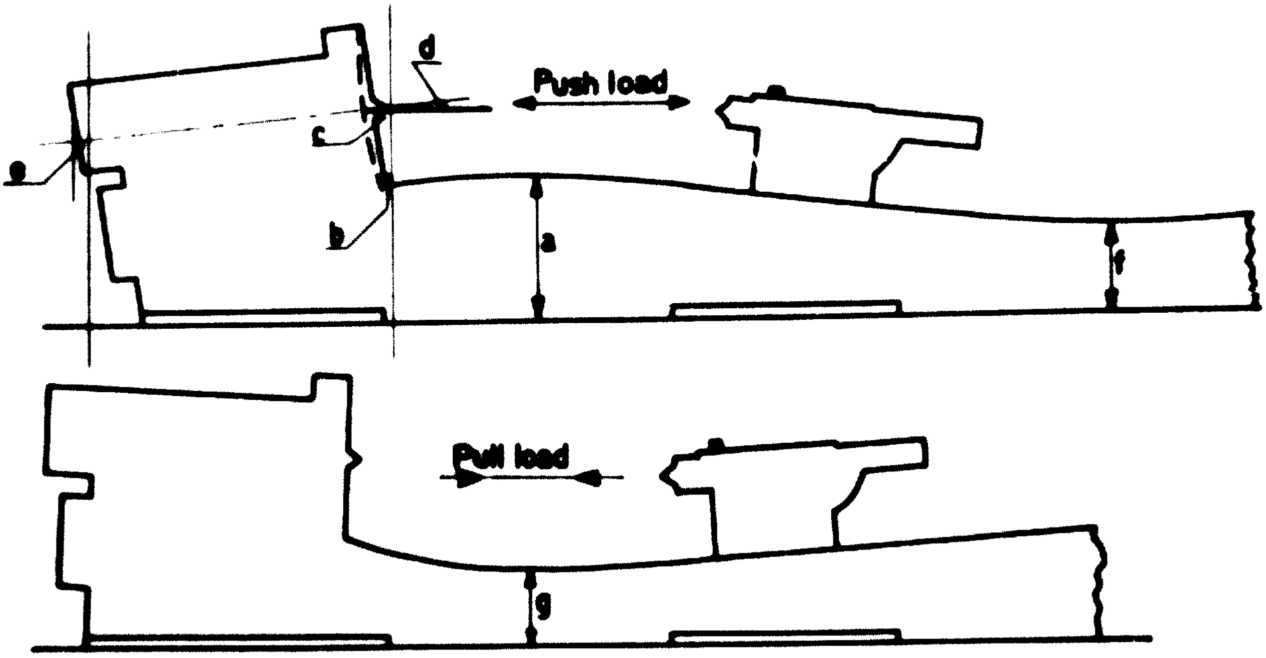


Figure 20

DISTORTION OF 50-INCH HEAVY-DUTY LATHE UNDER AXIAL LOADS

Measuring point	*Load (pounds)*	*Deflection at Guideway (inches)* Front	Rear	*Centre-line*	*Direction of deflection*
a	27,000	.0030	.0055		Vertical (increase)
	7,300	n.m.*	.0014		Vertical (increase)
b	27,000			.0013	Horizontal
c	27,000			.0075	Horizontal
d	27,000			.0025	Vertical (increase, 10 inches from spindle end)
e	27,000			.0065	Horizontal
f	27,000	— .0010	0		Vertical (decrease)
g	7,300		— .0014		Vertical (decrease, pull load)

*n.m. = not measured

speeds except the lowest ones of less than 180 rpm. In the new design, the intensity of vibration is well below this value, except in the area between 300 and 380 rpm.

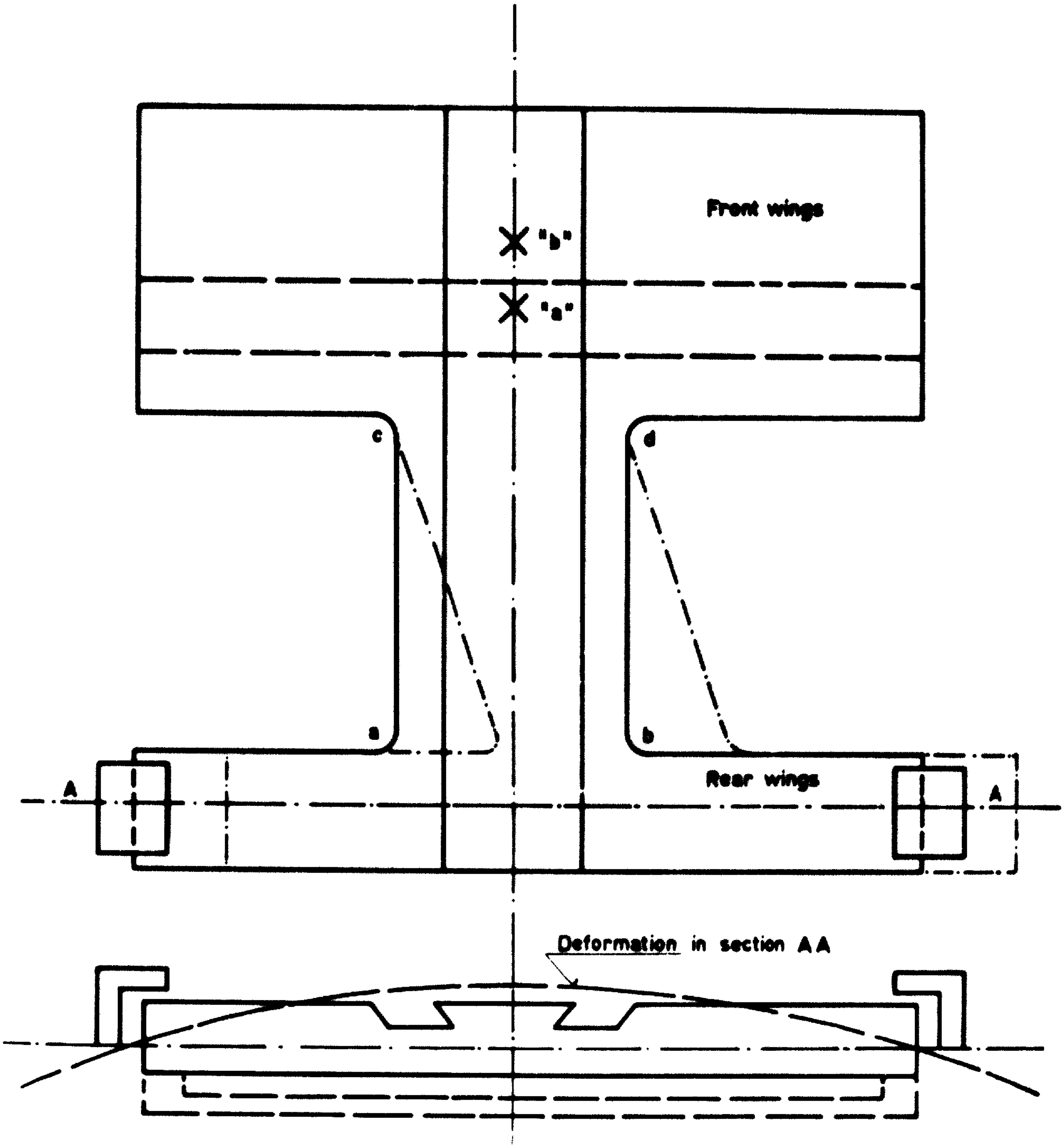
Figure 26 shows the enlarged surface with vibration marks of a workpiece rotating in the vertical direction of the paper. The change in the pattern from an inverted "v" at the right side to slightly slanted vertical lines at the left is owing to the stiffening effect of the chuck which the tool approached when travelling towards it. In this case, long slender bars had to be machined without the help of steady rests. Vibration was generated by the resilience in the compound rest for the tool, which was, however, reduced by the resistance offered by the chuck and by the shorter distance between tool and drive gears. After changing the design of the compound rest, vibration was reduced, although not entirely eliminated.

The vertical bending vibration is considerably less when the machine is supported by wedges than when it is mounted on rubber. The bending vibration in the horizontal plane, which is, in this writer's opinion, often more important than vertical vibration, follows the same trend. That is, it is better reduced by wedges than by rubber. These findings will be useful in the design of mounts and other support means.

While it has been customary to improve the design of machine tools on the basis of practical experience and customers' reactions to existing models, the trend is now shifting towards a more scientific approach based on thoroughly conducted research. The results are finding their way into the engineering offices more readily now than ever before.

The change in the bed design may serve as an example. The so-called "zig-zag" or "Peter" system of ribbing lathe bed has been used in Europe for many years, but it is being increasingly discarded, due to new findings in the Federal Republic of Germany (8). This bed design was never popular in the United States of America. The zig-zag girth has great torsional rigidity (see Fig. 27), but it is lacking in horizontal rigidity in comparison with other ribbing designs. It may thus tend to produce oversize workpieces. Also, it does not permit a free chip disposal; rather, they accumulate on the top of the ribs and heat up the bed, which is undesirable from the standpoint of accuracy. The new German design has 50 per cent more chip space and a built-in vibration damper. The built-in damper consists of the core sand, which is deliberately left in the cavities of the bed and is covered with metal plates to retain the sand at the desired places.

The three-bearing spindle design has already been mentioned in conjunction with the rigidity considerations. It is now being used in European machine tools also, due to findings that the tail bearing acts as a vibration damper. The pre-loaded front and middle bearings take the load, while the tail bearing provides, in addition to damping, support for the belt drive. The tailstock spindles of European machine tools are made more rigid and the overhang of the headstock centres is reduced.



Note: Figure 22 illustrates the deflection of rear wings when vertical loads are applied over front shear (at "a") or outside of front shear (at "b") and when the ends of rear wings are held down, simulating the effect of a rear gib. The —.—.— contour lines show the deformation of the bridge under dynamic testing (grossly exaggerated), is offering an approach for exploring some types of machine-tool vibration.

Figure 22—CARRIAGE DEFLECTION TESTS

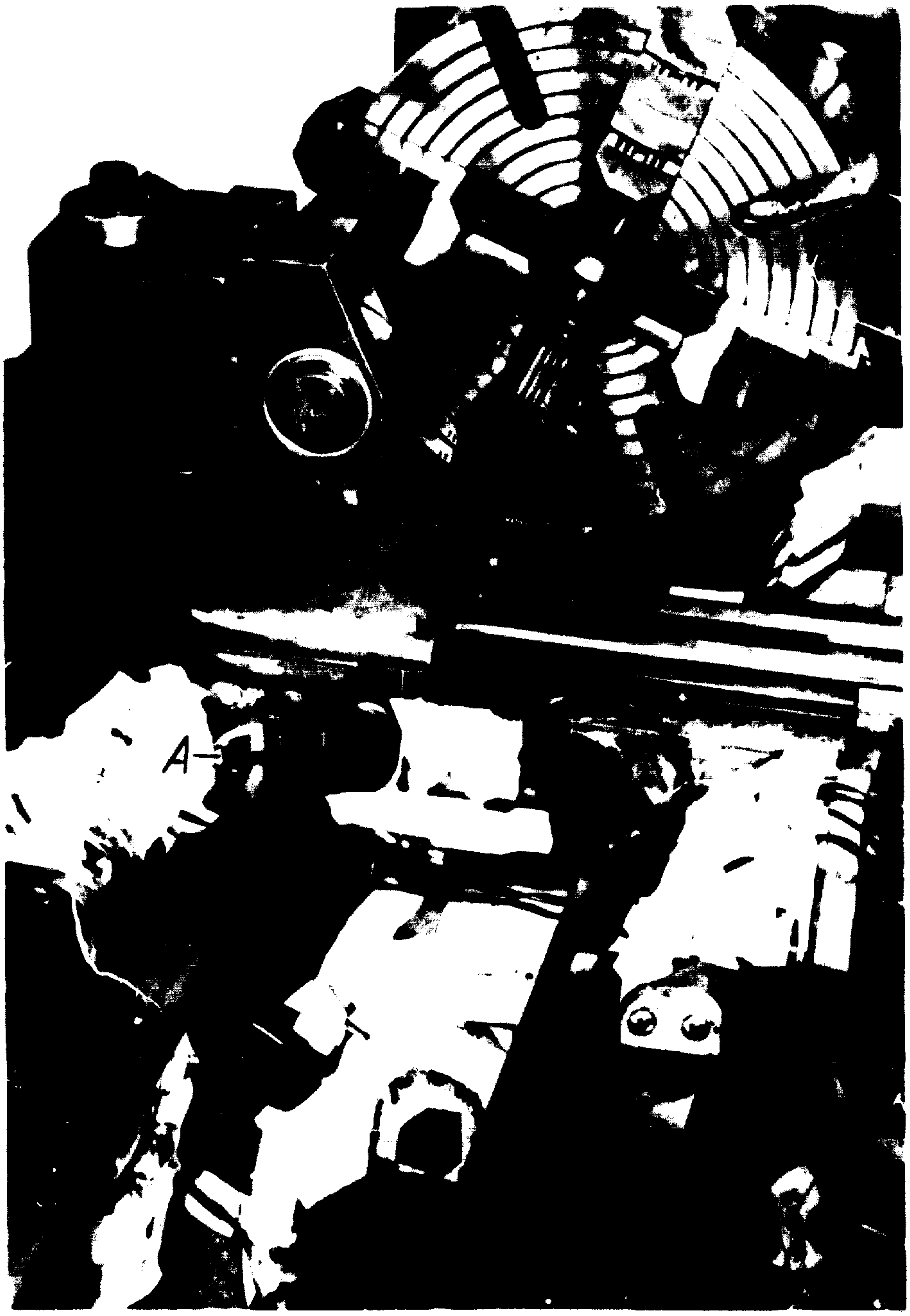


Figure 23

TESTING OF RIGIDITY WITH STRAIN GAUGES

Due to the fact that various types of vibrations — forced vibrations, self-induced vibrations etc. — occur in metal cutting, it is essential to find out, in every case of vibrational trouble, which type is predominant. In the author's experience with vibration in machine tools, it was found that many lathes, grinding machines, milling machines etc. have natural frequencies in the area of approximately 20 cps ± 20 per cent. It is thus essential to avoid motors and gear drives that may come into resonance with the natural frequencies mentioned. Often, it is advisable to separate motor and machine; in other cases, it is sufficient to balance the motor, while in still other cases, it is necessary to eliminate shaft speeds in the gearing running in the indicated area of natural frequencies.

It is considerably more difficult to reduce or eliminate self-induced vibration than forced vibrations becaus their origin often cannot be located. Sometimes it i advisable to modify the cutting conditions, that is, i cases where the rigidity and the damping capacity of

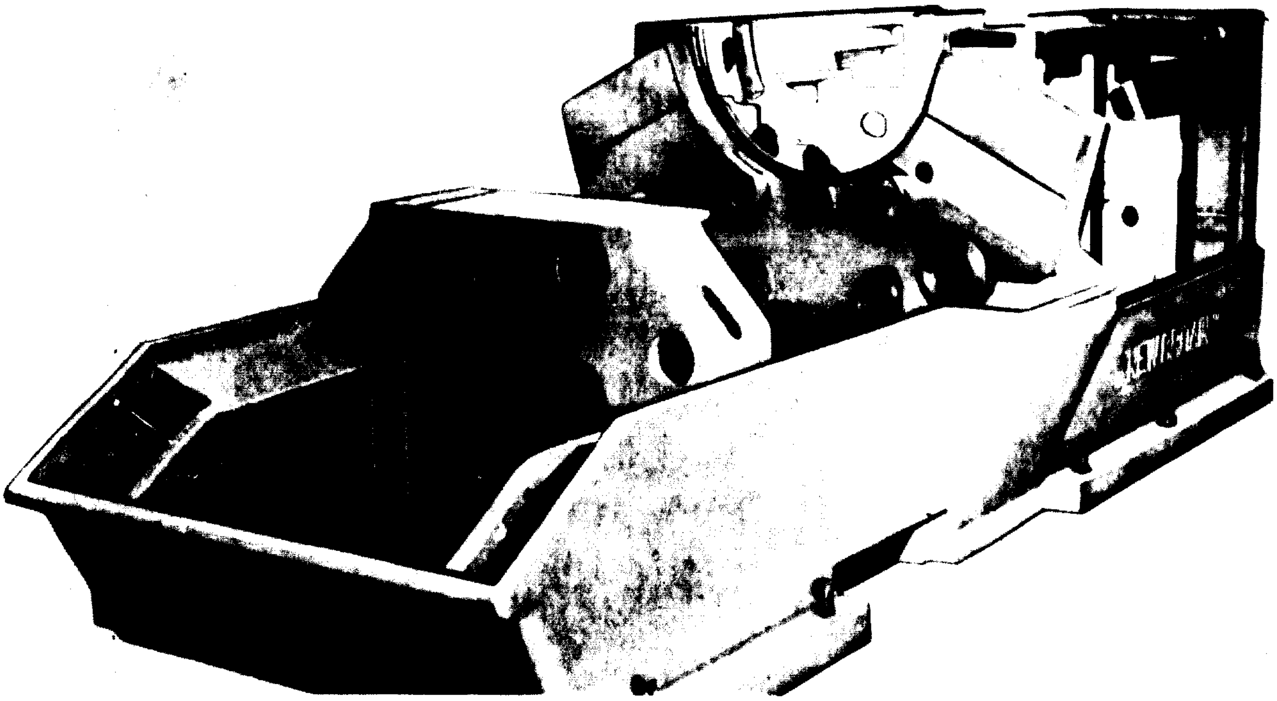


Figure 24

RIGID BED DESIGN

given machine cannot readily be changed. Such modifications include changes in speed, feed, tool geometry, coolants etc.

Reversing the direction of work rotation on a lathe has often eliminated or reduced vibration and thus improved production techniques. Figure 28 illustrates these improvements, expressed in reduction in amplitude of vibration. They are very substantial in both the horizontal and the vertical planes. As an example, consider the case of 97 rpm, where vibration amplitudes at the front bearing were measured. They were 0.000,030 inch when the machine was rotating in the normal direction, but dropped to 0.000,010 inch upon reversal of the spindle rotation and placing the tool at the rear side of the carriage. This is a reduction of 95 per cent. Similar improvements were realized in almost all cases, except when running at 97 rpm and measuring the amplitude at the rear bearing in a horizontal plane. A number of overlapping conditions contribute to these results, among them a change in the damping due to the reversal of the direction of the main cutting force. The reversed rotation does not tend to lift the workpiece, but pushes it down; similar considerations apply to the forces at the drive gears and at the tool-holder and to the mass distribution in the carriage and other machine parts.

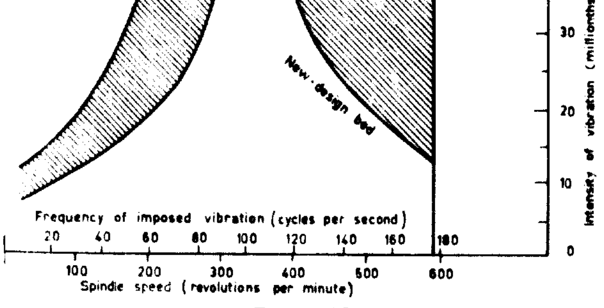


Figure 25

CARRIAGE VIBRATION

The damping capacity of cast iron is generally assumed to be greater than that of steel. This holds true in many cases, namely, when the same stress is applied to these materials. As an example, if the damping capacity for cast iron is 0.28 in.-lb/cu. in./cycle at a stress of ± 6,000 psi, it would only be 0.08 for steel at a vibratory stress of the same magnitude. However, by increasing the stress in steel to 9,000 psi the damping capacity would be raised to the same level as that of cast-iron at 6,000 psi. Hence, in order to obtain satisfactory damping in steel designs, it is necessary to increase the stress. This means using thinner walls in a steel structure than are used in a cast-iron structure. Duplication of cast-iron dimensions in steel must be avoided in machine tools, where it is not the rupture strength of the material that counts, but the deflection or rigidity. Reduced wall thickness means also less weight, which is often desirable because of the increase in natural frequency of a structure.

Figure 26

ENLARGED SURFACE WITH VIBRATION MARKS OF A WORK PIECE SHOWN ROTATING VERTICALLY

The following practical rules for vibration control in machine-tool design are recommended: (*a*) design for rigidity; (*b*) develop high damping capacity; and (*c*) design for light weight and high natural frequency (9). These rules have been effectively applied in the design of bases for internal grinding machines (see fig. 29). The centre portion, comprising plates "a", "b" and "c", and bottom "d", was designed as a closed-box section—the same as the rest of the base—for high torsional rigidity and also to establish a node of vibration at the centre. Cross-walls and internal walls were made of 3/16-inch sheet steel and the outside walls of ¼-inch gauge. The entire base has no openings except for a tube connexion, a feature which contributes to high rigidity.

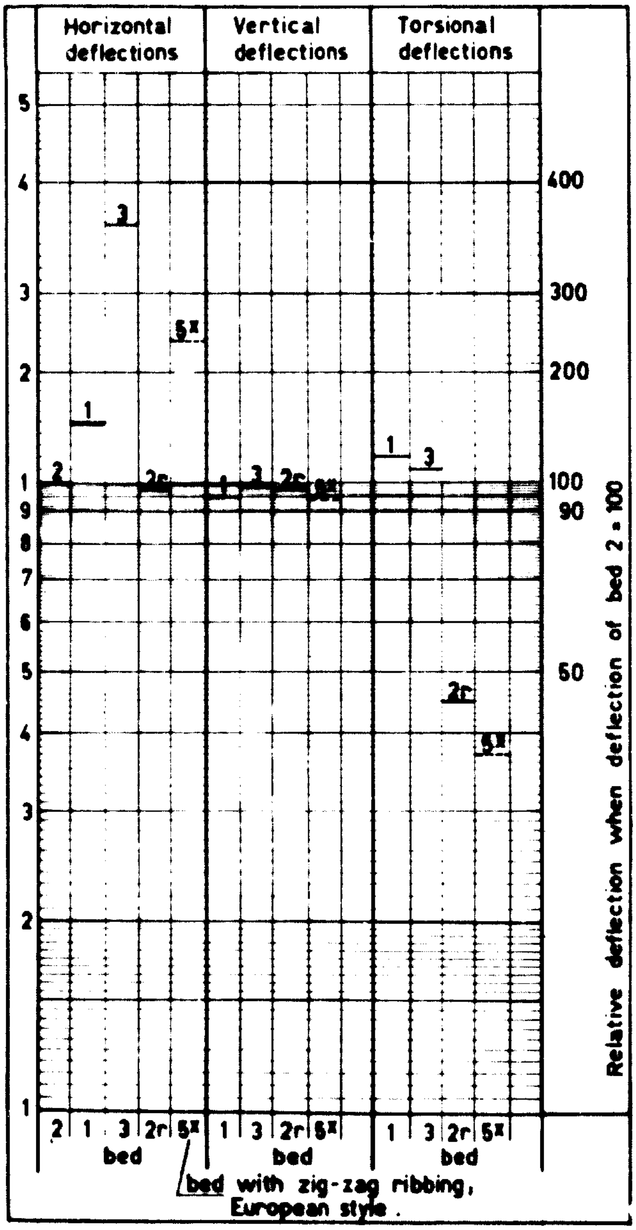
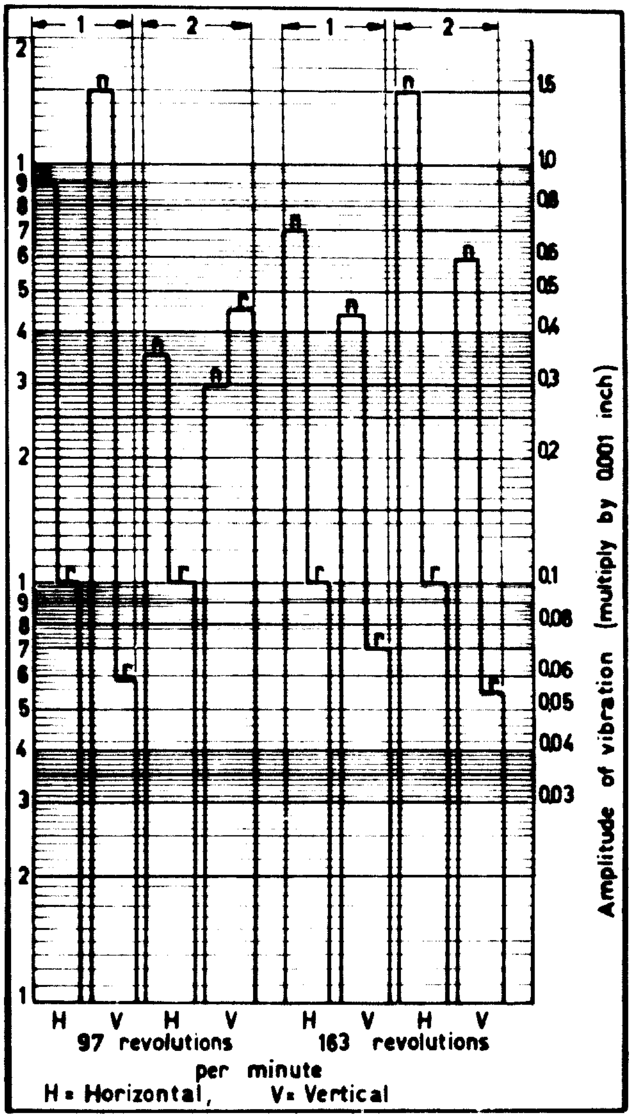


Figure 27—COMPARISON OF HORIZONTAL, VERTICAL AND TORSIONAL DEFLECTIONS (DEFLECTION OF BED 2 = 100)

In internal grinders, vertical rigidity is more important than rigidity in other planes because misalignment in the vertical planes has the greatest effect on workpiece accuracy. For this reason, walls "e" were placed vertically and were designed in a V-shape. The open ends of the V's contribute also to horizontal rigidity. Cross-walls "f" and "g" were run to the V-shaped walls in order to eliminate local "drum" effects and to increase the damping capacity by increasing the stress. The sequence of welding is shown on figure 29 by circled numbers.

Vibrations in vertical boring mills are largely influenced by the rigidity of the ram and cross-rail. This was confirmed by investigations in the Soviet Union (10). The ram and the tool with it vibrate in two directions, namely, perpendicular and parallel to the cross-rail. The



Note: n = normal spindle rotation, tool on front side of carriage; r = reversed spindle rotation, tool on rear side of carriage; 1 = measured at front bearing; 2 = measured at rear bearing.

Figure 28—DUAL-DRIVE LATHE, 15-INCH: AMPLITUDES OF VIBRATION UNDER FACE PLUNGING CUTS, EFFECT OF REVERSING SPINDLE ROTATION

ram itself contributes 80 per cent of this type of vibration, with the balance coming from the rail. In other cases—particularly when the rigidity of the cross-rail is low—the vibration of the tool is controlled by the oscillations of the cross-rail.

In the United Kingdom, vibration investigations on milling machines confirmed findings in the United States of America (11) on the initial impact of cutter and work, and the significance of placing the face mill, in relation to the workpiece, in such a position that the tip of the cutting edge does not enter first. In this way, production increases can be obtained because of reduced breakdown of the cutting edge. Supplementing these findings, investigations were also undertaken in the Federal Republic of Germany (12), as illustrated in figure 30. In the case of a long time (0.2 milliseconds) of engagement of cutter and work (see fig. 30A), the vibration due to impact is small. In the case of a short time (0.027 milliseconds) of engagement (see fig. 30B), the amplitudes of vibration are considerably heavier, causing rapid breakdown and production delay. These production troubles can be avoided by the proper positioning of work and tool, which is particularly important when machining aircraft materials with carbide or ceramic inserts in face milling-cutters.

G. *Accuracy, surface finish and thermal distortion*

Every skilled machine-tool operator is well aware of the fact that his machine performs differently in the morning and in the afternoon, rendering it necessary to reset the tools and adjust gibs often, and to watch the dimensions of his workpieces carefully.

His experiences are due to thermal expansion, which affects production particularly in so far as accuracy and surface finish are concerned. Scrap is often the consequence of neglecting the effects of thermal distortion. This applies to those countries in which high accuracy is required in the aircraft and spacecraft industries and also to developing countries located in climates where considerable temperature variations may take place during a short time period without the benefit of air-conditioned workshops.

The largest temperature differentials and distortions usually occur during the first two hours of warm-up. Thermal expansion is going to have increasing significance with the increase in spindle speeds. Although automatic inspection processes or control of workpieces may minimize the scrap due to thermal expansion, it is most important to know how a production machine reacts to changes in temperature.

In tests for thermal distortion, temperature rise

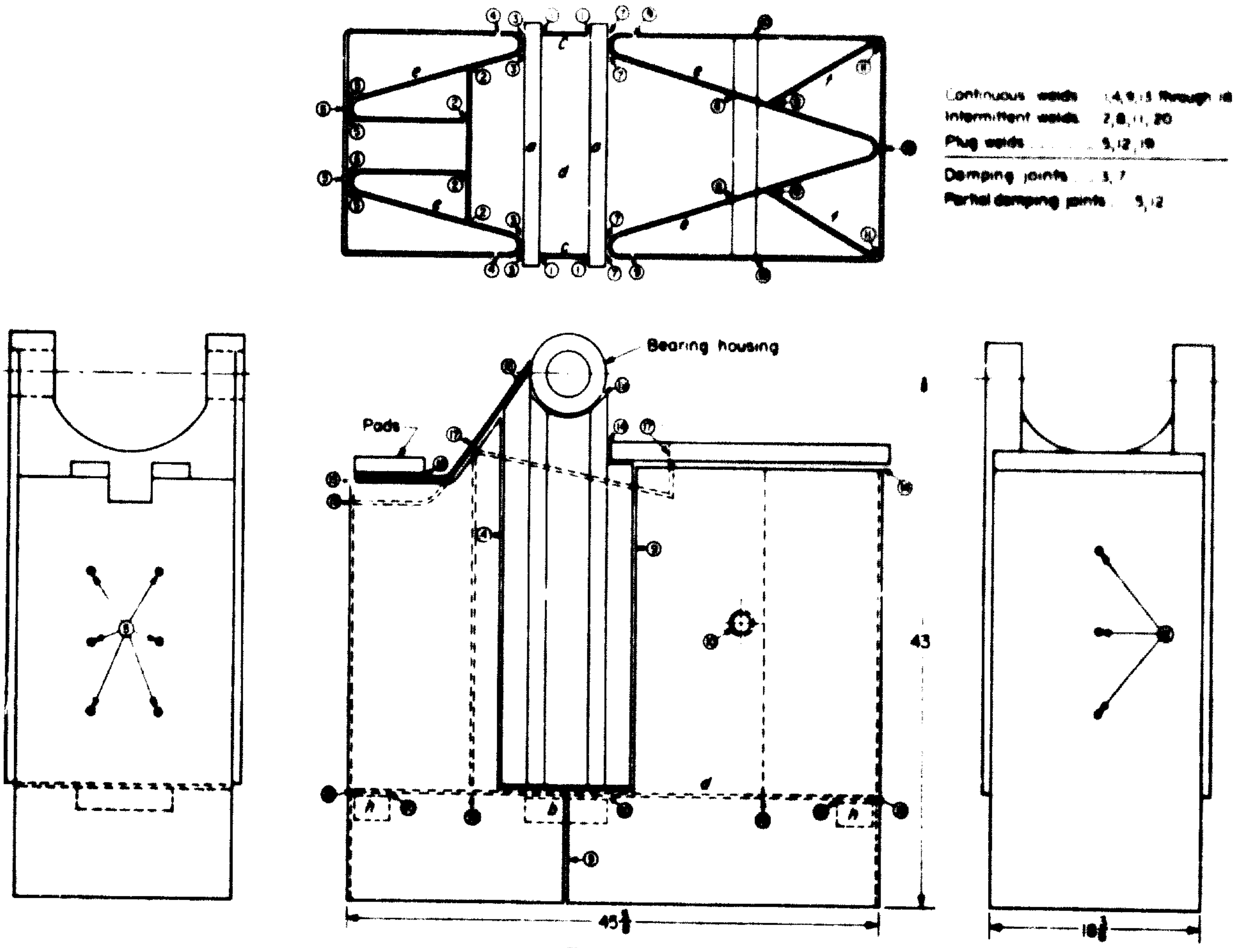


Figure 29

DETAILS OF WELDED GRINDING-MACHINE BED

should be measured with regard to ambient temperature. Test procedures vary in accordance with the requirements. They can be adapted to the conditions of idle-running machines or to machines running under load, and can even be so set up that a temperature rise inside a machine [illegible] is produced by employing electric or other [illegible] heaters.

Thermal [illegible] between the spindle and table of a vertical milling machine takes place in three major directions (see fig. 31, top). Heat developed in the column causes an upward movement of the head and spindle carrier. Heat generated in the spindle carrier itself causes the spindle to move down. These movements balance each other to some extent, but they do not necessarily occur at the same time. The spindle may rise slowly and then drop again until a condition is reached where only the spindle rises. This irregular rise usually occurs during the first two hours of operation of a vertical milling machine. In addition, there is an outward movement of the spindle carrier.

With horizontal milling machines, the spindle-table movement is more uniform; in most cases, it only rises.

Figure 31 gives an example of the temperature rise (upper portion of lower section) and the corresponding vertical expansion between table and spindle (lower portion of lower section) of a vertical milling machine running at 450 rpm. The curves indicate the conditions before and after improvement of the machine design, and of servicing it.

The temperature increased 30° F during a seven-hour period, resulting in an ultimate vertical expansion of 0.004 inch. The bearing design was changed, as was the supply system for the lubricant, reducing the amount of oil flowing to the bearings. It was found that too generous a supply of lubricant caused the bearing to heat because the oil was churning at high spindle speeds and lost its effectiveness. After these improvements were made, the temperature rise after seven hours was only 6° F, with an ultimate expansion of 0.0006 inch. The dip in the vertical expansion during the first two hours was even more pronounced after the improvements than before they were made. This is clearly indicated by the two lower curves. The reductions in temperature rise and in expansion were about 80 per cent.

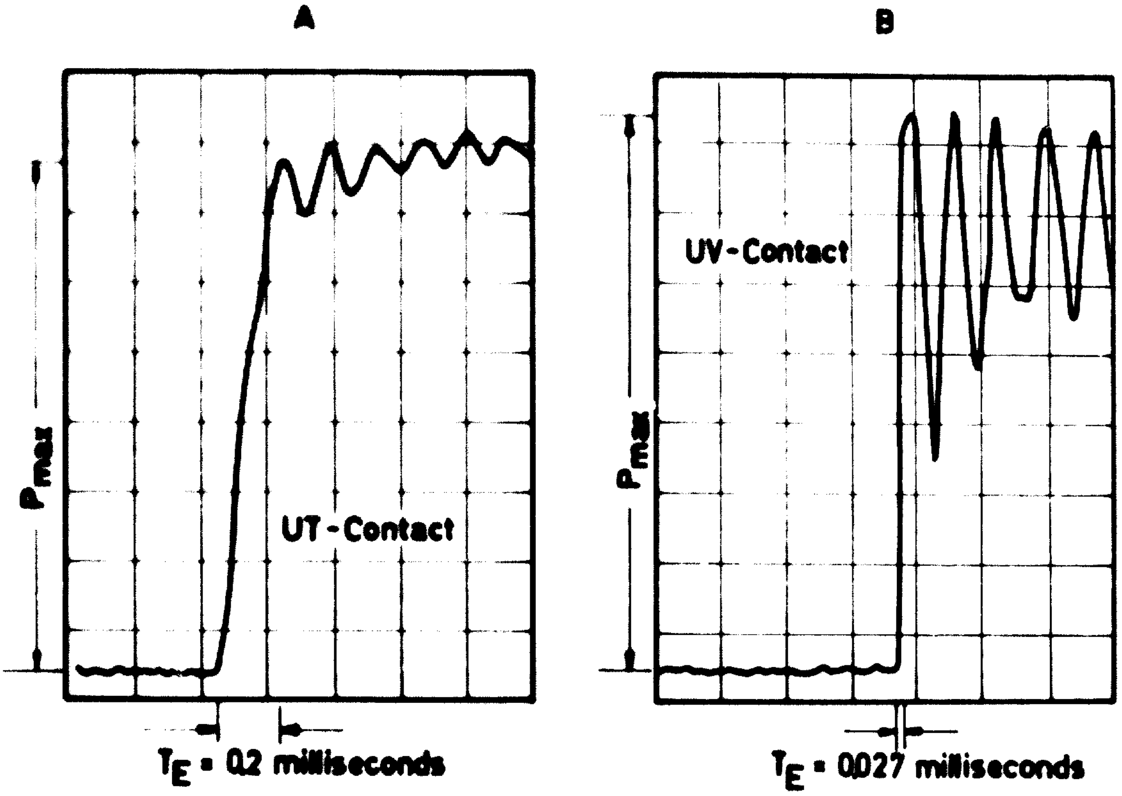


Figure 30

COMPARISON OF AMPLITUDES OF VIBRATION ACCORDING TO TIME OF ENGAGEMENT OF CUTTER AND WORK

In horizontal boring mills, even more complex conditions prevail. The machines bore more accurate holes when they are cold. To avoid vibration, however, a warm-up period is desirable. The main reason for these contradictory performances was found to be in the spindle-carrier assembly. The lubrication of the cold machine was insufficient, resulting in metal-to-metal contact in the anti-friction bearings. This condition resulted in self-induced vibration. After warm-up, no substantial metal-to-metal contact existed and the self-induced vibrations vanished. However, the hole accuracy was then poor. This could be traced to the spindle rise and the thermal expansion of the housing. In order to remedy this situation, the oil inlet system was redesigned to permit oiling of the rollers during the warm-up period, eliminating vibration. The oil supply was simultaneously decreased to reduce the thermal expansion and thus to improve the working accuracy of the respective types of horizontal boring mills.

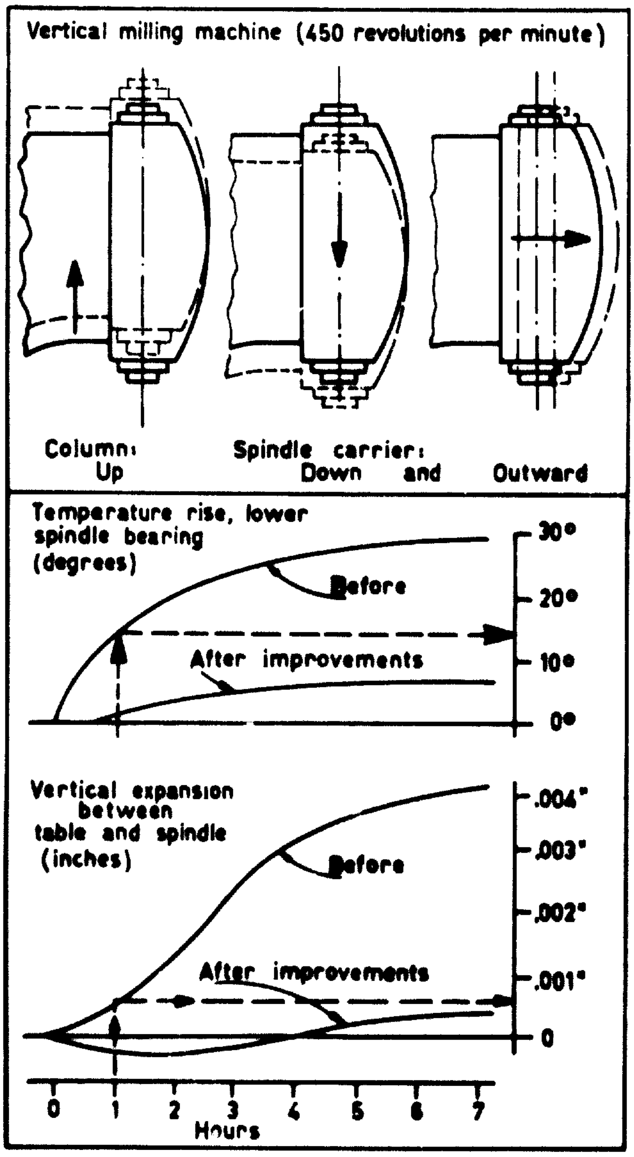


Figure 31

THERMAL EXPANSION OF VERTICAL MILLING MACHINE BEFORE AND AFTER IMPROVEMENTS

The heat developed by drive motors and pumps, which are often located in the base of machine tools, is another source of thermal expansion and corresponding deformation of the structures. To find remedies for these conditions, research was carried out using electric heaters placed in the motor compartment in order to simulate heating of the base under temperature-controlled circumstances. Figure 32 shows an example of the results. The front wall of the machine rose, while the rear wall dropped. This effect indicates that the heat generated in the drive compartment is equivalent to a torque applied in the opposite direction to the torque caused by the cutting force. Thus, in this case, the heat had an acceptable effect of compensating the cutting torque. It depends upon the wall thickness of the base, the location of louvers and the cut-outs whether the front or the rear rises more and in what direction. In the discussed case, the front rose more than the rear dropped. This could be improved and equalized by making the wall thickness at front and rear somewhat different.

On planers, the room-temperature variations affect the table temperature more than the bed temperature. Thus, the table expands more than the bed, a situation which is aggravated by the fact that the hot chips pile up on the table, heating it still more. When the width of the table increases as a result of thermal expansion, the table tends to climb out of the guideways, pushing against the outer walls of the V's. This tilts the table sideways and, with it, the workpiece changes its position in relation to the tool, causing inaccurate machining. Although the oil film tends to compensate for the table tilt, the stability of the table decreases with increasing temperature. Research is still under way in order to find out whether planers with a single V or with duplex V guideways will permit greater accuracy. The increase in table speeds for planers will have a considerable effect on the problems and the trend of future designs.

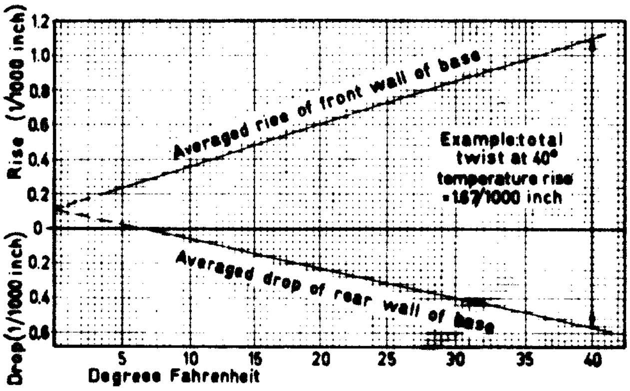


Figure 32

TWISTING OF BASE DUE TO HEAT IN VARIATOR COMPARTMENT, MEASURED HALF-WAY BETWEEN HEADSTOCK AND TAILSTOCK LEVELLING PADS

(INITIAL TEMPERATURE = 75°F)

H. *Acceptance tests for accuracy of machine tools*

The current situation in newly industrializing countries is reminiscent of the situation which prevailed nearly forty-five years ago, when the build-up of the industry in the USSR was initiated by purchasing machine tools from several industrialized countries. At that time, in conjunction with the need for examining numerous machine tools, the Schlesinger Acceptance Tests were developed, with the participation of the author.

Much can be learned from past experience and from an analysis of a few examples of the original Schlesinger data and a comparison of them with later modifications.

The requirements of countries which are currently developing may have a similar bearing on future trends of a significant sector of machine-tool development and design.

From the numerous accuracy data which comprise the Schlesinger tests, seven requirements have been selected for preliminary analysis and comparison. These requirements are listed in table 8, which covers data of the Schlesinger tests and of acceptance tests used in the United States of America, and data used by the Government of India.

Table 8

COMPARISON OF SEVEN ACCURACY REQUIREMENTS FOR ENGINE LATHES ABOVE 32-INCH SWING

(MAXIMUM PERMISSIBLE DEVIATION IN 1/1000 INCH)

Source	*1*	*2*	*3*	*4*	*5*	*6*	*7*
Schlesinger	0.36	0.60	0.60	1.20	0.4	0.8	0.8
National Machine Tool Builders Association	1.00	0.60	0.75	1.00	0.5	0.8	1.0
India	0.40	0.80	0.80	0.96	0.8	0.8	0.8

1 = bed level, longitudinal; 2 = run out of spindle; 3 = cam action of spindle; 4 = vertical headstock alignment; 5 = horizontal tailstock alignment; 6 = lathe must turn round, workpiece chucked; 7 cross-slide alignment.

The few examples given in table 8 show that the standards for accuracy do not agree entirely. In some cases, the Indian standards are less demanding; in other cases, the reverse is true. All three standards are in agreement, however, on the requirement that a lathe must turn round within 0.0008 inch when the workpiece is chucked.

All these data are based on idly running machines, i.e., without load. A trend which is gaining strength is to include tests for accuracy under load. The obstacles, however, are great. On numerous occasions, suggestions have been made to include load tests, for instance, as early as 1933, by Salmon in France (13). Thus far, however, such methods have not been adopted. Possibly an international organization could handle this situation, taking into consideration the requirements of the newly industrializing nations and the development in measuring instruments, some of which were not available when the first Schlesinger standards were prepared.

Among these instruments there are autocollimation telescopes for determining the waviness of machine-tool beds, the parallelism of spindles, the tilting of clamping devices etc. Fundamentally, such telescopes are reversed alignment telescopes in which the ocular is replaced by an illumination attachment. They are accurate within 48-millionths of an inch over a distance of 10 feet, which is about ten times better than the accuracy of conventional telescopes. While these instruments were developed in the Federal Republic of Germany, a device was designed in the United Kingdom for continuous measurement of alignment errors with feed-back compensation. Photocells measure the deviation of a light beam travelling through an optical micrometer.

1. *Surface finish*

While it may not be necessary to measure to one-millionth of an inch in many cases, the trend towards measuring to 50 Angström units is gaining momentum in the spacecraft industries. This dimension is approximately one-fifth of a millionth of an inch.

Similarly, the demand for better methods of producing and measuring a surface finish of high accuracy is increasing. The difficulties involved are related to the fact that surface-finish designations in micro-inches may signify different dimensional deviations in Europe and in the United States of America. As an example, in the Federal Republic of Germany, the *Rauhtiefe* (roughness valley) is taken to indicate surface finish; it is the value of the greatest depth of the surface in relation to the greatest peak. Such a system, it is claimed, represents values closely associated with the feed and depth of cut taken on a machine tool and can readily be realized by the man in the shop. Another dimension used in the Federal Republic is *Glaettungstiefe* (smoothness depth), the distance of a reworked surface from the initial peaks. A good surface is indicated by a small value for this dimension.

The wear resistance and strength of a surface are determined in the Federal Republic of Germany by the portion of the profile which supports the load in the longitudinal direction of the ups and downs. In the United Kingdom and in the United States of America, the arithmetical mean of the roughness valleys is used. It involves a mathematical concept which is difficult to understand in the shop. Formerly, the root mean square was used, and it still is in many instances, in the United States of America. The arithmetical mean has the advantage of a reduced scattering of data and permits the use of relatively simple measuring instruments.

There is also a trend towards the adoption of a later European suggestion (14) for surface-finish standards, based on the so-called "envelope profile" (E-profile) instead of the older mean line (M-profile). Roughness and dimensional deviation, which are often confused in the M-system, are clearer in the E-profile. This system has been incorporated into standards DIN 4760 and 4762 of the Federal Republic of Germany; it has also been adopted in Denmark, Hungary, Italy and Switzerland. It is claimed that production of accurate surfaces is simplified by the E-system because the mean line can be determined nine times faster than with the M-system.

Various methods have been developed for producing highly accurate surfaces; for example, the so-called "superfinish" method employing high-frequency oscillation of the grinding stones. Originally conceived by the automotive industry in the United States of America, this production method has been further advanced in the Federal Republic of Germany and in the Soviet Union. Coating of metals, honing and lapping with automatic transport of the workpieces indicate the trend in this area of manufacturing.

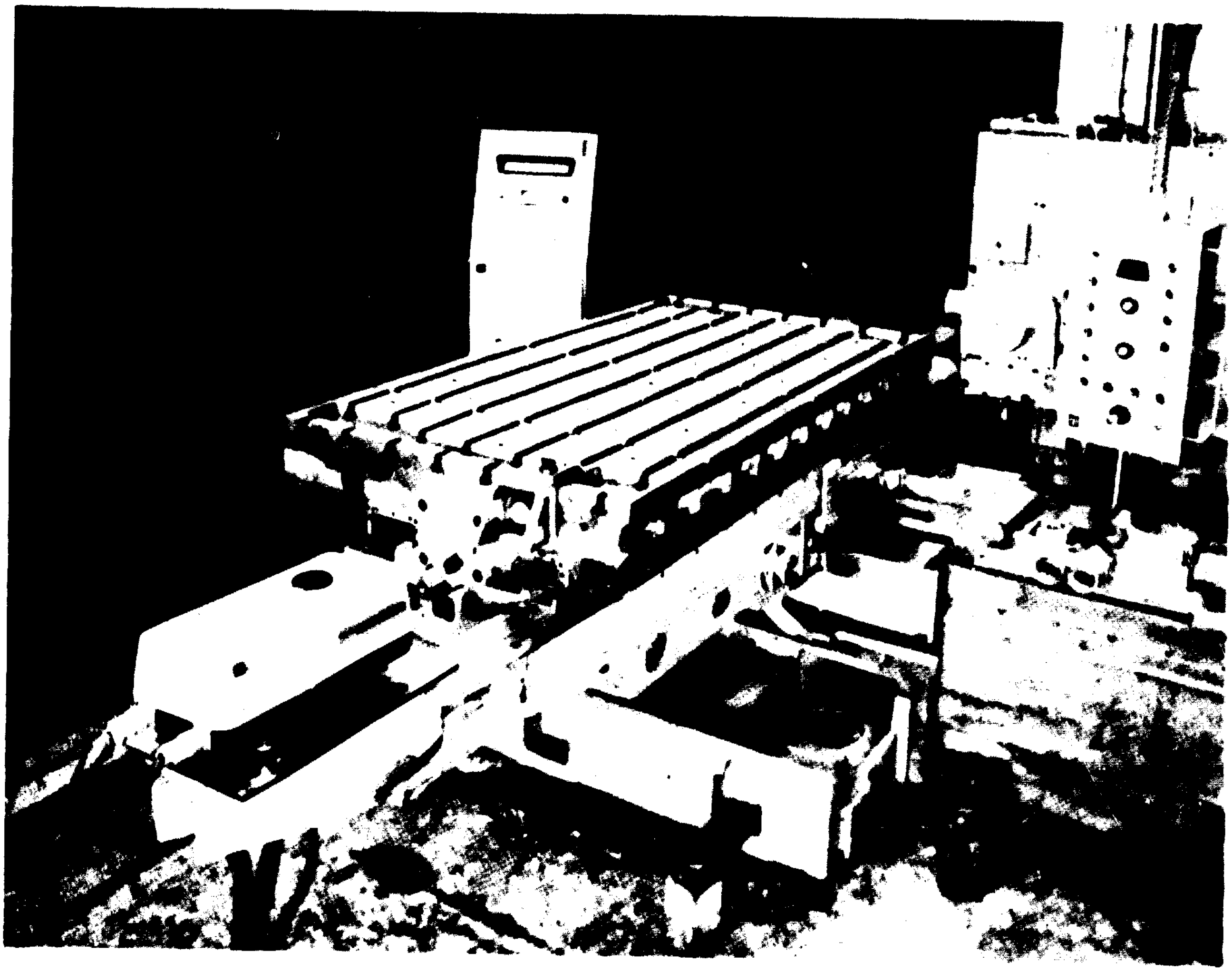


Figure 33

ACCURATE POSITIONING WITH A LASER INTERFEROMETER

Quality control has been advanced considerably by utilizing the so-called "laser principle" for accurate positioning and dimensioning of workpieces on horizontal boring mills. Figure 33 shows the set-up on a machine built by Giddings & Lewis. It consists of three parts and utilizes light waves radiated from a sender ("a" on fig. 33) for measuring movements of millionths of an inch of the table to which a reflector is attached (b). It reflects the light waves back into the sender. They are converted into decimal dimensions by a computer (c) equipped with a read-out used by the operator to control the dimensioning.

J. *Alternative production methods*

The advent of high-temperature alloys and of refractory metals currently used in industry has led and is still leading to alternative production methods which were unknown a number of years ago. These metals and alloys include beryllium, titanium, zirconium, hafnium, vanadium, niobium (often called columbium in the United States of America), tantalum, chromium, tungsten and rhenium, among others. These metals are difficult to machine with conventional production methods, as was previously mentioned in this paper.

It was found that hot machining of steels and alloys could be used to advantage and that substantial increases in cutting speeds and productivity were obtained by a proper co-ordination of heat, depth of cut, tool geometry etc. (15). The cutting forces drop as much as 50 per cent

Table 9

SURVEY OF ELECTRICAL METAL-REMOVAL TECHNIQUES

Symbol	*Name*	*Tool*	*Tool movements*	*Fluid*	*Note*
EDM	Electro-discharge machining	Electrode	Non-rotating	Non-conductive	Oldest method, producing cavities by spark
ECM 1	Electrochemical machining	Grinding wheel	Rotating	Conductive (electrolyte)	90% chemical, 10% mechanical surfacing
ECM 2	Electrochemical machining	Electrode	Non-rotating	Conductive (electrolyte)	Producing holes
EUS	Ultrasonic	Electrode	Oscillating	Non-conductive with grit	High-frequency

in some cases and vibration subsides. Mirror-like surfaces are obtained. Some danger is involved in that the hot chips often escape from the machine in long stringy bands. It can, however, be expected that future developments will eliminate this drawback and will also reduce the relatively high cost involved in heating the workpieces. The technological advantages justify the trend.

Ultra-high-speed cutting is another method—although one still in its infancy—for machining the newer metals. These metals are new only with regard to their use in industry, as many of them were discovered in the nineteenth century. Using cutting speeds of up to 120,000 ft/min gave the best results as far as tool life was concerned. The design of machinery capable of delivering speeds of this magnitude for any length of time is likewise an object of future development. The research results are satisfactory and need adaptation to workshop conditions.

The most rapid development in recent years—in addition to the trend in numerical control of machine tools—has occurred in the area of electrical machining. Various systems have been developed since the original tests were made in the Soviet Union. Electrical machining has expanded so rapidly that some confusion exists as to the differences between the various methods. Table 9 gives some indication of the trend and the differences in this area of manufacturing.

In addition to the above-listed electrical machining methods, which are the most important ones, several other electrical production techniques are coming up. Although the metal-removal capacity of electrical machining procedures is still very small in comparison with conventional machining, the advances already made are indicative of the trend. Among them there is electron-beam machining, used for producing tiny holes; the laser technique for the cutting and welding of sheet metal; electrochemical honing for the honing of holes, and electro-contact machining for turning, with a metal disc replacing the lathe tool.

Other alternative production techniques include explosive forming, magnetic forming, plasma machining and hydroforming. A number of these alternative manufacturing methods are still in the research stage, awaiting the development into production equipment for a rapidly expanding technology.

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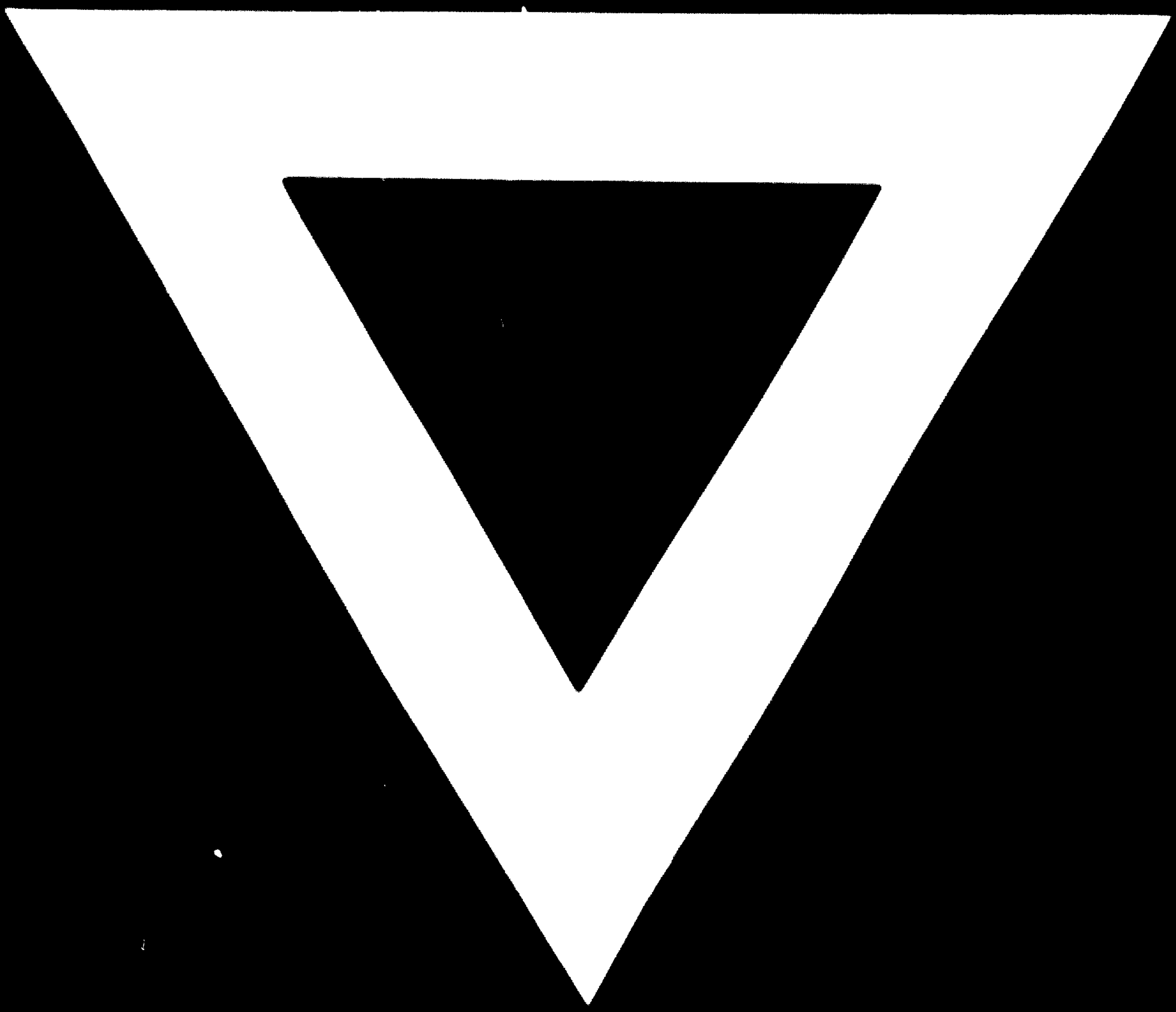

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