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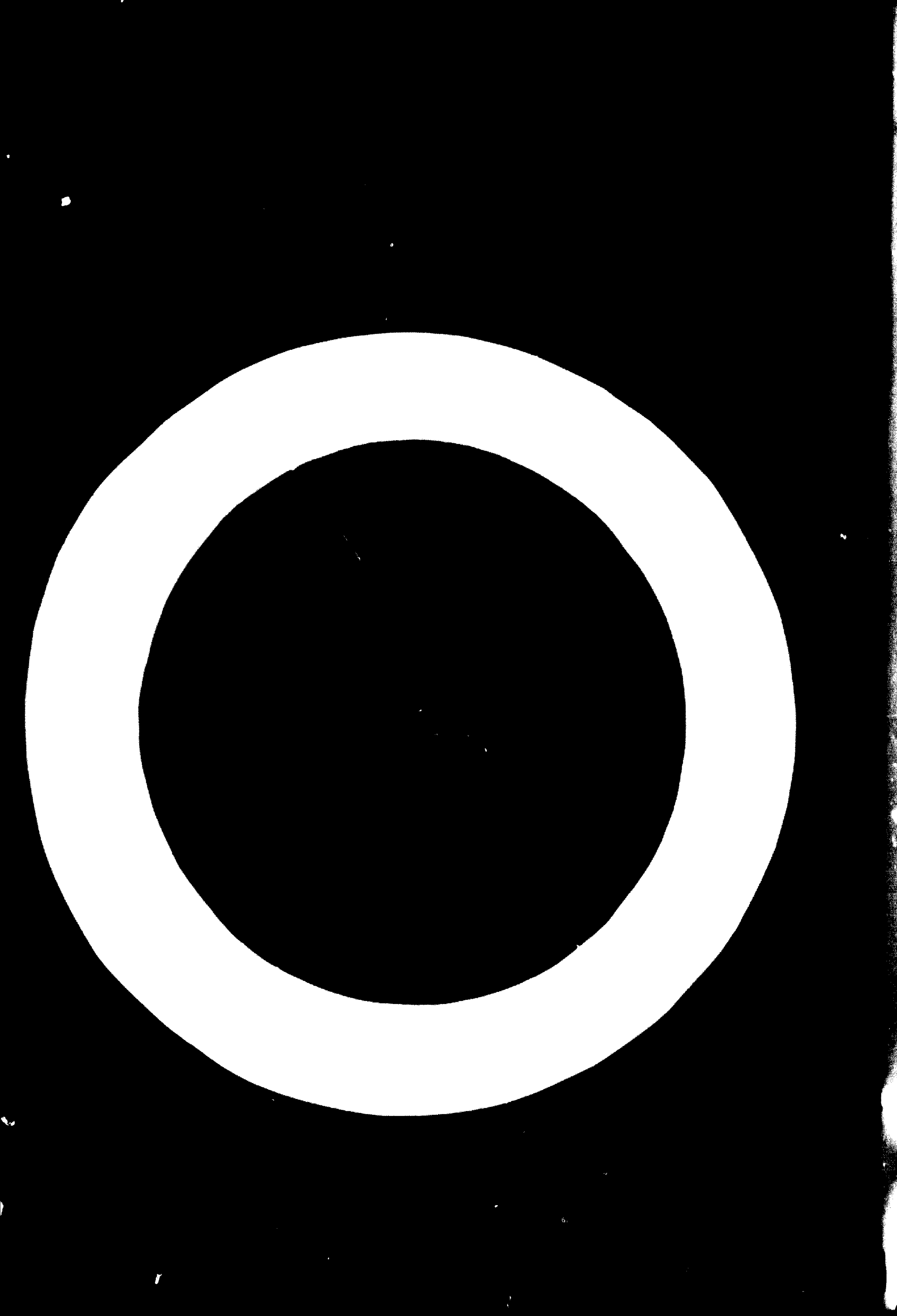

PROBLEMS IN THE DEVELOPMENT OF METAL-CUTTING TECHNIQUES

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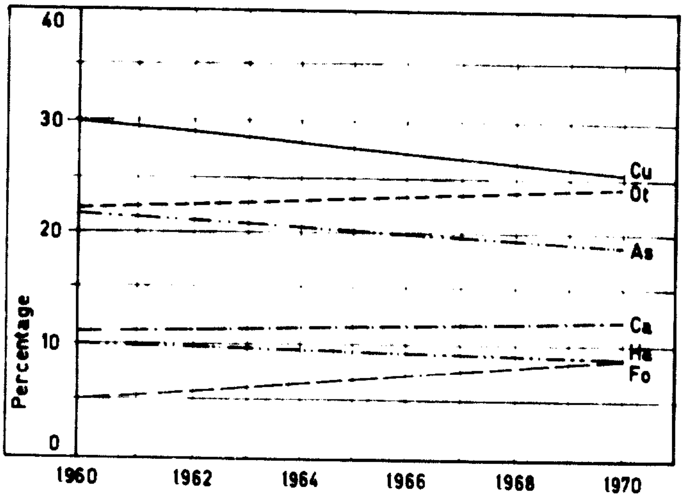
I. Significance and aspects of cutting development

Cutting technology is predominant in the production of machine components and metal parts. In mechanical engineering in Poland, for instance, in which it is possible to see symptoms of the changes typical of all the countries experiencing rapid industrial development, the participation of cutting machining in 1965 was about 28 per cent; casting, 12 per cent; handiwork (i.e., fitting and welding), 10 per cent; and plastic working, 7 per cent of total work-time (see fig. 1).

In 1970, according to development plans, there will be some changes in these proportions. Nevertheless, cutting will always be the method used for the greatest share of the whole work-time and value of production, and will constitute about 26 per cent of the total work-time, almost three times more than plastic working and about two times more than casting.



Cu cutting, Ot others, As assembly, Ca casting, Ha handwork; Fo forming

Figure 1 — Share of various production technologies in metal working industries of Poland, 1960–1970

(Percentage of work-time)

The significance of cutting is even more evident if one admits as a criterion of estimation, instead of the work-time share in the whole production, the share of components which are ready to assemble in the production process.

The situation in this field may be illustrated by the example of the Federal Republic of Germany, one of the most industrialized countries of the world. In 1960, the Federal Republic had one of the highest indexes of share of machine tools for plastic working. In spite of this, the number of parts produced by the plastic mean and in finished condition, ready to be assembled, was said to be only 5–15 per cent, independent of the industrial branch concerned (1).

In other countries, the share of finished components produced without use of the cutting process is far smaller.

Therefore, the reduction of cutting work-time (see fig. 1) derives, in fact, not from its elimination by other machining processes, but rather from the increase of cutting efficiency and the reduction of the share of roughing. It is characteristic that no real changes have been noted in recent years in the percentage share of cutting in the production of finished components.

This results from the fact that cutting has the best possibilities from the point of view of accuracy and universality. In addition to being one of the most economic and universal methods, cutting is the most technically advanced and the most rapidly developing method.

A. *"Peaks" and "pits" of technology*

The first of these aspects is the relative proportion of the "peaks" and "pits" of technology. From day to day one may observe the creation of peak technological realizations, which obviously influence the over-all level of technology, as well as the material conditions in existence. Nevertheless, they do not constitute a sufficient index of the actual production-engineering level.

Only the elimination and "raising" of technological "pits" can end the process of introduction and propagation of new achievements. For this reason, too, the real level of production engineering is represented by the percentage of the newest installations and production methods, and by the percentage of backward methods.

The rate at which the "pits" of technology are being raised has increased in comparison with that of the last ten years. In spite of this, however, the distance between "pits" and "peaks" is still important. That is why, when speaking of problems related to development, one must draw attention to not only the technological absolute novelties, but also the liquidation of technical backwardness and the propagation of achievements which are already known, but which are insufficiently used. These remarks concern all production engineering methods and, principally, cutting technology.

B. *Size of production run*

The second important problem of technical and economic character is that of the size of the production run. Every conclusion concerning directions and tasks related to the development of the cutting method must be adapted to the size of the production run and to changes in this field.

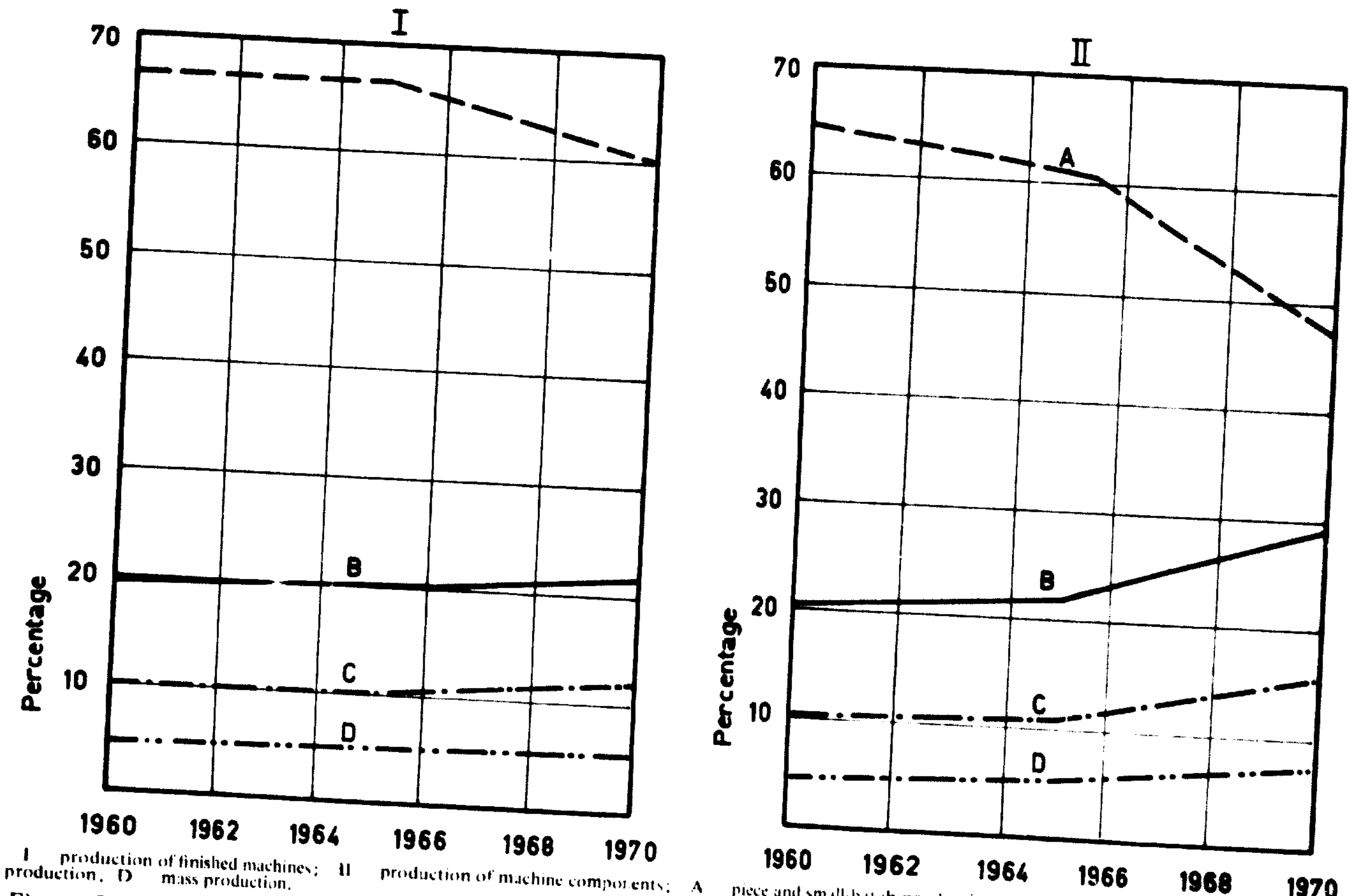
Figure 2 shows the changes achieved and foreseen in Poland in the field of so-called "final" run size (i.e., of machines and installations) and machine components. From the figure, one may see that up to 1970 small-batch production (A) will be dominant, but its share will decrease more rapidly in machine components production (II) than in the case of finished products (I). Batch production (B), large-batch production (C) and mass production (D) will also increase at a higher rate for machine components than for finished products.

C. Share of various processes in total cutting work-time

The third important aspect of the cutting technology development is the structure and participation in percentage of the different processes in the total work-time of cutting.

An example of the percentage share of the different processes in the total work-time of cutting in Poland during the period 1961–1970 is given in figure 3. Although this example concerns only one country, it gives, nevertheless, an idea of the trends and structure of times for the different processes in the world.

From the curve shown in figure 3, one may see that the greatest percentage is allowed for turning and, in order



I — production of finished machines; II — production of machine components; A — piece and small-batch production; B — batch production; C — large-batch production; D — mass production.

Figure 2—SHARE IN PRODUCTION OF FINISHED MACHINES AND OF MACHINE COMPONENTS OF PIECE AND SMALL-BATCH PRODUCTION, BATCH PRODUCTION, LARGE-BATCH PRODUCTION AND MASS PRODUCTION, 1960–1970

(*Percentage*)

Source: A. Prochowski, J. Sikora and S. Swigoń, *Stan obecny, kierunki i warunki rozwoju technologii obróbki skrawaniem w latach 1966–1970 w przemysle maszynowym PRL* (Actual state, trends and conditions of cutting processing development in 1960–1970 in mechanical engineering of Poland), Series Projekty, Opinie, No. F2W 003 (Kraków, Institute of Metal Cutting, 1965), p. 284.

This, of course, may be an illustration of the over-all trend towards decreasing small-batch production in favour of production in larger batches. One may yet see, in the field of machine components production, an increase in batch size, even for components which are used in products manufactured in small lots. This results from the development of designs by type classification, as well as from various forms of production concentration.

of importance from the point of view of work-time, drilling and boring, milling and grinding (each more than 10 per cent). Planning and parting, gear working, winding working, broaching and others each uses less than 10 per cent of the work-time.

For turning, one may observe a trend towards an increase, mainly owing to the increase of boring operations, multiple-spindle drilling and accurate drilling. Some percentage increase may be seen in milling, which mainly results from the overly slow increase in efficiency.

The relatively greatest increase of work-time is to be noted in grinding, which takes place in connexion with the increase of the accuracy requirements related to machine components and products.

The reduction of the share of planing and cutting off is mainly due to the reduction of use of less efficient planing machines.

An evident increase may be noted in gear working, which is a proof that regardless of the various means which are introduced for motion transmission, gear trains are still the most used. The same trend, but with less intensity, is to be observed in winding working.

many a disparity and their importance depends upon the economic situation of the industry and its organization, as well as upon the nature of the cutting process concerned.

Nevertheless, the problems of development may be reduced to common denominators; in other words, they may be generalized according to the circumstances. Thus, the generalized tendencies of development in the theory and technology of cutting are the following:

(*a*) Increase of savings and purposefulness of material use;

(*b*) Improvement of accuracy and quality of machined pieces;

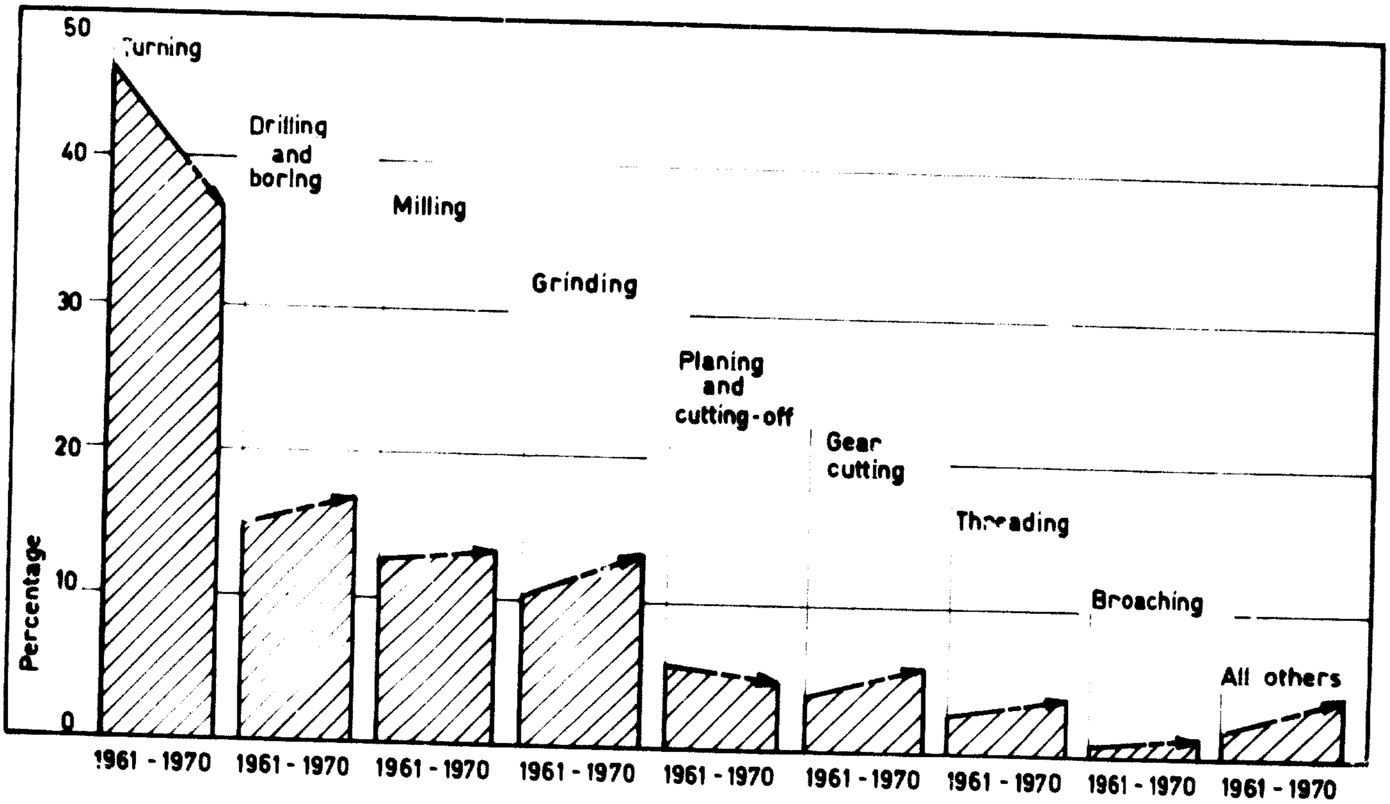


Figure 3

SHARE OF VARIOUS TECHNOLOGIES IN TOTAL CUTTING WORK-TIME: 1961–1965, ACCORDING TO STATISTICS, AND 1966–1970, ACCORDING TO PLAN

(*Percentage*)

Broaching also presents some increase, but in this case, the work-time increase is smaller than the increase in the number of operations. It results from the fact that there are relatively many possibilities of improving the efficiency of this method.

Numerous other machining processes—among them, in first place, machining on building-block machines and in-line machines—are showing an evident increase in the total work-time.

From this brief survey, one may see that the importance of a problem in the development of cutting processing varies with the degree of participation or percentage share of a given process in total cutting processing and with the rate of increase of its percentage share.

As a result of the above-mentioned aspects, the trends and problems of cutting-processing development present

(*c*) Work-time decrease and removal-rate increase;

(*d*) Enlargement of machining power.

These development tendencies reduce production unit costs and permit a better degree of utilization of the investment.

II. Improvement of material yield

A. *Importance and limits of material losses*

In the engineering industry, the greatest percentage of the production costs corresponds, in most cases, to the material costs. The importance of the material factor is reinforced by the fact that many raw materials are lacking and their acquisition by means of international exchange is often difficult.

In this connexion, the injunction of economy of materials is becoming the fundamental necessity for the designer, production engineer and user. By the same token, these questions must have their reflection in scientific research works.

Losses of materials in the cutting process involve: (*a*) losses of machined materials; (*b*) wear of tool materials; and (*c*) losses of auxiliary materials.

The losses of auxiliary and tool materials cannot be considered without taking into account the removal rate of the cutting process and the production efficiency, as well as the quality of machining. This is why the unitary or proper losses of these materials are discussed, together with the problems of efficiency.

As to the losses of stock, this is a separate problem and is discussed below.

B. *Stock savings*

The loss of stock may be characterized by the yield ratio:

$$U = \frac{g_n}{g_b} \cdot 100 \text{ per cent} \qquad \text{(Equation II-1)}$$

where g_n = weight of the workpiece after a given operation; g_b = weight of the workpiece before the given operation.

One may also use the notion of ratio of loss or coefficient of loss, which may be expressed as:

$$S = 1 - U = \frac{g_b - g_n}{g_b} \qquad \text{(Equation II-2)}$$

The coefficient of loss shows what percentage of the test bar material will be lost.

Principal losses of material in the cutting process may be classified as follows:

(*a*) Losses for ends and discards;

(*b*) Losses for parting;

(*c*) Losses for indispensable, technical machining allowances;

(*d*) Losses for machining over-allowances due to the bad workmanship of semi-products;

(*e*) Losses in rejects due to machining errors or other causes.

Losses for ends and discards, as well as for parting, are important in the case of production from rolled and drawn semi-products and from large castings and forgings. The value of these losses is difficult to generalize theoretically. Only the statistical method enables one to have an idea of its order of value in the various productions. Thus, when manufacturing on single-spindle automatic lathes, the discards are generally below 1–2 per cent.

In the case of quality production from rolled bars, attempts have been made for the application of linear programming with a view to reducing the losses (2). In percentage, these losses are not very important, but expressed in absolute numbers, they are sufficient to justify such theoretical works and practical tests for the application of linear programming.

Machining allowances are the major source of losses of material. One must distinguish between indispensable machining allowances, which are theoretically and technically justified; and real machining allowances, which are higher than the theoretical values because of the inaccuracy of the semi-finished products.

The technically justified machining allowances for one cut are the result of the algebraic stack-up of the following factors:

- T_a = the dimensional allowance of the former cut;
- H_a = the mean value of surface roughness after the former cut;
- W_a = depth of the damaged layer in the former cut;
- S_a = summaric geometr[ic] error resulting from error in setting up the workpiece in relation to the tool in the operation concerned.

Therefore, the total machining allowance of a given cut is:

$$S_b = T_a + H_a + W_a + S_a + S_b \qquad \text{(Equation II-3)}$$

and in case of multiple-cut operation, the total machining allowance will be:

$$C = \sum_{i=1}^{z} g_{bi}$$

where z = number of cuts.

The yield ratio and the coefficient of loss, taking into account only technically justified machining allowances, generally decrease when the dimensions of the workpiece increase.

This is illustrated in the example given in figure 4. This diagram represents the dependence between the yield ratio and the necessary losses of material and machining allowances (C) in the function of the material diameter. This example concerns the turning of multiple-stage shafts in centring points when $l/d > 3/1$, l = length, d = diameter of turning with a good rigidity of the system: machine tool-workpiece-cutting tool. Data are taken from standards elaborated at the Institute of Metal Cutting(3).

In this example, the losses of material are about 60 per cent for very small dimensions (d = 50 mm) and diminish almost hyperbolically when the diameter increases. When d = 100 mm, these losses are just 10 per cent.

Statistical data show that the real losses of material are far more important than they would appear to be from theoretical calculations. Therefore, in a small-batch industry producing machine tools, for instance, the material yield ratios are about 45–60 per cent when machining forgings and about 60–70 per cent when machining castings.

The average yield ratio for different branches of the metalworking industry is within the limits of 0.6 to 0.8, i.e., 20 to 40 per cent of the stock is converted in chips.

In conclusion, one may say, therefore, that the greatest part of unrational losses of material proceeds from bad production of semi-products rather than from the characteristics of the cutting process.

Technically and economically justified semi-products and the limitation of cutting processing to a range of

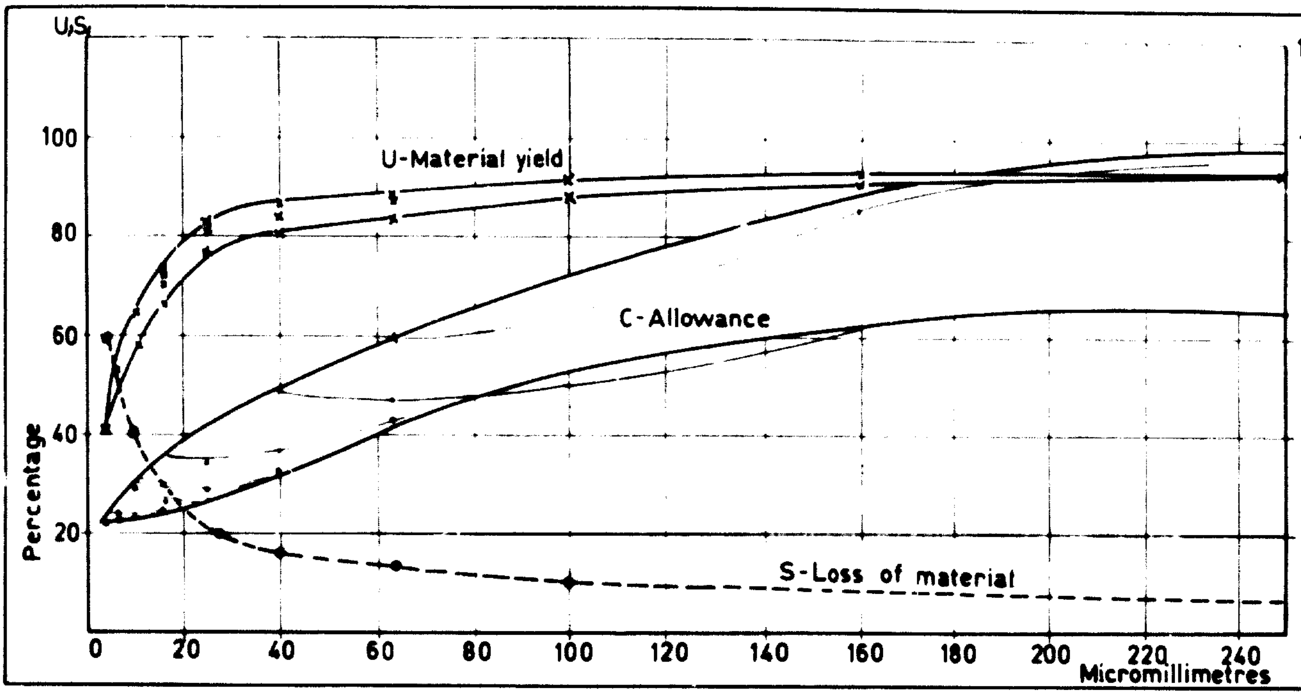


Figure 4

DEPENDENCE OF MATERIAL YIELD, PERMISSIBLE LOSSES OF MATERIAL AND TECHNICALLY JUSTIFIED MACHINING ALLOWANCES IN TURNING OF MULTIPLE-STAGE SHAFTS IN ROLLED STEEL.

works with suitable accuracy and quality requirements are fundamental prerequisites to the reduction of machining allowances.

Nevertheless, the task of reduction of stock losses must be distributed equally between the manufacture of semi-products and the cutting processing itself.

With regard to the influence of the allowance on the losses of material, it is important to admit, as a principle, that semi-products ought to be manufactured at the lowest dimension of tolerance, rather than as they actually are manufactured, at the highest dimensions of tolerance. As for workpieces produced by cutting, they ought to be manufactured at the highest dimensions of tolerance.

It is recommended also that in determining the value of the tolerance, designers should take into account losses of material on the value of the tolerance.

The greatest amount of work remains to be done in the field of the influence of the shape and dimension of the semi-finished product on the losses of material. In the first place, it is necessary to make investigations and analyses in order to know if the admitted dimensional series and the concentration of these dimensions correspond to the real needs in mechanical engineering. This concerns, in the first order, the rolled bars. However, it is first necessary to increase the proportion of more precise methods of production in casting, forging, moulding, etc.

In the field of the influence of surface microroughness and depth of the damaged surface layer, further thorough studies are necessary to elaborate instructions for the manufacture of the product. These instructions must take into account the needs of the smallest surface roughness and the depth of damaged layer, as well as the most economic course of production.

Particular attention should be paid to often repeated errors of decarbonization of the upper layer in some hot-machining operations, as well as to the appearance of micro-cracks, cold shut etc., all of which lead to the increase of allowances.

The following facts—based on the example of Poland may give an idea of the material savings it is possible to achieve by rationalization and reduction of allowances. One statistical machine tool in Poland gives 2 tons of chips. Simultaneously, it is known that the average machining allowances are 50 per cent to 100 per cent higher than those which are technically justified. This means that the introduction of technically justified allowances may result in savings of about 1 ton of chips *per annum* for each statistical machine tool. These savings, multiplied by the number of machine tools, amount to a very important quantity of material for every country.

For this reason, some countries have elaborated and are introducing new principles for the technical standardization of losses of materials.

III. IMPROVEMENTS OF TECHNOLOGICAL QUALITY OF MACHINE COMPONENTS

A. *Quality of a product and quality of a component*

In popular conception, the quality of a product is basically characterized by:

(*a*) Reliability in operation and accomplishment of its functions;

(*b*) Endurance or durability, in other words, the unchangeability of its features during its use;

(*c*) External aspect of the product in its totality and of its parts, particularly its surface, in other words, the surface "finish";

(*d*) Application of those materials whose properties are particularly suitable for this use.

One may see, therefore, that the quality of a product is dependent, in the first place, upon the manufacturer i.e., upon the production engineering. However, the designer also exerts a great influence on the quality, because he decides on the choice of material, as well as the external appearance of the different components and of the whole product.

Analysing more precisely the popular conception of quality, it is necessary to remark that the usual features of a product, which are the mean basis of estimation, depend also upon the conditions and method of use of the product.

At the moment when a given product has just been manufactured, it is impossible to know exactly if it will be used properly or not, i.e., to what degree the conditions of use may influence the opinion concerning its quality. Nevertheless, at this moment, the quality must be estimated.

The quality of a product composed of many parts depends upon their proper assembly and connexion, i.e., on the assembling process and on the quality of units or parts composing this product.

In this respect, attention must be limited to the influence of engineering technologies and methods on the quality of the components. It is obvious that the better the quality of the components, the better guarantee one may have of the complex quality of the final product. The problem, therefore, may be reduced to an estimation of the quality of the components.

Such an estimation is possible on the basis of the relationship existing between the features of the components at the end of the manufacturing process i.e., at the end of definite technological processes and the properties of the components when they are put to use.

With regard to the production of machines, the following technological qualities (J) of the machine components are important by reason of their functions in the final product:

(*a*) Accuracy of shape and dimension (D);
(*b*) Accuracy of surface, or surface roughness (P);
(*c*) Physical properties of the upper layer (W).

These three complex quality features of machine components influence the properties of the component in use (U), of which the most important and most frequently required are the following:

(*a*) Abrasion resistance, which is defined by what may be called the abrasion ratio (S);

(*b*) Friction resistance, i.e., resistance offered when working with another part (C);

(*c*) Fatigue resistance, of both the surface of the component and its shape (Z);

(*d*) Corrosion resistance (K);

(*e*) Power of reflection (R).

Apart from the above-mentioned features, there are many others which, in some cases, may play an important role.

In more precise considerations, it is necessary to introduce for the estimation the quality of machine components:

(*a*) The technological quality (J), defined by the properties D, P and W, and then: $J = f_1$ (D, P, W);

(*b*) The quality at work (U), defined by the properties S, C, Z and K and then: $U = f_2$ (S, C, Z, K . . .).

In condensed expression, the technological quality will be named "quality" and the quality at work, "workability".

The relationships between some technological processes, quality (J) and workability (U) are discussed in a subsequent section of this report.

B. *Increase of accuracy required and improvement of measurement possibilities*

1. *Requirements of accuracy*

In a design office of the railway industry, an interesting analysis concerning the increase of accuracy requirements in the machining of locomotive rotary pieces (rollers and holes) has been achieved. Figure 5 shows the percentage of pieces, with various accuracies expressed in values of the International Organization for Standardization (ISO) for 1930 and 1950, and the values planned for 1970.

As may be seen from this diagram, the accuracies are increasing relatively quickly. As a result, one may really foresee that in 1970 a higher percentage of this production will correspond to rollers and holes of the No. 6 grade, and the sum of pieces of classes below and up to 6 will reach about 43 per cent, in comparison with 34 per cent for the same group in 1950 and only 24 per cent in 1930.

This example shows that the increase of accuracy requirements in machine-element manufacture is typical for every kind of product. A particularly rapid increase may be noted in mass and quantity production, for instance, in the automotive industry.

It is not an easy task to reduce the machining errors, which are influenced by elastic strains of the machine tool, chucks and tools under the cutting forces, thermal deformation, geometric and kinematic inaccuracy and tool wear. In spite of this, there are reasons, from the technical and economic points of view, for trying to improve machining accuracy.

Machining errors have a great influence on the accuracy of the joints of machine elements, both at rest and in motion, as well as on a great number of important properties at work on the product as a whole.

2. *Possibility of measurement*

In order to achieve a high machining accuracy, the improvement of machining capacities must advance simultaneously with and even precede the increase of accuracy requirements concerning shape and dimension.

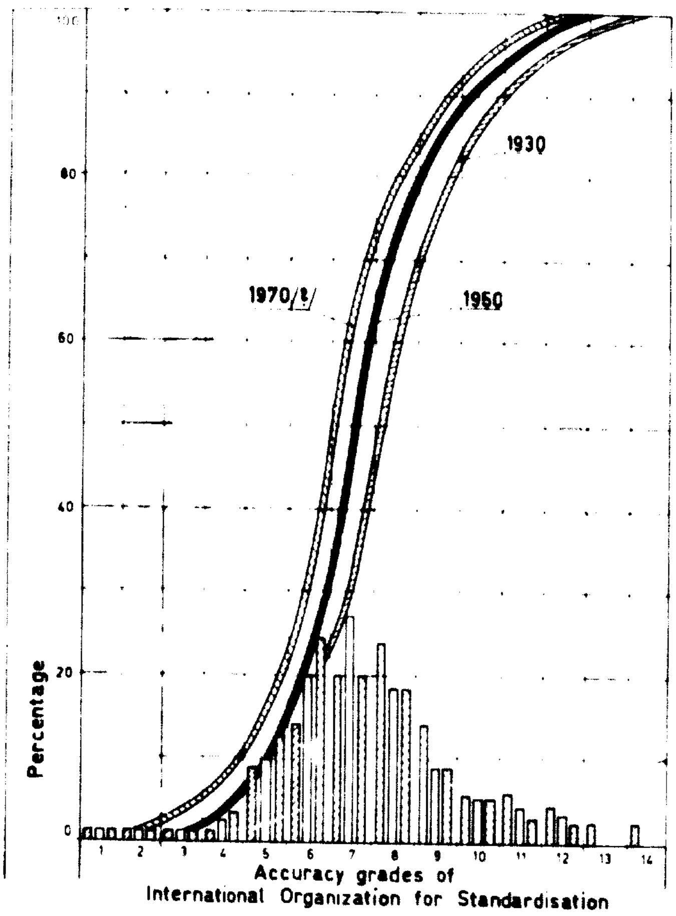


Figure 5

INCREASE OF REQUIREMENTS FOR MACHINING ACCURACY, BASED ON THE EXAMPLE OF ROTATIONAL PIECES OF LOCOMOTIVES IN THE UNITED STATES OF AMERICA

The basic condition in creating the desired machining capacities is to acquire measuring means whose accuracy would be suitably higher than the required machining accuracy. Analysis of the progress of the technical development of measuring means and machining capacities proves that the appearance of new, more accurate measuring means and methods has resulted in an improvement of machining accuracy.

Figure 6 shows, in an objective manner, the relationship between the possibilities of decreasing machining errors and the discovery of new measuring methods in the future.

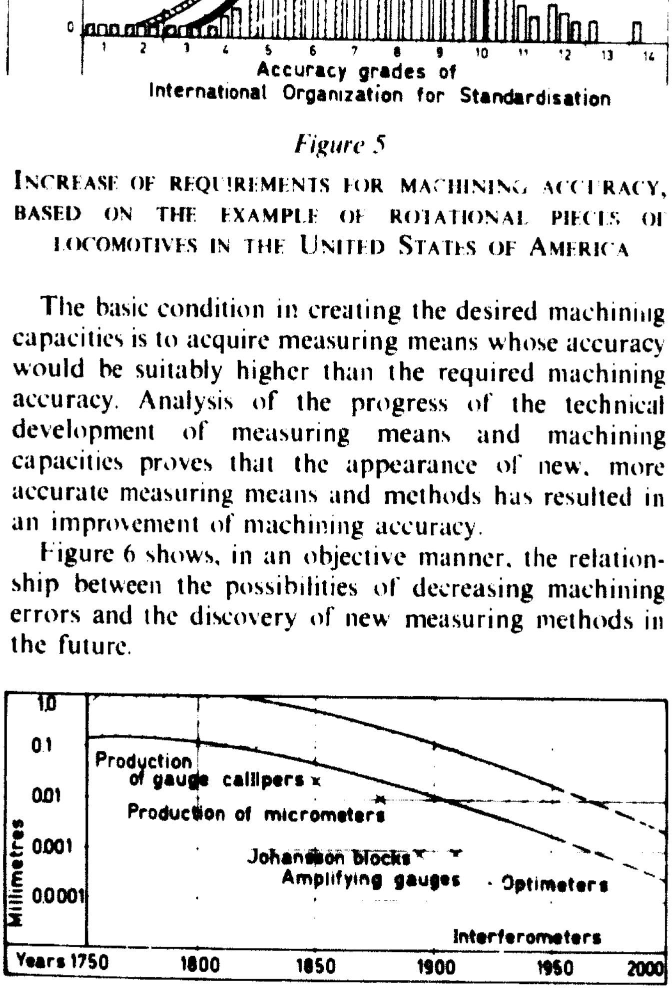


Figure 6

DEPENDENCE OF MEASURING AND MACHINING ABILITIES

In the period from 1750 to 1800, the accessible machining accuracy was characterized by errors ranging from one-tenth of 1 mm to more than 1 mm. This obviously resulted from the primitive machining methods in use, which are illustrated in figure 7.

Figure 7

METALWORKING IN THE EIGHTEENTH CENTURY

At first, however, the errors of machining were caused by the lack of sufficiently accurate measuring means. For example, at that time, the linear measure used in Great Britain was the mean foot, i.e., the arithmetical mean value of the lengths of the 2 feet of twelve persons chosen at random.

The invention of the vernier scale (see fig. 6), after the introduction of the metric scale, followed by the beginning of the manufacture of gauge calipers (about 1850), caused the improvement of the machining accuracy within the limits of 0.1 mm. Further improvements of measuring means and the expanded use of micrometric devices and gauge blocks permitted the improvement of machining accuracy within the limits of 0.01 mm.

Actually, in this period, when there are various optical and electronic devices which permit measurements with errors below 1 micron, measuring devices may be sufficient to control the machining accuracy within the limits of 0.001 mm.

From the analysis of the development rhythm of measuring means and range of accessible machining accuracy, one may conclude that:

(*a*) The development of measuring means has taken place sufficiently rapidly and does not constitute any restraint on the development of machining accuracy;

(*b*) On the basis of historical extrapolation, one may foresee that about the year 2000, the feasible range of industrial machining accuracy will be within the limits of 1 micron.

As a confirmation and guarantee of achievement of this prediction, mechanized and automatic measuring and controlling devices, which prevent subjective errors by the operator, are being used more and more frequently. For example, figure 8 shows an automatic device which meets the requirements of mass production. This device, which was designed and executed at the Institute of Metal Cutting, can select pits which do not fulfil the necessary dimensional conditions within the limits of 10 microns of accuracy.

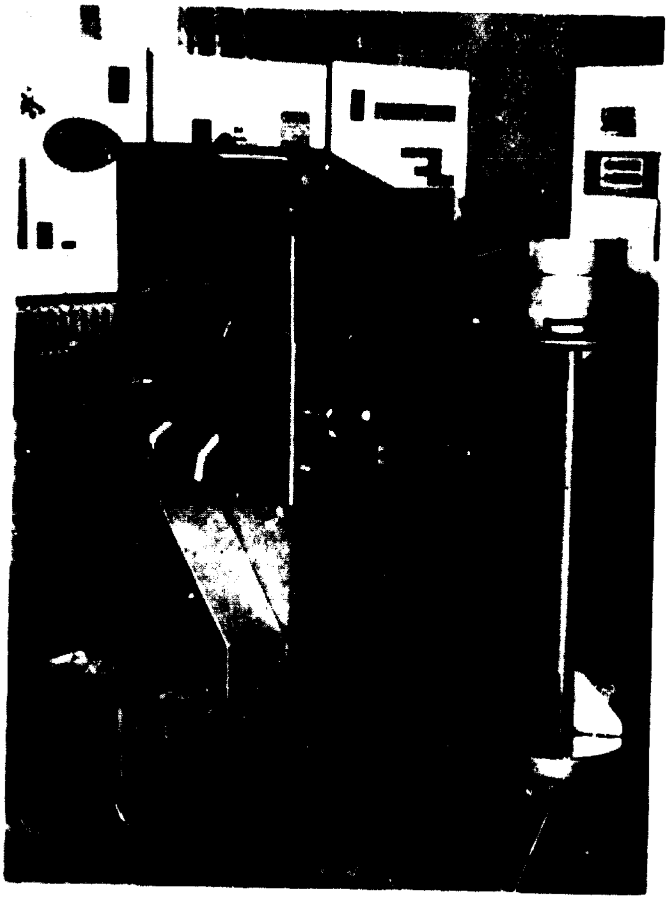


Figure 8

AUTOMATIC CONTROLLING AND SELECTING DEVICE

Long before this, measuring and controlling automatic devices with a far higher accuracy were known and used. For instance, at the bearing works in Moscow or at the concern RIV, controlling automatic devices which measure and select the balls with an accuracy of ± 1 or 2 microns are being used in industrial conditions.

Particularly valuable possibilities for measuring and machining purposes are obtained by the application of laser. The most valuable feature of this measuring method is its very high accuracy, independent of the dimensions of the part. All the methods known up to now have been characterized by the fact that the absolute value of the measuring error increased simultaneously with the dimensions of the machined part.

The practical introduction of laser as a measuring device will have a particularly great significance from the point of view of the construction of larger machines and attachments.

C. *Development of abrasive and surface working*

The reduction of machining allowances and the simultaneous increase of machining accuracy and quality requirements require a convenient increase of the percentage of grinding operations, superfinish, lapping and other methods of surface working.

An analysis of the range of application of various abrasive and surface-working processes (for example, lapping, honing, superfinish, superfinish by means of abrasive belts, blast lapping, shaving, burnishing, ball and roller burnishing) shows that it would be profitable to increase their use from two to eight times.

The reasons for the insufficient use of surface-working processes as finishing methods may be listed in the following order:

(*a*) Lack of machine tools and equipment for surface working;

(*b*) Difficulties in supplying with tools and agents for surface working;

(*c*) Designers' frequent limitation of the requirements of the upper-layer quality to surface finish only;

(*d*) The scarcity of production engineers and workers who are trained for surface working.

It is apparent, therefore, that management in the machine-tool and the tool industries must realize that surface-working equipment must be taken into account when considering their production plans.

It is important to emphasize that the basic condition permitting the stabilization of the quality of abrasive media and tools is the modernization of this industry.

In order to improve abrasive quality, one must analyse and study the role of percentages of grain size for each abrasive powder, as this seems to be the proper point at which to begin the definition and study of the workability of the abrasive. Investigations must be performed simultaneously on the assortment of abrasive tools, in order to establish their rational working parameters in various functions.

In connexion with this, the following procedures are suggested:

(*a*) The percentage of machine tools and equipment for abrasive and surface working in the whole production ought to be increased;

(*b*) The abrasive materials and tools industry must be systematically modernized and developed;

(*c*) The abrasive and surface-working processes must be well known and widely popularized on the basis of theoretical considerations and the results of investigations.

The utilization of self-sharpening grinding wheels in accurate and very accurate working is an important experimental and technical problem. Grinding in conditions of self-sharpening permits a stabilized removal rate, operating independently from time, and, simultaneously, a good surface finish.

The choice of the proper machining fluids and their filtration during the process are important steps in the development of precision working and, particularly, of abrasive working.

From the investigations conducted, it may be seen that filtration permits an improvement of the surface finish of one class at least. The improvement of the efficiency and output of filtration and the durability of filter papers, to reduce the over-all dimensions of filters, must be the most urgent task in the near future.

D. *The role of the machine tool-workpiece-tool system*

Machining performance of high accuracy and quality is dependent upon the machine tool, the tool and the equipment, as well as upon the workpiece itself and the measuring means.

The machine tool of the future must be characterized by a change of machining possibilities in the current trend of higher cutting speeds. This will result from the following factors:

(*a*) The dimension of the layer removed, i.e., the depth and feed, will gradually decrease. The reduction of depth will take place because of the increase in the number of accurate semi-finished products, and thus there will be a reduction of machining allowances. The reduction of feed will take place because of the increase in surface-finish requirements. In these conditions, the increase of the removal rate may take place only as a result of the increased cutting speed;

(*b*) The cutting capacity of tools will continuously increase. It will result mainly from the excellent properties of tool materials, and also from the optimization of their shape.

Figure 9 illustrates the range of value of cutting-speed performance per hour through the use of known materials for tool-points, when machining carbon steel with a tensile strength of

$R_r = 70$ kg/sq. mm (Equation III-1)

The machining properties of materials may produce the increase or decrease of cutting speed. However, in the range of one given kind of material, the machinability will be improved, particularly by optimization of the cutting conditions, which will cause the increase of cutting speeds.

From a statistical point of view, if one compares the influence of these three factors, one will find that the economically justified increase of cutting speeds in industrial conditions will be as represented in figure 10. Therefore, if one takes into account only the improvement of known materials, one must admit that the next decades will bring a further increase of cutting speed.

In relation to this, the dynamic properties of the system, machine tool-workpiece-tool (M-W-T), are of particular importance. The problem of vibrations and resistance to vibrations is currently the theme of numerous investigations in every important research centre. This work must be continued on yet a larger scale, with the objective of making possible the construction of machine tools which will permit machining without vibration at a cutting speed of 200 to 400 m/min. in the whole range of diameters.

Increasing requirements with regard to accuracy and changes of machining conditions, and particularly of cutting speed, must produce important changes in the technical acceptance of machine tools. The current procedure of checking the geometric accuracy of measurements will, in some cases, be replaced by dynamic investigations, as well as by studies of deformability under loading. The introduction of these changes still requires a series of investigations on the methods of measurement, in accordance with international agreements.

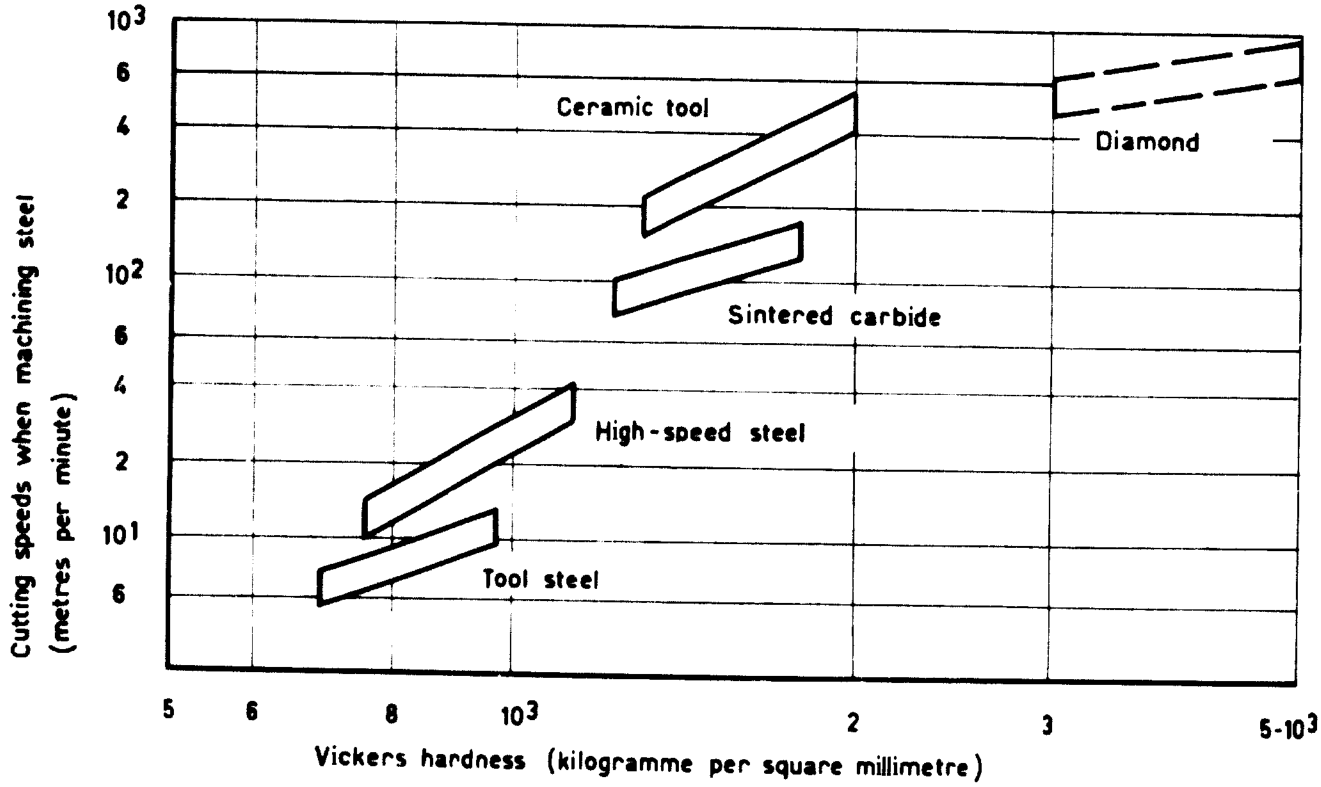


Figure 9

RANGE OF CUTTING SPEEDS FOR A CARBON STEEL, $\sigma B = 70$ kg/sq. mm, WITH VARIOUS TOOL MATERIALS

Source: "Fortschritte bei spanabhebenden und abtragenden Fertigungsverfahren: Bericht über das 12te Aachener Werkzeugmaschinen-Kolloquium, 1965", *Industrie Anzeiger*, No. 69 (1965).

Cutting tools will play an important role in the development of precision machining. In conditions of accurate machining, particularly automatic and programmed machining, tool wear must be evaluated in a different manner. In these conditions, the most appropriate evaluation is the "precision criterion of wear", i.e., changes in the tool-point geometry, in which the required dimension of the workpiece will not be considered. This problem is still in a preliminary stage of development and requires intensification of investigations and experimental work on tool design, construction and exploitation.

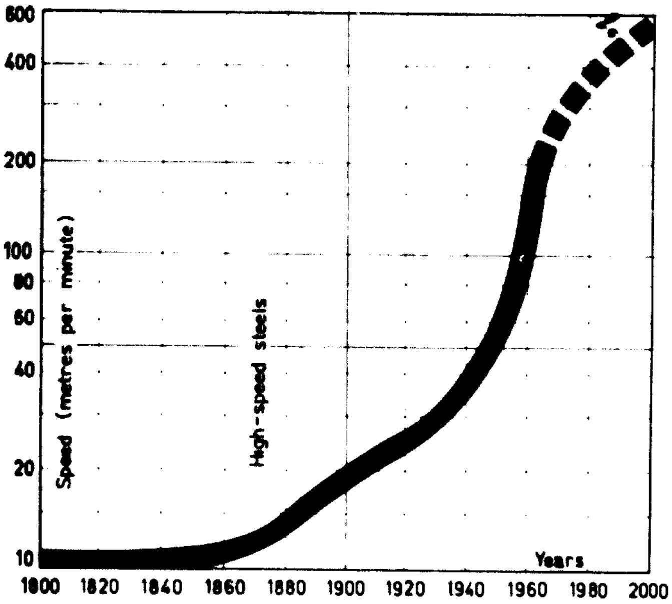


Figure 10

CUTTING SPEEDS OF CARBON STEELS IN INDUSTRIAL CONDITIONS DURING YEARS OF USE

Of far greater significance is the capacity of tools to use the least possible cutting force during machining, as this reduces the machining errors.

Because of the increasing requirements of accuracy, it is necessary to develop automatic measuring and compensating systems, which may be built into the machine tool to reduce the unfavourable influence of deformations under loading, thermal deformations and errors due to tool wear. These difficult tasks should be given top priority in developing cutting processes.

The application and choice of the method of removal processing determine the ability to ensure the lowest production costs. Studies must be undertaken in order to obtain quantitative information on the technological dependence, abilities and characteristics of machine tools and tools. Decisions on the practical application of the results obtained by these investigations must be taken independently of organizational and economic factors existing in a given plant. Thus, technological and economic works which are undertaken for the purpose of elaborating guide-lines to ensure the most economic means of application of the various machining processes and to permit the most rational set-up of operations must play a very important role in the development of accuracy and quality in machining. These guide-lines must give data, from the economic point of view, on the machining accuracy it is possible to reach on machine tools. Such data will be important not only for production engineers as users, but also for designers and manufacturers of machine tools for they will be a basis for the introduction of changes and improvements in machine tools.

F. *The role and significance of the upper layer of the workpiece*

The purpose of cutting, processing and other removal-machining methods is to give to the workpiece the required shape with the necessary dimensional precision required for its workability or for the properties of its upper, or surface, layer. The machining process, by itself, must be achieved in such a manner as to ensure the highest possible efficiency and the lowest unitary production costs.

The actual normatives for the choice of cutting conditions take into account, to only a small degree, the dependences existing between the cutting conditions and the properties at work of the workpiece. The mean point of departure for a quantitative determination of the cutting conditions must be the principle of the lowest operating costs appearing in the method of choice, based on the so-called economic durability of the cutter, or, in some cases, on the durabilty of the highest removal rate.

Such a juncture is not sufficient, particularly in the fields of accurate and very accurate machining, which consist mainly of finishing operations. An urgent task of the theory of metalworking processes is the elaboration of principles for the choice of machining conditions, which would take into account both the cheapest and the most efficient processing, and which would ensure all the required features of the workpiece. In other words, the principles for the choice of machining conditions must take into account not only the interests of production engineers and manufacturers, but also the interests of users.

For this reason, the properties of the upper layer of the workpiece are as important as the dimensional accuracy, and, in some cases, they are more important from the point of view of quality and exploitability of machine elements. This also applies to machines and installations.

Figure 11 illustrates a typical, but simplified, scheme of the disposition of the upper layer after mechanical working.

The layer often named "superficial", i.e., that which is directly under the geometric surface, is a layer of absorbed gas, liquid or solid particles; for instance, it may be air particles, particles of the tool material, impurities, etc. Furthermore, this layer is also composed of oxides from the metal submitted to working. The global thickness of this layer is very small and often does not exceed 80 Å. Nevertheless, it plays a very important role in the processes of wear.

The basic part of the upper layer is composed of a layer of the machined material (crushed layer) submitted to plastic deformation by the effect of forces acting during the technological process. The thickness of this layer may range according to the machining means and conditions, from a few hundredths to some tenths of microns.

In numerous cases, especially after machining with

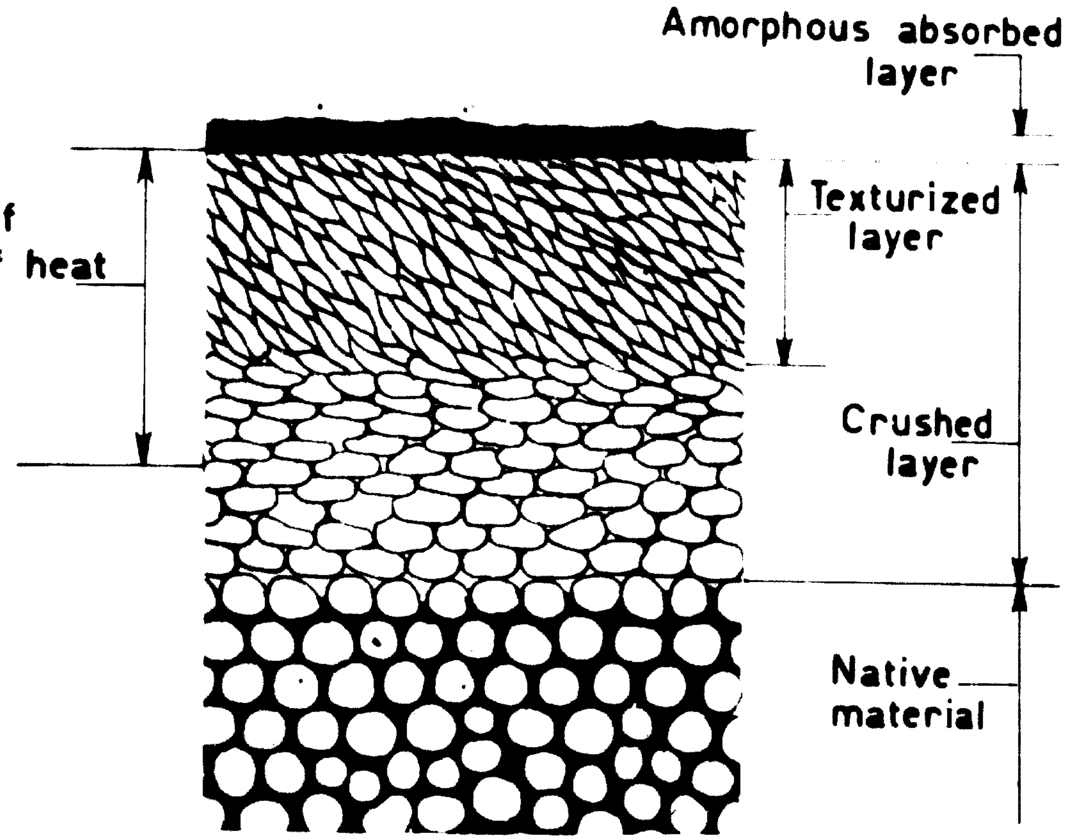


Figure 11

SIMPLIFIED SCHEME OF THE UPPER-LAYER COMPOSITION AFTER MECHANICAL WORKING

chips' formation, one may see the evident texture of the microstructure of the layer being crushed. This results from the friction forces between the machined material and the tool.

In addition to the plastic deformations caused by the mechanical forces, the distribution in the field of temperatures may also influence the microstructure. As a result of the heat created during the technological process, various transformations may occur in the structure of the upper layer, such as hardening, tempering, allotropic transformations, grain-size changes etc.

The depth of influence of heat in the upper layer in mechanical working is generally only a fraction of the depth of the crushed layer. In such processes as electro spark machining, heat changes affect almost the whole of the upper layer and its thickness may become even more than 1 mm.

Among the most important properties at work in the upper layer, one may include: resistance to abrasion; friction; load; fatigue; corrosion; and grip. These properties are dependent upon the geometric and physical state of the workpiece and its upper layer, and upon the properties of the workpiece before working, as well as upon the changes which occur during the working processes. The state of the upper layer after working is defined by its geometric features, i.e., the parameters of surface finish: waviness; roughness; shape and direction of microirregularities of surface; defects; damages etc.; and by its physical features: structure and thickness of the upper layer; microhardness, and value and sign of final stresses; i.e., resulting from the superposition of stresses proceeding from the working process on the preliminary specific stresses.

All these features are dependent upon many parameters of the working process; the most important of them being the nature and the shape of the tool-point, the shape and the dimensions of the unformed chip thickness and the cutting speed.

In research development and the theory of accurate and finishing cutting, the trends must be to define:

(*a*) The quantitative dependence between the parameters of the cutting process and the features of the upper layer after cutting. This is a particularly important problem for the production engineers who may direct the machining process;

(*b*) The quantitative dependence between the features of the state of the upper layer after cutting and the properties at work. This is a particularly important problem for designers, who may then define, where necessary, not only the requirements concerning the accuracy of shape and dimensions, but also the properties at work.

To achieve these results, which may be the basis of a rational collaboration between designers and production engineers, a number of problems need to be solved and many investigations should be carried out.

First of all, there is a need for theoretical works, to achieve a close, although conventional, classification of notions. In addition, there is a need for an agreement on a methodology of a universal character of the properties of the upper layer. It seems suitable to proceed to the characterization of the upper layer by simultaneous studies of microstructure, microhardness and stresses. An example of such a characterization is given in figure 12.

It seems particularly urgent to clear up the differences between the results obtained and opinions concerning the influence of the upper layer on some characteristics at work. As an example, one may present the question of the influence of final stresses on one of the most important characteristics at work-abrasion resistance.

There is a need not only for investigations in the field of finishing operations, but also in the field of rough operations, as well as on the influence of sequence, association of machining operations and means.

The expeditious achievement of such a cycle of investigations is very important for practical purposes, if one takes into account that changes occurring in the upper layer give variations of the tool-wear intensity and duration of some hundredths of 1 per cent. It denotes that only by a convenient choice of machining conditions is it

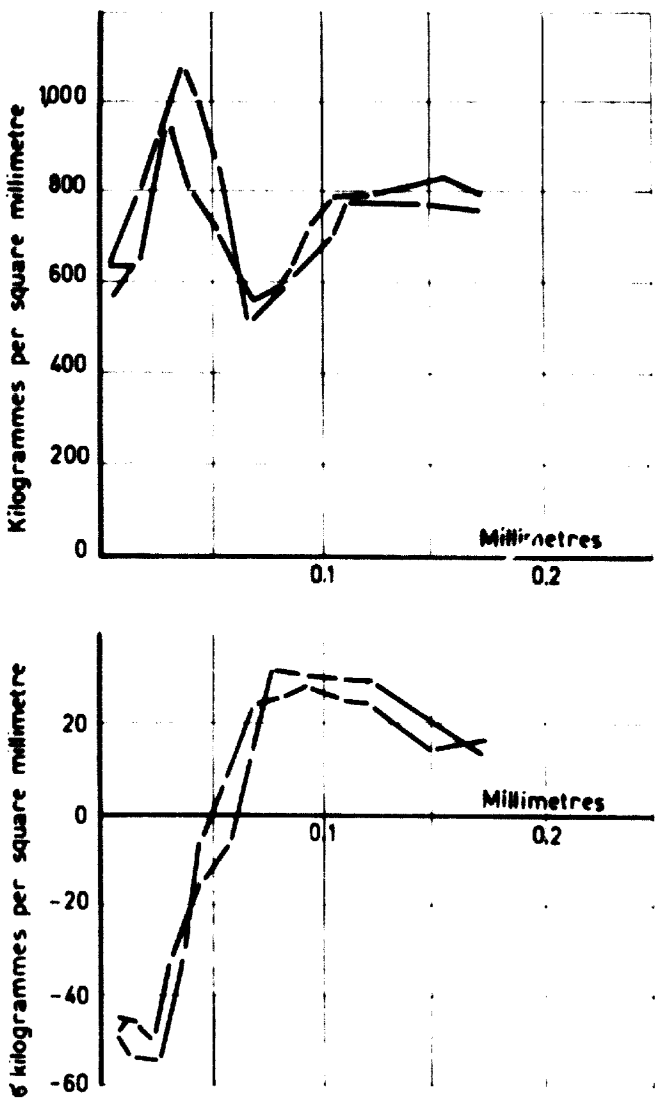


Figure 12

COMPLEX CHARACTERISTICS OF PROPERTIES

Source: Jan Kaczmarek, "Eigenschaften der Oberflächenschicht und deren Abhängigkeit von der Bearbeitungsart", *Annals of the International Institution for Production Engineering Research*, No. 3 (1962-1963).

possible to achieve important savings through a reduction in the number of repairs and replacements of worn-out parts.

The practical application of the results of these investigations must be made according to their achievement. As an example of fairly advanced investigations, one may mention investigations on the dependence of surface roughness measured perpendicularly to the machining marks from the machining conditions.

The aim of the theory of metal cutting must be that in the near future the requirements concerning the properties of the upper layer should be given in the design and technological documentation.

IV. Problems related to improvement of efficiency and reduction of work-time in cutting processes

A. *Means of improving production efficiency*

Statistics for the last ten years show that the increase of production potential in the machine-tool industry is not following production increases in mechanical engineering and metal processing. This may be illustrated by a comparison of orders for machine tools and the times of their fulfilment in machine-tool plants of highly industrialized countries.

In 1960, about 15 per cent of the machine tools manufactured were stored—currently, the number of orders is surpassing production possibilities. In some cases, plants received orders amounting to about 70 per cent more than the quantity of machine tools which they estimated they would produce.

In 1960, the time of fulfilment of 60 per cent of the orders of machine tools ranged from four to twelve months. Actually, the analogical time is valued at ten to eighteen months.

It is obvious that the improvement of the production potential in the metal-processing industry may take place only through the quantitative increase of the production means. The basic aim in industrial development is to produce the greatest mass of products giving prosperity to man and to reduce increasingly the work-time required for production.

Increased efficiency in machining operations may be achieved by reduction of the machining time, t_m; the auxiliary time, t_p, for various preparatory and auxiliary operations; and the time of organization of service on the machine tool, t_{or}. The efficiency of a given machine tool, W_o, may be expressed as follows:

$$W_o = \frac{i}{t_m + t_p + t_{or}} \left[\frac{i}{\min}\right] \qquad \text{(Equation IV-1)}$$

For many years, the increase of efficiency was achieved by the improvement of the removal rate itself, therefore, by the reduction of machining time. As a result, the share of the machining time in the total operating time, which was very important at first, has been reduced. In small-batch and medium-batch production, this share, according to data of the Experimental and Research Institute of Metal-Cutting Machines (ENIMS) varied from 36 to 65 per cent for different groups of machine tools (see table 1). The rest is the amount of t_p and t_{or}. This was a

Table 1

MAIN COMPONENTS OF PRODUCTION TIME IN DIFFERENT RANGES OF PRODUCTION AND WITH VARIOUS MACHINE TOOLS

(*Percentage*)

Machine tools	*Production*					
	Small-batch production			*Large-batch production*		
	t_m	t_p	t_{or}	t_m	t_p	t_{or}
Lathes	36	45	19	47	34	19
Turret lathes	45	35	20	61	24	15
Upright and column drilling machines	50	35	15	65	25	10
Multiradial drilling machines	40	44	16	55	35	10
Cylindrical grinders	48	35	17	59	31	10
Multiple-spindle automatic lathes	—	—	—	48	47	5
Multiple-tool semi-automatic lathes	—	—	—	43	50	7

Source: Data of Experimental and Research Institute of Metal-cutting Machines, Moscow.
Notes: t_m — machining time; t_p — auxiliary time; t_{or} — time for organization of service on the machine tool.

stimulus for directing efforts towards a reduction of the service time, t_{or}, mainly by means of a better organization of production and work-stand, as well as of the auxiliary time, t_p, mainly by means of technical improvements on machine tools. A particularly broad impetus may be noted in such development works during the past fifteen years.

B. *Possibility of reduction of non-machining times*

1. *Specialization and universalization of machine tools: mechanization and automation*

The most efficient method for improvement of production efficiency is to specialize machine tools in defined works. This permits a reduction of the time of service on machine tools, as well as in most of the auxiliary operations. Such a specialization involves, however, a decrease of universality, and by the same token, its ability depends upon the size and stabilization of the production.

The question of the narrow specialization of machine tools—the so-called "unipurposefulness"—is, therefore, relatively clear, because it is bound with the needs of small-batch production.

The in-line machine tools, whose use requires an even more stabilized production and longer periods of assured outlets, also constitute a development in the field of narrowly specialized machine tools. The above-mentioned conditions are seldom fulfilled in the metal-processing industry, but they frequently are in such industries as electrical engineering. Analogous conditions for automation of in-line machines in mechanical engineering and metal processing may be created through a major unification and concentration in the manufacture of similar elements and units for various products. As an example, one may mention the manufacture of gears, pumps, electrical motors, bicycle and motorcycle parts and units, roller-bearings and others.

The most numerous plants in the metal-processing industry have been and continue to be those with small-batch or medium-batch production. The greatest difficulty for designers of modern, highly efficient machine tools results, therefore, from the necessity of oscillating between requirements deriving from universality and those aimed at the advantages of specialization. Solutions combining both of these requirements in a profitable manner result in more users.

The development in this field during the last few decades has progressed. After the introduction of mechanical tracing (which came into view on a larger scale in 1935), turret lathes and automatic single- and multiple-spindle lathes, new achievements appeared after the Second World War. These were the building-block machine tools, or transfer machine tools, and programme-controlled machine tools.

The development in programme-controlled machine tools is increasing steadily. The large number of new achievements shown at international fairs and exhibitions is a reflection of this fact. Developments in this kind of machine tool control are progressing, and it is difficult to foresee precisely which programming system will be the most convenient. Nevertheless, there is no doubt that programme-controlled machine tools have an economically justified use in small-batch production.

To ensure a sufficiently rapid development in the design and use of transfer and programme-controlled machine tools, it is necessary to intensify research, design and construction work in this field.

In addition to the electronic and electrical problems, the development of programme control depends, to a large extent, upon the resolution of difficulties in the field of rigid reversible microtravels, mechanisms with the smallest coefficients of friction and the lowest inertia, driving systems etc.

Studies and theoretical works on the exploitation and technology of transfer, programme-controlled, automatic and in-line machine tools are of great importance. The common feature of all these machine tools is that they are able to perform multiple-tool cutting. The first problem to solve is the development and simplification of calculations for the establishment of economical cutting conditions and economical tool life, as a point of departure for rational design and exploitation of special machine tools and in-line machines. Errors in this field may have such consequences as those which occurred in the case of a machine production line provided for electrical-motor production, where at least 50 per cent of the down-times were caused by discrepancies in the organization of the exploitation of tools and the line itself.

2. *Mechanization of previously manual operations*

Table 2 illustrates the results of measurements of the duration of auxiliary operations in machining on lathes, drilling machines and grinding machines. From this table, one can see that the major part of the auxiliary time is spent in technical service and machine-tool control, and is followed by the clamping and unclamping of the workpiece, as well as measurements and control.

This fact must be taken into account as a departure point in taking steps for the reduction of the duration of machining operations through mechanization and automation of the most time-consuming operations.

Table 2

AUXILIARY TIMES FOR TURNING, DRILLING AND GRINDING OPERATIONS

(*Percentage*)

	Lathes	*Grinders*	*Column drilling machines*
1. Clamping and unclamping of workpieces	25	10	40
2. Inspection and measurement of workpieces	30	20	10
3. Clamping and unclamping of tools	13	70	10
4. Control and technical service of machine tools	30		40

The problem of mechanization in the clamping and unclamping of the workpiece is difficult to solve because of its connexion with the shape and dimensions of these workpieces.

In view of the fact that they do not reduce the universality of the machine tools, the units mechanizing the clamping and unclamping of workpieces must be designed as additive attachments, instead of being structurally bound with the machine tool. Such a solution permits changing the mechanizing attachments in accordance with the workpiece. It may be added in favour of this solution that it is not possible to wait in reaching economical effects related to the mechanization of clamping and unclamping until the whole machine part is modernized by machine tools with a mechanized working cycle. All machine tools currently in use in industry must be equipped with loading equipment.

The brunt of this task must be borne by designers from technological sections. The production rationalizers may also have important assignments in this field. The development of a mechanized control has a double significance, as it reduces both the operational work-time and the number of rejects, particularly when mechanization of the control is developed to a state of "in-process" control, i.e., possessing a feed-back.

The development and popularization of mechanized control depend at first upon the developments in fine mechanics. Problems relating to contacting and uncontacting sensing devices, rigid and inertialess transmitting and recording mechanisms must be the theme of investigations in adequate research laboratories, design and construction offices and the engineering industry.

The classification and unification of elements and units for controlling devices are of prime significance in the popularization of mechanical clamping and unclamping, as well as control. This procedure permits an increased production of standardized elements and units, without which individual attempts to mechanize manual operations would be expensive and laborious.

Reduction of the time required for the installation and change of blunt tools may be achieved by stages. The first stage is the introduction of quick-change tool-holders and bit tools. This stage must concern all general-purpose machine tools.

The introduction of bit tools and others into practical use is going relatively slowly, if one takes into account the advantages they are giving.

It seems, however, that this question is both technological and psychological; a technical one because many of the previous designs present defects which make their work more difficult; and a psychological one because, as for every novelty, there are objections from many workers.

More attention should be paid to bit tools and other quick-change tool-holders; the assortments must be expanded and introduced on a far larger scale of industrial use.

The question of reducing the duration of change of blunt tools on special machine tools, which are, to a lower or higher degree, automatically working, consists in the need for a new design permitting the automatic change of blunt tools.

The first successful tests in this matter have already been achieved and have been mentioned in technical papers published in, among others, the Union of Soviet Socialist Republics. It must, however, be said that this continues to be a problem which requires a detailed knowledge of the dependences between the blunting of the tool-point, the cutting time and many other working conditions, such as the strength wear and the methods of wear measurement.

In relation to the foregoing statement, the achievement of the automatic change of tools, not according to a forced rhythm, but at the moment when the admitted criterion of tool wear will be reached, will be an important step in the field of complex automation of machine tools.

C. *Possibilities of reducing machining times*

1. *Criterion for evaluation of the removal rate and choice of cutting conditions*

The machining time is strictly connected with the removal rate, which, in the case of general-purpose machine tools, is accepted as an index of production efficiency.[1] Up to now, however, the removal rate has

[1] Production efficiency is understood to mean the number of pieces produced during the unit of time. The production efficiency is a criterion permitting the estimation of the output of specialized machine tools.

involved the volume of chips which could be obtained in the unit of time. Such an index is significant for the energetic estimation of the process and has been helpful in conditions of large depths of cut. In conditions of fine machining with small machining allowances, the area machined by unit of time, i.e., the surface-removal rate, seems to be a more suitable index for evaluation of the efficiency of general-purpose machine tools.

$$Q_F = 100 \frac{F}{t} \left[\frac{\text{sq. mm}}{\text{min}}\right] \qquad \text{(Equation IV-2)}$$

where

F [sq. mm] — the machined area;
t [min] — the machining time.

In turning, for instance, where

$F = \frac{p \cdot v}{10}$, formula G becomes:

$$Q_{Ft} = 10 \cdot p \cdot v \left[\frac{\text{sq. mm}}{\text{min}}\right] \qquad \text{(Equation IV-3)}$$

where

p [mm] — the feed;
v [m/min] — the cutting speed.

A far better and more comparable index for the estimation of the efficiency of general-purpose machine tools is the specific surface-removal rate:

$$qF = \frac{QF}{N_s} \left[\frac{\text{sq. mm}}{\text{kW min}}\right] \qquad \text{(Equation IV-4)}$$

where N_s [kW] — the power of the motor.

The machining time may be expressed as follows:

$$t_m = \frac{F}{100 \cdot Q_t} = \frac{F}{1{,}000 \cdot p \cdot v} \text{ [min]} \qquad \text{(Equation IV-5)}$$

The cutting speed is taken according to the recommended durability, i.e., the periodic cutting speed.

The formula giving the periodic cutting speed is the following:

$$V_T = \frac{C_v}{T^m \cdot g^{e_v} \cdot p^{u_v}} \qquad \text{(Equation IV-6)}$$

where

C_v — a coefficient, taking into account various factors not considered apart;

T — the tool-point durability;

m, e_v, u_v — exponents found by experimental means.

From this, it results that:

$$t_m = \frac{F}{1{,}000 \cdot C_v} \cdot \frac{T^m \cdot g^{e_v}}{p^{1-u_v}} \qquad \text{(Equation IV-7)}$$

Therefore, owing to the definition of the criterion of efficiency in the form of surface-removal rate, it results that increasing the depth of cut may improve the machining time.

The attention of designers, production engineers and users is drawn to the fact that the basic trends for the increase of machine-tool efficiency are towards the increase of cutting speed and particularly feed, simultaneously with small depths of cut.

For the production engineer, the notion of surface-removal rate associated with the principle of the smallest possible—taking into account the accuracy—number of cuts will be a convenient guide-line in the choice of machining conditions.

It is therefore necessary to elaborate tables giving a comparison of the indexes of specific removal rate for every type of general-purpose machine tool.

2. *Role of tools and cutting fluids*

If one considers the possible surface-removal rate (Q_t) of a defined machine tool-workpiece-tool system, the results of these considerations may be illustrated by the diagram shown in figure 13. For a constant diameter of turning, d; depth of cut, g; and other factors; and submitting to variations only the feed, one may ascertain that for different values of the feed the cutting speed is limited either by the rotation speed of the spindle (when $p < p_i$), by the tool-point durability (when $p_i < p < p_{opt}$) or by

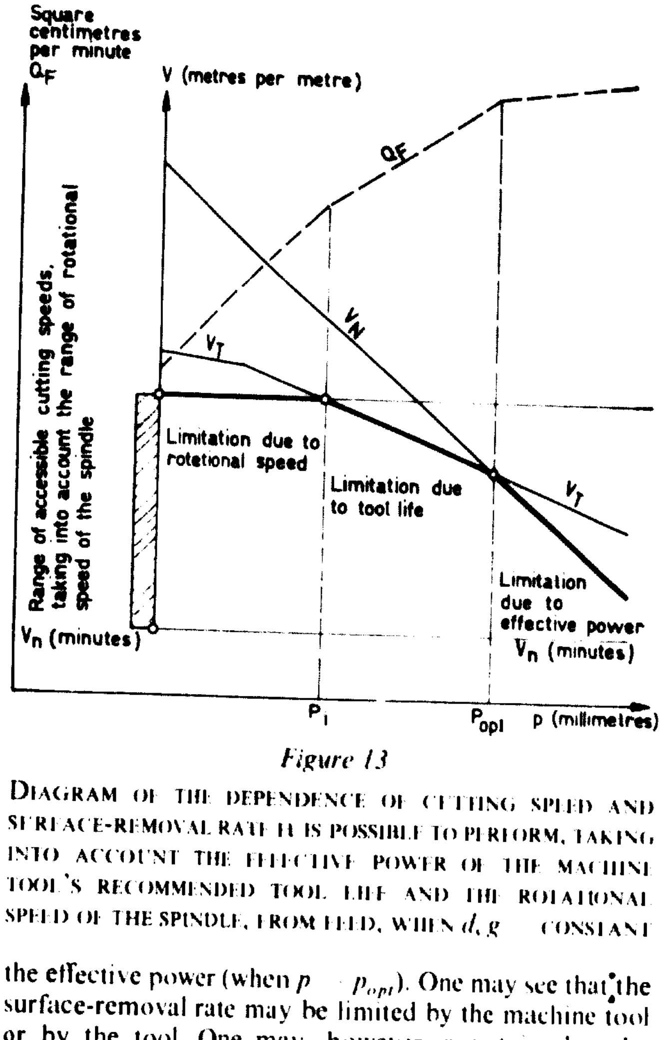


Figure 13

DIAGRAM OF THE DEPENDENCE OF CUTTING SPEED AND SURFACE-REMOVAL RATE IT IS POSSIBLE TO PERFORM, TAKING INTO ACCOUNT THE EFFECTIVE POWER OF THE MACHINE TOOL'S RECOMMENDED TOOL LIFE AND THE ROTATIONAL SPEED OF THE SPINDLE, FROM FEED, WHEN d, g = CONSTANT

the effective power (when $p > p_{opt}$). One may see that the surface-removal rate may be limited by the machine tool or by the tool. One may, however, ascertain that the limitation due to the machine tool is strong only when the power of the motor and the speed of the spindle are badly fitted by the designer to the cutting possibilities of the tool. This may be easily corrected even by the user, by means of a convenient change of the speed and power of the motor – the so-called "modernization" of the machine tool.

Therefore, if the power of the motor has such a value that p_{opt} is in the maximum range of applicable feeds, and the limits of rational speed of the spindle are sufficiently high, the only limit to the cutting speed and the surface-removal rate factor is the tool life. For this reason, one often hears that the development of the removal rate depends upon the tool. The history of the development of machine tools and machining shows that this is true.

The improvement of the cutting properties of tools is, therefore, a difficult but fundamental task in developing the machining removal rate.

One means of achieving progress in this field is the improvement of the shape of the tool-points. Far better results have been obtained and continue to be obtained by improvement of the properties of the tool materials. The cutting properties of tools are related to their abrasion resistance and strength resistance, irrespective of temperature, under machining conditions. The development of the cutting process is still directed to the purpose of increasing the cutting speed and the temperature on the tool-point. Therefore, development of materials for tools must be aimed at research on materials with the highest strength at high temperatures. This is a reason for studies on the usability of mineral materials for tool-points, although their mechanical properties at normal temperature are far lower than the properties of metal materials. This factor is reversed in some cases for high cutting temperatures.

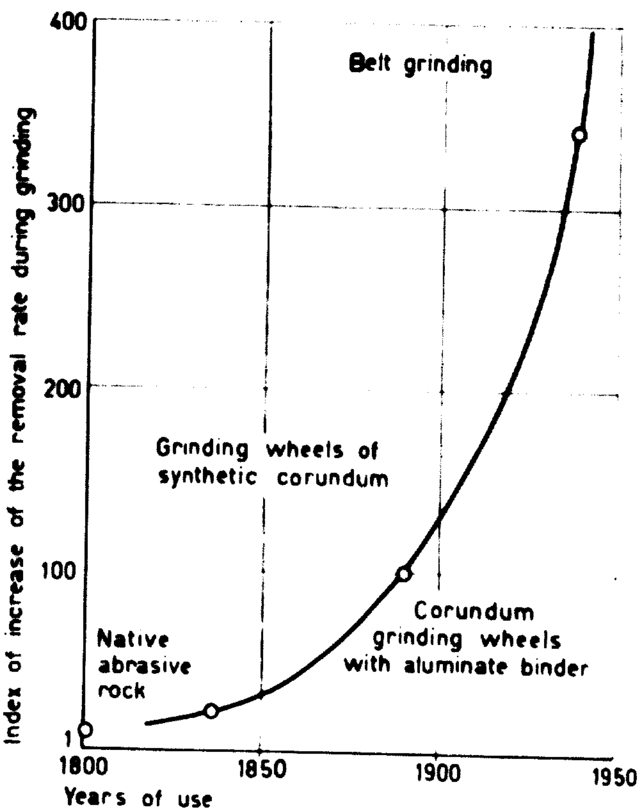


Figure 14

INCREASE OF GRINDING REMOVAL RATE, 1800–1950

Investigations undertaken with a view to producing and putting into use materials which are more resistant to abrasion and which have higher strength properties in normal temperatures must also be considered interesting. These investigations concern the improvement of the "classical" and most popular tool materials, such as sintered carbides and high-speed steels.

Such a tendency may also be noticed in abrasive materials. Figure 14 shows how the surface-grinding removal rate increases with the development of grinding wheels, i.e., abrasive materials and binding materials.

The development and application of cutting fluids may also lead to an increase in the removal rate. Progress in this field within the past few years is shown in figure 15.

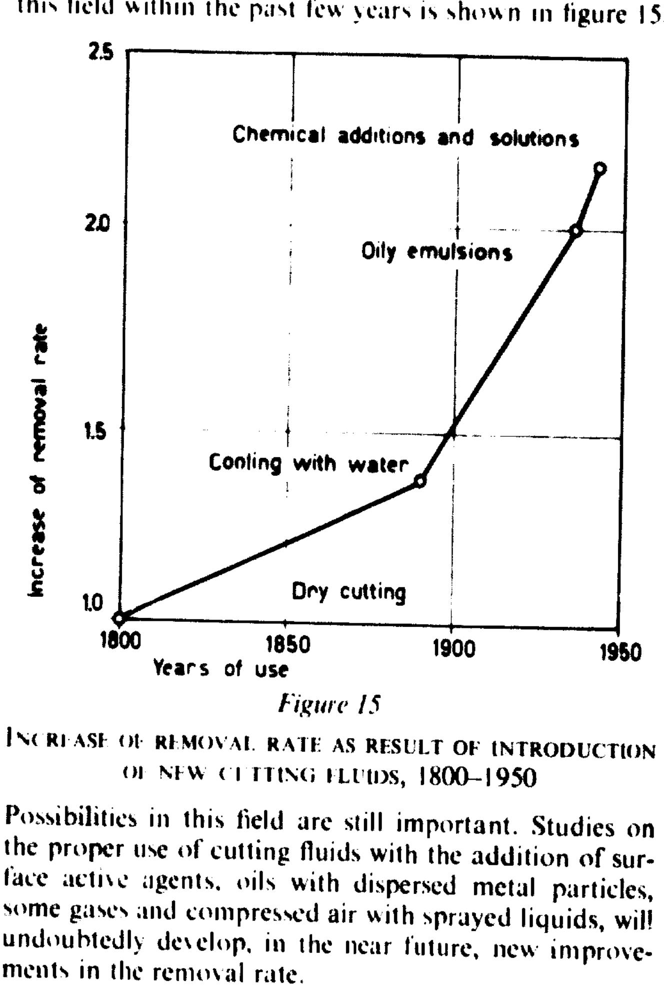


Figure 15

INCREASE OF REMOVAL RATE AS RESULT OF INTRODUCTION OF NEW CUTTING FLUIDS, 1800–1950

Possibilities in this field are still important. Studies on the proper use of cutting fluids with the addition of surface active agents, oils with dispersed metal particles, some gases and compressed air with sprayed liquids, will undoubtedly develop, in the near future, new improvements in the removal rate.

An additional possibility for increasing the removal rate may be the introduction, on a larger scale than heretofore, of tools with interior cooling. However, it is necessary to begin production of both the tools with built-in cooling and the auxiliary equipment necessary for the use of such tools.

V. PROBLEMS OF IMPROVEMENT OF MACHINING POSSIBILITIES AND MACHINABILITY

A. *Specific machining properties of new construction materials*

One of the characteristic features in the development of mechanical engineering is the introduction, on a larger scale, of materials which are entirely new or are improved from the point of view of strength requirements. As a rule, however, the improved strength properties are combined with worse machinability. Taking everything into consideration, the new materials with high strength properties or peculiar physical properties have specific machining properties.

Thus, when machining molybdenum and tungsten, one may observe very strong wear of an adhesive kind, which is relatively small when machining conventional materials. The order of influence of the various machining conditions on the machining effects is different also. The effect of cutting fluids on the tool life and the influence of tool materials on the removal rate and tool life are different.

The machining of fissionable materials, which present additional difficulties with regard to their radio-activity, has been insufficiently studied.

Some non-metallic materials, which are being increasingly used in mechanical engineering, constitute a distinct group.

From this situation, it appears that many systematic, thorough studies need to be undertaken with a view to elaborating optimal conditions in order to permit an efficient development of the machining process on the basis of theoretical knowledge.

Taking into account the tendencies to introduce new materials in mechanical engineering and the perspectives for machining in entirely different conditions—such as vacuum machining in planetary stations—one must concede that investigations in this field are particularly important and progressive.

B. *Methods and means of improving machining possibilities in the cutting process*

1. *Change of state of the material by changes of temperature and speeds of deformation*

Many attempts have been made in the field of improvement of machining possibilities by the classical cutting means. These attempts present the following common trends:

(*a*) An increase of the cutting capacities of tools by means of improvements in their resistance to abrasion and choice of shape of the tool-point;

(*b*) Improvement of the material machinability.

The increase of the cutting capacities of tools has been achieved, owing to an improvement in the strength and abrasion resistance of tool materials. As a proof of progress in this field, one may note that the bending strength of sintered-carbide manufactured thirty years ago reached about 100 kg sq. mm, and actually produced grades of sinter which were about 80 per cent more resistant. One may presume that further important improvements may be made in these materials. The most important difficulty is that in improving the strength one must take care not to reduce, but to improve, the abrasion resistance of the tool material under cutting conditions. This problem requires further studies on the phenomenon called the adhesive affinity of the tool and workpiece materials, upon which depends—often in a decisive manner—the tool wear.

Improvement of the cutting properties is frequently achieved by means of a change of the tool-point shape. As proof of this, one may mention the numerous improvements announced and popularized in technical papers. Almost all of these works are of an entirely empirical character and may have only a very narrow range of use. This is a result of the lack of engineering methods for calculation of the tool-point's strength. Works in this field are just beginning and are progressing very slowly. Investigators and theorists dealing with material strength must work on this urgent question.

However, advances in the field of cutting properties are important; they are insufficient in regard to the needs in machining of new "difficult-to-work" alloys. Therefore, more and more tests are being undertaken with a view to ameliorating the machinability. This may be achieved by one or both of the following methods:

(*a*) Changes in the chemical constitution or structural composition of the material in such a manner as to avoid reducing the properties at work, simultaneously improving the machinability;

(*b*) Changes of the state of the material during the cutting process, i.e., the change-over to a state of momentary brittleness or momentary high plasticity, which results in a decrease of the specific cutting work.

The improvement of machinability by change of chemical constitution and momentary or constant change of structure is difficult to do and not many results have been achieved, because such changes are possible only in some peculiar cases. Not without significance in this field is the insufficient attention paid to this question by metal physicists and metallurgists, and the lack of collaboration between them and production engineers.

Much attention is being paid to the machining methods, which aim to produce profitable changes in the state of the machined material. Such changes may be reached through preliminary heating of the workpiece—which leads to a plastic state and reduces the limits of strength; by artificial cooling—which leads the material to a state of increased brittleness; and by a considerable increase of cutting speed and change of the tool geometry. The tool geometry may be changed in the process to make the material pass in the state of increased brittleness, or to have a more advantageous distribution of heat and temperature in the workpiece, chip and tool point, or to produce both effects at once.

The reduction of metal alloys which have been heated to a high temperature, the so-called "hot cutting", has been practised for several decades. From a theoretical point of view, this method is based on the phenomenon of decrease of the cutting resistance in heated metal alloys. Thus, an increase of the temperature of carbon steel to about 600°C causes, for instance, a decrease of 40 to 60 per cent of the cutting resistance.

The hot-cutting method is, however, difficult to perform in practice. There are difficulties in operating with a hot workpiece, possibilities of structural changes, novice influence on the tool life and the machine-tool durability, difficulties in obtaining good accuracy and surface finish, difficulties related to the heating of the workpiece and so on. These difficulties, together with the insufficient knowledge of the hot-cutting process, lead to the opinion that this method may be used in machining conventional metal alloys only in the case of discontinuous fine machining, for instance, in machining hot ingots, hot forging and so on.

The introduction of highly resistant alloy steels, which are very difficult to machine, and the progress in theoretical knowledge of the cutting process lead to the opinion that hot cutting may be in a defined range of a purposeful and economic process.

From investigations, it appears that the basic factor for a successful performance in hot cutting is the temperature of preliminary heating. This is illustrated in figure 16, representing the dependence of the tool-point and machined-material hardness upon the temperature.

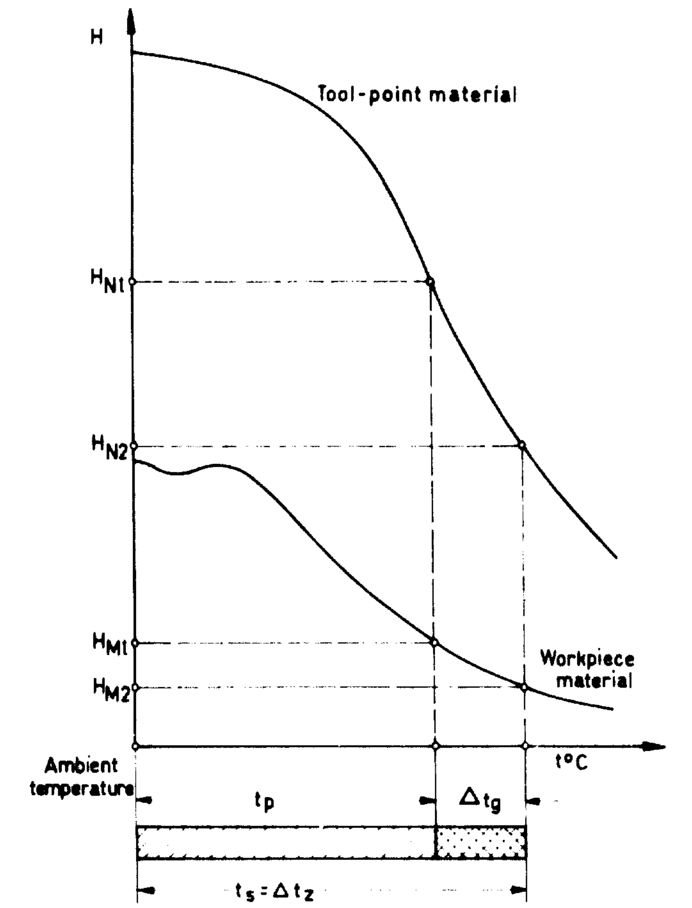


Figure 16

SCHEME OF THE DEPENDENCE OF THE TOOL-POINT MATERIAL AND THE WORKPIECE MATERIAL HARDNESS UPON TEMPERATURE

In the case of normal cutting, the highest temperature on the friction surface, called the cutting temperature, reaches t_s. This temperature results from the transformation of the cutting work into heat.

However, if the workpiece—particularly, the upper layer—is heated to temperature t_p before the beginning of the cutting process, the cutting resistance is much smaller and the cutting work performed by the tool-point is far smaller also. It follows, therefore, that the mechanical load acting on the tool-point will be far smaller, which creates a protection against the possible denting of the tool-edge and a reduction of its abrasion resistance.

The increase of temperature, Δt_g, which is created by the transformation of the cutting work into heat, is generally so small that the sum is $t_p + \Delta t_g < t_s$. This signifies, especially in discontinuous cutting, that the heating of the tool-point is lower in machining a hot workpiece than in cold machining. Therefore, if other difficulties of this method are overcome, it may become profitable.

At the current time, the hot-cutting method is used with good results in the iron and steel industry and in some plants of the aircraft industry when machining materials which are difficult to work.

On a smaller scale, investigations have been made on cutting through freezing of the cutting zone and the tool. Freezing is frequently performed by means of compressed or liquid carbon dioxide. By decreasing the temperature to some tens of degrees under 0 C, the ductility of some "difficult-to-work" and ductile steels, such as austenitic steel, decreases,and the machinability of these steels increases. The handicap of this method is the cost. Nevertheless, it is worth while submitting it to tests with a view to putting it into use in some cases.

The tests undertaken on cutting with very high speeds are interesting. Reports on these tests refer to "gun-fire speeds", i.e., about 30–60 km/min. However, this speed is not considered the final point of possibility; in the near future, a speed of 110 km/min., i.e., about one-third of the sonic velocity in steel, will be achieved.

Efforts to develop high speeds are due to increased efficiency requirements, but the primary need is for machinability of steels which are very difficult to work. This is based on some fundamental principles, resulting from the extrapolation of properties already known for the cutting process in the range being used. It has been ascertained that with the increase of cutting speed there will be a decrease of the specific cutting resistance, which is due to the decrease of the friction and plastic deformation work, and the increase in temperature will be slower in proportion to the increase in cutting speed.

One can foresee that a very important increase in cutting speed—and in the plastic-deformation velocity—must bring about a state of brittleness in the machined layer and produce a decrease of friction work and cutting resistances.

This theory was put forward in 1929 by C. Salomon and was analysed and developed by W. D. Kúzniecow. The most recent tests performed in the United States of America only partially corroborate the expectancies related to very high cutting speeds.

It would be hazardous to advance any practical conclusions from the actual investigations, mainly because the cutting time in these tests is very short. Such cutting speeds are performed by shooting the workpiece in a barrel. At the muzzle, the workpiece meets the cutting tool. There is a need for designing equipment to permit a longer cutting time, even with smaller than "shooting" cutting speeds, but allowing some comparisons and evaluation of its possible practical use.

2. *Other development trends in chip removal and abrasion machining*

The development of many branches in heavy industry—the power industry, iron and steel industry, chemical industry—requires machines and equipment of very large dimensions. These industries are presenting the greatest indexes of increase. For this reason, the need for machine tools designed for machining large pieces is important. There is not only a need to develop the production basis of heavy machine tools, but also a need to overcome many technological difficulties related to the dimensions and accuracy of the workpiece. Research and technical works related to the fine machining of heavy, huge workpieces will be one of the most important areas of study for the expansion and improvement of chip-removing machining processes.

In the field of abrasion machining, an important improvement of machining possibilities is in the development of curvilinear-surface grinding by means of abrasive belts and liquid honing.

The abrasive-blast treatment is especially suitable for honing and, particularly, for the cleaning of free surfaces or curvilinear or nearly inaccessible surfaces, for grinding surfaces to be covered by electroplating or lacquer and so on. The applications of the abrasive-blast treatment are numerous, but the limits and rate of increase of their use depend upon the degree of production of cheap, efficient equipment.

An important improvement in the machining of exceptionally hard and brittle materials, such as semi-conductors, by means of loose abrasive grains, has been achieved by utilization of the tool energy due to its longitudinal vibrations at a supersonic frequency of about 16–18 kHz. This abrasive and erosive means, called ultrasonic machining, only appeared during the last few decades. Nevertheless, in many countries, the first abrasive and erosive machine tools, although not exactly known as "ultrasonic", have already been designed.

All of these abrasive machining methods are already at an initial state of popularization. They promise to become useful improvements and extensions of the classical abrasive means, and investigations in this field must be considered most urgent.

C. *Improvement of machining possibilities by means of other removal methods*

Mechanical energy is not the only form of energy which may be used in removal shaping of pieces. Twenty years ago, development of the erosion treatment of metal alloys commenced by means of electrical and chemical energy. More recently, investigations and tests have been undertaken for the purpose of putting into practical use various other forms of energy, namely:

(*a*) Ionic machining, called plasma machining, by means of energy provided by a plasma stream, the machining process taking place by fusion and partial vaporization;

(*b*) Electron machining, by means of energy provided by a stream of electrons (in vacuum);

(*c*) Photonic machining, by means of energy provided by a strongly condensed stream of photons. This method is called laser machining.

The above-mentioned methods are currently in the research stage and will not play an important role in the production of machine elements in the immediate future. Rather, they will constitute an improvement of the cutting method.

Among the different methods of electrical erosion, the most popular at the current time are the electro-erosion and electro-impulse methods. In spite of their specific features, both of the above-mentioned methods may be compared to a chip-forming method of a discontinuous character. The removal rates of these processes depend upon the energy of each discharge and upon the frequency of these discharges. They are analogous to the removal rate in milling, which depends upon the volume of the removed layer by one tool-point and upon the frequency with which the tool-points dive into the material. The greater the energy of each discharge and the smaller the frequency, the worse is the surface finish. This phenomenon may be compared to the influence of the feed and of the dimensions of the removed layer. The tool wear in electrical machining, as in chip-forming machining, plays an important role. The dependence of accuracy and surface finish upon the removal rate is analogous also.

The most important difference between electro-erosion machining and chip-forming machining consists in the technological indexes; in the first place, the removal-rate indexes of the former are dependent upon the machined-material properties only to a low degree. The specific removal rate in the electro-erosion machining of "easy-to-work" metal alloys is far smaller than the cutting removal rate.

This situation is reversed for "difficult-to-work" cutting materials. Therefore, electro-erosion is currently (and in the near future, will be) most suited for machining materials which would be difficult to work or which would be unmachinable by the cutting method.

The application of electrochemical erosion in machining processes is very encouraging. Compared with electro-erosion machining, the advantages of this method are:

(*a*) It is an almost "cold" process, ensuring eventual changes in the upper layer;

(*b*) The tool is practically unwearable;

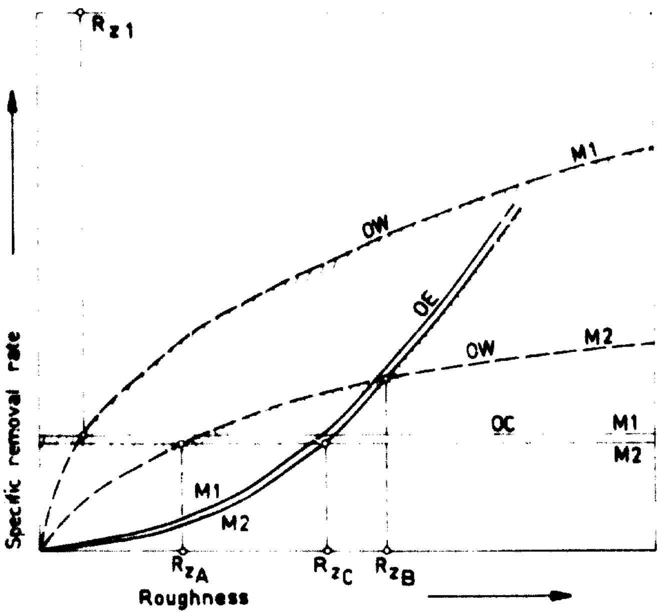
(*c*) The surface finish is dependent upon the removal rate.

The specific removal rate in electrochemical erosion has an upper limitation, but, theoretically, the possibilities of increase of its surface-removal rate are unlimited. Electrochemical erosion is, therefore, particularly suitable for machining large areas.

In figure 17, one may see the curves for the chip-forming removal rate (OW), the electro-erosion removal rate (OE) and the electrochemical removal rate (OC) for two materials, M1 and M2. M2 is very difficult to work in comparison with M1, as regards the surface roughness.

In the case of an "easy-to-work" material and surface finish ($R_z < R_{zl}$), the electrochemical method gives a higher removal rate. This method may, therefore, replace grinding and other abrasive means. On the other hand, in the limits of R_z – R_{zB}, the chip-forming machining allows a far higher specific removal rate. The value of the volume removal rate is, in this case, about 20–30 mm³/kWmin.

In the case of the poorer machinability of the M2 material, the cutting removal rate either rapidly decreases, as is shown in figure 17, or the material is not machinable



OW – chip-forming removal rate, OE – electro-erosion removal rate, OC – electrochemical removal rate, M1, M2 – workpiece materials

Figure 17

REMOVAL RATE PERMISSIBLE IN VARIOUS REMOVAL PROCESSES, ACCORDING TO ROUGHNESS NEEDED FOR THE WORKPIECE

by cutting. In the illustration given in figure 17, within the limits of necessary roughness, $R_z < R_{zA}$, the more profitable method is electrochemical machining; and within the limits of $R_{zA} < R_z < R_{zB}$, the most profitable would be chip-forming machining. Above $R_z > R_{zB}$, the more profitable would be electro-erosion machining. In the case of a material not machinable by cutting, the limiting point of partition in the application of electro-erosion machining and electrochemical machining would be the R_{zC} roughness.

From the diagram shown in figure 17, it may be noted that if any important changes occur in the relationship between the removal rate and surface finish, the two methods mentioned may be considered complete in the different limits of their use.

None of these methods competes with the other in the whole range of its use. Further progress in removal machining must depend upon collateral development of chip-forming and abrasive machining, as well as upon electro-erosion and electrochemical machining, along with methods using other sources of energy.

The history of the development of removal machining shows that it has progressed over the years. Will this rate of progress be maintained? It is impossible to make qualitative predictions, but it may be affirmed that as more investigations are developed, they will exert an important catalytic influence on technical progress.

The final result of development in the field of cutting machining depends – as in other fields of technical progress – upon the organization of work for the application of investigation results in production. The term, "the bond of science and practice", must imply that practice does not only create needs for investigations, but also leads to progress in economic development and productivity, as a result of new inventions deriving from theoretical and research work.

Finally, one must remark that the effects which may result from the activities of the science-production system depend, to a certain degree, upon the organization and economy of industry and production. Therefore, questions of improvements in the economy, organization and direction of industry constitute an inseparable part of production development.

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