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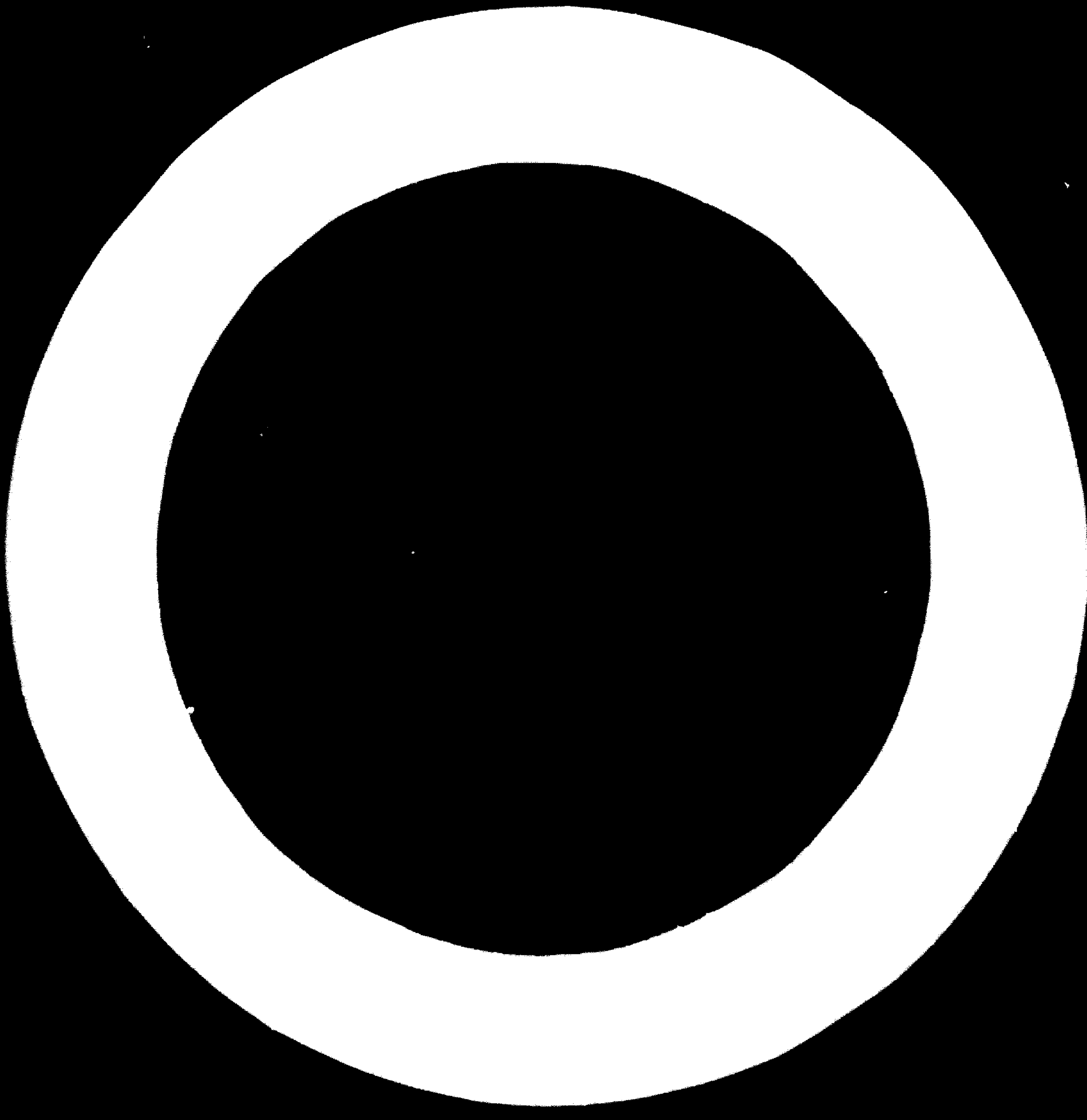

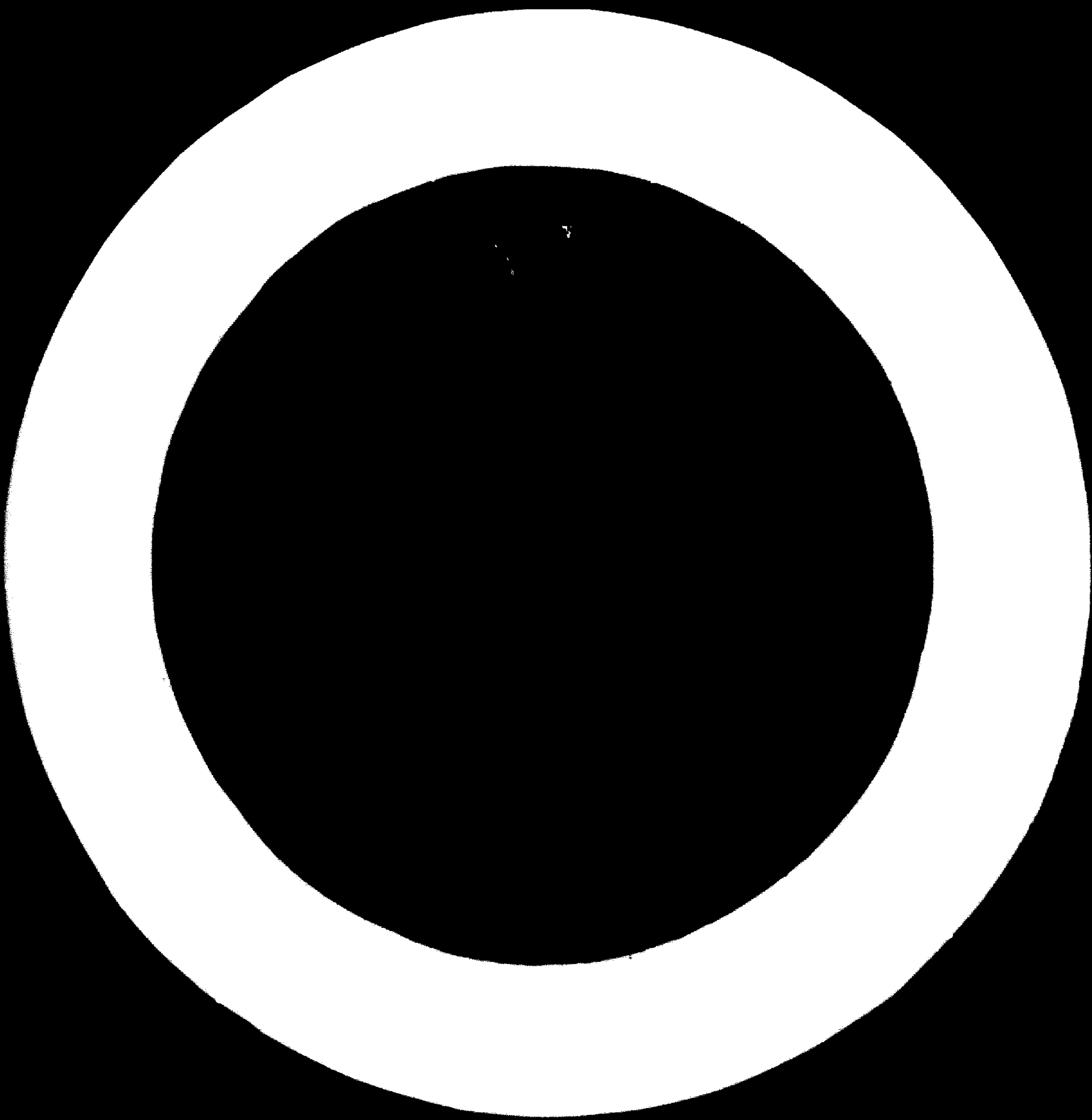

REPAIR AND MAINTENANCE OF MACHINE TOOLS IN DEVELOPING COUNTRIES

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INTRODUCTION

Machine tools, together with welding equipment, occupy a special position in relation to other machinery, such as that used in the textile industry, transport, light industry, printing and so on. Machine tools are used to produce parts of other machines, i.e., to manufacture new machines and instruments, and to repair existing ones.

A country's stock of machine tools—its technical level, structure and condition—to a considerable extent determines the national productive capacity and ability to solve technical and economic problems independently.

The structure and growth of the machine-tool stock are closely connected with a country's level of industrialization. As the country develops, it continues to use general-purpose machine tools of normal accuracy, but it makes increasingly extensive use also of precision tools, automatic tools and lines, specialized tools for specific branches of mechanical engineering and heavy tools for parts of large machines.

Thus, table 1 shows the number of types of machine tools put into production in the Union of Soviet Socialist Republics since the establishment of a domestic machine-tool industry. These figures indicate how the need for machine-tool mechanisms depends, to a considerable extent, upon the methods used to operate, maintain and service it.

If insufficient thought is given to these methods, great waste of resources and, most important, of foreign exchange, can result. Such waste is due to two factors which arise when individual units and mechanisms are taken out of service prematurely.

First, there is an increase in the amount and, accordingly, the cost of repair work. Often the repairs may entail the importation of spare parts.

When the failure occurs in a complicated precision part, such as a precision lead screw, the bushings of a jig borer, a reading mechanism or the like, it is not always possible to repair and recondition it locally. This may be avoided by adequate methods of operation and servicing.

Secondly, wear and breakdowns increase idle time in repair and reduce the tool's use coefficient. Consequently, extra machine tools have to be acquired to do the same amount of work, and shop space has to be increased correspondingly.

Furthermore, improperly repaired and maintained machine tools may fail to meet their technical specifications, particularly as regards accuracy.

Table 1

NUMBER OF TYPES OF MACHINE TOOLS IN SERIES PRODUCTION IN THE USSR

Categories of machine tools produced	*1932*	*1937*	*1940*	*1945*	*1950*	*1955*	*1957*	*1965 (planned)*
Precision	—	4	7	9	41	109	115	180
Automatic and semi-automatic	7	42	87	40	115	250	295	650
Specialized	6	39	54	47	141	346	370	620
Heavy	3	5	29	12	90	247	180	420
Total, all types	47	190	320	150	384	788	900	1,500

tools has grown in the Soviet Union as its industry has developed.

Given a stock of machine tools, the problem arises of how to use them most efficiently and to extend their service life as long as possible. This can be achieved only through the organization of a special repair and maintenance system.

This is a very serious problem, for modern machine tools are highly complicated machines which include precision devices, hydraulic and electrical systems, high-speed and power transmission systems and automatic and control devices.

The functioning of a machine tool's units and mech-

Thus, it is important not merely to acquire a stock of machine tools, but also to maintain it in efficient condition, which can be done by applying a repair and maintenance system and by developing methods of increasing the reliability and durability of equipment.

It is important to train national personnel armed with modern technical ideas in this field.

I. ECONOMIC ASPECT OF THE MAINTENANCE AND REPAIR OF MACHINE TOOLS

Expenditure on the repair and maintenance of equipment accounts for a considerable proportion of production costs.

Research has shown that every year approximately 10 per cent of the stock of technical equipment undergoes a major overhaul; 20–25 per cent, an intermediate overhaul; and 90–100 per cent, a minor overhaul.

The loss of time and resources involved in keeping the stock of machine tools in good order is substantial, depending to a great extent upon the methods of operating and servicing the machines and the technology and organization of maintenance. For example, in an average-size or small enterprise, the cost of major overhaul alone is normally up to 60 per cent of the cost of a new machine in the case of medium-size turning lathes, up to 40 per cent in the case of universal milling machines and up to 75 per cent in the case of capstan lathes. It must also be remembered that prior to the major overhaul, a machine tool undergoes two intermediate overhauls, each of which takes about half as much labour as a major overhaul, and six minor overhauls, each of which takes about one-quarter as much labour as a major overhaul.

In addition, machine tools are periodically checked for accuracy, lubricated and given preventive treatment.

Thus, the cost of maintaining and servicing a machine tool during one maintenance cycle (i.e. up to and including the major overhaul) is greater than the cost of a new machine, and if maintenance and repair are badly organized, it can be several times greater.

A factor of no less importance in evaluating the economics of maintenance is the idle time lost by equipment during the various kinds of overhaul.

As an example, one may consider the periods of forced idleness for maintenance work on screw-cutting lathes and cylinder-and-core grinding machines of average size and complexity of design. These data are taken from the standards for machine-tool maintenance applied in the Soviet Union (1), under which maintenance of all equipment is carried out in accordance with a special system known as the "planned preventive maintenance system".

The figures given in table 2 are for maintenance teams working a single shift and indicate how many days a machine tool must remain idle for the given type of maintenance.

Table 2

IDLE TIME OF MACHINE TOOL DURING VARIOUS TYPES OF MAINTENANCE, WITH MAINTENANCE TEAM WORKING ONE SHIFT

(*Days*)

Type of maintenance	*Lathe*	*Cylinder-grinding machine*
Major overhaol	11	18
Intermediate overhaul	6.5	11
Minor overhaul	2.75	4.5
Accuracy checks	1	1.5

As was stated above, under the current maintenance system a machine tool undergoes two intermediate and six minor overhauls before its major overhaul. Accordingly, the number of days which a screw-cutting lathe, for example, will lose for maintenance from the time it is put into operation until its major overhaul is completed (i.e. over the period of the maintenance cycle) will be:

$$11 + 6.5 \times 2 + 2.75 \times 6 = 40 \text{ days}$$

A machine's operating life before major overhaul, and similarly between intermediate overhauls, depends, to a large extent, upon the methods of operation. For example, a screw-cutting lathe working single shifts at a series production factory and turning out steel parts to a normal degree of accuracy will have a working life of four to nine years before major overhaul.

If the machine tool runs for eight years before major overhaul, it follows that the time lost for maintenance will amount to an average of five days a year. If the shop has sixty machines with the same average maintenance complexity as a screw-cutting lathe, the total idle time will be 300 days, i.e., the maintenance crew will have to work steadily all year round on maintaining the machines (not allowing for lubrication and preventive and other measures).

If, because of insufficient attention to operating methods, the maintenance cycle is four years, the relative volume of maintenance work will be twice as great.

These figures show that great attention must be given to methods of maintaining and operating equipment. It is necessary to know why a machine tool loses its efficiency, as well as the methods by which its reliability and durability can be increased; in maintaining equipment, up-to-date technological processes and methods must be applied. In addition, the equipment maintenance system must be so organized as to act in advance to reduce the progressive wear of equipment, bring maintenance costs to a minimum, and ensure the proper preparation and planning of maintenance work and the efficient use of equipment.

II. CAUSES OF LOSS OF EFFICIENCY IN MACHINE TOOLS

In approaching machines and mechanical systems, the classical sciences, such as mechanics, attempted to idealize the conditions in which they functioned. The errors and inaccuracies caused in the actual performance of a machine by component wear, temperature deformation, defective materials, technological factors etc. were viewed as aberrations from the performance of the perfect machine and as undesirable and fortuitous phenomena.

Modern science, particularly cybernetics, takes a different view of the errors in a given system. Errors and inaccuracies in a machine's execution of an assigned programme (e.g., a technological process) are regarded as a natural feature of any real system. The need thus arises to investigate the sources and causes of adverse influences acting on machines and to study the machines' reactions to them.

A machine cannot be completely isolated from the effects of its environment, nor can it be isolated from the influence of the processes going on within itself as it functions.

A. *Influence of energy*

The units and working parts of a machine tool in an industrial shop are subject to the influence of energy in all its forms, which affect its technical performance.

Mechanical energy is not only transmitted through the various working parts of the machine as it performs the given technological process, but also acts on the machine as a whole, in the form of vibrations transmitted by other equipment running in the shop, vibrations generated as the machine is fed material and so on.

The forces at work in the machine are the product of both the technological process and such forces as those arising from friction in kinematic couples or inertia in moving parts. These forces cannot be strictly defined since the very nature of their occurrence is bound up with complex physical phenomena.

It is, indeed, this degree of indefiniteness of the influences at work that gives rise to the errors and inaccuracies in the operation of mechanical systems. Furthermore, even a constant force produces wear, deformation and fatigue, i.e. causes a component's parameters to change with time.

Thermal energy affects machine parts as a result of fluctuations in shop temperature, the operation of driving gear or electrical equipment, or heat generated during the cutting process.

These phenomena also affect the operation of both individual working units and the entire machine. Studies have shown, for instance, that as little as two hours' exposure to the sun (at mean latitudes) of the face of a cylinder-and-core grinding machine produces a shift in the table guides, causing the table to deviate 45 microns from true linear displacement. Performance can be affected even more by the heat generated in electric motors, bearings, gear-boxes, hydraulic systems etc. Thus, oil heating in the hydraulic systems of power heads in standard-unit machine tools can increase oil losses and decrease feed. As a result, the duration of the working cycle in the machine or automatic machine line spontaneously increases and productivity falls. It is practically impossible to make accurate allowance for thermal effects.

Chemical energy also has an effect on machine performance. Air containing moisture and aggressive elements can cause corrosion in various machine parts. Emulsion used to cool a tool may drip onto essential machine parts, especially the electrical system, causing premature failures.

Electromagnetic energy in the form of radio waves electromagnetic oscillations) permeates the space around a machine and may affect the performance of the electronic apparatus, which is being increasingly employed in modern machine tools.

Thus, all forms of energy attack the machine and its working parts, initiating a great many undesirable processes and creating conditions making for technically inferior performance.

B. *Reversible processes affecting efficiency*

Before dealing with the methods by which these harmful influences may be combated, it is appropriate to examine briefly the processes that cause a machine to lose its working efficiency.

Some processes occurring in a machine and affecting its performance are reversible, since they alter the parameters of parts, units and the entire system within given limits, without tending to cause progressive deterioration.

The most typical example of a reversible process is the deformation of machine parts and units which occurs under the influence of external or internal forces. The sources of deformation in machine tools include not only deformation of the parts themselves, but also deformation at surface junctions, e.g., slideways, bearings and other linkages. Deformation of parts and junctions alters the relative positions of machine units, including the position of the tool and the workpiece. The result is a loss of precision, the machine's most important technical feature. When the forces change, so does the deformation; and when the stress is removed, elastic recovery takes place and the machine parts return to their original positions. It is for this reason that the deformation process is regarded as reversible.

If circumstances arise in which the forces change periodically and very frequently, vibration of the machine units occurs, i.e. rapid deformation changes of minor magnitude. Vibration also seriously affects the quality of work. It usually results in inferior surface finish.

Another example of a reversible process is the temperature deformation of machine parts and units.

Heat production in the cutting zone or in friction couplings and ambient temperature variations lead to temperature deformations which alter the original positions of machine units and consequently reduce precision. Thus, observation of the position of a lathe spindle has shown that after some hours of operation (three to seven hours) the spindle is gradually displaced, owing to the heating-up of the headstock face. The displacement reaches 20 to 120 microns and then stops, a certain degree of heat exchange being established. After the machine has been switched off, the spindle gradually returns to its former position.

Machine tools can sometimes be adjusted to reduce inaccuracies due to temperature deformation, but this makes their operation more difficult.

Accuracy of work is particularly affected by temperature deformation in precision units and framework members.

C. *Irreversible processes affecting efficiency*

Whereas reversible processes occurring in a machine tool lower its efficiency, as compared with its potential performance in the absence of deformation, temperature effects and the like, irreversible processes result in the progressive deterioration of the machine's performance with time.

The most typical irreversible processes in machines are wear, corrosion, the gradual redistribution of internal stresses and creep (the slow building-up of deformations).

The most important cause of loss of efficiency in machine tools is wear of machine parts. Wear is the result of a process of gradual change in the dimensions of the surfaces of machine parts under the influence of friction. The process of wear arises out of numerous complex physical phenomena occurring on the friction surfaces of machine parts.

As the surfaces interact, they deteriorate and give off minute particles. At various points of contact, the temperature rises, changes occur in the structure of the surface layers and there develop chemical processes and processes connected with the molecular attraction of the contiguous materials.

The most common types of wear met with in machine tools are the following.

Abrasive wear, in which abrasive particles found on friction surfaces attack the surfaces by cutting or scratching and produce tiny chips. The particles usually enter the lubricating fluid from the outside and travel with it to the friction surface, but they can also be produced by wear in the couple itself, or they may be hard structural components at one of the abutting parts. In many cases, therefore, abrasive particles cannot be completely eliminated from the friction surfaces of machine parts. Even with efficient oil filtration and the isolation of friction surfaces, conditions for abrasive wear continue to be present (2).

Fatigue in surface layers manifests itself in the scaling of minute particles of metal from the contact surfaces of machine parts. The appearance of fatigue in the surface layers does not mean the complete breakdown of the part, but there is usually a speeding-up of the destructive process (gradual chipping).

Plastic deformation (warping) of surface layers is usually manifested in a displacement of the metal beyond the contact surface. It occurs as a friction, accompanying the process of wear, and in the absence of relative sliding motion. This type of failure is typical of materials having plastic properties.

In practice, the various kinds of surface deterioration develop concurrently, rarely occurring in pure form. To each type of friction surface there corresponds a basic form of deterioration, determined by the mechanical properties of the material, the lubricant, the magnitude of the stresses applied, the operating speed and other factors.

All processes occurring in a machine, whether reversible or irreversible, affect its performance, causing errors, reducing the quality of the technological process and necessitating periodic overhaul.

III. Principal methods of increasing the durability and reliability of machine tools

A machine tool's reliability and durability are the indicators of its performance as a function of time: that is to say, they define the magnitude and nature of the changes in its main characteristics which take place in the course of its operation. A machine tool must have high initial qualitative and quantitative indicators, but that alone is not enough to make it an efficient machine. Those indicators must be maintained in the course of its operation.

A. *Durability*

The durability of a machine tool is its ability to carry out its operational functions with minimum expenditure for the replacement of worn parts, readjustment, repairs and servicing. The smaller the total money and time spent on maintaining the efficiency of the machine tool throughout its period of use, the greater its durability (3).

As the indicator of a machine tool's durability, one may use the coefficient of durability n_D, which equals the ratio of the operating time to the sum of the operating time and the time the machine is out of action for repair:

$$n_D = \frac{T_o}{T_o + T_2} = \frac{1}{1 + \sum_{i=1}^{n} \frac{\tau_i}{T_i}} \qquad \text{(Equation 1)}$$

where:

T_o is the operating time of the machine tool;

T_2 is the time the machine tool is out of action for repair;

T_i is the service life of the nth part or unit of the machine tool;

τ_i is the time (amount of work) required to repair the nth part or unit, including dismantling, reassembly and adjustment;

n is the number of repairable parts of the machine tool.

The coefficient of durability may vary from 0 to 1. The higher its value, the more durable the machine tool.

The time the machine tool is out of action depends upon the service life of its component parts and units and the amount of work required to repair them.

Stoppages of the machine tool which lower its coefficient of durability may have the following causes: breakdown of individual parts, loss of efficiency of drives and mechanisms, changes in the initial service characteristics of the machine tool (precision, freedom from vibration), and so forth.

The coefficient of durability should be calculated on the basis of the machine's entire period of operation, or, at least, of a period equivalent to the length of its maintenance cycle (the length of time before a major overhaul becomes necessary).

B. *Reliability*

The reliability of a machine tool is the indicator of its ability to carry out its functions continuously for a given period of time.

Uninterrupted operation is an important requirement for modern industrial equipment. Flow-line methods of production, where the work is transferred from machine to machine, and automatic production lines make it essential for every unit to operate without interruption.

The reliability of a machine tool is determined on the basis of indexes of probability. It may be defined as the probability (p) that the machine will operate without breakdown for a given length of time under normal operating conditions. If the probability that a machine tool will operate for one year without breakdown is $p = 0.95$, for example, this means that out of a large number of machine tools of the model in question an average of 5 per cent will lose its efficiency in less than one year of operation.

What does "loss of efficiency" or, as it is called in reliability theory, "failure" mean in relation to machine tools? Does a "failure" occur, for example, when it becomes necessary to change a drive belt or adjust a clutch?

The meaning of "failure" must be defined in the light of analysis of the operating and servicing methods used for machine tools of the given type. Brief "interventions" by the operator in the work process and the adjustment of the machine tool, when provided for in the servicing instructions and resulting from the relative imperfection of the machine tool itself, should not be included under the heading of "failures" (breakdown).

Thus, for example, the adjustment and replacement of a tool, the adjustment of individual mechanisms and preventive maintenance are included in the standard running adjustments and between-overhaul servicing of many modern machine tools.

The more highly perfected a machine tool is, the fewer such "legitimate" stoppages it will have and the more suitable it will be for continuous operation. Thus, in order to assess the reliability of a machine tool one must take into account all interruptions of its operation (stoppages) which are not provided for in the servicing plan.

The most convenient period of time to select for the operation of the machine tool with a given degree of reliability is the period between two scheduled overhauls. The higher the guaranteed probability of operation without failure, (p) is, the more reliable the machine tool.

Of great importance for machine tools is reliability from the point of view of output quality, i.e., from the point of view of ensuring the desired precision of machining and quality of surface finish.

The production reliability of a machine tool, which is an index of its capacity to continue to satisfy the qualitative requirements of the production process for a given length of time, can also be evaluated from the probability that the machine tool will satisfy those requirements throughout the period between overhauls or for the period before intermediate overhaul, at which any loss of precision by the machine tool is made good.

The reliability and durability are the characteristics which define a machine tool's capacity to realize its technical potential in actual operation, its serviceability and its degree of perfection.

C. *Methods of combating harmful influences*

To improve the reliability and durability of machine tools, it is necessary to combat the harmful influences which result in loss of efficiency.

The designer, the technician and the operator always have at their disposal a number of ways of achieving high indexes of reliability and durability.

First of all, the machine must have high resistance to external influences. The units and mechanisms which make it up must be sufficiently sturdy, must be built on the frame principle, must have the smallest possible number of members etc., so that they will withstand loads, undergo the least possible deformation and be as free as possible from vibration. Wear-resistant anti-friction materials must be used for friction couples, while all points of friction must be protected from dirt and thoroughly lubricated. Observance of these rules lays the foundations for good wear-resistance.

The causes of possible failure must be borne in mind in the design of the entire machine tool and its units, and precision mechanisms must be protected from shocks and other influences (4).

The correct placement of driving gear, symmetry of design and the use of materials with low coefficients of linear expansion help to improve a machine tool's resistance to temperature deformations.

Corrosion is combated by protecting the machinery with special coatings and paints and by the use of additives in oils and coolants.

The above-mentioned and other similar measures will result in the production of highly perfected machine tools of advanced technical performance.

The latest advances in mechanical engineering, materials and chemistry (lubricants and plastics) are continually being brought into use in up-to-date machine construction.

The possibilities of combating harmful processes are not unlimited, however. There are no completely wear-resistant materials, it is practically impossible to exclude all but liquid friction in all mechanisms and there are no materials which do not suffer deformation and do not change their dimensions with temperature fluctuations.

When it is also borne in mind that the sources of internal and external influences on the machine tool remain and that increasingly exacting demands are being made as regards output quality, it will be seen that the above-mentioned methods of combating harmful influences, while essential, are inadequate, being limited by the level of development of one or another field of technology—for example, by the possibilities of producing wear-resistant materials.

The second way to increase the reliability and durability of machine tools is to use the most highly rationalized methods of operating and maintaining equipment.

The method of operation of a machine tool determines, to a great extent, its rate of wear and the rate of development of other processes resulting in loss of efficiency.

Systematic supervision of the functioning of the machine tool and of the lubrication of its moving parts, prompt adjustment of its various mechanisms, regular care and protection from accidental blows and damage are all essential conditions if the machine is to have the durability for which it was designed.

The system of planned preventive maintenance in operation in Soviet factories embraces not only overhaul operations proper, but also a complex of preventive operations which form part of the interoverhaul servicing system.

Both the machine-tool operator and the members of the maintenance staff (fitters, greasers, belt-drive servicemen and electricians) take part in the interoverhaul servicing operations.

Interoverhaul servicing includes checks to ensure that the equipment is in good condition, that it is being operated correctly, that necessary adjustments are being made and minor faults corrected, and that proper lubrication is maintained.

In addition, the services included in the periodic overhauls, such as cleaning, changing the oil and flushing the lubrication system, and checking the equipment for precision and rigidity also help to create proper conditions for correct operation.

In the operation of equipment, the protection of friction surfaces from dirt is of great importance. The protection of friction surfaces from atmospheric dust, abrasives and chips from the work material considerably affects their wear-resistance. It is particularly important to protect the surfaces if the surrounding atmosphere has a high abrasive content. For example, when polishing machines are in operation, abrasive particles from the polishing discs accumulate in great quantities in the air and on the surfaces of the machines.

In such working conditions, therefore, rational operating procedures are extremely important, i.e., changing and filtering of lubricants, protection of mechanisms from abrasives, removal of dust from the working area, removal of the products of grinding and polishing, e.g., by magnetic separation, etc. (5).

The nature of the material being worked is an important factor in the fouling of the machine surface. When cast-iron is worked on lathes, milling machines or other machine tools, damage is caused by scale or particles of grit falling onto the mechanisms; in the case of aluminium alloys, the harmful elements are hard aluminium oxides. Thus, the rate of wear of lathe slides in light machining operations, even with shields (which only partially protect the slides), is three to four times higher in the machining of aluminium alloys than in that of steel or cast-iron parts.

This demonstrates the need for more effective ways of protecting the slides in the machining of aluminium.

In some factories, machine tools may be seen operating without slide shields, the slides being protected only by felt padding. Measurements have shown that in such cases slide wear is two to three times greater.

In machine-tool operation, therefore, careful attention should be given to the use of various protective devices to prevent the fouling of key parts (6).

It is of great importance when operating machine tools to ensure that the lubrication system functions without interruption.

Defects in the lubrication system may cause accelerated wear and the breakdown of key parts of the machine. For example, if the flow of oil to the spindle of a polishing machine is cut off, not only are the sleeve bearings damaged, but the spindle is often heated to the point where heat cracks appear on its surface and it breaks down. While working with machine tools, operators have noticed that abrasive and other dusts in a state of suspension in the air settle on the bed guides and combine with the oil to form an abrasive mixture.

This accelerates the process of wear, especially if the machine with oiled slides has been idle for a time. The extent of wear may increase by 30 per cent. For this reason, experienced workers clean the slides thoroughly at the beginning of their shifts, particularly after non-working days.

Wear depends upon the hardness of the abrasives falling into the lubricant. In ascending order of abrasive capacity, these particles may be rated as follows: steel and cast-iron filings; scale; grit; and cutting particles from polishing discs.

It is also desirable when operating machine tools to check the wear of their key parts, particularly the slides. This may be done with special wear gauges developed in the USSR (3, 7), which measure precisely the amount of wear of the slides in industrial operation. The extent to which deterioration can be corrected depends upon the methods and technological processes employed in machine-tool maintenance. In wear-resistance, accuracy and other characteristics, reconditioned parts or units should be as good as new ones.

The system of maintenance should be so organized that the restoration of the efficiency of equipment requires a minimum expenditure of time and resources.

A third way of improving and maintaining the technical characteristics of a machine tool is to isolate the machine from harmful external influences. This method is particularly applicable in the case of precision machines which are required to turn out a high-quality product.

Thus, in order to reduce temperature deformation, precision machines are placed in special temperature-controlled rooms or shops equipped with special devices to maintain the desired temperature, usually 20 C. For example, co-ordinated boring machines, which are required to be exceptionally accurate in performance, are generally operated in temperature-controlled rooms; where that is not possible, each machine is placed in a separate room, where it can be better isolated from temperature changes, dust in the atmosphere and the vibrations of other machines.

Insulating machines from vibrations is also one of the methods of increasing their precision. Many machine tools and other machines and equipment operating in any part of a factory subject the bed on which they rest to periodic stresses. The resulting vibrations are transmitted to other machine tools and if they reach a certain degree of intensity and frequency, they can lower the quality of performance of the latter substantially. The usual method of insulating machine tools from vibrations is to set them on individual beds, 2–3 metres deep in the case of medium-sized precision machines and up to 5–6 metres deep in the case of some heavy and special-purpose machines.

Although placing the machine tool on an individual bed considerably improves its resistance to vibration, the process is a laborious one and makes it difficult to move the equipment about in the shop. To an increasing extent, therefore, machine tools are being placed on special resilient supports or vibration dampers. The resilient component consists of steel springs or grids, plastic packing, rubber, cork etc. If they are given the proper degree of rigidity, they damp vibrations transmitted from other machines and equipment.

Devices for removing dust from the air and strict atmospheric-dust control are other widely used means of improving the accuracy of performance of machine tools. In some cases, there are standards which specify the permissible quantity of dust particles per cubic centimetre of air. This procedure not only is essential in connexion with the manufacture and assembling of certain key parts of instruments, but also helps to maintain the efficiency of the machine tools themselves, since it considerably reduces the quantity of abrasives which can fall on their friction surfaces.

Isolating the machine tool from temperature changes, vibrations, dust and other external influences increases its efficiency, but this method has its limitations also.

First, internal causes of error remain, for example, the heat generated by the working mechanism of the machine tool, abrasive particles produced by wear of the machine's parts and vibrations produced by cutting and by the operation of the mechanisms of the machine itself.

Secondly, complete isolation is difficult to achieve because external influences are variable and, to a certain extent, indeterminate in nature. Thus, the intensity and character of external vibrations affecting the tool depend upon the operation of other machines and vary quite widely, while insulation from vibration is most effective only for vibrations of certain frequencies.

Thirdly, the very principle of isolation from external influences stems from an old non-cybernetic view of mechanical error as something which can be eliminated.

For these reasons, there has been a growing tendency in recent years to use a fourth means of improving the efficiency of today's complicated machine tools, namely, the use of special mechanisms which automatically regulate the parameters of the machine. The use of these mechanisms makes it possible to maintain the fundamental characteristics of the machine over a long period of use, through interaction with the environment, through the automatic reaction of the machine to changes in its operating conditions. A complicated machine should possess the function—similar to that of a living organism—of automatically recovering its lost efficiency.

Such mechanisms are already being used on machine tools, ranging from the simplest devices which automatically eliminate gaps produced by wear, break the kinematic circuit in case of overloading and ensure uniformity of stresses within the mechanisms, to systems which restore accuracy of performance, replace worn-out tools, react to the effects of temperature etc. For example, the following controls are coming into use: automatic regulation of the kinematic precision of the rolling chain in gear-cutting machines; automatic regulation of the thickness of the oil layer in the slides in vertical boring and turning machines; active control and automatic minor adjustments in polishing machines; automatic elimination of vibration and imbalance in lathes; automatic compensation for wear in the tables of certain types of machine tools; and other self-regulation systems (8).

These automatic regulation systems are opening up broad prospects for the development of reliable and long-lasting machines, but they require that even closer attention be given to the methods of maintaining and operating them. The more complicated the equipment used and the better its quality, the more important the correct organization of machine-tool servicing and maintenance becomes.

V. Need for dependability and continuity of service of machine tools meant for use in developing countries

The indexes of dependability and continuity of service of a machine tool are the most important characteristics of its quality. They determine the duration and stability of the tool's retention of its initial parameters (precision, output, ease of maintenance, efficiency etc.), its adaptability to different operating conditions and the continuity of service of separate mechanisms.

Insufficient dependability and continuity of service involves a considerable increase in expenditure for the maintenance and repair of machine tools, especially under intensive use of the equipment and in unfavourable operating conditions. In quite a number of developing countries, comparatively strained conditions of exploitation of technological equipment prevail. Such conditions are accounted for by the high humidity and temperature, fewer opportunities for the production and acquisition of spare parts and for the repair of machine tools, the more frequent employment of less well-qualified workers and the absence of production within the country of the types of machine tools being used.

In the case of the developing countries, therefore, it is especially important to give consideration to all the major aspects of the problem of the dependability and continuity of service of machines and machine tools, as this is the only way to minimize the expenditure of time and means involved in breaks in the normal operation of machines.

In the Soviet Union, this problem is given serious attention. There are planning and large-scale implementation of measures aimed at raising the dependability and continuity of service of machines of different types. The development of scientific-research works in this field, the theoretical elaboration of the problem and the analysis and summing up of data on the exploitation of machines permit the formulation of sound means and the use of different methods to increase the operating capacity of machines.

A. *Special methods of creating lasting units*

When designing and modernizing machine tools, as well as when assessing their working capacity, it is essential to take into account all the major possibilities of improving the dependability and continuity of service of their various units and parts. There are well-known methods for prolonging the life of parts for example, the use of wear-resistant materials, increased precision in the machining of separate parts, the lubrication of surfaces and prevention of their soiling.

Nevertheless, in order to improve the wear-resistance and to prolong the life of different parts and mechanisms, it is essential also to employ special principles of designing and calculation, which are briefly described below.

1. *Principle of minimum influence of wear on working capacity of mechanism*

In order to design lasting machines and machine tools, it is essential to select for a mechanism that design scheme in which the wear of interconnexions only minimally affects its normal operation. The value of interconnexion wear does not yet, in itself, characterize the degree of break in the normal operation of a mechanism, that is, with the same wear, mechanisms of the same kind may, in one case, cease to operate normally, while, in another case, they may continue to operate for a long time.

In the Soviet Union, the principle outlined above is taken into account in the development of new machine tool designs: when arranging the main units of a machine tool and analysing the acting forces, e.g., in multiple-tool semi-automatics, internal-grinding machines etc.

2. *Principle of uniform wear*

A break in the normal operating of mechanisms which is brought about by wear often depends not so much upon the extent of wear as on the non-uniformity of its distribution on the surface of friction. For example, non-uniform wear along guide screws results in a decrease in the accuracy of movement of rests or beds; non-uniform wear among the contour of the cam gear distorts the character of conveyed movement; non-uniform wear of straight-line motion guides adversely affects the accuracy and vibration resistance of machines. When designing the main machine elements which are subject to friction, the designer must strive to reduce the non-uniformity of wear and thus to create conditions under which the mechanism will retail its working characteristics for a longer period of time.

Wear, temperature deformations, violations of the lubrication régime etc. lead to the deterioration of the original parameters of a machine tool. The usual methods of combating these phenomena, e.g., compensation of wear and removal of gaps, only partially correct the indexes of a machine tool.

The most progressive method is one which involves the creation of special mechanisms to restore automatically the characteristics lost and to remove possible disturbances. In the Soviet Union, the work is conducted along these lines. As a result, mechanisms have been developed for the automatic correctional setting-up of machine tools in case of tool wear, rise of cutting force, disturbance in the smoothness of motion of rests and beds, wear of guides etc.

The equipment and machines incorporating the principles described above will, other conditions being equal, work longer and require less expenditure for their repair and maintenance.

VI. TESTING OF TECHNOLOGICAL DEPENDABILITY OF MACHINE TOOLS

In order to assess the dependability of a machine and the probable continuity of its service, special tests should be conducted to obtain an objective evaluation of the machine's qualitative indexes. In the case of machine tools, such tests should, first of all, aim at assessing the precision of their work throughout the period of their use. In the USSR methods of testing the technological dependability of metal cutting lathes are being developed.

The technological dependability of a machine tool is its capacity to retain the qualitative indexes of the technological process (precision of machining and quality of surface) during a given period of time. When a machine tool is exploited, its qualitative indexes, which are affected by different processes, gradually change.

It is essential that a new machine tool should not only give the required precision in machining, but also that it should retain it within the specified limits during the interrepair period. To attain this precision, technological-dependability tests should be conducted. These tests are designed, first, to assess the reserve in the precision of machining possessed by a given machine tool and, secondly, to give some prognosis as to the period of time during which that reserve will be present. When conducting such tests, one must evaluate the probability of faultless (from the point of view of precision) operation of the machine tool for the given period of time—usually during the interrepair period or until the average repair.

Processes of varying speed result in a change in the various parameters — geometric, kinematic, force, precision etc. — of a machine tool, which leads to precision failures.

Rapid processes, such as vibration by cutting and relaxation vibration by friction in the guides, lead to dispersion of sizes of machined parts and to errors in the initial setting-up of the machine tool.

Processes of average speed, such as temperature deformations of machine-tool units and tool wear, lead in time to displacement of the initial level of setting-up of a machine tool.

Finally, slow processes, such as wear of guides and warping of frames and posts, lead to worsening of the geometric indexes of a machine tool and, as a result, to a distortion of form of machined parts, as well as to change or errors in the initial setting-up and an increase in the zone of dispersion of sizes of machined parts.

When testing the technological dependability of a machine tool, it is essential, following specially devised methods, to assess the change over time of its initial qualitative indexes under the influence of processes of varying speed, i.e. to determine how the precision reserve is spent during the machining of parts with given allowances. This test will yield objective indexes of a machine tool's technological dependability and provide a basis for finding the most rational methods of improving it.

For such a test, one selects a typical part with the most characteristic demands as to shape and size to be attained by machining. The regime and methods of machining are fixed, proceeding from the most difficult operating conditions for which the machine tool was calculated.

The calculation of technological dependability and the test of the machine tool's parameters are conducted using methods based on the theory of probability, as the dispersion of sizes of machined parts and the processes accompanying machining are incidental values, or functions. Let:

- X — size of a machined part (incidental value)
- t — time of work of the tested machine tool
- δ — allowance for machining
- D_{min}; D_{max} — allowed minimum and maximum sizes of the part (i.e., $\delta = D_{max} - D_{min}$)

The value of the initial setting-up of a machine tool (X_H) has a dispersion range (A_H), which, by the normal law of distribution, can be expressed by $A_H = \sigma \cdot \sigma_H$, where $\sigma \cdot \sigma_H$ is the root mean deviation of the setting-up error.

In addition, an instantaneous dispersion of sizes of the machined part takes place (dispersion range $A = \sigma \cdot \sigma$).

The required level of the initial setting-up of a machine tool with a given parameter (D) will be:

$$X_H = D_{min} + \frac{A_H}{2} + \frac{A}{2} \quad \text{(Equation 2)}$$

or, when adding by the theory-of-probability method and the law of Gauss:

$$X_H = D_{min} + 3\sqrt{\sigma^2 + \sigma_H^2} \quad \text{(Equation 3)}$$

When assessing the precision possibilities of a machine tool, it is essential to assess also the error in shape, $\Delta\phi = X_{max} - X_{min}$, as the difference between the maximum and minimum sizes of the machined part. The shape error depends upon the initial inaccuracy of a number of machine-tool units. Thus, for example, inadequate roundness of the part depends first of all upon the inaccuracy of the spindle unit, specifically of the spindle bearing.

Errors of shape in length depend upon the inaccuracy and wear of machine-tool units, e.g., guides, which affect the motion of the rest as to its parallelism to the axis of the part rotation. Shape errors involve also the expenditure of a part of the total allowance on machining (δ).

Some time after the machine tool begins operating, a displacement of the initial level of setting up, caused by average speed processes, takes place. For the readjustment period t_1 (changes or readjustment of tool) or for the period of stabilization of temperature deformations, the precision indexes of the machine tool deteriorate by some value (Δm).

It should be kept in mind that function $X_H(t)$, which determines the value of Δm, is incidental, and it is essential, in the process of testing, to assess its average value (the mathematically expected value) and dispersion parameters.

Then, taking into account the initial inaccuracy of the machine tool, the action of rapid processes and the displacement of the setting-up level caused by average speed processes, one finds the precision reserve, δ_T, allowing slow processes equal to:

$$\delta_T = \delta - (A + A_H + \Delta\phi + \Delta m) \quad \text{(Equation 4)}$$

or, adding to the theory-of-probability method:

$$\delta_T = \delta - \left(\sqrt{\left(\frac{A}{2}\right)^2 + \left(\frac{A_H}{2}\right)^2} + \sqrt{\left(\frac{A'}{2}\right)^2 + \left(\frac{A'n}{2}\right)^2} + \Delta\phi + \Delta m\right) \quad \text{(Equation 5)}$$

Here, possible changes of dispersion ranges A and A_H by the end of the interadjustment period are taken into account.

Accuracy reserve δ_T will be exhausted after some period of time: $T = nt_1$. This will result from: *(a)* The enlargement of range A caused by the enlargement of gaps in the joint, changes in rigidity and other characteristics influencing rapid processes (vibration etc.), *(b)* the enlargement of range A_H caused by wear of machine-tool units; *(c)* an increase of $\Delta\phi$ caused by wear, warping and other phenomena in a number of units (e.g., nonroundness increases with wear of the spindle-bearing races and errors of shape in length increase with wear of rest guides); and *(d)* an increase of Δm, owing to redistribution of internal stresses and deformations in machine-tool parts which lead to an increase of their "pliability" when irregularly heated, to an increase in the speed of dimension wear of the tool, with the increase of vibration etc.

These changes can be determined by long operation testing. For a particular machine-tool design, however, the data obtained will, as a rule, lose actuality because the design will become obsolete by that time.

Therefore, technological-dependability tests should be brief and should be aimed at determining the precision reserve (δ_T) and the precision reserve coefficient ($K_T = \frac{\delta}{\delta_T}$) for the main parameters of the machine tool being tested.

The value of K_T is a very important characteristic of the technological dependability of a machine tool.

In order to prognosticate the decrease in the accuracy of a machine tool in the course of time, owing to wear of its base units, it is essential to calculate the shape of the worn surface and to assess its influence on the accuracy of machining. Such calculations have been devised by the author of the present paper.

In evaluating the average speed of wear and its dispersion, on the basis of operating conditions and data of wear tests of materials, it is possible to calculate, with a sufficient degree of probability, the duration of operation of a machine tool with the required precision of machining, as well as the probability of its faultless operation.

For modern machine tools, the technological-dependability test is an indispensable part of the complex testing which permits the assessment of the major technological parameters of the tool and which provides the beginning data for the most effective improvement of its design.

VII. Organizational principles for machine-tool maintenance and servicing systems

In order to keep equipment permanently in working order with the minimum expenditure of time and resources, it is necessary to institute a maintenance system with strict rules concerning the basic measures to be taken for this purpose.

In the Soviet Union, a uniform planned preventive-maintenance system has been especially formulated and is applied in all branches of industry. This system, which is now thirty years old and which has been steadily improved, has shown its great possibilities and the correctness of the underlying organizational principles.

The basic principles of the planned preventive-maintenance system are as follows:

1. All operations necessary to keep equipment in working order are divided into two groups:

(*a*) Servicing in the intervals between overhauls, which includes regular checking of the equipment and correction of faults, preventive measures, adjustment of mechanisms and occasionally replacement of quick-change parts;

(*b*) Periodic overhauls, which are carried out in accordance with a plan laid down in advance and which represent the bulk of maintenance operations.

2. Periodic overhauls, in accordance with the plan, are subdivided into various types, depending upon the scale of the operations. There are usually three types of overhaul: minor (type I); intermediate (type II); and major (type III).

A machine tool which has undergone major overhaul must be able to meet all the basic demands placed upon a new tool.

3. All overhauls of a particular model of machine tool under the plan are carried out at regular intervals, the intervening periods being called "intervals between overhauls". The length of the interval is one of the main characteristics of the maintenance system and depends upon the type of machine tool and its operating conditions.

4. The maintenance system also fixes the pattern of the maintenance cycle, i.e., the number of planned overhauls and the order in which they are carried out. Most machine tools now have a cycle of nine planned overhauls, in the following order: I-I-II-I-I-II-I-I-III.

This pattern is the same for all types and models of metal-cutting lathes and all operating conditions. The period of time over which it is completed, i.e. the period from one major overhaul to the next, is known as the maintenance cycle.

5. The expenditure of labour for a given type of overhaul is indicated by the number of machine-hours and man-hours allocated for it under the plan.

The relationship between the volumes of major, intermediate and minor overhaul work is the same for all machine tools.

6. Machine tools are broken down into different categories according to their degree of complexity. Each category is assigned a conventional coefficient which compares the labour consumed by a machine tool in that category with the amount consumed by a standard tool. The tool taken as the standard was a general-purpose turning-lathe of average complexity, whose labour consumption is indicated by a complexity coefficient R 10.

7. The standard values for the volume of overhaul work are average figures and are used to plan the total volume of overhaul work in a workshop or enterprise. Deviations are allowed for, depending upon the actual state of a machine tool when overhauled.

The basic idea behind the principles underlying the maintenance system is that by establishing a maintenance cycle with a permanent pattern, preserving the average ratios between the volumes of work involved in the different types of overhaul and comparing different types of equipment by placing each in a maintenance complexity category, it is possible to plan maintenance in advance and to calculate the labour, equipment and time required.

On the other hand, the system allows for the variety of equipment and working conditions to be found in industry. It provides for different intervals between overhauls, allows for deviations from the average values for labour consumption and lays down a whole complex of preventive measures to prevent sudden breakdowns and cumulative wear.

Standard rates have been worked out in the Soviet Union for determining the expenditure of labour in maintenance of technological equipment (1). From the standard rates it is possible to calculate in advance the periodicity of maintenance, the amount of time and resources to be expended on it, the amount of labour and equipment required, the cost of maintenance operations, the quantity of spare parts and other necessary data.

The standard rates are drawn up in such a way that the labour consumption in the overhaul of each unit of complexity is determined; this value is then converted for the tool in question. Thus, according to the 1962 rates, the time to be spent per maintenance unit should not exceed the figure shown in table 3.

Table 3

STANDARD RATES FOR LABOUR CONSUMPTION IN MAINTENANCE OF TECHNOLOGICAL EQUIPMENT

Overhauls and preventive maintenance operations	*Number of hours* Mechanics etc.	*Number of hours* Machine tools
Cleaning	0.35	—
Checking accuracy	0.4	
Minor overhaul (I)	0.75	0.10
Intermediate overhaul (II)	4.1	2.0
	16.5	7.0
Major overhaul (III)	26.0	10.1

Thus, the labour consumption ratio for planned overhauls is;
I : II : III 6.1 : 23.5 : 36.1, or approximately 1 : 4 : 6.

These standard time rates are intended for planning and calculating the labour force required. In order to determine from them the number of hours required for maintenance of a given model of machine tool, the figures given must be multiplied by the complexity coefficient for the machine tool concerned.

For example, in the case of a thread-grinding machine with complexity coefficient R = 17, 17.(26 + 10.1) = 615 hours which should be planned for major overhaul, 400 hours for intermediate overhaul and so on. The standards give examples of how to make the calculations and tables of complexity coefficients for different types and models of machine tools.

Table 4 gives the most characteristic complexity coefficients for certain types of machine tools.

The length of the maintenance cycle (in hours) is calculated from formulae in which the operating conditions of the tool are expressed by empirical coefficients.

For metal-cutting lathes the value of T can be calculated from the formula:

$$T = 24{,}000\ \beta_1\ \beta_2\ \beta_3\ \beta_4 \text{ hours}$$

Table 4

CHARACTERISTIC COMPLEXITY COEFFICIENT, SELECTED MACHINE TOOLS

Type of machine tool	*Complexity coefficient*
1. Lathes, medium size	9–13
2. Heavy lathes	17–19
3. Vertical drilling machines	3–8
4. Radial drilling machines	6–12
5. Open-side jig borers	20–35
6. Horizontal borers, medium-sized	16–18
7. Cylinder-grinding machines	10–15
8. Gear-cutting machines, medium-size	10–12
9. General-purpose horizontal milling machines	8–14
10. Planing machines, medium-sized	12–15

where β_1 is the coefficient for the type of production, with values $\beta_1 = 1$ for mass and large-series production, $\beta_1 = 1.3$ for series production and $\beta_1 = 1.5$ for small-series and unit production. The coefficient β_2 relates to the type of material worked on the machine tool, with values $\beta_2 = 1$ for structural steel, $\beta_2 = 0.7$ for high-strength steel, $\beta_2 = 0.75$ for aluminium alloys and $\beta_2 = 0.9$ for cast-iron and bronze. The coefficient β_3 relates to operating conditions, with values $\beta_3 = 1$ for normal operating conditions, $\beta_3 = 0.7$–0.8 for dusty and humid conditions, $\beta_3 = 1.1$–1.2 for high-precision tools in machine-shop conditions and $\beta_3 = 1.3$–1.4 for tools housed separately. The coefficient β_4 relates to the size of the machine tool, with values $\beta_4 = 1$ for light and medium-sized tools, $\beta_4 = 1.35$ for heavy tools and $\beta_4 = 1.7$ for especially heavy and special-purpose tools.

The formula for the interval between overhauls (t), with nine planned overhauls per cycle, is $t = \frac{T}{9}$ hours.

When equipment is worked on a single-shift basis, its rated annual working time is 2,000 hours.

The interoverhaul period can be determined roughly from these functional relationships and then corrected in accordance with the specific operating conditions and methods.

Suppose, for example, that it is necessary to determine the duration of the maintenance cycle for a heavy turning lathe (complexity coefficient R = 17, $\beta_4 = 1.35$) working two shifts in small-series production conditions ($\beta_1 = 1.5$). The tool processes mainly high-strength steel and cast-iron $\left(\beta_2 = \frac{0.7 + 9.0}{2} = 8.0\right)$ and humidity in the workshop is very high ($\beta_3 = 0.7$).

$$T = 24{,}000 \times 1.5 \times 0.8 \times 0.7 \times 1.35 = 27{,}000 \text{ hours,}$$

or

$$T = \frac{27{,}000}{2 \times 2{,}000} = 7 \text{ years}$$

$t = 9.5$ months—the interoverhaul period.

On the basis of these data, the machine's maintenance schedule can be drawn up and the labour consumed and the time spent idly in maintenance can be determined as shown above.

There are three main systems of maintenance at industrial enterprises—centralized, decentralized and mixed.

Under a centralized maintenance system, all maintenance work is carried out at the factory with the labour and resources of a chief mechanical engineer's section and its maintenance machine shop. This kind of organization is typical for plants with a small amount of equipment.

Under a decentralized maintenance system, all kinds of maintenance operations—interoverhaul servicing and periodic overhauls, including major overhauls—are carried out under the direction of shop mechanics by so-called "shop maintenance units", which are general maintenance squads. The maintenance machine shop under the chief mechanical engineer carries out only the major overhaul of complex units. In addition, it manufactures and reconditions equipment parts for the shop maintenance units when this requires special technology.

Under a mixed maintenance system, all kinds of maintenance, except major overhauls, are carried out by shop maintenance units and major overhauls (and sometimes intermediate overhauls of large assemblies) are handled by the maintenance machine shop.

A. *Scope of each type of overhaul and determination of the service life of machine-tool parts*

The scope of the planned periodic overhauls depends upon the design of the machine tool and the conditions under which it is operated.

A minor overhaul entails the replacement or reconditioning of a small number of worn parts, the adjustment of the machinery and checks to see that the machine tool is in satisfactory condition and that its lubrication system is functioning properly.

An intermediate overhaul entails a greater amount of maintenance work, including the partial truing of the machine tool and the restoration of any precision which has been lost. It is carried out without removing the machine tool from its bed.

A major overhaul entails the complete restoration of the efficiency of the machine tool. The tool is normally completely dismantled and degreased, and its parts are sorted, on the basis of measurements and visual inspection, into three categories.

The first category covers serviceable parts which do not need reconditioning and are fit to serve for another maintenance cycle.

The second category covers parts which require reconditioning because of surface wear, deformation or other reasons. The most suitable reconditioning process is specified for each part (e.g., building up the part by welding, chromium plating or other methods, grinding to the reconditioned dimensions etc.).

The third category covers parts which it is impossible or uneconomic to recondition. Such parts are replaced with new ones made to the same technical requirements. Typical parts which fall into this category are roller-contact bearings, friction clutch plates and so forth. In order that the various parts may be correctly sorted into categories and their suitability for further service in the machine tool properly evaluated, it is essential to set maximum permissible limits of wear for them and to establish their service life.

This is an extremely complicated matter, as the parts of any machine tool have to satisfy the most varied requirements. So far, no completely satisfactory method of calculating maximum wear levels has been developed.

The criteria (characteristics) of the maximum wear of machine-tool parts may be divided into two groups.

The first group comprises criteria relating exclusively to the proper functioning of a given assembly or part. This covers such cases as the breakage of parts as a result of wear (the teeth of slow-speed worm gears); the wearing away of the case-hardened layer, resulting in a sharp increase in the rate of wear (the slide blocks of link gear); and the breakdown of liquid friction (slider-type bearings). In many cases, however, the functioning of an assembly cannot be considered in isolation from the functioning of the mechanism or the machine tool of which it is a part.

The criteria in the second group relate to the performance by the machine tool or mechanism of the functions for which it is intended. The most typical criterion of this group, as far as machine tools are concerned, is precision of machining.

Table 5, for example, gives lists of figures calculated by the author which show, for various degrees of machinery precision, the maximum wear of lathe slides (measured at the point of greatest wear) which will permit these precision requirements to be satisfied. The figures in the table show only the reduction in precision due to wear of the slides, and do not take into account the influence of other factors (such as the rigidity of the slide rest, the spindle and other parts and wear of the cutting tool).

Table 5

MAXIMUM WEAR OF LATHE SLIDES PERMITTED FOR VARIOUS DEGREES OF PRECISION

Maximum permissible variation in diameter of workpiece (microns)	*Class of precision at d = 50–80mm*	*Maximum permissible wear of slides (millimetres) when turning workpieces with lengths of up to:* 25	50	100	200 (millimetres)	300	400
13	1	0.16	0.08	0.04	0.02	0.013	0.01
20	2	0.24	0.12	0.06	0.03	0.02	0.015
30	2a	0.40	0.20	0.10	0.05	0.035	0.025
60	3		0.40	0.20	0.10	0.07	0.05
120	3a	—	—	0.40	0.20	0.13	0.10
200	4	—	—	0.65	0.32	0.21	0.16
400	5	—	—	—	0.65	0.43	0.32

This table shows that there is a direct connexion between the permissible wear of the slides, on the one hand, and the desired precision of machining and the dimensions (length) of the workpieces, on the other hand.

When the workpieces are short and a large allowance is made for variations in their diameter, the permissible wear may be very considerable. However, operational and overhaul considerations and the need to avoid vibration of the slide rest make it inadvisable to allow the wear to exceed 0.2 mm.

In many cases, the maximum permissible wear of key parts of each model of machine tool can be established on the basis of practical overhaul and operating experience.

In order to determine the service life (T) of a part, it is necessary to know the nature of the wear process in the part as a function of time and the maximum permissible value of wear (U_{max}). As, in the majority of cases, normal wear takes place at a constant rate (γ = constant), then for known values of γ and U_{max}, the service life of a part will be:

$$T = \frac{U_{max}}{\gamma} \qquad \text{(Equation 6)}$$

The value of the rate of wear (γ) is determined either on the basis of measurements or from operating experience with the machine tools of the type in question.

Formula (6) for determining the service life of machine-tool parts is applicable to parts which are replaced only when they become unserviceable, i.e. when their wear has reached the value U_{max}. Quick-change parts which are replaced when the machine tool is serviced between overhauls fall into this category.

In the case of parts which are reconditioned or replaced during the periodic planned overhauls, the acceptable values of wear (U_o) will be equal to or less than the maximum permissible values (U_{max}), as the parts must not become unserviceable in the interval before the next overhaul. If the interoverhaul period, i.e. the period between two planned overhauls, is T_1, then over that period of time the wear of the part will increase by an amount γT_1. The maximum acceptable amount of wear (U_o), after which it is essential to replace or recondition a part at the current periodic overhaul, will therefore be:

$$U_o = U_{max} - \gamma . T_1 \qquad \text{(Equation 7)}$$

Bearing in mind that $\gamma = \frac{U_o}{T}$ (where T is the service life of the part before overhaul) one obtains:

$$U_o = U_{max} - \frac{U_o \cdot T_1}{T} \qquad \text{(Equation 8)}$$

whence:

$$U_o = \frac{U_{max}}{1 + \frac{T_1}{T}} \qquad \text{(Equation 9)}$$

If a given periodic overhaul is the Kth since the last overhaul of the part, then the service life of the part will be $T = KT_1$ and the formula for calculating the acceptable wear will take the form:

$$U_o = \frac{K}{K+1} U_{max} \qquad \text{(Equation 10)}$$

For example, a part has a case-hardened layer 0.8 mm in depth and the maximum permissible wear is $U_{max} = 0.65$ mm (80 per cent of the depth of the case-hardened layer). Should the part be reconditioned if, when measured at the third periodic overhaul, its wear is found to amount to 0.55 mm?

If one calculates U_o according to formula (10):

$$U_o = 0.65 \frac{3}{3+1} = 0.49 \text{ mm}$$

The part must therefore be reconditioned; although its wear is less than U_{max}, it will not last until the next periodic overhaul.

If the maximum permissible amounts of wear and the service lives of the main parts of the machine tool are known, the scope of the various types of overhauls can be defined more accurately, the durability of the machine tool increased and the cost of maintaining it reduced.

VIII. Theoretical bases for establishing the main parameters of a maintenance system

The main parameters of a maintenance system are a maintenance-cycle pattern which is applicable to all machine tools and an interoverhaul period which takes into account the special features of the equipment and the way it is operated.

The maintenance-cycle pattern and the interval between overhauls must be such that through fuller utilization of the service lives of the machine-tool parts and assemblies, other things being equal, the equipment is idle for overhaul for the shortest possible time and expenditure on its overhaul is kept to the minimum.

In order to select the best values for these parameters, it is necessary to determine how their values influence the durability of the machine tool—the coefficient n_0 (see formula (1)).

When using formula (1) in connexion with periodic overhauls, it must be borne in mind that:

(*a*) The periodicity of overhauls will be defined by the minimum service life (T_1) of the parts subject to periodic overhaul;

(*b*) At each overhaul, all parts whose service life will expire before the next overhaul must be replaced.

In order to analyse the maintenance-cycle pattern, all machine-tool parts which are subject to periodic overhaul must be divided into groups according to length of service life.

Each group comprises parts whose service life (T_1) is within the range $n_i \cdot T_1 \leq T_i < (n+1)T_1$, where n is the ordinal number of the group of parts in question and T_1 is the minimum service life, which determines the periodicity of overhauls. For the nth group of parts, the periodicity will be $n.T_1$, as parts of the first group will be overhauled after T_1 hours, parts of the second group after 2 T_1 hours and so forth. The number of groups of parts (n) overhauled at the periodic overhauls is determined from the relation $n = \frac{T_{max}}{T_1}$ where T_{max} is the service life of the most durable part.

If the maintenance-cycle patterns used are analysed from this point of view, more advantageous variants than the nine-period pattern may be found.

It is a fact that although the pattern shows the first two periodic overhauls as being of the same type (minor overhauls), this is an index only of their average scope. In reality, these two overhauls will be different from each other, as after the period T_1 (the period between overhauls), the first-group parts will be overhauled, while after the period $2T_1$ both the first-group and the second-group parts will be overhauled. The amount of overhaul work carried out on the second occasion will, consequently, be greater, although both are classified as minor overhauls, and the time and resources allocated for them are identical.

Similarly, it can be shown that the volume of overhaul work involved in the first and second intermediate overhauls in the cycle will be different in each case.

In the interest of more accurate planning of maintenance, it is therefore desirable that there should be not three, but four, types of overhaul (the fourth type being termed a complete overhaul).

As the author's calculations show (3,6), it is more advantageous from the point of view of reducing the idle time of equipment to use a six-period pattern with a I-II-III-II-I-IV cycle and a ratio of volumes of overhaul work of I : II : III : IV = 1 : 2 : 4 : 6.

The change to a cycle pattern with four types of overhaul requires a higher level of maintenance organization and will constitute a further development of the maintenance system.

Attempts are now being made in the Soviet Union to introduce optimum maintenance-cycle patterns which take into account the work which has been done in this field. The existing maintenance system, which has been of great economic value to industry, will thus be further developed and perfected.

The length of the period between overhauls (T_1) is that basic parameter of the maintenance system which reflects the special features of the equipment in question and the nature and intensity of its operation.

The length of the period between overhauls must be determined after the maintenance-cycle pattern has been selected; it is, therefore, the second task in establishing the basic parameters of the maintenance system.

The aim in determining the length of the period between overhauls and the maintenance-cycle pattern must be to achieve the highest possible durability of the equipment. The optimum period will be that which, other things being equal, gives the highest coefficient of durability (or the minimum loss of machine time on overhauls, which amounts to the same thing).

The main consideration in selecting the optimum period between overhauls ($T_1 = T_{opt}$) is to establish such a ratio between the amount of work carried out at the periodic overhauls and the amount carried out in the course of servicing between overhauls as will make possible the minimum expenditure of labour on overhauls in the given conditions.

When the length of the interoverhaul period is extended, a larger number of parts will be replaced in the course of the servicing between overhauls. As a result of this, the durability of individual parts will be more fully utilized during the servicing interval, but the amount of assembly and disassembly will be increased.

On the basis of these considerations, the author proposes the following formula for calculating the optimum interval between overhauls:

$$T_{opt} = \frac{1.8}{K} \cdot \left(\frac{\tau_k}{\tau_1} - 1\right)\left(\beta - \sqrt{\beta^2 - 1}\right) \cdot T \quad \text{(Equation 11)}$$

where T is the length of the actual interval between overhauls established in practice; K is the number of overhauls in the cycle ($K = 6$ or $K = 9$); τ_k is the actual time required for a complete overhaul (in hours) for a length of cycle K.T; τ_1 is the actual amount of time required for a minor overhaul (in hours); $\beta > 1$ is a coefficient which indicates the increase in the amount of time spent on the overhaul of machine tool parts and assemblies in the course of interoverhaul servicing because of increased assembly and disassembly work.

β is normally between 1.5 and 3. This formula permits the calculation of the value of $x = \frac{T_{opt}}{T}$ which is an index of the advisibility of lengthening or shortening the period between overhauls in the given operating conditions; i.e. it makes possible more accurate correction of the value of T established from the norms.

The coefficient β greatly influences the value of T_{opt}.

If the time spent on assembly and disassembly work can be reduced by using quick-change parts and introducing wear-compensation adjustments, the interval between overhauls can advantageously be lengthened.

If changes are made in the overhaul and operating conditions of the equipment, the interoverhaul period should also be adjusted accordingly.

Improvements in overhaul methods, in the durability of the individual parts and in the design of machine tools will be fully effective in increasing the durability of the equipment, provided that the main parameters of the maintenance system—particularly the maintenance-cycle pattern and the length of the interoverhaul period—are correctly selected.

IX. Organization of Maintenance Services at the Plant

The organization of maintenance work at the plant must provide for the execution of all technological processes necessary for maintenance operations, the receipt of spare parts from the machine-tool factory and the overhaul of individual assemblies or machine tools at special maintenance centres.

The organization of maintenance, as shown above, depends upon the types and number of machine tools at the plant.

The plant's maintenance machine shop usually comprises the following sections or units: (*a*) a machine-tool section; (*b*) a fitting shop; and (*c*) a welding shop. In large maintenance machine shops there is a further department for restoring and increasing the wear resistance of parts, with sections for metallization, chrome plating, cementing, heat treatment etc.

The machine shop is headed by a superintendent, who is subordinate to the factory's chief mechanical engineer, and the various sections or units are headed by foremen, under the shop superintendent. Under the latter's authority also are a technological office, a planning office and other administrative units.

Shop maintenance units, as has already been shown, form part of production shops. Their purpose is to carry out interoverhaul servicing and to perform individual repair work on all the various types of equipment installed in each workshop. The scale of operation of a shop maintenance unit depends upon the system of maintenance followed at the plant.

Under a centralized system of maintenance, in which work is carried out exclusively with the labour and resources of the appropriate workshops of the chief mechanical engineer's section, the shop maintenance unit is responsible only for interoverhaul servicing. Where the workshops of the chief mechanical engineer's section have insufficient work, they are also made responsible for interoverhaul servicing.

Under a decentralized system, the shop maintenance units carry out interoverhaul servicing of mechanical equipment and all types of overhauls, except major overhauls of the most complex units. They are also responsible for interoverhaul servicing and minor and intermediate overhauls of electrical and diesel equipment.

Under a mixed maintenance system, major overhauls of production-shop equipment are carried out by mechanical and electrical repair shops.

The Model Regulations recommend the establishment of shop maintenance units in workshops where the total number of maintenance and repair operations runs to upwards of 600–700. In small workshops, independent maintenance units are not set up. Such shops are served by so-called "central district units" (one unit for several shops), which are headed by district mechanical engineers who are subordinate to the chief mechanical engineer.

Central district units are staffed by squads of fitters, who are attached to production sections, bays or shops. The size of each squad is established according to the labour requirements for the projected maintenance operations given on an annual schedule and for carrying out the interoverhaul servicing of the equipment assigned to the squad.

In choosing the particular system of maintenance for the factory as a whole, account is taken of its effect on the structure of the central maintenance-service apparatus —the chief mechanical engineer's section. With a decentralized system of maintenance, when the bulk of the work is undertaken by the shop maintenance units, it is advisable to augment the latter's planning and accounting staff and correspondingly to simplify the structure of the central maintenance-service apparatus, making the latter responsible only for the methodical direction and supervision of the shop maintenance units' work.

The structure of maintenance services in the chief mechanical engineer's section also depends upon whether there is an independent chief mechanical engineer's section at the plant. If there is such a section, one of its functions is to ensure the correct use and planned maintenance of all power equipment.

An independent chief power engineer's section is usually set up at large plants which have a great deal of equipment and which use substantial quantities of power. In factories using small amounts of electricity and having small power installations, a combined chief mechanical engineer's and power engineer's section is formed, which includes a power-engineering office and is responsible for the work of the electrical and diesel shops.

In plants with large numbers of machine tools of the same kind and in mass production factories, it is advisable, in order to reduce machine idle time during repair, to carry out repairs by the unit system.

The essence of the unit system of repair is the removal of machine-tool units requiring repair and their replacement with spare units, either previously repaired, rebuilt or newly purchased. In metal-cutting machines, such interchangeable units include the headstock, the apron and the carriage saddle, the drive mechanism, the spindle-casing, the grinding and turret heads etc. The range of interchangeable units and interchangeable parts must be made more and more comprehensive, and the rebuilding (repair) of these units and parts must be centralized.

In addition to the unit system, there is the successive-unit system of repair and overhaul, in which the units of the assembly are overhauled in a particular sequence during normal breaks in the operation of the equipment. During meal-breaks and on rest-days and non-working shifts, different units requiring overhaul are dismantled and their worn-out parts replaced.

The successive-unit system is particularly well suited for the repair of standard-unit machine tools and other tools for which the various subassemblies are individually designed (9).

The more equipment is standardized and the more its individual units and assemblies are unified, the simpler will the organization of maintenance services become. It is expedient, therefore, in equipping any given factory, to use the minimum number of machine-tool contractors.

In the Soviet Union, efforts are now being made on a broad front to produce machine tools in various technological versions and types on a single base, to standardize regular machine parts and assemblies, and to unify construction. These measures not only reduce the cost and increase the quality of machine-tool production, but also substantially simplify their repair and maintenance.

X. Technical problems of machine-tool maintenance

In the maintenance of machine tools and other equipment, the correct choice of the technical processes to be used to restore the impaired efficiency of the various units and parts is important.

This is a somewhat complex problem, for several reasons: first, the range of repairable parts is extremely wide; secondly, the parameters of the parts have to be fully restored in repair and, in many cases, increased wear resistance and toughness are called for; and, thirdly, expenditure on repairs and idle time during repair must be kept to a minimum.

In addition to the ordinary methods of mechanical machining, extensive use is made of electroplating, metal-improvement processes, pulverization and other technical processes to restore the dimensions of the worn parts (10).

Processes to harden the surface of parts and increase their wear resistance and fatigue strength are used also. These processes include heat and thermo-chemical treatment, electric-spark surface toughening and surface toughening by rolling and shot-peening

In repairing equipment, it may also become necessary to modernize individual units, to replace some materials by others and to economize in the use of non-ferrous metals. In some cases, therefore, bimetallic parts have to be made—e.g., slider bearings, worm wheels and lead screw nuts using bronze for the friction surface and steel or cast-iron for the main body of the part. Metallo-ceramic parts are also used—for example, iron-graphite bushings and plastic parts (11). All this calls for special equipment and skilled labour.

In the repair of machine tools, particular attention has to be given to the technical processes for reconditioning or repairing certain parts, since their quality determines the precision of the machine tool.

Normally, the most labour-consuming operation is the repair of machine-tool slides, since these determine the precision of movement of the basic units of the machine and the accuracy of their relative positions.

The technical processes for repairing worn slides are varied, and, depending upon the circumstances, may be carried out by machining at the lathe, by the use of suitable appliances or by hand.

The machining of slides by planing, milling or grinding is the most exact and productive method of reconditioning worn slides. However, its use is not infrequently limited by the factory's lack of machine tools of suitable size and adequate precision.

The repair of bed slides with the help of suitable appliances necessitates no special equipment; the appliances used for the purpose are of simple construction and can be made at any machine-building plant. But the drawback of this method is its high labour consumption as compared with machine work, since treatment with appliances normally takes place at a lower tempo and usually necessitates a certain amount of manual labour in preparing the setting bases and some rather labour-consuming work in installing and setting up the appliance. Nevertheless, it is often preferable, because it can be carried out at the site of the machine tool, so that the bed does not have to be dismantled and reassembled, and time is saved on transporting it to the repair shop and back. This method is best suited to the repair of particularly large bed slides.

The repair of slides by hand (powdering, scraping etc.) is the most labour-consuming and outmoded method, and is permissible today only in one of the following cases: (*a*) when the wear on the slides is so slight that hand reconditioning requires less time than mechanical methods; (*b*) when the equipment for mechanical treatment (machine tools and appliances) has not yet been obtained or made.

The Soviet Union has developed portable appliances for grinding and clean planing machine-tool slides in the process of repair, mechanized scraping tools and technical processes and methods for machining slides with the use of machine tools (10). Model technical processes have also been developed for repairing spindles, lead screws, precision worm couples and other key machine-tool parts.

The overhaul of the hydraulic equipment of machine tools presents special features of its own, including technical processes characterized by the use of precision and finishing work in the repair of hydraulic cylinders (honing) and hydraulic pump parts (grinding) and by checking to ensure precise clearances and relative positions in reconditioned parts returned to use.

Units are assembled with the help of universal and special appliances ensuring correct and efficient assembly.

In order to ensure accurate assembly, it is necessary to apply the theory of dimension sequences and compensators (12), since the method used to restore precision can then be selected on rational grounds; e.g., one can regulate or adjust the part, use trial and error or fit a compensator in one of the members of the subassembly.

Great importance for high-quality assembly attaches to the checking and testing of the machine tool after an overhaul.

In addition to the familiar tests for geometrical precision, efficiency, machining precision and surface quality obtained, methods of checking to determine the quality of separate subassemblies are also being introduced into the practice of machine-tool overhaul.

One may mention first the rigidity standards and methods of checking the rigidity of machine tools which have been worked out in the Soviet Union (13). For example, in the case of lathes, a load is applied to the spindle and tailstock into which the mandrels are inserted. Force is created with the help of a special dynamometer, which exerts pressure on the mandrel at an angle of 60° from the horizontal (in the direction of total cutting thrust). Under the standards applied for normal precision lathes, the permissible displacements of the slide rest in relation to the mandrel are as in table 6.

Table 6

Maximum machining diameter of machine tool (millimetres)		100	200	400	800	1,600
Force applied (kilogrammes)		70	200	560	1,600	4,500
Maximum displacement in relation to mandrel (millimetres)	Spindle	0.04	0.10	0.21	0.47	1.05
	Tailstock	0.05	0.13	0.27	0.61	1.40

By means of rigidity testing, one can ensure a high repair quality and detect any couplings requiring more careful adjustment.

In the case of gear-milling, thread-grinding and other precision machines, it is also desirable to check the kinematic accuracy of the mechanisms linking the rotation of the blank to the movement of the tool. For this purpose, universal and specially developed tools are used.

The use of technically advanced repair and testing processes is essential to the achievement of high efficiency and economy in the overhaul of machine tools.

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