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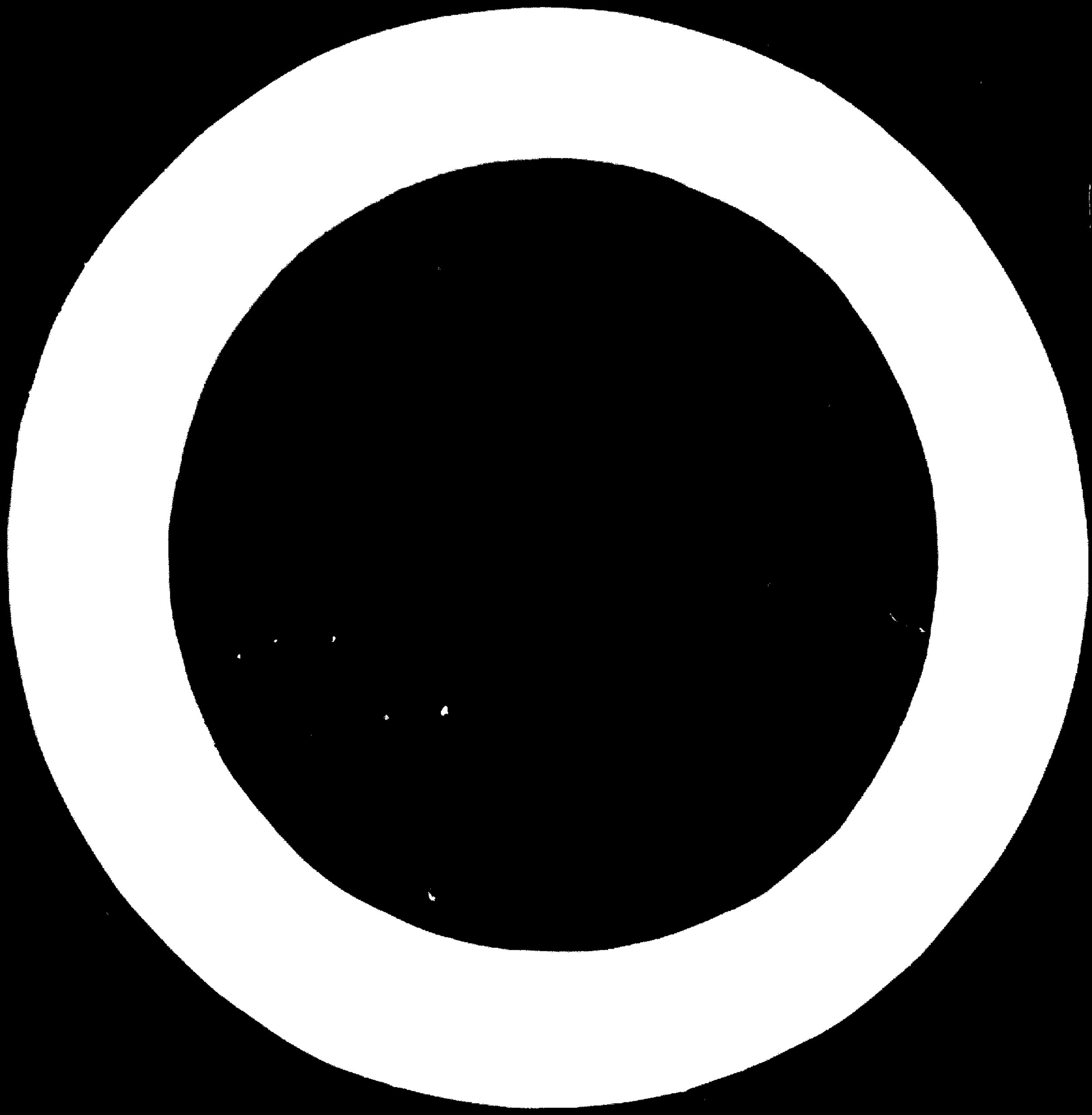

METHODS OF PROCESS CONTROL IN ENGINEERING INDUSTRIES

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I. General problems

A. *Process control as a way of increasing efficiency of production*

An industrial process is that procedure which converts materials and half-finished products into end-products by means of labour. Labour can be spent by direct activity in the form of living labour or in the form of past labour, embodied in the machines formerly manufactured. One objective of technological progress is to decrease the amount of labour realized in products in the process of manufacture; the total amount of labour embodied in the products and equal to the sum of living labour and labour realized in products should continuously decrease. At the early stages of technological progress, the share of living labour prevails in products, but along with technological development, its share decreases. In the process of decreasing of the share of living labour, automation gains the leading role.

The introduction of automation changes the nature of labour: manual labour is gradually replaced by mental work; man ceases to participate directly in industrial process, but begins to carry out the functions connected with the creation of controls and maintenance services of machines. From being a direct participant in the manufacturing process, man, as Karl Marx said, becomes "a superviser and controller of this process".[1]

B. *Scales of production and their effect on the level of automation*

At the current time, nearly every level of automation is technically feasible, but it should be taken into account that automation is associated with complexity and with an increase in the cost of equipment. Therefore, its reliability and economical efficiency become of prime importance. The increase of requirements with regard to the servicing of more complex and more expensive equipment is also of great significance. For instance, poor quality of tool shaping or the absence of a proper system for its adjustment and storing can depreciate all the positive properties of an automatic machine or a system of machines where this tool is used. This is also the case with the maintenance service arrangement and other services in the process of manufacture.

Automation can be realized either by reconstruction of the existing technological equipment or by designing new equipment. It can cover all operations of the machining of workpieces or only part of them. The reasonable degree of automation depends upon technological features of the manufactured products, the required yield, the layout of equipment, the degree of its universality and other factors.

In order to find an optimal solution, the question of expediency of automation should be considered differentially for each group of operations, and the most efficient measures should be chosen by realization.

C. *Ways of decreasing the cycle or out-of-cycle time requirements*

One of the main criteria of equipment efficiency is the possibility of ensuring its required productivity. The time required for the production of workpieces is summed up from the cycle and out-of-cycle time requirements. The cycle time requirements include technological time of machining, consisting of the shaping time, the time of reciprocal travels of tools and workpieces, and the time for change of workpieces at the machining stations of technological units and transportation of these workpieces between machining zones. The out-of-cycle time requirements include regular down-time of the equipment connected with rehabilitation of the equipment components' capacity for work and the imposed down-time occurring because of malfunctions of other equipment combined with the first one into a co-ordinated operating system.

Separate elements of the cycle and out-of-cycle time requirements can be partially matched with each other. The degree of matching depends upon the nature of the technological process and the adopted layout of the equipment. For example, in machining on rotary-table machine tools, the time required for the change of workpieces can be nearly completely matched with the technical machining time; in work on centreless grinding machines and on drum milling machines, the complete or nearly complete matching of cycle time with shaping time is possible, so that efficient operation can be achieved; in an automated machine-tool line with flexible link, it is possible to match the idle times of one part of the equipment with the operation of its other part.

Ways of decreasing cycle and out-of-cycle time requirements on automatic machines and automated machine-tool lines are discussed in detail in sections II and III.

D. *Readjustment and reconstruction of means of production*

Automation is more readily feasible under conditions of mass production, since in this case the sound solutions

[1] Karl Marx, unpublished manuscripts of 1857 58, *Bolshevik* (Moscow), Nos. 11 12 (1939), p. 62.

may be of partial character, which is more adequate for the properties of the given product. It is also important, however, to provide for a possibility of utilization of automatic equipment in some changes of pieces or technological processes. For this purpose, the nature of possible changes should be determined prior to the development of corresponding equipment. The rapidity of realization of the required reconstruction is of secondary importance in this case, since changes in mass production take place relatively rarely.

Under conditions of batch production, it is necessary not only to provide for a possibility of readjustment of means of production for machining a piece, but also to minimize time requirements. Apart from this, the character of the required readjustment may become more complicated. These requirements are intensified with the growth of productivity of the used means of production and with the decrease of the batch pieces due to the increasing frequency of the required readjustments. Thus, automation of batch production becomes considerably complicated as a result of the growing requirements for the universality of the utilized means.

To simplify the problem, the method of selecting the nomenclature of technically allied pieces is used. In this case, the required readjustments are reduced to the minimum. At the current time, the problems of development of rapidly readjusted automatic loading and handling devices have been less studied. Therefore, the automation of batch production is usually reduced to partial automation by conventional means, i.e., through the use of automatic and semi-automatic machine tools equipped with the adjustments of turret lathes and readjusted automatic lines.

One of the most complicated problems in the field of machining automation is that of small-batch production automation, which, in engineering industries and metal-working, constitutes not less than 30 to 40 per cent of the total volume of production. Within the past eight to ten years, the solution of this problem has been advanced considerably by way of the design and commercial use of the so-called "programme-controlled" machine tools.

II. Automatic and Semi-Automatic Machine Tools

The automatic and semi-automatic metal-cutting machines refer to the group of so-called "technological" or "working" machines. The importance of the technological machines is rather great. It is known that the industrial revolution of the eighteenth century, which resulted in manual production being replaced by machine production, was caused by the wide application of technological machines rather than of engines only. The invention of mechanical engines stimulated the growth in the size of technological machines, the increase of speeds and productivity. However, the possibility of transfer of any branch of industry to machine production occurs only after the corresponding technological machines have been designed.

A. *Structure of the operating cycle and methods of shortening its duration*

The working cycle on metal-cutting automatic machines involves the following operations: feed of materials or blanks, execution of shaping operation on them, transporting from one position to another; fixation, clamping and release, moving forward and removal of working organs; and the switching of separate mechanisms. All these operations require a certain amount of time. On some automatic machines, the machining, readjustment and, occasionally, the change of tools are carried out by automatic control.

The out-of-cycle time requirements consist of the time for change, installation and adjustment of tools; the time for rehabilitation of working capacity of automatic machine mechanisms in failures; and the waste losses and time taken by organizational matters.

The basic way to increase the output of automatic machine tools is the simultaneous decreasing of both cycle and out-of-cycle time requirements. The decrease of cycle time requirements should involve simultaneously both the time for the main shaping operations, t_p, and the time for auxiliary operations, t_r. The decrease of only the time t_p without a simultaneous decrease of the time t_r would lead to the increase of the share of the latter and, consequently, to the decrease of the efficient use of the equipment for direct machining.

The problem of decreasing the cycle requirements is solved by both the development of advanced machining methods and the improvement of mechanisms for realization of working and idle running. At the same time, the concept of matching the separate elements of the cycle time requirements is applied. For instance, for decreasing the value t_p, it is possible to (*a*) time-match different idle-running operations, and (*b*) time-match idle-running operations with working ones. For decreasing the value t_r, two methods are also possible: (*a*) the simultaneous machining of pieces in one position with several tools (multiple-tool machining); and (*b*) the simultaneous machining of pieces in several positions with several tools (multiple-position machining).

The decreasing of out-of-cycle time losses connected with the change and adjustment of tools is rather a difficult problem, particularly with regard to multiple-tool and multiple-spindle machines, when numerous tools operate simultaneously. The main problem in this case is the determination of the optimal intensification of machining conditions and of the degree of concentration of the technological process.

The losses connected with the rehabilitation of the working capacity of the automatic machines' mechanical unit depend upon the durability and reliability of these units. Each machine has, along with units which are quite reliable and durable, units of lower durability. For example, in automatic bar lathes, such units are the split-socket clamping mechanisms, cams and push-rod supports; in automatic internal-grinding machines, the comparatively short-lasting units are the rolling bearings of high-speed spindles which, in grinding small parts, rotate at the speed of tens of thousands of revolutions per minute.

In order to increase the durability and reliability of automatic machine mechanisms, it is necessary:

(*a*) To achieve, by means of constructive measures, as well as by improving the quality of production, prolongation of the service period of such mechanisms, possibly without increasing their size and weight.

(*b*) To strive for the development of quickly replaceable units and parts, and for a decrease in the time required for repair and replacement of the mechanisms which fail.

B. *Methods of automatically securing the required machining accuracy*

In the main branches of mass production, technical control is required for about 40 per cent of production operations. Therefore, the automation of technical control is important to these areas of production. The problem of choice of a system and of control facilities is simplified in cases when automatic production utilizes machines of modern, tested types. It is more difficult to solve this problem for new types of machines. For new machines, over-estimation of both the stability and the accuracy of the design may occur; and, due to this unreasonable failure of control of important dimensional parameters of pieces and the like, it is possible to make unreasonable solutions concerning the necessity of introducing 100 per cent taking-over control and of designing for this purpose sophisticated control facilities.

1. *Active and passive controls and their applications*

Automatic-control devices are divided into two main groups: those operating by "passive" control; and those employing "active" control. The first group includes:

(*a*) Devices for taking-over control which sort workpieces into valid and faulty ones;

(*b*) Devices for the classification of valid pieces into a number of dimensional groups for selective assembly;

(*c*) Devices for control of definite important parameters prior to machining in order to prevent damage to machines or instruments as a result of a discrepancy between these parameters and the established requirements.

In the passive-control method, the control devices normally are not connected with the machining process and cannot affect the machines' working components. On the contrary, the active-control devices can, according to the results of measurements in the process of work or right after it, actively interfere with machine control and give instructions for changing operating conditions or stopping the machine after achieving the desired dimensions of machined pieces. The active-control devices which control pieces after machining can also carry out the following functions: make adjustments, i.e. change the working-tool position; classify valid pieces into groups; stop the machine in case of tool failure.

Active-control devices are used in various branches of mass production and, first of all, in systems of machines. Different types of grinding and lathe machines are equipped with these means.

2. *Automatic tool-wear compensation*

The active control and automatic adjustment of tools are currently used mainly in grinding operations and quite rarely in lathe and boring operations, where greater accuracy and better machining quality are required. For such operations, the adjusting devices are designed mainly for individual pieces and are not of a universal nature. In this category are adjusting devices for automatic lathes which machine railway bearing rings, motor-car axles, valves and the like. In some automatic machines (for instance, drilling and boring of heatproof valves) mechanisms for the automatic changing of worn and failed tools are also introduced.

Devices for the adjustment and dressing of tools of grinding machines have found the widest application. Two main modes of grinding operations are:

(*a*) Grinding on a machine, with an automatic cycle and control "along the path" (indirect control of machine components' moves);

(*b*) Grinding on a machine with an automatic cycle with grinding-process controlling by active-control instruments with machine adjustment on the basis of measurement results.

The first mode is cheap and simple because it does not require complex measuring equipment and servicing by highly skilled personnel. Thus far, however, it is not possible to achieve high accuracy of machining by this method, due to the fact that it is based on indirect measurements of the path of transfer of the grinding-wheel centre with respect to the piece, and the actual dimensions of pieces are not controlled directly.

The second method uses active-control instruments which determine the direct result of machining during the whole cycle of machine operation and give instructions for changing operating conditions or the stoppage of grinding. In this method, complicated measuring instruments and apparatuses, as well as programming, are necessary; and their cost is often equal to that of the machine itself.

The ever-increasing requirements as to the machining accuracy on grinding machines give rise to the study and analysis of the reasons for their inaccurate operation. One should distinguish two groups of these reasons: random and regular errors. The random errors lead to dispersion of the pieces' dimensions. These errors do not depend upon the duration of work and are associated with specific features of machine design, measuring instruments and their quality. These are irregularity of feed (usually transversal), non-rectilinearity, insufficient system rigidity, random instrument errors, illegibility of fulfilling instructions, etc. The random-error distribution law is usually normal. Systematic errors depend upon the time of operation; they are accumulated slowly and cause gradual change of the shape and size of pieces. These errors can be periodic or growing. Systematic errors include the wear of the grinding-wheel, diamond wear, machine and piece heat deformations, deformations associated with blunting of the grinding-wheel and systematic errors of instruments and transfer mechanisms. Systematic errors are eliminated by means of adjustments.

The piece dispersion zone connected with both random and systematic errors should correspond to machining-accuracy requirements. This correspondence is expressed in that the dispersion zone should be located within the production tolerance zone, and the sum of systematic errors should not accumulate rapidly, since this would cause the frequency of adjustments to be very high.

3. *Dressing and adjustment of abrasive tool*

In rough works on face grinding machines operating by the butt end and on centreless and circular grinding machines, diamond substitutes, the so-called "milling-cutters" or "abrasive discs", are widely used for the dressing of grinding wheels. In the case of an automatic cycle and automatic grinders, the diamond dressing of wheels with the aid of special dressing tools having diamond automatic feed and wheel-wear compensation mechanisms is mainly used. In order to avoid the dressing by blunted diamond, which leads to smoothing (over) the grinding-wheel surface and deterioration of its cutting properties, it is desirable to use tools which have automatic rotation of the diamond holder. Recently, tools having special rotary mandrels with several diamonds have found wide application. The application of such "multiple-blade" diamond tools makes it possible to increase the speed of dressing and to obtain a higher accuracy. For the dressing of shaped wheels, the following methods are applied:

(*a*) Dressing with a single-blade tool by the diamond along the former. In the dressing of profiles having steep zones, occasionally two diamond tools are applied separately for longitudinal and transverse profile sections;

(*b*) Dressing of shaped wheels with a knurling roll has found wide application. This method has a number of advantages: relative simplicity; high productivity; and the possibility of dressing steep profiles. The disadvantages of the method are: the low resistance of knurling rolls; their high cost; and non-stability of the abrasive waste due to quick wear of rolls;

(*c*) A new method of wheel dressing with rolls covered by a layer of diamond fines is of great interest. This method has a number of advantages, as compared with the earlier methods used. These advantages include: a reduction of dressing time by thirty to sixty times; the simplification of shaped-wheel dressing; and a reduction of dressing cost since tools with diamond fines have a very long service life and diamond fines are cheaper than large diamonds.

III. Automatic machine tool lines

A. *General layout concepts*

The connecting of several technological aggregates into a co-ordinately operating system, or automatic machine tool line, is always associated with a certain limitation as to the independence of their operation. This limitation displays itself specifically in the fact that during the operation each aggregate of the automatic machine tool should stand idle for some time, not only for rehabilitation of its own working capacity, but also due to failures of other associated aggregates. The degree of limitation of the aggregate independent run of the automatic machine tool line depends upon its layout. Therefore, the general principles of the line layout, i.e., the methods of interconnexions of the units involved, considerably affect its productivity.

As mentioned above in section 1, the time requirements for making workpieces on an automatic machine-tool line are composed of cycle and out-of-cycle time requirements.

The cycle time requirements include:

(*a*) Technological machining time on the line, consisting of shaping time and the travel time of mutually accelerated tools and work-pieces.

(*b*) The time for the change of workpieces, which includes the change time in the machining station of an aggregate and the time for transporting workpieces from one machining zone to another.

The out-of-cycle time requirements include:

(*a*) Idle standings of the line equipment associated with rehabilitation of the working capacity of the components of this equipment;

(*b*) Imposed idle standings occurring as a result of failures of other equipment combined with the first one into the co-ordinately operating system.

The layout of the automatic machine-tool line determines the character of the transporting-loading motions within the line and the intercommunication of individual groups of its equipment. Therefore, the layout affects the time elements enumerated in (*b*) of both kinds of requirements, that is, the time for workpiece change and the degree of matching of imposed idle standing of the line.

Consider the effect of the layout on each of the enumerated kinds of time requirements.

1. *Cycle requirements*

The cycle time requirements for the change of workpieces in the machining zone and for transporting them between machining zones consist of a number of elements. The release, taking down, setting up and clamping of the workpiece take place in machining zones, whereas the forward and backward motion of the workpiece transporter, as well as the different rotations and tipping of workpieces for their transfer with respect to zones of technical actions, take place between the zones. Depending upon the adopted layout of automatic machine-tool line, the elements of cycle time can, to some extent, coincide with each other. This leads to a reduction of the rated cycle of line operation, which, in the limit case, may include only technological time or even the shaping time only.

2. *Out-of-cycle requirements*

According to the nature of the intergroup link, the automatic machine-tool line can have rigid or flexible connexions. In the first case, the active interoperational preparations do not exist between stations of the automatic machine-tool line and the transportation connexions are of a synchronous character. The stopping of one of the units of the line immediately causes the stopping of the whole line. The imposed idle standing cannot be coincided and reach maximum quantity.

Automatic machine-tool lines with flexible connexions are characterized by the presence of active interoperational preparations or several parallel flows connected by an asynchronous interunit link. In this case, the technological aggregates of the line operate more or less independently and the failure of part of them does not cause direct stopping of the whole line. The imposed idle standing times can coincide with each other and their total value can be considerably decreased.

The above-described general principles of automatic machine-tool lines have been developed at the Design Office-I of the Experimental Research Institute of Metal-cutting Machines (ENIMS) and other design offices which are working on the analysis of structural schemes of automatic machine-tool lines and on the determination of the efficiency of their use.

B. *Reconstruction and readjustment of lines*

The field of application of automatic machine-tool lines designed for the machining of only one workpiece, the so-called "single-item" or "single-nomenclature" lines, is limited by the requirement of a sufficiently large output of workpieces because one of the conditions of the economic efficiency of lines consists in high productivity. In the last few years, however, both in the Union of Soviet Socialist Republics and abroad, multiple-item automatic machine-tool lines have been developed, on which the machining of several different workpieces is possible, either directly or with little readjustment.

The application of such lines may be sufficiently effective even with a relatively small output of each item.

The following main types of multiple-nomenclature automatic machine-tool lines may be mentioned: (*a*) non-readjustable lines; (*b*) lines with manual readjustment; (*c*) lines with automatic selective operation of machine; and (*d*) readjustable programme-controlled lines.

It is easier to solve the problem in the case of the machining of similar workpieces, whose design difference does not affect the outlay of the line. In this case, several (normally two or three) workpieces of similar configuration can be machined without any readjustment.

In other cases, the automatic machine-tool line has to be readjusted manually when machining similar workpieces. This may involve changing the cutting tool and jig bushes, and the transposition of control stops. Occasionally, auxiliary power packs have to be switched on or switched off manually. The time required for such readjustments is different and lasts from several minutes to one shift-period.

The disadvantage of the lines with manual readjustments, apart from time losses for readjustment itself, is also the necessity of working out or removing workpieces of the same type from line-stations and after readjustment feeding them with workpieces of another type.

Both in the Soviet Union and in other countries, a certain number of multiple-item lines with automatic readjustment have recently been built. They are also known as lines with "selective operation of machines".

Lines of this type permit the machining of several workpieces, mainly of two, in any sequence without requiring manual labour for readjustment and without the necessity of removal of workpieces and feeding-line transportation systems with other type of workpieces. The conveyors of such lines are adapted for the transfer of workpieces having different sizes. The lines are equipped with identification devices for determining the type of workpiece or satellite and for switching on the power packs. Several multiple-nomenclature lines have been designed on the basis of the specimen described here. Each of these lines is designed for the machining of two workpieces of different size. The increase of nomenclature leads to a considerable complication of the design and to difficulties in determining the type of workpieces, as well as to some difficulties in readjustments.

For small-batch production, the solutions described here may turn out to be of low efficiency. In these cases, the questions of sufficient universality of the used means of automation and the speed of tool readjustment become of great importance. In a number of foreign and domestic designs, these questions are solved through the use of programme control. The machines of the lines are equipped with tool feeders containing a considerable number (up to thirty) of various tools.

The tool changes, as well as a number of other elements of readjustment, are done automatically with the aid of various programme-control systems. At the end of the 1950's, some periodicals in the United States of America published information on programme-controlled automatic machine-tool lines of the Hughes Aircraft Company, for the machining of workpieces of interceptors; and of another machine manufacturing company for the production of piston rods for slush pumps. In the USSR, an experimental readjusted line for the machining of nine sizes of beds for crane motors was designed in 1963.

Automatic machine-tool lines for the machining of rotating workpieces usually permit the handling of workpieces of one type with slightly varying dimensions with the aid of manual readjustments. In this case, the technological equipment, measuring and controlling instruments and electrical automatic devices are readjusted. The conveyors, gutters and tool feeders require no readjustment. The duration of such readjustments usually does not exceed one shift-period.

Apart from readjustment, the so-called "rebuilding" (reconstruction) of automatic machine-tool lines is currently practised. Reconstruction is undertaken when the manufactured products suffer cardinal modifications or are replaced by other similar products which are more or less different from the previous ones. The concept of reconstruction is broader than that of readjustment and usually includes the latter as one of the elements. In reconstruction, in addition to the readjustment of technological and control equipment and electrical automatic equipment, the reconstruction (rearrangement) of conveyors and gutters takes place. It is more difficult to reconstruct tool feeders: very often one has to replace them with new ones and only in certain cases is it possible to replace some units and parts, rather than the whole.

C. *Satellite devices*

The mode of conveying workpieces on automatic machine-tool lines is determined to a considerable extent by their shape.

For instance, the cylindrical blanks of small length-to-diameter ratio (rings, flanges, etc.) very easily move along gutters; the blanks of box-body parts with large flat surfaces can be easily pushed through over slideways with the aid of side-guiding planks for elimination of shifting. Due to the complex shape of workpieces, it is often impossible to convey them directly over slideways. In these cases, the workpieces can be clamped into intermediate device-satellites, which may be especially shaped to simplify the conveyance of workpieces of simple shape. If they are made from insufficiently hard materials, however, their bearing surfaces may be damaged in sliding along the conveyor slideways.

Some companies use satellites for operations which require the rotation of workpieces in machining. In such cases, a satellite consists of a spindle with a chuck for clamping the workpiece. The driving mechanisms are placed in stationary position on the line working-stations and are equipped with clutches for transmitting rotary motions to the satellite spindles. Such devices have been used by the Excello and Cross Companies (United States of America) and the Honsbery Company (Federal Republic of Germany).

The use of the automatic machine-tool line layouts with satellites is connected with a number of peculiarities of both a positive and a negative character. The main advantages of the use of device-satellites are as follows: the possibility of machining on automatic machine-tool lines the difficult-to-convey pieces of complicated shape or of insufficient hardness; the high reliability of orienting workpieces in conveying; the possibility, in individual cases of simplifying the construction of stationary devices; and the simplification of conditions for cleaning and washing of surfaces basing the blank.

There are, however, some disadvantages in using the device-satellites.

First, the introduction of satellites requires extra, often rather considerable, expenditures. The cost of production of satellites is usually high since they must be interchangeable and must have sufficiently long durability, and the number of them, particularly in large automatic machine-tool lines is considerable.

The other disadvantage connected with the use of satellites is the necessity of introducing additional surfaces for joining, basing and fixation. For these reasons the range of tolerances is reduced to cover the errors of technological operations, which, in this case, should be performed with higher accuracy than those on the lines without satellites.

The third disadvantage of the layouts employing satellites consists in the complication of the conveying systems of the lines. This complication is connected with the necessity of returning the device-satellites from the last to the first position of the line, with the introduction of stations for automatic cleaning and washing of the satellites and with the introduction of devices for clamping and release of workpieces on satellites.

Finally, one more disadvantage of the layouts of automatic machine-tool lines using the device-satellites consists in the difficulty of accumulating interoperation stocks between their stations. In the stock accumulators of such lines, the workpieces should be allocated with the satellites, which leads to an increase of the necessary number of satellites and a complication and increase of the dead load of feeder construction, as well as to the total rise of the line cost. For these reasons, the device-satellites are rarely used on multiple-station automatic machine-tool lines with flexible links.

D. *Stock accumulators*

In modern automatic machine-tool lines, stock accumulators find a wide application. At the same time, the theoretical premises for their efficient use are developed. The basic conclusions in these respects are as follows:

(*a*) Accumulators of larger capacities should be chosen to correspond with longer average single idle standings of units of automatic machine-tool lines;

(*b*) It is not reasonable to use very large, cumbersome accumulators because, along with the increase of their capacity, the intensity of decreasing losses conditioned by their presence becomes lower;

(*c*) From the point of view of losses decreasing, it is preferable to have a greater number of low-capacity accumulators than a smaller number of higher capacity accumulators (it is assumed that the sum of accumulator capacities is the same in both cases)

In automatic machine-tool lines of different types, two kinds of accumulators are mainly used – dead-end accumulators and continuous-path ones. The first are located outside the main conveying path of the line and run only when failures occur in the line sections for which they are designed. In normal operation of the line, the dead-end accumulators do not work, and their own idle standings do not occur at that moment. The continuous-path accumulators, on the contrary, are located on the main conveying path and operate during the whole line-operation time. In fact, they constitute a part of the interstation conveying system of the line.

Both types of accumulators possess positive and negative properties which make it difficult to give unequivocal recommendations on the use of one particular type.

For example, the dead-end accumulator is more advantageous than the continuous-path one from the point of view of its effect on the total efficiency of the automatic machine-tool line. Furthermore, it usually occupies a smaller production area. On the other hand, the dead-end accumulators have more complicated automatic-control systems and interlocks, and worse possibilities for the compensation of losses of the automatic machine-tool line sections for which they are designed. The latter property is explained by the fact that the dead-end accumulators are connected synchronously with the line-stations' work and cannot compensate idle standings with a duration which is less than these cycles. Apart from this, the dead-end accumulators may accumulate and store for a long time a considerable amount of semi-finished workpieces. The continuous-path accumulators which are manufactured in the form of drive rotary trains are cheap and reliable. Due to the constant additional pressing of workpieces to the zone of use, these accumulators compensate all kinds of idle standings, irrespective of their duration. The continuous-path accumulators of this type can be distributed on the line with higher density than can the dead-end ones, and with the same total capacity they are able to decrease more intensively the losses of the neighbouring stations of the line. Maximum reliability and simplicity are obligatory conditions for the working capacity of both types of accumulators.

The study of accumulator operation has not yet been developed and the experience of their operation is insufficient.

In automatic machine-tool lines of building-block machines, blind-path accumulators are sometimes used. These are located in the points of technological discontinuities of the line, i.e., in the points of tipping of the workpieces or of transferring them from one station to another. The capacities of these accumulators are usually rather large and provide for a continuous run of the line during one-and-one-half to two hours. The locations of these accumulators often do not satisfy the requirements of equality of idle standings of the neighbouring stations. The operation control of such accumulators is usually completely automated and rather complex because it requires consideration of the state of the neighbouring stations in the automatic switching of the accumulator. The above-described accumulators do not always operate successfully. This is explained by both the complexity and the insufficient reliability of automatic control systems and the reasons of the organizational order, consisting in incomplete leading of the line (especially in the initial stages of operation) and the absence of necessity in the accumulation of workpieces, as well as the low exploitation level of comparatively complex accumulators.

The other type of accumulator for automatic machine-tool lines of building-block machines is a continuous-path accumulator of the driven roller path type. Such accumulators are integrally connected with the common conveying system of the line and cannot be disconnected arbitrarily. Due to the advantages listed above, these accumulators are often applied by foreign companies in the lines of machining of body parts.

In automatic machine-tool lines for the production of small-size workpieces of the rotating type (bearing rings, valves, piston pins, bush sleeves etc.), the continuous-path accumulators are mainly used. Some of them, for instance, brush feeders for bearing rings, have a wide application and are sufficiently reliable and perfect designs.

E. *Control-interlocking and signalling devices*

Various control methods and different types of control devices for maintaining the necessary machining accuracy are used in automatic machine-tool lines:

(*a*) Checking procedure which is done manually by an adjuster;

(*b*) Automatic active control in the process of operation by measuring built-in instruments of the automatic machine-tool line;

(*c*) Automatic active control after an operation with the aid of built-in measuring instruments, which automatically adjust the instruments on the basis of the measurement results;

(*d*) Automatic interlocking control carried out for the purpose of eliminating workpieces which do not meet the standards set;

(*e*) Final automatic control after machining on the line.

The most comprehensive application of the above-mentioned kinds of control takes place on automatic machine-tool lines for the machining of small parts of the rotating type requiring precise machining: rolling-bearing rings, valves, wrist pins, bush sleeves and the like.

On the building-block machine lines, provision is made for a manual checking procedure, as well as for automatic control of the performed operation, with the aid of the measuring devices built into the lines. Usually, the diameter of the precise ports and the depth of precise grooves are controlled; the ovalness and taper of ports can be checked during the adjustment cycle.

F. *Tool consoles*

As a rule, a considerable number of tools operate on modern automatic machine-tool lines. On large lines of building-block machines, there are 800–1,000 tools. Variable tool endurance and the absence of operators hampers the supervision of the state of the tools. However, the reliability and efficiency of the line performance depend, to a considerable extent, upon the state of an instrument and its timely replacement. It is desirable that the tools be positively changed within a predetermined time after receiving signals from cycle counters located in special tool-storing cabinets.

The counters, after reaching the definite (for the given group of tools) minimal cycle number, warn the adjuster of the necessity of a change of this tool group; and, after reaching the maximum cycle number, they stop certain sections of the line.

Experience has shown that the use of tool cabinets and cycle counters does not always give a possibility of passing over to positive tool change. The reason for this is the wide range of variation of tool durability periods. The durability depends upon a number of factors, for example: quality of sharpening; rigidity of tool clamping; constancy of allowance; and hardness and state of the machined workpiece surface. Depending upon some of these factors, the tool durability may vary tens of times. In general, durability periods are considerably random values with a large range of variation. Therefore, the determination of real terms for tool change by guidetables and durability formulae does not give satisfactory results.

It would be incorrect, however, on the basis of the foregoing, to neglect the use of tool cabinets and cycle counters. The tool cabinets provide convenient storage of tools, control of their availability and simplification in finding them. Counter recording of the number of pieces processed by each group of tools after resharpening is also useful. It seems reasonable to introduce, instead of positive tool change, their forced inspection by the cycle counter signals, for instance, each one-third of the rated mean period of durability. While inspecting, the adjuster should change only those tools of the given group which turned out to be blunted. Such a scheme of inspection and tool-changing decreases the hazard of breaking the tool at the minimal time of its change, because the adjuster must change only those tools which need changing.

The decrease of time losses for tool change is achieved by the introduction of the high-speed setting-in of tools and the preliminary off-line adjustment of them with respect to the size on special instruments.

In performing accurate finishing operations, the dimensional durability of cutting tools and their adjustment plays the main role; therefore, automatic tool adjustment on accurate lathe and milling operations is often introduced on automatic machine-tool lines which produce accurate workpieces. In modern lathe and boring machine tools designed for work in automatic machine-tool lines, mechanisms for the automatic change of worn or broken tools are used.

G. Conditions and field of efficient application of automatic machine-tool lines

The shop prime cost of mechanical workpiece machining in mechanical engineering is summed up from the main wages of industrial workers and the so-called "shop expenditures", of which the basic ones are depreciation and maintenance of the equipment, the cost of tools, electric-power, wages of technical personnel, labour and so on. The introduction of automation usually dec[illegible]ses expenditures for the main wages of industrial workers, whereas it increases expenditures for depreciation and maintenance, the total value of production cost being decreased. The degree to which the production cost is decreased is one of the main points of automation efficiency.

The efficiency of introduction of automatic machine-tool lines depends basically upon the following factors:

(*a*) The nature and degree of improvement of the technological processes realized in the line;

(*b*) The availability of standard sizes of specialized reliable and cheap equipment which is suited for use in an automatic machine-tool line;

(*c*) A sufficiently large scale of production;

(*d*) Rational organization of works connected with the exploitation of an automatic machine-tool line.

Various technological operations are, thus far, not suitable for automation. It should be taken into account that the modes which are performed manually with difficulty are often easily and simply carried out with mechanisms; and, on the contrary, the model easily carried out manually often require complex mechanisms in automation. This is explained by a number of principal differences between the peculiarities of the human body and the kinematics of the machine. Not a single organ of the human body has, for example, the continuous rotary motion widely used in machines. Man, however, easily performs spatial transfer, whereas the overwhelming majority of mechanisms of modern machines carry out only planar movements of working organs. Man's arms are a very perfect tool and can perform various and complex motions, whereas the working parts of a machine fulfil only relatively simple motions. It is relatively easy to automate working and idle motions of working organs of technological machines, but it is more difficult to handle auxiliary operations associated with the maintenance of machines and to include transfers of machined articles from one machine to another, loading and unloading of machines, clamping and releasing of workpieces and the like.

Great difficulties are encountered in assembly automation. Assembling operations usually consist of a number of manual tasks which are very difficult to automate. Among these are, for instance, operations associated with the change of position of workpieces and assemblies, and with their mutual orientations, the operations of pre-screwing nuts, the assembling of ball-bearings, etc. Recurring difficulties are often connected with automatic conveying and feed from bind of such workpieces as spiral springs, slotted rings and the like; these are easily coupled into chains and balls, which prevents their piece-by-piece feeding.

In the cutting machining of workpieces, some difficulties arise in the automation of precise finishing operations whose performance is accompanied by stops for change and adjustment of tools, and for checking of machine tools and devices.

Realization of advanced technological processes is largely dependent upon the availability of quality, reliability and cheapness of metal-cutting equipment. This problem can be solved by the design and improvement of the complex of standard technological and transportation equipment which is suited for incorporation into automated machine-tool lines. Due to the stability of standard types of such equipment and the larger scale of its manufacture, the cost may be considerably lowered, compared with special equipment manufactured on an individual basis. The reliability of such equipment may be higher.

With the decrease of production, the cost price of machining rises, due to increased time losses for readjustment of the equipment. The readjustment problems on automatic machine-tool lines are complicated by the necessity to readjust not only the technological equipment, but also the conveying and loading devices and feeders. Therefore, the single-item automatic machine-tool lines designed for the manufacture of a standard size of article can be efficient only in case of comparatively large batches of production. The problems of quickly re-adjustable automatic machine-tool lines, as mentioned above, are rather complicated and are currently far from being solved in a satisfactory manner.

The idle standings occurring in the course of running of the lines are the consequences of a number of factors, which are basically divided into the following three groups: (*a*) idle standings due to technical reasons; (*b*) idle standings due to organizational reasons; and (*c*) imposed idle standings.

The first two groups of idle standings are subdivided in turn into a number of smaller groups, for example, the idle standings associated with the work of tools, mechanical devices of the line, electric and hydraulic apparatuses, the lack and quality of blanks, the lack of power, the skill of maintenance personnel, waiting for adjusters and the like.

The detailed division of idle standings due to real reasons is difficult in a number of cases and may be of a subjective character. For instance, the idle standings associated with tool change depend not only upon a number of design factors, but also upon the arrangement of tool-keeping, i.e., upon the area in which tools are stored, how their sharpening and adjustment are arranged etc. The length of idle standings due to failure of mechanical, electric and hydraulic devices depends upon design factors, the quality of manufacture and assembly, the number and skill of maintenance personnel, the organization of technical services etc. The situation is often complicated by the absence of reasonable data on the determination of the necessary number of maintenance personnel, the payment system for this personnel, the organization of tool and repair services and so on.

In general, the defects in different stages of the building of automatic machine-tool lines, i.e., in design and manufacture, become most strikingly apparent during the operation of the lines. Therefore, the acquisition and practical analysis of data on running automatic machine-tool lines is an important measure which contributes to the improvement of their construction and the quality of their manufacture.

At the current time, automatic machine-tool lines are used mainly for mass production. The lines of building-block machines usually handle large and medium-size body parts, as well as parts of the roll type, crankshafts, oscillating and rear axles, connecting rods etc. Preparatory operations on milling, drilling and boring are mainly carried out on such automated lines, whereas the finishing and precise operations are mostly carried out off-line.

Mass-produced articles of one type, e.g., rolling contact bearings, valves, piston pins, straight axle shafts and bush sleeves, tap borers and threading discs, are machined on automated machine-tool lines of special and specialized automatic machines: lathes, grinders, milling and broaching machine tools, etc.

Projects on the extension of the field of application of automatic machine-tool lines are being carried out mainly in the direction of the development of readjusted lines which are suited for multiple-item machining. As mentioned above, the use of these lines may turn out to be efficient even in relatively small-scale production of parts of each nomenclature, apart from their efficient application in series production.

IV. Automation of Mechanical Processing with Programme-Controlled Machine Tools

Until recently, works on the automation of small-batch production in machine-building enterprises were directed only towards solving individual problems concerning parts. However, the problem as a whole did not find a solution. The extensive development of electronics and computing techniques in the USSR has become a basis for the complex automation of industrial processes in small-batch machine-building operations with the aid of programme control of machine tools and other production mechanisms.

The programme control of metal-cutting machines makes it possible to solve a number of complicated problems of automation of universal and specialized machine-tool equipment.

Some of them are the following:

(*a*) Automation of machine tools working in small-batch or individual production, which currently comprises no less than 60 to 70 per cent of the total mechanical-engineering production, with provision for the rapid readjustment of machine tools for other pieces or batches;

(*b*) Provision of highly productive automatic machining of workpieces of complicated shape without preliminary production of master forms, special tools or camshafts, and the carrying out of similar labour-consuming works;

(*c*) Automation in series production and even in large-scale production brings about a sharp decrease of the number of special-design machine tools and the maximum unification of controlling devices, including machine tools of different designs and groups;

(*d*) Radical facilitation of the introduction of corrections into the kinematic scheme of accurate machine tools for elimination of production errors and wear compensation of individual components in the process of work;

(*e*) The foundation on a uniform constructive basis of a range of machine tools with different degrees of automation, according to the requirements of customers with different production conditions.

The systems of programme control of machine tools are divided into two classes: numerical and cyclic. Each of these classes has its own field of rational use.

Numerical systems are distinguished by relative complexity and by principally new, for machine-tool building, technical solutions and means (use of electronic circuits, methods of computing technique, complicated electric drives and data-input devices, programme writing on magnetic tapes, punch cards and tapes, etc.). Numerical systems are intended to resolve the problems associated with the processing of complex shapes.

Cyclic systems, being simpler in construction and using sufficiently commonplace means and methods for modern machine-tool building, more successfully solve the problems of unification of equipment and control devices, as well as the on-line readjustment of régimes and sizes on a running-station.

The construction of programme-controlled machines has been undertaken in Soviet industry for seven or eight years. The introduction of separate assemblies with the use of cyclic programme control in machine tools began considerably earlier, approximately at the end of the 1940's.

A. *Numerically controlled machine tools*

A whole set of numerically controlled (NC) systems of metal-cutting machine tools has been developed; these NC machine tools can be divided into three groups:

(*a*) *Machine tools for contour machining.* This group includes millers, electro-erosion cut lathes and other machine tools for machining parts of complex configuration with simultaneous interconnected motion along several co-ordinates;

(*b*) *Co-ordinate machine tools.* This group includes boring machines, co-ordinate-boring and other machines with positional controllers; the tool is set up along the co-ordinate according to the programme;

(*c*) *Position-control machine tools.* These are lathes for the machining of stepped shafts, millers with linear motion along co-ordinates etc.

In numerically controlled machine tools, machining of the workpiece with the use of marking or a master form is replaced by the mathematical computation of a machining programme with a further record of computation results on punched or magnetic tape. The written programme is then transferred to the shop. The operator has only to instal the blank on the machine and to switch on the programme-control panel.

As a result of two years' operation of programme-controlled milling machines, it is possible to present the following indexes: the machine time in machining parts of complex configuration was decreased by three times; and the accuracy of machining became higher, which made it possible to avoid "locksmith" finishing. The availability of facilities on the correctness of programming permitted the elimination of control measure of workpieces. The programming of speed, depending upon the allowance, increased the durability of the tool. It is now possible to increase the speed and accuracy of machining. The machine setting-up time is considerably reduced when machining a new workpiece.

Experience with programme-controlled machine tools has confirmed the possibility of considerably accelerating the machining and improving the workpiece machining accuracy. The data on the machining of sixty-seven parts on a universal machine tool and on a programme-controlled machine tool are presented below as an example.

Table 1

MACHINING DATA FOR UNIVERSAL AND PROGRAMME-CONTROLLED MACHINE TOOLS

Indexes	*Universal machine-tool*	*Programme-controlled machine tool*
Average number of operations for 67 parts (one-shift annual operation of machine)	197.0	70.0
Labour consumption (machine time, preparatory finishing time and "locksmith" finishing time) per part (hours)	23.3	4.93
Labour consumption (machine time, preparatory finishing time and "locksmith" finishing time) per article (hours)	88.6	21.8
Decrease in labour consumption per article (one-shift machine operation during one year) (hours)	—	7,154.3

The parts machined were mainly of light alloys. Examples of such parts are given in table 2. As a result of higher machining accuracy, the parts have become interchangeable.

The accuracy obtained on programme-controlled machine tools is determined, to a high degree, by the proper selection of cutting conditions and the size of allowance.

The cost and time savings in the use of such machine tools depend upon the type of parts selected and their series production. As may be seen from the tables, a large class of parts has been determined for which the use of milling machines with numerical programme controls is rather efficient. As the computation methods and recording means develop, the field of use of these machine tools will be extended.

Table 2

DATA ON MACHINING OF SOME PARTS ON UNIVERSAL AND PROGRAMME-CONTROLLED MACHINE TOOLS

Type of part	*Material*	*Blank*	*Feed (millimetres per minute)*	*Accuracy of machining (millimetres)*	*Marking machining time (minutes)*	*Machining time on programme-controlled machine (minutes)*	*Notes*
Guard	Steel alloy	Sheet	300	±0.07	21.0	6.0	
Sector	Steel alloy	Sheet	800	0.01	126.0	27.0	
Body	Steel alloy	Ingot	600	±0.1	Decreased 4.2 times	...	
Shoe	Steel alloy	Forging	300	±0.1	Decreased 3.5 times	...	
Fitting	Steel alloy	Compressed profile	300	±0.1	8.5	5.0	
Link	Steel alloy	Sheet	450	±0.1	65.0	12.0	
Pintle	Steel alloy	Roll	175	±0.05	19.0	4.0	

The characteristic feature of the current stage of machine-tool programme-control development in the USSR and abroad consists in the use of these machine tools for individual workpieces, as well as for small-batch and series production.

In small-batch and series production, these machines provide from two to three times greater productivity, compared with reproducing machines, due to the smooth speed control in passing along the contour.

Other advantages are the facilitation of adjustment (there is no need to advance the guiding-block with respect to the workpiece), the better use of working surfaces of the machine and the elimination of storage space for guiding-blocks. The latter is of particular importance for large machine tools.

The experience of machine-building plants has shown a high efficiency of such machines in the production of lots of parts ranging from 1,000 to 10,000 pieces at machine times of processing ranging from 10 to 30 minutes per part.

Another specific feature of programme-controlled machine tools, which has been clearly revealed within the last few years, is the construction of sections and shops equipped with these machine tools.

By grouping the programme-controlled machine tools in separate sections, their use becomes still more efficient. This has been especially successful in a number of machine-building plants. Those plants which combined programme-controlled machine tools into sections were able to provide for their uninterrupted operation. With more than five controlled machine tools, the establishment of a technological group for designing and writing programmes at the plant, as well as the use of general-purpose electronic computers, becomes justified. When a plant has a considerable number of programme-controlled machine tools distributed at different shops, the provision of multiple-machine services, personnel training and maintenance becomes complicated.

Programme control leads to the possibility of employing workers with less skill and to a decrease in manual labour requirements.

A number of the programme-control systems which have been developed in the USSR are applicable to various types of machine tools (drilling and milling machines, lathes etc.)

The milling machine tools of Model 6H1319-2, which are equipped with a step programme-control system, have been used in industry since 1960 and are highly appreciated by the users. The system is fully transistorized.

The machining programme is written on magnetic tape. The world's highest speed stepping motors and original hydraulic servo-systems have been developed. The step-control system has, at the same machining accuracy, fewer electronic components than other programme-control systems performing the same functions. This system was borrowed from the USSR by the Japanese Fuji Company.

The Experimental Research Institute of Metal-cutting Machines, in co-operation with a machine-tool works, developed a range of highly productive and precision programme-controlled machine tools. The milling machine plant in Gorky has begun the manufacture of multiple co-ordinate milling machines of four size-types with a step programme-control system.

The use of a programme-controlled electro-erosion machine tool designed for the shaped cutting of a die from hard alloys has proved very effective.

Programme-controlled systems for unique metal-cutting machine tools have been developed and commercially used.

The factories of the heavy machine-building industry produce heavy plano-boring and plano-milling programme-controlled machine tools (the longitudinal travel is equal to 25 metres).

Programme control changes the aspect of metal-cutting machine tools. Machines with entirely new kinematic schemes have appeared, for instance, four- and five-co-ordinate millers, four-co-ordinate turret lathes, drilling machines with turret heads and combined machines with automatic tool change.

At the current time, the whole complex of programme-control equipment for machine tools has been developed. This complex includes the facilities for programme preparation, consisting of puncher, code converter and co-ordinatograph for control plotting of the given component configuration on paper. The programme preparation sets are available for both individual machine-building plants and interplant centres where programmes are prepared.

To ensure better saving of the programming time, a system of automatic programming with the use of high-speed electronic computers has been designed. In this case, the programming time is reduced from five to ten times, as compared with manual programming, which increases still further the efficiency of the use of programme control.

The computing centre established at ENIMS fulfils orders for compiling and writing programmes for plants. The establishment of such centres has been also planned for other cities.

Programme control makes it possible to solve many problems of production organization in a new way. For instance, it is possible to write a programme while a new component is still in the process of design and to pass it over to the manufacturer together with the component drawings. If the production of a new machine is carried out by several manufacturers, the design office provides them simultaneously with an identical programme.

In this case, the numerical programme is written by the leading enterprise in manufacturing a pilot machine and is given, together with technical documentation, to the plants for series production of the machine. Thus, the commercial production time of new types of machines is considerably reduced. This yields a great economic benefit.

The Institute has developed standard methods for manual and automatic programming of two co-ordinate processing.

In the case of manual programming, the design data are recorded in tables and the tape is then punched. The punched tape is fed into the interpolator, which yields the programme in the form of an impulse sequence. This programme is recorded on magnetic tape. In those cases when the interpolator is installed at the machine tool, there is no need to have an intermediate programme carrier.

For control of a programme, it is plotted on the co-ordinatograph. Essential facilitation of programming is provided by a circular interpolator.

In programming with the aid of an electronic computer, the programme is obtained at the output in the form of a punch card.

The punch card can either be used directly for machine tool control, if the built-in interpolator is available, or can be used for recording on magnetic tapes. The use of magnetic tape is reasonable in small-batch and series production if a comparatively small number of different programmes is required during the year.

The enterprises using programme-controlled machine tools should be equipped with complete facilities for writing programmes.

In commercial use of numerically controlled machine tools, one should be aware of the fact that:

(*a*) Numerical-control equipment, while providing an essential extension of technological potentialities, is, at the same time, a principally new type of equipment which differs from the existing one by the quantitative and qualitative complication of the electrical equipment and the necessity of special preparation of programmes, which requires special skill of personnel and the application of complex equipment;

(*b*) The application of such equipment is inefficient without very careful technological preparation to determine the nomenclature of the components, loading of equipment and examination and correction of the technological process with regard to new possibilities and requirements;

(*c*) The application of programme-controlled equipment is inefficient without making special arrangements for repairs and maintenance, for establishment of special programming services and for training of maintenance personnel. Only the thorough realization of all the organizational and technological measures in a full complex can provide for efficient operation of numerically controlled equipment;

(*d*) The greater effect yields a group use of programme-controlled machine tools;

(*e*) Even in the use of a general-purpose electronic computer, the programming should be carried out with the participation of a skilled plant technologist.

For provision of the most rapid commercial use of numerically controlled machine tools and to obtain the economic benefits, it is necessary to make the arrangements discussed below.

It is most economical to concentrate programme-controlled machine tools in groups of not less than five or six. It is necessary to group the plants with similar technological processes and to begin commercial use of programme-controlled equipment with most advanced works, arranging it in an item-classed or specialized section. Such a section should include, as a rule, some units of programme-controlled equipment; the organizational and technological principles of programme-controlled machine operation should be checked, and some recommendations as to equipping other enterprises with programme-control facilities should be worked out.

Secondly, taking into account the novelty and complexity of programme-controlled equipment, as well as the difficulties involved in programme preparation, it is expedient that machine-manufacturing plants should provide users, at least during the initial stage of using the machines, with assistance in repairing and adjusting the programme-controlled equipment, in training personnel and in writing programmes for the processing of complicated parts with the use of computers.

B. *Cyclic programme-controlled machine tools*

The systems of programme control of cycles and régimes of machining differ from numerically controlled systems mainly by the absence of numerical programming of sizes and, consequently, displacement or position transmitters, as well as electronic or complex relay circuits ensuring the obtaining of desired sizes.

In cyclic systems, the sizes are controlled, in most cases, by track switches of either conventional or special (small-size) types, which are effected by transposed stops. Such an arrangement of cyclic systems provides, on the one hand, for their essential simplification, as compared with numerical systems, and, on the other hand, defines the field of their use, mainly in batch production.

It is true that such machine tools only permit the machining of components with contours which are parallel to the axes of tool co-ordinates, but the operation of such machine tools is extremely simple and their cost is only a little higher than that of universal machines.

Such machine tools (of practically all groups) are manufactured in great quantities by the machine tool industry. As the number of operations which can be programmed increases, the field of use of these machines will be extended.

The prevailing commercial use of cyclic-control systems is dictated not only by their lower cost, simpler arrangements for commercial production and easier manufacturing and adjustment, but also by the absence of the necessity for programming services and by lower maintenance cost.

One should take into account, however, that the economic efficiency of commercial use of these machine tools and the level of production automation is considerably lower than that of machine tools with a numerical system of programme control.

C. *Development of numerically controlled machine tools*

The advance of programmed control of machine tools tends towards the development of a self-adjusting system. In a self-adjusting system, the feed is set up according to the condition of maximum machining accuracy, productivity or tool endurance.

Here, the programming and computation of machining technological parameters are considerably simplified, and the scattering of machining parameters (differences in the hardness of metals, allowance of blanks, blunting of tools etc.) is compensated.

These systems are particularly important for work-pieces of hard-to-machine materials. Many types of machine tools are equipped with self-adjusting combined systems. The operation of such machine tools has shown that the insignificant complication of the control system for providing feed self-adjustment is fully justified.

Together with control-system improvement, the introduction of automatic tool-change for increasing the efficiency of programme-controlled machine tools is rather essential.

D. *Technical and economical indexes of operation of numerically controlled machine tools*

On the basis of published sources and the analysis of the operation of numerically controlled machine tools (domestic and foreign), the following average indexes of their operation can be outlined:

(*a*) Productivity increases by two to six times;

(*b*) Pay-off: up to two years, 20 per cent; up to three years, 67 per cent; up to five years, 13 per cent;

(*c*) Technical and economical efficiency in the use of numerically controlled machine tools (according to published data on experience in the United States of America), is as follows:

(i) Labour cost decreases by 70 per cent;
(ii) Tool cost decreases by 67 per cent;
(iii) Productivity increases by 51 per cent;
(iv) Improvement of product quality increases by 42 per cent;
(v) Improvement of utilization of means of production increases by 26 per cent;
(vi) Other expenditures decrease by 31 per cent.

Of all the currently existing technical solutions of automation of mechanical processing in small-batch and series production, the use of programme-controlled machine tools is considered to be the most efficient from the economic point of view. Apparently they will have good perspectives in the future.

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