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# Development of Metalworking Industries in Developing Countries

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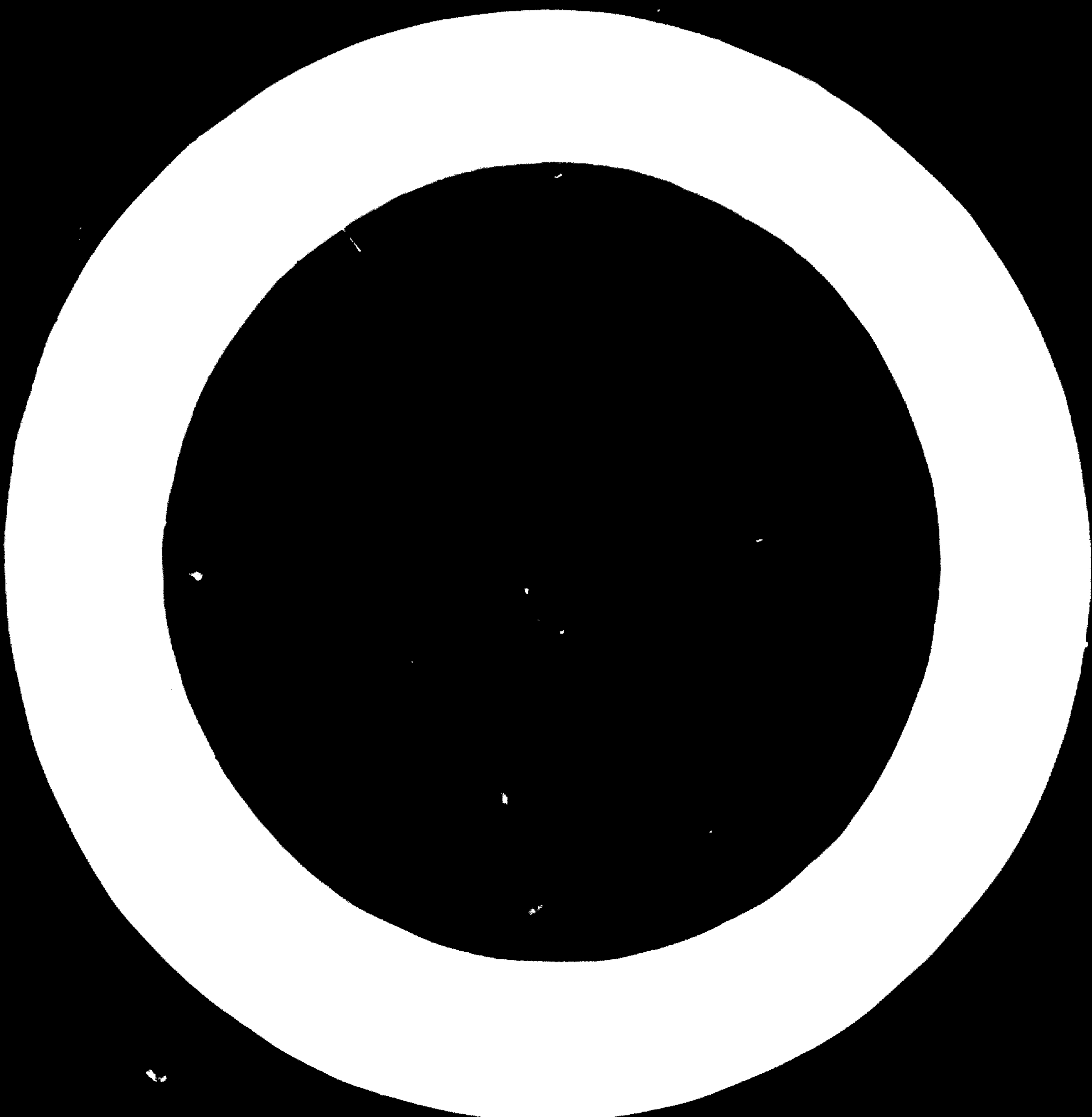

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# NEW METHODS FOR NON-MECHANICAL MACHINING OF MATERIALS: ELECTROPHYSICAL AND ELECTROCHEMICAL METHODS

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## I. CLASSIFICATION OF MACHINING METHODS

The laws governing any kind of development, combined with increasingly exacting requirements on the part of customers with regard to metalworking practices, lead to general engineering progress, in particular, to machine-building advances. These advances not only stipulate further improvement of the conventional methods used for metal shaping, such as pressworking, cutting and casting, but also result in new machining processes, methods and techniques. The latter usually bring about a pronounced increase in certain performance data.

Some of the new methods are of an unusual nature and make use of new energy agents; they are not infrequently based on rather uncommon practices. These factors tend to make them a self-contained group, as opposed to other machining methods. Their thorough study, however, reveals the elements which are common to all methods used in dimensional machining. Both common and individual properties can best be found by studying the classification characteristics of the methods and processes used in dimensional machining of materials. Table I illustrates many possible machining methods and presents the results of each clearly, thus permitting study of the existing methods and selection of suitable characteristics for new processes of dimensional machining. The table also gives some indication of the lines to be followed in investigations.

The characteristics of group 0 are those of the type of energy (and the energy agent required) which is directly fed to the workpiece, i.e., thermal energy in casting processes, mechanical energy in metal cutting and pressworking, electrical energy in electro-erosion or electrochemical machining.

Group 1 refers to the energy and energy agent at the border between the medium and the workpiece. Thus, in electro-erosion machining, the energy agent changes: both electrons and ions, rather than electrons alone, perform a motion which breaks the current and, in this particular case, a formation of plasma at its border.

Group 2 refers to the main energy and energy agent, that is, those doing the physical work of forming. In case of electro-erosion machining, it is thermal energy, which is transformed at the border in the workpiece itself.

Group 3 refers to how the energy is fed to the workpiece with respect to time: continuous feed throughout the process, feed in portions or impulses, or pulsating feed, in which case the amount of energy being fed does not go as low as 0, as happens when energy is fed in the form of separate impulses.

Group 4 refers to the main physical process aimed at obtaining the specified change in the shape of a solid body or at reproducing such a shape from melt or solution by solving to size ("chemical milling"), by using the laws of particle motion (in particular, those of electron-ion processes – electroforming in electrical field), plastics deformation (metal cutting and pressworking), vaporizing to size or melting (electro-erosion processes), tearing off particles to size (ultrasonic machining) etc. The characteristics of this group are closely related to the first three "energy" groups. The characteristics of group 5 refer to an extremely broad principle of shaping. The groups that follow refer to the machining medium, its pressure and the kinematic characteristics of the shaping process. These characteristics are supplementary and, to some extent, are factors of those listed in the first five groups.

The data found in table 1 can be diagrammatically summarized on a punch card, as shown below in table 2.

Each point of intersection of the columns and rows in table 2 corresponds to one of the characteristics found in table 1. For example, the index "4(2)" – the group index is put first and the index inside the group follows in brackets – indicates group 4, characteristic 2, i.e., brittle destruction. Should a few characteristics inside the group be identified, they are to be put in brackets in order corresponding to the characteristics. An analysis of the different types of machining is greatly facilitated by digit indexes, such as those shown in table 2.

With the aid of the data given in table 1, the basic characteristics of the electrophysical and electrochemical methods used in size-shaping may be considered. These methods are referred to as EPECh methods.

EPECh methods imply a combination of electrical, electromagnetic, magnetic, electrochemical, chemical and nuclear processes and methods in which a solid body is subjected to direct, simultaneous and successive thermal, mechanical or chemical effect, or to a combination thereof, to obtain the specified shape and size of workpiece.

The first part of the foregoing definition refers to the main types of applied energy (see table 1, group 0) and the latter to the transformed energy (group 2), which is used directly for shaping purposes. The main types of energy do not include mechanical or thermal sources: those are the main types when machining metal by cutting or pressworking, or in the foundry processes.

*Table I*—CLASSIFICATION OF CHARACTERISTICS OF METHODS AND PROCESSES USED IN DIMENSIONAL MACHINING

| Group of characteristics: Description of group | Group No. | Characteristics inside group: Characteristic No. | Description of characteristic |
|---|---|---|---|
| 1 | 2 | 3 | 4 |
| Energy and energy agents Directly fed to workpiece | 0 | 0 | Thermal energy (oscillations of molecules) |
| | | 1 | Mechanical energy (motion of body or change in its shape) |
| | | 2 | Electrical energy (motion of electronsl |
| At border between workpiece and medium | 1 | 3 | Electrical energy (motion of ions) |
| Means used to remove material or to obtain required shape and size | 2 | 4 | Electrical energy (motion of charged particles in electrostatic field) |
| | | 5 | Magnetic energy (motion of magnetized particles in magnetic field) |
| | | 6 | Electromagnetic energy (motion of electromagnetic waves) |
| | | 7 | Electromagnetic energy (motion of photons) |
| | | 8 | Chemical energy (motion of ions) |
| | | 9 | Energy emanated by nuclear interaction |
| Time distribution of energy | 3 | 0 | Continuously fed energy |
| | | 1 | Pulsating energy |
| | | 2 | Time-spaced impulses of energy |
| Main physical process which does the work of size-shaping (removal of material to size, sized deformation, connexion of particles to size) | 4 | 0 | Melting (solidification) |
| | | 1 | Vaporizing (condensation) |
| | | 2 | Plastic deformation |
| | | 3 | Brittle destruction |
| | | 4 | Chemical dissolving |
| | | 5 | Electrolysis |
| | | 6 | Crystallization from melt or solution |
| | | 7 | Directed interaction of electrified and/or magnetized particles |
| | | 8 | Interaction of disperseu particles and binding material |
| | | 9 | Nuclear changes in matter |
| Type of shaping | 5 | 0 | Due to removal of allowance |
| | | 1 | Due to change in distance between points of solid body |
| | | 2 | Due to change in aggregation state of solid body |
| | | 3 | Due to directed connexion of particles of solid body |
| Type of machining medium | 6 | 0 | Vacuum |
| | | 1 | Inert gases |
| | | 2 | Chemically active gases |
| | | 3 | Plasma |
| | | 4 | Air |
| | | 5 | Commercial water |
| | | 6 | Solution of salts, alkalis and acids |
| | | 7 | Dielectric liquids |
| | | 8 | Suspensions |
| | | 9 | Emulsions |
| Pressure developed in machining medium | 7 | 0 | Negative pressure |
| | | 1 | Normal pressure |
| | | 2 | Higher pressure |
| | | 3 | Very high pressure |
| Direction of shaping processes | 8 | 0 | Tangentially to surface being machined |
| | | 1 | Normally to surface being machined |
| | | 2 | At an angle to normal in all directions |
| Shaping process as related to travel of workpiece | 9 | 0 | Forward travel along X axis |
| | | 1 | Forward motion along X and Y axes |
| | | 2 | Forward motion along X, Y axes |
| | | 3 | Rotation round X axis |
| | | 4 | Rotation round X and Y axes |
| | | 5 | Rotation round X, Y and Z axes |

At the same time, these types of energy reveal themselves after they are transformed in the workpiece and in some cases they may prove basic (for example, thermal energy in electro-erosion methods, mechanical energy in press-working when using magnetic impulses).

The basic types of transformed energy, in turn, do not include electrical or electromagnetic energy. The reason for this is as follows: the physical processes used for dimensional machining and shown in group 4 (table 1) pertain to the nature of solid body but are not connected with these types of energy, though they may be initiated by them.

In fact, when dealing at the atomic or molecular level, one can state that the major processes are thermal and chemical, while for macrosystems the mechanical processes predominate. For this reason, in the long run, all e.g., electric charges, focused light, and electron and ion beams, provide grounds for certain EPECh methods being referred to as industrial electronics, particularly as "electronic technology".

In a manner similar to that of mechanical machining, EPECh methods can be classified into broad classes. The first class, covered by index 5(0), presents the methods wherein shaping is achieved owing to removal of allowances (chips); the second class, covered by index 5(1), can be compared to pressworking performed without removal of chips. A new method is about to be introduced: the one wherein the prescribed shaping will be exercised by applying directed motion of dispersed charged or magnetized particles, which are afterwards coupled to one another. Additional methods are also in the offing.

*Table 2*

PROCESS CHARACTERISTICS AS SUMMARIZED ON PUNCH CARDS

| *Machining methods* | *Groups* | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | *0* | *1* | *2* | *3* | *4* | *5* | *6* | *7* | *8* | *9* |
| Metal cutting (turning) | 1 | 1 | 1 | 0 | 2 | 0 | 49 | 1 | 0 | 03 |
| Pressworking (hot stamping) | 10 | 1 | 1 | 2 | 2 | 1 | 4 | 1 | 1 | 0 |
| Electro-spark machining | 2 | 2 | 0 | 2 | 1 | 0 | 7 | 1 | 1 | 013 |
| Electro-impulse machining | 2 | 3 | 0 | 21 | 0 | 0 | 7 | 1 | 1 | 013 |
| Anodo-mechanical machining | 2 | 38 | 08 | 20 | 05 | 0 | 6 | 1 | 0 | 31 |
| Electro-contact machining | 2 | 3 | 0 | 2 | 0 | 0 | 45 | 1 | 0 | 31 |
| Ultrasonic machining | 1 | 1 | 1 | 2 | 3 | 0 | 86 | 12 | 1 | 013 |
| Electrochemical machining | 2 | 8 | 8 | 0 | 5 | 0 | 6 | 2 | 1 | 013 |

*Source:* Data given in table 1.

the methods and processes used for dimensional machining are based on thermal, mechanical or chemical energy (if one disregards that chemical connexions are based on electrical phenomena). These considerations seem to be also valid with respect to employment of nuclear energy, although no concrete methods of dimensional machining involving this type of energy have been developed as yet. In general, a desired change in physical and mechanical properties, or in the aggregate state of workpiece allowance layer, can be brought about by means of neutron bombardment. Should this method be used, however, the shaping will again be based on the employment of the same three basic types of energy, the difference being that the workpiece material will undergo some changes, with a resultant drop in consumption of these types of energy.

EPECh methods are a part of processes embraced by a broader class, that of electrotechnics, or electrical technology, which deals not only with dimensional machining but also with electric welding, high-frequency electric heating and melting, electrometallurgy, electrolysis and many others. Another area of electrotechnics is an extensive class of electron-ion processes, which, among other things, permit certain shaping operations by using charged dispersed particles, which are made to move in strong electrical fields in the desired directions (group 4, characteristic 7-4 (7)).

Some of the physical processes used in EPECh methods,

## II. DESCRIPTION OF NEW MACHINING METHODS

Brief descriptions of some of the new machining methods which have already found industrial application are given below. The discussion is concentrated on the first class, i.e. those methods described by the characteristic index 5(0)—shaping by chip removal. The part they play in modern manufacturing processes can be made clear by three major factors corresponding to the trends of development of machine building, instrument manufacturing and machining of materials.

The first factor is the need to increase the speeds, loads and working temperature of critical machine parts, as well as from the need to increase their reliability and service life; the widening of the assortment of materials with special properties is also important. These requirements can be met with by a wider application of fire-resistant, magnetic, stainless, cavitation-proof and other high-alloy steels, sintered carbides, semi-conductors (germanium and silicon), diamonds, rubine, quartz, ferrites and other materials whose machining is difficult or impossible by conventional methods.

The second factor is that pressworking and casting are occupying an ever-increasing part among machining methods; it is of special importance also that plastics are gaining wider popularity and that plastic items are mainly made by pressing. All this calls for more and more dies, casting moulds, press tools and other similar articles of intricate shape which are difficult to manufacture and which require highly skilled manual work.

The third factor is that connected with the need for holes, slots and shaped slits of extremely small sizes, as well as for various ducts in spots which are hard to reach. Other similar operations are also beyond the scope of mechanical methods, e.g., when the gearing diagrams of the cutting tools and machines prove unsuitable for the purpose, or a workpiece of low rigidity and strength cannot stand the required cutting rates, or the tools of the desired size and shape are impossible to make.

When any of the above-mentioned conditions, or a combination of them, come into play, EPECh methods provide an adequate alternative for dimensional machining purposes.

The following specific features are common to all of the EPECh methods:

(*a*) They can be applied irrespective of how hard or ductile the material is (this does not refer to ultrasonic methods, for which the harder and more brittle the material, the better the workability, while materials of higher ductility are more difficult to handle);

(*b*) The shape of the tool can be reproduced (copied) over the entire surface of the workpiece by using a simple reciprocation of the tool (in mechanical methods, the three-dimensional shape can be obtained only by successfully following along the surface according to the line method). High power can thus be applied in the working zone, with higher efficiency being obtained when making articles with shaped cavities. Simple kinematics used in such shaping processes permit operations which cannot be performed by mechanical machining;

(*c*) The workpiece receives practically no force loads;

(*d*) The machining process can be easily automated and one operator can attend a few machines at a time.

According to the adopted classification, EPECh methods — both those currently used in engineering and those still under development — can be classified into four groups (see fig. 1).

### A. *Electro-erosion methods*

The first group includes the electro-erosion methods used in machining conducting materials, i.e. metals and alloys. These methods are based on the utilization of heat converted from the energy of electrical charges generated between the tool and the workpiece. Depending upon the type of electrical charge (spark or arc), the parameters of the current impulses, voltage and other conditions, electro-erosion machining includes four basic forms: spark-over-initiated discharge (electro-spark); electro-impulse; contact-initiated discharge machining (electro-arc); and anodo-mechanical. Each form uses a certain range of application. The electro-erosion method and all its varieties were suggested in the 1940's and early 1950's in the Union of Soviet Socialist Republics, which undertook extensive research, designing and technological work to provide a basis for the method. At the current time, there are a few score of companies, producing both special and general equipment, which manufacture

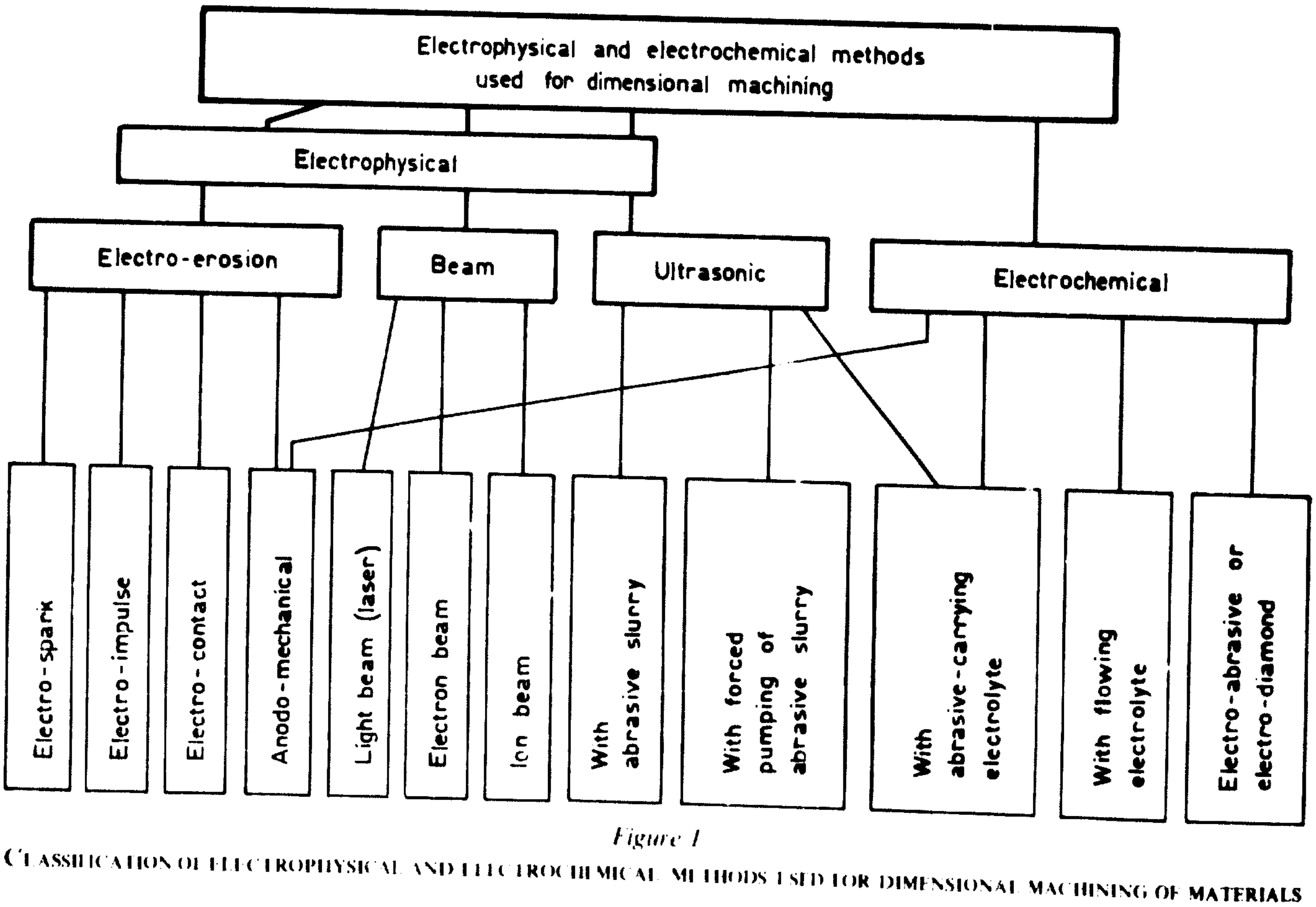



*Figure 1*

CLASSIFICATION OF ELECTROPHYSICAL AND ELECTROCHEMICAL METHODS USED FOR DIMENSIONAL MACHINING OF MATERIALS electro-erosion machines along with conventional metal-cutting machine tools; electro-erosion machines are made in the USSR as well as in many other countries, for example, Belgium, Czechoslovakia, Eastern Germany, Federal Republic of Germany, France, Japan, Poland, Switzerland, the United Kingdom of Great Britain and Northern Ireland, and the United States of America.

Electro-erosion is the most popular electrophysical machining method used in industry, and electro-erosion machines comprise 80 per cent of the machine tools used for electrical machining.

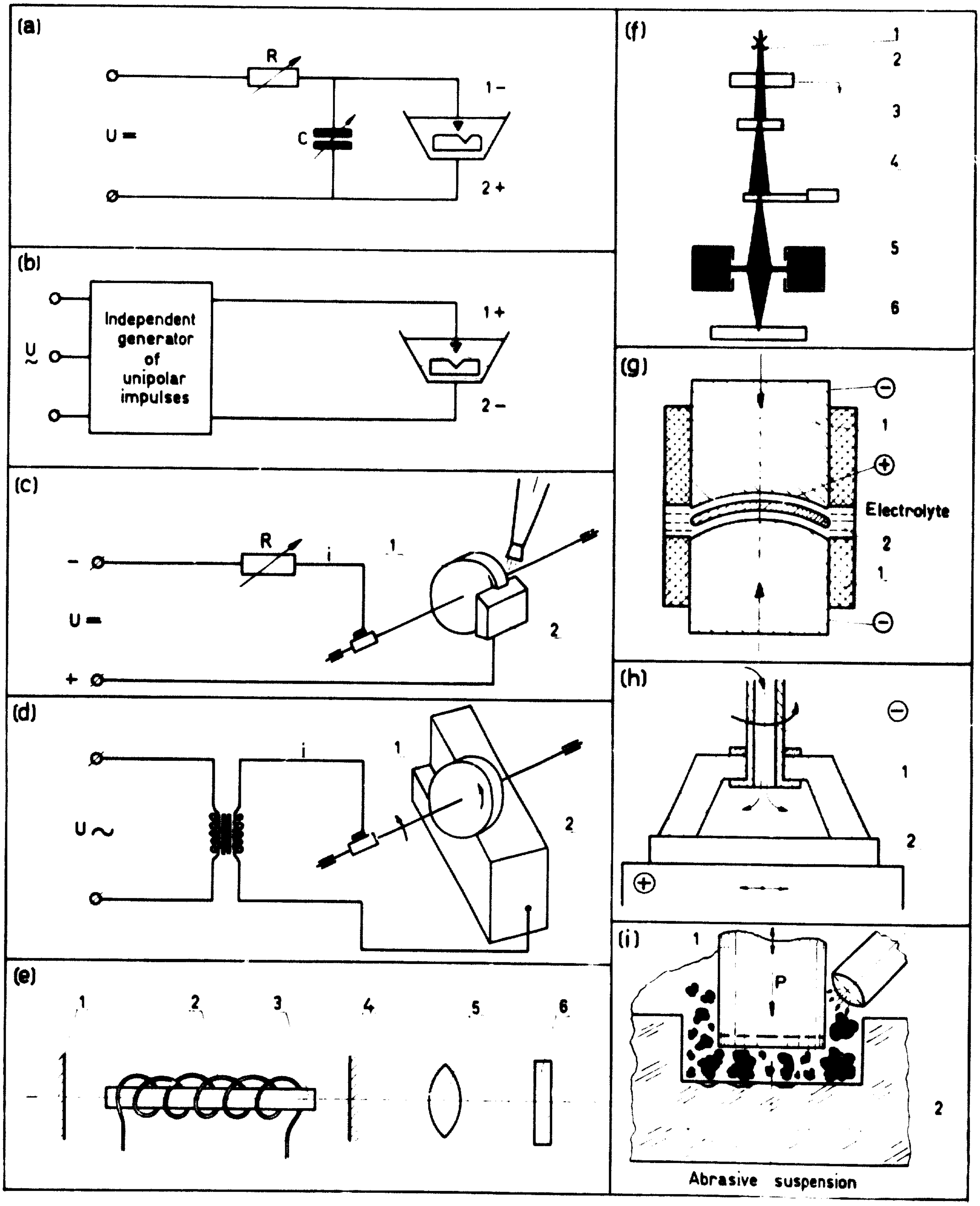
As stated above, electro-erosion is mainly based on the thermal effect produced by electric-current impulses which are continuously fed directly to the spots of the workpiece to be machined, with an aim of imparting to the latter the specified shape and size, while retaining the structure and quality of the workpiece surface. The primary factor in this process is the electrical impulses (electrical charges), which are converted, in the working zone, into the thermal charges which do the actual work of metal removal.

As the process is of an impulse nature, a generator of even moderately average power can provide instantaneous electrical charges of sufficient strength to loosen the ties between the particles of solid body, to sever them from the workpiece and to withdraw them from the working zone. Since, other conditions being equal, the electrical impulses generate in succession, governed by a change in the minimum distance between the interacting surfaces of electrodes (selectivity condition), the workpiece electrode reproduces the shape of the tool electrode. The ratio of necessary removal of metal from one electrode and of unnecessary removal of metal from the other, the way the removed metal is disposed, the specific consumption of energy and the technological output depend upon the thermophysical parameters of the process: heat conductivity; temperature and heat of melting and evaporating; specific gravity and electrical resistance of electrode materials; kind of environment in which the electrode is placed and its physicomechanical properties; duration, amplitude, efficiency and frequency of impulses; clearance between the tool and workpiece electrodes, the conditions of evacuating erosion products; and some other factors. The erosion stability or workability is characterized by the equation $\Pi = C\lambda\gamma T n^2$, where $\Pi$ is the Palatnik criterion proportional to the time required for melting a certain volume of metal, C is heat capacity, $\gamma$ is specific gravity, $\lambda$ is the factor of thermal conductivity and $Tn$ is the reduced temperature of melting. It follows that the mechanical properties of electrode materials, i.e., their hardness and ductility, influence the metal removal rate not directly but *via* the changed thermophysical properties.

Designing of the technological processes of electro-erosion machining is based upon the following principles.

The first is to bring the properties of impulse energy into the best possible coincidence with the thermophysical properties of the metal from which the article is made. This will govern the efficiency, specific consumption of energy, extension of the zone where structural changes take place, surface finish and other technological factors. To achieve this correlation, provision is made for the adjustment, within a specified range, of the frequency, duration, amplitude or efficiency of impulses, these being adjusted individually or as a combination thereof. Duration of impulses can be varied within a range of $10^{-7}$ to $10^{-2}$ per second, and frequencies, within a range of $0.5 \cdot 10^2$ to $2 \cdot 10^6$ cycles. The amplitudes of voltage impulses vary from dozens of volts to a few hundred volts; the efficiency can be changed in the range of one to a few dozens. The extreme limits within which the power can be varied lie in the range of dozens of watts to hundreds of kilowatts. Impulses of short duration ($10^{-7}$–$10^{-4}$) are preferable in finishing operations and for work on alloys which are liable to crack (those composed of metal and ceramics); impulses of $10^{-4}$ and $10^{-1}$ seconds duration and longer ($10^{-3}$–$10^{-2}$) are employed in machining where the surface finish is of minor importance, the articles being made mainly from steels and their alloys.

Secondly, the electrical régime must be matched and shaped, while the material of the article is predetermined, i.e., there must be a determination of the optimum electrical and technological machining duties. In the systems involving electrical power units, the rate of metal removal is essentially dependent upon the area and shape of article, notwithstanding that the metal is removed at each particular moment by a single impulse that acts upon a certain section of the article. A single impulse causes the melting of a partial volume of electrode metal and a formation of vapours and gases in the zone where the metal particles discharge. These vapours and gases are to be transported from the working zone. One may suggest that the higher the energy of an impulse or its amount of current passing through the gap, the greater the amount of the erosion products which form in the active zone of the impulse. To withdraw such products through the gap will take some time. If the area to be machined is small, whereas the impulse energy (or current) is incommensurably great, then an impulse may form not only in the liquid, but also where a gas bubble appears. In such a case, no metal will be removed; instead, the welding of electrodes to the workpiece or their fusion may take place. With a drop in area, the chances of such a departure from the specified process become much lower, since in the extreme case of a very small area, a gas bubble may fill the entire gap between the electrodes. On the other hand, when the area is too great, the energy of impulses proves insufficient to withdraw the products of erosion through a very long (dozens of centimetres) and small (tenths of fractions of millimetres) gap; the products of erosion will accumulate, the repetitive charges will go through previously dispersed particles and the rate of metal removal will drop. Now, repetitive charges will cause extra shock-waves, which are stronger than those produced by the primary charges and which spread in liquid filling a narrow gap. Such waves are of high energy and move the erosion products very rapidly (up to 1.5 km per second) taking them away from the working zone, i.e., from the gap. Stronger evacuation vortices will lead to additional cleaning of the gap and, thus, to reduction of repetitive charges, i.e., to a certain rise in the rate of metal




a, b, c, d: electro-erosion machining, 1 tool, 2 work; e: light-beam machining, 1 and 4 mirrors, 2 pumping valve, 3 ruhine, 5 focusing optics, 6 work; f: electron-beam machining, 1 electron gun, 2 anode, 3 and 4 diaphragms, 5 focusing system, 6 work; g: electrochemical machining, 1 tool, 2 work, h: electrochemical electro-diamond machining; i: ultrasonic machining

*Figure 2*

GENERAL DIAGRAM SHOWING THE IMPLEMENTATION OF ELECTROPHYSICAL AND ELECTROCHEMICAL MACHINING METHODS removal in a new stabilized state. This means that under these particular working conditions (material and shape of electrodes, depth, frequency, working liquid etc.), the correlation of currents, areas and rate of removal will be the best. Such dependences are of a static character and make their appearance under the conditions of mass influence of the impulses upon the surface being machined, the impulses going under a certain frequency and efficiency. A spatial diagram of "current-area-efficiency" represents the basic dependence to be observed when deciding on electrotechnical duties, similar to the situation with mechanical machining. As the tool electrode goes deeper into the workpiece, a change takes place in the area projected on the plane perpendicular to the direction of feed, while the electrical machining duties are set to the optimum for each section; this is done either manually or by a system of programme-controlled adjustment. The rate of metal removal depends also upon the resistance encountered on the path along which the products of erosion are withdrawn, such resistance being a factor of machining depth, article shape, the mode in which fresh working liquid arrives at the machining zone and other conditions essential for quantity and intensity of the repetitive charge.

Finishing operations, which follow the roughing, are performed by using the régime which permits the specified finish to be obtained within the shortest time possible by a successive adjustment of the régime with respect to frequency (increase) or current (decrease). For this purpose, modern machine tools are fitted with power units rated for a number of frequencies, while permitting a simultaneous adjustment of an amplitude or efficiency of impulses.

With a current source of unlimited power, the time required for making a shaped cavity depends, approximately, upon its depth and is independent of the sizes on the two other co-ordinates. This makes the electro-erosion machining of shaped articles essentially different from that performed on the milling machines, where the machining time depends upon the stock of metal to be removed, i.e., upon the dimensions of the three co-ordinates. Consequently, electro-erosion machining is especially advantageous when machining intricately shaped and large-sized articles.

The general characteristics of electro-erosion machining have been analysed. Different types of this machining are characterized by a certain range of physical parameters employed for the process; they have their own applications and need specific equipment.

### 1. *Electro-spark machining*

Electro-spark machining is based on utilization of impulse spark discharges of short duration (from fractions of a microsecond to a few hundred microseconds) and energy which is fed under a high efficiency.

The tool electrode is switched on direct polarity (cathode). A power unit is a relaxation impulse generator or high-frequency generator (see fig. 2a). Power of the generator varies from hundreds of watts to a few kilowatts. The maximum rate of metal removal when working on steel is 600 mm$^3$ per minute, when working on sintered carbides (rough machining), 100 mm$^3$ per minute. The maximum surface finish produced on sintered carbides is class 7. When machining steel, a relative wear of tool comprises 25–100 per cent. The method is mainly used for precision machining of small parts in radio and electronic industries, fuel devices (small holes, polishing operations), cutting shaped contours of punching dies made from sintered carbides. Used as a tool is a wire electrode which is made to travel along two co-ordinates according to the programme or on a flat tracer (see figs. 3 and 4).

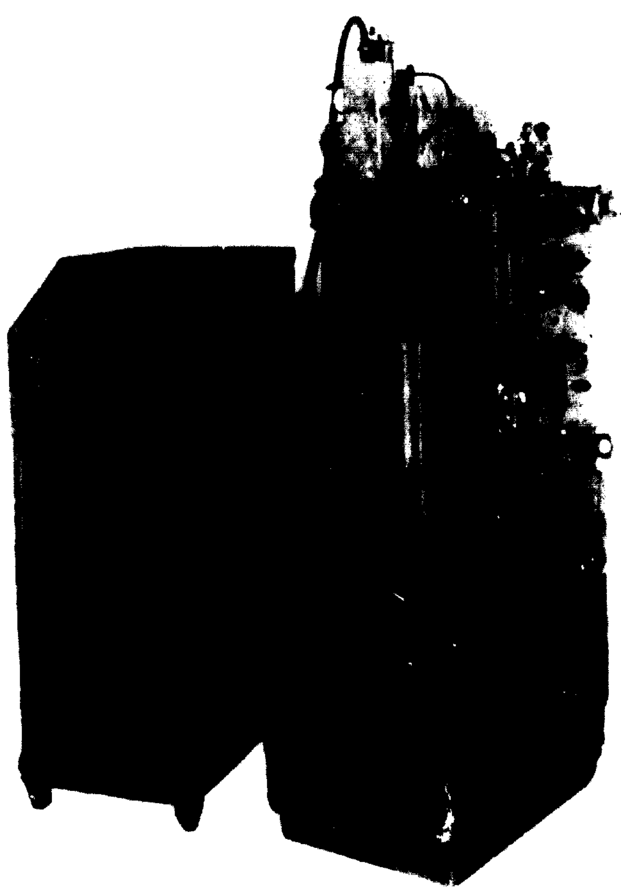


*Figure 3*

UNIVERSAL ELECTRO-SPARK COPYING BROACHING MACHINE, MODEL 4B721

### 2. *Electro-impulse machining*

Electro-impulse machining is based on the utilization of arc discharges of long duration (from hundreds of microseconds to 10,000 microseconds) and high energies (for rough machining) which have a small efficiency, as well as of high-frequency, low-energy impulses and small efficiency (for finish machining). The tool electrode is switched on for the reverse polarity.

The power is supplied by a power or magnetic-im-

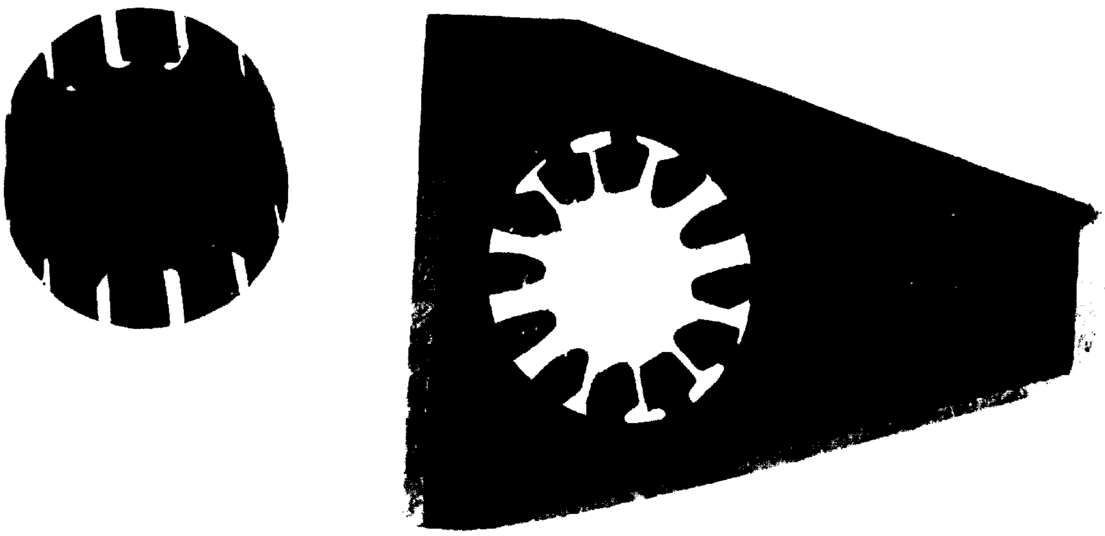


*Figure 4*

HARD-ALLOY DIE MADE ON CUTTING-OFF ELECTRO-SPARK MACHINE; CUT-OFF CORE AT LEFT

pregnated generator (for rough machining) or a high-frequency electro-transistor, or induction generator (for finish machining). The generator power ranges from a few kilowatts to a few dozen kilowatts. The maximum rate of metal removal which was actually obtained in working on steel was 25,000 mm³ per minute, on sintered carbide (using electronic transistor of high-frequency induction generators), 70–120 mm³ per minute. The maximum surface finish of steel articles was class 5 or class 6, that of sintered carbide articles was class 5 or class 7. A relative wear of tools when working on steel is 0.3 per cent. The method is mainly used for three-co-ordinate machining of shaped cavities of steel forging dies (the maximum size of a cube is 1,000 × 1,600 mm), press tools, casting moulds, turbine blades and wheels, impressions for rollers of profiled shape, connexion ducts in hydraulic apparatus and the like (see figs. 5 and 6).

Recently, the Experimental and Research Institute of Metal-cutting Machines (ENIMS) has worked out a method for vortex copying which allows an automation and dozen fold acceleration in manufacturing shaped carbon-graphitized electrodes for three-co-ordinate electro-spark machining (see fig. 7).

### 3. *Anodo-mechanical machining*

Anodo-mechanical machining is one of the types of electro-erosion machining based on utilizing a combined process of anodic solution and erosion effect upon the workpiece while the disc or strip tool electrode travels. The electrode is switched on for direct polarity (cathode) (see fig. 2b). The power source is direct current from the rectifier, voltage of 22–26 volts, and the power varies within the range of a few to a few dozen kilowatts. The machining medium is electrolyte, which is a solution of liquid glass.

The technical characteristics achieved by this method are as follows: cutting speed of up to 50 cm² of cut area per minute; surface finish, up to class 4 (in cutting operations) and up to class 7–8 (in grinding operations); the relative wear of tool is 15–25 per cent.

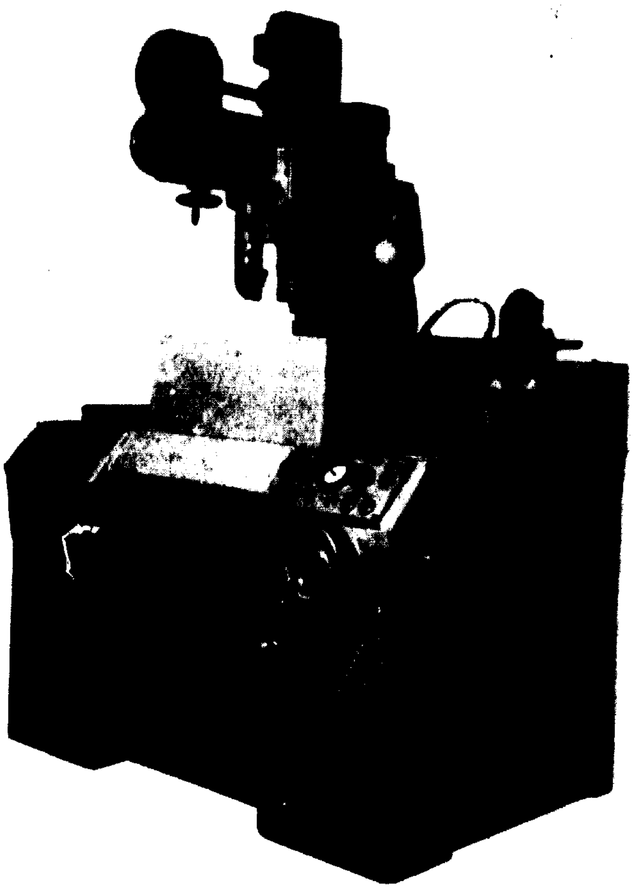
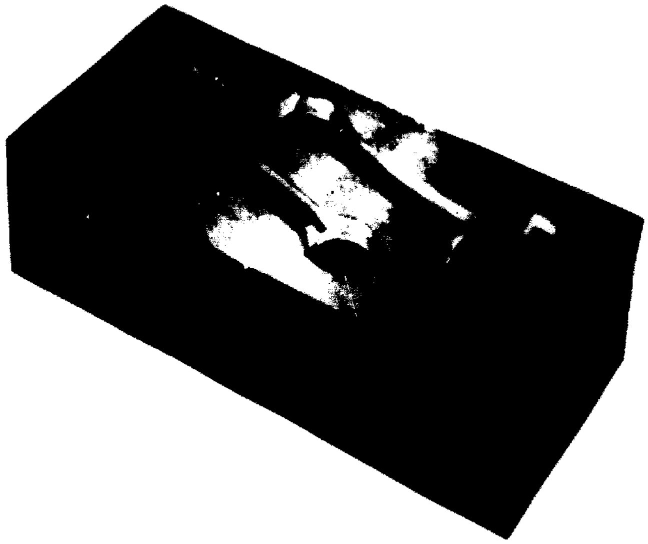


*Figure 5*

UNIVERSAL COPYING ELECTRO-IMPULSE MACHINE, MODEL 4723

(a) Stamped connecting rod



(b) Sector of press-tool protector

(c) Shaped casting for electric motor

(d) Gas turbine runner

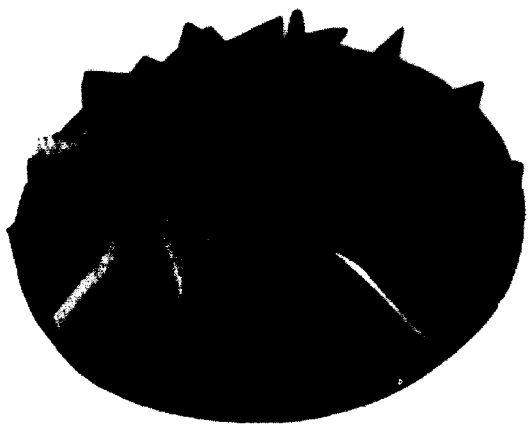


*Figure 6*

REPRESENTATIVE ARTICLES MADE BY ELECTRO-IMPULSE MACHINING

(a) (b) (c)

*Note:* The first electrode is made of graphitized material on the electro-impulse machine by fitting, in 6 hours; it is then used for machining the metal cutter (a), which is done in 3.5 hours. The cutter (a) serves for reproducing the replica (b) of the first electrode on the vortex machine in 15 minutes. The stamped valve (c) is machined on the electro-impulse machine in 3.5 hours instead of 8 hours when machining on the miller with subsequent fitting.

*Figure 7*

SUCCESSIVE STAGES IN MAKING TOOL ELECTRODE (VALVE) BY VORTEX METHOD

This method is preferred for severing blank pieces of special-grade steels which may be up to 750 mm in diameter (see fig. 3) and for the internal and external grinding of sintered carbide bushings and draw plates.

4. *Electro-contact machining*

Electro-contact machining (electric-arc process) is another branch of the electro-erosion method. It is performed in the air by using rotary discs. Formed between the disc and the workpiece is a powerful alternating-current arc (25,000 ampere up to 40 volts). A step-down transformer with power ranging from dozens to hundreds of kW (shown in fig. 2d) is used as a source of energy.

The maximum rate of metal removal achieved by electro-arc milling amounts to 0.5 ton of metal per hour. This method can be successfully used for roughing special-grade steel ingots before rolling them, machining such shaped surfaces as those of hydro-turbine blades, slicing metal etc.

B. *Beam machining methods*

The second group of methods which is used for machining both conducting and non-conducting materials comprises beam machining methods, i.e., those based on the removal of metal by attacking it with concentrated beams of high-density energy. In a manner which is similar to electro-erosion machining, the metal removal is accomplished by converting this energy to heat directly within the zone of machining. The beam methods include machining by light, electronic or ion beams.

1. *Light-beam machining*

The coherent light beam, which is generated by a monochromatic optical quantum generator (laser), is

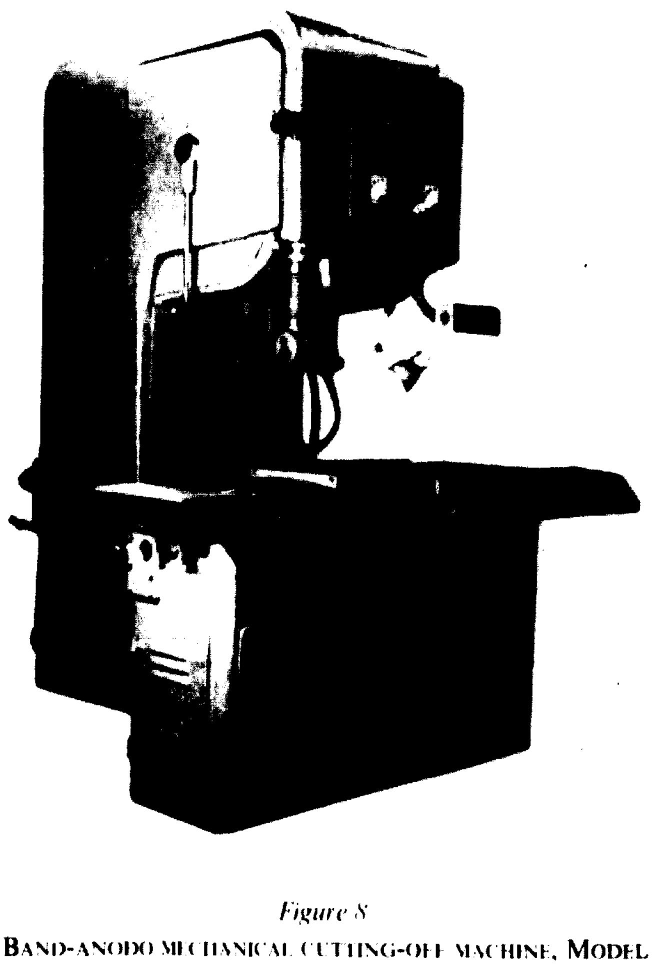


*Figure 8*

BAND-ANODO MECHANICAL CUTTING-OFF MACHINE, MODEL 4A822 directed through the optical system of the workpiece being machined (see fig. 2e). The beam is focused to have a diameter of a few microns, with a high temperature (1,000 degrees) arising in its working zone. The method is good for making small-diameter holes in any material to produce diamond draw plates, fine screens, draw plates for producing man-made fibres and for other similar purposes. The machining is carried out in the air. The efficiency of the method is from 30 to 60 holes (from 0.03 to 0.5 mm in diameter) per minute with depth ranging from a few tenth fractions up to a few whole millimetres with a power source of a few dozen kW.

2. *Electron-beam machining*

In electron-beam machining, the cathode-radiated electrons (in deep vacuum) are accelerated in a powerful electric field and are focused to become a narrow pencil-beam directed to the workpiece anode. During this process, the kinetic energy of electrons is converted to thermal energy, thus allowing the piercing of small holes and the making of slots which are a few dozen microns in size. The method is applicable for machining precision components employed in radio and electronic instruments etc.

3. *Ion-beam machining*

Ion-beam machining makes use of cathode spraying, which takes place as the gas is being discharged. The electrons initiated by the cathode ionize the gas molecules. The ions accelerated by a strong electric field are focused in a narrow place whose apex is on the workpiece. Such a method is possible to pierce holes which are 5 microns in diameter, and over, in thin sheets.

With regard to the kinematics of the forming process, the beam machining can be compared to machining by means of a thin liquid jet of extremely high pressure, which is also capable of piercing holes and cutting sheets.

### C. *Ultrasonic method*

The third group comprises a method of impulse percussion mechanical effect applied to material. This method is known as ultrasonic because the frequency of impacts produced corresponds to the range of inaudible sounds. The method is successfully used in machining hard and brittle materials whose particles can be removed by impacts. Strictly speaking, the ultrasonic method cannot be considered one of the EPECh methods; rather, it belongs to one of the kinds of mechanical machining wherein chips are removed as mechanical energy is brought to the workpiece, and it also does the work of removing metal. The type of energy agent — mechanical motion — governs the impulse process of a brittle departure. This method is referred to as one of the electrophysical methods only arbitrarily, the reason for such classification being that it is based on high-frequency mechanical oscillations which are electromagnetic in nature. The ultrasonic-frequency electrical oscillations (16,000–25,000 cycles) are converted in a special electromechanical magneto-strictive transducer consisting of a set of nickel or Permendur (iron-cobalt alloy) plates capable of changing their linear dimensions into mechanical in an alternating magnetic field. The tool-tip receives oscillations through a system of acoustic concentrators. The machining zone under the tool-tip is supplied with slurry of small abrasive grains suspended in water (see fig. 2i). The tool oscillating under the ultrasonic frequency strikes against the abrasive grains which take off the particles of material, thus reproducing the shape of the tool on the blank. The power source is represented by an electronic oscillator with power ranging from hundreds of watts to a few kilowatts (see fig. 9).

The method is useful for machining hard and brittle materials, including those which are non-conducting — e.g., ceramics, quartz, rubine, diamond, glass, porcelain, germanium and silicon — as well as sintered carbides.

The technological output characteristics of this method are as follows: the maximum rate of metal removal for work on glass is 9,000 $mm^3$ per minute; for work on sintered carbide, 200 $mm^3$ per minute, the maximum surface is up to class 10. Relative wear of the tool for work on sintered carbide is 40–60 per cent. The removal rate and surface finish under a particular rate are the highest, as compared with all the other methods.

The method is preferred in making punch and embossing dies of sintered carbides, cutting transducer discs of germanium and silicon, machining diamond and sintered carbide draw plates, rubine bearings etc. (see fig. 10).

### D. *Electrochemical methods*

The fourth group covers electrochemical methods used for dimensional machining. Such methods utilize an anodic solution, the essence of which is that when current passes through electrolyte the electrode, connected to the positive pole (anode), dissolves (see fig. 2g). During this process the blank metal is transformed in an ion state and is taken away from the machining zone by the flowing electrolyte. The material mainly used as electrolyte is an aqueous solution of sodium chloride pumped through a very small (0.10–0.5 mm) interelectrode gap. The process results in the tool shape being reproduced on the workpiece, as the workpiece sections nearer to the tool surface dissolve more rapidly. When an adjusted feed of an electrode is used, smooth surfaces which are accurate to 0.2–0.9 mm are reproduced. The method is especially advantageous when used for machining such surfaces as those of blades, since, in this case, the conditions for electrolyte flow are the best and there are no eddies.

The electrochemical process can also be used in conjunction with grinding by abrasives or diamond on the conducting bond (electro-abrasive or electro-diamond machining) depending upon the composition of the electrode rotary disc. With this method, the process of anodic solution facilitates the metal removal, thus raising the efficiency by one and one-half to two times while saving diamonds.

The electrochemical method currently is used in machining turbine-blade tips, piercing shaped holes, electrochemical grinding and sharpening, trimming gear-wheels and other machine components etc.

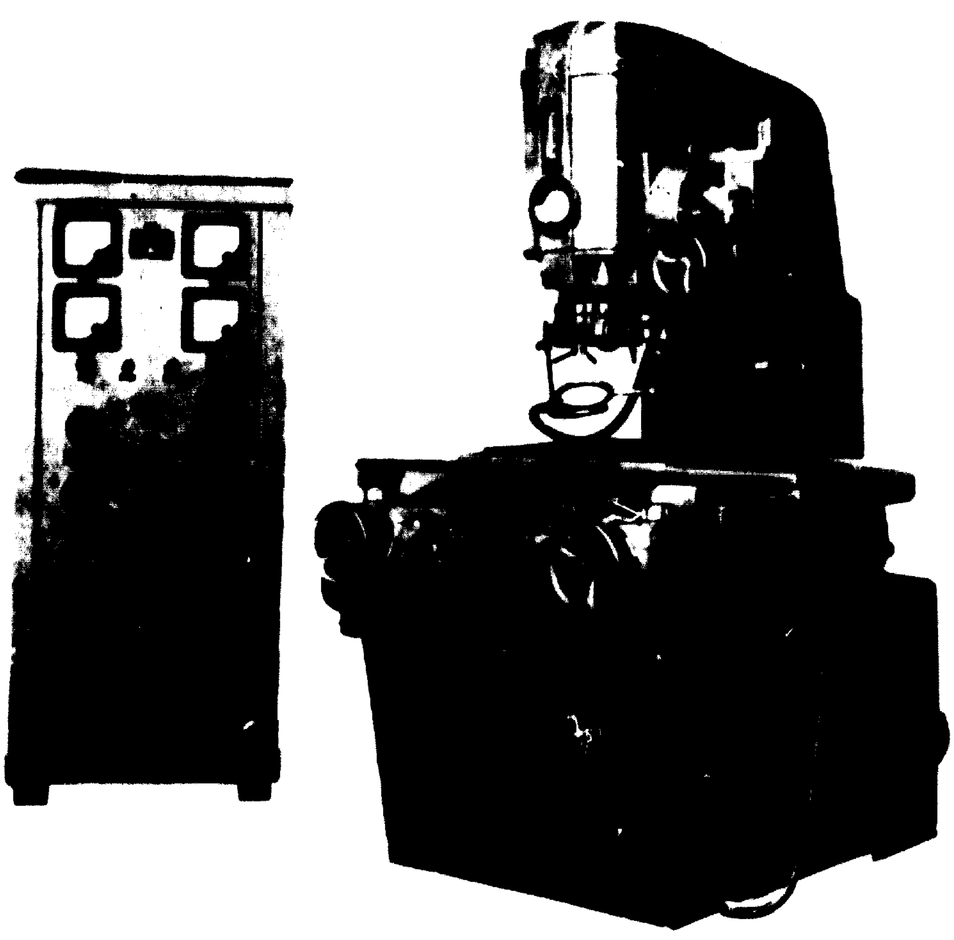


*Figure 9*

UNIVERSAL ULTRASONIC MACHINE, MODEL 4773A

The advantageous feature of the process is the high surface finish (class 7 or 8) obtained with good efficiency — a few hundred mm$^3$ per minute — while consuming as little energy as 15–25 kW per kg.

Related to this group are the chemical machining methods used without applying current and known as chemical milling, the metal being removed by dissolving it with the aid of strong acids or alkalis. The rate of metal removal for work on aluminium amounts to 0.5–1 square decimetre per minute.

The first three groups discussed above are physical machining methods; the fourth is an electrochemical method.

The methods of the first, third and fourth groups allow the machining to be performed on all the three co-ordinates, while those of the of the second group permit only two-co-ordinate machining.

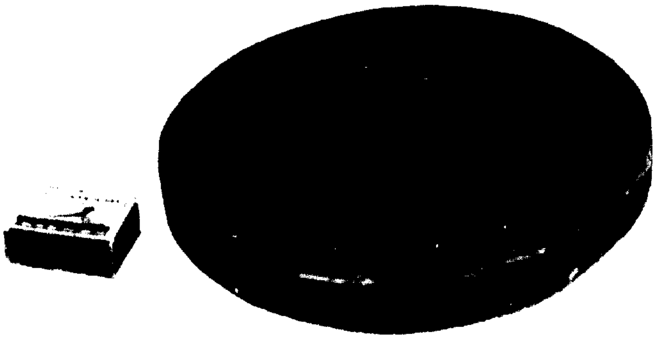
### III. APPLICATIONS OF ELECTROPHYSICAL AND ELECTROCHEMICAL METHODS

Electro-erosion methods have found the widest application (about four-fifths of all EPECh machine tools are those designed for electro-erosion operations, while one-fifth are used for other jobs). This ratio, however, does not predetermine the prospects and the actual comparative value of the methods discussed. This is especially true with respect to electrochemical machining, which has not been developed as it should be, the reason being that it is not yet sufficiently accurate. If one estimates the technological powers of each of the above-mentioned methods and takes into consideration the prospects for large-scale production of the equipment involved, one may assume that in the years to come the proportion of electrochemical machines will increase to 25 per cent, that of electro-erosion machines to about 55 per cent and that of ultrasonic machines to 15 per cent of the total number of electrophysical and electrochemical machines.

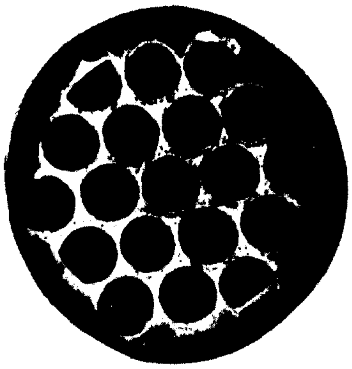
The foregoing ratio has been, of course, made up without including new machining methods and conceptions which are not yet known and which will, no doubt, permit the extension of the application range of the existing methods.

Compared with the over-all production of metal-cutting machines, the proportion of electrophysical and electrochemical machines is very small and varies from hundredths to tenths of 1 per cent from country to country. This branch of the machine-building industry is developing very rapidly, however, so that one may expect an increase in the above-mentioned figures by one or two orders.

Nevertheless, these facts do not really illustrate the role of machining methods in modern technology. One



(a) Hard-alloy die for drawing a relay casing



(b) Trepanning the silicon dies

(c) Hard-alloy die of a watch casing

*Figure 10*

REPRESENTATIVE ITEMS MACHINED BY AN ULTRASONIC METHOD

cannot disregard that new machining methods revolutionize a number of the industries, such as production of dies, press tools, turbine blades, sintered-carbide tipped tools, electronic instruments etc., which lay a foundation for the development of machine-building industry as a whole and open up new possibilities for designers, allowing them to construct reliable machines and apparatuses of long service life. The new methods often prove to be the only ones possible for tackling complicated technological tasks. One should also appreciate that the high efficiency provided by new methods in performing various operations will make it unnecessary to increase the number of machines when changing over to a new technological method. Thus, the proportion and significance gained by electrochemical and electrophysical methods will be greater than the proportion of the corresponding machines, as compared with all the rest of the machines.

The 1970's may witness a transfer of about 5–10 per cent of the technological operations used in machine building, instrument making and other branches to new machining methods.

An application of electrophysical and electrochemical machining methods will especially pay for itself when used in conjunction with mechanical machining at specialized enterprises.

To cite one example of high efficiency, one can mention a central specialized enterprise organized for making dies, press tools and casting moulds, based on utilizing electro-impulse, electro-arc, ultrasonic and electrochemical methods, in conjunction with the diamond-tool machining of carbide-tipped tools, the enterprise being equipped with all necessary metal-cutting machines.

To make steel frames of forging dies and moulds, the electro-impulse method is preferred; for making carbide-tipped tools, the ultrasonic, electro-arc and electro-diamond methods are good. Soviet designers are currently engaged in working out projects for typical specialized factories of different capacities which will make extensive use of electrophysical and electrochemical methods. Based on such factories, special enterprises will be set up in economic regions for manufacturing the required items for shaped technological jigs and fixtures.

The estimation made shows that, when organized in one of the industrial regions of the USSR, the centralized production of dies and moulds planned to meet 40–50 per cent of the demand of that particular region, i.e., 100,000 dies, moulds and similar items, will save 10 million roubles per annum, while a few thousand machines will be dispensed with, the floor space decreased and the fitting operations made easier.

Higher efficiency will be achieved, owing to reconstruction of die-mechanical shops at factories engaged in large-lot and mass-production (motor-cars and tractors), building and similar industries.

Seven electro-impulse machine tools operating at the Gorky motor-car factory permit the machining of more than 1,500 sets of dies a year. The same operations are performed at some other factories.

Another example of comprehensive utilization of new methods is that of setting up an automated production of turbine blades based on using electro-impulse, electrochemical and grinding machines. In this case, new methods are especially good since such production deals with intricately shaped articles to be made of hard-to-machine heat-resistant alloys.

Electro-impulse machining of runners for transport gas-turbine engines requires ten times less labour than milling; the period required for fitting and finishing operations is cut by two or three times. The EPECh machines pay their cost, as a rule, within brief periods, from six to eighteen or twenty-four months.

Table 3 shows the main industrial applications of EPECh methods and their comparative efficiency.

*Table 3*

SUGGESTIONS ON THE MAIN APPLICATIONS OF ELECTROPHYSICAL AND ELECTROCHEMICAL METHODS FOR DIMENSIONAL MACHINING

| *No.* 1 | *Description of operation* 2 | *Method suggested* 3 | *Advantages compared with mechanical machining* 4 |
|---|---|---|---|
| 1 | Making steel dies, casting moulds, press tools | EP | Saved labour and cost in repairing jobs by 1.5–5 times, in making new items by 1.5–3 times. Shorter machining cycle, less or no manual work, especially for finishing and lapping. Provision of basis for centralized production. |
| 2 | Machining intrically shaped parts made of heat-resistant alloys (runners and blades of gas turbines, shaped holes in wheels, etc.) | EP (ECh) | Labour cut by 2–5 times, automated production, floor space cut by 2–3 times, much saving in tools, application to all materials |
| 3 | Making blades, rotors and discs | EP | Operations cannot be done by mechanical machining. |
| 4 | Making connexion ducts and holes in hard-to-reach spots of hydraulic and pneumatic apparatuses and special components, piercing curvilinear holes | EP ES | Operations cannot be done by mechanical machining. |
| 5 | Making hard-alloy punch dies; non-shaped wire electrode can be used, among other means. | ES US EB (ES) | Operations cannot be done by mechanical machining. |
| 6 | Removal of broken tools and remedying defects in heat-treated parts | EP | Fewer rejected items |
| 7 | Making small-diameter holes (0.1–0.5 mm), including those for injectors | RS (LB) (EB) (IB) | Higher efficiency, less rejection, saving in expensive tools. Automation is possible. |
| 8 | Piercing many holes and slots in sheets of heat-resistant, magnetic and other alloys | EP ES (LB) (IB) (EA and D) | Labour cut by 3–10 times, tools saved, automation possible |
| 9 | Making hard-alloy draw plates | ES (US) (LB) (AM) (EP) (IB) (EA or D) | Labour cut, machining process automated |
| 10 | Making intricate shapes by rolling or copying methods (tracers, rolling shafts etc.) | EP | Labour and cost cut by 4–8 times, machining process automated, stronger shafts made |
| 11 | Engraving, stamping or branding | ES US (ECh) | Engraving relief on hard-surface automation possible |
| 12 | Metal strengthening and plating | ES (EP) | Higher wear-resistance of some parts |
| 13 | Cutting to a design and severing of semi-conductor plates and plates made of commercial stones, engraving lines | US | Efficiency increased 3–5 times, materials saved higher quality of machining |
| 14 | Making diamond draw plates | US (LB) (ES) | Efficiency increased 10–15 times |
| 15 | Cutting cut blanks of optical glass and their roughing | US | Efficiency increased 2–3 times |

*Table 3 continued*

| *No.* | *Description of operation* | *Method suggested* | *Advantages compared with mechanical machining* |
|---|---|---|---|
| *1* | *2* | *3* | *4* |
| 16 | Machining part of fuel installations, including the grinding of sprayer nose and other operations | ES | Efficiency increased 3-5 times, machining process automated |
| 17 | Trimming intricately shaped parts, such as gear-wheels, toothed millers etc. | ECh | Efficiency raised, process automated |
| 18 | Making intricately shaped precision parts for radio and electronic instruments (screens, magnetron anodes etc.) | ES (LB) (EB) IB | Operations cannot be done by mechanical machining. |
| 19 | Surface and circular grinding, both external | EA, AM (ES, EP) | Abrasives saved, hard and magnetic alloys can be ground. |
| 20 | Sharpening shaped sintered-carbide tipped tools | EA, AM (US) | Abrasives saved, better sharpening with higher efficiency |
| 21 | Slicing special-grade steel blanks (up to 750 mm in diameter) | AM | Sparing use of metal, owing to narrow cut, less labour |
| 22 | Roughing many-sided or cylindrical ingots, mainly of special alloys, before rolling them | EC | No abrasive tools required, labour cut by 4-5 times, lower prime cost |
| 23 | Roughing intricate curvilinear large-area surfaces, such as hydro-turbine blades | EC | Labour cost cut by a few times |
| 24 | Machining thick-walled stamped aluminium panels | Ch | Less labour, simpler operations |

*Notes:*

ES—electro-spark
EP—electro-impulse
AM—anodo-mechanical
EC—electro-contact
LB—light beam
EB—eletronic beam
IB—ion beam
US—ultrasonic
ECh—electrochemical
EA—electro-abrasive or electro-diamond
Ch—chemical

Methods useful in certain cases only are shown in brackets

One should not, however, ignore the disadvantages of the EPECh methods which restrict their application range. When dealing with conventional construction materials and solids of rotation (by turning on a lathe, drilling, circular grinding and similar methods), surfaces by milling, planing, piercing, flat grinding and similar methods), the surface produced by combined rotation and reciprocation (thread-cutting, tooth-cutting etc.), the efficiency, accuracy and surface finish usually are superior to those obtained by EPECh methods, while less energy is consumed. Mechanical machining constitutes the basis of the machine-building technology because the amount of hard-to-machine materials is relatively small, if compared with the total amount used in industries (although there is a trend towards appreciable growth of their application), while the number of articles with conjugated simple surfaces outnumbers those with intricate shapes.

Some features connected with the introduction of EPECh methods and the problems faced by the developing countries are discussed below. One such feature is that EPECh methods are very efficient when applied for machining materials which are difficult to cut mechanically. As a rule, such materials are needed in industries popular in industrialized countries (aircraft industry, rocket building, electronics and others). From this it follows that EPECh machining will be needed at some future stages to be achieved by developing countries. On the other hand, there are other trends which favour the earlier application of EPECh methods in the developing industries. As stated above, centralized enterprises will be an efficient means for manufacturing shaped technological jigs and fixtures, in particular, dies, press tools, casting moulds etc. The introduction of advanced and economically reasonable methods for making many items by stamping, casting or pressing is, to a certain extent, hampered, owing to high costs and the extensive labour involved in manufacturing jigs and fixtures. The production of dies, press tools and casting moulds is one of a few technological processes of modern machine-building which call for a very high proportion of highly skilled manual labour, with the resultant rise in cost of items. Training a highly skilled gauge maker, who is the main worker in such processes, takes many years. The development of some industries, as a whole, may be retarded because of a lack of highly skilled craftsmen or perfect "know-how". Thus, the making of press tools, which are indispensable for manufacturing items of synthetic materials, essentially governs the possibility and periods of mastering the methods for production of many types of such items. EPECh methods will make their manufacturing much easier with the employment of less skilled personnel, while the manual operations required for making shaped jigs and fixtures will be either reduced or completely dispensed with.

Furthermore, setting up specialized and centralized enterprises in the developing countries is an easier process because it is not hindered by the existence of old technology and provides conditions for laying up-todate foundations for industry without wasting time on technology which belongs to the past. Since EPECh machines are highly automated—an inherent factor in the nature of EPECh methods—the training of manufacturing engineers, machine operators and workmen can be considerably accelerated to the advantage of the developing countries. All these factors combined make it reasonable to introduce EPECh methods from the very outset of industrial development, while taking into consideration the local conditions peculiar to each country. The best way of introducing EPECh methods is to begin with the largest enterprise in which a section of such methods can be organized. This section will be a kind of centre for training operators and manufacturing engineers. In the opening stages, the section will service not only the particular plant, but also handle the orders of some neighbouring enterprises. With the growing demand for dies, press tools and similar products, such a section may present a basis for a new centralized enterprise which will fill orders from factories which are not too distant so that transportation costs are not too high. The production capacity of a section or a special plant should be increased steadily while acquiring experience and gaining customers.

At the first stage of development, it is expedient to have the EPECh machines collected at large plants and to use them for filling orders of smaller enterprises which cannot afford a special machine because they cannot use it to the full capacity. This holds true not only for the production of dies, but also for all the operations mentioned in table 3.

The Soviet Union has pioneered in the development of methods and has worked out an extensive assortment of universal and special-purpose machines capable of performing practically all the operations which can be done well by such methods. Original ideas used in designing such machines and their high performance are known to all those engaged in EPECh methods.

For example, a French company, USEM, got the Soviet licence for manufacturing electro-impulse machines, it sells to enterprises in many countries throughout the world. Table 4 shows brief specifications of some Soviet-made EPECh machines and the ranges of their application, in accordance with the data given in table 3.

*Table 4*

CONDENSED SPECIFICATIONS OF SOME ELECTROPHYSICAL AND ELECTROCHEMICAL MACHINES MADE IN THE UNION OF SOVIET SOCIALIST REPUBLICS

| *Name of machine* | *Model* | *Main specification* | *Purpose of machine* |
|---|---|---|---|
| | | *Electro-erosion machines* | |
| Universal electro-spark copying broaching machine | 4B721 | Maximum height of work: 180 mm<br>Table dimensions: 160 · 250 mm<br>Surface finish after finishing cuts: class 6–7<br>Machining accuracy:<br>of through holes, 0.02 mm,<br>of shaped surface, 0.05 mm<br>Capacity: 40 mm³ per minute | Machining through holes 0.5–30 mm in diameter; slots, draw plates, punch dies, including those of hard alloys |
| Universal electro-impulse copying broaching machine | 4B722 | Maximum height of work: 288 mm<br>Table dimensions: 250 · 400 mm<br>Surface finish after finishing cuts: class 5–6<br>Machining accuracy:<br>of shaped surface, 0.03 mm<br>of shaped surface, 0.07 mm<br>Capacity: 1,500 mm³ per minute | Machining press tools, chills for forging dies, shaped parts made of hard-to-machine alloys, rough profiling of hard-alloy draw plates, removing broken tools |
| Universal copying broaching machine | 4723 | Maximum height of work: 380 mm<br>Table dimensions: 400 · 500 mm<br>Surface finish after finishing cuts class 5–6<br>Machining accuracy:<br>of through hole, 0.03 mm,<br>of shaped surface, 0.07–0.1 mm<br>Capacity: 3,500 mm³ per minute | Machining forging dies and press tools, chills, shaped parts made of hard-to-machine alloys, blades, runners; cutting shaped holes; rough profiling cemented-carbide tipped tools and hard-alloy draw plates |
| Universal electro-impulse copying broaching machine | 4A724 | Maximum height of work: 480 mm<br>Table dimensions: 630 · 1,000 mm<br>Surface finish after finishing cuts: class 4–5<br>Machining accuracy: 0.2–0.3 mm<br>Capacity: 7,000 mm³ per minute | Machining forging dies, press tools, chilis, shaped parts of hard-to-machine alloys, turbine runners; cutting shaped holes; rough profiling hard-alloy dies and draw plates |
| Universal three-spindle electro-impulse machine | 4723 | Maximum height of work: 700 mm<br>Table dimensions: 1,000 · 600 mm<br>Surface finish after finishing cuts: class 4–5 | Machining large-size shaped parts, casting moulds, forging dies, turbine blades etc. |

*Table 4—continued*

| *Name of machine* | *Model* | *Main specification* | *Purpose of machine* |
|---|---|---|---|
| | | *Electro-erosion machines* | |
| Universal three-spindle electro-impulse machine—*continued* | | Accuracy in machining shaped surfaces: 0.3–0.5 mm<br>Capacity: 12,000 mm³ per minute | |
| Universal portable electro-impulse machine | 4611 | Diameter of broached holes: 2–25 mm<br>Table dimensions: 485 × 320 mm<br>Surface finish: class 1–2<br>Capacity (deepening rate): up to 2–3 mm per minute | Removing pieces of broken tools stuck in large-size workpieces (main purpose); broaching holes in large-sized parts of hard-to-machine materials (hardened, heat-resistant steels etc.) placed in the machine bath |
| Electro-spark machine for cutting contours to copying device | 4531 | Maximum size of blank: up to 160 mm<br>Surface finish: class 6<br>Capacity; up to 10 sq. mm of cut area per minute<br>Accuracy: 0.22 mm | Cutting out punch dies, dies, gauges by means of electrode wire |
| Programme-controlled electro-spark machine for profile cutting | 4532 | Surface finish: class 6<br>Accuracy: 0.02 mm<br>Capacity: up to 10 sq mm per minute | Cutting out punch dies, dies, gauges up to 315 × 315 mm in size by means of electrode wire. Apart from machining to programme, copying to flat master can be performed. |
| Multiple-spindle semi-automatic machine for electro-impulse machining of cambered rolls | MA-53 | Capacity (when machining No. 12 profile rolls): 7,000–8,000 grooves per hour | Machining grooves in rolls for reinforced steel, from grade 10 to grade 45 |
| Electro-impulse machine for making screens | ME-9 | Capacity: 800 holes per hour | Making screens for screening machines of sheets 0.5–1.5 mm thick and 710 mm wide, wherein holes of 1.0 mm diameter are provided. |
| Anodo-mechanical cutting-off machine | 4A822 | Capacity: 18–20 sq cm per minute | Severing blanks up to 750 mm in diameter |
| Anodo-mechanical cutting-off disc machine | 4821 | Width of cut: 2.0–2.5 mm<br>Surface finish: class 1–2<br>Capacity: 20–40 sq cm per minute | Severing blanks up to 160 mm in diameter |
| Electro-contract machine for many-sided ingots | ME-10 | Capacity: 0.6–1 ingot per hour | Removing defective layer from many-sided ingots, 500 × 500 × 1,500 mm in size, of high-alloy steels and alloys |
| | | *Ultrasonic machines* | |
| Ultrasonic universal broaching machine | 4770 | Table dimensions: 125 × 160 mm<br>Machining depth: up to 30 mm<br>Accuracy: 0.02 mm<br>Surface finish: up to class 9–10<br>Capacity: in glass, 300 mm per minute in cemented carbide, up to 8 mm³ per minute | Machining holes up to 10 mm in size in hard, brittle materials, such as glass, ceramics, germanium, ferrites, cemented carbides |
| Ultrasonic universal broaching machine | 4772A | Table diameter: 300 mm<br>Machining depth: up to 50 mm<br>Accuracy: 0.02 mm<br>Surface finish: up to class 9<br>Capacity: in glass, up to 5,000 mm per minute; in cemented carbide, up to 100 mm³ per minute | Machining cavities and holes in parts 1–40 mm in diameter, made of hard and brittle materials |
| Ultrasonic universal broaching machine | 4773A | Table dimensions: 500 × 400 mm<br>Machining depth: up to 90 mm<br>Accuracy: 0.02 mm<br>Surface finish: up to class 9<br>Capacity: in glass, up to 9,000 mm³ per minute; in cemented carbide, up to 200 mm³ per minute | Machining cavities and holes in parts 15–60 mm in diameter made of hard and brittle materials |

*Table 4—continued*

| *Name of machine* | *Model* | *Main specification* | *Purpose of machine* |
|---|---|---|---|
| | | *Electro-erosion machines* | |
| Ultrasonic cutting-off semi-automatic machine | 4770A | Diameter of plates when cutting off in packets: up to 35 mm<br>Rate of cutting off and out: up to 1.5 mm per minute | Severing discs 1–50 mm in diameter and cutting into square plates made of germanium or silicon 0.1–2 mm thick |
| Ultrasonic broaching semi-automatic | ME-22 | Surface finish: class 10<br>Capacity when working on aluminium: up to 3 $mm^3$ per minute | Machining diamond draw plates, cemented-carbide draw plates with holes 0.5–1.2 mm in diameter |
| | | *Electrochemical machines* | |
| Electrochemical trimming machine | MA-31 | Capacity when machining gear-wheels 300 mm in diameter; 1,000 pieces per hour | Trimming gear-wheels up to 200 mm in diameter |
| Electrochemical grinder for precision single-point tools | | Surface finish: class 12<br>Capacity: 300 $mm^3$ per minute | Grinding cemented-carbide-tipped tools up to 50 mm in height |

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