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ELECTRICAL MACHINING METHODS

by

Professor K.V.Olsen,

C.E., Institute of Machine Tool Research, D.T.H.

621.791.7.054

In the course of the last half score of years one has occasionally heard of and seen descriptions in technical journals of methods for machining electrically conductive materials - primarily iron and metals, especially the hard types - in which, along with mechanical machining in various forms, use is made of electric energy. All of this technology has been of rapid growth, and although young in years - at least, as it is practiced now - it has been divided up into a series of different methods of machining, which differ primarily in electric principles; each of these, individually, can apparently be adapted to definite lines of work. Within these lines, the methods can be profitably applied to various tasks which are otherwise quite difficult.

At present, extensive research is being done in many places, and the results achieved have partly led to directives for applying the methods to practical use, and partly to the development of a series of machines which have already been placed on the market. In the Danish literature, as far as is known, only one short mention (Bibl.41) is made of this new technological field; consequently, a survey will be given below of the various electric machining methods, their basic principles, fields of application, advantages, drawbacks, and limitations. It should be mentioned at the same time that the discussion includes only actual machining, whereas other methods of treatment for which electrical energy is also employed are disregarded, for example surface treatment in electrolytic baths, electrolytic polishing, and others which have been known for a fairly long time.

The most modern electric machining methods which have appeared in recent years-

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– more exactly those with which more systematic work has been done since about 1940– all have their roots in the technological development in other fields. Exactly in this period of time there has been a great advance in the automobile and aircraft industries; jet engines, gas turbines etc. are in the process of rapid development, where the limitations, in many cases, seem to lie in the procurement of suitable materials and their ability to retain great strength, hardness, etc., at constantly higher temperatures.

The treatment of such materials, new and better ones of which are constantly coming on the market, requires special machining techniques, since such materials are often difficult to work. This is specifically true in view of the fact that the very parts made of the most difficult materials often require the most complicated machining. More indirectly, the more difficult materials result in a shorter life for the cutting tools, i.e., they must be ground more frequently and thus make increased demands on the tool-grinding mill.

Since increasing use is being made of tools clad with hard metal, both in general and in the case of the processes mentioned, heavier demands are being made on the grinding process; it seems that the demands are actually becoming too high for the available types suitable abrasives i.e., primarily diamonds and diamond dust, which are used either directly in the grinding of hard metal or in precision grinding and lapping of these materials.

The Diamond Shortage

In the U.S.A., and in England, and Russia as well, a sever shortage of diamonds for grinding has prevailed during and since the war; at the same time, the demand has risen considerably, leading to a sharp increase in price. In the U.S.A. and Russia, efforts have therefore been made to save diamonds and to develop grinding methods which would eliminate or at least reduce the consumption materially; one of the means toward this end was the use of the above-mentioned electric machining methods.

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Insofar as Russia is concerned, no data seems to be available to throw light on this situation, but in the U.S.A. developments are being followed closely by a special commission which evaluates the current situation. In its reports, the shortage of diamonds is established as a fact, and it is made clear that this constitutes a long-term phenomenon which can only be expected to be further aggravated. From a long-range viewpoint, therefore, it is necessary both to economize and to search for other abrasives and methods.

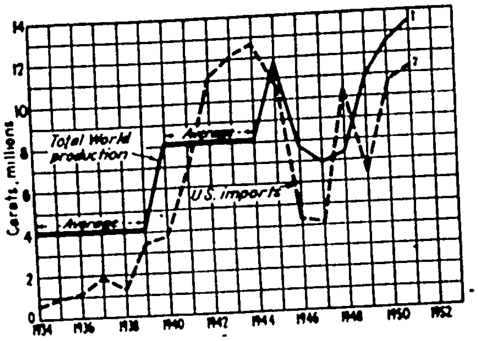

Fig.1 - Graph of the World Production of Industrial Diamonds in the Years 1934 - 1952. The broken line indicates the U.S.A. import for the same time. The reason that, in 1941 - 1945, this exceeded the total production be several million carats is due to the fact that during this time a stockpile of about 20 million carats was used up. (U.S. Bureau of Mines)

A statistical evaluation of this situation is given in a report (Bibl.36) which also emphasizes that, practically speaking, all industrial diamonds come from the Belgian Congo, from which they are imported either in the form of whole diamonds for use in the manufacture of cutting tools (diamond tools) or as diamond bort for use in diamond disks for grinding of tools. At present, there are no possibilities for an exact definition of how much of the total consumption must be attributed to each purpose, but it is stated, according to the best opinion, that as far as the U.S.A. is concerned the requirements for diamond dust constitute about 80% of the total diamond import.

Figure 1 shows the world production of industrial diamonds in the years 1934 to 1952 and also the quantity imported into the U.S.A. The curves show that, for all

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practical purposes, all industrial diamonds go to the U.S.A. and that the consumption is rising sharply. The sudden jump upward after 1940 is due both to the greatly increased production on account of the war and to the fact that just at this time a change was made to an increased use of hard-metal tools.

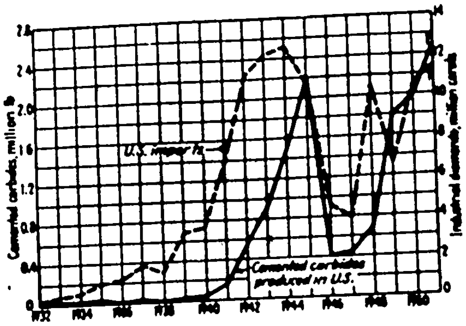

Fig.2 - Import Curve from Fig.1, and Solid Curve Showing the Hard Metal Production of the U.S.A., with Certain Applications Omitted

That the import of the U.S.A. alone in the years 1941 - 1945 was able to exceed the world production by several million carats is due to the fact that a stockpile of about 20 million carats was worked up beforehand, of which 11 million was in England and the rest in Africa and other places. This surplus had been exhausted at the close of the war, after which the consumption dropped somewhat, only to climb once more from 1949 to the present heights.

Figure 2 shows the same import curve, but related to the production of hard metal in the U.S.A.; it will be noticed that the hard-metal curve for the last few years deviates from the diamond curve.

Before the appearance of hard-metal tools, the demand for diamonds was limited. Since hard metal has come into general use, and since it has become standard practice to grind them with diamond wheels, the consumption has risen sharply and will rise further with further development in hard-metal tools. As an indication of this growth, the commission mentions that the sale of hard-metal tools in a certain period of 1952 was 67% higher than the sale in the corresponding period of the year before.

To arrive at practical conclusions it is necessary to calculate how much of the

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imported diamond dust is consumed in the various operations for which diamond wheels are used. This is done in Table 1, which shows that not less than 80% of the total import is used for diamond wheels for grinding of hard metal.

Table 1

How crushing bort is used.

Application	Total crushing bort imports pct.
Diamond wheels for grinding cemented carbides	80.4
Diamond saws of all kinds	6.0
Glass, quartz, grinding and optical curve generators	3.0
Diamond dressing tools, drills, dental tools, optical laps	4.3
Diamond and carbide wire dies, and other dies	4.3
Diamond compounds for lapping	1.5
Miscellaneous small uses	0.5
	100.0

Percentagewise Distribution in the U.S.A. of Diamond Bort over the various Fields of Application (From the Iron Age)

A further analysis of the distribution of diamond consumption is given in Table 2. The last three groups are still so new that they do not take up appreciable quantities of diamond bort, but it is expected that in the future they will increase greatly in importance and require increasing amounts of diamond bort. The first five groups comprise actual tool grinding and (aside from group 4) account for about 70% of the total consumption of diamond bort in the U.S.A., only 50% of it for single-point tools, i.e. turning steel, milling steel etc., and an apparently so minor an item as grinding of chip breakers takes up no less than 20% of the consumption.

The Table gives also a comparison of the four electric machining methods, electrolytic grinding, electrosparking, electroarcing and ultrasonic as well as grinding

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by means of diamond wheels. The letter A denotes that the method in question is already in use under production conditions; the letter B denotes that the method seems applicable and that it is promising, but that for the present it is limited because of incomplete knowledge of its behavior; the letter C denotes that the method may be applicable, that it does not seem immediately promising, but that it can eventually be developed so that it will become useful; finally, D denotes limited applicability

Table 2

Job Item or Operation	Percent use of Diamond Bort	Applicability of Methods				
		Diamond-wheel Grinding	Electrolytic	Electrosparking	Electroarcing	Ultrasonic
1. Sharpening of single-point tools	30	A	B	B	C	B
2. Grinding single-point-tool chip breakers	20	A	B	B	C	B
3. Sharpening milling cutters and broaches	15	A	B	B	C	B
4. Grinding projectile cores	5	A	B	B	C	B
5. Shaping and finishing dies	4	A	D	A	D	A
6. Forming of turbine-bucket attachments	-	B	B	B	C	B
7. Rifling of gun barrels	-	B	C	B	C	B
8. Machining and grinding of compressor disks	-	B	B	B	C	B

The Table shows percentage distribution of the total diamond consumption in the U.S.A. percentagewise among eight important fields. The first five groups account for about 75%, while all of the grinding with diamonds takes up about 85% of the total consumption. The remaining portion, or about 15% is used for all other purposes.

(From American Machinist)

or none at the present stage of development. The three asterisks next to the B's indicate that the method is not suited for hand grinding but is applicable to machine grinding.

According to the Table, the demand for diamonds is mainly for chip-removing tools, while group 5, for the time being, accounts for 4%. It should be remembered that the development of the cutting and punching techniques is not included. As the application of this technique becomes more widespread, there is a steadily increasing tendency to manufacture most tools of hard metal in order to get the benefit of the very much longer life of these materials.

These tools, depending on circumstances, can be manufactured of a single piece of hard metal or assembled of many, but both types have in common that the basis for the often complex form of the tools requires extensive designing. The situation is very difficult in cases where the tools contain fairly small irregular holes, which must be milled directly in the hard metal. Although the production of hard metal is a technology which has been brought to great perfection and permits sintering of precise molds with correctly placed cut-outs, holes, and even finished threads etc., all tools assembled from such ready-sintered parts must be further treated to give the necessary precision and sharpness.

Survey

On the basis of this information on the American situation (which certainly is also valid for other places) and in view of the known fact that the consumption for the period after 1951 has surpassed the import, together with the assumption that this will not appreciably increase in the future - intensive work has been done on bringing down the consumption by economy and by development of new grinding and machining methods, of which the most important methods at present seem the electric types.

In addition, it can be more generally stated that the electric machining meth-

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ods may be valuable in cases where, in general, it is a matter of machining the many hard materials appearing from time to time on the market and which are hard to machine with conventional methods. Examples of such materials which are difficult to machine, in addition to hard metal, are titanium, vitallium, vanadium, Alnico, chrome-nickel steel, tantung, manganese steel, stellite and others, and of course also ordinary tempered steel.

Although the above discussion has only mentioned the application of the electric methods in combination with grinding, there is nothing to hinder their use in turning, boring, milling, etc. The more detailed account to follow will show examples of this. The methods seem to be in vigorous development, and the larger industrial countries are working intensively on improving the technique and advancing a productive scale.

Leading in that respect are apparently the U.S.A., Russia, and England, with Germany following closely in recent years. All these countries today have machines and equipment on the market for one or more of the electric machining methods. American statements indicate that a large number of experimental machines are used in the U.S.A. for the individual machining methods and that constant work is being done on developing and improving the technique and in perfecting the machines and equipment. It is also stated that, as early as 1950, there were more than 4000 "Electro-Spark" machines in use in Russia and Poland. Corresponding figures for other countries are lacking.

All in all, it seems that the electric machining methods, in broad outline, have been developed in the period since around 1940. Certain of the fundamental principles however have been known much longer - since around 1925 - but did not, at that time, acquire great significance and therefore have apparently remained neglected until a short while ago.

The Americans maintain in their journals that they are the originators of this development which, according to their interpretation, had its beginning around 1940

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and resulted in Electro-Sparking machines put on the market in 1943. They loaned the Russian Purchasing Commission in 1944 prospectus material on the equipment and in 1945 furnished Russia with Elox plants for electro-sparking. They maintain now that the Russians imitated this equipment with the result mentioned above, that a very significant number of machines are in use today in Russia and Poland.

Without taking a position on this assertion, it must be conceded that the Americans since 1940 and later have done intensive work in this field; this is attested both by the journals and the patent literature. But at the same time it should be pointed out that the electric machining methods consist of four processes which are different in principle, and that there is not always a sufficiently sharp distinction possible between them. This also brings up the possibility that one country can be first in the one field while others are first in other fields. Finally it should be pointed out as a simple fact that one of the electric methods is based on a German discovery of 1924 (Bibl.48) while another rests on an observation which a Russian, Vladimir Gusev, had protected by patent No.335 003 in England in 1929. In addition, another fundamental work was carried out by a Russian - Lazarenko - described in the Russian technical journals after 1946, and patented in England - No.637 793 of 1946. An Englishman, Rudorff, also contributed to the development with his patent No.637 872 of 1947, and finally may be mentioned the patent of an American, Teubner, No.2 650 979 of 1950

When subjecting this new technological field to a closer examination, it will be natural to subdivide it according to the electric machining principles, which are quite divergent since the methods have different spheres of application and require different apparatus. Unfortunately, the terminology is very ambiguous (there is as yet none in Danish) so that Danish denotations must be taken as a choice of words which include the concepts but which must not be conceived as the absolutely correct or only terminology which can be used. Also some of the foreign terms are misleading; therefore the following classification gives the usage most often applied in the

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foreign literature.

The field can accordingly be subdivided into the following five groups; an attempt will be made below to give a complete account of the technology, possibilities, equipment etc. for each of the mentioned electric machining methods.

1. Electrolytic Grinding:

   Electrolytic process,
   Elektrolytische Abtragung,
   Elektrolytisches Schleifen,
   Elektrolytisk bearbejdning,
   Elektrolytisk metode.

2. Spark Machining:

   Electro-sparking process, occasionally, but incorrectly arc-machining,
   Electro-erosion machining,
   Atom expulsion, now most frequently electrical discharge machining,
   Funkenerosion,
   Funkenentladung,
   Elektrisches Bohrverfahren,
   Elektro-Funken-Methode,
   Elektrisk gnistbearbejdning,
   Gnistmetode.

3. Electro-Arcing Process:

   Arc Machining,
   Disintegration,
   Electrical erosion,
   Electro-drilling,
   Lichtbogenerosion,

Gesteuerter Lichtbogen,

Elektrisk buebearbejdning,

Buemetode

4. Ultrasonic Process:

Ultrasonic drilling,

Electro-abrading,

Ultraschallverfahren,

Ultralydbearbejdning,

Ultralydmetode.

5. Combination Processes:

Andre metoder

Kombinationsmetoder.

It should be noticed that the division into groups is not always sharp and that certain characteristics can produce a cumulative effect of several processes. Group 5 contains the processes which cannot be classified in other places and processes used in combination with one or more of the other methods.

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ELECTROLYTIC MACHINING

The idea of replacing the conventional mechanical machining with a method for removal of a layer of material by chemical agents is very old. The principle has also found extensive application, for example, in mordanting, where dross etc. are removed and in chemical pickling baths where metal surfaces are freed of impurities.

Various other attempts were made to machine the materials chemically, including the suggestion by de Fehse in 1931 (D.R.P. 564 081) to change the dimensions of the hard metal while maintaining the geometric form, by exposing the metal to a hot stream of an oxidizing gas or by direct heating to 700 - 800°C in atmospheric air with subsequent mechanical removal of the oxide layer.

Somewhat later - in 1943 and occasioned by the shortage of suitable abrasives during the war - Ballhausen (D.R.P. 847 390) attempted to sharpen the edge of hard-metal tools by heating them to about 800°C and then brushing off the oxide layer formed. Attempts to dissolve the hard metal by chemical means are well known and constitute essentially a modification of the technique applied in the sharpening of steel files. None of these methods, however, led to the desired results, and they have never come into extensive practical use.

Electrolytic machining is based on anodic dissolution of the workpiece in an aqueous electrolyte. This machining method is applied preferably in combination with grinding - and then, as a rule, with lathe tools and the like - or for shortening hard materials such as cutting hard metal plates from longer pieces, etc.

In principle, the method consists in connecting the workpiece to the positive pole of a direct-current source and the negative pole to a rotary disk, while the object to be machined - just as in conventional grinding - is passed quite close but without actual contact taking place. The workpiece is meanwhile immersed in a highly conductive electrolyte, or the electrolyte itself is applied to the disk in the form of a stream, like the antifreeze solution in grinding. When the positive workpiece

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being machined passes the negative disk, an anodic disintegration of the part takes place; the amount of material removed will be directly proportional to the current strength and the time. In addition, the amount of material removed from the place of work will be much greater, the more the distance between anode and cathode is narrowed.

The method which thus is a purely electrochemical process, apparently was first suggested in 1924 by the Germans Pirani and Schroeter (Bibl.48), and in 1929 the Russian Gusev took out an English patent (335 003) on a similar procedure.

Practical Data

The direct voltage applied is as a rule quite low, normally less than 25 volts and most frequently only between 15 and 20 volts. The amperage on the other hand is large; American sources indicate that 25 amp/cm^2 are necessary for operations that are more than mere experiments. Other information mentions up to 65 amp/cm^2 in grinding hard metal and up to 240 amp/cm^2 for work on steel.

The feature which makes electrolytic machining a new process and differentiates it from the well-known electrolytic polishing - which is based on the same principle but uses a current intensity of only a few amperes per square centimeter - reportedly is the much higher current density. The great speed with which the process takes place, and the fact that it can be kept under complete control, are especially emphasized.

Since the space between the work and the wheel can be made very narrow - of the order of magnitude of 0.01 - 0.02 mm - the current density, as mentioned, becomes high. Moreover, there is some indication that this clearance is significant for the precision which can be obtained in the machining and for the resultant quality of surface finish. It is emphasized that the local heating is very slight, so that the surface is not damaged by scratches, crack formations, etc. and that practically no wear of the wheel takes place.

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s cathode, preferably ordinary soft carbon steel of a thickness of 0.5 to 2.0 mm is used. The lower of these values is used in work on the periphery or shortening, while the higher value is best applied in grinding on the side of the wheel. The most common thickness used seems to be about 1 mm and it is also stated that the speed of working increases with thinner wheels. Other wheel materials, which are occasionally used, are copper-plated carbon steel and cast iron. The diameter of the wheel seems to vary between about 100 and 300 mm but is most often near 150 mm. The peripheral speed is stated by the various sources, with considerable uniformity, to lie between 8 and 12 m/sec and cannot be confused with the about twice as high peripheral speeds which are used in some of the other machining methods like, for example, those in groups 3 and 5.

As electrolyte, an aqueous solution of a metal salt or a weak acid is used. Different sources mention more or less identical aqueous solutions of concentrated sodium silicate, concentrated hydrochloric acid, sodium salt of weak acids, sodium chloride, caustic soda, etc., and there seems to be agreement that waterglass gives the best effect and the fastest working. The specific gravity of the electrolyte is given as between 1.28 and 1.34, and it appears that increased specific gravity produces more rapid grinding.

It is pointed out as a defect of the method that the current is not limited to a fairly small localized portion of the work, but extends over the whole of the surface covered by the electrolyte. Since the relative current intensity, as mentioned before, is greater the less space there is between the anode (workpiece) and the cathode (wheel), different current intensities will pass through different portions of the work, resulting in an uneven "grinding". As a consequence, no excessive accuracy can be expected.

The requirements normally made in grinding a tool with hard metal are that the tool, when magnified about 200 times, will not show scratches and will not have, a surface roughness above 50 μ in. r. m. s. The first requirement is easily met in

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electrolytic grinding, and the second can be met: although this is not always so, some specimens showed surface finishes of the order of 5 - 15 μ in r. m. s.

More or less successful attempts have been made to limit the electrolytic effect to a smaller area by using uncoated electrodes, but this complicates the conditions considerably. However, it seems that, at proper selection of all factors concerned - not the least of these being the choice of a suitable electrolyte - surfaces with a finish acceptable for general purposes can be obtained.

Results Obtained

This electric machining method apparently is highly suitable for the above-mentioned tool grinding, especially where material is to be removed from large surfaces. On the other hand, the method is not suitable for machining of small surfaces or for boring of small and deep holes. This is apparently due to the above-mentioned dissimilar current passage which also has a tendency to remove corners and edges. This is without doubt a condition to be taken into consideration in tool grinding, where a sharp edge is desired. The edge grinding is moderate, but can be tolerated, especially since honing of the sharp edge phase grinding is usually performed.

Another important question in this connection is the life of an electrolytically ground tool compared to that of the same tool ground in a conventional fashion. The available experimental data are insufficient to give a general answer to this question and the pertaining statements are extremely divergent. American information tends to indicate that the electrolytically ground tool has essentially the same life as one ground by a ceramic-diamond wheel, while Russian information indicates that electrolytically ground tools have a service life 2 to 3 times as long as normally ground tools. An independent consideration would indicate that the correct answer to the question lies somewhere between these two positions, since it is quite natural to count on a longer life for the electrolytically ground tool, inasmuch as it is free of the cracks and scratches which even the best, normally ground, tool cannot

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escape.

Concerning the working speed with pure electrolytic machining methods as described here there is no sufficient information available, but a comparison with other related electrical methods perhaps permits the conclusion that the grinding time is more or less the same, possibly a few per cent less than with ordinary grinding.

The electrolytic method is not used extensively in practice; among other things for the additional reason that it has a tendency to change into other methods. For example, if contact takes place between the work and the wheel, which can easily occur with the small space involved, and electric arc is formed which changes the effect to that described under electric-arc machining in group 3. Another natural variation consists in replacing the metal wheel with a diamond wheel; this results in a purely mechanical effect, and the process changes character and must be placed in group 5, where it will be described in more detail.

Setup Assemblies

In practice, the machining can be carried out by machines designed especially for the purpose or by conventional grinding machines rebuilt so as to include a tank for the electrolyte, a metal wheel, insulation between the wheel and the work, and finally a suitable direct-current source. If absolutely necessary, built-up experimental equipment can be used. It is the two last forms which up to now have the greatest dissemination, while the first type is only seldom found described in the literature or met in practice. If the pure electrolytic machining is abandoned, for example if, as just mentioned, the process changes in character, then this modified technique - which will be described in more detail in the other group - will have available several machines of the two first types.

As a typical example, Fig.3 shows a Russian electrolytic tool grinding machine for hard metal. The table dimensions are 450 × 160 mm with a 250 mm displacement. The transverse movement is effected by the spindle dock and amounts to 85 mm. The chuck height is 180 mm and tools up to 30 × 45 × 315 mm can be ground.

As cathode, a wheel of steel or cast iron is used, with a diameter of 85 mm and a rotational speed of 1280, 1600, and 2000 rpm corresponding to peripheral speeds of 5.7, 7, and 9 m/sec. The wheel and the workpiece are immersed in a suitable electrolyte and all working parts are entirely closed-in during grinding, while the machine is operated by pushbuttons from the panel. The current is supplied by a direct-current unit built into the base. The machine works as described above. This grinding method and machine obsoleted the use of ordinary grinding wheels, eliminated subsequent patching, and avoided the risk of grinding cracks and local deformation of the hard metal. Reportedly, the grinding time is also shortened materially.

Fig.3 - Russian Electrolytic Tool Grinding Machine for Hard Metal. The machine is operated by pushbutton and the moving parts are entirely enclosed to prevent leakage of the electrolyte.

Electrolytic Turning

Electrolytic turning has been successfully applied, although up to now only under laboratory conditions. This was done at the N.P.L. in Teddington, where some very small specimens are said to have been used which cannot be produced by ordinary methods, since the structure and the surface layer are destroyed and the measurements are misleading. In addition, the method satisfied requirements for tolerances of ± 0.001 mm and high surface finish. The machining therefore had to be done by electrolytic means, using the arrangements shown in Figs.4 and 5.

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A suitable electrolyte was fed from a retort along a rubber tube to a metal cathode in a glass chamber and discharged from a nozzle in this chamber onto the workpiece. As cathode, first a copper tube was used which was later replaced - to prevent attack by the electrolyte - by a platinum wire in the glass chamber. The workpiece represented the anode and was simultaneously turned and passed back and forth past the jet, in which the current density can attain 200 amp/cm^2.

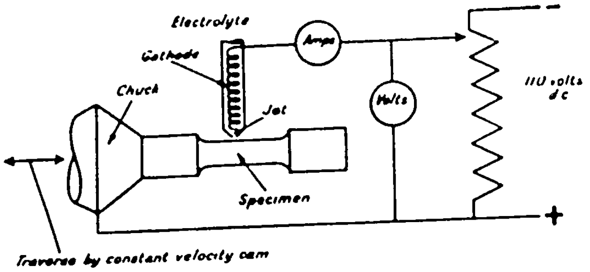

Fig.4 - Diagrammatic Sketch for Electrolytic Turning.
The electrolyte, size of the jet, and electrical data must be matched to the different materials.

The movement of the workpiece must be adjusted in such a way that the anode dissolves the metal evenly on all portions of the surface. The cam wheel must therefore be especially adapted with this in view and, in this case, is heart-shaped, a design that has given good results.

As starting material, bars 16 mm long and about 1/8" in diameter were used. These are screwed into a brass cartridge and locked tight. The spindle runs in two ball bearings and a tube and is driven at a speed of 2000 rpm by a belt drive. Thus the "cutting speed" is at maximum about 20 m/min or around 0.33 m/sec, thus being significantly lower than in electrolytic grinding. The spindle dock, i.e., the tube, is moved back and forth by the heart-shaped cam wheel in connection with a spring, and is guided in this movement by five ball bearings.

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As electrolyte, a combination of ammonium chloride and hydrochloric acid was used in this experiment, and to avoid corrosion the workpiece, before clamping, was rinsed with water from another flask. This setup was combined with an optical instrument from which the diameter of the workpiece can be read off, with an accuracy of 0.0001" *.

In another experiment with the same workpieces, a voltage of 70 v, and an electrolyte consisting of a mixture of copper ammonium chloride and hydrochloric acid, the workpieces were "turned down" from 3.2 mm to 1.6 mm in 15 min. To achieve a tolerance of ± 0.0025 mm at this speed of machining, the "turning lathe" had to be stopped within an accuracy of 1.5 sec. It is very probable that this can be obtained more easily and quickly if the machining is halted by cutting off the current.

The turning can, in addition, be varied in many ways. The rough planing can be done for example on a watchmaker's bench and the polishing as indicated here. The speed can be changed almost continuously by changing the composition of the electrolyte, and the precision can be correspondingly increased by lowering the speed.

Attempts have also been made to use two flasks, each with its own electrolyte, one for rough planing and one for slow polishing to great surface smoothness.

If the workpiece is turned around slowly without the forward and back motion, a necking is obtained instead of a longitudinal turning; if the process is continued long enough, this will finally shear off. The width of the necking is about twice as great as the nozzle.

For metallurgical purposes electrolytic turning seems to offer advantages in

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* It is not inconceivable that this electrolytic turning is based on a modification of the principles which underlie the Danish "electrolysis pipette". This apparatus was used for electro-polishing and has been known everywhere - even abroad - since about 1943. The principle in the two installation is entirely the same, only the workpiece is moved in the "turning", while in the electro-polishing it is stationary. (Information given the author by Prof. Dr. Tech. Knuth-Winterfeldt).

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several areas. Among others, this is true in the production of test specimens where the structure and surface layer must not be ruined by mechanical machining and where there is need for great precision and mirror-finished surfaces. The industrial possibilities cannot be estimated at present, since they have not yet been tested. It is however not out of the question that the method can be of value in some areas.

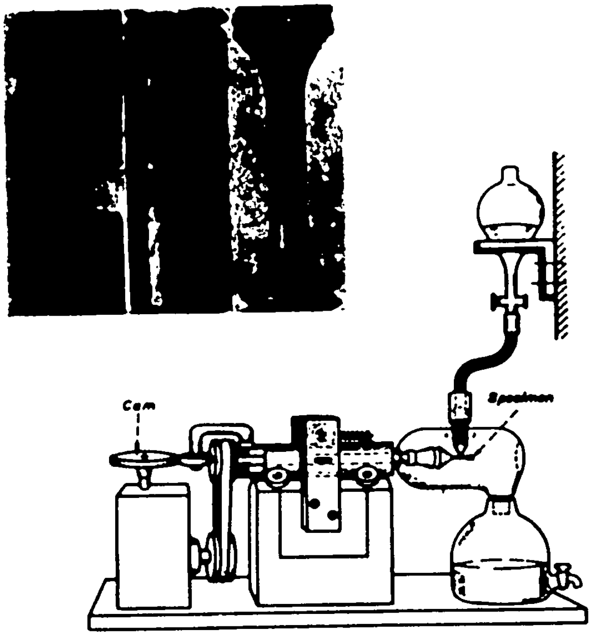

Fig.5 - Electrolytic Turning Lathe, Schematic Representation. Simultaneously with the rotation, the workpiece is moved back and forth when the cylinder which carries the spindle is displaced by the cam arrangement shown. The insert shows, magnified 20 times: On the left, a notch turned in a workpiece of pure iron with a diameter of 1/8"; in the center, the starting material; and on the right, an electrolytically turned specimen.

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The fact that experiments have shown that hard materials can be machined by this method speaks for this assumption as does also the rapidity with which the machining can take place, as well as the control of surface smoothness through regulation of the speed.

Despite the applicability of the electrolytic machining method within certain fields, it still is the least used of the electric machining methods and has resulted in the least production equipment on the market. If this is so, despite the fact that the method definitely has the advantage over the other methods, because of the relatively simple electric equipment, of being considerably cheaper, the reason presumably lies in the circumstance mentioned under grinding, namely that it is difficult to obtain exact planes and surfaces of high quality with this method.

Experiments by the N.P.L. seem to contradict this statement since there high machining precision and smooth surfaces were obtained. The comment on this is that a different technique was used, that the experiments are of a more recent date, and finally that the method may be better suited for turning than for grinding.

If this is the case, it will be interesting to follow future developments, and to keep track where and how the method can be adapted to industrial purposes.

Literature: Bibl.5, 7, 8, 12, 14, 15, 16, 20, 32, 36, 42, 45d, 48, 59, and 60.

Patents: Swedish No. 76 026, German Nos. 564 081 and 847 390, English No. 335 003.

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ELECTRIC SPARK MACHINING

THE DEVELOPMENT IN RUSSIA

It is apparently in this machining method that the greatest development has taken place. Young as the technique is, a comprehensive periodical literature exists on the subject, and the method is also rather fully treated in the patent literature. Apparently, the development is carried on - at any rate in the western part of the country - by individual industrial concerns; it is also typical that this has resulted in there being put on the market several machines ready for production which are at the disposal of the industry for making use of the advantages offered by this method.

Since Russia, the U.S.A., England, and Germany have individually made important contributions to the clarification of the subject, not only by theoretical considerations but also by descriptions of the machines and equipment produced, it is hardly possible or useful - also because of the great number of sources - to give a generally valid cross-sectional view over this large volume of data where divergent concepts still exist. It will be more useful to summarize the development in the individual countries and then draw conclusions on this basis. This will be done in the following Section where, for practical reasons, we begin with the Russian development, because the available literature contains chiefly theoretical considerations, while the sources from the other countries have, in many cases, placed great weight on the practical problems.

The Development in Russia

As far as can be seen, the point of departure here is apparently the discovery by W.Gusev, which is described for example in the Swedish patent No. 76 026 of 1929. By means of the device described there, round or arbitrarily shaped holes are produced in the metal by forcing an insulating tube of the desired shape against the

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workpiece. The tube is surrounded by a gasket abutting the workpiece; inside the insulated tube a shorter hollow electrode is installed. Through the resultant space an electrolyte, e.g. a 3 - 8% hydrochloric acid solution is fed; if the workpiece is connected to the positive pole of a current source while the hollow electrode is connected to the negative pole, a current will be produced, resulting in an arc which will disintegrate the metal; the loose particles are flushed away by the electrolyte.

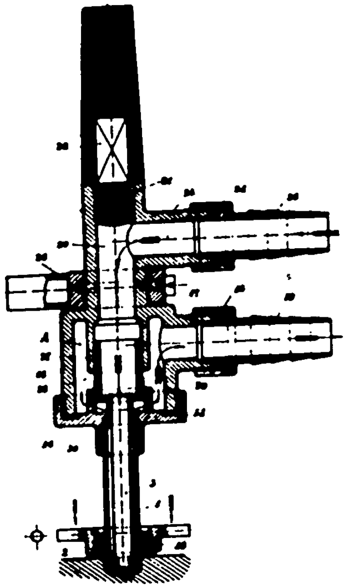

Fig.6 - W.Gusev's Swedish Patent, No.76 026 of 1929, Showing the Head of the Tool, with the Insulating Tube (1) pressed against the Workpiece. Between (1) and the cathode (3) an electrolyte is circulated which is prevented from leaking by the gasket (2). The current between the anode and the cathode produces a hole with a bowl-shaped base which corresponds to the outer dimensions of (1).

The hole produced will exactly correspond to the outer dimensions of the insulating tube. There seems to be a rather great distance between the end of the hollow electrode and the workpiece. The "drilling speed" is determined by the current density and the speed of circulation of the electrolyte. At a voltage of 110 v; a current density of 150 - 300 amp/cm^2, and a speed of circulation of 300 - 600 m/min, the patent claims state that a satisfactory drilling speed is attained, but without indicating what is meant by this.

This is not a spark method, but belongs in group 1, or possibly in group 3, and is only included here in order to give the logical development, the next step of which is the work by Natalia and Boris Lazarenko, de-

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scribed in the Russian technical journals in the period after 1946 and patented in England, France, and Switzerland.

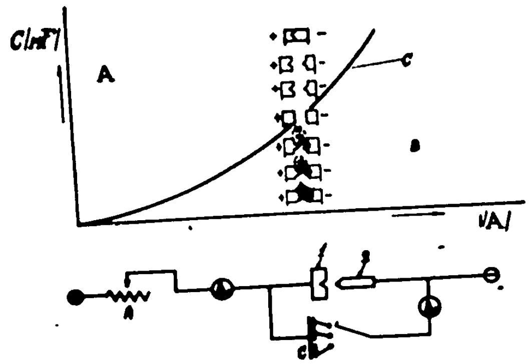

Fig.7 - Basic Principle of the Electric Spark Method. The workpiece (1) and the tool (2) are connected to the positive and negative poles of a direct-current source, while the current is regulated by the resistance R and is read off the ammeter A_1. Parallel to this, a variable capacitor C is connected, and the discharge current is read off A_2. Above the schematic, a diagram, with the discharge current as abscissa and the capacitance as ordinate, shows the limiting curve C between the area A where spark discharge is produced, and the area C where arc discharge is produced.

(Lazarenko: Swiss patent No. 257 468)

The basic idea of Lazarenko's discovery - and thus of all forms known up to now for electric spark machining - is given in Figs.7 and 8, which are taken from the Swiss patent No. 257 468. As shown in Fig.7, at the bottom, an electrode (2), suitably shaped as the tool, is connected with the negative pole of a direct-current source whose positive pole is connected across the variable resistance R to the workpiece (1), while at the same time the current intensity can be read off the ammeter

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A_1. Parallel to the workpiece and tool a variable capacitance C is connected, and the discharge current in the circuit can be read off the instrument A_2.

According to the patent specifications, changes in this circuit will produce electric discharges between the workpiece and tool, during which particles are torn from the workpiece or tool, so that a metal transfer is initiated. If the discharge takes place through an electric arc the direction of transfer is from cathode to anode, while if the circuit is made to discharge with electric sparks, the metal transfer proceeds in the opposite direction, i.e., from anode to cathode.

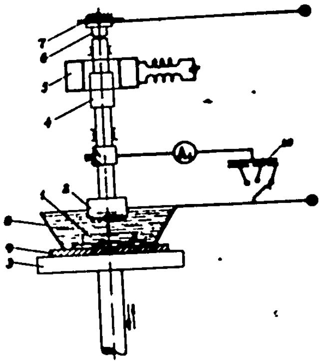

Fig.8 - "Drilling Machine" using the Spark Method. The workpiece (1) is immersed in a vessel (8) with fluid and connected to the plus pole. (9) is an insulating plate. The tool (2) is set in a holder (4) and can be vibrated by the solenoid (5), opening and closing the circuit.
(Lazarenko, Swiss patent No.257 468)

It has been found by experiment that, for a definite value of the electric field intensity between the electrodes, the direction of the transfer will change and that this value is dependent (among other things) on the chemical properties of the electrodes. It is further indicated that, by changing the constants of the circuits, it is possible to determine whether spark or arc discharge is produced and thus to change the direction of metal transfer.

In the main, there are three factors which are decisive for the conditions, namely the type and composition of the electrodes, the medium through which the discharge takes place as well as its condition, and finally the magnitude of the electric parameters. It is further indicated that the optimum effect is obtained at the instant of transition between spark and arc discharge.

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Briefly stated, the electric spark machining method consists in accumulating a high electric energy in the circuit and then discharging this energy in the form of a spark which, for a brief instant, touches the place on the workpiece which it is desired to machine. The high density of energy applied to this spot causes a breakdown of the surface, so that its particles are torn loose and carried away.

Figure 7 at the top shows the relationship between the discharge current A and the capacitance, with the curve C indicating the limiting line between the area A where spark discharge takes place, and the area B where there is an arc discharge.

The working should therefore be done in the area A, since the heat generation is less with spark formation than with arc formation, so that the risk of ruining the workpiece by heat, or structural changes, etc. is less here. In addition, the spark is easier to direct against a single exact point than the arc, which increases the precision of the work; finally, the spark gives a more concentrated energy discharge than the arc and thus produces an instantaneous and powerful effect.

In practice, this machining method is carried out by inserting the workpiece and the tool as electrodes in an electric oscillatory circuit which gives a spark discharge with a suitable predetermined frequency. When the circuit is closed, particles are dislodged from the positive workpiece and transferred toward the negative tool. If the operation is stopped here, the particles will continue their travel and precipitate on the tool, changing its form and size. The particle transfer must therefore be stopped. This is most easily done by filling the spark gap with a fluid which, according to the patent specifications, can be stationary or flowing and consist either of a dielectric material or a passive electrolyte.

Machines for Electric Spark Machining

Mechanically, the method is carried out by machines which greatly resemble small bench drilling machines. However, there are no rotating parts, since the only necessary movement is a suitable perpendicular potential which can maintain a constant

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spark gap under the workpiece.

Such a "drilling machine" is shown, in principle, in Fig.8. The workpiece is mounted in a vessel (8) filled with liquid and connected with the positive pole of a direct-current source. The vessel is insulated by a plate (9) from the tension plate (3), which is adjustable in all three directions. The tool (2) (here intended for cutting) fits in the holder (4) and is connected to the electric circuit as shown, while the resistance R is omitted here, so that the capacitor charges and discharges directly. This is accomplished by a vibratory motion which is imparted to the holder by means of the solenoid (5), which causes a rapid opening and closing of the contact (6).

Lazarenko also mentioned application of the method with rotating tools. He used wheels of 0.5 to 1 mm thickness, approached to the workpiece until formation of a spark, while water or a dielectric fluid was run over the point of cutting.

In a paper (Bibl.2), Lazarenko describes complete drilling machines and a grinding machine, operating on these principles. In addition to the above description, it should be mentioned that the vibration unit consisted of a cam wheel which, driven over belts by a motor, raised the spindle 1 mm after which it was returned by a spring in the hollow spindle. The tool, with which arbitrarily shaped holes could be "drilled", was made of brass. The partial voltage was created by a special variable motor through a double worm gear, with a change-over ratio of 1:360. Besides this, the voltage could be regulated through a special gear with the three transmission ratios of 3:1, 1:1, and 1:3. Finally, the machine was also equipped with manual tension.

The electric system was built into a separate panel and consisted of a rheostat which permitted a variation in current intensity from 1.3 to 30 amp, and of a capacitor C which could be adjusted between 2 and 500 u f.

As liquid, oil or kerosene was used, to a depth of at least 100 mm over the workpiece.

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After the resistance and capacitance were adjusted to the job to be done, the only point that needed watching was the voltage, since a constant spark gap had to be maintained. This control is exerted over the ammeter in the oscillatory circuit. If the voltage is reduced, the current drops from the determined value to zero, while an increase in the voltage causes the current intensity to rise to the maximum. The control can therefore be effected automatically by installing a relay into the voltage circuit and adjusting it according to the desired current intensity. Then, on any variation in the circuit, the relay will cut the voltage motor in or out. The power is 2.5 kw, including 0.25 kw for the vibrator and 0.25 kw for the partial

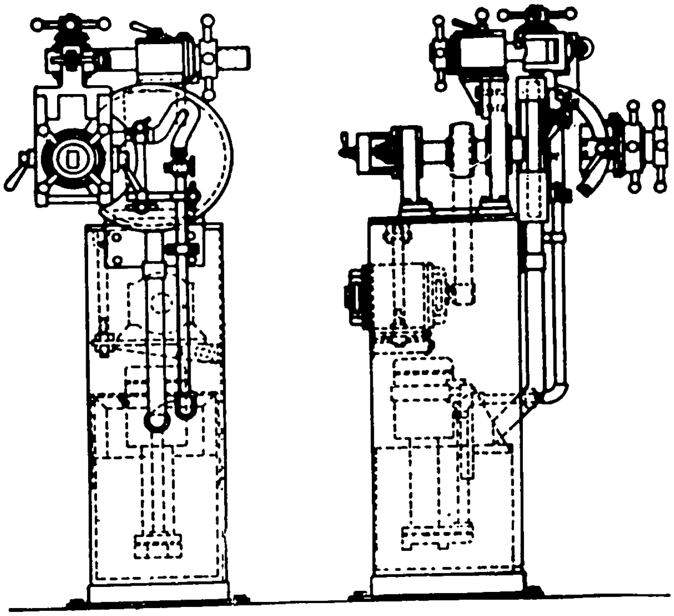

Fig.9 - Grinding Machine for Turning Steel, etc. The grinding is done with a rotating metal wheel. Speed 500 rpm. Good results were obtained without defects in the tool. Time required unknown.

(According to Lazarenko)

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voltages.

Figure 9 shows a grinding machine tool for turning steel etc. The machine has three translational and three rotational movements for adjustment so that right and left-handed tools can be ground with any angles desired. Tools up to 20 × 30 mm shaft cross section can be fixed in a suitable holder.

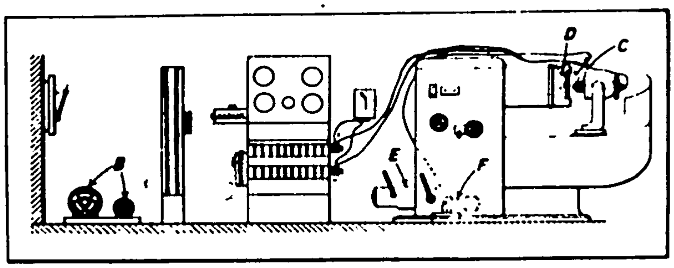

Fig.10 - General Setup of Experimental Apparatus for "Grinding" of Tools by the Electric Spark Method. B is motor-alternator to supply the unit with direct current. C denotes the tool that is to be "ground" and D the "grinding wheel". This is driven by an AC motor E, while the pump F circulates the "coolant". (According to V.A.Krivoukhova)

The "grinding" was done with a metal wheel rotating at 500 rpm or, in some cases, with variable resistances and capacitances were used so that current intensities between 0.1 and 30 amp and capacitors between 2 and 400 uμf.

It is asserted that good results were obtained, with flat surfaces without scratches or other defects.

Results of the Experiments

As background for this theoretical work and the first attempts to construct machines for the practical application of the method, the Russian professor V.A.Krivoukhova investigated grinding methods and precision grinding with the help of the spark method. The purpose was to find out the requirements for speedy and effective

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grinding of hard metal, resulting in excellent surface finish while preserving the characteristics of the hard metal during the grinding process.

In Krivoukhova's experimental setup, the work was done with rotating wheels whose peripheral speed could assume the values of 5, 10, and 15 m/sec (980, 1970, and 2950 ft/min). Lazarenko's electric circuit was used, with the voltage being regulated between 20 and 220 volts, the current changed between 0.1 and 150 amp, and the capacitance in the oscillatory circuit varied between 1 and 400 uμf.

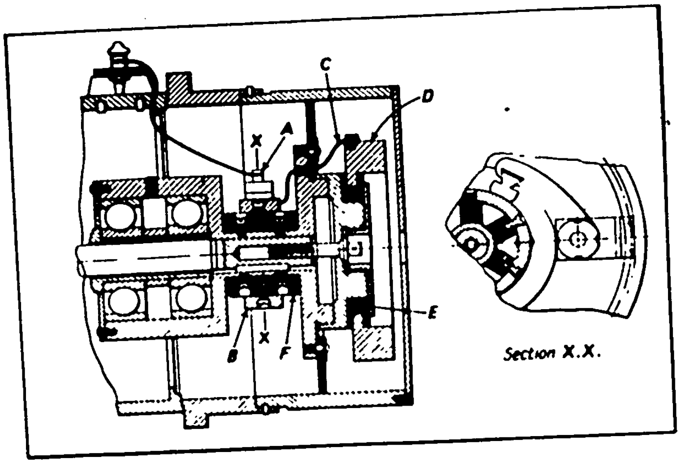

Fig.11 - The Modified Spindle in the Experimental Machine (a Standard Grinding Machine). The current is supplied to the holder A and the ring B and is fed from there to the "grinding wheel" D. E and F are insulating wheels. (From V.A.Krivoukhova)

As wheel materials, cast iron, steel, copper graphite, or aluminum were used. Experiments were made on hard metals of types T 15 K (79% WC, 16% TiC, and 6% Co) and BK8 (92% WC and 8% Co). As medium in the spark gap various oil emulsions and air were used.

The setup for the experiment is shown in Fig.10, where a suitable rebuilt grinding machine of otherwise conventional design is used. The electrode wheels are mounted on the modified spindle, and the entire arrangement is shown in Fig.11. A motor-alternator B (Fig.10) furnishes the required direct current. The tool is denoted by C and the "grinding wheel" by D. This is driven by an AC motor E. The parts are hooked into an oscillatory circuit, as described before. The pump F circulates the stream of liquid.

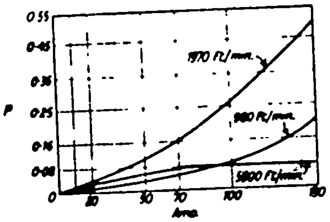

Fig.12 - The Quantity of Material P gr/min which is "ground away" placed in Relation to the Current Intensity at various Peripheral Speeds of the Wheel. Materials, hard metal, grade T 15 K. Tension 20 volts.

(From V.A.Krivoukhova)

The details of the spindle are shown in Fig.11. The current is conducted from a brush holder A to the ring B and from there through C to the grinding wheel D. B and D are insulated from the spindle by textolite rings E and F. This change of the spindle represents the greater part of the modification to permit use of a standard grinding machine for electric spark machining.

With this arrangement, a series of experiments was made to determine the influence of the individual factors. For example, Fig.12 shows the amount of material removed P, measured in gram/min, as a function of the current intensity J amp, at a constant voltage of 20 v disregarding the capacitance. The hard-metal quality used is T 15 K.

The greatest efficiency is obtained at a speed of 10 m/sec (1970 ft/min), and practical experience has shown that an optimum value is reached at a wheel speed of 12 - 15 m/sec. If softer materials than hard metal are ground and a low current intensity of about 20 amp is applied, peripheral speeds of 25 - 30 m/sec (4900 - 5900 ft/min) are recommended. These latter speeds must be considered as the absolute maximum in fine-grinding.

Throughout the experiments, an attempt was made to determine the optimum electric data; from more than 2600 individual experiments it was found for example that, for the hard metal BK 8, the voltage should be 20 - 25 v. Figure 13 shows the relationship between P (gm/min) and I (amp), at different values of the capacitance C, for which many curves are included. The wheel speed is constant, 10 m/sec, the voltage 20 v, and the hard metal used, BK 8.

In Fig.14 the relation between P (gm/min) and the capacitance C (µf) is plotted for BK 8 at the two wheel speeds of 5 and 10 m/sec (980 and 1970 ft/min). The voltage is 220 v. These two odd curves indicate that the effect increases with increasing capacitance, and also that, at constant capacitance, the effect increases with increasing peripheral speed.

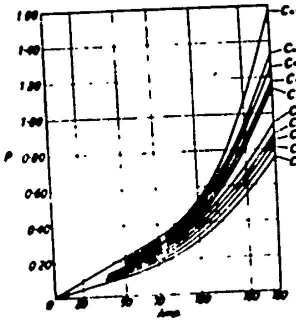

Fig.13 - At a voltage of 20 v and a Peripheral Speed of 10 m/sec the Relation between the Material Removed P in gm/min and the Current Intensity is Plotted at various Values of the Capacitance C, for the Hard Metal BK 8

(According to Krivoukhova)

The influence of the capacitance on the surface finish was also investigated and is plotted in Fig.15. The height of the roughnesses was measured (unit unknown) and correlated with the capacitance (µf). Four curves are plotted for various values of the voltage V and the current intensity A. In these experiments a cast iron wheel was used, and a fluid known as "Aviation Oil Mark M.S.".

It is assumed that the best surfaces are produced with a current intensity from 3 to 5 amp and capacitances from 1 to 5 µf, at voltages of about 20 v and wheel speeds of 5000 - 6000 ft/min (25 - 30 m/sec).

The ground surface of the hard metal was examined metallographically and showed no scratches or structural changes. This means there is no danger of damaging the.

material, thus making the technique suitable for production purposes.

A better criterion for the finish can be obtained in experiments on the life of tools ground by the spark method and conventional grinding methods. Several materials, including steel and cast iron, were machined under the following conditions: rough planing t × s = 1.5 × 0.47 mm; polishing t × s = 1.0 × 0.21 mm; and fine polishing t × s = 0.50 × 0.16 mm; t denotes the depth of cut and s the voltage.

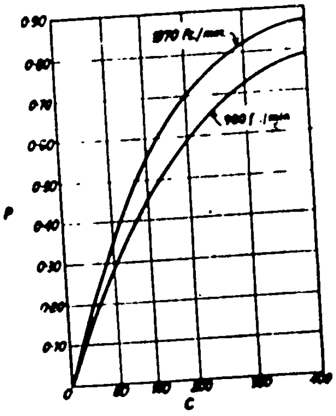

Fig.14 - Relation between the Amount of Material Removed P (gm/min) and the Capacitance C (u f), Plotted for the Hard Metal BK 8 at Peripheral Speeds of 5 and 10 m/sec (980 and 1970 ft/min) The voltage is constant at 220 volts

(According to V.A.Krivoukhova)

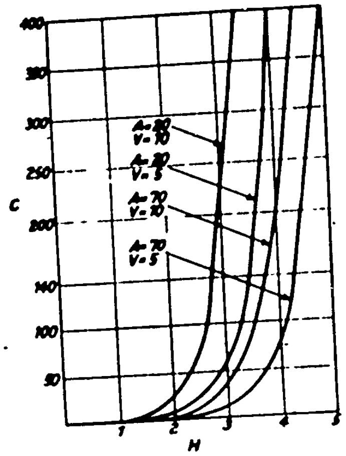

Fig.15 - The Four Curves show the Variation in Surface Smoothness with the Capacitance C. The curves are marked with the voltage and current intensities used. The symbol H is the maximum height of the roughness, in a unit not indicated

(According to V.A.Krivoukhova)

Figure 16 shows an example of such a life curve, where X denotes a tool ground by the spark method and Y a normally ground tool. The spark method here resulted in 5 - 10% longer life, and it is claimed that industrial experiments on a larger scale

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gave even more pronounced differences, since an up to 50% longer life is mentioned for spark-ground tools.

Finally, Fig.17 shows the relation between the surface smoothness H of the workpiece and the cutting speed in m/min, for a tool X ground by the spark method and another Y ground normally. Here too the spark method is superior.

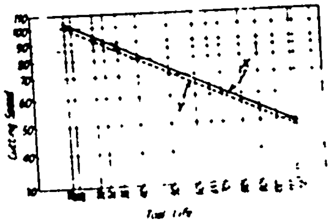

Fig.16 - Life Curve for a Tool X Ground by the Spark Method and a Tool Y Ground by Conventional Methods. X has a 5 - 10% longer life than Y

(According to V.A.Krivoukhova)

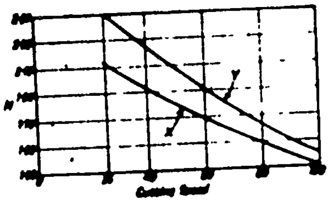

Fig.17 - Relation Between the Surface Smoothness H of a Workpiece and the Cutting Speed in m/min, for a Tool X Ground by the Spark Method and a Tool Y Ground Normally

(According to V.A.Krivoukhova)

Since the hard metal is brittle, the strong pressure against a grinding wheel may cause crack formation, especially if the wheel pitches somewhat. In addition, harmful heat effects may occur. In the electric spark method, tool and wheel do not touch each other at all, and these risks are entirely avoided. The method is therefore especially suitable for brittle materials.

General Pointers

In industrial application of the method, it can be recommended that the following general lines be followed:

As "coolant" it is advisable to use a well-filtered "Aviation Oil" or an emulsion consisting of "Emulsol" boiled with 30 - 50% water. Deposits of dirt, dust,

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and metal particles or other impurities should be removed from time to time. The flow of liquid to the cutting point should be ample, but fully controlled.

The rotating grinding wheel is preferably made of tempered cast iron; if profiles are to be shaped it is best for it to be made of steel or copper. The grinding surface should be kept even and smooth and in normal grinding the tool should be moved back and forth so that the grinding is not done in the same place all the time.

The direction of rotation should always be such that "grinding" is done toward the edge; checking that the wheel is under negative voltage is done by testing whether there is contact before the work is begun. When the side of the wheel is used, the spark gap should be kept below 0.01 mm, while with "grinding" toward the periphery this can be increased to 0.03 mm. The wheel should run freely and without noticeable vibrations.

The tool should have good electric contact with the positive direct-current source, and all contact surfaces must therefore be absolutely clean.

The total time for grinding a hard metal tool (turning steel) with a shaft cross section 20 × 30 mm by the spark method is given as 6 min, of which the machining time takes up 3.5 min. For comparison, the total time for standard grinding of the same tool is given as 4.5 to 5 min. In coarse grinding of the various surfaces, a voltage of 20 - 30 v is recommended at a current intensity of 120 - 250 amp and a capacitance of 300 - 500 µf. In fine-grinding, values of 15 - 20 v, 3 - 7 amp, and 1 - 20 uf can suitable be chosen. The speed of the wheel in coarse-grinding is between 12 and 14 m/sec and in fine-grinding, between 25 and 30 m/sec.

It is stated that the cost of conventional grinding is 70 - 100% greater than in the spark method, and the new technique is regarded as especially suitable for "grinding" of forming steel, thread steel, millers, and cogwheel tools, or wherever a great surface smoothness is desired.

Literature: Bibl.2, 25, 42, 49, 50, 59, 60, and 61.

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Patents: Sweden No. 76 026, England Nos. 335 003 and 637 793, France No. 937 762, and Switzerland No. 257 468.

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THE DEVELOPMENT IN THE U.S.A.

The American development of the spark method seem to have started around 1920 and originated with forms of machining in which electric energy was used for producing higher temperatures. Holz (U.S.A. 1 333 311; 1918) used a friction saw without teeth for connecting the workpiece and the wheel, each with its pole connected to an alternating-current source; this resulted in quicker sawing since the heat of friction was increased by the heat developed by the electric current at the point of contact.

Similarly, Clawson discovered (U.S.A. 1 620 519; 1922) that an extra grinding effect would be produced between two conducting surfaces which moved over each other, when each of them was connected with its pole to a source of current.

Grumpelt (U.S.A. 1 556 325; 1924 and 1 701 919; 1925) suggested a friction saw with toothed edge, which was shaped like a cam wheel in that the many small teeth were supplemented by one large tooth. The workpiece and the wheel were attached to a current source and the actual friction effect was increased by the heat from the electric arc formed between the workpiece and the wheel, whose length increased constantly towards the large tooth of the wheel. Strobel's patent (U.S.A. Re 20 035; 1922) is in line with this.

None of the investigations mentioned concern spark machining, but they are included here to give the general background. They seem, on the other hand, to be the direct point of departure for arc machining, and several of them have essential points in common with it, without however being identical. In addition, the arc method can actually be regarded as a step on the road to spark machining.

The literature search had meanwhile advanced to the middle of the Thirties without finding traces of the spark method, and the first study which the author succeeded in finding which even faintly suggests spark machining is Clark's patent No. 2 308 860 of 1940. This concerns a tool for drilling rock, concrete, etc., and is

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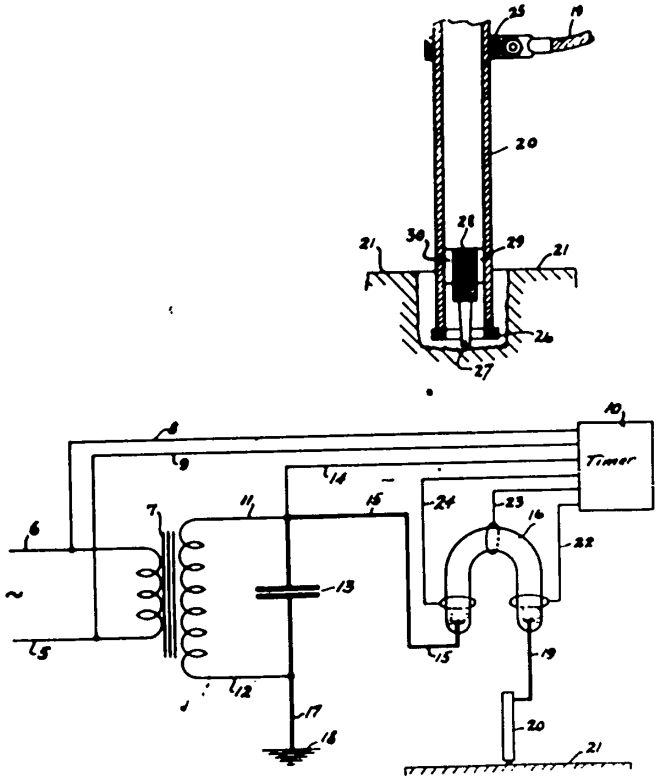

Fig.18 - Tool for Drilling Bedrock, Concrete, etc. Across the capacitor (13) a voltage is built up which, at a certain strength determined by the "timer" (10), is discharged through the mercury-vapor tube (16) and the mining drill (20), so that an electric spark jumps between the tungsten electrode (26) and the rock (21). This is heated locally, and the resultant thermal tensions split the surface layer. First American experiment found in spark machining.

(M.S.Clark, U.S.A. patent No. 2 308 860) shown in Fig.18. In this arrangement, a power source between (5) and (6) is connected with a transformer (7) and, at the same time, provides a "timer" (10) with energy across (8) and (9). Across the secondary of the transformer a capacitor (13) is connected. One side of the capacitor is connected with the ground, while the other side leads across (15) to a mercury-vapor tube (16) and across (14) to the "timer". The mercury-vapor tube is connected over (19) with the hollow mining drill (20). The "timer" is connected with three grids in the tube (16) across (22), (23), and (24). The mining drill consists of a metal tube whose lower end carries a tungsten electrode (26), whose distance from the ground is determined by the shoe (27), mounted to an insulated plug (28) with the air passages (29) and (30).

During operation, the capacitor is charged, and when the voltage has reached a certain point, determined by the adjustment of the "timer", the mercury vapor is ionized and the circuit from ground across the capacitor, mining drill, and back to ground is closed; this releases a spark discharge between the electrode (26) and the bedrock (21). The rapid discharges and the relatively high energy which is discharged will cause considerable heating of the rock surface, and since bedrock has only a low level of conductivity such high thermal tensions will form rapidly that the layer breaks up.

After this time, the development seems more rapid. Starting with the beginning of the Forties, a series of patent specifications appears - Harding, Holfelder, McKechnie - which, from the technique of the Twenties and Thirties via the arc method, finally arrive (around 1950) at the pure spark method. Primarily, the development seems to have been carried forward by the Elox Corporation, Michigan, and sometime later by the Method X Company, Philadelphia, the daughter company of Firth Sterling Steel and Carbide Corporation. Others also have taken part in the work, such as the National Bureau of Standards which solved a single concrete problem, and staff members of the Carnegie Institute of Technology, who have collaborated with Method X; finally, also other firms have become interested in the matter in more recent times.

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Spark-Drilling of Diamonds

The drilling of small holes in diamonds for use as draw dies, etc. is the field worked most intensively during recent years. In the course of this, application of electric methods was introduced, particularly spark machining, and it appears that the technique gradually developed in this field has promoted spark machining in general.

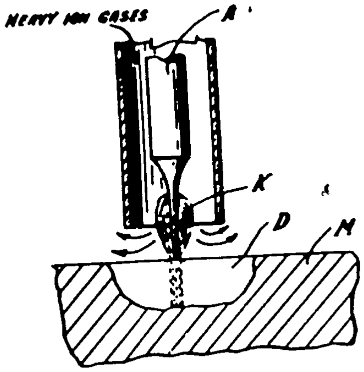

Fig.19 - Setup for Spark Drilling Of Diamond Nozzles. Hole diameters of 0.05 mm and less. The electric equipment consists of a vacuum-tube generator which furnishes high-frequency currents (6000 - 30,000 kc) to the spark gap. Working voltage up to 5000 v

(From U.S.A. pat. No. 2 300 855)

V.O.Allen and R.A.Macintosh suggest in U.S.A. patent No. 2 300 855 of 1941 to drill holes with a diameter of 0.05 mm and less in diamonds, with the help of electric sparks. Their method is a further development of the idea in German patent No. 672 832 (Bergmann et al, 1937; see also "Development in Germany"), and the setup is shown in Fig.19.

The diamond is mounted to a holding plate of a conductive material and immersed into an electrolyte. The electrode A, which preferably should be of tungsten, is tapered so that its diameter is less than the desired hole and it rests against the surface of the diamond with a light pressure. The setup operates on high-frequency alternating current which is provided by the Hartley generator shown. The frequencies are normally between 6000 and 30,000 kc, and voltages up to 5000 v are used.

The surface of the diamond is coated with a thin film of electrolyte through which the spark strikes. This film can be replaced by a stream of humid air blowing through the spark gap (see Fig.20). It is suggested that gases be used which are readily ionized and as a container heavy metal ions, since this promotes the machining speed.

It is maintained that the use of high frequencies and high voltage gives high drilling speeds. It is said that, under the conditions mentioned, holes can be drilled in a diamond of 1.30 m thickness in 2 - 3 hours, while this would take days under the conditions of the German patent mentioned.

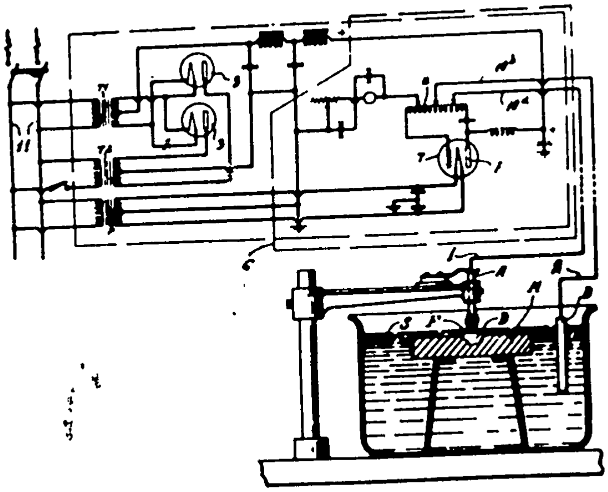

Fig.20 - Increase in Machining Speed, as Claimed, by Replacing Immersion of the Diamond in an Electrolyte by Blowing a Stream of Readily Ionizable Moist Air or Gas through the Spark Gap

(From U.S.A. patent No. 2 300 855)

In U.S.A. patent No. 2 377 159 of 1943, J.Kurtz at al begin with the same fundamental idea. Diamond nozzles are normally bored from two sides, and it is now proposed to eliminate difficulties by making the two holes coincide exactly. This is done by first plane-grinding the diamond in the conventional way and then centering it on one side. With this preliminary drilling as point of departure, the specimen is spark-drilled to a depth of a little over half the thickness of the diamond, so

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that a conical hole results. The mechanical arrangement is, on the whole, analogous to that shown in Fig.19, but the tungsten electrode is made to rotate. As electrolyte, nitric acid or sulfuric acid is mentioned. High-frequency currents of 25 kc or more are also used here. The design is for about 100 watts, and machining is done at voltages of 350 - 1500 v.

After the one side has been drilled, the other side is centered carefully (in the regular manner), and a hole is drilled in the same position as the first, but not so deep that the holes come together. The diamond is then dried carefully and placed between two tungsten electrodes resting on the conical walls of the holes. After this the diamond is drilled through, with a cylindrical hole joining the two conical drillings by letting a high-frequency current with a voltage of 10,000 to 30,000 v pass between the electrodes in gas.

It is said that this method permits drilling holes as small as 0.006 mm.

The National Bureau of Standards developed a method for producing quite small holes - under 0.35 mm - in draw plates of diamonds for drawing hard thread (chromium-nickel, carbon steel, etc.) where great roundness and small tolerance are required. An arrangement similar to the one used is shown in Fig.21, and ten different steps in the drilling are given in Fig.22.

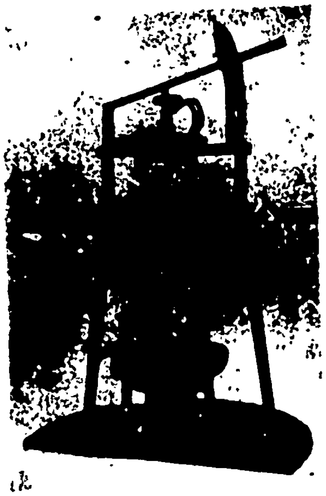

Fig.21 - Device for Spark Drilling of Small Holes in Diamond Draw Plates. The diamond rests on a brass block and the needle electrode, representing the "drill", is held with a light pressure against the surface of the diamond. The machining is done at high voltages (General Electric Co.)

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The first step in the drilling is making a hole of 0.35 - 0.50 mm depth. An electric circuit similar to Lazarenko's is used, only the capacitor is charged to a high voltage before it is allowed to discharge through the point of a needle-shaped electrode, which is held in contact with the surface of the draw plate. The spark jumps from the point of the needle over the surface of the diamond to a brass block on which it rests. The drilling speed rises with the electric energy to an upper limit where the diamond will become damaged; however, there is warning beforehand when the needle, whose diameter is about 0.5 mm, becomes red hot.

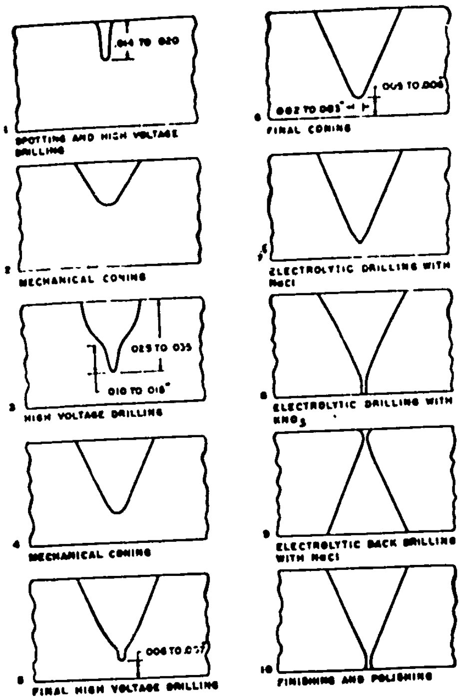

Fig.22 - Drilling of Draw Plates Proceeds in the Ten Steps Shown and is Done by a Combination of Spark Drilling, Mechanical Drilling, and Electrolytic Drilling. This method is said to have resulted in savings of over 100 hours per draw plate

(National Bureau of Standards)

The secondary cone is drilled by low voltage sparks which are discharged into an electrolytic solution. A platinum-iridium needle is used, which is lowered till it touches the botton of the primary cone and rests against it with a light pressure (about 0.2 gm). Another electrode is immersed in the electrolyte, at a little distance. If low voltage - about 90 v - is applied between the electrodes, a spark jumps from the point of the needle, and a conical hole is formed directly under the point. The hole is even and smooth and its form and conicity can be controlled through proper choice of the electrolyte; the size depends on the pressure of the needle against the bottom of the hole.

The entire operation is done in ten steps which, besides the two mentioned electric operations, includes pure mechanical drilling (see Fig.22). The report indicates that this method, in comparison to the ones ordinarily used, saves about 100 machining hours, and that draw plates drilled in this way, compared with others by photoelastic methods, are demonstratably free of stressed surface layer, which otherwise reduces the life and leads to destruction.

Elox Machines

The appearance of equipment for spark machining is due not only on the above-mentioned research but undoubtedly also to the observations which were made in electric etching of metal surfaces, where the wear was observed which occurred each time a spark jumped at the point of contact.

The first machines built - placed on the market in 1943 - also used the same electric alternating-current circuit as the etching equipment. Such a piece of equipment was developed about 1942 by Waidler and Holfelder at Curtiss-Wright Corp. and is described in "Wings" of July 1942. The machining voltage was 110 v, and as an electrode a copper tube was used, through which air was passed to entrain the particles. The first equipment of this construction is shown on the left in Fig.23, while the right side shows a diagrammatic representation.

The equipment contains a transformer producing a secondary voltage of 3 - 15 v, whose one side is attached to the workpiece, while the other pole is connected to a cooling tube, coiled around the magnetic electrode holder. During the machining, the electrode will therefore vibrate and thus open and close the circuit, thus producing the spark.

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These first types were difficult to control and worked slowly; in addition, the electrodes were worn out in about the same time as the hole was bored. They were

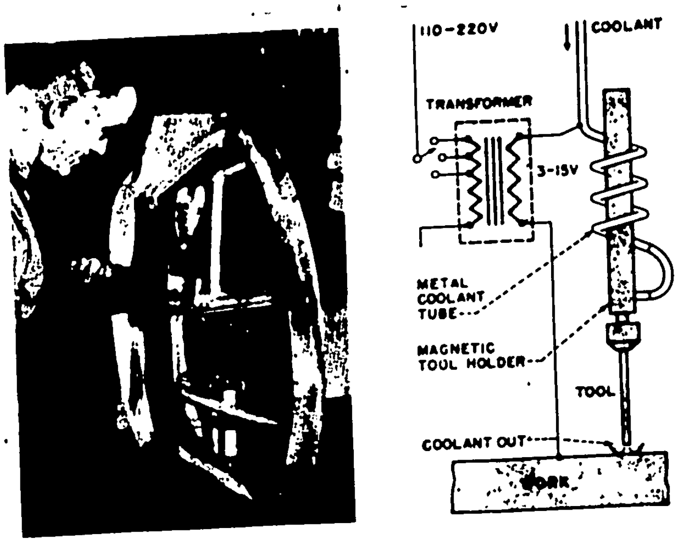

Fig.23 - The First Spark Machining Equipment with Electric Alternating Current Circuit of the Type Used with Electric Etching. Put on the Market in 1943. The equipment worked slowly, had a very large electrode consumption, and was difficult to control. To the right is seen one of the earliest applied principles for a device for removing broken fragments. It works with 3 - 15 v alternating current from a grid transformer. One side of the secondary winding is attached to the workpiece and the other side to the tube for the coolant and, through it, to the electrode. The cooling tube is coiled around the electrode holder, which is magnetic. This imparts a vibrating motion to the electrode, which closes and opens the circuit thus effecting the spark formation.

originally built to salvage parts in which taps, rivals, drills, etc. had become stuck and which were too expensive to discard for this reason. From this came the

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name "disintegrator".

The machinery was further improved when McKechnie abandoned the alternating current and caused a direct current to discharge across a spark gap of a certain length, filled with liquid, electrolyte, or dielectric material (see Fig.24). The left-hand portion shows an Elox machine, model M-10, put on the market in 1950 and working with electrodes of 36-inch length, which, aside from up and down displacement, can also rotate in both directions. The machine is calculated for disintegration and has a servo-controlled voltage which maintains a definite spark length.

The top right of the figure shows rectification of the current, without the principle in Fig.23 being otherwise altered. The bottom of the diagram, at the left shows the transfer of the principle to "grinding" or "sawing" and, at the right, a servo control which, by the changes in the mean voltage of the spark, moves the electrode and the workpiece closer together or farther apart, so that the spark gap is kept constant.

According to this system, "drilling" can be done considerably faster than with the earlier one, and since the electrode is now negative, excessive wear is avoided. The model M-10 "drills" holes down to about 1 mm, and at that size a hardened steel plate of 1 inch thickness can be drilled through in 4 - 5 min. Similarly, it is stated that a $\frac{5}{16''}$ hole is "drilled" in about 10 min.

The holes are about 0.15 mm larger than the electrode and the precision, for the rest, depends on the speed. The possibilities of variation are great, and as a curoisity is can be mentioned that a special machine has been built for deep-hole drilling which operates with a head on each end for drilling from two sides. Holes are "drilled" by this from 2 mm and less to a depth of more than 700 mm.

The development described here as well as the pertaining machinery, originated with the Elox Corp. and can hardly be considered a pure spark method, since the machines lack the oscillatory circuit which otherwise characterizes all spark machining. Actually, the method is intermediate between spark and arc machining and is

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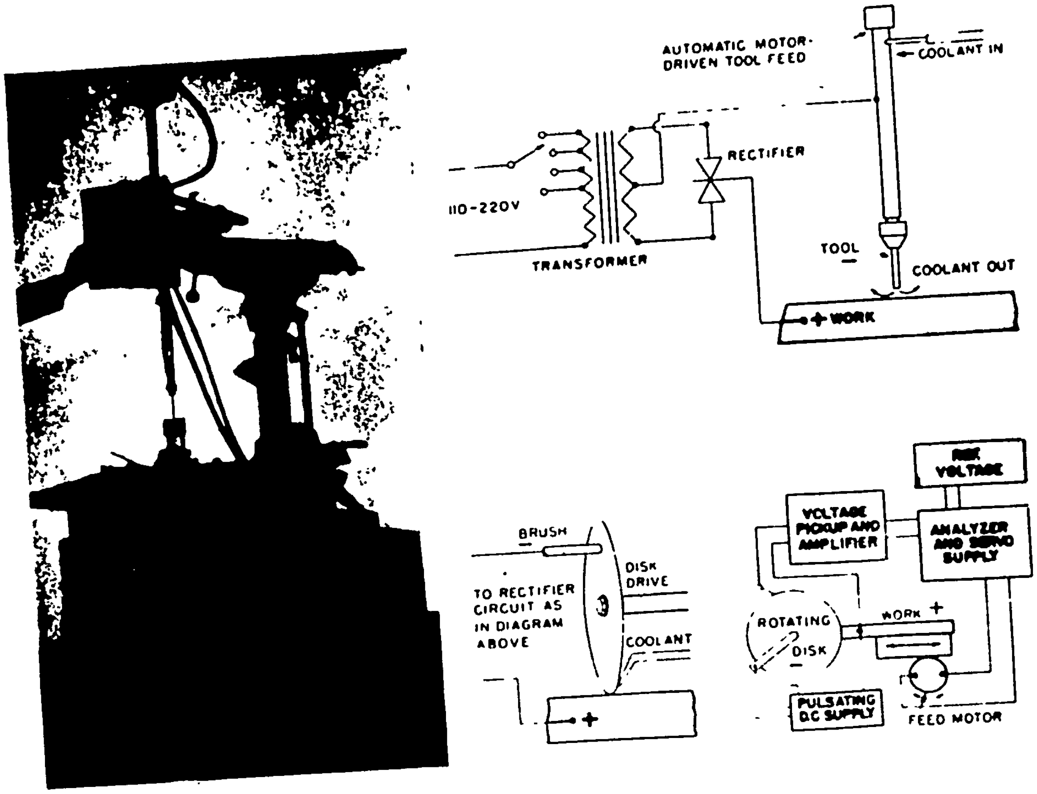

Fig.24 - On the Left an Elox Machine, Model M-10, Put on the Market in 1950 and Intended for Extracting Broken Taps, Drilling of Holes, etc. It operated with 36" long tube-shaped electrodes and has a servo-controlled tension mechanism to maintain a constant spark gap. The electrode holder can rotate both ways as in a drill press, whose standard parts are incorporated in the machine. The right top shows the electric wiring diagram of the machine; note that now it is operated by direct current. The left bottom shows the principle used in sawing, cutting, grinding, etc., and to the right the servo circuit, which records the average tension of the spark and causes variations in it to affect the pressure, so that a constant spark gap is maintained.

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characteristically also known as "intermittent arc".

Accordingly, spark machining is a method for removing metal from the workpiece without physical contact between it and the tool. The principle consists in causing carefully controlled electric sparks to jump between an electrode serving as the tool and the spot on the workpiece to be machined. The method can be applied to all types of a machining such as drilling, thread-cutting, turning, etc., but for the present it is used mostly for the first of these types.

Up to now, the methods have been considered to be slower than normal and only in the most recent years - presumably from around 1952 - has the technique been so developed that this situation changed.

In practice, the spark method has been used in extracting cracked taps, rivals, etc., drilling irregular holes, contour machining, grinding tools, and it should be mentioned that the economical area of application will increase greatly in the future. The materials machined are therefore those of the hard type which can be machined only with difficulty or not at all in the desired form by other methods. As typical examples may be mentioned tempered tool steel, hard metal, alnico, chrome-nickel alloys, manganese steel, stellite, hardened cast iron, tantung, etc., but also softer materials like copper, copper alloys, aluminum alloys, lead, zinc, etc. can be machined by this method.

The spark method is thus based on the realization that it is possible, by causing a spark to jump between tool and workpiece, to remove from the latter particles of a predetermined size and in the desired quantity, while the exact dimensions of the workpiece are accurately maintained, resulting in great smoothness of the surface. The control of the voltage and discharge current, the spark time, and the time intervals between the different sparks, the frequency and other factors determine the machining speed, the precision, and the surface smoothness.

Since these electric data can be varied inside wide limits, the particles torn from the workpiece can be from atom size up to a pinhead. The bombarding material

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is not affected, since the spark effect of the circulating liquid is strictly limited to heating up only a very small localized area of the workpiece. This is heated to very high temperatures, which are in fact indicated up to 10000° to 15000° C.

Normally very little material is removed from the tool electrode in relation to that which is machined off the workpiece, when only direct current is used, with the workpiece connected to the positive pole. The abraded material is continuously rinsed away from the spark zone by the fluid flow as well as by the electric forces. There is no physical contact between the workpiece, and the tool and since the spark gap can be made quite small, machining can be done with voltages as low as 10 - 15v.

Theory

There have been many theories on the mode of operation of spark machining. The following theory - as well as the preceding discussion - was originated by the Elox Corp. It is assumed that the negative tool electrode normally has a number of free electrons which arrive at and depart from the surface. As soon as the voltage between the electrodes has reached a certain magnitude, a stream of electrons will jump from the tool to the workpiece; these electrons will strike the surface of the workpiece and cause the atoms in this area to increase in activity, so that the temperature of the solid surface increases until the material is first fluidized and then vaporizes, with great increase in volume.

When this increase in volume occurs suddenly, such high voltages are generated that particles are torn from the surface. The torn-off particles have a positive charge and are ionized, and will concentrate at the negatively charged tool. Therefore, a stream of liquid is fed through the spark gap, which is to flush away the particles and prevent them from settling on the tool. Nevertheless, some particles will reach the tool and gradually erode its surface. The individual steps in this process are illustrated in Fig.25.

The tool electrode does not need to rotate, but if this is possible, it should

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be mentioned that, in such a case, high precision is achieved, making it difficult for the particles to adhere to the surface and short-circuit the spark gap.

Viewed theoretically, there is no limit to the speed at which the machining can be done, since the amount of energy that can be discharged through the spark may be tremendous. Therefore, practical considerations set a limit here. The size of the particles can be determined from the voltage, the current intensity, and time, i.e., the energy; there are great possibilities of variation. The speed of machining, the size of the particles, and the wear on the tool vary with these three factors, even when their product is kept constant.

General Pointers

As for the speed of machining, the following values are given (1952) for cubic centimeter which can be removed per minute, provided that there is a surface roughness which, measured with a profilometer, does not exceed about 60 μ inches (≈ 1.50 μ): zinc alloys 3.25, steel and steel alloys 0.4, nickel and nickel alloys 0.8, tungsten carbides 0.065, and titanium carbides 0.33, entirely disregarding the hardness of the material. Lower speeds give better surfaces, while higher speeds decrease it. The figures given (which, in addition, seem rather high) are not always a measure for the machining speed. Thus, in drilling, a hollow electrode is generally used; with this, only a ring-shaped opening is drilled so that the piece in the center drops out entirely.

The machining can also be divided into a rapid rough grinding and a slower polishing, where the precision, with care, can be made nearly as great as in lapping, i.e., within about 0.005 mm.

The electrode material can be chosen according to the end use. Often, technically pure copper is used for tap-drawing, drilling of less exact holes, etc. If great precision is needed, ground molybdenum electrodes can be used. With proper control of the process, however, it is impossible to make full use of the higher

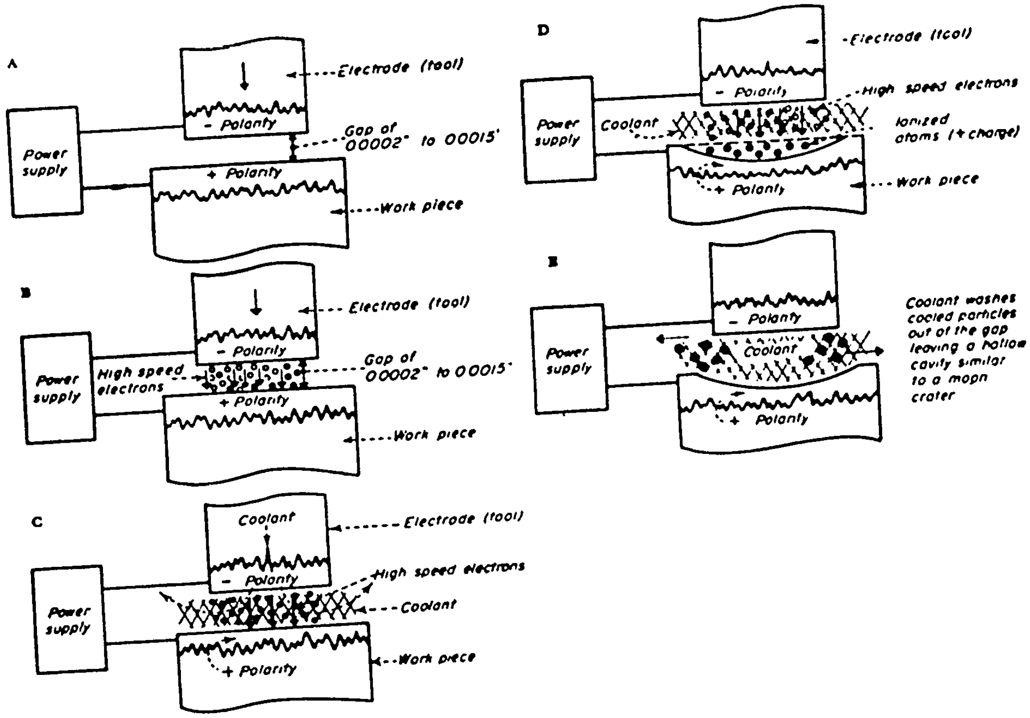

Fig.25 - Assumed Operating Principle of the Spark Method During a Single Discharge, which must be Regarded as an Independent Operation. At point A, the voltage between the electrodes increases, and the negatively charged electrons move toward the surface of the tool. At point B, the voltage becomes so high that the electrons strike the surface and move toward the tool at high velocity. At point C, the same process takes place, but now a liquid flows through the hollow tool electrode and out through the spark gap. At D, the electrons strike the surface of the workpiece and activate its atoms. This portion of the surface is heated to such a high temperature that it vaporizes. At the same time, some of the electrons strike the atoms in the surface and knock the electrons out of their paths, so that a positively charged cloud is produced above the surface. At E, the negative tool attracts the positively charged and overheated particles in the form of vapor, which moves toward the tool. The particles are cooled off rapidly and are washed away by the stream of liquid. The spark ceases at this instant, so that only the removed metal has been heated.

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melting point of molybdenum, and for many purposes the price is too high. Brass and similar alloys are both mechanically and electrically well suited to many jobs.

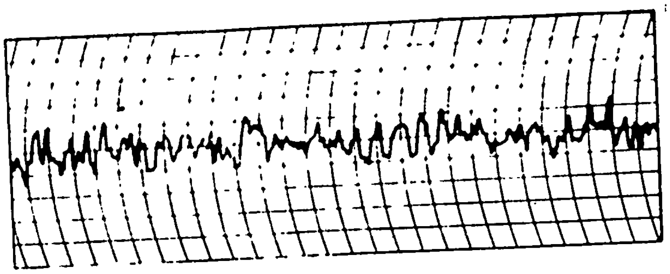

Fig.26 --Profilometer Diagram of Fine Grinding of the Hard Metal Carboloy 55-B, Magnified 25 times. 1 mm = 10 μ in. The surface roughness is 19 μ r.m.s.

In machining a suitable "cooling liquid" is used. Water and soluble oil mixtures can be used for rapid and coarser jobs, as for example tap-drawing. In more precise jobs, hydrocarbon or dielectric fluids are recommended. The fluid is fed through the spark gap under a pressure which, depending on circumstances, may vary between 3 and 30 kg/cm^2, at an average value of about 8 - 9 kg/cm^2. The liquid can be supplied in three ways, either from above through the hollow electrode, or from below through the electrode or, as the case may be, through a hole bored in the workpiece, and finally it can be supplied from the side.

The number of sparks per second is said to lie between 20,000 and one million, while other sources indicate much lower values.

Electric Spark Grinding

Grinding can be done by rebuilding an ordinary grinding machine and providing it with electric equipment. In this machine, a brass wheel is used rotating at a speed of 50 - 500 rpm. The speed is not critical, but it must be below the normal speed of a grinding wheel. Figure 26 shows a profilometer diagram of fine grinding of the hard metal Carbaloy 55-B, magnified 25 times.

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Tool grinding by this method has recently been taken up by the Pratt & Whitney Aircraft Division, which has installed a rebuilt Browne & Sharpe No.10-N tool-grinding machine as well as an Elox machine in the grindery, which every year grinds around two million tools. The equipment is used especially for figure tools. The table of the machine carries a fiberglass vessel, with transformer oil as the dielectric where the profiled brass is immersed halfway into the liquid. The travel of the table is varied by installing a special gear, to obtain a variation between 4.25" and 10" per minute. The spark gap is kept constant from 0.003 to 0.005 mm, with the help of the previously discussed servocontrol. In addition, see Fig.27.

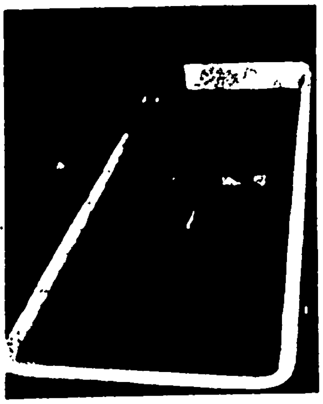

Fig.27 - Machine, Modified for Spark Grinding of Hard Metal Tools. This is clamped in a vise on the platen which carries a vessel with transformer oil. The tools are kept submerged under the workpiece.

With a normal finish of about 60 μ in r.m.s., 0.055 cm^3 of hard metal and 0.06 cm^3 of hard steel could be removed per minute, considerably less than the previously mentioned amounts.

The wheel shows very little wear and is cheap in comparison with diamond and grinding wheels; roundings can be produced with a precision within a few hundredths, without formation of ridges or heat as is the case in normal grinding. An additional advantage lies in the fact that all materials can be ground with the same wheel, which therefore can be permanently installed.

Investigations have shown that hard-metal tools, ground in this way, make a better cut than diamond wheels without lapping. The surface roughness is kept stationary between 20 and 25 μ in r.m.s., but if desired this can be reduced to 2 - 5 μ

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in r.m.s. Experiments have also shown that the spindle must be extremely rigid in order to maintain the very small spark gap and that the dielectric liquid must be carefully filtered.

Pratt & Whitney state that spark machining of tools is simple, quick, and cheap and predict considerable future expansion of the method.

Method X Equipment

The other American firm, Method X Co., which has worked with the spark method, maintains that this is a purely electromechanical process without thermal features. The electric forces in the spark gap become so great that the resultant stresses in the workpiece exceed the fatigue limit. Metal particles are removed from both workpiece and tool electrode without melting, and the surface is left physically and chemically unchanged. It is expressly stated that the "cooling liquid" must be a dielectric, and most often a hydrocarbon is selected. Normally, kerosene is used and a specially developed fluid "Dielectro X", which is said to give increased speed of machining, since the spark will free hydrogen which, in turn, will ionize the path of the spark. The Method X Co., also gives

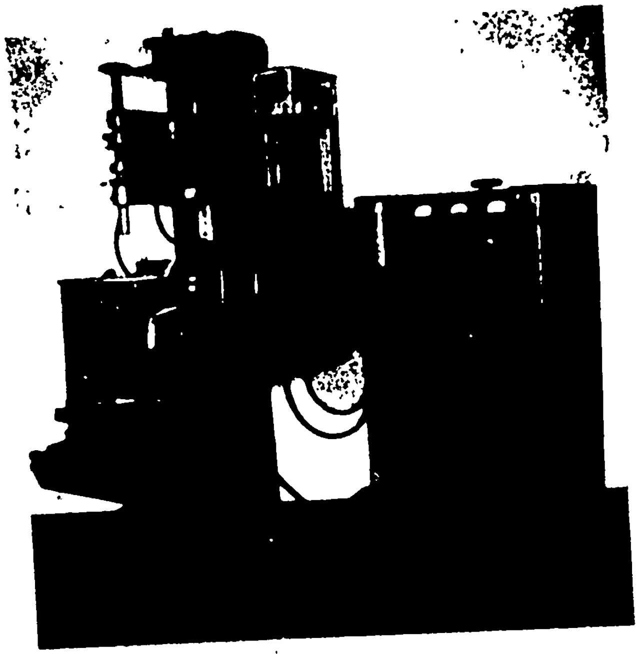

Fig.28 - Method X Machine for Spark Drilling with Amplidyne-Controlled Electrode Voltage. Capacity 7kw.

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another theory which is more in line with the one developed by the Elox Corp.

Figure 28 shows a Method X machine, rebuilt as a drill press. The electrode voltage is automatic and is controlled by an amplidyne amplifier. The capacity is 7 kw, and the time of discharge is given as $3 - 5 \times 10^{-6}$ sec.

Figure 29 shows a diagram of a Method X machine for thread cutting. The thread electrode is carried to the control 32. Also shown is the cutting of threads in ground holes and removal of the core by boring. If an electrode with internal thread is used, an outside thread can of course be produced

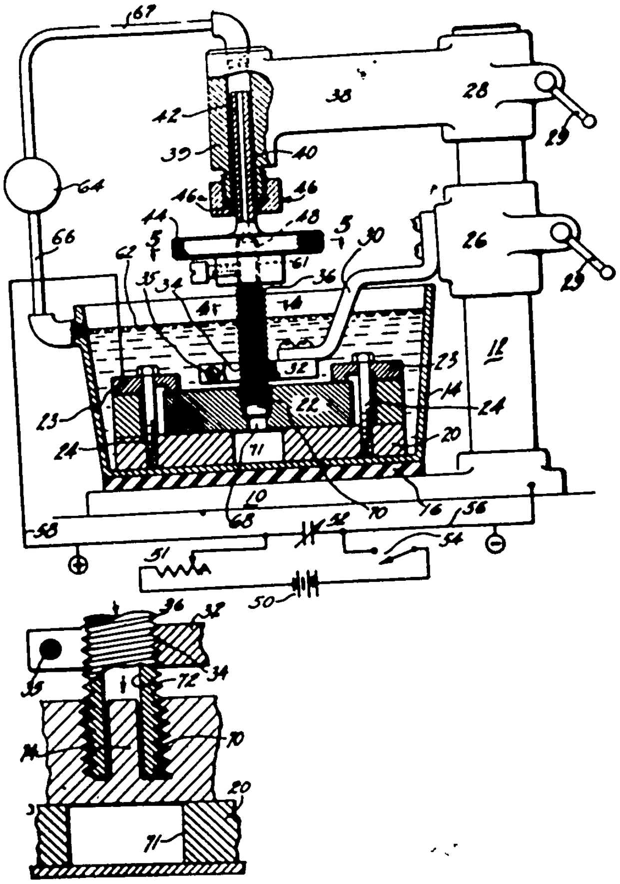

Fig.29 - Operating Principle of the Method X Equipment for Thread-Cutting. The thread electrode is brought forward by the thread control 32. At the lower left thread cutting is shown, perhaps in a bottom cavity with simultaneous drilling of the center. Notice that here too Lazarenko's circuit is used. (E.E.Teubner, U.S. Patent No. 2 650 979).

A 6.3 mm hole can be drilled through a hard metal plate of 5.3 mm thickness in 35 - 38 sec, and if the inductance in the secondary of the pulse transformer is lowered, the time can be further reduced to 22 sec. In a hard metal plate of 12.5 mm thickness, a thread can be cut in barely 10 min, while the time was formerly about 90 min.

It is of interest that the surface smoothness reportedly at this high machining speed is not inferior to that obtained with older equipment; this is explained by the fact that passage of the sparks is more regular. The drawback in the oscillator circuit was the fact that the spark, with all its irregularities, formed a definite link in the discharge circuit. In the new model 5 developed by Method X a series of steeply rising and falling current-producing pulses is superimposed on the discharge point. With the rapid rise and steep drop, the path of the spark becomes ionized more rapidly, so that machining can be done at a higher frequency. The pulses are produced by a capacitor, charging across a transformer and discharging across the rotating spark gap.

This high energy also necessitates a more rapid circulation of the dielectric, since most of the energy is transformed into heat. While this was formerly adequate at a circulating speed of about 1 ltr/min, about 5 ltr/min are required in the new model. This amount is also necessary in order to remove the large quantity of particles which must be carefully filtered. It must be borne in mind that more than 2 mm^3/min machined-off material is involved here, to which must be added the material abraded from the tool electrode.

Spark Grinding of Chip Breakers

At the Watertown Arsenal, a Method X machine has been in use for grinding chip breakers in hard metal plates. Originally, brass electrodes were used, which resulted however in considerqble wear; later, change-over to copper electrodes with an 0.003 mm chromium layer was made. This resulted in a reduction in wear on the electrodes to a fourth, about equal to half the amount of hard metal.

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In the grinding process, a special holding tool is used, where 40 pieces of 1" plates are set up in four rows of 10 inches (in some cases, 80.5" plates). Four plate electrodes, one for each row, "grind" the chip breakers during the machining. As a coolant, kerosene was used, and the electrodes had to be adjusted from time to time with a file. With this arrangement, it was possible to grind 6000 chip breakers per month in one shift, where formerly it took the work of three shifts to achieve the same result in grinding with diamond wheels.

The next step in the development was to test hard metal as electrode material. It was shown that the wear of the electrode amounted to about one half the wear of the workpiece. Therefore, if a hard-metal plate is used as electrode it is provided with a chip breaker at the same time as it itself produces chip breakers in two other hard-metal plates.

A holding tool was therefore constructed for ten plates in one row, just as the electrode holder could also take care of ten plates, so that the one plate, during the machining process, grinds chip breakers in the next one. The chip breakers were about 0.40 mm deep. First, about 0.25 mm was removed from the lower plates by a quick rough planing (approx. 12 min), followed by two polishings which removed the rest (time, about 5 min each) and finally by a fine polishing in which practically no material was removed (time, 3 - 5 min).

After each such cycle the lower plates were shifted outward, while the top plates were exchanged after every second cycle. Two complete operations thus give 30 completed plates and take 50 - 60 min. The surface smoothness achieved by this machining is 25 - 30 μ inch r.m.s. ($\approx$ 0.70 μ).

As a final example, Fig.30 shows a production spark drilling machine which can drill eight radiating elliptic holes in a ring-shaped housing of stainless steel, with an inner and outer wall. The drilling takes place in four steps, each in its head, and the hole tolerance is 0.13 mm. Floor to floor time is 110 min. The machine was built by the Cincinnati Milling Machine Company.

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Bibliography references: 3, 4, 5, 7, 10, 23, 24, 31, 32, 33, 34, 35, 38, 39, 42, 44, 59, and 60.

Patents: British Nos. 578 933 and 580 411; U.S. Nos. 2 300 855; 2 308 860, 2 377 159; 2 438 941; 2 476 965; and 2 650 979.

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THE DEVELOPMENT IN ENGLAND

The first British machine for spark machining appeared about 1952. The development apparently is based on U.S. and Russian inventions as well as on D.W.Rudorff's British Patent No. 637 872 of 1947. The idea in it has been used and developed by "Sparcatron Ltd., Tuffley Crescent, Gloucester, which now, under the name of "Sparcatron", furnishes spark-machining equipment in the prevalent form as small drill presses.

Parallel with this, but no doubt not much earlier, machining was taken up by another British firm, Wickman Ltd., Coventry, which developed a corresponding machine sold under the name "Erodomatic" which, as far as is known, was given great publicity during the International Machine Tool Exposition in Brussels in 1953*.

Electric Spark Turning

Rudorff's patent also made use of Lazarenko's oscillator circuit, but, in principle, it gave a more constructive elaboration not only of the machines used but also of the electric circuit used. Rudorff also showed more diversified types of machines, such as a band saw, a circular saw, and a lathe.

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*In the March and June 1955 issues of "Machines Francaises", G.Cany in the article "Intermittent Arc Machining" with "Steel" as source, mentions that the first patents on which spark machining is based can presumably be traced back about 75 years. It is also mentioned here that even Priestley (1733 - 1804), while causing a spark to jump between the tip of a needle and a plate noticed a dark central stain, surrounded by colored rings. "The surface looked as though it had been ground or corroded by violent explosions." This is due to the fact that very small pits and melted metal particles are present in the center plate. (Solution advanced after printing of the manuscript.)

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Figure 31 thus shows a greatly schematized lathe, with the corresponding electrical circuit. Rudorff expressly presupposes spark formation and wishes to prevent

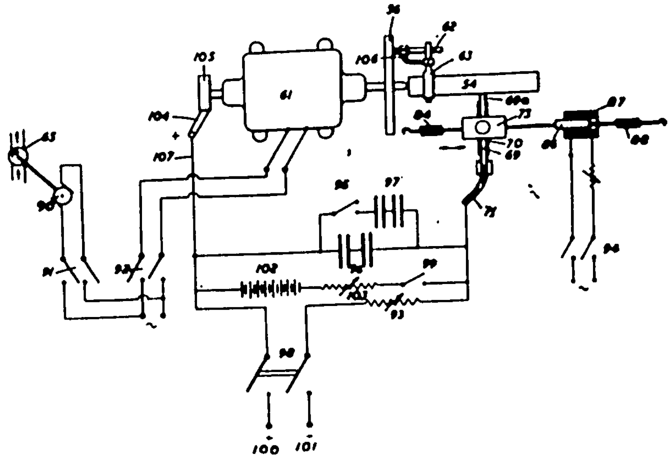

Fig.31 - Schematized Spark Lathe. The work is carried out as with conventional lathes. The electric circuit is as indicated by Lazarenko, but for higher voltages is tapped from the auxiliary battery 102. The coil (87) with the iron core (86) and the springs (84), (88) cause the "Turning steel" (69a) to vibrate with an amplitude of several millimeter, so that the "turned-off" surface is even and smooth. (D.W.Rudorff, from Swiss Patent No. 273 469)

arc formation by feeding a coolant through the spark gap. He claims that the type of liquid is less essential, and the patent specifications include electrolytes, dielectric materials, mixtures with at least one of each type, and gas mixtures consisting of at least two gases.

The claims also include control of the tool electrode so as to maintain a spark gap of constant size; simultaneously, this prevents the hydrodynamic boundary layer from being penetrated.

In the lathe shown in Fig.31, the workpiece (54) is clamped between pinions and driven by the motor (61). The "turning steel" consists of an iron rod (69), which

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is surrounded by an insulating layer (70) and mounted in the steel holder (73) so that only the point (69a) is free. The electrode is connected with the negative pole. The steel holder can be shifted freely back and forth in a lead parallel to the turning line and is fastened over the springs (84) and (88) to a pair of standards on the upper carriage. The slide system of the lathe is otherwise normal of the conventional type. In front of the spring (88) an iron core (86) belonging to the solenoid (87) is inserted. The elasticity is so adjusted that the steel holder is drawn to the left when the coil has no current and is made to vibrate when an alternating current is sent through the circuit. The amplitude of these vibrations is of the order of magnitude of very few millimeter and is controlled during the "turning" process in order to achieve a smooth and even surface.

The motor (61) and the coolant pump (90) are started by the switches (91) and (92). In the main circuit, the current is controlled by the variable resistance (93); by means of the switch (95) the capacitance can be adjusted to two values. The positive pole (100) is connected to the spindle through the brush and tow-ring (104) and (105). In starting, it was found advisable to connect the auxiliary battery (102), which produces a higher voltage than the main current source.

Theory

Rudorff himself thinks that the effect in spark machining results from the thermal effect (46). The temperatures in a spark are much higher than in an arc, so that the spark strikes the surface very suddenly in a quite small area - rather at a point - and will cause a vaporization. The high temperatures in the electric spark are explained by the high current density which prevails in the spark cross section. For a spark current strength in air of 250 amp, Meek (Bibl.54) has calculated a current density of 29,000 amp/cm^2 after a time of 0.5 μ sec from the beginning of the discharge. Since the cross section of the spark increases rapidly during the discharge, this current density decreases, after an additional 0.3 μ sec, to 3700 amp/cm^2. For an arc of 250 amp, Meek computes, by way of comparison, a current density of only 500 amp/cm^2; this would explain the higher temperature of the spark.

The same author also calculated the instantaneous effect in the spark and indicates, for a spark of 500 amp, an effect of 1000 kw/cm^3 after one microsecond from the beginning of the discharge. The temperature of the spark, accordingly, can be determined by spectroscopic means; in thus manner, temperatures up to 12,000° C have been established.

The atomizing effect of the electric spark has been known for a long time and presumably applied for the first time by Th.Svedberg more than 50 years ago for the production of metal colloids; in this connection, it should also be mentioned that spark discharge across a capacitor circuit was used as early as 1919 by V.Kohlschutter for the same purpose [Z. Elektrochem. Vol.25 (1919) p.309]. For machining, the electric spark has only recently been applied (cf. the previously discussed development). Aside from the sources mentioned, the field has also been explored by Jones (Bibl.55,56,57) who assumes that the vaporized amount of material, outside of the energy of the spark, is also dependent on the melting point of the metal in question.

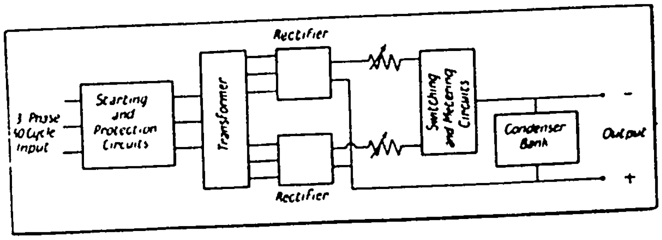

Fig.32 --Diagram of Sparcatron's Spark Generator, Fed by an Ordinary Mains, with Holder Transformer, Rectifier, Control Circuits, and Row of Capacitors

In all spark machining, the tool is given negative and the workpiece positive voltage, since this will cause more material to be removed from the workpiece than from the electrode. Jones explains this with the following example: A spark jumps between two nickel electrodes with a current density of 1,000,000 amp/cm^2. The current density in the anode can be calculated as 100,000 amp/cm^2 and the cathode drop as 20 v. The cathode will have an energy density of 2000 kw/cm^2, while the energy density in the anode will be 20,000 kw/cm^2. Jones shows that, under these conditions the cathode will, within a time of 2.5×10^{-6} sec, heat to the melting point of nickel, while the anode reaches this temperature in 2.5×10^{-8} sec. Since the current strength is high and since the cloud of electrons reaches the anode before the positive stream of ions reaches the cathode, the surface of the anode is machined more rapidly than the surface of the cathode. In the case of spark discharges, which vary from 10^{-4} to 10^{-5} sec, the time difference for the heating of the anode and of the cathode will nevertheless be without significance.

The results cited by Jones were obtained with discharge in air at atmospheric pressure and, in a single case, at 3 atm pressure in a spark chamber. In spark machining, the spark jumps nearly always (at least in practice) through a liquid, which is preferably a dielectric. This is, however, of no significance for the above explanation since the spark will vaporize the surrounding fluid so that the path of the spark goes through a vapor atmosphere. The material removed from the workpiece will be entrained as metal vapor by the cooling fluid and condense in it, and the flushed-away particles will mainly have a spherical shape.

It is possible that, aside from the vaporizing of the metal, mechanical forces are involved, such as oscillations which arise on pulsations in the vapor layer of the spark path (Bibl.58).

The quantity of removed metal is proportional to the discharged energy which, in turn, is proportional to the capacitance and the square of the voltage. However, there are limits to the increase in these amounts; obviously, the energy will increase, but an increase in capacitance will necessarily lead to a decrease in the time constant, so that lower discharge frequencies result. The curve giving the ratio of quantity of material removed to the capacitance will therefore rise to a certain point and then level off (cf. Fig.14).

Sparcatron Machine

Figure 32 shows the principle of the electric system used by Sparcatron, built up as a special panel. The voltage and capacitance of the oscillator circuit can be varied and adapted to different jobs, whether it is a question of rapid rough planing or slower fine machining with greater need for precision and surface finish.

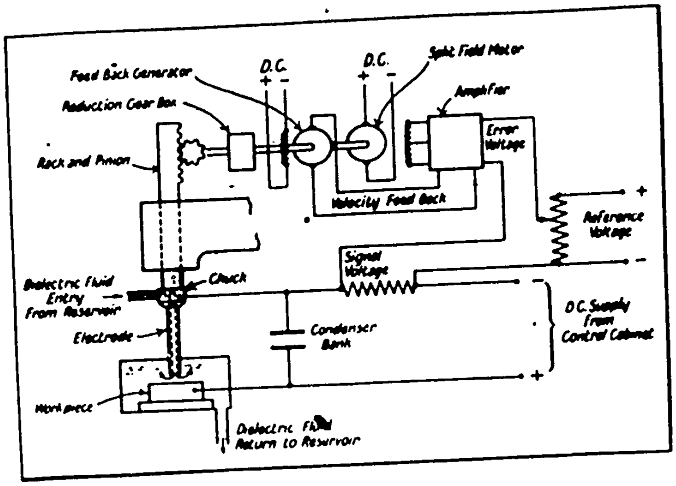

Fig.33 - Sparcatron Spark Drill Press with Electronic Servocontrol to Keep the Spark Gap Constant

Figure 33 shows Sparcatron's construction of a drill press with servocontrol of the spark gap. The tool electrode is mounted in a cartridge which is held in place by the servo system. The clamping of the workpiece and the mechanical parts of the machine are standard and have been described before. The fluid is a dielectric fed downward through the hollow electrode; the reservoir is combined with an effective filter.

Across a resistance, a voltage proportional to the discharge current is supplied; this voltage is compared with a reference voltage of such magnitude that the system is in balance when the spark gap has the proper size. If the position of the electrode is wrong, a pulse is generated which leads to a positive or negative error

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signal, depending on whether the spark gap is too small or too large. This signal is fed to an electronic amplifier and, after amplification, is supplied to a DC motor which, across various gear transmissions with cogwheel and racks, builds up the voltage at the electrode. By means of this control over the DC motor, the spark gap continuously tends to stabilize itself at the preset value.

Fig.34 - Surface Layer of a Spark-Machined Surface, Magnified 100 Times. No changes or only minor changes can be seen in the outermost layer.

By reason of the system's inertia, the adjustment can be delayed slightly, just as the spark gap can be inclined to execute oscillations about its proper position. This is counteracted by introducing a stabilizing feedback. Therefore, a DC generator is coupled to the DC motor, and the voltage furnished by it - which is proportional to the rate of discharge - is fed back to the amplifier. In the newest models, the spark gap, at a working voltage of 110v can be kept constant within 1/100 - 1/200 mm. The spark frequency is given as between 300 and 1800 per second, or significantly lower than indicated by the Americans.

Despite such excessive temperatures in spark discharge, the material is not affected by this; investigations have shown that the surface layer, affected by the temperature rise, is less than 0.002 - 0.003 mm (see Fig.34).

Figures 35 and 36 show a fairly simple Sparcatron bench drill press, with the corresponding cabinet for the electric control equipment. The machine itself can be more complicated, as is the case in the equipment with greater table movement. The "drilling dock" contains the elements which, through the electronic servocontrol, keep the spark gap constant. The machine also can be furnished with rotating elec-

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trode holders and in a model in which the electrode rotates additionally about a given axis.

Figure 37, finally, shows a setup for spark machining of one half of a well for turbine blades. The well, made of tool steel, is tempered. An extra brass electrode is placed on top of the well.

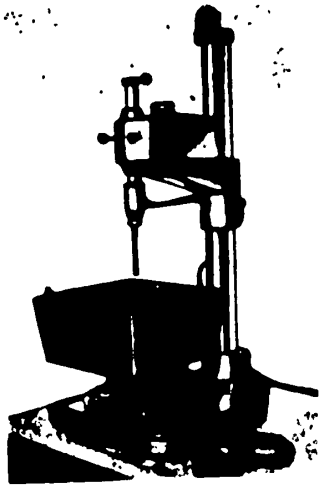

Fig.35 - Simple Sparcatron Spark Drill Press with Table Displaced in Two Directions. The "drilling head" with the electrode holder has a servo-controlled discharge. In other models, the holder can rotate and turn about a prescribed axis.

General Observations

Sparcatron states in some sources that in general, paraffin can be used as a coolant, while other sources recommend kerosene or special fluids. It is said that, for the electrodes, almost any soft material which is a good conductor can be used. Graphite has been used, but generally brass is preferred since it is easily machined to the desired shape. A drilled hole acquires the same shape as the electrode but is a little larger. For round holes, the excess is about 0.03 mm and with properly performed machining, the excess may be twice the spark gap. Under equal conditions, the excess will be constant; it is possible to make allowance for this by making the electrode correspondingly smaller. Such corrections or allowances can be set up in Tables or curves. It is also worth noticing that tapered or stepped holes of many diameters can be produced.

For simple drilling, the electrodes are fairly cheap to produce. However, this method is often used in actual shaping work. This applies to the production of forms, sinks, pressing tools, etc. In this case, the electrode is naturally much more expensive. With this as a model, the workpiece is prepared and can be used as an electrode to fabricate a new electrode exactly like the original.

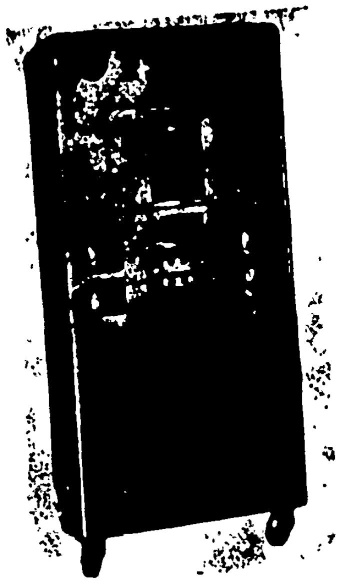

Fig.36 - Cabinet for the Electric Equipment of the Sparcatron Machine

A much used and simple method for reducing the diameter of an electrode, in order to produce the desired free access to a given hole size, consists in immersing it in an acid bath for a suitable time.

In the production of more complicated electrodes, it has been the practice in some plants to execute these in phosphor bronze and "Cronite", casting them so that all refinishing is reduced to an absolute minimum.

The speed of machining is said to be less than with conventional machining, but it is thought nevertheless that it can be increased considerably in the future. As a concrete example, it is mentioned that a glass-hard steel plate of 1/8" thickness was drilled through with a 1/4" graphite electrode in 3 min. Hard metal was drilled through with a 7/32" graphite electrode to a depth of 9/16" in the space of an hour. These speeds seem considerably less than those given by the Americans, which is possibly due to the fact that the American equipment apparently has a somewhat greater power. Besides this, such data on speed can hardly be compared unless all conditions are alike, not the least of these being the surface smoothness achieved, which, generally speaking, is inversely proportional to the speed of machining.

Electric Spark Grinding

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The method does not seem immediately suited to free-hand grinding, but in spite of this, Sparcatron has developed a small hand grinding machine. In all essentials, it resembles a conventional grinder with diamond wheels.

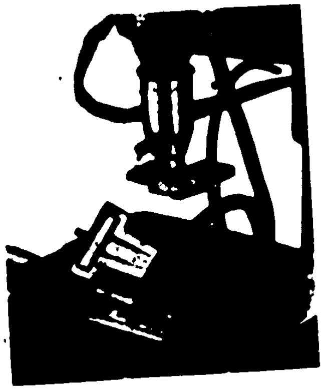

Fig.37 - Spark Machining of One Half of a Tempered Well for Turbine Blades. On top, an extra brass electrode is shown

Sparcatron has also developed the spark method with round grinding. An ordinary round grinding machine is rebuilt so the spindle dock is insulated from the machine and the voltage is applied across a brush and draw-ring. The machining is done as in conventional round grinding, except that the workpiece and electrode do not touch. The electrode which is a wheel can, in some cases, be stationary, but it is preferred to let it rotate. Such an arrangement is shown in Fig.38, while Fig.39 gives a spark-ground workpiece with four different surface smoothnesses.

The change from one smoothness to another is performed at the same voltage without change in the machine itself, merely by regulating the electric constants in the circuits. By this process, surface smoothnesses down to about $5\ \mu$ inch can be achieved; at lower capacities, it can be reduced still further. In addition, it should be mentioned that all electric spark machining produces surfaces which, in comparison with those produced in standard machining, are absolutely free of longitudinal grooves of machining. The surface pattern is completely smooth and without scratches. This also explains that microcracks disappear, which leads to higher fatigue strength and less risk of breaking. The smooth surface pattern has the special property, like bearing surfaces, to hold the oil; therefore, such spark machining is suitable for mating surfaces.

No data are given on the peripheral speed of the wheel or on the optimum table speed and rotation of the workpiece. Here the previously mentioned figures by Pratt & Whitney may be instructive. Conversely, it was reported that, from a workpiece of a diameter of 3/4" and a length of 4 3/4" 0.04 mm per minute (measured on the diameter) can be removed by grinding.

Fig.38 - The Spark Method Applied to Round Grinding and Carried out by a Suitably Rebuilt Machine

In rough planing, a voltage of about 22 v and a current intensity of about 15 amp are suggested. In polishing, the current intensity must be reduced to about 3 amp.

Erodomatic Equipment

The other British firm which builds spark-machining equipment - Wickman Ltd. - gives more or less the same explanation of the process as the previously mentioned one. However, while many sources quote electrolyte, dielectric material, or sometimes air as coolant, Wickman states expressly that the liquid must not be a conductor or a dielectric; this is regarded as a criterion for whether a given method is to be considered spark machining or another form of electric machining. The function

[redacted]

of the fluid there is to deionize the spark gap after each discharge, which is stated as having a duration of some few millionths of a second, and to flush away the removed particles.

[redacted]

Fig.39 - A Spark-Ground Workpiece with Four Different Surface Smoothnesses.

It is said that spark machining, done at high speed, cannot stand comparison with conventional machining processes. However, it is believed that this situation will improve in the future. The application of greater energies increases the speed, but with the limitations mentioned above.

Wickman maintains also that the wear of the electrode is excessive and increases with increasing machining speeds. In certain jobs, where only simple and cheap electrodes are required, it can nevertheless often be worthwhile to force the speed, particularly in rough planing. In addition, it is claimed that the load capacity of a given material is also a contributing factor for the speed with which it can be spark-machined.

The spark gap here is also chosen up to about 0.013 mm and, according to available information, machining speeds between 0.008 and 0.013 mm are reached. The surface smoothness, as a rule, is between 20 and 8 μ inch, but can easily be as much as for example 4 μ inch; in this respect, it is emphasized that the surface smoothness for a given job can be selected in advance and adjusted by regulating the machine constants - something which can hardly be done to the same extent in traditional machining methods.

Wickman also remarks that spark-machined surfaces do not have a glossy or shiny appearance but rather that of a fine sand-blasted surface. The advantage in the smooth surface without directional traces is emphasized, and the significance of the fact that the surface does not (as is usual) have cracks, scratches etc., is easy to comprehend. The many small depressions of which the surface is composed reportedly have a depth-diameter ratio of around 0.3.

In this connection it is of interest that it is claimed that a spark-ground tool has a 5 - 10% longer life that one ground by conventional methods and that the method is cheaper in addition.

Wickman's spark drilling machine "Erodomatic" is for 6.6 kv-amp. In one operation, the "drill dock" is mounted to two cylindrical columns along which it moves. The significance of the precision of such a machine is strongly emphasized, and in consequence of this the two slides of the table are moved by precision lead screws with accurately graduated scales.

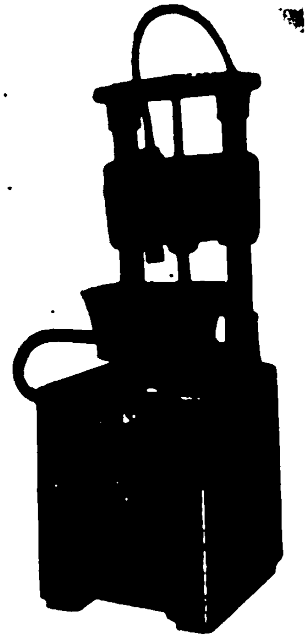

Fig.40 - Wickman's 6.6 kv-amp Spark Drill Press Erodomatic

The machine is equipped with an effective filter for the coolant and a pump for circulating it. The flow of liquid can be changed in direction so that it either can run down through the hollow electrode or be sucked up through it, depending on whether the inside or the outside shape is to be transferred to the workpiece.

Erodomatic also has servo-controlled voltage feed to keep the spark gap constant. The various possible feeds are: 1. manual voltage; 2. automatic voltage with a) nonrotating electrode, b) rotating electrode, c) rotating and oscillating

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electrode, d) oscillating but nonrotating electrode; 3. automatic servo-controlled rotation, in combination with a lead screw unit for producing thread and spiral tracks.

Wickman has also produced an electric free-hand spark-machining unit, available under the name Erodosharp. With this, hard-metal tools are "ground" by electric means in the same manner as with carborundum or diamond wheels. The machine (see Fig.41) is constructed like a conventional grinding machine for turning steel and is of the regular revolving design so that grinding can be done at the desired angles. Instead of the standard grinding wheel, a cast-iron wheel is used here, which constitutes the negative tool electrode.

Fig.41 - Wickman's Free-Hand Spark Grinding Machine Erodosharp Constructed like an Ordinary Grinding Machine for Steel. Inset shows the "grinding wheel", which is provided with radially slanted grooves which feed oil from a central chamber over the periphery of the wheel.

The forward-turning end face of the wheel has an annular oil chamber, with several slanted grooves cut in the surface, forcing the oil from the chamber by centrifugal force. The oil will then coat the end face of the wheel in a thin film and act as a dielectric during the grinding, while simultaneously maintaining a spark gap between the turning steel and the grinding wheel. It is emphasized that it is quite easy in practice to do grinding in this way, but the steel must not be forced against the wheel to the extent that the oil film would break.

With regulation of the electric constants of the circuit rough grinding, fine grinding, and polishing are performed, where the latter replaces the usual lapping

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with diamond wheels. The wheel speed is around 1400 rpm.

Despite the fact that the method can be adapted to practically all forms of machining, Wickman considers the spark method as the best suited for machinings in which simple cutting tools are not normally used, since then advantage can be taken of the fact that the electrode works on a larger area, so that the wear is reduced. As stated above, the spark method is considered slower than normal machining, but in an evaluation of this fact it must be taken into consideration that the spark method is often applicable where ordinary machining fails. It is estimated that the sole purpose of drilling out cracked taps, rivals etc. will justify the purchase of such equipment for an ordinary business.

Wickman claims that the staff working on the development of this process and on the production of the necessary machinery are of the opinion that electrospark machining is a method which offers great possibilities for the future. Theoretical considerations have shown that, in coming years, it will be possible to increase the present operating speeds so greatly that per unit time, it will be possible to remove just as much or even more material than with conventional methods.

The spark machining, therefore, justifies not only the investigations on new machining methods and the work on developing suitable machine tools, but it is also expected that this new technique will make its mark in allowing a freer and less traditional design and elaboration of many machine elements and tools and make possible the use of harder and less easily worked materials, whose application is, for the moment, somewhat limited.

Bibliography references: 9, 113, 16, 17, 18, 22, 26, 30, 31, 42, 46, and 59.

Patents: USA No. 2 526 423; Switzerland No. 273 469.

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DEVELOPMENT IN GERMANY

Spark machining seems to have appeared later in Germany than in the other countries mentioned, and the German development apparently is also based on their technique. However, it must not be forgotten that fairly early and especially in the other electric machining methods (especially Groups 1 and 3), a valuable independent contribution was made (cf. the earlier cited sources).

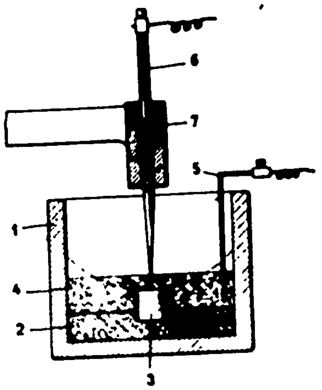


Fig.42 - Procedure for Drilling Holes in Diamonds. The diamond (3) is set in a lead plate (2) and is coated with the electrolyte (4). The needle-type electrode (6) touches the workpiece with a light pressure. If the voltage between the electrodes (5) and (6) exceeds a certain value, there will be a spark discharge, which hollows out the diamond. (From German Patent No.672 832)

The first contribution to actual spark machining which the author succeeded in finding is the German patent No.672 832 of 1937 granted to A. Bergmann, W.Dawihl, and O.Fritsch. It concerns a method for producing depressions and holes in diamonds and other materials difficult to machine and is shown in Fig.42.

Here (1) is a glass container with a holding plate (2) in the bottom. This is made of lead or similar material, and the workpiece (3) is set into it. Over the whole is poured a conductive liquid (4) such as diluted sulfuric acid, sodalye, or a salt solution. An electrode (5), which is not attacked by the fluid is submerged in this without touching the diamond or the holding plate. Another needle-shaped electrode (6) is inserted in a bushing (7) and is held against the workpiece with a light pressure by a weight (not shown) or by a spring arrangement.

If voltage is applied across (5) and (6), a current will flow between the electrodes. If the voltage is increased above a certain amount, e.g., 40 volts, then, according to the patent specifications, the current will drop sharply, accompanied by a spark discharge between the point of the electrode (6) and the diamond; this produces a depression in the diamond. If the voltage remains below the given amount only an electrolytic discharge will take place, which does not affect the diamond. At a sufficiently high voltage, the electrolysis is replaced by the spark formation mentioned.

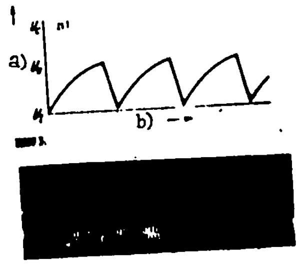


Fig.43 - Above, Schematized, the Charging and Discharging of the Capacitor; Below, the Voltage Course as Shown in a Cathode-Ray Oscillograph. Only the charging can be seen. The discharge occurs so rapidly that the light intensity is too low to blacken a film. (Reference frequency 5 kc) a) Capacitor voltage; b) Time t

The form of the depression or the hole is governed by the magnitude of the voltage If this is high, i.e., above about 80 v, a cylindrical drilling will result, while voltages of about 40 - 60 volts give conical holes.

The machining speed is dependent on the workpiece, the electrolyte, and the voltage, but data are lacking. The method can be used with direct as well as with alternating current and is said to be purely electromechanical.

The process seems basically similar to that developed by the National Bureau of Standards for drilling holes in small diamond draw stones (see Figs.21 and 22) and may possibly have been the point of departure for it.

The investigations in Germany of actual spark machining were apparently started around 1951; at present, there are two firms in each field which have developed the machinery to a point where it could be placed on the market. These are Friedrich Krupp, Essen, and Deutsche Edelstahlwerke (D.E.W.) Krefeld, and as far as can be determined from available information, both also have obtained a license from the above-mentioned American firm Method X Company.

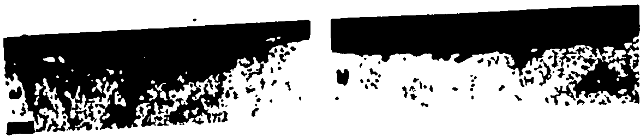


Fig.44 - Surface of a 4-mm Drilling in a 2.5-mm Thick H2 Plate, Spark-Drilled with 220 Voltage. On the left: $C = 2\,\mu f$; $J = 0.8$ amp; working time = 12 min. On the right: $C = 31\,\mu f$; $J = 2.2$ amp; working time = 6 min.

Both German equipment is designed along the lines of the previously mentioned equipment and also make use of Lazarenko's circuit. The first of the mentioned firms explains that the line voltage U_o across the resistance R charges the capacitor whose voltage U_c will increase exponentially with the time constant $\tau 1 = RC$. If the spark gap is so small that it can be bridged, the capacitor will discharge through the spark with an essentially smaller time constant. The brief spark will be maintained until the capacitor voltage drops below the breakdown of the spark; due to the (very small) inductance of the circuit, high-frequency oscillations may be generated. This again changes the capacitor. Determining factors for the frequency of the sawtooth oscillations produced in this way are not only the line voltage U_o, but also the time constant $\tau 1 = RC$ and the size of the spark gap.

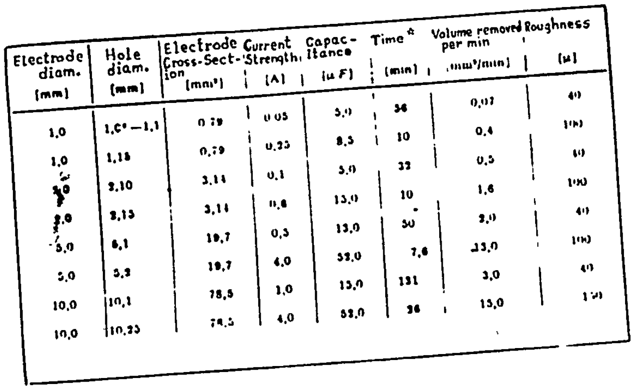
The upper portion of Fig.43 shows schematically the flow of the voltage past the capacitor; the bottom gives an oscillogram in which, by a suitable choice of the resistance R and the capacitance C, a suitably slow series of sparks is produced. The increase in the voltage is clearly defined, while the discharge took place so rapidly that the light intensity of the cathode-ray oscillograph was too low for blackening the film.

Results Obtained

The machining speed is regulated by varying R and C. However, this cannot be done entirely independently, since in the case of a high capacitance, the resistance must not be too low, which would result in an arc rather than in a spark. The most favorable values for a given job are best found by experiment. Table 3 shows the values found by this firm under various machining conditions.

Table 3

Favorable Electric Conditions in Drilling Through a 5 mm Thick Plate. Line Voltage 220 v. Working time, quantity of material removed, and surface roughness are also given.



Electrode diam. (mm)	Hole diam. (mm)	Electrode Cross-Section (mm²)	Current Strength (A)	Capacitance (μF)	Time* (min)	Volume removed per min (mm³/min)	Roughness (μ)
1,0	1,0*–1,1	0,79	0,05	5,0	36	0,07	40
1,0	1,18	0,79	0,25	8,5	10	0,4	100
2,0	2,10	3,14	0,1	5,0	32	0,5	40
2,0	2,15	3,14	0,8	13,0	10	1,6	100
5,0	5,1	19,7	0,5	13,0	50	2,0	40
5,0	5,2	19,7	4,0	52,0	7,6	13,0	100
10,0	10,1	78,5	1,0	13,0	131	3,0	40
10,0	10,25	78,5	4,0	52,0	36	15,0	100

* For a plate thickness of 5 mm.

Column 1 gives the diameter of the electrode, while column 2 indicates the measured size of the drilled hole, followed by the cross section of the electrode in mm^2, the current strength in amp, and the capacitance in μf. It does not appear directly from the source what material is under discussion, but from the context it

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can be estimated that it must be hard metal with a thickness of 5 mm. The next columns give the working time in minutes for drilling through plates and the quantity of material in mm^3 removed per minute, while the last column indicates the profile depth of the machines surface in μ . The working voltage, in all cases is 220 v.

It will be noticed that two sets of electric conditions are given for each electrode diameter. One of these is so selected that there will be a short working time and resulting lack of surface smoothness, the other so that a good surface is obtained, at a still acceptable working rate.

Finer surface finishes are easily obtained, but at the cost of working time. The roughnesses given in the Table are said to be the maximum occurring profile differences of the surface and therefore also contain waviness. As also indicated by the photomicrographs (Fig.44) of the surface, the microgeometry is significantly better than would be assumed from the figures in the Table; if these figures had been given for example in h_{ave} or h_{rms}, the resultant values would have been of the same general magnitudes as previously given by the British and Americans.

Fig.45 - Surface in a Spark-Drilled Hole. Material: chromium-vanadium steel. Capacitance C = 50 μf ; current strength 2 amp. The fusion beads are clearly discernible

Roughly speaking, the Table indicates that the least roughnesses (at the limitations cited above) obtainable with still acceptable speeds is about 25 - 30 μ, while a greater working speed will result in destruction of the surface to a depth of about 100 μ. Figure 44 gives an idea of the obtained finish, showing the surface of a 4-mm drilling in an H2 plate of 2.5 mm thickness and a working voltage of 220 volts. For the picture on the left we have C = 2 μf , I = 0.8 amp, drilling time 12 min. On the

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right C = 31 μf, I = 2.2 amp, and a drilling time of 6 min.

It is stated that, in the luminous arc itself, temperatures as high as or even above 50,000°K. The temperature of the electrode in an arc or a spark, on the other hand, does not exceed 4000°K. Thus, spark machining is based on the very brief and very high temperatures which arise in extremely localized areas. This produces thermal stresses which lead to the detachment of individual crystals or separation of the crystal bond, as shown in Fig.44 on the left.

Fig.46 - Grinding of a Surface in the Same Material as in the Preceding Photograph. Working conditions: voltage 220 v; current strength 2 amp; capacitance 56 μf ; thickness of the material 6 mm, electrode diameter 6 mm; drilling time 15 min.

If a spark-machined surface is examined under a microscope, signs of fusion will be observed even with hard metal. These fused particles are not exclusively due to the cobalt but apparently also fusion of the tungsten carbide in machining. If the particles are filtered from the fluid and the powder residue is examined under the microscope, it is possible to demonstrate ditungsten carbide. A smaller portion of this powder consists of the normal hexagonal carbide W_2C with a lattice constant of a = 2.986 Å, while the main part consists of a cubic face centered crystalline phase which probably also has the formula W_2C. It is known from investigations by K.Becker [Z.F.Elektrochemie 34 (1928) pp.640-42] and J.J.Lander and L.H.Gerner (Am. Inst. Min. and Met. Eng., Tech. Publication No.2259, 1947) that W_2C has a high-temperature modification for which the latter authors found a lattice constant of a = 4.16 Å, while the constant for particles from spark machining is an insignificant 4.228 Å.

It is interesting that the same cubic phase also appears when pure tungsten carbide without a binder is spark-machined with a pure tungsten carbide electrode. The same phase also appears in drilling of metallic tungsten with a tungsten metal electrode.

The fusion appears more pronounced when working fusible metals such as iron or zinc. Thus Figs.45 and 46 show the surface of a spark-machined tempered chromium-vanadium steel (EFM 8272) with a composition of 0.4% Cr, 0.8% Ni and 0.1% V. In Fig.45, where C has a value of 50 µf and the current strength is 2 amp, fusion beads are clearly seen.

The high temperatures cause formation of a special surface, in which copper particles appear; this means that these particles must have traveled from the cathode to the workpiece and deposited there or were welded to its surface. In drilling electrolyte iron with a microhardness of 170 kg/mm^2 (20 gm load), the surface layer produced has a microhardness of 790 kg/mm^2. This layer contains small amounts of cementite and individual needles of martensite; the main part cannot be eroded metallographically and, to judge from X-ray examinations, consists of austenite. Since, among other things, this phase is stabilized by a high carbon content, it is possible that this is due to a carburization. The particles produced in the spark machining consist of cementite and tetragonal martensite. This surface hardening might have significance in production of sinkers and similar tools of steel.

In summary, it is stated that this machining is of a complex nature and that it proceeds somewhat differently, depending on the characteristics of the machined material. Apparently the removal of material is due to several causes, in that spalling caused by thermal stress, vaporization, and cathode atomization each plays a role, and a more exact analysis of the whole process must be reserved for later thorough investigations.

It is further indicated that a spark-machined surface for most applications must be retouched, to remove the affected surface layer. Although this is only thin (according to Table 3, between about 40 and 150 µ) it nevertheless indicates destruction of the surface, making it preferable to remove it by subsequent polishing

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or lapping; this, however, is not considered an obstacle in practical spark method.

Experience by D.E.W.

The other German firm interested in spark machining, D.E.W., has named its method Elbo-process (from "electric boring process"). The fundamental principles are as previously described. This equipment works with voltages between 10 and 110 v and can give between 1000 and 10,000 discharges per second. Kerosene is used as a coolant, and it is stated that the size of the spark gap depends on the penetrating power of the dielectric fluid and the applied voltage. During flashover of the spark local fusion and vaporization takes place in most metals accompanied in hard metals by detachment of small particles. Beads of fusion and accumulated small particles have a diameter between 10 and 40 μ; smaller machining voltages give smaller particles and better surface finish.

The surface smoothness achieved is stated by this source as about 20 - 40 μ; only on application of very high voltages will more or less deep grooves and occasionally small scratches appear.

In different hard metal types, the roughness and the tendency to scratch formation increases in the same order as the sensitivity in grinding, other conditions being equal. The qualities F1 and H2 should always be machined with low voltage; the tougher qualities such as G2 to G6 are far less sensitive. Sintered parts of drill carbide cannot, from what is said, be spark-machined, since particles of millimeter size are torn out.

It is therefore asserted by this firm that retouching is necessary, and a machining allowance of 50 - 100 μ is given as suitable in most cases. Workpieces which can be mounted in round or plane grinding machines are easily retouched with diamond wheels. Irregular workpieces are lapped with crushing bort, or drilling carbide paste, smeared on cast-iron forms of the desired shape is used for speedy removal of the rough surface layer. This applies especially where the work can proceed auto-

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matically, as in cases where the workpiece can be mounted in a filing machine and forced by a weight against the up-and-down moving lapping strip.

For the electrode, copper or brass is recommended and for smaller holes, tung-

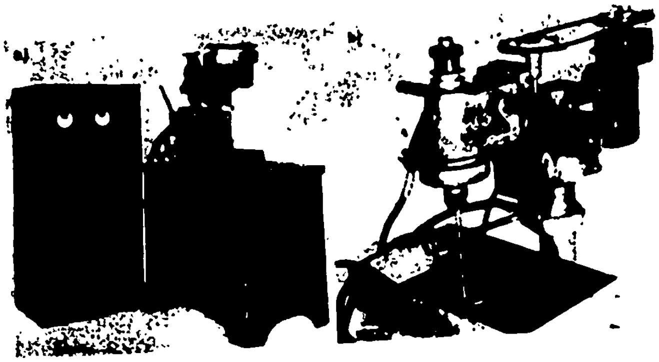

Fig.47 - Friedrich Krupp's Electric Spark-Machining Equipment, Consisting of a Drill Press with Electronically Controlled Voltage Feed and Electric Control Panel. On the right, the drill press is shown in more detail.

sten. The spark gap is given as 50, 100, and 150 μ with 20, 60, and 110 volts machining voltage, i.e., somewhat higher than that indicated by other sources.

Elbo mentions, in contrast to other sources - apart from the first Elox machine - a considerable electrode wear. In machining of hard metal, the wear of the electrode reportedly is three times the amount of material removed, i.e., a 30-mm piece of electrode is used to drill a hole of 10 mm depth. In addition, the electrode is worn along the periphery so that a lancet-shaped hole is formed or, in drilling through, a conical opening. If the hole is to be cylindrical, a long electrode is needed, at least 4 times the drilling depth. For bottom holes, several sharp-edged or hollow electrodes must be used. Extremely tapered drillings require electrodes, whose conical shape is considerably more tapered than the desired hole. For example, a tapered drilling with a 90° cone angle without pre-drilling was produced with a copper electrode whose cone angle was 22°.

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In the production of cylindrical holes, it is preferred to have the electrode rotate. For very fine holes a wire is used, which must be accurately running and sufficiently rigid. If the thinnest practicable electrode is assumed to consist of a 0.10 mm thick tungsten wire, then the smallest spark gap - 50 μ - will result in a minimum hole diameter of 0.2 mm. The greatest drilling depth with this diameter is 2 mm. If the hole diameter is increased to 0.3 mm, the drilling depth rises to 5 mm. The electrodes must then, as mentioned before, be sufficiently long to keep the hole from becoming conical.

The limitations in the drilling depth become obvious when considering that kerosene must be able to penetrate to the bottom of the hole and flush away the loosened particles. In larger drillings, this presents no difficulties, since kerosene can be fed through the hollow electrode. If the electrode is rotating, the effect can also be achieved by providing the electrode with milled-off surfaces, to permit easier penetration of the fluid.

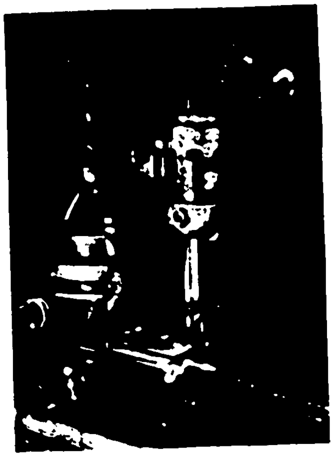

Fig.48 - Electric Spark Drilling Machine by D.E.W. (Elbo process) with Automatically Controlled Voltage Feed to Keep the Spark Gap Constant

The electrode wear, Elbo states, seems to be far greater than that indicated by the other sources mentioned. Only for the first completed American Elox machine (Fig.23) is a wear approximately comparable with this ever mentioned, where it was reported that the electrode became worn nearly as fast as the hole was bored. The wear was sharply reduced, however, on changing to a DC circuit. Wickman also mentions a relatively great electrode wear, without its reaching, however, the values given here.

With respect to the machining time, it is also stated by the Elbo people that this is longer than with standard types of machining. This is stated to be the reason why it is used primarily where ordinary machining is possible only with difficulty or not at all, as for example with hard metal. The ratio of working speeds in spark machining and ordinary machining is said to be of the same general order as that of lapping with drilling carbide or diamond dust to grinding with carborundum or diamond wheels.

When one considers that, at each spark discharge, a certain amount of the workpiece, and three times this amount of the electrode, is vaporized and that for electrical reasons the spark frequency cannot be increased above certain limits, it will be understood that the working speed and the energy which can be converted in the spark gap are limited; this is even more true if, for a suitable surface finish, the sensitivity of the workpiece must also be taken into consideration.

The longer time required is counterbalanced by the fact that electric machining requires no hand work and, being set up, often can proceed entirely automatically.

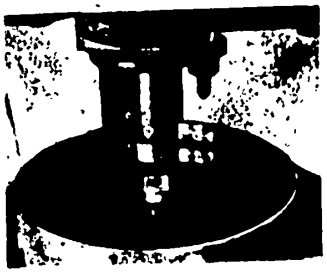

Fig.49 - Simultaneous spark drilling of 5 0.8 mm holes in a 1 mm thick cut plate of hard metal. Working time in all 20 minutes.

As a typical example, it is mentioned that a copper electrode will remove 0.08 - 0.15 gm of hard metal per minute and that, in this process, an electric force of about 1 kw is converted in the spark gap.

Both German statements as to the machining speeds indicate considerably lower speed than the Russian, British and especially the American data, a fact which is no doubt due to the newness of the technique and the relative low power of the machines.

In Fig.48 the D.E.W. drill press for spark machining is presented. This mach-

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ine does not differ basically from the other equipment described. The voltage feed is controlled in this machine by a Leonard device, which maintains the proper size of the spark gap.

Figure 49 gives an example of the drilling of a series of holes in a 1.0 mm thick plate of hard metal. The diameter of the holes is 0.8 mm. Five wire electrodes are fixed in the holder, and application of a low working voltage all holes can be produced simultaneously in 20 min.

Fig.50 - An Example of a Job not Producible with Conventional Machine Tooling Methods. With spark machining, the miller with inside toothing was produced with the help of the electrode shown, which was fixed in a holder. On the left a new electrode, on the right a used one which has produced three teeth.

Figure 50 shows a ring shaped miller with inside toothing, which cannot be produced by conventional methods of machine tooling. The electrodes used are shown in the lower portion of the photograph, on the left a new one, on the right a used one. The electrode is attached to a holder so that it can slide into the opening. The excessive wear is clearly indicated by the difference between the new and used electrode, especially when it is taken into consideration that the used electrode had only produced three teeth.

Finally, Figure 51 shows two flash tools, whose thread profiles are produced by the electrode shown. The steel was first shaped like the one shown on the left. It will be noticed that is is possible to machine the steel shaft and the hard metal plate simultaneously.

From the preceding it appears that the results obtained in Germany up to now do not compare with those of the Russians, British, and especially the Americans. It is emphasized, however, that this is only the beginning of a development, and

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that the future may show how far the process can be improved and which jobs should preferably be done by spark machining.

Bibliography references: 23a, 42, 44, 45b, 59, and 60.

Patents: German No.672 832.

Resumé

The account given in the preceding with respect to spark machining development in Russia, the U.S.A., England, and Germany shows that in all these countries intensive work is being done on the related problems and that apparently the method is considered valuable as a means of saving expensive diamond grinding wheels. In addition, the method is considered of great significance for machining newer materials, which are always being produced and which can be machined only with difficulty when using conventional methods. This is true whether such materials enter into structural elements or are used in the production of tools.

Fig.51 - Flash Tool in which the Thread Profile (M20) was Produced with Spark Machining, with the electrode shown. The hard metal as well as the steel shaft are provided with profiles.

The same principle used as a basis for the spark machining applies everywhere. An electric spark is caused to jump between a negative electrode and the positive workpiece, while simultaneously a liquid is fed through the spark gap which is to deionize the spark path, cool, and flush away the removed material. The spark voltage is always produced by charging a capacitor across a resistance with this capacitor being connected in parallel, across the spark gap; direct current is used. This oscillator circuit is characteristic of all spark machining and was described for the first

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time by Lazarenko, who was also the first to use this circuit in combination with suitable equipment for applying the process.

Although the type of cooling liquid is given by different sources as widely varying, there is general agreement, at least in practice, in using a dielectric material, preferably kerosene, transformer oil, or certain liquids produced for the purpose.

The circuit constants can be varied within wide limits, and the choice has an influence on the machining speed and the fineness of the surface. High voltage, current strength, and capacitance give great speed but little fineness, and vice versa. Also of influence is the spark frequency and thus the amount of energy discharged.

The statements by various sources are quite different, and since the conditions used for the available experimental results cannot always be determined with sufficient certainty, it would be difficult to find a common denominator for the widely divergent information on machining speeds, available from the many publications on the item.

The American reports seem to be the most optimistic, the German the least, and the reports from Russia and England occupy a middle position. This obviously is connected with the entire development in which the U.S.A. is, for the moment, far out in front, while Germany entered the field only a short time ago, and England and Russia take up the intervening position.

This is also reflected in the machinery which has been put on the market in the respective countries. In the beginning, these operated with effects of one or two kilowatt, while the German equipment is now at about 3 kw, the Russian slightly higher, and the British at 6 - 7 kw. Opposed to this are American spark machining equipment with effects which, a year ago had reached 12 kw.

It also seems that the Americans, aside from increasing the working speed by applying greater effects, have also been able to preserve and improve the process control by modifying the electric circuit and, by making suitable structural arrange-

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ments, have also been able to control the spark discharge itself so that some of the limitations mentioned by others have, to a certain extent, been successfully eliminated.

There seems to be considerable agreement as to the surface finish which can be achieved by spark machining. For many purposes, where an even smooth surface is desired, it is common to encounter orders of magnitude of 60 μ inch (≈ 1.50 μ), and often values as low as 15 - 20 μ inch (0.4 - 0.5 μ), or even down to about 5 - 10 μ inch (0.10 - 0.25 μ). The requirement for a sufficiently fine surface is apparently not an insurmountable technical obstacle but can be achieved only at the cost of greater machining time.

The possible machining precision is also, generally speaking, a matter of agreement. According to the various accounts, it can reach thousandths of a millimeter, but here too it is true that the closer tolerances involve increased time.

On the other hand the opinions are somewhat divided as to the surface layer after spark machining. The Americans say that it is not affected or destroyed, while the Germans mention a destroyed surface layer of 0.05 - 0.10 mm thickness, which must be removed by subsequent lapping with crushing bort or drilling carbide. Midway between these two concepts, the British maintain that the surface is affected to a depth of 0.002 - 0.003 mm, but in general this is not considered to require a refinishing.

The working speed depends on the effect used, the electric constants in the circuit, charging and discharging frequencies, and on the controllability of the spark discharges themselves; in addition, the material in the workpiece to be machined is of essential significance, inasmuch as the materials which traditionally are considered difficult to machine require the longest time also in this process. At the same time, it is important that the spark gap be maintained constant; in practice this is quite impossible unless the electrode voltage is servo-controlled. This, in turn, has the advantage that entire machinings, once started, can run automatic-

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ally without continual inspection. To give general guide lines for the working speeds, it can be stated with all possible reservation that, at a surface smoothness of about 60 μ inch (≈ 1.50 μ), 0.05 - 0.15 cm^3/min or 0.80 - 2.25 g/min of hard metal can be removed, while the corresponding figures for hard steel are 0.05 - 0.25 cm^3/min or 0.40 - 2.0 gm/min and for tempered steel around 0.1 cm^3/min or 0.80 gm/min. Softer materials can be machined more rapidly, and it should furthermore be remembered that figures can be obtained which are considerably above or below those mentioned here.

The electrode material is not critical, and often brass or copper is used. As to the wear, there seems to be some disagreement. Aside from the first equipment, the Americans claim that it is extremely minimal. The Germans report excessive wear leading to distortion of the workpiece. It is emphasized that three times as much of the electrode is abraded as there is material removed from the workpiece. The Russians mention nothing as to wear, while the British, with reports of a reasonable wear, take the in-between standpoint.

Spark machining has taken place mainly as a type of drilling, but has also often been applied to thread-cutting. Not only inside but also outside shapings can be performed merely by shaping the electrode correspondingly. The method has also been applied with success in other forms for machining such as round grinding, plane grinding, freehand grinding, turning, reducing, and sawing.

The spark method must indeed not be hastily compared with the conventional forms of machining, so long as it is a question of usual materials. This is not the case when it comes to materials that are difficult to machine, where standard methods either are very slow or fail entirely. Here the spark method can often compete or even be the only answer. This must be taken into consideration in evaluating the circumstances, and it must also be remembered that the process, once started, can run automatically, so that the same operator can take care of many spark machines at the same time, or perform other work in the meantime. Under conditions where this

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can be practiced, the question of a slightly longer or shorter working time is therefore of less significance.

Although spark machining must be considered a new working process, it is so far developed that it has been successfully used in various machinings. At the same time, the development of machines for the process has been so steady that equipment is now on the market, meaning that the method has moved from the preliminary stage of laboratory tests into the shop as a piece of production equipment like the rest of the machine equipment.

The new technique is only in its infancy, but if it fulfills its promise it should be interesting to follow its future development, to observe its adaptation to normal jobs of the shop, and to see what place it will take among the conventional methods of machining.

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ELECTRIC ARC MACHINING

In discussing the electric spark machining in the Section "Development in the U.S.A." reference was made to the first beginnings of arc machining; at the same time, an American device by the Elox Corp. was described which must be considered as closest to an electric arc machining equipment. Figure 52 shows schematically another arc machining equipment and the corresponding electric circuit. This consists merely of a current source which generates a steady or pulsating direct current and which is connected across a variable resistance with the workpiece and tool. It is preferable to use direct current, since the electrode wear is otherwise too great.

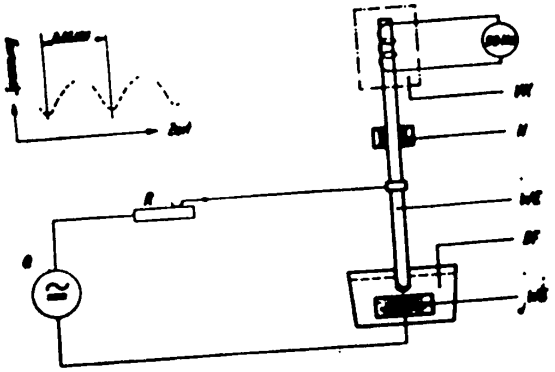

Fig.52 - Diagram for Arc Machining. The current source Q furnishes a continuous or pulsating direct current and is connected across the variable resistance R with the electrode and workpiece. The latter, WS, is immersed in a coolant DF. The spindle is set in H and carries the electrode WE. At the top, there is a vibrator head VK which makes the spindle swing, so that an arc is continually turned on and off between workpiece and electrode. The inset shows an oscillogram of the voltage slope. (W.Ullmann)

The workpiece WS is immersed in a vessel with cooling liquid and the electrode WE is fixed in the spindle, which is controlled in the bearing H. Above the spindle, the vibrator head VK is fed by a usual 50-cycle mains. This causes the electrode continually to rise and drop on the workpiece, thus continually connecting and disconnecting an electric arc. The inset in the picture shows an oscillogram of the voltage slope.

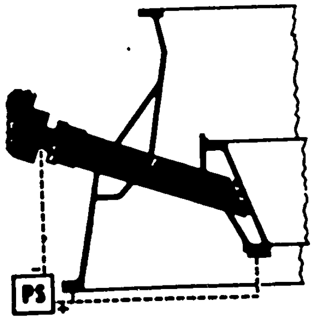

Fig.53 - Schematic Diagram of the Fourth Stage of the Production Equipment of the Cincinnati Milling Machine Co., Shown in Fig.30. The elliptical holes are drilled out with a tube-shaped electrode. In the three preceding stages the holes are drilled in the three outer covers.

In this method, a dielectric can be used as coolant, such as kerosene, transformer oil, or specially prepared liquids (electrolytes such as waterglass or ordinary water). The two latter liquids are used especially for jobs which do not place excessive demands on surface smoothness, such as reducing and drilling of cracked cutting taps, etc.

The result in arc machining are analogous to those given earlier for spark machining. However, the arc frequency is considerably lower than the spark frequency so that the machining is done to a greater degree by fusion of the surface. If the liquid used is an electrolyte, the condition mentioned is supplemented by a chemical effect. The surface will be less good, partly as a result of the rougher fusing, partly because the arc has a tendency to follow the once established and ionized path, regardless of whether, at a given moment, this represents the shortest way between tool and workpiece.

Arc Machining Equipment Produced

Arc machining can presumably be traced back to around 1920, and the first commercial equipment appeared around 1942. Although equipment of this type has mostly been used in jobs in which the smoothness of the surface is less essential, this does not preclude finer machinings from being carried out. There are only a few machines of this type on the market.

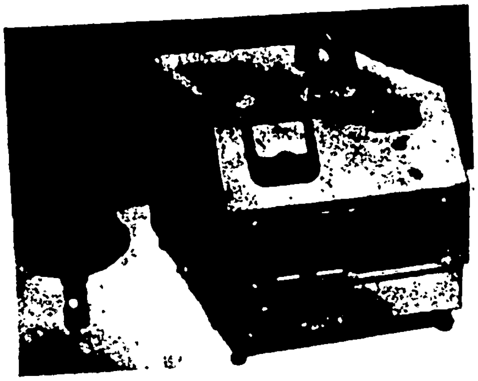

Fig.54 - Portable Elox Machine for Extracting Cracked Cutting Taps, etc. The electrode holder is attached in a drill press, and the cabinet with the electrical circuit is connected to the power line. As coolant, ordinary water is used. Weight about 25 kg.

Figure 23 shows a diagram for an Elox machine, and Fig.24 gives a machine with an effect of 2.5 kv amp. The spark gap is kept constant with the help of a servo control. It is stated that, with this machine, a 1-inch steel plate can be drilled through with a 5/16" electrode in 5 min, and correspondingly a ½" tap can be drilled out to a depth of 3/4" in 5 - 6 min.

Figure 27 shows electric arc grinding with an Elox machine, and the production equipment shown in Fig.30, built by the Cincinnati Milling Machine Co., also works with an Elox machine. The last stage of the machine is shown in Fig.53. The outer diameter of the housing is 38" and the inner 22". The tolerance of the elliptical holes to be drilled is ± 0.13 mm, and the four holes are to be flush within 0.025 mm while the angle between the axis of the holes and the vertical is to be kept within a tolerance of ± 5°. The 32 holes in the housing were drilled in a total time of 110 min. Tube electrodes of brass are used, having the shape of the elliptical hole; the electrodes are fixed in four carriages, whose voltage feed is servo-con-

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trolled and which, in addition, is provided with an auxiliary feed driven by compressed air. As coolant, a dielectric material is used, kept in a jacket which encases the entire housing.

Since the end faces of the electrode must accurately fit against the surface of the housing, four electrodes, each on its carriage, must be used because of the different diameters of the four walls. The first electrode drills through the outer wall, the next electrode projects through the hole formed and drills the next wall, etc. The drilled-out pieces are held in the cavity of the electrode by means of a permanent magnet.

Machines especially designed to drill out cracked taps etc. are often made portable. They consist of an electrode holder which can be mounted on the spot in an available drill press, together with a cabinet with the electric equipment. The entire unit need only be connected to the electric circuit, and the coolant can be taken from an ordinary faucet at the site. Such an outfit is shown in Fig.54; it works rapidly and cheaply and is quite mobile, since it only weights around 25 kg.

Aside from the Elox machine mentioned, corresponding machines for extracting taps are made by the French firm Qualitex in Paris and by the Czekoslovaken Research Institute VUMA.

General Pointers

The working time in arc machining, as in spark machining, depends on the voltage, current strength, and arc frequency. The tension is preferably low, usually 20 - 30 v, while the current strength may be as high as a few hundred amperes.

The precision varies with the electrical constants, so that high machining speed gives little surface smoothness and vice versa. It is possible to reduce the roughness depth as far as 5 μ inch r.m.s., but values of 20 - 60 μ inch are more usual. The precision can normally be kept within some few hundredths millimeter and, with care, it is said that it can be reduced to 0.005 mm.

The electrode, which is generally brass or copper - in rarer cases with finer work, ground molybdenum rods are used - is subject to some wear which, however, is relatively small in arc machining. It is stated that, in tool steel, it is possible to drill a combined hole depth of 4" with a total wear of the copper electrode not exceeding 1".

Arc Grinding of Spheres

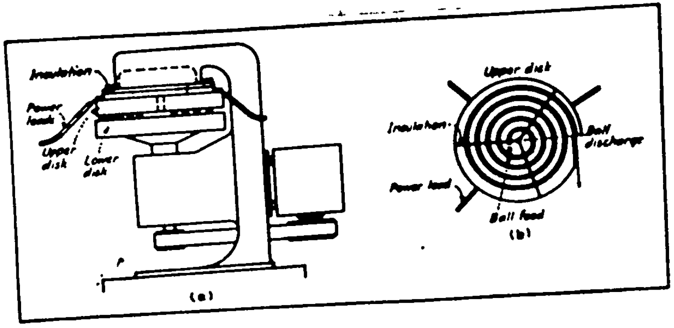

Fig.55 - Russian Arc Machining Equipment for Lapping Balls for Ball Bearings. The upper wheel is divided into three mutually insulated segments, each of which is connected to the secondary of a three-phase transformer. The lower wheel rotates at a speed of 500 - 600 rpm. The balls are fed in the center of the upper wheel and move toward the periphery where they drop down.

As a special application of the arc method, it was used around 1950 by a Russian firm to refinish ball bearings. This was done in a special lapping machine (see Fig.55) whose upper stationary wheel consisted of three segments insulated from each other as well as from the stand. Each of the segments was connected to the secondary of a three-phase transformer which furnished a 20 - 25 volt voltage. The lower wheel rotated with a speed of 500 - 600 rpm. The balls were fed through a hole in the center of the upper wheel and gradually worked themselves toward the periphery where they dropped down. At the points of contact between balls and lapping wheel a series of fine electric arcs was formed, which partly decarbonized the outer layer and partly removed smaller particles, which were flushed away by a stream of water. The current strength was of the order of 1200 - 1500 amp.

At a At a voltage of 15 - 20 v, balls of 13/16" (= 20 mm) balls were reduced in diameter with a speed of 0.3 - 0.4 mm/min, while the rounding was kept within 1/100 - 2/100 mm. It was a prerequisite that all the balls had the same original size. The surface, after machining, showed grooves of about 0.05 mm, depth which were later removed, along with the decarbonized surface layer, by ordinary lapping.

If the voltage is lowered to 7 - 12 v, the ball diameter is reduced at 0.06 - 0.10 mm/min, and the surface is considerably improved. If the voltage is lowered further to 0.5 - 5 v, a surface is obtained which, practically speaking, has a polished appearance and great regularity of shape. In this case, the working speed is so greatly reduced that only 0.03 mm of the diameter per minute is removed. It is claimed that the old method could han-

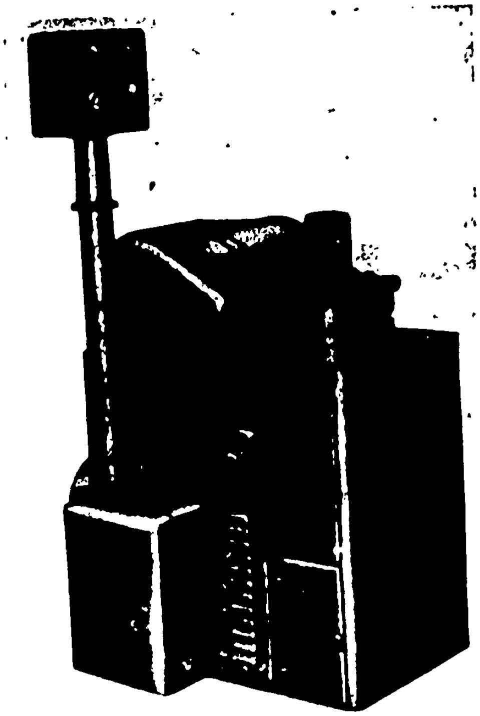

Fig.56 - Arc Machine for Reducing Materials. Capacity 30° mm. The spindle dock is set on a carriage which is operated by compressed air. The wheel is a soft iron plate of 300 mm size and 1 mm thickness, which rotates at 800 rpm. The working voltage is 15 - 25 v, current strength up to 40 amp (VUMA)

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dle 3000 balls in 8 to 9 days, while the arc method mentioned here required only 3 to 4 days, and at the same time resulted in considerable current saving.

Reducing with Electric Arc Machines

A special field for arc machining lies in sawing, reducing, etc. Figure 56 shows a Czech machine, designed like a circular saw. The spindle dock is placed on a carriage which moves on rollers against a compressed-air cylinder. The amount of voltage is regulated by the electric working circuit. The spindle dock carries a 0.5 kw motor which, over V-type belts, drives the working spindle at a speed of 800 rpm. As a wheel, an ordinary soft iron plate of about 1 mm thickness is used. If this is about 300 mm in size the cutting speed will be about 13 m/sec. As a coolant waterglass of 1.30 sp.gr. is used, sometimes with an admixture of Na_3PO_4 at a ratio 1:20, which is said to reduce the wear on the wheel.

As a current source, a cooled three-phase selenium rectifier is used, which can give around 40 amp, with 15 - 25 v. With a variable resistance in the circuit, the machine can work in four steps at varying amperage. The capacity of this machine is as high as 30 mm round material.

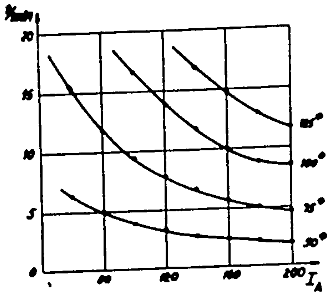

Fig.57 - Dependence of the Cutting Time, on the Current Strength in a Large Reducing Machine (VUMA)

A larger analogous machine can cut material up to 150ø mm. The wheel is 800 mm in diameter and runs at about 300 rpm, driven by an 0.8 kw motor. The wheel width is 1.5 - 2 mm, the voltage as in the small machine, i.e., up to about 25 v, while the current strength may reach 200 amp. Figure 57 shows the cutting time for this machine as a function of the current strength, indicating for example, that a 100 mm round iron piece can be cut in

10 min at 160 amp.

A similar arc machining equipment, but somewhat smaller, was constructed about three years ago in the metallurgical laboratory of the Darmstadt Polytechnic Institute where it has been frequently used with good results (Bibl.40,41). This machine uses a pulsating direct current which is produced by superimposing a steady direct current with the alternating current from a transformer connected in the circuit. The remaining data are in line with what was indicated before.

This machine, as far as can be seen, represents the first Danish experiment in which use was made of electric machining methods. But it should be mentioned in this connection that the Laboratory for Machine Tools, Darmstadt Polytechnic Institute, as early as around 1948 - 1950, had an electric arc machining device for testing. The machine was of quite simple construction and exclusively intended for drilling out cracked cutting taps, etc. The tests were very brief and not very successful, since the electric circuit proved to be out of order; therefore, work was discontinued and the machine returned.

Bibliography references: 4, 5, 7, 10, 16, 22, 23a, 32, 37, 38, 39, 40, 41, 42, 43, 45a, 49, 59, 60, 61.

Patents: Swedish No.76 026; German No.672 832; British No.335 003, No.507 392, and No.578 933; French No.1 024 353; Swiss No.298 974; and U.S.A. Nos.1 333 311, 1 620 519, 1 556 325, 1 701 919; Re.20 035, 2 258 480, 2 374 348, 2 383 382, 2 415 690, 2 441 954, 2 650 979.

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ULTRASONIC MACHINING

Including ultrasonic machining in a discussion of electric machining methods is not entirely correct. The chip removal proceeds here purely mechanically; however, the method of producing the necessary energy as well as the working procedure in the entire process, makes it natural to treat ultrasonic machining together with electric machining methods.

Ultrasonics, as is generally known, is mechanical vibrations of such high frequency that they cannot be perceived by the human ear, i.e., from about 20,000 cycles upward. If a bar is exposed to ultrasonic vibrations in a longitudinal direction, it can in the presence of resonance and at sufficiently high energy, be set into mechanical longitudinal vibrations, with amplitudes of several hundredths millimeter.

It has been known for some years that it is possible to bore holes in hard metal with such a vibrating rod. Since this moves only in a longitudinal direction, holes can be drilled with arbitrary profiles, corresponding to the cross section of the rod. This effect can be increased greatly if, during the working process, a finely divided grinding compound is added since this will permit direct grinding or lapping. Since the machining is thus purely mechanical, this method is the only one of those described here, which can be used with nonconductive materials.

The process can actually be compared with the effect of a compressed air hammer, whose chisel vibrates at low frequency, in that the individual grinding grain corresponds to the chisel. The use of the numerous cutting edges and the change to higher frequencies denote a great increase in the precision of the work. At the same vibration energy per surface unit, the acceleration forces increase proportionally to the frequency. A grain which performs 10,000 vibrations per second exerts, at the same amplitude, the same force on the workpiece as a 10,000 times heavier grain which executes only one vibration per sec. It is therefore possible with fine grains and

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high frequencies to achieve precise and rapid work.

Normally, frequencies between 20 and 30 kc are used in ultrasonic drilling, as a rule around 25 kc. Higher frequencies will improve the precision, but at the same time give lower efficiency, just as the drill holder whose length is determined by the resonance factors, becomes shorter with increasing frequencies. Even at 100 kc, the drill holder may be as short as 3 cm, which is impractical in many cases.

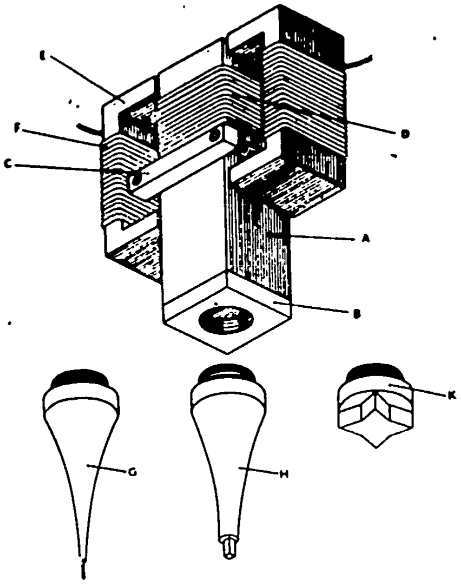

Fig.58 - Drill Head in an Ultrasonic Drill Press. A is a vibrator heat consisting of a stack of nickel plates, which under the influence of high-frequency vibrations in the coil D will execute longitudinal vibrations. At the node of the vibrations, the vibrator head is attached to C. A highly permeable yoke E carries polarizing poles F which are fed with direct current. B is a soldered piece of stainless steel with attachment thread for the drill holders G,H, and K (Mullard).

Principle of the Ultrasonic Drilling Machine

Ultrasonic machines are constructed like small drill presses, which may be more or less complex. Examples are known of the simplest design, in which the drill head slides in precision ways and in which the material is moved by precise cross slides; in this type, the machines are actually similar to jig drill presses.

A vacuum-tube generator is included in the equipment, which delivers high-frequency vibrations to the drill head, where they are converted to mechanical longitudinal vibrations. The process is shown in Fig.58.

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In the sketch, A is the vibrator head which is constructed of a stack of nickel plates whose magnetostriction properties are utilized. This is demonstrated by the fact that certain materials (iron, nickel, cobalt), when exposed to an alternating current, will change dimensions in time. The length of the plates corresponds to a half a wavelength; at the vibration node, the plates are attached to the cross piece C.

The upper end of the plates is surrounded by a coil D which is fed with alternating current from the generator, so that the vibrator head A will execute longitudinal vibrations in synchronism with the imposed high-frequency vibrations. Here, E is a highly permeable yoke, wound with a polarizing pole F which is supplied with direct current. The lower end of the vibrator head is soldered to a piece B of stainless steel, with attachment thread for the drill holders G, H, and K.

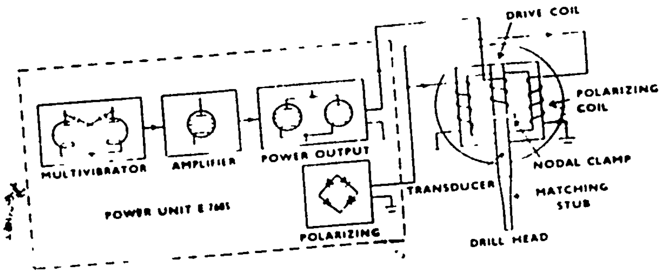

Fig.59 - Schematic Setup of an Ultrasonic Drill Press with Electric Circuit (Mullard).

The length of the drill holder must be so adjusted that its natural frequency corresponds to that of the vibrator head, in order to obtain maximum amplitude. At 25 kc, this means that the drill holder should be about 12 cm long. The vibration energy is transferred from the end face of the vibrator head to the usually much smaller end face of the drill holder; if this is to take place without loss, the vibration amplitude must be inversely proportional to the size of the faces. This presupposes a definitely conical form of the drill holder, which is made in practice

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with an exponential producer curve.

The amplitude at the end face of the vibrator head in the equipment described here (which is for 50 watts) is 13 μ and three drill holders are used which, according to shape and size, increase the amplitude in the end faces of the drill holder 2, 3, or 6 times, so that the amplitudes here are 26 μ, 39 μ, and 78 μ. The thickest drill holder gives the least oscillation. The drill holders can thus be regarded as a sort of mechanical transformer.

Ultrasonic Drilling Machines

Figure 59 shows schematically the entire arrangement with electric circuit. Figure 60 shows a very simple 50-watt ultrasonic drill press by the British firm Mullard. It can hardly be of simpler design, since it consists only of the drill head attached to a column and moved with the arm shown, which is counterbalanced. The material is placed loosely in the dish-shaped base plate.

The generator, forming part of the equipment, supplies 50 watts with a normal frequency of 20 kc which, however, can be varied slightly in either direction. The direct current to the polarizing pole is also tapped from the generator which, for this purpose, contains a rectifier.

This small machine drills holes from 0.15 to about 13 mm, at a depth up to 13 mm. If an abrasive is used with grain size 120 (American mesh), the dimensions can be

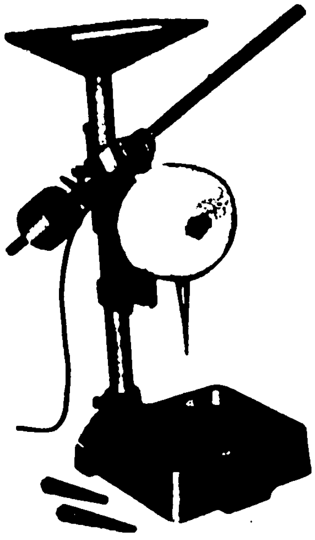

Fig.60 - Small 50-Watt Ultrasonic Drill Press, Consisting of a Drill Head on a Column, Counterbalanced and Manually Operated with an Arm. The material is placed in the dish-shaped base plate (Mullard).

kept within 0.05 - 0.06 mm. If finer grains are selected, such as 1000, the precision can be increased to around 0.01 mm. The depth of roughness can be brought down to less than 1 μ, depending on the grain size selected.

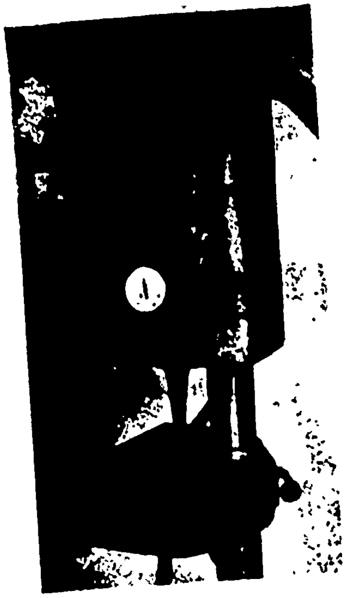

Fig.61 - Drill Head for a 250-Watt Ultrasonic Device. The drill head is in principle as in the machine in Fig.60, but the voltage is applied by means of a built-in compressed-air cylinder. The drill dock contains a soldered way and is intended for attachment to an available machine (Mullard).

The working time is dependent on the hardness of the workpiece and the size of the drill. A square hole with sides of ¼" can be drilled with silicon carbide in sodium glass at a speed of 2 mm/min. With tungsten carbide, when using drilling carbide as an abrasive, a speed of about 0.1 mm/min can be achieved.

In addition it must be remembered that, in this method, it is useless to try to increase the speed by exerting more force on the drill, since the only result is a reduction in vibrations that partially stop the machining process. The pressure should be quite low at all times.

Figure 61 shows a 250-watt ultrasonic device, also by Mullard. Here the entire "drill ~~dock~~" with the vibrator head, etc., is constructed as a unit which contains a soldered precision way for movement of the head. The drill head itself is constructed in principle as in the smaller machine, but instead of being operated manually, a compressed-air cylinder is added which automatically performs the operating motions and periodically lifts the drill to permit feeding of new abrasive, after which the drill is lowered again. The air pressure is applied at about 4 kg/cm^2, and the air consumption is

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around 0.2 m^3/min.

The electric as well as the pneumatic equipment, together with all control units and instruments, is assembled on a panel from which all connections lead to the drill dock via a simple flexible hose.

The capacity of this machine is up to hole diameters of 50 mm and depths to 50 mm. The machine shown here can be attached to an available drill press or to a more precise machine, so that precision work can be undertaken, e.g., changing from hole to hole by means of the slides of the machine; it can also operate automatically without supervision, since the abrasive can be supplied by a pump and the drill depth is controlled by the dial gage shown.

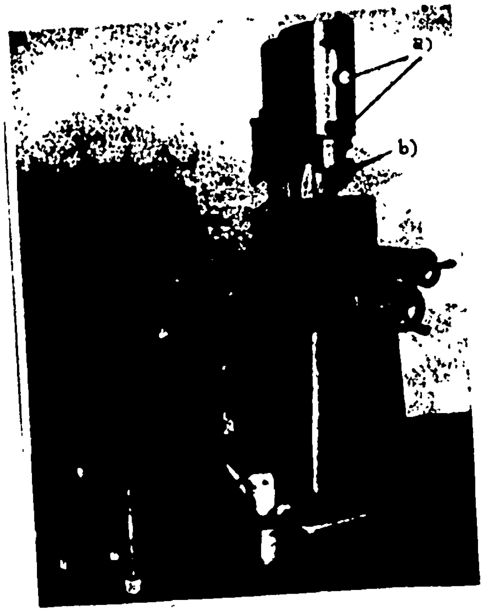

Fig.62 - 500-Watt Ultrasonic Drill Press of Precision Design. The vibrator head is cooled in an oil chamber, which contains a copper coil through which water flows. The tool is held with a constantly regulated pressure against the workpiece (Diatron). a) Drill pressure; b) Exchangeable drill head

Figure 62 shows the German ultrasonic drill press Diatron for 500 500 watts. It is designed like an actual precision machine with cross slides for shifting the material, and the drill dock is fixed on a column. The drill head is mounted in the dock with a soldered precision way and can be moved by counterbalance and almost without friction. During the work, the tool is held elastically against the workpiece with a constant pressure which can be read from a dial gage and whose amount can be set between 100 and 1500 gm, depending on the diameter of the hole.

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The vibrator head is constructed in a way similar to that previously described, but is based on the greater electric effect applied in an oil chamber, which is kept cooled by sending a stream of water through a copper coil in the oil bath. This prevents overheating of the vibrator head since the efficiency at best is about 70% and since 30% of the energy introduced is therefore converted into heat. The amplitude is near 0.1 mm.

In the U.S., ultrasonic drill presses have been built, which accurately correspond to those mentioned here, e.g., Cavitron and Raytheon. In these, effects as high as 1.5 kw are used so that the working speed is naturally increased. Figure 63 shows a full-scale Cavitron machine.

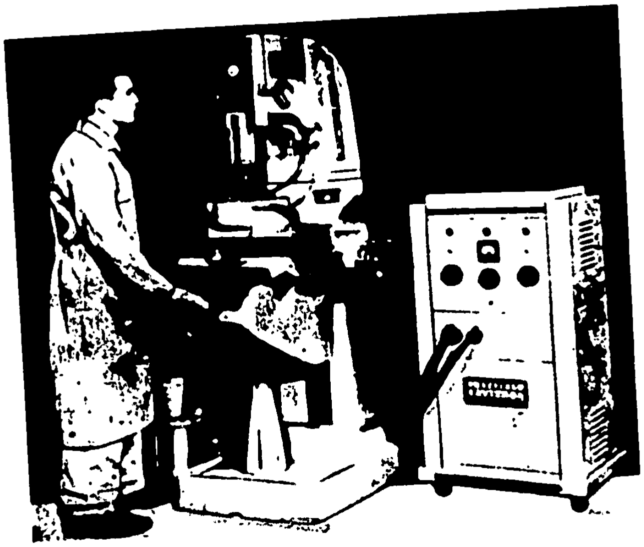

Fig.63 - American 1.5 kw Ultrasonic Drill Press with Electric Equipment in the Control Panel (Sheffield Cavitron).

General Pointers

Concerning the working speed, it is to be expected that this will rise with increasing effects. This is true, however, only within certain limits. If, for example, the 500-watt machine is considered and it is remembered that the end faces of the vibrator head have an area of about 10 cm^2, this corresponds to an evenly distributed vibration energy of 50 watts/cm^2. Such a value presupposes a relatively high fatigue limit of the material of the vibrator head. It has, therefore, been necessary to develop materials which partly had a high breaking strength and partly possessed a high magnetostriction effect with small eddy current loss - hysteresis - and low magnetic loss.

There is an even greater need for good breaking strength and elastic properties of the drill holder. In the end face of the holder, all the energy is concentrated; since it is quite thin - probably about 1 cm^2 - this means that the energy density is of an order of 500 watt/cm^2. Such an energy concentration cannot be withstood by even the best types of steel, since stresses and strains are set up which lead to deformations far above the elastic limits. This result in overheating of the material and, after a fairly long time, lead to fatigue cracks. With smaller holes, it is therefore impossible to force the speed by increasing the effect, since the materials used set an upper limit for the power of the machines. With the use of small tool dimensions and large effects, the tool will become red-hot in a short time.

The effect is therefore so laid out that the vibration energy is imparted to the individual grinding grains, which are distributed over the end face of the tool and make this execute vibrations about its resting point in the longitudinal direction of the tool. The end face of the tool, meanwhile, is also ground and acquires a hollow shape. With through-holes, this makes no difference, but with part-way holes the end face must occasionally be smoothed if a level bottom is desired.

Obviously there will also be grinding grains between the walls of the hole and the sides of the tool, which leads to a grinding effect here which makes the hole slightly conical. This is more pronounced at deeper holes. If a hard metal plate of 5mm thickness is bored through, the hole will be about 0.1 mm larger at the top. Under certain conditions, e.g., with a matrix, this conicity can be used to advantage while in other cases it is impermissible, so that the hole must be made cylindrical by using two or three successive drillings and making these remove less and less material.

The method can be used in machining hard and brittle materials, such as hard metal, tempered steel, titanium, glass, ceramics, germanium, diamonds, etc., but it is not adapted to softer and tougher materials. In the latter, the grinding grains cannot work effectively, since they will settle firmly in the workpiece and just lap the tool. A case-hardened workpiece thus can be drilled rapidly as long as the machining is done in the hardened surface layer, but after this layer is broken through, the speed quickly reduces.

The drill holder is preferably made of high-quality steel. In cases where the end face is to be especially small, monel metal can be used with advantage, since the breaking strength and elasticity limit of this material are very high, so that the previously described difficulties disappear to a certain extent.

The drilling tool itself is made of a tough but not brittle material such as ordinary soft iron, pure carbon steel with 0.2 - 0.5% C, St. 85.11, or a tough and nonwearing Cr - Ni steel. The choice depends on the requirements made. If the tool is to be nonwearing and keep its shape, Cr - Ni steel is chosen, i.e., for example in drilling deep holes. With more complicated shaping, St. 85.11 is often preferable since it is easier to machine, etc. In all cases, the drill holder as well as the drilling tool are soft and therefore fairly easy to machine. The tool cannot be screwed or brazed to the drill holder.

As an abrasive, depending on the circumstances, aluminum oxide, silicon carbide, drilling carbide, or perhaps diamond dust is selected, with the size of the grains adjusted to the purpose. The abrasive is preferably triturated in water or oil and circulated by pumping.

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Precision and Working Speed

With careful working, a precision of several thousandths millimeter can be achieved. This presupposes the use of many tools in succession which work each with a decreasing grain size; nevertheless, the first drilling may easily take from 10 to 100 as long as each of the subsequent drillings, when there is considerably more material to be removed. If possible, it is profitable to use a tube-shaped drill and to drill a piece or prebore by another method - with conductive materials, e.g., with one of the earlier named electrical methods.

At 280 grains (grain size 60 - 80 μ), a surface roughness of 1 μ can be achieved, and with finer grains even less. As opposed to the electric methods, ultrasonic machining gives a smooth and shiny surface, which can simply be polished, so that a completely finished tool can be made with this method.

It should be mentioned that this method is also useful for rapid cutting. In that case, the tool must have a thread and neither the tool nor the workpiece must be permitted to rotate with a speed adapted to the pitch of the thread. Another feature is the fact that it is also possible to drill crooked holes by using a correspondingly bent tool.

The working speed is dependent on a series of factors, such as the hardness of the workpiece and its breaking strength. The more brittle the material, the more rapidly can it usually be machined. The depth of the hole also plays a part, in that the work progresses more slowly the deeper the drill penetrates. This is due to the difficulty of the abrasive in penetrating through the narrow opening between the wall of the hole and the tool. The method is nevertheless always slower than the conventional methods of machining and also slower than the electric machining methods. Its main advantage is the great precision which can be achieved and which only in exceptional cases demands refinishing. There is no destruction of the surface as described for the electric methods.

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Table 4

Amount of Material Removed in mm^3/min and Electrode Wear

Material	Material Removed mm^3/min.	Wear Tool/Workp. in %
Glass	200	0.8
Agate	54	4
Ruby.	30	8
Hard ceramic.	26	6
Hard metal H 1.	10	50
Hard metal G 5.	6	70
Sintered drilling carbide	4.5	50
Dural	3.8	25
Brass Ms 63	3.6	40
Quick steel	2.2	200
Steel	1.8	100
Chrome steel,12%	1.6	200

From a German source, Table 4 lists working speeds for various materials. The tool used was a hollow six-sided piece of St. 85.11 with 27 mm^2 area (8mm needle width); the abrasive was drilling carbide, 220 mesh, and the machine effect was 500 watts. In addition, the wear of the tool, measured in percent of the wear of the workpiece, is given. The figures must be accepted with some caution and can only be considered indicative.

Fields of Application

The ultrasonic method is widely used for producing tools which are used for non-chip-removing machinings. As mentioned, the limitation is mainly in the size of

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the workpiece, but with just such tools usual grindings can also be difficult, especially if the workpiece cannot be divided.

Figure 64 shows an example of ultrasonic machining in which a chipbreaker is ground with a piece of flat iron soldered to the drill holder. As an abrasive, drilling carbide is used. The work, according to the statements, took several minutes which, generally speaking, corresponds to the time for ordinary grinding with diamond wheels.

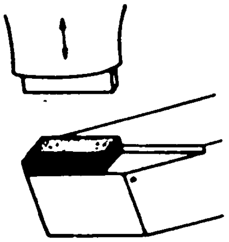

Fig.64 - Grinding of a Chip Breaker. The tool is a piece of flat iron. Drilling carbide was used.

Figure 65 shows an example of a cutting plate, executed in hard metal and drilled by means of ultrasonics.

Bibliography references: 5, 6, 7, 19, 22, 27, 29, 38, 42, 45, 45c, 60.

OTHER ELECTRICAL MACHINING METHODS

Aside from the electric machining methods mentioned previously there are others which are less known or which find application within more limited areas. These methods cannot be quite as readily classified in the groups mentioned before and, in many cases, consist of combinations of one or more of the other methods.

Drilling of Very Small Holes

By spark machining, holes with a diameter as small as about 0.1 mm can be drilled by means of thin tungsten wire; in the watchmaker's technique it is known that, with special drills and with extreme care, this can be reduced to hole diameters of 0.05 mm. By a specially developed technique, using precision-ground ordinary sewing needles it is possible to drill through thin foil plates with holes down to 0.005 mm, but here the possibilities cease.

It is rather rare that such small or even smaller holes are required, but such sizes are occasionally required for diaphragm apertures in precision optical instruments and, for example, in electron microscopes.

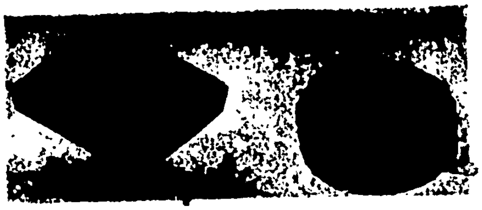

Fig.65 - Cutting Plate Drilled by Ultrasonics. Executed in hard metal and set in a steel block.

By means of recent electronic optics, it is now possible to obtain sharp focusing of corpuscular rays and thus produce an intense heating of a very small area. If a surface is struck by such an electron ray, whose voltage may reach over 100,000, it is vaporized and a hole appears, while the material is again condensed by the cold parts of the equipment. The drilling is done in special devices under vacuum.

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The drilling time is extraordinarily short; in a few seconds, holes with diameters between 5 and 10 μ can be drilled in 7 - 8 mm thick plates of glass, ruby or similar material. This permits drilling of holes with diameters below 1 μ.

Coating of Steel with Hard Metal

Another method, which perhaps has somewhat greater possibilities of practical application, consists in coating parts subject to excessive wear (as, for example, cutting tools of carbon steel and high-speed steel) with a thin layer of hard metal, so that it acquires a considerably increased resistance to wear; as far as tools are concerned, this will result in a longer service life - judging from reports, up to 3 to 5 times.

In this method a vibrator can be used, designed roughly like an electric recording pen. A hard-metal electrode is used, which is held against the tool at the spot where it is to be coated; when the electrode vibrates, a series of sparks is generated so that hard metal passes from the electrode to the workpiece, where it is deposited as an evenly distributed thin layer. During the process, the workpiece is connected to the negative pole of the circuit and the electrode to the positive pole.

Instead of the simple setup mentioned, a spark-machining device can be used, where the process is allowed to take place in air.

It is assumed that the very fine hard-metal particles, which are transferred to the workpiece, diffuse into its surface and that the abrasive resistance is further increased as a result of the reaction of the surface with atmospheric nitrogen. Finally, it is possible that a local thermal reaction takes place as a result of the rapid heating and cooling during spark flashover.

The applied layer is very resistant, but it is claimed that it is too thin to serve as an anticorrosion coating. The coating is so hard that it can be worked only by lapping with drilling carbide.

The characteristics of the surface layer depend on the electrode material, the

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voltage, capacity, and current strength in the electric circuit, the duration of the process, and also on the roughness of the surface treated. Hard metal which contains titanium carbide gives a more wear-resistant layer than pure tungsten carbide. In parts for measuring instruments and in tools for fine machining, graphite electrodes are often used, which give a very smooth surface finish.

According to the desired fineness of the layer, voltages can be selected between 50 and 220 v, capacitances between 30 and 350 µf, and current strengths between 0.25 and [illegible] amp. The obtained layer thickness is from less than 0.01 to about 0.1 mm. The lower these values, the finer will be the layer and the less the thickness. The finer the surface to be treated, the better will be the layer; the workpiece must be absolutely clean and free of grease, rust, etc.

Under given conditions, the quality of the surface layer is determined to a high degree by the duration of the process. If this is continued beyond a certain limit, dark stains appear in the surface layer which indicate that local destruction has taken place. Normally, the surface is treated until the spark picture changes character. This is indicated by the sparks losing their brightness and original form, after a certain time has passed.

As far as it is possible to say now with respect to general practice, tools treated in this way are preferably used in heavy cutting of hard metals and only to a lesser degree in jobs with great speed and small chip areas, in softer materials, or in simple machining.

When a tool treated in this way is ground, it must be refinished and a new coating of hard metal must be applied. The coating is applied only at spots of greatest wear, and it is important that the edge is not directly exposed to the effect of the sparks. The treatment therefore begins slightly in back of the edge and moves slowly toward it, but without proceeding so far forward that the sparks are drawn directly from the cutting edge.

As far as can be determined, the method was first proposed in 195[illegible] by the

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Russians Ivanov and Titov and has apparently found extensive use in Russia, not only for cutting tools but also in machine parts in general. In a large factory in Czechoslovakia the author had the opportunity to see all spiral drills treated by this method, where a female worker in the tool grinding shop, in addition to watching several automatic grinding machines, also coated drills with hard metal.

According to Russian sources, the price for such equipment is between 2000 and 6000 kr. The necessary effect is about 0.8 - 1.2 kw. The time for treating a surface of our square centimeter varies between 0.5 and 3 min, and the power consumption in treating 1000 tools with 16 × 25 mm shaft cross section is 1.2 - 1.5 kw - hr. The consumption of hard metal containing titanium is 2 to 5 mg per tool.

Electrolytic Grinding with Diamond Wheels

Electrolytic grinding has already been described. This method, however, can be varied in different ways so that the process, to some degree, shifts character. Figure 66 shows three such possibilities. The top portion shows pure electrolytic grinding with a simple DC circuit and the tool connected to the positive pole. As liquid, an electrolyte is used, and as a blade an iron plate or cast-iron wheel. If the circuit is modified so as to correspond to Lazarenko's the center picture is obtained. This results in a type of spark grinding, rising a dielectric material as fluid. The wheel is preferably of steel or cast iron. Machines of this type have been built in individual cases, and such a small grinding machine is shown in Fig.41. The process is actually that of spark grinding. Finally, an alternating-current circuit can be used, as shown in the bottom figure.

If the conventional wheel in the upper two pictures is replaced by a metal-bound diamond wheel, a process will result which has proved highly advantageous in grinding hard-metal tools and other hard materials. This procedure apparently was developed originally in America, around 1950.

Figure 67 shows an experimental setup. The diamond wheel is mounted to the machine and is insulated, and the negative voltage is fed to the spindle through a mercury bath. The workpiece is attached in a holder on a cross slide, which is displaced on rollers. The spindle speed is infinitely variable, and the workpiece is guided back and forth over the wheel by means of a crank mechanism which is attached to the slide. The workpiece is forced against the wheel, with a suitable pressure tapped from a compressed-air cylinder.

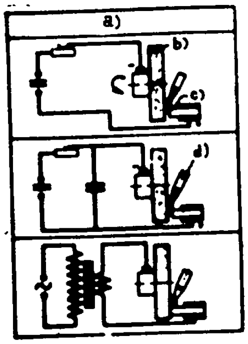

Fig.66 - Three Methods of Electrolytic Grinding, Shown Schematically. At the top a simple DC circuit, next a system with Lazarenko's oscillator circuit, and at the bottom an AC circuit. If the iron wheel in the two upper figures is replaced by a metal-bound diamond wheel, an especially effective grinding is obtained.

a) Circuit diagram; b) Disk;
c) Workpiece; d) Working fluid

In the experiments, the workpiece was made to move back and forth for 20 mm over the wheel, at a rate of 35 times a minute and at a pressure between the workpiece and the wheel of 3 kg/cm^2. The wheel speed was about 2600 - 3500 rpm which, for the 6" wheel used, corresponds to grinding speeds of 20 - 27 m/sec.

The rectifier furnishes a voltage up to 20 v and 75 amp, and the machining is done at current densities of 25 - 50 amp/cm^2.

The effect in the process is partly an anodic solution as in the pure electrolytic grinding, partly a mechanical removal of material by means of the diamond wheel.

It is asserted, however, that there is no regular grinding involved. The wheel will circulate the coolant which otherwise would tend to deposit a film on the workpiece, rapidly halting the process. It is the function of the diamond grains to assure a suitable distance between wheel and workpiece and to cut the film which settles on the workpiece. The cobalt of the hard metal will also be dissolved more rapidly than the

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carbides and these, which are relatively poor conductors, will remain behind; however, since they are now exposed, it is relatively easy to remove them by the diamond.

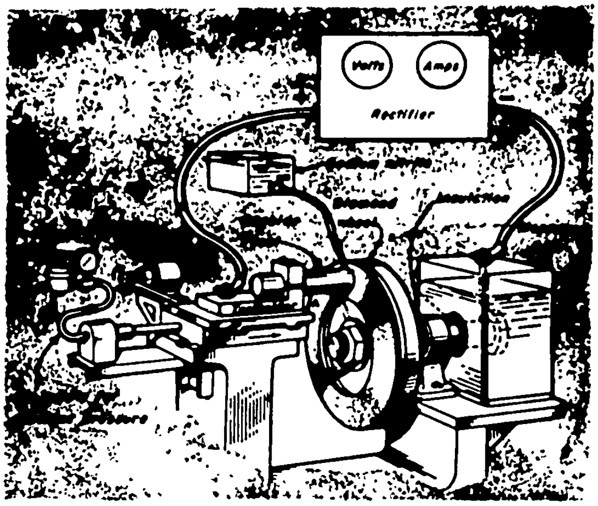
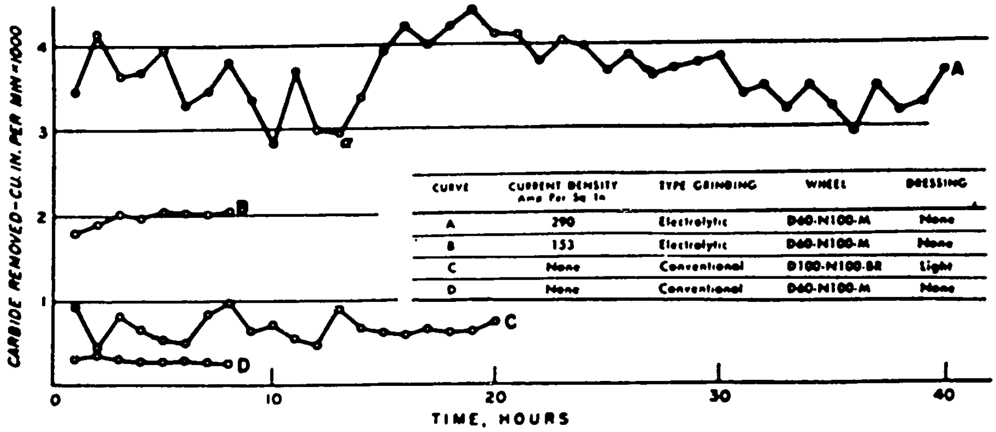


Fig.67 - Experimental Setup for Electrolytic Grinding with Diamond Wheels. A crank motion leads the workpiece back and forth over the wheel, while it is held against it with a constant pressure by the compressed-air cylinder.

Figure 68 shows some experimental results. The curves A and B give the quantity of hard metal (Carboloy 78 B) in cubic inches per minute times 1000, which can be removed. Here, A corresponds to a current density of 45 amp/cm^2, B to 24 amp/cm^2; C is the result of a normal grinding with bakelite-bound diamond wheels and D with a metal-bound diamond wheel just like those in curves A and B. The curves also show the duration of the experiment, which in many cases was fairly long, to get an opportunity to judge the wear of the diamond wheel.

The surface roughness was measured every half hour with a profilometer and average values for the grindings A, B, C, and D of 14, 11, 6, and 6 μ in rms.

The wear of the diamond wheel was so negligible in the electrolytic grinding that it could only be measured after 40 hours. At that time, there was a wear of 1.5 μ, per cubic inch of hard metal removed. For the wheel according to curve C,



CURVE	CURRENT DENSITY Amp Per Sq In	TYPE GRINDING	WHEEL	DRESSING
A	290	Electrolytic	D60-N100-M	None
B	153	Electrolytic	D60-N100-M	None
C	None	Conventional	D100-N100-BR	Light
D	None	Conventional	D60-N100-M	None

Fig.68 - Ground-Off Hard Metal (Carboloy 78 B) in Cubic Inches per Minute, Times 1000.

A - Electrolytically ground, current density 45 amp/cm^2, B - Ditto, current density 24 amp/cm^2, C - Normal grinding with bakelite-bound diamond wheel, D - Ditto, with metal-bound diamond wheel. The time axis indicates increased duration.

the corresponding wear was 203 μ, i.e., the diamond consumption in the electrolytic grinding is less than 1% of the consumption in normal grinding with a bakelite-bound wheel.

The surface roughness can be reduced farther than the figures indicate, if proper care is exercised; especially good results are obtained if the grinding is done for the last few seconds without fluid. The surface is dull and smooth as in all other electric machining methods. It is also indicated that, in this form of grinding, there is a certain rounding of the corners which is greater the longer the grinding lasts. If the grinding process is short, the problem is of practically no significance and the effect can be reduced or avoided by coating the corners with a

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thin layer of shellac.

As liquid, various electrolytes were used here, of which a 5% sodium nitrite solution proved to be the best suited, all things considered.

With this simple electric circuit, care must be taken that no spark or arc formation occurs, since this may cause excessive destruction of the surfaces, which means that there is an upper limit for the useful current densities. If a more complicated electric circuit is used, a certain spark formation can be allowed, since this can now be better controlled. Such an electric machine has been built by the American firm Anocut Engineering Co., Chicago, and is furnished for use in combination with conventional grinding machines which must be modified so as to have the spindle insulated. Figure 69 shows this equipment in combination with a rebuilt plane grinding machine.

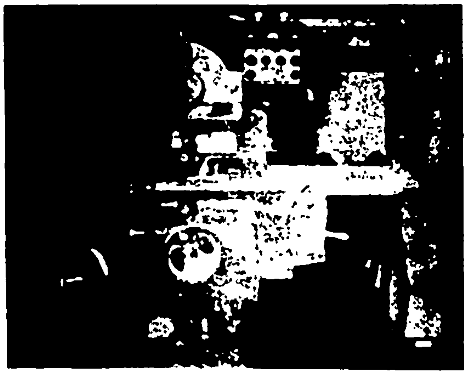

Fig.69 - Electronically Controlled Power and Control Machinery for Use in Electrolytic Grinding, in Combination with Rebuilt Machines with Insulated Spindle

The equipment consists of a rectifier which furnishes 4 - 16 v and 300 amp, and is thus considerably more powerful than the one mentioned previously. In addition, the cabinet contains an electronic control system with two functions: First, it adjusts the voltage and current strength to the right amount for the greatest possible removal of material and next, the spark formation is adjusted to a suitable value. On the one hand, this is sufficiently intense to speed up the grinding process considerably and, on the other hand, not so intense as to prevent a smooth and satisfactory surface or as to lead to arc formation. This is done by reducing the voltage; the entire control is fully automatic, without assistance by the operator.

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Electrolytic grinding with diamond wheels apparently is a promising electric machining method, not only due to the fact that the necessary equipment is relatively cheap and readily obtainable but also to the fact that the grinding itself offers great advantages. These primarily include economy which consists in savings of diamond bort over ordinary grinding; laboratory experiments showed a saving of 99% while the saving under shop conditions is given as 80 - 90%. In addition, on the average about six times as much material per unit time is removed in electrolytic grinding as in normal grinding, which means that the grinding costs are reduced to about 33% of the normal. To this must be added the fact that a surface is obtained, whose roughness is similar to or less than that obtained in regular grinding and which, in addition, is free of grinding scratches and in the long run will be more uniform than a normally ground surface. This should mean - is apparently confirmed by experiments - longer life for the tool or higher rates of cutting.

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