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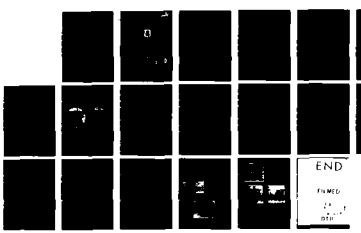

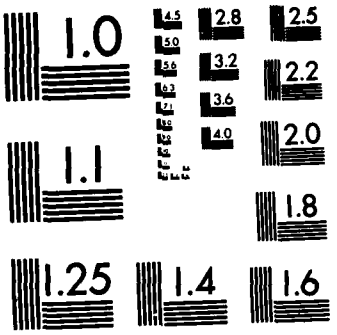

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U. S. BOARD ON GEOGRAPHIC NAMES TRANSLITERATION SYSTEM

Block	Italic	Transliteration	Block	Italic	Transliteration
А а	*А а*	A, a	Р р	*Р р*	R, r
Б б	*Б б*	B, b	С с	*С с*	S, s
В в	*В в*	V, v	Т т	*Т т*	T, t
Г г	*Г г*	G, g	У у	*У у*	U, u
Д д	*Д д*	D, d	Ф ф	*Ф ф*	F, f
Е е	*Е е*	Ye, ye; E, e*	Х х	*Х х*	Kh, kh
Ж ж	*Ж ж*	Zh, zh	Ц ц	*Ц ц*	Ts, ts
З з	*З з*	Z, z	Ч ч	*Ч ч*	Ch, ch
И и	*И и*	I, i	Ш ш	*Ш ш*	Sh, sh
Й й	*Й й*	Y, y	Щ щ	*Щ щ*	Shch, shch
К к	*К к*	K, k	Ъ ъ	*Ъ ъ*	"
Л л	*Л л*	L, l	Ы ы	*Ы ы*	Y, y
М м	*М м*	M, m	Ь ь	*Ь ь*	'
Н н	*Н н*	N, n	Э э	*Э э*	E, e
О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

*ye initially, after vowels, and after ъ, ь; e elsewhere.
When written as ё in Russian, transliterate as yё or ё.

RUSSIAN AND ENGLISH TRIGONOMETRIC FUNCTIONS

Russian	English	Russian	English	Russian	English
sin	sin	sh	sinh	arc sh	$\sinh^{-1}$
cos	cos	ch	cosh	arc ch	$\cosh^{-1}$
tg	tan	th	tanh	arc th	$\tanh^{-1}$
ctg	cot	cth	coth	arc cth	$\coth^{-1}$
sec	sec	sch	sech	arc sch	sech^{-1}
cosec	csc	csch	csch	arc csch	csch^{-1}

Russian	English
rot	curl
lg	log

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EROSION EFFECT OF PULSED DISCHARGES IN ELECTROLYTES

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Introduction

One of the most widely used methods of electroerosion treatment is the so-called anode-mechanical method, which was proposed by the three-time Stalin Prize recipient V. N. Gusev. This method is distinguished from other similar methods by the fact that the discharges arise in an electrolyte rather than in a dielectric medium. The use of an electrolyte as the working medium complicates the already inately complicated process of erosion of the electrodes to such a degree that ideas concerning the processes which occur with the electrodes differ considerably. the electrolytic medium may affect both the discharge mechanism and the magnitude of energy losses. In addition to the complications which arise as a result of electrochemical processes, there may also appear other complications, for example, with the development of an arc discharge between the electrolyte and the metal electrode, if the electrolyte is an anode (electrolytes may serve as the cathode only in the case of a glowing discharge at low pressure [1]). Furthermore, the presence in the electrolyte of atoms or ions with a low ionization energy may be manifested such that the discharge occurs primarily in a medium consisting of these ions. Increased energy losses may develop

if the medium in which the discharge occurs contains highly electronegaitve atoms or molecules (oxygen, halides, H_2O), from which negative ions can easily arise.

As we see from the incomplete description above, it is first necessary to resolve some basic problems. For this our aim was to: 1) compare the effect of the condensed and short-term pulsed discharges, 2) study the effect of the surrounding electrolyte on the behavior of the discharge, 3) study the effect of electromechanical changes on the surface of the electrode on the discharge mechanism. We now offer the results of this study obtained thus far to the attention of the reader.

Experimental Set-Up

In order to obtain results which could be easily analyzed we refrained from measurements taken directly from the processing machines. A device was used in which a mercury switch, capable of generating pulses 100 μs or more in length, was employed to form the pulses. The source of current was a battery with a maximal current strength of 100 A. The discharger consisted of an electrode in the form of a rectangular plate of constant dimensions and a cylindrical electrode ending in a spherical surface. The discharger was immersed in the working medium. The discharges were produced without external excitation and developed on the as yet untouched portions of the rectangular electrode. During the formation of the condensed discharges the mercury switch was switched into the discharge circuit of a 150 μF capacitor. The magnitude of energy per one discharge was regulated in both cases by voltage. In the case of the pulsed discharges it was sometimes regulated by changing the length of the pulse.

The erosion effect of the discharges was monitored by weighing, the electrical values - by means of an oscillograph. Oscillograms were taken directly on the discharger by an oscillograph with a single (pulsed) scan, controlled by means of an auxiliary impulse from a mercury switch.

Results of Experiments

a) Comparing effect of condensed and short pulses. These experiments were conducted in a dielectric (kerosene). The distance between electrodes was constant and below 10^{-1} mm. Figures 1 and 2 show a typical form of the discharge for a short-term pulse and a capacitor discharge. For pulsed discharges we found:

At a voltage of 20-27 V, maximal discharge current of 40-50 A, discharge length of 350-400 μs an energy of 0.248-0.32 W·s was liberated and specific erosion of the anode material was $10.7 \cdot 10^{-5}$ g per W·s. For condensed discharges at a constant capacitance of $1.5 \cdot 10^{-4}$ F we found: At a source voltage of 35-70 V and a total energy in one discharge of 0.06-0.21 W·s, a mean specific erosion of $31 \cdot 10^{-5}$ g/W·s was obtained. From these values it follows that specific erosion (wear) of the material in the case of condensed discharges is three times greater than wear in the case of pulsed discharges.

These measurements were supplemented by measuring the wear [erosion] of electrodes with a constant pulse energy of 0.24 W·s for certain metals. The results of these measurements have been compiled in the table:

Pb - $22.2 \cdot 10^{-5}$ g/W·s,
Zn - $10.7 \cdot 10^{-5}$ " ,
Cu - $6.5 \cdot 10^{-6}$ " ,
Al - $6.2 \cdot 10^{-6}$ " ,
Fe - $4.1 \cdot 10^{-6}$ " .

The ratio of anode wear to cathode wear oscillate within limits of 1.1-2 and remain constant under the same discharge type and mode.

b) Effect of electrolyte on wear (erosion) of material and course of discharge process. Electrode wear as a function of the concentration of the electrolyte (NaOH) was studied under constant discharger proportions and constant electrolyte temperature (Fig. 3).

A Pb anode and a W cathode were used during the measurements. If the property of any element of the electrolyte exerted a substantial influence on the distribution of energy in the discharger or if the properties of the electrolyte caused a charge to develop between one of the electrodes and the electrolyte, then the magnitude of the resultant erosion effect or the ratio of anode to cathode wear would be reflected as a dependence on electrolyte concentration. From the course of the curve representing the erosion of the electrodes (see Fig. 3) we learn that this reflects the dependence of electrical conductivity on the concentration of the electrolyte. The altered erosion of the electrodes in this case must be explained by changes in voltage on the discharger, resulting from the voltage drop on the internal resistor of the power supply source, in turn, the result of the current passing through the electrolyte. It is from this current that there arises the electromechanical component of electrode wear, which must be measured separately. Measurements conducted at a constant voltage on the discharger confirm the fact that the magnitude of the erosion effect does not depend on the concentration of the electrolyte.

Subsequently studied was the effect of different electrolytes at identical concentrations and strength of the parallel current flowing through the electrolyte on the wear of the electrodes resulting from the erosion effect of the discharges. Studied were 2-normal aqueous solutions of NaCl, $CaCl_2$, NaOH, $NaNO_3$, Na_3PO_4 and pure distilled water. The measurements were taken at a constant solution temperature. Resultant wear remained constant within the limits of standard measurement error, namely: When a zinc anode was used at total discharge energy of 0.24 W·s a value of $2.68 \cdot 10^{-5}$ g/discharge was measured on the anode; with an aluminum anode and at the same discharge energy - $1.68 \cdot 10^{-6}$ g/discharge. The same erosion was obtained when a fluid with dielectric properties (kerosene) was used.

The monitoring of the electrode erosion value was also supplemented by measuring the conductivity of the discharge column by means of registering voltage and discharger current measurements.

This ruled out the effect of different conductivity by the electrolytes employed. The conductivity of the discharge column maintained a constant value with a constant column length and discharge energy regardless of which electrolyte or dielectric was used. Measurements were taken at different discharge energies. Here the energy of the discharge was regulated by its length within limits of 100-1000 μs and by altering the current and voltage on the discharger within limits of 15-100 A and 20-50 V.

Thus, from the above results it appears that the electrical and chemical properties of the medium in the indicated range have virtually no effect on the discharge process.

c) Effect of electrochemical alterations on the surface of the electrodes. In addition to the effects of the electrolyte indicated above, which may directly influence the properties of the discharge itself and which, as we learn from the described experiments and other results, are negligibly small, there is yet another factor which may influence the erosion mechanism. In the absence of an electrolyte the development of electrochemical processes on the surface of the electrodes is possible. As a result of these processes there develop semiconductive layers on the surface of the electrodes, which alter the properties of the surface of the treated object. The effect of these layers on the magnitude of erosion which develops as a result of the erosion effect of the discharges was studied on an aluminum and a zinc anode. The layers were formed as by the eloxation of sheet aluminum in a 5% solution of oxalic acid (layer thickness 0-3.5 μ [2]), and in a 5% borax solution (maximal thickness 1 μ). The layer on the Zn anode was formed in a solution of potassium zincate K_2ZnO_2. To eliminate the further effect of the electrolyte during the measurements, discharges were conducted in a dielectric medium. The curves which reflect the influence of these layers on the wear of the electrodes had the same nature. The results of measurements on Zn, which best demonstrate the effect of the layer, are shown in Fig. 4. Here we see that although the layer has a certain effect, the magnitude of erosion remains within the limits of the same order of magnitude.

However, this same layer has a greater effect on the opposing electrode in the case where the latter is not covered by a layer.

d) Summary of experimental results. For the sake of clarity let us now summarize the results of our experiments.

1. Discharges in an electrolytic medium arise at electrode distances dictated by the thickness of the semiconductor layers which form on the surface of the electrodes.

2. The electrolytic medium does not affect the course of the discharge, although it does increase the voltage drop on the outer discharger circuit.

3. The mechanism of electrode failure is identical in pulse discharges and condensed discharges.

4. The magnitude of erosion depends on the quality of the metal which has been transformed into higher states of aggregation and on the intensity of the pressure wave which arises during the discharge and erodes the metal from the electrodes.

5. The electrochemical component in the erosion of the material remained below 15% of total erosion in our formulation of the experiments.

Discussion of Results

Unfortunately we are not able to compare the described results with results obtained by other authors, since we are not familiar with the work pertaining to those problems. It would also be difficult to compare our results with the experiments of industrial workers, since their experiments and views differ considerably from ours in this direction. In our opinion the negative result obtained in determining the effect of the electrolytic medium can be explained by the extremely short discharge channel and by the briefness of the discharge. In all probability the discharge occurs in the vapors of the metal.

From all of our experiments it appears that there is no basic difference between the erosion mechanism in the dielectric and electrical mediums. The nature and geometrical structure of traces of erosion obtained in both cases and with the use of the two types of discharge described above are essentially the same (Figs. 5, 6). The fact that in the case of condensed discharges we found an erosion effect three times greater than that of the short pulses can be explained as follows. The amount of electrode material which is eroded is decisively affected, not only by the amount of metal which is transformed into higher states of aggregation but by the magnitude of the pressure wave which develops as a result of the expansion of the discharge channel and from sprays of vapor ejected from the electrodes. From the course of the change in energy spent we learn that a greater increase in energy spent in time is observed with the condensed discharges. The magnitude of erosion is closely related to this increase. This is also confirmed by the well-established fact [3], that specific erosions during condensed discharges (at constant capacitance) increase with decreasing voltage, beginning at a certain voltage value. The erosion mechanism which is caused by condensed discharges is described in [4]. Although in this study the dependence of specific erosion on voltage is not indicated, we can nevertheless assume from the agreement of the other dependences that the connection between the magnitude of specific erosion and the change in energy spent in time has been proven. This different magnitude of erosion can also be used to explain the following fact: Whereas in the case of pulse discharges with a slow increase in the energy imparted to the electrodes from a metal with a high melting temperature or with the great quantity of heat required for melting, the erosion of the electrode materials does not develop, under the effect of condensed discharges and the same total energy consumed, traces of erosion do develop.

As for the energy liberated from the collision of the carriers, we note the following. In [5, 6] it was established that in transient discharges the value of the anode and cathode drop represents a function of time as well as voltage. The same can be said of the energy accumulated in the plasma. Energy in pulse discharges,

particularly in the present case of low voltage, cannot in any case be attained as a pronounced maximum as in condensed discharges. The erosion mechanism in pulse discharges therefore coincides with the so-called "arc stage" of condensed discharges, during which the magnitude of erosion is influenced by all three energy processes [4]. As for the semiconductor layers on the electrodes, they localize the energy which develops during the discharge in a single place and intensify the pressure wave caused by the discharge in the medium. These layers also help to establish the electrodes at the correct distance.

Conclusion

As indicated by the discussion above, we have proven that no substantial difference exists between the erosion mechanisms of the anode mechanical and electric-spark methods. The electrolyte remains virtually unaffected during the course of the discharge itself. More precisely, the erosion mechanism in the anode-mechanical method coincides with the erosion mechanism in the "arc stage" of the condensed discharge of the electric-spark method. Our assertion then pertains to the posing of the experiment, in which we used a voltage above 15 V. In this case the electrochemical component of erosion seldom exceeds 10% of total wear, which, of course, does not occur with a further reduction in voltage. The fact that the anode-mechanical method has proven to be more effective in practice can be explained as follows:

1. In view of the formation of semiconductor layers on the electrodes with the anode-mechanical method, metal short circuiting between electrodes, which hinders the development of the erosion effect, occurs much less frequently.

2. Electroerosion treatment methods are significantly more productive at lower voltages than at high voltages.

3. With pulsed discharges it is easier to achieve an optimal utilization regime for energy conducted to the discharger than in

condensed discharges, where, unless special measures are taken, plasma energy cannot be totally utilized.

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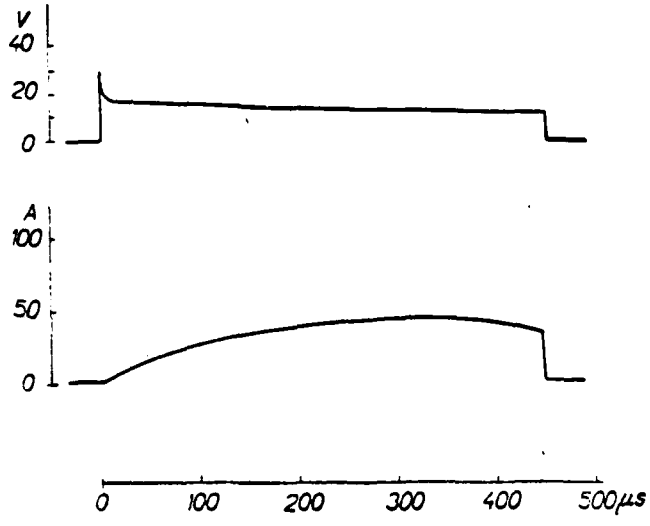

Fig. 1

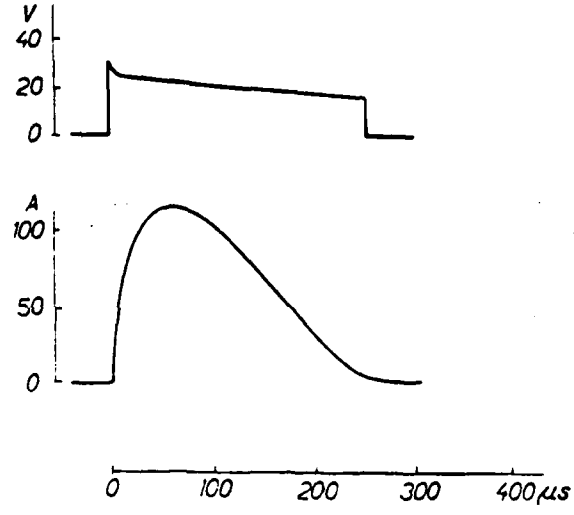

Fig. 2

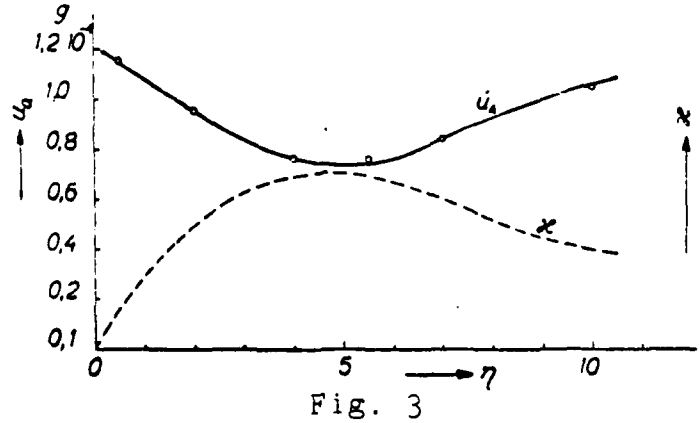

Fig. 3

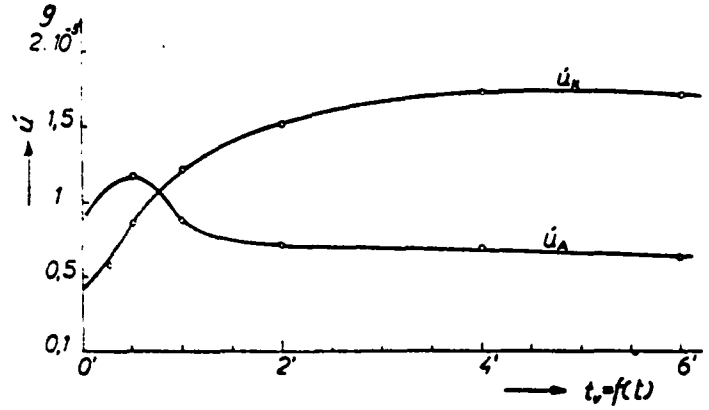

Fig. 4

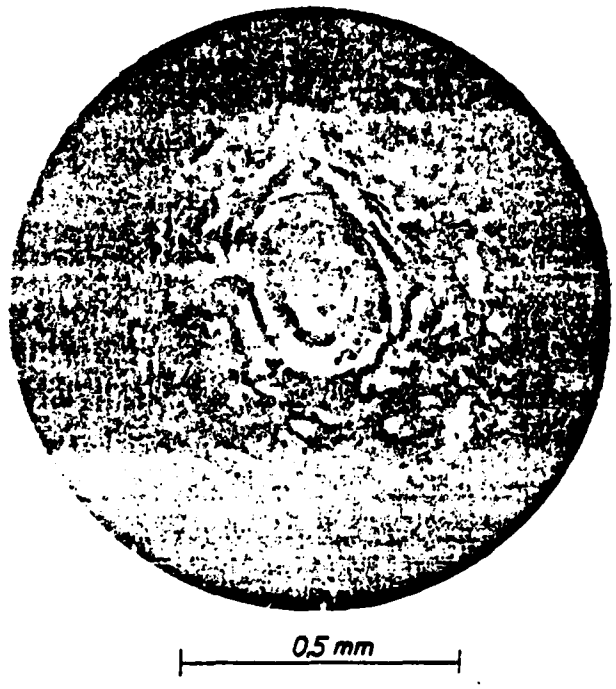

Fig. 5

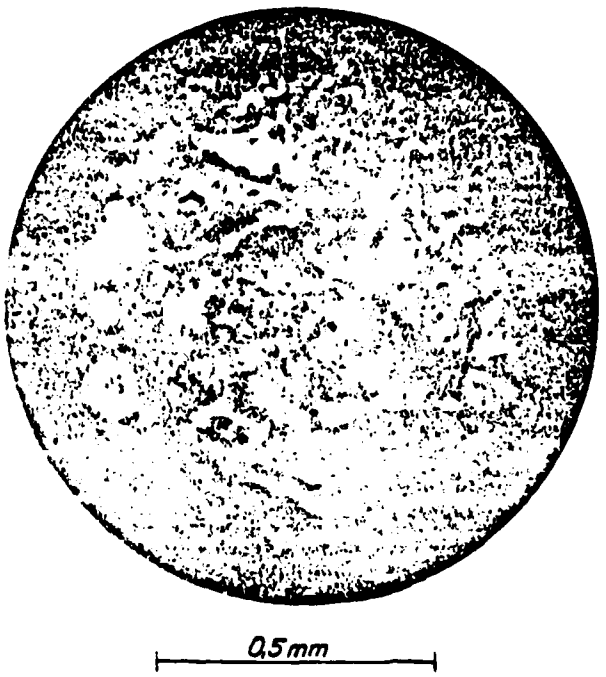

Fig. 6

EROSION EFFECT OF CONDENSED DISCHARGES IN A DIELECTRIC MEDIUM

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The so-called electrospark processing methods have, as a result of the pioneering work of Professor Lazarenko and his school, become so widespread that they now constitute an important branch of technology. For many reasons their implementation has been very rapid, since the investigation of the physical essence of the phenomenon has until now lagged behind the development of the specific methods, which if irrational experimentation is to be avoided, must have a sound theoretical basis. Everywhere the need is felt to fill this void as soon as possible. It is for this reason that the Institute of Technical Physics has included in its program a systematic investigation of the physical processes which occur during electroerosion.

A divergence of opinion among various authors concerning the mechanics of electroerosion processes is characteristic of our time. One assumes that this disparity results primarily from the incompleteness of the information on which the studies published thus far have been based. For this reason we consider it necessary to, first, supplement these results with sufficiently solid material which will cast light on the phenomenon from different viewpoints, and,

then, on the basis of this material obtain a unifying interpretation. The results of observations described in the present article do not, of course, exhaust the phenomenon as a whole - they only summarize studies conducted in the first stages of plan, whose final purpose is the derivation of general relationships defining the erosion effect of condensed discharges in a dielectric medium.

Before beginning systematic measurements we conducted several preliminary experiments on the basis of which we created a working hypothesis and developed a technique for our initial experiments. Since measurements on the machines which are usually employed in the industry do not give us reproducible results, we used a discharger with stationary electrodes ignited by means of an auxiliary spark from a high-frequency generator. This device made it possible, first, to precisely monitor the distance between electrodes and, thus, the necessary uniformity of the discharges. Secondly, we were able to select the voltage independently of the discharge gap.

Based on the results of the preliminary experiments we formulated our initial working hypothesis on the erosion of the effect of spark discharges: The failure of the electrodes is caused by change in the state of aggregation, i.e., by melting and vaporization of the electrode with metal. The resultant effect is that of removal of the material which has been transformed into higher states of aggregation and of its solidification at some distance from the electrodes. The escape of material in the form of vapor depends on the concentration of energy on the surface of the electrodes and on the thermal properties of the material. In addition to the above, the spraying [spattering] of the material is significantly influenced by the pressure which develops during the decay of the plasma or under the effect of the jets of vapor. The medium in which the discharge occurs is an important factor which partially influences the amplitude of the pressure wave, then localization of the energy, and finally, the cooling of the removed material and the electrodes themselves. In selecting a technique the following fact is important: in a series of discharges falling upon the same place on the electrode surface, total losses do not increase in

proportion to total energy. Consequently, between the energy of a single discharge and the frequency of the sparks there does not exist the rule of reciprocity, which is often taken for granted.

Proceeding from the preliminary hypotheses we worked out a plan for the first stage of the study, which consisted of the following: 1. Observation of the removal of material with different combinations of electrode materials with partial determination of the value of certain physical constants of the material and investigation of the mutual effect of the electrodes in mind. 2. Determination of the dependence of total erosion on the distance between electrodes as a basis for the argument of secondary redistributions of energy in the discharge. 3. An explanation of the effect of the geometrical proportions of the interelectrode expansion gap on the magnitude of erosion and on the course of the discharge, and based on this, ideas on the value of the energy accumulated in the plasma for transfer of material in the discharge. 4. Determination of the dependence of the total magnitude of erosion a) on working capacitance and b) on working voltage to study the effect of the course of change in instantaneous power on wear.

In view of increased requirements the apparatus was redesigned in accordance with the results of the preliminary experiments. The discharger was now arranged such that during each discharge a fresh portion of the surface of the electrodes was engaged. Since the high-frequency generator previously used was not capable of exciting reliable discharges of more than 1.5 mm in duration, for ignition we now used a low-voltage spark discharge from a pulse generator, which provided satisfactory results in intervals of up to 35 mm. To switch in the two-beam oscillograph scanning circuit it was advantageous to use the advance primary pulse of a pulse generator. The engagement of scanning, and along with it regulation of the appropriate initial point of the curve on the screen, is controlled by a corrector, which affects the magnitude of advance of the starting pulse at the inlet on the scanning circuit. Thus we avoided the distortions which are usually introduced by the delay lines which are used. The overall arrangement of the device can be seen in the diagram (Fig. 1).

Using this apapratus we began taking systematic measurements while studying the effect of the electrode material on the magnitude of erosion. In the measurements the following selected regime was maintained throughout: working capacity fo 500 μF, capacitor charge voltage 500 V, and distance between electrodes 0.25 mm with discharges in air. The measurements were taken on lead, tin, zinc, copper, aluminum, iron, and nickel with all combinations of these elements. Weight monitoring of the magnitude of erosion was usually done after 32 discharges. The average values of the measurement results on four pairs of electrodes for one discharge have been compiled in the table. The oscillograms taken during the measurements did not diverge from the curve shown in Fig. 2. Here we should mention that, in view of the hindering effect of the high voltage excitation, which we were unable to eliminate, it was not possible to monitor the course of voltage directly on the discharger, but only on the capacitor terminals. Thus, the voltage oscillogram does not provide reliable information on the discharger regime. Nevertheless, the course of the current can be smoothed by a gas-discharge tube or by other resistors in the main circuit. Thus, it has not yet been established that the material of the electrodes does not influence the course of the discharge.

The following series of measurements was taken for the purpose of studying the dependence of the magnitude of erosion on the distance between electrodes. On the same apparatus we studied this dependence for electrodes made of

$$+\text{Pb}/-\text{Pb}, \quad +\text{Zn}/-\text{Zn}, \quad +\text{Al}/-\text{Al}, \quad +\text{Fe}/-\text{Fe}$$

in a spark gap range of from 0.02 mm to 20 mm at a working capacitance of 500 uF and a working voltage of 500 V. The results of the measurements are shown in the diagram of Fig. 3. Since in this case the oscillograms retain their form, the hypothesis of the smoothing effect of the ballast in the external discharge circuit was proven beyond a doubt, and no conclusions could be drawn from this.

The purpose of a further series of experiments was to determine the role played by the energy accumulated in the plasma in the erosion effect of the dischare. An insulating barrier with a drilled

channel, which formed the expansion chamber in which the discharge occurred, was placed between the electrodes. Constant air gaps of 1 mm were maintained on both sides of the barrier between the barrier and the electrodes. The thickness of the barrier varied from 1.0 mm to 10.5 mm; the initial diameter of the channel was 0.4 mm and 1.0 mm, respectively. Note that, since a more suitable material was not available, the barriers were prepared from Plexite - a material with low flame resistance, so that the original diameter of the channel increased during the course of the discharge. The narrower and shorter the channel, the greater was this increase. The wear values determined on the copper electrodes at a capacitance of 500 μF and a voltage of 500 V are shown on the diagram in Fig. 4 as a function of the length of the chamber at a channel diameter of 0.4 mm, 1.0 mm, respectively. From the diagrams in Figs. 5 and 6 we learn how the chambers affect the behavior of the currents and voltages.

Finally, we studied the dependence of wear on the capacitance and voltage which determine the shape of the pulse in the capacity of the main parameters. The dependence on capacitance at a voltage of 500 V and a distance of 0.25 mm between electrodes for lead is shown in the diagram of Fig. 7. Figure 8 shows the same dependence, although this time for copper electrodes at a distance of 4.5 mm, symmetrically separated by a barrier 2.5 mm thick with a channel diameter of 1 mm. The dependence of the magnitude of erosion on the working voltage, observed on lead electrodes at a distance of 0.25 mm and a capacitance of 500 μF is shown in the diagram of Fig. 9.

Let us now attempt to analyze the results of the measurements. From the table on page 23 we learn that erosion in the case of identical materials on both electrodes is approximately inversely proportional to melting heats. Low-melting metals are subject to this law, while in the higher melting metals we observe rather substantial deviations. However, putting these deviations aside for a moment, we can see in this dependence the confirmation of the main thesis of the original hypothesis, namely that wear is the result of a change in the state of aggregation and, from this,

we conclude that the erosion of material from the electrodes occurs primarily in the liquid state. This conclusion is confirmed by the fact that on the surface of the crater traces of melting (Figs. 10, 11) are always present and that the metal which is removed usually solidifies in the form of regular spheres (Fig. 12). Furthermore, the table shows that anode erosions of a certain material diminish in the direction of the "harder" cathode materials (downward in the columns) and, analogously, that cathode erosions of the same material diminish in the direction of the "harder" anode materials (from left to right in the rows). Thus, it was shown that the wear of any electrode is influenced by the material of the opposing electrode. This fact can be most easily explained by the secondary redistributions of energy between the electrodes, caused by the streams of vapor [1, 2]. There are exceptions to this rule. For example, higher losses are obtained in the case of a tin electrode opposite a lead electrode than in the case of lead opposite lead. Such anomalies over the entire surface indicate that the problem of resultant wear is resolved by the temperature constants of the developing equilibrium points. The fact that there actually occurs a transfer of material from one electrode to the other is confirmed by the detection of brass (or bronze) on copper electrodes placed opposite zinc (or tin).

Further information on internal energy shifts between electrodes is provided by measuring the magnitude of erosion as a function of distance between electrodes. From the curves in diagram 3 it is clear that erosions diminish quite rapidly with distance. Since the discharge current remains virtually the same (under the influence of the impedance of the external discharge region), wear depends primarily on the energy transmitted by the vapor to the opposite electrode, since wear also increases rapidly with distance during this transfer. Irregularities on the edges within the range of particularly large or particularly small distances can be explained by the different energy concentration of the streams of vapor during the discharge process and by other influences, which will be indicated below. From the voltage oscillogram in Fig. 13, which we were later to obtain by a new excitation method [3] directly from the discharger,

we see the two characteristic discharge stages: the spark stage, in which a voltage drop in observed between the electrodes, and the arc stage, in which the discharge now occurs with a constant voltage. We are justified in assuming that the behavior of the anode and cathode drop is generally affine [4]. As a result the response of instantaneous power in the spark stage shows a significant maximum. Consequently the vapor jets (henceforth "sprays" according to Mandel'stam) should in this stage display a high energy content, which is intensified by the fact that at the rate at which energy in this stage is transmitted to the electrodes heat cannot penetrate to any great depth and is thus spent on surface vaporization of the material. Henceforth one can assume that the "pronounced" sprays which develop in the spark stage act at a much greater distance than the subsequent arc sprays. The main erosion at great distances between electrodes can be attributed to the action of these pronounced sprays. When the distance is reduced, other arc sprays begin to participate. Their impact energy falls rapidly with the length of the path, and, thus, at great distances is insufficient for melting the surface of the opposing electrode. Subsequently, in this case they cannot be the reason for the weight loss. Conversely, their condensation on the opposing electrode causes an increase, which appears as the saddle on the erosion curve. The impact energy of the sprays, and, thus, the amount of molten material, increases more rapidly as the distance between the electrodes decreases.

Of course the problem of the energy of the sprays is resolved by energy first liberated on the electrodes on impact of the carriers. The ratio of anode dissipation to cathode dissipation can be estimated by the ratio of erosion detected on the discharger with the barrier, where the effect of the sprays has been eliminated by the screening effect of the barrier. From the diagrams in Figs. 4 and 8 it is clear that anode wear in this case is always greater than cathode wear. Logically, therefore, anode losses are also greater than cathode, which justifies the hypothesis of thermionic emission on the cathode. One can therefore expect that anode wear will be greater than cathode in cases where the effect of the sprays does not exceed the effect of the energies which enter the electrodes

by other paths. onversely, the ratio $u_A u_K < 1$ will occur where erosion is caused primarily by sprays, particularly the pronounced sprays of the spark stage of the discharge. Such a case develops, for example, in short-term discharges with an underdeveloped arc stage. This also explains the inversion of the u_A/u_K ratio in diagram 7 at capacitances below 1000 μs. Such ratios also develop at great electrode distances. The critical distance at which inversion of the u_A/u_K ratio begins also depends, of course, on the temperature constants of the material of both the "base" electrode (determining the energy content of the sprays) and the opposing electrode (determining the amount of molten material).

In general one can say that the softer the cathode material and the harder the anode material, the smaller will be this critical distance. This is also apparent from the erosion table on page 23.

Measurement of erosion on the discharger with the expansion chamber revealed that, in addition to the conclusions already drawn above, the energy accumulated in the plasma has a significant influence, first, in the melting of the material and, more importantly, in the removal of the molten metal. In the proper regime its effect may be greater than the effect of the sprays. In the oscillograms of diagrams 5 and 6 the effect of the expansion chamber can be seen primarily as a change in the current maximum, which with the increasing length of the chamber becomes lower and shifts in the direction of the origin of the coordinates. A decrease in the diameter of the chamber has a similar effect. The time of the discharge increases simultaneously. Voltage in the longer and narrower chambers decreases more slowly and ends with a greater residual value. We can therefore assume that the expansion of the discharge channel in the experiment regime begins as early as the plasma formation stage [5, 6, 7]. It appears that the curves representing the magnitude of erosion as a function of the length of the chamber in diagram 4 generally repeats the behavior of the plasma energy in the chamber. The fact that the erosion effect is caused not only by plasma energy is, however, indicated, first, by the fact that anode wear is always greater than cathode and,

second, by the fact that this has been shown in a control experiment, already mentioned above [8]. Thus, in the case of the given experiment (copper electrodes) we have the simultaneous effect of the energy liberated during the decay of the plasma and the energy liberated upon impact of the carriers. On soft metals, however, wear may result merely from the effect of the expanding channel, which indicates the participation of the latter in the heat balance. Most significant, however, is the pressure wave, which resolves the problem of the quantity of molten metal removed from the surface of the electrode and, thus, the actual magnitude of erosion. The photographs of craters in Figs. 14 and 15 are very revealing. The deep wall-less crater in Fig. 14 was created by the effect of pressures focused by a chamber with an initial diameter of 0.4 mm, while the smaller crater with its radial grains of molten metal spray in Fig. 15 was created by the effect of a chamber 1 mm in diameter with a high discharge energy. The effect of pressures can also further explain the decrease in the steepness of the loss curves in diagram 3 in the range of least distances. Here the short discharge columns in the case of a limited discharge current do not have sufficient energy, since effective wear decreases, even though the amount of molten metal even rises as distance is decreased.

The observed dependence of wear on working power (diagram 7) is almost strictly linear with the exception of the deviation already explained. The dependence on working voltage is approximately square (diagram 9). Both cases show that the total magnitude of erosion (at least in the observed range) is directly proportional to discharge energy.

If, in conclusion, we compare the results of the described measurements with the original hypothesis, then we will see that the hypothesis is generally confirmed by the measurements and refined to the degree that it is possible to qualitatively describe the mechanics of the electroerosion process with condensed discharges in a dielectric medium:

The energy first liberated by the collisions of the carriers causes a change in the state of aggregation on the electrodes. Here, as a result of the thermionic emission on the cathode, less energy is liberated than on the anode. In the first stage of the discharge (with the voltage drop on the discharger) the specific power transmitted to the electrodes is so great that the energy does not permeate the material, but is spent on surface vaporization. The vapors which are ejected from the electrodes therefore transfer (at a rather small distance) most of the primary energy from the main electrode to the opposing, since in this stage greater melting develops on the cathode. In the transition to the arc stage the primary expended power on both electrodes decreases, and energy begins to permeate the material, thus decreasing the amount of material vaporized. At the same time the effect of the sprays recedes to the background, since most of the melting occurs on the anode. With the expansion of the discharge channel, which in all probability begins immediately after the transition to the arc stage of the discharge, pressures develop in the interelectrode gap which under certain conditions remove the molten material from the surface of the electrode. Thus, a droplet type of wear is obtained, which exerts a dominating influence on the resultant erosion effect.

According to these concepts of the mechanics of electrode erosion, three energy processes participate in the development of wear: The primary process, in which energy is transferred to the electrodes by carrier impact; the secondary process, wherein energy is exchanged between the electrodes under the influence of the sprays and, finally, the tertiary process, where we have the effect of the energy accumulated in the plasma. The total energy transferred to the discharger, minus unavoidable losses, is divided between both the electrodes and the plasma. The longer the discharge column, the smaller the amount going to the electrodes, and vice versa. Therefore, an exceptionally short channel results in intense melting but a weak pressure pulse, since most of the material remains on the electrodes. Thus, an optimal regime exists in which the greatest wear of the electrodes can be achieved by an assigned total energy.

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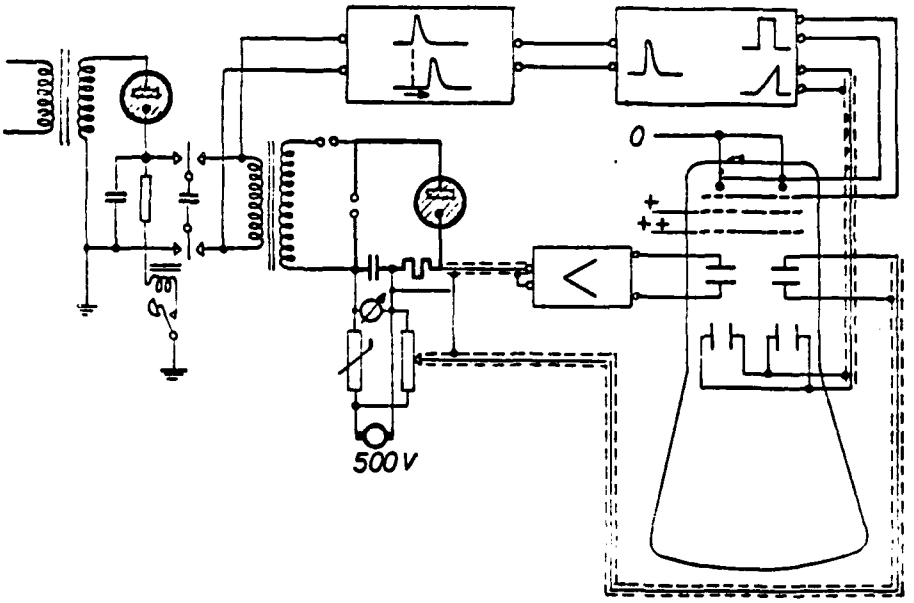

Fig. 1. Diagram of apparatus.

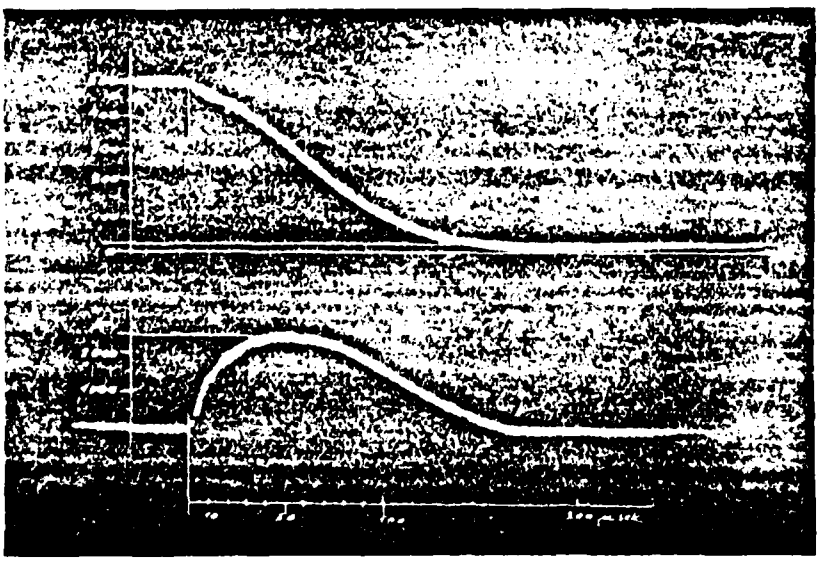

Fig. 2. Oscillogram of voltage (on capacitor terminals) and current at C=500 uF; V_C= 500 V.

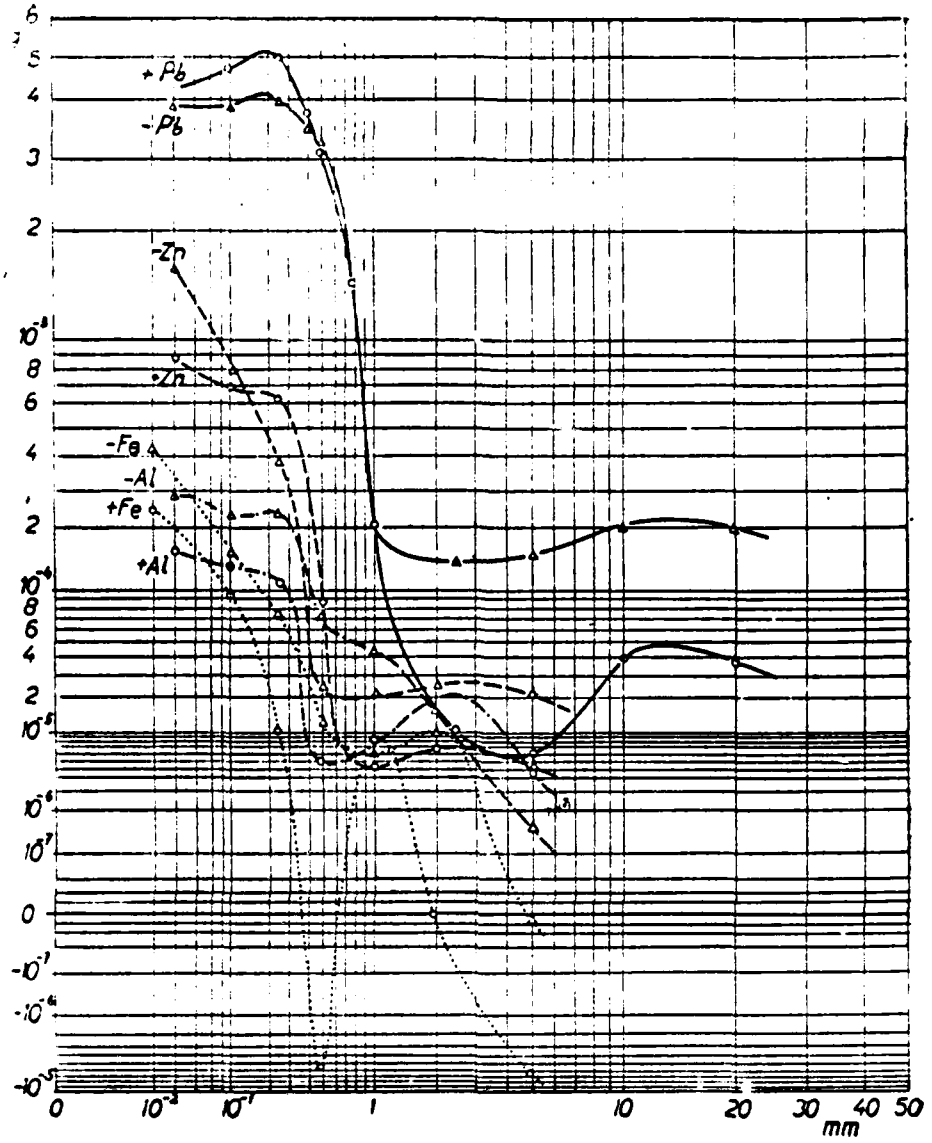

Fig. 3. Magnitude of erosion as function of distance between electrodes.

Table representing erosion with different combinations of electrode material. Discharges in air, distance between electrodes 0.25 mm, working capacitance of 500 μF, voltage 500 V, wear on electrodes 10^{-4} g/l discharge.

(2) Катод \ (1) Анод	Pb	Sn	Zn	Cu	Al	Ni	Fe
	50,5	*52,2*	*10,0*	*12,2*	*8,8*	*6,5*	*3,9*
Pb	41,3	22,7	35,0	24,4	15,2	22,8	28,2
	28,2	*19,4*	*6,4*	*8,3*	*7,1*	*6,2*	*4,0*
Sn	59,5	15,2	33,0	14,5	9,8	11,5	12,3
	41,8	*22,5*	*8,7*	*6,4*	*5,9*	*2,0*	*2,3*
Zn	8,4	1,5	6,9	1,2	0,4	0,6	1,7
	21,9	*9,7*	*2,8*	*0,3*	*0,9*	*0,2*	*0,2*
Cu	6,1	1,6	1,1	0,6	0,9	0,8	0,9
	21,9	*14,5*	*2,6*	*1,4*	*1,4*	*0,0*	*0,2*
Al	8,8	2,8	5,9	2,2	2,9	1,3	1,8
	25,5	*7,3*	*5,1*	*2,5*	*1,3*	*1,1*	*0,1*
Ni	3,9	0,9	0,7	0,6	0,3	0,9	0,7
	45,0	*11,5*	*2,7*	*5,5*	*1,4*	*2,7*	*0,1*
Fe	3,8	2,3	0,7	0,9	0,3	1,1	0,8

Key: 1) Anode; 2) Cathode.

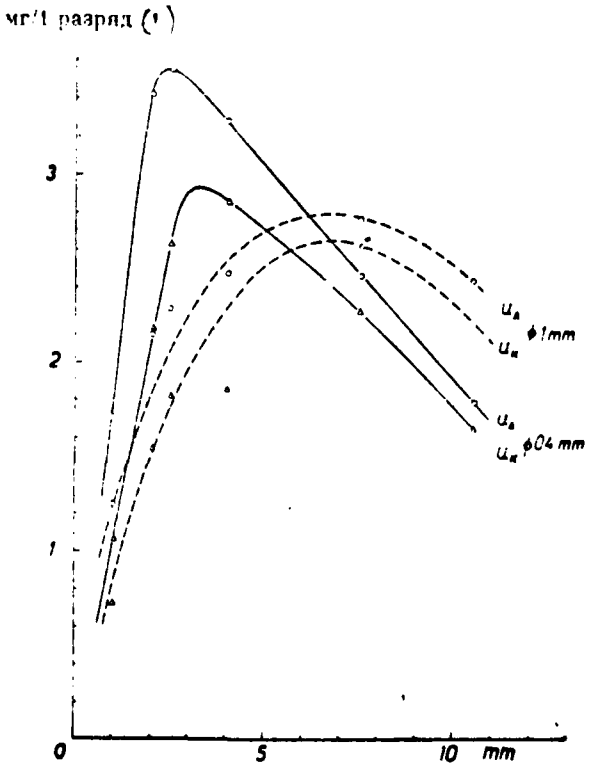

Fig. 4. Wear as a function of length of the expansion chamber, copper electrodes, 500 μF, 500 V. Key: mg/l discharge.

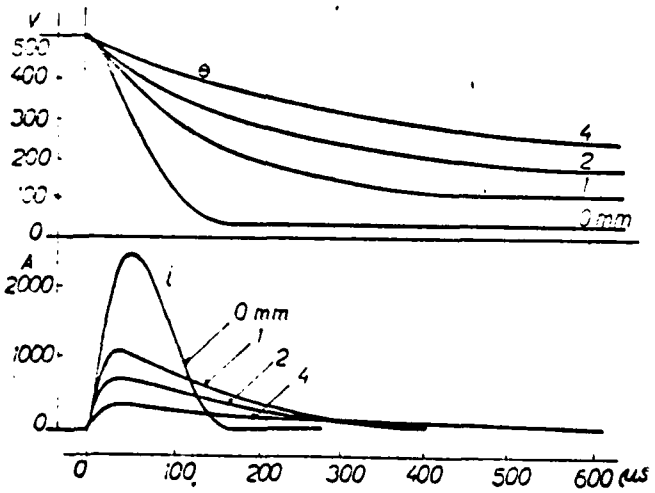

Fig. 5

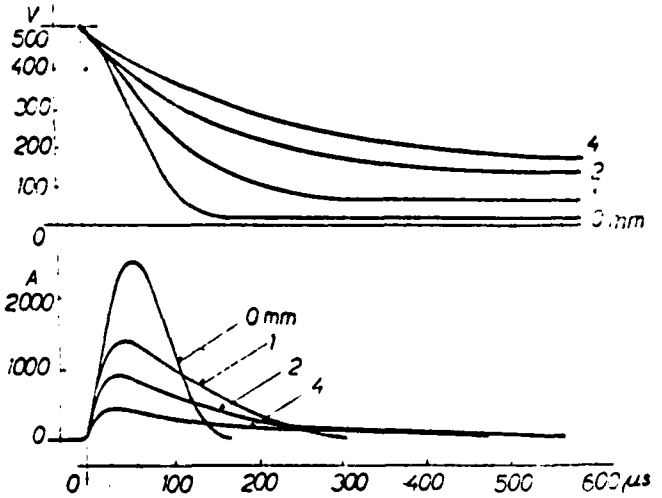

Fig. 6

Fig. 5. Oscillograms representing voltage (on capacitor) and current with expansion chamber diameter of 0.4 mm and length of 0-4 mm.

Fig. 6. Oscillograms representing voltage (on capacitor) and current with expansion chamber diameter of 1.0 mm and length of 0-4 mm.

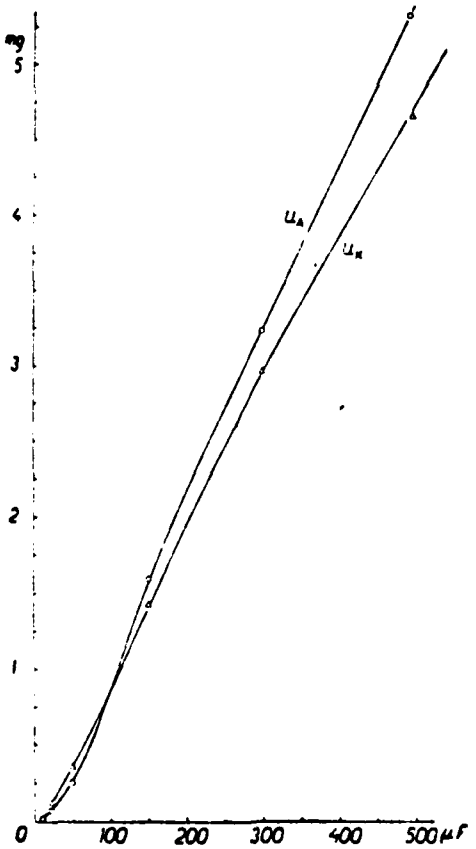

Fig. 7. Wear as a function of capacitance, lead electrodes at a distance of 0.25 mm, capacitor voltage 500 V.

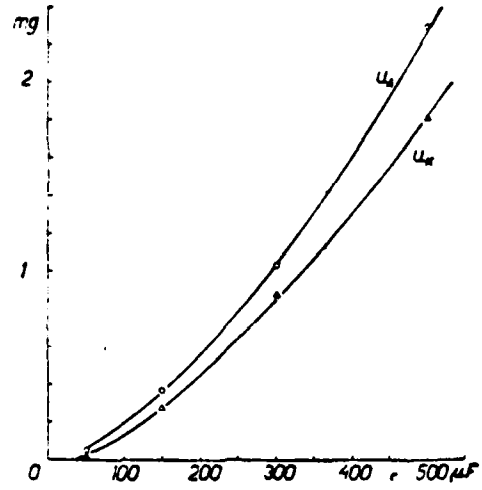

Fig. 8. Wear as a function of capacitance, copper electrodes at a distance of 4.5 mm in inserted expansion chamber 2.5 mm long and 1.0 mm in diameter. Capacitor voltage 500 V.

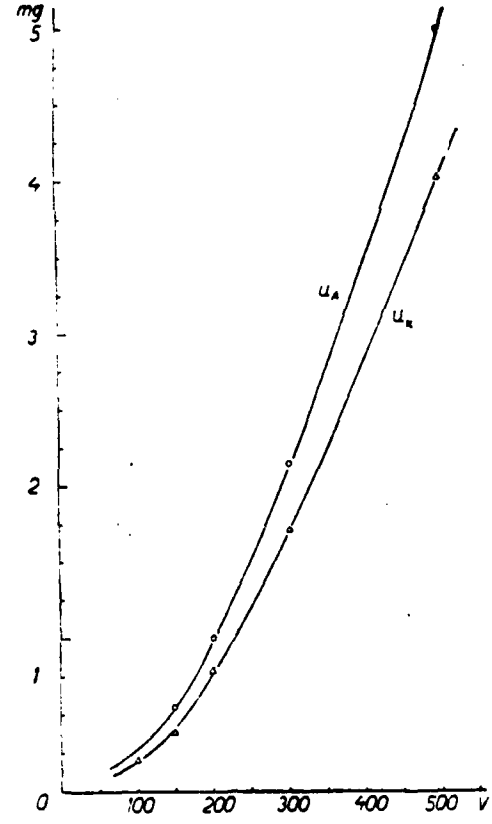

Fig. 9. Wear as a function of voltage, lead electrodes at a distance of 0.25 mm, capacitance 500 μF.

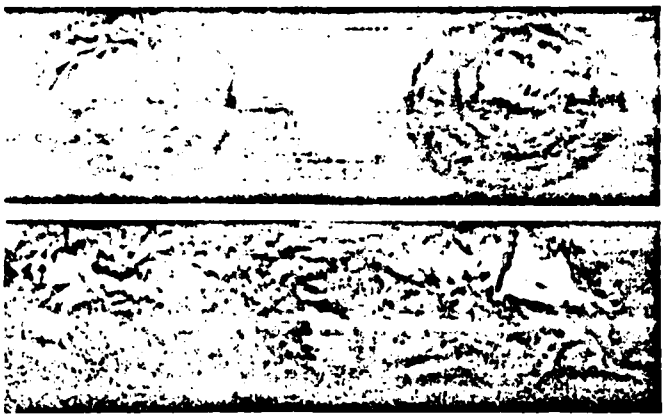

Fig. 10. Craters on aluminum, current peak 2440 A. discharge time 175 ms, anode above, cathode below.

Fig. 11. Craters on copper, current peak 2440 A, discharge time 175 ms, anode above, cathode below.

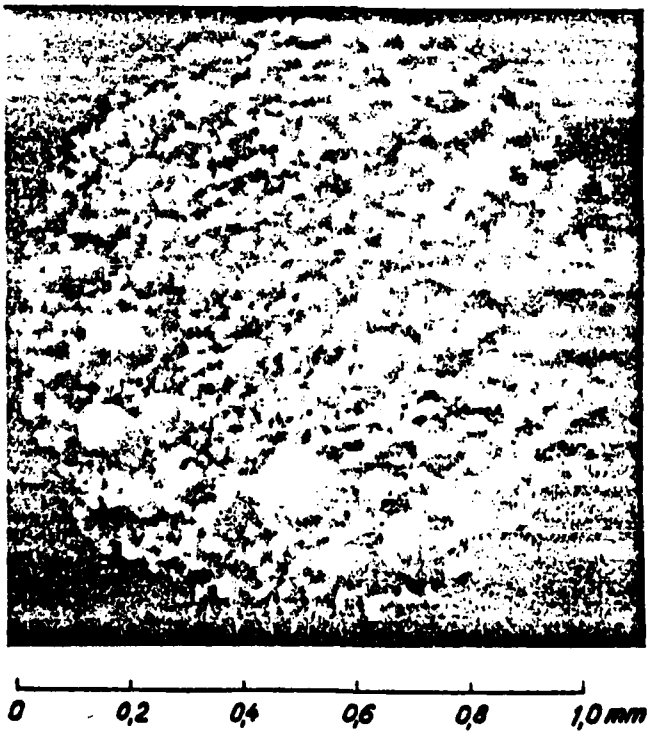

Fig. 12. Zinc sputtered by electroerosion.

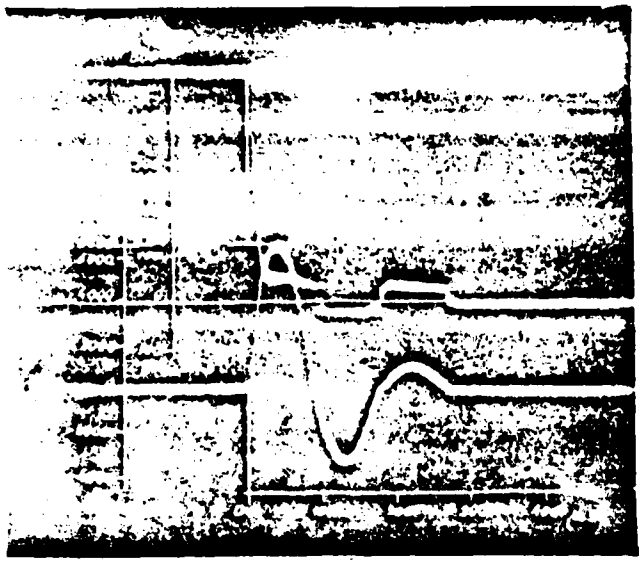

Fig. 13. Oscillogram representing current and voltage on discharger at C=500 μF, V_c=500 V.

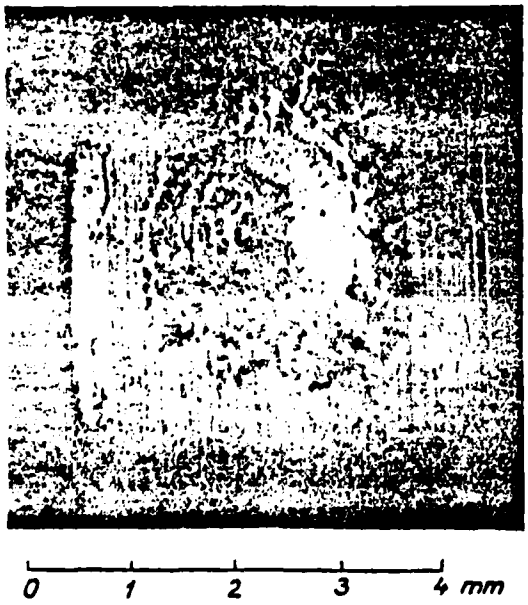

Fig. 14

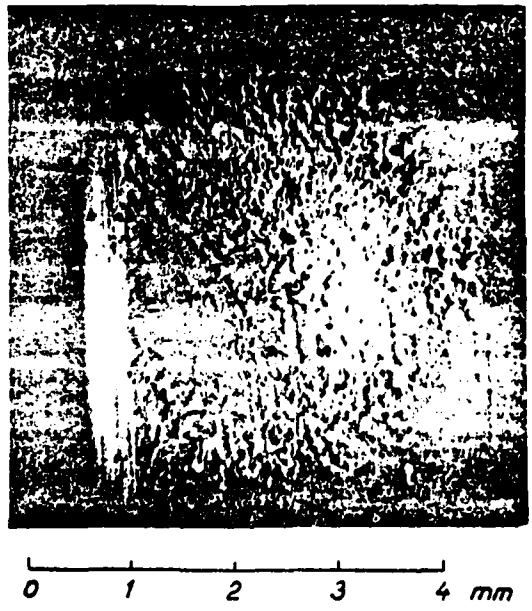

Fig. 15

Fig. 14. Crater on copper anode created by effect of concentrated pressures of chamber with an initial diameter of 0.4 mm.

Fig. 15. Crater on copper anode created by effect of concentrated pressures of chamber with an initial diameter of 1.0 mm.