INVESTIGATION OF THE ELEMENTARY PHENOMENA IN ELECTRICAL SPARK-MACHINING

By

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(Received September 22, 1962)

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Introduction

During the last 10—15 years the pace of modern industrial development is characterized by the appearance of several machining methods, each differing from the traditional ones and more economical in its proper field of application [1]. Such methods are, e.g. the chemical removal of material, ultrasonic machining, the electrical erosion methods. These machining methods came into being from practical necessity and to-day each one is widely used in sectors of industry suitable for its application. Amongst the above mentioned new machining methods without doubt the electro-erosion methods ought to be mentioned in the first place, some of these being destined to provide an important contribution towards the solution of the problems arising in mass production.

Several variants of electro-erosion machining have been developed [2, 3] and to-day each has its own distinct field of application. The principal erosion machining methods are, according to the terminology used at present, the following:

1. Electrical spark method,
1*a* Spark machining,
1*b* Surface hardening,
2. Electromechanical method,
3. Electrical arc machining.

With the metal machining methods, many theoretical and practical problems arise. One part of these are questions concerning the electrical gear, the other part embraces the technological problems arising from the practical use of the methods. As for these subjects, literature giving a very good summary of the matter is available [4, 5].

The discovery of the use of electro-erosion for the machining of metals is the merit of N. I. Lazarenko and B. R. Lazarenko [6]. Hardly twenty years have passed since this discovery and to-day there is no industrially developed country, where some sort of electro-erosion machine is not being produced. In the leading industrial countries, special research institutes and enterprises are created for the investigation of the physical characteristics of the method, for designing installations providing the best realization of the principles and for developing the new production method and its industrial introduction further. In the Soviet Union thus is the CNIL-ELEKTROM (Tsentralnoy nautchno-isledovatelskoy laboratorii elektricheskoy obrabotki materialov) Research Institute of the Academy of Sciences, in the USA the Method X Co. of Philadelphia. In France basic research is carried out in the Laboratory of Chemical Physics of the Sorbonne and in the Physics Laboratory of the École Nationale des Ingénieurs. In Czechoslovakia the VUMA Industrial Research Institute and in the German Federal Republic the Aachen Technical University is engaged in working out the questions mentioned above.

In Hungary, electro-erosion machining methods and especially spark-erosion has considerable traditions. In the years after the liberation — hardly a few years after the first Soviet publication — research work started in Hungary too. In the first place the basic experimental research carried out by KONCZ [7] at the Mechanical Technology Institute of Budapest Technical University must be mentioned. His remarkable results were also taken over by the foreign technical press [8]. Later on research combined with realization of industrial machinery was carried out in the Technological Institute of the Machine-Building Industry, as a result of which the first Hungarian spark-drilling machine, the "Spinthor" was invented, which has since found its way into the workshops [9]. The first Hungarian designed, series-built spark-erosion machine of machine-tool character was the "Erosimat" designed in 1955—56 and which was further developed since then. This machine — which was built with the cooperation of the author — won a Grand Prix at the Brussels Universal Exhibition 1958. The "Erosimat" spark-erosion machine was designed at the General Machine Design Institute, where research still continues, chiefly aimed at the practical use of spark erosion. Lastly, theoretical research was done under the direction of PÓCZA [10, 11] by the research workers of the Experimental Physics Institute of the Eötvös Lóránd University, Budapest. Their novel results have drawn attention to several, at present still unsolved problems.

This very incomplete enumeration shows the importance of the method. But it must be mentioned that notwithstanding the comprehensive and complex research work there are numerous unexplained questions which greatly hinder the general use of the various methods, and also in placing them on exact bases. By this latter remark the author wishes the basic phenomena characterizing the various methods take place under such special circumstances which are almost unique in theoretical as well as in applied research to be understood. This is also the final reason why the design of the electrical circuits of the installations is based on experimental data, although these circuits have been known since long in the other branches of electrical engineering.

The situation is no better as far as practical application is concerned, where at most only approximate data are known for e.g. the making of a tool. It is not possible to specify beforehand, for a given metal, those electrical parameters and technological data with which the production of the tool will be, within the limits offered by the method, most economical. These problems arise first of all with spark-erosion, because here the most complex tasks occur and, compared to the other methods, it is here that the most exacting requirements arise. The root of these problems is the fact that the questions, due to the special conditions of spark-machining have not been elucidated yet. They may be collected into two principal groups:

a) What is the mechanism of break-through and its progress in time, in a liquid and polluted dielectric at an electrode distance of 10^{-3} mm—10^{-2} mm order of magnitude and at 300—400 V maximum voltage?

b) What is the mechanism of the erosion caused by the electrical discharge, and how is the degree of erosion related to the physical and chemical characteristics of the electrodes and to the parameters of the discharge (power, voltage, current, discharge time)?

The first question and the problems connected with it are important from a practical point of view, because by solving these the equations describing the discharge characteristic might be established: the impedance charging the spark-erosion circuit — the impedance of the discharge channel — would become known. This would make possible the exact design of the spark-erosion circuit.

The questions raised at *b)* are closely related to the first one, the final aim being a production of spark-eroded hollows by methods more economical than the present ones and this can be attained only by solving the above problems. By increased economy the author understands maximum practical use of the theoretical possibilities offered by the method. E.g. the electrode quantity required on the application of the method should not, or only by little, exceed the total need of the traditional machining processes.

The author believes that this extremely important basic question can be approached only from the theoretical side, i.e. after having elucidated the above questions. From the point of view of direct practical work, the second group of questions is of greater importance, the first being only its complementary part.

Accordingly, also the present paper deals with two principal questions:

(i) The development of the conducting channel (disruption).

(ii) The mechanism of material removal (electrical erosion).

The efforts aiming at te elucidation of the above-mentioned questions are as old as the discovery of the basic phenomenon. By regarding both questions several opinions were developed, up to now we cannot speak of a uniformly adopted standpoint. The main reason for this is that most of the research workers disregard the special circumstances of spark-erosion as mentioned above.

I. The development of the disruption channel

As for the problem of the disruptive breakdown of the working fluid under conditions of spark-machining, the point of view of the majority of authors is characterized by the application of some of the theories — by far not free of contradictions elaborated for the disruption of pure insulating liquids, to the special case in question. There are but a few exceptions from this [12, 13]. If a true picture of the discharge channel is desired, it is indispensable to take the pollution in the spark gap into consideration. The concentration of the pollution in the working liquid (usually kerosene or transformer oil) is of varying value, but its importance is brought into relief also by the following sample example. Let us consider a machine of medium machining power. Let us assume that the volume of the liquid surrounding the erosion gap is 10 litres and that the maximum material removal is 250 mm^3/min. If the relative wear of the working electrode is 40%, so, during 1 minute 350 mm^3 of metal mud gets into the liquid, and after 8 hours of operation this amounts to 168 cm^3. After 10 days of operation, the pollution originating from the electrodes amounts to 17—18% of the original volume of the liquid. In reality the situation is more favourable, as the liquid is circulated through a decanting tank or is filtered, so the above concentration of pollution is reached only after a longer time.

Nevertheless, the degree of contamination in the erosion gap between the electrodes generally amounts to the above mentioned value. For a machine of higher performance the situation is similar, because with increased metal removal, an increased cooling liquid volume is generally used.

Obviously, if the disruption of the working fluid is to be described, of all the theories of the disruption of liquid dieletrics which have been evolved, that one ought to be considered which also takes the part played by the foreign polluting matter present in the fluid into consideration. The elaboration of such a theory is due to EISLER [14]. According to this theory, all liquid insulating materials contain ions and pollution, and consequently every liquid can be considered as an electrolyte. The concentration of the electrolyte is determined by the degree of contamination. The conductivity of the dielectric can be considered as conductivity originating from the pollution, and in case of higher field strengths as the sum of this conductivity and of the conductivity due to the contamination. The conductivity due to the electrolytes is

$$\sigma_1 = C \exp\left(a_1 T - \frac{a_2}{T}\right) \tag{1}$$

where a_1, a_2 = constants,
T = temperature,
$C = k \sqrt{c_0}$—a constant uniting the various material parameters,
c_0 = the electrolyte concentration.

In the case of higher field strength the conductivity arising from the field strength appears as an additive member:

$$\sigma_2 = C_2 \exp\left(a_1 T - \frac{b}{\mathscr{E}}\right) \tag{2}$$

where b = constant
C_2 = material constant,
$\mathscr{E}$ = strength of field.

The total conductivity is the sum of (1) and (2). Formula (1) shows that for a constant temperature, the conductivity of the insulating liquid, which is due to the contamination, is proportional to the root of the pollution concentration. The actual situation is more complicated than this, because the local and the integral temperature of the cooling liquid continually varies under the action of the various discharges, furthermore, the field strength $\mathscr{E}$ appearing in the exponent of formula (2) also varies. The variation of the electric field strength has two causes: on the one hand, voltage changes and on the other hand, the distance between electrodes changes. The first phenomenon is due to discharge, the second one to erosion. The dependence on time of these two variables is still unknown today, one must resign to quantitatively applying Equs. (1) and (2). Nevertheless, these two relations provide a reasonable basis for assuming that in the discharge, contamination plays a part.

For a particular examination of the question, the following realistic assumption may serve as a starting point. Because of the discharge causing erosion craters on the surface of the electrodes, the field strength between the electrodes can be considered as being strongly inhomogeneous, at least locally. The value of the electrical field strength is, for a voltage of 200 V and $5 \cdot 10^{-3}$ cm electrode distance,

$$\mathscr{E} = 4 \cdot 10^4 \frac{V}{\text{cm}} \tag{3}$$

The relative dielectric constant of kerosene is chosen to be $\varepsilon_1 \approx 2$ and $\varepsilon_2 \approx 1$ for the grains. Microscopic examination of the metal grains shows that they may be considered as spheres with a radius of generally

$$r = 10^{-4}\,\text{cm} \tag{4}$$

The dielectrophoretic force acting on such a grain is expressed, according to Pohl [15] by

$$P_d = 4\, r^3 \pi \varepsilon_0\, \varepsilon_1 \frac{\varepsilon_2 - \varepsilon_1}{\varepsilon_2 + 2\, \varepsilon_1} \operatorname{grad} \mathcal{E}^2 \tag{5}$$

where $\varepsilon_0 = 8.86 \cdot 10^{-14} \frac{A \sec}{V \mathrm{cm}}$ is the dielectric constant of vacuum,

P_d = the dielectrophoretic force acting on particle $\frac{VA \sec}{\mathrm{cm}}$

Using the above data, in the present case the force acting on the removed particle is

$$|P_d| = 1.42 \cdot 10^{-13} \frac{VA \sec}{\mathrm{cm}} \tag{6}$$

or

$$|P_d| = 1.45 \cdot 10^{-9}\, g \tag{7}$$

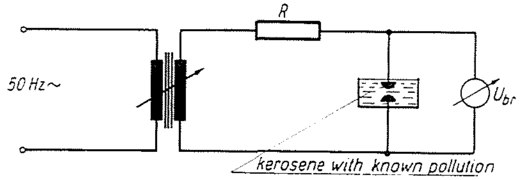


Fig. 1

If the greater part of the particle under examination comes from a steel electrode, its weight will be

$$G \approx 3.26 \cdot 10^{-11}\, g \tag{8}$$

The ratio of the force acting on the particle and its weight is approx. 50. Therefore, the dielectrophoric attractive force of an order given by formula (7) is safely sufficient to draw the given contaminative particle to the place of maximum local field strength. Therefore, it is highly probable that conducting bridges can build up between the electrodes, the explosion of which starts the discharge.

In order to prove that the pollution caused by the erosion plays a role in the discharge, tests were carried out on the disruptive strength of the working liquid containing a pollution of known concentration. The measurements were made at the Chair of High Tension and Apparatus, Budapest Technical University, with 50 Hz sinusoidal voltage. The circuit diagram of the measuring device is shown in Fig. 1. The electrode device complied with the specifications of Hungarian Standard MSZ 153—50.

The electrode voltage was measured with an electrostatic mirror voltmeter. It was intended to arrive to a conclusion from the breakdown voltage at known electrode distance, determined as a function of fluid contamination, on the electrode distance existing under conditions of spark-machining. This idea seemed justified by the fact that the breakdown voltage is a linear function of the electrode distance ([16], p. 67). This method of evaluating the electrode during operation is as accurate as the absolute measuring, and is more comfortable. The measuring procedure was as follows: with the arrangement shown in Fig. 1 the distance between electrodes was adjusted by a micrometer screw, being 1 ± 0.005 mm during measurements. The previously carefully cleaned glass vessel was filled with the working fluid containing a known contamination. The mixture of metal mud and soot polluting the examined liquids was obtained by filtering the kerosene previously used for spark machining. The mixture was dried first in the open air and then in a drying furnace until it became dust. A known quantity was then mixed with 2 litres of clean kerosene. 12—15 minutes after filling the glass vessel, the first discharge was started and afterwards repeated every 12—15 minutes (5 times for each measurement). Waiting time between the breakdowns was necessary because the air bubbles absorbed in the liquid and the gases produced at the discharge caused a wide dispersion of the measuring results. Under conditions prevailing at spark-machining, the gas bubbles created by the discharge have no time to escape, therefore, the results of measurements must be considered as good approximations of reality. The results (means of 5 measurements) are shown in Table I and Fig. 2.

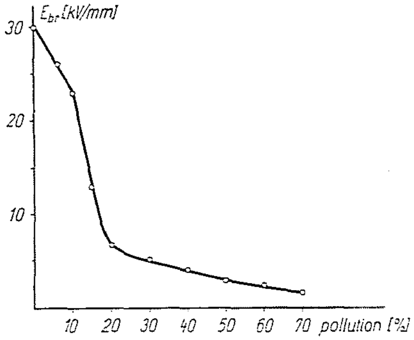


Fig. 2

The table and the figure show that the breakdown field strength decreases rather slowly from 0 to 10% pollution and is followed by a steeper decrease from 10 to 20%. After that the decrease becomes slower. The results prove that the degree of contamination greatly influences the breakdown strength of the working fluid.

Table I

Contamination [%]	U_{br} [kV]	Contamination [%]	U_{br} [kV]
0	30	30	5
6	26	40	4
10	23	50	2.8
15	13	60	2.2
20	6.6	70	1.2

During spark machining the degree of contamination of the gap, depending on the power of the discharges and on the filtration of the liquid, can be taken as being 6—15%. According to the measurements, the breakdown field strength is $23 \cdot 10^3$ V/mm at 6%, $13 \cdot 10^3$ V/mm at 15%. With few exceptions the voltage used in spark-erosion machines is 150—300 V. At 6% contamination the breakdown distances belonging to these values are $6.25 \cdot 10^{-3}$ mm and $1.25 \cdot 10^{-2}$ mm and at 15% contamination the respective distances are $1.15 \cdot 10^{-2}$ mm at 150 V and $2.3 \cdot 10^{-2}$ mm at 300 V. In reality the liquid contains absorbed gases and thus the above distances are still smaller. But even if we disregard this latter circumstance, the mentioned breakdown distances are of the same order of magnitude as the grains, they are comparable to them. Therefore, the contamination plays a decisive role in the development of the discharge channel.

It should be mentioned that the author does not attribute any part of the development of the discharge to the cold emission assumed by other authors. This statement is based on the fact that in the presumed field strength of 10^4—10^5 V/cm the cold emission of the electrons is negligible.

II. Examination of the mechanism of erosive material removal

Several theories on the erosion caused by the short-time transient electrical discharge have come to light during the past 10 years, but up to date no universally accepted point of view has been evolved. In order to prove the various concepts, measurements were made under different conditions and so the results cannot be criticized collectively. Nevertheless, the view begins to gain ground that for discharges shorter than 10^{-4} sec the field strength between the electrodes is decisive. Above all, the test results of Williams [17, 18] and Pócza [10, 11] point to this, but is is not possible yet to talk of the measuring results being firmly based on theory.

The theory of electro-erosion based on the thermal action of the discharges was founded by Zolotikh [16, 19, 20]. According to his opinion, at the discharge instantaneous, two-dimensional thermal sources arise on the surface of the electrodes, and the thermal current starting from them unequivocally determines the erosion.

The Mandelstam—Rayskiy-theory [21] identifies the erosion with the destructive action due to the kinetic energy of the high-speed jet of molten metal which is found in the discharge. The measurements made in order to prove this concept were carried out under conditions completely different from those of spark-machining.

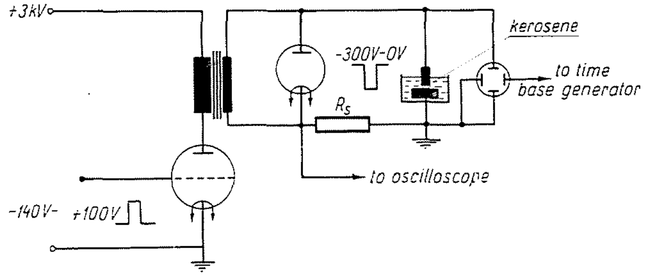


Fig. 3

According to their basic assumption the various theories of material removal give differing results in regard to the dependence on time and electrical power of the erosion. The dependence of erosion on these two factors is not only important from a theoretical point of view. The practical solution of the question is important because knowing it, design of spark-erosion circuits and the technological process could be accessible to numerical calculation.

In order to investigate in detail the above problems a series of tests were made with square voltage pulses of variable power and duration. The duration of the pulses varied from 10^{-4} sec to $1.5 \cdot 10^{-3}$ sec, the electrical power from 116 W to 360 W. The cathodes were made of type Sr 58 brass and Cu—T copper, the anodes consisted of type K 1 steel (formerly called Cr S 1). The description of the measuring device is omitted as it has already been published elsewhere [22].

The principle for measuring was the following. Discharges of known duration and electrical power were generated between the electrodes made of a given material. After a predetermined time the reduction in weight of the electrodes was measured by weighing. Dividing this loss by the number of discharges the anode erosion γa and the cathode erosion γc caused by one discharge was obtained. The measuring apparatus designed and realized for this purpose and the application of the above principle of measuring are convenient and comfortable in use, and conditions of measuring agree in every respect with the conditions of spark-machining. By a suitable selection of the space factor of the pulse train the advantages of the 'individual pulse' method of Lazarenko and Zolotikh are also obtained. It must be remarked that the use of the so-called relaxation generator for measuring purposes, though generally employed in practice, was very cumbersome and uncertain, as shown by the work of several authors [4, 23, 24]. The circuit diagram of the measuring apparatus is shown on Fig. 3. The diode connected in parallel with the electrodes serves for cutting off the repercussion of the pulses transmitted by the coupling transformer. The resistance R_s of $0.5 \pm 0.01\ \Omega$ serves for measuring the intensity of the discharge current. Voltage and current were measured with an oscilloscope which had been calibrated with a known voltage.

Before starting with the real measurements of metal removal it appeared necessary to carry out some preliminary tests and measurements. The more important ones concerned:

a) Does the amount of erosion for a given pulse power depend on the electrode distance?

b) With a given no-load voltage, what is the suitable gap size for machining?

c) How many times must a measurement be repeated for getting reliable results?

d) What is the accuracy of the measuring results?

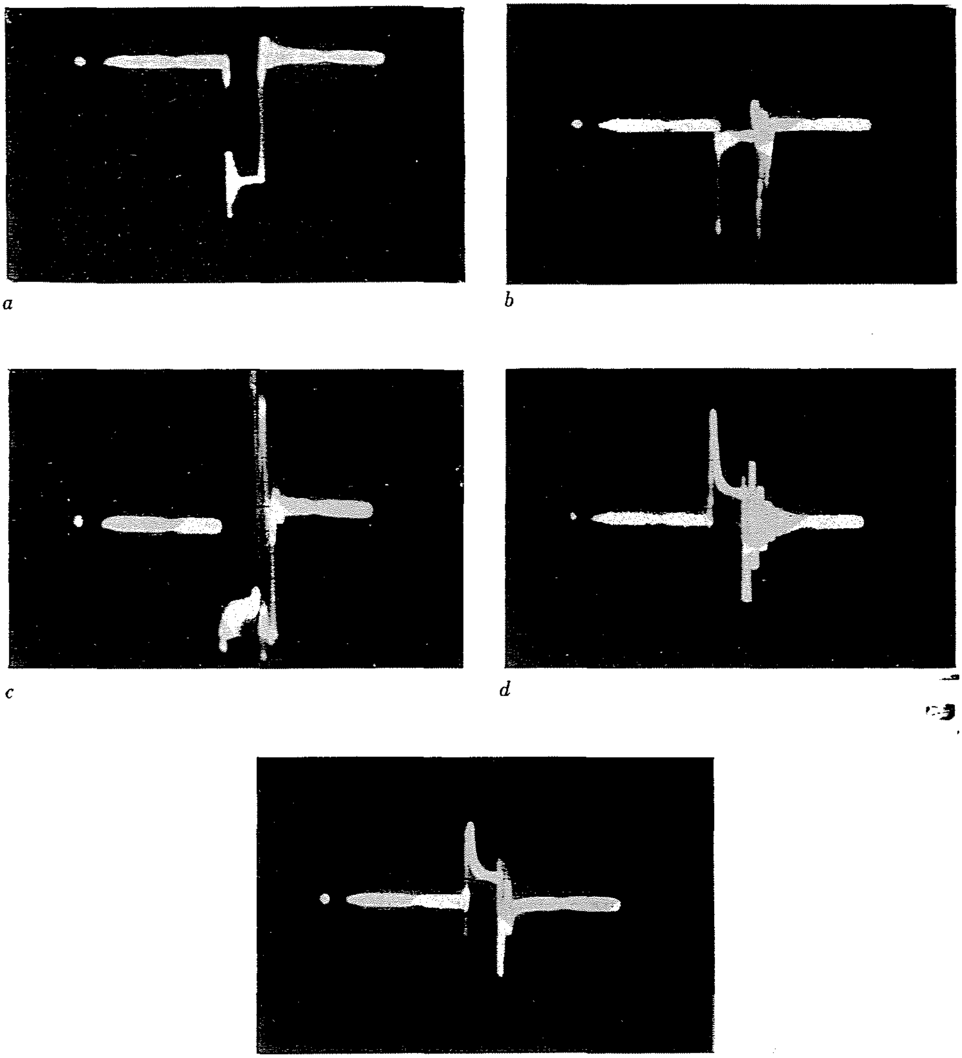
In order to answer these questions trial runs were made with pulses of various duration and 100, 150, 200 and 300 V no-load voltage. This trial machining led to the following results:

α) The breakdown voltage is determined by the distance between the electrodes. It can be proved that this does not depend on the quality of the electrode material.

β) The discharge occurs after a time shorter than 0.5 μsec. During this time, current intensity drops to the value determined by the impedance of the conducting channel, the burning voltage. This value is independent of the no-load voltage and of the electrode distance. Its value is constant until the end of the pulse and lies between 19.5 and 20.5 V. Its value does not depend on the maximum power of the supply.

γ) The amount of erosion of the electrodes (not considering short-circuit and no-current state) does not perceptibly depend on the electrode distance. The amount of erosion is determined unequivocally by the voltage after discharge (approx. 20 V) and by the current passing through the electrode gap.

δ) After the occurrence of the discharge, the intensity of the current through the gap is determined by the power of the supply. This intensity is, with good approximation, equal to the short-circuit intensity. A difference



a b c d e

Fig. 4

can be observed only at the beginning and at the end of the pulse, presumably because of the inductances and the stray capacities in the circuit.

In order to illustrate these statements, a few voltage and current oscillograms were shown. Fig. 4 shows the voltage and current pulses of $\tau = 5 \cdot 10^{-5}$ sec duration. Fig. 4*a* represents the $U_0 = 250$ V no-load voltage, Figs 4*b* and 4*c* the burning voltage, Fig. 4*d* the short-circuit current and Fig. 4*e* shows the discharge current. On Figs 4*a* and 4*b* one division corresponds to 50 V, on Figs 4*c*, *d*, *e* to 5 V. Time markings are 10^{-5} sec. everywhere.

The decay at the start and the end of the pulses are probably due to the stray capacities of the discharge circuit. With larger pulses, they are reduced to a relatively negligible value, as is shown by Figs. 5 and 6. The series of oscillograms in Fig. 5 shows the pulse of $\tau = 5 \cdot 10^{-4}$ sec duration, the series in Fig. 6 shows the voltage and current pulses of $\tau = 1.2 \cdot 10^{-3}$ sec duration. The time markings correspond to 10^{-4} sec. Fig. 5*a* shows $U_0 = 250$ V, Fig. 6*a* the $U_0 = 150$ V no-load voltages. The figures marked *b)* show the operating voltages, the *c)* figures show the short-circuit currents and the *d)* figures the operating currents. The voltage scale of the *a)* figures is 10 V/mm, that of Figs. *b)*, *c)*, and *d)* is 1 V/mm. The expression 'current' used above is, of course, the voltage drop proportional to current intensity.

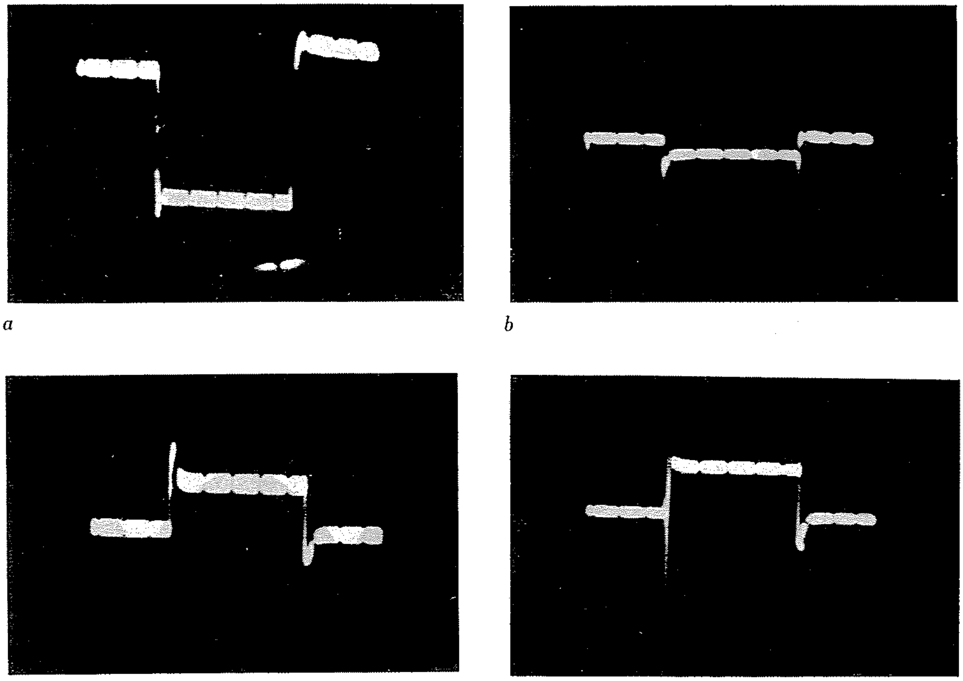


Fig. 5

When evaluating the informative metal removal measurements it appeared that the mean of 5 measuring results and the mean of 10 measuring results did not differ by more than 10%, taking as base the mean of 5 measurings. As it is not worth while to strive for greater accuracy, each measurement was made 5 times. Nevertheless, the results cannot be accepted as having 10% accuracy, because the total error of voltage, current and weight measuring is also approx. 10%. The cause of this is that for the determination of weight, the soot which was baked on to the electrodes and other impurities could have been completely eliminated only by mechanical action (this method would have obviously biased the results to a still greater extent). The greater part of the soot baked on to the electrodes was eliminated with pure kerosene and a paint brush. A part of the soot remained and contributed in increasing the error. Weight measurements were carried out with 10^{-4} g accuracy. The measuring results were well reproducible, with the exception of the erosion of Cu—T cathode. This erosion agreed qualitatively with the other erosion curves, but because of the great dispersion these measuring results could not be evaluated. The explanation for the great dispersion is probably the increased formation of soot on the surface of the Cu—T cathode. The value of γa attained with the Cu—T cathode is smaller than that attained with the Sr 58 cathode. This also seems to prove that general law that the material of the cathode, all other circumstances being equal, greatly influences the erosion of the anode. The inverse of this rule does not hold.

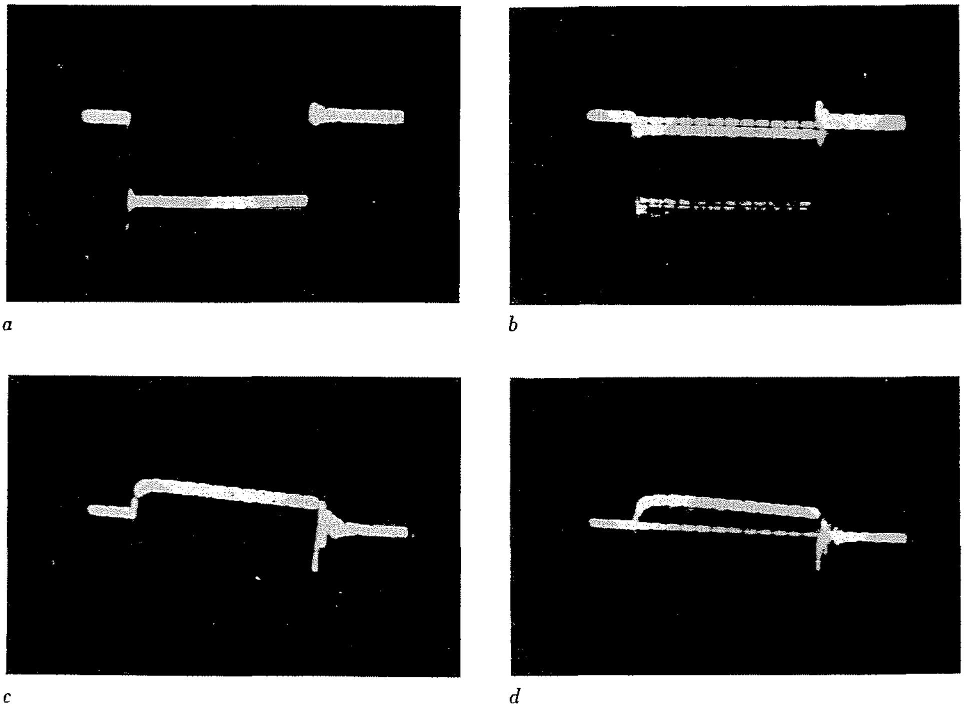


Fig. 6

Now several series from among the very great number of measurements will be communicated. In the tables, the following notations are used:

γac = the calculated value of anode erosion
γcc = the calculated value of cathode erosion
γam = the measured value of anode erosion
γcm = the measured value of cathode erosion.

Index 1 refers to the Sr 58 cathode, index 2 to the Cu—T cathode.

The curves shown on the figures are the calculated values of the erosion, the points are the measured values. For characterizing the discrepancy between the measured and the calculated values the coefficient Δ was used:

$$\Delta = \left| \frac{\gamma_c - \gamma_m}{\gamma_c} \right| \cdot 100\,[\%]. \tag{9}$$

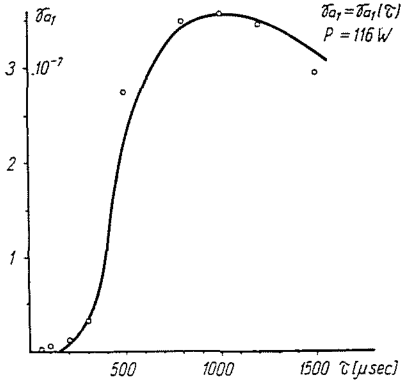


Fig. 7

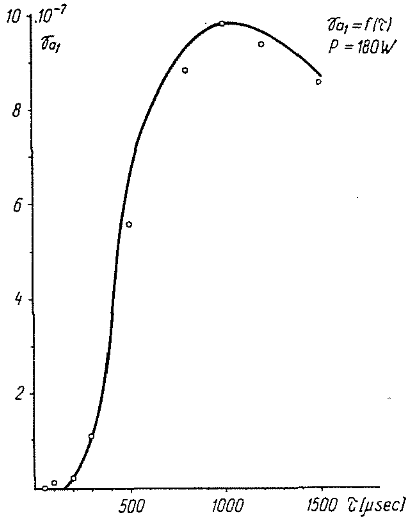
In the tables pulse time is designed by τ.

Table II

$P = 116$ W

τ [sec]	$\gamma\ ac$ [gr/imp]	$\gamma\ am$ [gr/imp]	Δ [%]
$5 \cdot 10^{-5}$	—	$1.5 \cdot 10^{-9}$	—
10^{-4}	—	$5.0 \cdot 10^{-9}$	—
$2 \cdot 10^{-4}$	$9.83 \cdot 10^{-9}$	$1.03 \cdot 10^{-8}$	5.5
$3 \cdot 10^{-4}$	$3.7 \cdot 10^{-8}$	$3.23 \cdot 10^{-8}$	15
$5 \cdot 10^{-4}$	$2.27 \cdot 10^{-7}$	$2.55 \cdot 10^{-7}$	11
$8 \cdot 10^{-4}$	$3.41 \cdot 10^{-7}$	$3.48 \cdot 10^{-7}$	2
10^{-3}	$3.56 \cdot 10^{-7}$	$3.56 \cdot 10^{-7}$	0
$1.2 \cdot 10^{-3}$	$3.50 \cdot 10^{-7}$	$3.45 \cdot 10^{-7}$	1.5
$1.5 \cdot 10^{-3}$	$3.19 \cdot 10^{-7}$	$2.93 \cdot 10^{-7}$	8

Anode: K 1, Cathode: Brass 58.



Fig, 8

Table III

$P = 180$ W

τ [sec]	γ *ac* [gr/imp]	γ *am* [gr/imp]	Δ [%]
$5 \cdot 10^{-5}$	—	$3.4 \cdot 10^{-9}$	—
10^{-4}	—	$1.58 \cdot 10^{-8}$	—
$2 \cdot 10^{-4}$	$2.71 \cdot 10^{-8}$	$2.45 \cdot 10^{-8}$	10.5
$3 \cdot 10^{-4}$	$1.02 \cdot 10^{-7}$	$1.15 \cdot 10^{-7}$	11.3
$5 \cdot 10^{-4}$	$6.18 \cdot 10^{-7}$	$5.62 \cdot 10^{-7}$	10
$8 \cdot 10^{-4}$	$9.07 \cdot 10^{-7}$	$8.87 \cdot 10^{-7}$	2.5
10^{-3}	$9.85 \cdot 10^{-7}$	$9.85 \cdot 10^{-7}$	0
$1.2 \cdot 10^{-3}$	$9.67 \cdot 10^{-7}$	$9.45 \cdot 10^{-7}$	2.5
$1.5 \cdot 10^{-3}$	$8.79 \cdot 10^{-7}$	$8.60 \cdot 10^{-7}$	1

Anode: K 1, Cathode: Brass 58.

Table IV

$P = 240$ W

τ [sec]	γ *ac* [gr/imp]	γ *am* [gr/imp]	Δ [%]
$5 \cdot 10^{-5}$	—	—	—
10^{-4}	—	$3.36 \cdot 10^{-9}$	—
$2 \cdot 10^{-4}$	$8.58 \cdot 10^{-9}$	$9.33 \cdot 10^{-9}$	7
$3 \cdot 10^{-4}$	$3.23 \cdot 10^{-8}$	$3.00 \cdot 10^{-8}$	7.8
$5 \cdot 10^{-4}$	$1.96 \cdot 10^{-7}$	$1.74 \cdot 10^{-7}$	12.8
$8 \cdot 10^{-4}$	$2.97 \cdot 10^{-7}$	$3.33 \cdot 10^{-7}$	11
10^{-3}	$3.10 \cdot 10^{-7}$	$3.10 \cdot 10^{-7}$	0
$1.2 \cdot 10^{-3}$	$3.06 \cdot 10^{-7}$	$3.18 \cdot 10^{-7}$	3.7
$1.5 \cdot 10^{-3}$	$2.48 \cdot 10^{-7}$	$2.66 \cdot 10^{-7}$	4.5

Anode: K 1, Cathode: Cu—T

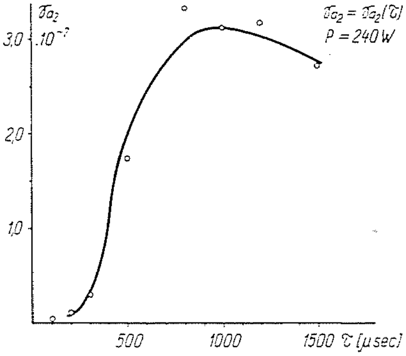


Fig. 9

Table V

$P = 300$ W

τ [sec]	γ *ac* [gr/imp]	γ *am* [gr/imp]	Δ [%]
$5 \cdot 10^{-5}$	—	$3.35 \cdot 10^{-9}$	—
10^{-4}	—	$1.82 \cdot 10^{-8}$	—
$2 \cdot 10^{-4}$	$1.50 \cdot 10^{-8}$	$1.45 \cdot 10^{-8}$	3.5
$3 \cdot 10^{-4}$	$5.05 \cdot 10^{-8}$	$4.89 \cdot 10^{-8}$	17.6
$5 \cdot 10^{-4}$	$3.43 \cdot 10^{-7}$	$2.96 \cdot 10^{-7}$	16
$8 \cdot 10^{-4}$	$5.20 \cdot 10^{-7}$	$4.76 \cdot 10^{-7}$	8.5
10^{-3}	$5.41 \cdot 10^{-7}$	$5.41 \cdot 10^{-7}$	0
$1.2 \cdot 10^{-3}$	$5.33 \cdot 10^{-7}$	$5.18 \cdot 10^{-7}$	2.6
$1.5 \cdot 10^{-3}$	$4.89 \cdot 10^{-7}$	$4.36 \cdot 10^{-7}$	11.5

Anode: K 1, Cathode: Cu—T

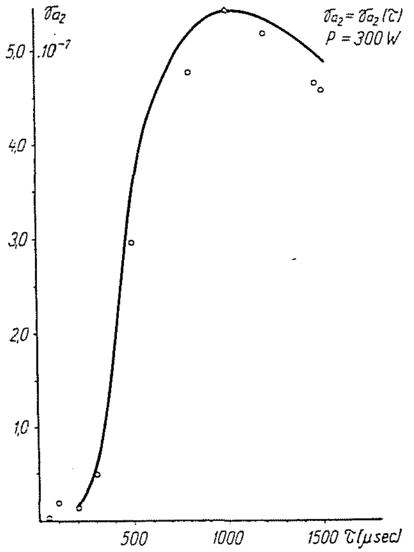


Fig. 10

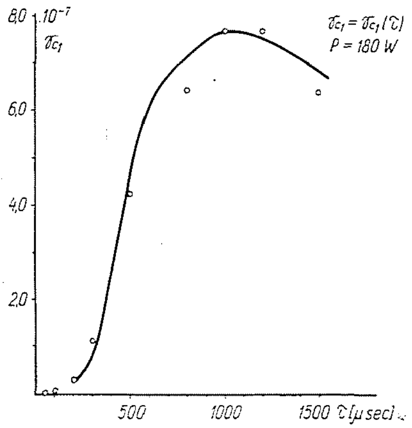


Fig. 11

Table VI

$P = 180$ W

τ [sec]	γ cc [g/imp]	γcm [g/imp]	Δ [%]
$5 \cdot 10^{-5}$	—	$1.49 \cdot 10^{-9}$	—
10^{-4}	—	$2.40 \cdot 10^{-8}$	—
$2 \cdot 10^{-4}$	$2.09 \cdot 10^{-8}$	$2.68 \cdot 10^{-8}$	22
$3 \cdot 10^{-4}$	$8.00 \cdot 10^{-8}$	$1.11 \cdot 10^{-7}$	27.3
$5 \cdot 10^{-4}$	$4.85 \cdot 10^{-7}$	$4.23 \cdot 10^{-7}$	15
$8 \cdot 10^{-4}$	$6.76 \cdot 10^{-7}$	$6.23 \cdot 10^{-7}$	9
10^{-3}	$7.68 \cdot 10^{-7}$	$7.68 \cdot 10^{-7}$	0
$1.2 \cdot 10^{-3}$	$7.57 \cdot 10^{-7}$	$7.70 \cdot 10^{-7}$	0.5
$1.5 \cdot 10^{-3}$	$6.90 \cdot 10^{-7}$	$6.40 \cdot 10^{-7}$	7.9

Anode: K 1, Cathode: Brass 58.

The data and the graphs show that each erosion curve varies in accordance with the same laws. This fact greatly facilitates the numerical evaluation of the measurements. An exception is only the already mentioned erosion γk_2, which is shown as a function of τ in Fig. 13.

For the evaluation of the measuring results it was assumed that the distribution of temperature T arising during the explosion of the conducting

Table VII

$P = 360$ W

τ [sec]	γ cc [g/imp]	γ cm [g/imp]	Δ [%]
$5 \cdot 10^{-5}$	—	$9.6 \cdot 10^{-8}$	—
10^{-4}	—	$1.25 \cdot 10^{-7}$	—
$2 \cdot 10^{-4}$	$1.71 \cdot 10^{-7}$	$2.08 \cdot 10^{-7}$	17.6
$3 \cdot 10^{-4}$	$6.44 \cdot 10^{-7}$	$6.82 \cdot 10^{-7}$	5.5
$5 \cdot 10^{-4}$	$3.68 \cdot 10^{-6}$	$3.32 \cdot 10^{-6}$	10.8
$8 \cdot 10^{-4}$	$5.90 \cdot 10^{-6}$	$5.58 \cdot 10^{-6}$	5.5
10^{-3}	$6.18 \cdot 10^{-6}$	$6.18 \cdot 10^{-6}$	0
$1.2 \cdot 10^{-3}$	$6.09 \cdot 10^{-6}$	$6.00 \cdot 10^{-6}$	1.5
$1.5 \cdot 10^{-3}$	$5.75 \cdot 10^{-6}$	$5.80 \cdot 10^{-6}$	0.7

Anode: K 1, Cathode: Brass 58.

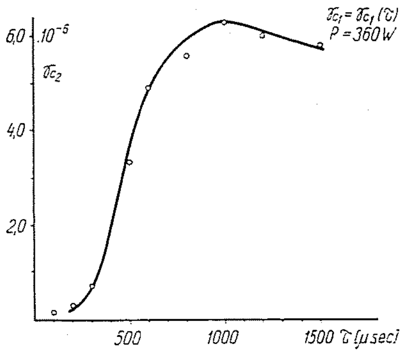


Fig. 12

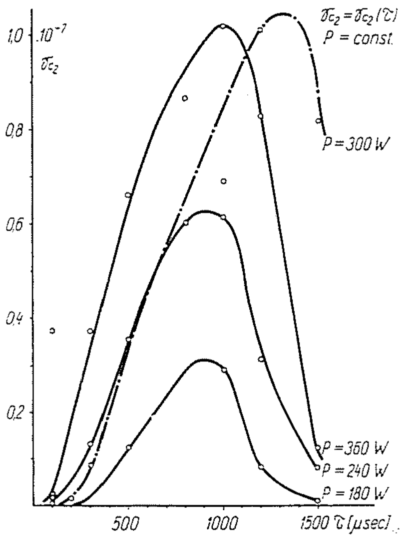


Fig. 13

bridge and the subsequent voltage equalization in the material of the electrodes is given by the solution of the partial differential equation

$$a^2 \Delta T + \frac{f}{c\varrho} = \frac{\partial T}{\partial t} \tag{10}$$

The symbols used in the formula denote:

a = temperature conductivity,
c = specific heat,
ϱ = density,
$f = f(x, y, z, t)$ is the function describing the density of heat sources.

This assumed equation also includes the statement that the heat sources generated in the described way cannot be considered as instantaneous nor as surface sources. The solution of the differential equation (10), i.e. the temperature in the point (ξ, η, ζ) of one elementary volume is:

$$T = \frac{1}{c\varrho} G(x, y, z, \xi, \eta\, \zeta, \tau) \cdot f(\xi, \eta, \zeta, \tau) \cdot d\xi\, d\eta\, d\zeta \tag{11}$$

where

$$G = A' \tau^{-3/2} \exp\left(-\frac{r^2}{4a^2}\frac{1}{\tau}\right) \tag{12}$$

is the temperature action function (source function) and

τ = the time of the action of the heat source (the pulse duration).

The quantity of heat generated in the elementary volume $d\,\xi\, d\,\eta\, d\,\zeta$ is proportional to the temperature, according to the Equ.

$$Q = c\,T \tag{13}$$

It is assumed that within the examined range

$$f = f(\tau) \tag{14}$$

and does not depend on the location coordinates. According to the aforementioned the measuring results prove that the quantities γ_a and γ_c, that is the volumetric density of the quantity of heat generated in the elementary volume $d\,\xi\, d\,\eta\, d\,\zeta$ (in the volume corresponding to γ_a, γ_c), is proportional with its velocity of increase:

$$\gamma\; a,\, c \approx \mathrm{G.\,f.} \tag{15}$$

It can easily be shown that the function f is at first approximation proportional with the electrical input energy. Thus, the assumed erosion equation will be

$$\gamma_{a,c} = A\,\tau^{-\frac{3}{2}} \exp\left(-\frac{r^2}{4a^2}\frac{1}{\tau}\right) \tag{16}$$

where

$$r^2 = (x - \xi)^2 + (y - \eta)^2 + (z - \zeta)^2$$

is the distance between point (x, y, z) of the heat source and the examined point (ξ, η, ζ).

Expression (16), as a function of τ, has a maximum at point

$$\tau_0 = \frac{3\,r^2}{8\,a^2}\,. \tag{17}$$

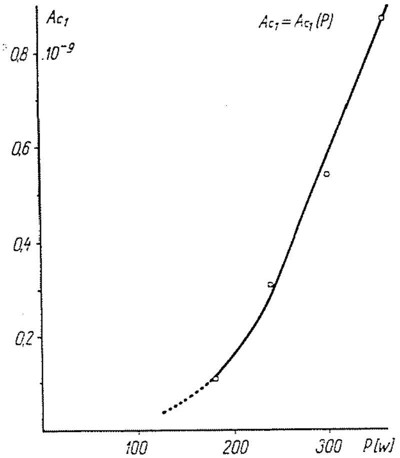


Fig. 14

According to the measurements this maximum point is constant and its value is

$$\tau_0 \approx 10^{-3}\ \text{sec} \tag{18}$$

or, if we do not take into consideration that the crater radius r depends on the power, in first approximation this radius is proportional with temperature conductivity

$$r \sim a. \tag{19}$$

The relation (16) gives a correct value for the dependence on time of the erosion. The dependence on power of the amount of erosion is described only by first approximation, because it has not been taken into account that not only γ, but also r depend on the electric power. This is also reflected by the graphs of Fig. 14, 15 and 16, where the values "A" belonging to the various values of erosion have been shown, as functions of the electrical input power P of the electrode gap. The graphs show that the quantities in question can be considered as linear functions only of the electrical power for powers greater than $P = 200$ W.

On the figures the following symbols have been used:

A_{a1} = value of A belonging to the value γa_1 for machining with Sr 58 cathode,
A_{a2} = value of A belonging to the value γa_2 for machining with Cu—T cathode,
A_{c2} = value of A belonging to the value of γc_1 for machining with Sr 58 cathode.

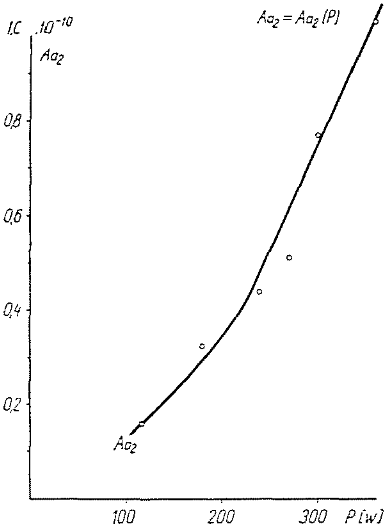


Fig. 15

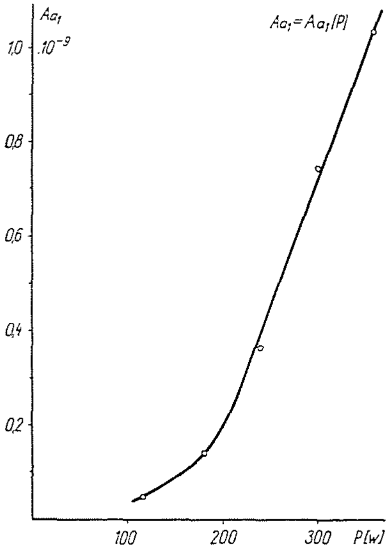


Fig. 16

It must be remarked that at present it is still impossible to establish the exact theory of erosion, because of the too complex nature of the circumstances and for lack of an adequate number of conforming experimental data. Nevertheless, it is hoped that the measuring results published in this paper and ideas put forward for their explanation will contribute to the establishment of a complete solution of the problem as soon as possible.

Summary

The paper deals with the examination of the phenomena which are of basic importance for spark-machining. It is shown that the pollution of the working fluid plays a leading role in its breakdown, and this is proved by a numerical example and by measurements.

The results of the material removal test, made with square pulses of $5 \cdot 10^{-5}$ — $1.5 \cdot 10^{-3}$ sec. are expounded and numerically evaluated. In the range of pulse times from $2 \cdot 10^{-4}$ sec. to $1.5 \cdot 10^{-3}$ sec. the determining role of thermal action can be quantitatively proved. The paper is a short extract from a thesis on a similar object, submitted for obtaining the degree of Candidate.

Acknowledgements

The author may thank Prof. Dr. J. Eisler, D. of Eng. Sc., his professor, for the effective aid provided during his work.

The author offers his thanks to Mr. R. Kolos, deputy-minister for allotting the funds necessary for constructing the experimental installation.

To Mr. N. Klimets, research technician, are due the amicable thanks of the author for his useful and devoted help in constructing the experimental apparatus and for his very valuable practical advice.

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