QUENCHING OF A DEVELOPED ARC THROUGH SHOCK COMPRESSION BY EXPLOSION PRODUCTS

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In [1] it was shown that the compression of an electric arc by shock waves (SW) can be used effectively for its quenching and for the switching of large currents. Below we present experiments set up for the further investigation of the physical picture of the process.

The quenching of an electric arc was performed in a rectangular channel (Fig. 1a) formed by copper electrodes 1 and plastic walls 2. Along the channel the arc was confined to the size of the electrodes (20 mm) by the explosive material (EM) 3 used to create the SW. The width of the channel was 10 mm and the distance between electrodes was 15 mm.

To increase the area of the contact discontinuity between the detonation products and the plasma of the arc we also used a construction with a cylindrical channel (Fig. 1b, where the electrodes 1 are 35 mm in diameter, the distance between them is 10 mm, the charge 2 is 30 mm in diameter, and the outside diameter of the channel is 40 mm). The cylindrical charges were ignited at the center through an opening in one of the electrodes.

In the plane channels we used poured pentaerythrityl tetranitrate (PETN), separated from the arc by ÉVV-8G plastic EM 4 with a thickness of 6 mm, while in the cylindrical channels we used pressed charges of PETN and hexogen, with admixtures affecting their electrical conductivity, and cast TG 50/50.

The experiments were conducted in two schemes of inductive storage (Fig. 2a, b), their parameters being $L_0 = 11.1\ \mu H$, $L_1 = 2.6\ \mu H$, $L_2 = 2\ \mu H$, and $R_l = 1.09\ \Omega$ for the first variant and $L_0 = 22\ \mu H$, $L_1 = 1.2\ \mu H$, $L_2 = 0.3\ \mu H$, and $R_l = 0.8$-$3.2\ \Omega$ for the second variant. The investigated channel R_V was connected to the supply circuit of the storage, fed from a battery of capacitors with a capacitance of 880 μF. The current in the circuit was varied by varying the initial voltage.

The current in the circuit and in the load was measured in the experiments conducted by the scheme of Fig. 2a. In the case of Fig. 2b, we measured the current in the circuit containing the investigated channel and its derivative and the current in the load. The current in the load, the resistance of the quenching arc, the voltage on it, and the power released in the channel during quenching were calculated numerically on a computer from the measured currents and the derivative. The calculated current in the load differed from its measured value by no more than 5%. Photographic recording of the process was also done in the plane channels; the location of the slit 5 of the streak camera is shown in Fig. 1a. Before the experiment the gap was shorted with a thin copper conductor, which explodes under the action of the current supplied by the storage.

The charges were ignited in such a way that the compression of the arc occurred at the moment the current in the circuit reached the maximum value. In the scheme of Fig. 2b, the current maxima in the circuit and the storage practically coincided for the indicated parameters.

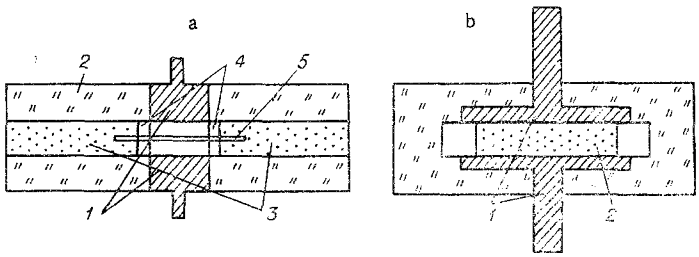

Fig. 1

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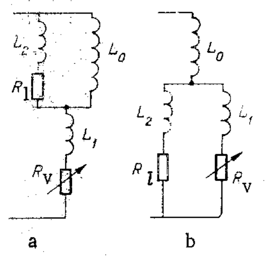

Fig. 2

Experiments by the Scheme of Fig. 2a. In Figs. 3 and 4 we present characteristic oscillograms (upper beam: current in load 2.2 kA/div., lower beam: current in circuit 5 kA/div., sweep 25 μsec/div.) and a photographic scan of the process in a plane channel, in which the burning arc 1, the detonation waves 2, propagating through the EM opposite to each other, and the SW which are formed by them in the current-conducting channel are seen. The emission intensity of the compressed part of the arc grows sharply. After the collision of the SW the luminous region expands somewhat, then the emission intensity declines, and after a certain time it disappears entirely.

The SW velocity hardly depends on the current and lies in the range of 9–10 km/sec. Behind the wave front one sees a sharp line corresponding to a velocity of about 7 km/sec and dividing the region of intense emission from the smeared-out emission at the boundary with the detonation products. The luminous region expanding after the SW collisions has smeared-out boundaries and is separated into several channels before quenching.

A sharp decline of the current and a corresponding rise of the current in the load are seen in the oscillograms; after the latter reaches a maximum an LR discharge follows with complete quenching of the arc.

In Table 1 (column 1 corresponds to the data of Fig. 1a) we give the current I_c in the circuit at the start of compression, the maximum current I_l in the load, the maximum voltage U_V on the gap, the maximum power W released in the arc being compressed, and the quenching time τ, determined from the start of decline of the current and its reaching the oscillographic zero. In those cases when breakdown developed in the gap, we determined the time the maximum voltage was reached. In Table 1 it is marked by asterisks.

The quenching time and the maximum voltage on the investigated gap increase with an increase in the current. At a current of 18 kA the maximum voltage on the gap reaches 20 kV and the character of the process changes. A situation similar to breakdown develops. The current in the circuit first rises sharply and then falls slowly over a time of several tens of microseconds.

The resistance of the gap is ~1 Ω and grows slowly.

In a series of experiments a plastic wall was installed in place of one of the charges to restrict the ionized region. The characteristics of the process are somewhat degraded in this case. Data for a current of 12 kA are presented in Table 1 for comparison.

It must be noted that the breakdown of the gap is not recorded at all on the photographic scan. The region involved in breakdown evidently has a small size and is hidden by opaque detonation products.

The results of experiments on the quenching of an arc in a cylindrical channel using poured charges of TG 50/50 are also presented in Table 1 (column 2 corresponds to the data of Fig. 1b). For the same currents the quenching time decreased, the power released in the gap increased, and the maximum voltage on it increased. Now the character of the process began to change at a voltage of about 50 kV. The use of a massive insulator shell in the experiments led to an increase in the maximum voltage to 67 kV.

TABLE 1

	1						2			
I_c, kA	5,5	12	12	18	24	30	5,5	15	23	24
I_l, kA	4,9	8,9	8.5	13	11	9	5,0	13	14	17
U_V, kV	15	18	17	20	19	19,5	16	29	51	67
W, MW	48	121	98	186	340	413	78	195	521	754
τ, μsec	2,9	3,2	3,0	2,5*	2,1*	1,7*	2,5	1,8*	1,3*	1,2*

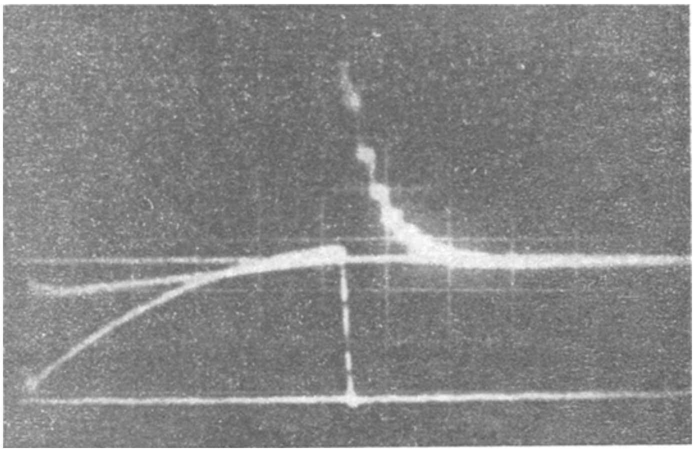

Fig. 3

An important role in the process of quenching of an arc in a cylindrical channel is played by its shunting by the intrinsic conductivity of the detonation products. To clarify the role of shunting, we set up special experiments with pressed charges of PETN and hexogen with 10% and 20% admixtures of Teflon and paraffin, different mixtures of trotyl with hexogen, and pure trotyl.

In these experiments it was found that in the construction of Fig. 1b, PETN and hexogen with Teflon have a conducting zone of ~1 mm behind the detonation front, with admixtures of paraffin the conductivity declines with a characteristic gasdynamic time of ~1 μsec, and the characteristic time of variation of conductivity is more than 5 μsec for trotyl and is not determined by gasdynamic dispersion.

In the quenching of an arc by charges containing admixtures of Teflon one observes a sharp decline of the current in the circuit in a time of 1 μsec and then a break and a smoother decrease to zero in a time of about 10 μsec. At the moment of the break the maximum voltage of 30 kV is reached, and then it declines and remains practically constant at the level of 10 kV. There is an oscillogram of the process in Fig. 5 (5 kA/div., 5 μsec/div.).

For charges with an admixture of paraffin the decline of the current has a smooth character and the maximum voltage is reached at the middle of the decline and comprises 35 kV. In the quenching of an arc with a current of 30 kA the characteristic breaks appear after 2.5 μsec at a voltage of 50 kV and an insignificant current through the gap.

When charges of trotyl are used the current through the gap decreases more smoothly and the change in the character of the process starts after 6-10 μsec at a voltage of 20 kV. After the characteristic break the current through the gap may grow.

The results of the experiments with charges of a mixture of hexogen and trotyl lie in the intermediate region between the results with pure trotyl and with hexogen and paraffin. The insulation of the electrodes with Teflon from the detonation products leads to results close to those for charges containing Teflon.

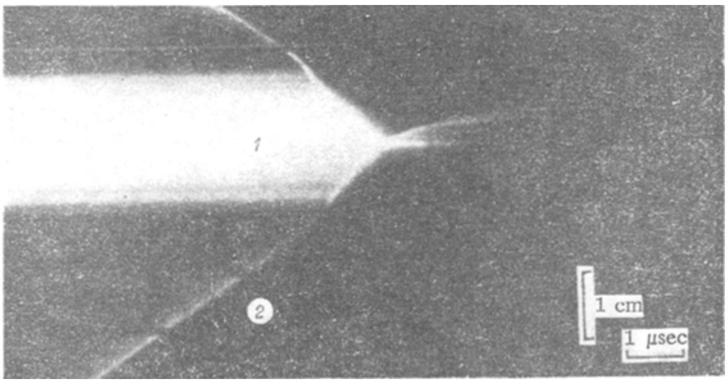

Fig. 4

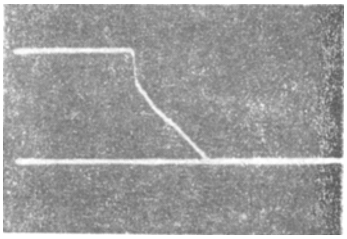

Fig. 5

Experiments by the Scheme of Fig. 2b. We mainly conducted experiments with a plane channel and a storage load of 0.8 Ω. Synchronized photography of the process with oscillography of the derivative of the current in the circuit of the investigated gap was carried out. The currents in the gap and in the load were also recorded.

The synchronization was accomplished with a sensor located at a known distance from the gap and operating upon closure of the conduction zone behind the detonation front. The accuracy of synchronization was no worse than 0.05 μsec.

In these experiments one of the charges was replaced by a plastic wall.

In the investigated setup the compression of the conducting channel hardly affects the current in the gap, its resistance, or other parameters up to the moment of arrival of the SW at the opposite wall. A synchronized photographic scan of the process and the reults of the calculation of the current derivative are presented in Figs. 6 and 7. The arrow on the photographic scan corresponds to the start of the graph in Fig. 7. The pronounced change of the parameters starts after reflection of the SW from the wall. The voltage U reaches the maximum value in a time of ~1 μsec and remains at this level until the complete quenching of the arc, and then it declines to the value determined by the current in the load. The power W released in the gap has a characteristic maximum, reached at the same time, after which it falls to zero by the moment of quenching. The resistance R_V of the gap constantly grows, especially rapidly after the power starts to decrease.

Discussion of Results. The results of the experiments on arc quenching in plane and cylindrical channels containing charges whose detonation products have a low and rapidly declining conductivity, as well as the fact that the quenching starts at a moment close to the moment of reflection of the SW from the opposite wall, allow us to conclude that the loss of conductivity of the arc plasma and its decay can take place as a result only of its compression by the SW and the interaction with the propelling piston.

The intrinsic conductivity of the detonation products, which shunts the conducting channel and declines with time as a result of gasdynamic dispersion, supports the quenching process, protracting the increase in voltage on the gap. In the case with trotyl the decline of the current is due to the decline of the conductivity of the detonation products. The breakdown of the gap at 20 kV 6-10 μsec after the start of decline of the current is not clear. The level of power dissipated during quenching in all the experiments described above

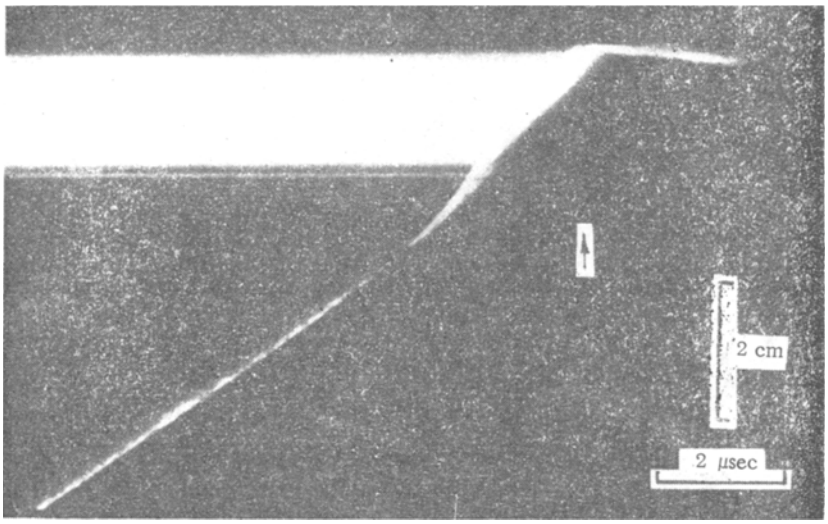

Fig. 6

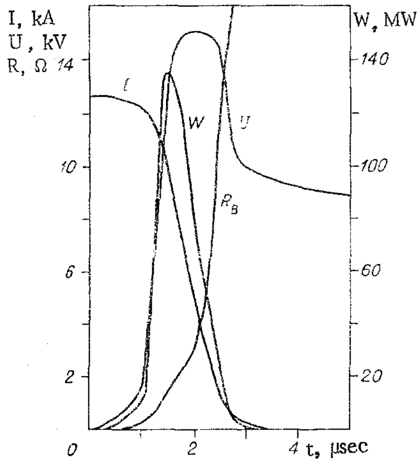

Fig. 7

attracts attention. It is two orders of magnitude higher than the level in the undisturbed arc. Therefore, it is clear that no one mechanism of heat conduction in pure form can explain the cooling, loss of conductivity, and decay of the arc plasma after its compression by the SW.

Hydrodynamic instabilities developing at the contact surface evidently play the main role in the process of arc quenching.

The presence of developing instabilities can be judged from the smeared-out boundary between the detonation products and the luminous conducting region, as well as from the separation of the conducting channel compressed by the SW into several channels before quenching.

The hydrodynamic instabilities of a contact surface upon the passage of an SW through it were investigated experimentally in [2] and theoretically in [3]. In the experiments being described other types of instabilities are also possible, such as a Rayleigh–Taylor instability. Temperature nonuniformity in the arc leads to nonuniformity of density and to gradient accelerations of the SW and of contact surfaces, as a result of which they may prove to be unstable.

In Fig. 8 we present a photographic recording of the quenching process in a plane channel, taken through the plastic wall confining the arc in place of one of the EM charges. The strong nonuniformity of the emission of the compressed arc may be connected with the development of instabilities at its contact boundary with the detonation products.

The hypotheses advanced are supported by the experiments conducted by the scheme of Fig. 2a, in a plane channel at nearly atmospheric pressure in the arc plasma. In this case the quenching time decreases approximately twofold while the maximum voltage sustained by the gap increases by 1.6 times.

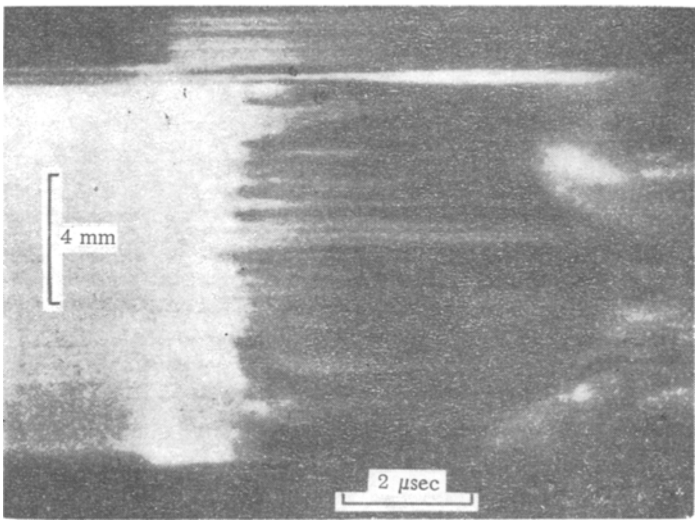

Fig. 8

The size of the instabilities in the direction of SW propagation is evidently on the same order as the transverse size of the compressed arc. Therefore, a decrease in the initial size of the arc should lead to higher quenching parameters, which was observed in the experiments with a cylindrical channel.

The instabilities developing at the contact surface lead to a considerable increase in its area, which increases the energy flux due to radiant heat transfer and promotes the fine-scale mixing of detonation products with the arc plasma, its cooling, and decay. As the estimates show, the detonation products in a cylindrical channel can absorb about 600 J without a change in their properties.

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PRESSURE DEPENDENCE OF ELECTRICAL CONDUCTIVITY IN HIGH MAGNETIC FIELDS

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Obtaining pulsed high magnetic fields by flux compression in an explosive-driven metal shell is limited primarily by two processes: the dynamics of the compression and the diffusion of the field, related to the finite electrical conductivity σ of the liner. The character of the dependence of the electrical conductivity on the physical properties of the medium (the density ρ and the specific thermal energy q) significantly affects the results of theoretical calculations [1-3]. The dependence of the electrical conductivity of metals on q and ρ has not been adequately studied for high temperatures and high and low densities. Therefore such semiempirical relations as [3, 4]

$$\sigma = \sigma_0(1 + \beta q)^{-1}\ [2],\quad \sigma = \sigma_0(1 + \beta q)^{-1}(\rho/\rho_0)^n$$

are generally extrapolated into the range of densities and temperatures which are developed in a medium when high magnetic fields are produced. Numerical calculations in [2] made under the assumption that the electrical conductivity of copper depends only on Joule heating are in good agreement with experiment for fields $H \leq 3$ MOe. Numerical calculations of theoretical upper bounds of magnetic fields presented in [3] agree with experiment for $H > 10$ MOe only when account is taken of the dependence of the electrical conductivity of the shell on both Joule heat and density in the region of compression. A relatively weak dependence of the maximum value of the field on Joule heat is noted. Thus, an arbitrary change of the heat coefficient β by a factor of three did not lead to better agreement of the calculated results [3] with experiment. Fields $H > 10$ MOe exert pressures $p > 4 \cdot 10^{11}$ Pa on a conductor, which leads to an increase in density, and consequently to an increase of the electrical conductivity of certain metals [5, 6]. Estimates show that the change of the electrical conductivity as a result of heating is more than an order of magnitude larger than the change due to pressure. Therefore, taking account of the above, it is of interest to find out in which cases a correction to the change of the electrical conductivity as a result of pressure may turn out to be substantial. The investigation of the penetration of high magnetic fields into a conductor is complicated by nonlinear effects related to the decrease of its electrical conductivity during heating and vaporization and the increase in density under increased pressure, and is possible in general only by numerical methods. We note that numerical calculations do not permit an estimate of qualitative regularities. An analytic solution which takes account of the fundamental physical processes, even if it is obtained by greatly simplifying the problem, gives a deeper understanding of the phenomena,

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