CALCULATIONS OF REAR SPLITTING OF A COPPER ANODE UNDER THE ACTION OF AN ELECTRON BEAM IN THE X-RAY REGIME OF A NONCYLINDRICAL Z-PINCH

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One of the phenomena accompanying the interaction of a plasma with electrons in powerful electrical discharges of the noncylindrical Z-pinch type is rear splitting of the anode. The possibility of using this phenomenon as an additional form of diagnostic for a plasma discharge was discovered comparatively recently. However, the first theoretical investigations [1] showed that the experimentally observed splitting cannot be caused by the thermodynamic pressure of the self-pinch at the anode surface, which is not high enough for this effect. An attempt was made in [2] to explain the splitting by the formation of an electron beam in the plasma and by its action on the anode. The noncylindrical Z-pinch regime in which splitting is observed is called the x-ray regime. It was later ascertained that in the x-ray regime a dense high-temperature pinch is not formed in the final stages of the discharge, but that an electron beam is produced which carries almost the entire current of the system, about 1 mA, and creates strong x-ray radiation from the surface of the anode. Dissipation of electron energy in the anode material causes simultaneous intense vaporization of the anode accompanied by a pressure pulse at the anode of $\sim 10^6$ atm. The whole set of phenomena, characteristic for the x-ray regime of a noncylindrical Z-pinch, is described in [3], where it is also shown that the pressure at the surface of the anode can be linked fairly accurately with the energy parameters of the beam. The possibility of determining the pressure on the anode and obtaining an independent diagnostic of the electron beam in a noncylindrical Z-pinch has given a new impetus to the study of splitting.

Experimental measurements of x-ray radiation and also the accepted model for electron acceleration were used in [4] as the basis for establishing the time–energy characteristics of electron beams formed in a series of different discharges in the x-ray regime, which were then used to produce curves of the pressure at the vaporization boundary of the metal as functions of time. The pressure at the metal surface was given in the form

$$p = 8.7 \cdot 10^{13}(i\beta^{1/2}/h^2u^{1/2})t^{1/2}\exp(-t/\tau), \ \text{dyn/cm}^2 \tag{1}$$

where i is the total current in the electron beam, 10^6 A; u is the propagation velocity of metal vapors, $4 \cdot 10^6$ cm/sec; h is the thickness of the anode, cm; and β and τ are parameters of the electron beam determined in [4] from the characteristics of the x-ray radiation ($\beta \sim nZ^2$, where n is the concentration of ions of charge Z in the metal vapors, and τ is the lifetime of the beam).

In the one-dimensional formulation of the gasdynamic problem of splitting, it is assumed in Eq. (1) that the effective area to which the pulsed pressure is applied is equal to πh^2, where h is the thickness of the anode. This assumes that the thickness of the beam and its possible displacement over the surface of the anode do not exceed the thickness h, which is quite reasonable for $h \geqslant 3$ mm. Equation (1) and all the subsequent calculations are made with reference to a copper anode.

The gasdynamic model of the phenomenon under consideration reduces to solving the following plane problem. At the initial moment of time (t = 0) the undisturbed metal (pressure and velocity equal to zero, and density equal to ρ_0) is situated between the planes x = 0 and

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$x = h$, while for $x < 0$ there is a vacuum. A pressure $p = p(t)$ defined by Eq. (1) is applied to the plane $x = h$. At the time $t = 0$ a shock wave arises which passes from the plane $x = h$ to the plane $x = 0$. The following equation of state is assumed for the metal after the passage of the shock wave:

$$p=\frac{\rho_0 c_0^2}{\gamma}\left[S\left(\frac{\rho}{\rho_0}\right)^{\gamma}-1\right], \tag{2}$$

where S is the entropy variable, $\gamma = 3$, and ρ_0 and c_0 are the density and velocity of sound in the undisturbed metal. At the time $t = t_1$ the shock wave emerges to the plane $x = 0$. As a result of decay of the discontinuity a centered rarefaction wave arises, emerging from the point $x = 0$, at $t = t_1$, bounded by the two α-characteristics. On the interaction of the two rarefaction waves with large pressure gradients oriented in different directions, splitting occurs. It is assumed [1] that splitting corresponds to a pressure $p < -2\cdot 10^{10}$ dyn/cm^2. The following convenient units have been introduced to simplify the calculations (denoted by the bar above):

$$p = 10^{10}\bar{p},\ t = 10^{-5}\bar{t},\ v = 10^{5}\bar{v},\ c = 10^{5}\bar{c},\ x = \bar{x},\ \rho = \bar{\rho}.$$

The metal investigated was copper with the following values of the constants: $\bar{c}_0 = 3.97$, $\bar{\rho}_0 = 8.93$. Everywhere, with the exception of the region boundaries, the calculations were carried out by a method close to that of [5]. The region boundaries were calculated explicitly.

In accordance with the flow pattern described, the calculations up to the moment $t = t_1$ were carried out in one region bounded by the trajectory z_1 emerging from the point $t = 0$, $x = h$ and the shock front.

For $t > t_1$ the entire flow was broken down into three regions. The first region is bounded by the z_1 trajectory and the right-hand α-characteristic, bounding the centered rarefaction wave and emerging from the point $x = 0$, $t = t_1$. The second region is the centered rarefaction wave bounded by the two α-characteristics, and the third region is bounded by the α-characteristic, the left-hand boundary of the rarefaction wave, and the free boundary.

Because the boundaries were calculated explicitly the time step Δt corresponded roughly to the Courant condition in the form $\tau = L/(c + u)$, where L is the distance between the boundaries of the region. For the same reason the apex of the pencil of characteristics at $x = 0$, $t = t_1$ is artificially smeared over a segment of length $\Delta t(u_b - c_b)$, i.e., by a distance which the β-characteristic traverses in a time Δt from the apex of the pencil.

The number of points in the method of differences applied to the problem was chosen as follows:

for $t < t_1$ in the first region, 100 points,
for $t > t_1$ in the first region, 100 points,
in the second region, 32 points,
in the third region, 48 points.

If a pressure $\bar{p} = -2$ is attained at some time t° at a point x°, it is assumed that the metal in the layer $x < x^{\circ}$ splits off. The trajectory emerging from the point x°, t° was again taken as the free boundary, i.e., it was assumed that $\bar{p} = 0$ for $t > t^{\circ}$ on this trajectory. As a result, a shock wave closing the split arose traveling to the right through the material.

Thickness of the splitting Δ are given in Table 1 for various parameters of Eq. (1) ($u = 1$, and $i = 1, 2$ in all variants).

It can be seen from Table 1 that the thickness of the split has a tendency to increase as the time τ increases and to decrease as the maximum pressure increases. This dependence is approximated by the following formula with an accuracy to 10%:

$$\Delta \sim \tau p_{\max}^{-1/3}. \tag{3}$$

It is still not possible at present to verify this law reliably and with any great accuracy. The very identification of the observed splitting with the energy parameters of the electron beam is still rendered difficult by the presence of a host of accompanying phenomena, as well

TABLE 1

Variant No.	τ, 10^{-7} sec	β	h, cm	p_{max}, 10^{10} dyn/cm^2	Δ, %
1	0,845	2,87	0,3	24,5	2,74
2	0,810	2,69	0,3	23,2	2,74
3	1,56	1,27	0,3	22,1	5,34
4	1,40	0,88	0,3	17,5	5,81
5	0,688	4,15	0,3	26,6	2,37
6	0,845	2,87	0,5	8,82	3,12

TABLE 2

τ, 10^{-7} sec	β	h, cm	p_{max}, 10^{10} dyn/cm^2	Δ, %
0,845	2,87	0,1	22,0	1,61

as by the extreme complexity of existing beam diagnostics. However, on the basis of experimental results which are not open to doubt, it can be asserted that the basic character of Eq. (3) is correctly expressed. The calculations which have been made are confirmed not only by the form of the function, but also by the absolute values of the resulting splits, which lie in the range of thicknesses observed experimentally. This allows us to assume that we are fully justified in applying the physical model of the electron beam, on which the theoretical investigation carried out above is based.

The application of the simple criterion of splitting $p = -2\cdot10^{10}$ dyn/cm^2 requires further discussion. It was shown in [6, 7] that the critical pressure for which splitting occurs depends on the time during which the given tensile stress is applied to the layer of copper. It could even be said that no simple criterion of splitting exists and that the real criterion depends on time. Thus, for a loading time $\Delta t \approx 10^{-8}$ sec the negative splitting pressure $p_{sp} \approx -10\cdot10^{10}$ dyn/cm^2 and decreases linearly to $p_{sp} \approx -2\cdot10^{10}$ dyn/cm^2 for $\Delta t \approx 10^{-7}$ sec. Calculations show that for the second criterion of splitting $p_{sp} = -4\cdot10^{10}$ dyn/cm^2 the values of Δ approximately double, i.e,, it can be roughly assumed that $\Delta = \Delta_0 p_{sp}/(p_{sp})_0$. On the other hand, for the existing linear law $p_{sp} = A - B\Delta t$ [6, 7], where $\Delta t = \Delta h 10^2/c_0$, we can make the estimate $\Delta \approx 2.6\Delta_0$, where Δ_0 are the quantities in Table 1, and $p_{sp} = 5.2\cdot10^{10}$ dyn/cm^2. Thus, with a more complete criterion of splitting, the thickness of the splitting layer increases by a factor of 2-3 compared with the data of Table 1.

However, within the framework of the model adopted — Eq. (1) — use of the results of calculations from Eq. (3) can be considered justified only for $h \geqslant 3$ mm.

Results of the calculations for an anode of thickness h = 1 mm are given in Table 2. The value of the pressure $p_{max} = 2.2\cdot10^6$ atm and the thickness of splitting $\Delta = 1.61\%$ (0.00161 cm in absolute units) do not agree with experiment at all, where the thickness of splitting is much larger. It is quite clear that in this case there are larger corrections due to the stricter criteria of splitting mentioned above. Apparently, this is also a result of the fact that in reality the beam thickness and the characteristic dimensions of its displacement over the surface of the anode become comparable with the anode thickness h, or even exceed it. This was not taken into account in Eq. (1). Moreover, in the case of a thin anode the thickness of the vaporizing metal layer cannot be neglected, nor can the contribution made by the electron beam energy to the unvaporized metal, as was done above.

The problem of multiple splitting arises in the gasdynamic model adopted above. In fact, continuation of the calculations after the reflected shock wave has closed the split shows that new splits can appear. Thus, for example, for variant 1 of Table 1, after the first split, 11 more splits followed of overall thickness $\Delta_S = 23.4\%$, while for variant 6, there followed 3 more of thickness $\Delta_S = 8.2\%$. For the variant of Table 2 there were as many as 13 subsequent splits with $\Delta_S = 34.1\%$, and estimates showed that this number is inconclusive. Thus, the quantities Δ_S exceed Δ by about an order of magnitude. It is interesting to note that for these variants the thickness of subsequent splits decreased, by comparison with the first split Δ, in a manner which was qualitatively the same to start with, subsequently increased to the value of the first split, and finally decreased again for possible further splits. It should be said, in justification of these calculations, that the very concept of the split having a discrete character, which could be regarded as questionable, has little effect on the thickness Δ_S. If the gasdynamic calculations are pursued, allowing any $p < -2$, and if Δ_S is defined as the maximum depth to which the negative pressure $p = -2$ penetrates, the calculated results for Δ_S will not differ much from the values obtained. However, the reality of multiple splits can be doubted. First of all, the time interval between subsequent splits is too small. It is less than 10^{-8} sec. During this time the split layer can only travel a distance of 10^{-3}-10^{-4} cm, since the layer velocity is almost always 10^5 cm/sec.

Thus, the refined criteria of splitting mentioned above require a considerable increase in the value of $|p_{sp}|$ (even larger than that estimated for the first split). It is clear that for $p_{sp} < -5 \cdot 10^{10}$ dyn/cm^2 the thickness of the secondary splits will increase and their number will decrease. It follows from the experiments that after the first split the surface of the fractured metal in fact becomes rough, whereas it is always taken to be ideally flat in the calculations. There is no doubt that the nonflat nature of the real problem, as well as elastoplastic deformation effects which have not been taken into account, even if they do not lead to the complete disappearance of secondary splits, will change the pattern of their formation appreciably. However, the phenomenon of double or even triple splitting has been detected in a series of experimental samples. Here the thickness of the secondary splits turned out to be of roughly the same order of magnitude as that of the first split.

It is clear from the experiments that have been carried out, first, that the calculated thicknesses of the first split agree satisfactorily with the thicknesses measured experimentally. When the corrections for stricter criteria of splitting are taken into account, the typical calculated splitting thickness for a copper anode of thickness $h = 3$ mm is about 0.2 mm. The thickness of split found experimentally was within the limits of 0.1-0.2 mm. Second, for the majority of experiments multiple splitting was not observed, in any case its total thickness was much less than the results described above. Third, the thicknesses Δ given in Table 1 [cf. Eq. (3)] change only slightly for very large changes in the discharge parameters (cf. Table 1, variants 4 and 5). The resulting variations were comparable within a factor of two with the uncertainty introduced by the criterion of splitting, as well as by the other approximations (used in the theoretical treatment) made above: 1) in determining the pressure via the energy flux; 2) on the introduction of the factor πh^2 in formulating the plane problem; 3) in the two-term equation of state of copper [Eq. (2)] beyond the shock front, as well as some others.

Thus, as a result of the uncertainty which exists in the criterion of splitting, and in the part played by the multiple splitting effect, as well as in connection with other approximations made in the theoretical treatment, it can be concluded that measurements of the splitting thickness cannot serve as a diagnostic method for the electron beam in a noncylindrical Z-pinch, when its parameters vary within the limits characteristic for the experiment. A more natural and reliable diagnostic is probably a direct measurement of the total momentum imparted to the metal lamina by the electron beam. From this measurement we can make a direct evaluation of the characteristic pressure at the boundary of the nonvaporizing metal, proportional to p_{max} from Table 1.

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COMPARISON OF THE SIGNALS OF DIELECTRIC AND MAGNETIC PICKUPS WHEN RECORDING SHOCK WAVES OF INTENSITY UP TO 100 kbar

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To measure the profile of a stress wave in condensed media under pulsed loading conditions, quartz [1], manganin [2], and dielectric [3] pressure pickups, capacitive [4] and electromagnetic [5] methods of measuring velocity, etc. have recently been widely used. These enable one to obtain different characteristics of elastoplastic flow and their dependence on the loading parameters.

It is of interest to compare the data obtained using the different methods under identical experimental conditions. In this paper we present the results of a comparison of the pressure profiles obtained by dielectric and manganin pickups for a plate of No. 3 steel loaded with the impact of an aluminum container of diameter 90 mm and bottom thickness 10 mm in a pneumatic-powder impact apparatus described in [6]. The rate of impact was varied from 0 to 900 m/sec. The probes were placed between two steel disks of diameter 120 mm and thickness 20 mm (Fig. 1). Terylene films 0.03 and 0.06 mm thick were used as the dielectric. The manganin pickups were made of PÉMM wire of diameter 0.12 or 0.06 mm, bent in a zigzag manner. Leads of copper foil 0.15 mm thick were soldered to the ends of the pickup. The pickups were then left in a press. The thickness at the point of contact with the lead was not greater than 0.04 mm. The resistance of the pickup together with the lead was 10-15 Ω. Some of the pickups were annealed for 4 h at 160°C.

However, as a result of the measurements we found no difference between the readings of annealed and unannealed pickups outside of the limits of error of processing the oscillograms. The signals were recorded on a bridge circuit similar to that described in [7]. The construction of the dielectric pickup and the recording circuit are shown in [3]. An estimate of the maximum transmitted frequency with respect to the growth time of the pressure in the elastic forerunner carried out as in [8] gives a value of the order of 0.5 MHz for both methods. The average piezosensitivity coefficient of the manganin probe is $\sim 2.5\cdot 10^{-3}(\Delta R/R)$ kbar^{-1}. The piezosensitivity coefficient of the dielectric probe in the pressure range up to 100 kbar varied in the limits $(20-6.5)\cdot 10^{-3}(\Delta C/C)$ kbar^{-1}, which corresponds to a sensitivity of 2-0.65 V/kbar for a preliminary polarization voltage of 100 V. Typical oscillograms of the experiments are shown in Fig. 2 for a pressure of 23 kbar. The frequency of the calibration sinusoidal signal is 500 kHz.

To determine the pressures recorded by the dielectric pickup we used a calibration curve, shown in Fig. 3, and the dependence of the relative resistance of the manganin on the pressure taken from [9] for a manganin pickup. Both methods gave similar results when determining the times and pressures at the characteristic points of the profile of the wave in the load phase. The values of the maximum pressures and the pressures corresponding to the elastoplastic transition in the load phase found from the oscillograms agree for both pickups to within 5%. For

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