MAGNETOHYDRODYNAMIC INSTABILITIES DURING AN ELECTRICAL EXPLOSION

PHYSICS

1966

SovietRxiv

Fig. 1

Figure 1: Fig. 1

Abstract

Full Text

UDC 534.143

PHYSICS

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MAGNETOHYDRODYNAMIC INSTABILITIES DURING AN ELECTRICAL EXPLOSION

(Presented by Academician B. P. Konstantinov, May 31, 1965)

1. In work (^{1}) it was established that there exists an energy threshold for an electrical explosion: if the magnitude of the energy introduced into the conductor, E_{in}, is less than a certain threshold value E_{thr}, the process does not have the character of an explosion. The energy E_{thr} proved to be greater than the melting energy but less than the energy required for evaporation of the wire. This made it necessary to abandon the generally accepted notion of the mechanism of explosion, according to which the explosion is the rapid, "instantaneous" evaporation of a strongly overheated metal (^{2}).

Fig. 1

The aim of the investigation, the principal results of which are presented in this communication, was to elucidate the mechanism of destruction of the conductor material during an electrical explosion. The investigation was carried out by means of a pulsed x-ray apparatus that made it possible to obtain shadow photographs of the wire and of the explosion products with an exposure of 0.1 –0.2 μsec. In the course of a single experiment it was possible to obtain 4 x-ray photographs corresponding to arbitrary instants of time specified relative to the beginning of the current flow through the wire. The experiments were carried out with copper, tungsten, molybdenum, and lead wires and with a jet of liquid lead.

2. Figure 1 shows current oscillograms and x-ray photographs of a copper wire of diameter 0.5 mm and length 70 mm ($E_{\text{thr}} = 290$ J.(^{1})). The x-ray-

radiographs in Fig. 1a were obtained in the prethreshold regime, $E_{\text{in}} = 180$ J;

Fig. 2

Figure 2: Fig. 2

Fig. 1b—in the electric-explosion regime, $E_{\text{in}} = 800$ J. Projections of the wire onto three mutually perpendicular planes at $E_{\text{in}} = 180$ J $< E_{\text{th}}$, obtained with the aid of three x-ray tubes triggered simultaneously, are shown in Fig. 1c.

The totality of the numerous radiographs and oscillograms obtained in the course of the study, analogous to those shown in Fig. 1, gives an idea of what happens to the conductor in the prethreshold regime and in the electric-explosion regime. When a current of high density flows through the conductor, instabilities of two types arise and develop, leading to a change in the shape of the conductor and, ultimately, to its numerous ruptures. In the prethreshold regime a helical instability develops (Figs. 1a and 1c). In the electric-explosion regime a necking instability develops (Fig. 1b), which never appears in the prethreshold regime. It is natural to suppose that the instabilities have a magnetohydrodynamic origin. Similar phenomena have been observed in linear pinches.

Fig. 2

3. An analysis was carried out of the stability of a liquid cylinder in the magnetic field of a current flowing through it, taking into account finite conductivity and surface-tension forces. Since $E_{\text{th}} > E_{\text{m}}$, the wire, at least at the moment when the necking instability arises, is in fact in the liquid phase. Estimates show that the skin effect in the experiments performed does not play a noticeable role; therefore the current distribution was taken to be uniform over the cross section of the conductor. It was assumed that, in the equilibrium state of the conductor, the pressure in the liquid is determined by surface-tension forces and by magnetic pressure.

Starting from the usual system of magnetohydrodynamic equations, the stability of the conductor was studied with respect to a perturbation $f(r)\exp[i(m\varphi + kz + \omega t)]$, where r, φ, z are cylindrical coordinates, t is time, m is an integer, $k = 2\pi/\lambda$, and λ is the wavelength of the perturbation.

The method of deriving the dispersion relation without taking surface-tension forces into account was developed in papers (^{3,4}), and with surface-tension forces taken into account—in papers (^{5,6}). Dependences were obtained for the dimensionless increment $\Omega = i\omega r_0\sqrt{4\pi\rho}/H_0$ on $x = kr_0$ (r_0 is the cylinder radius) for $m = 1$ and $m = 0$ and for various values of the parameters q and f, which take into account the density ρ, the conductivity σ, the surface-tension coefficient α, and the field at the cylinder surface H_0;

$$q^2 = \frac{r_0\sigma H_0}{c^2}\sqrt{\frac{4\pi}{\rho}}; \qquad f = \frac{4\pi\alpha}{r_0 H_0^2}.$$

The curves of these dependences in the range of values $0 \leq x \leq 3.5$ are shown in Fig. 2. At $x \gg 1$ the increment reaches the maximum value $\Omega_{\text{max}} \approx \sqrt{2}$ at the point $x = 1/\sqrt[4]{3f}$ for the perturbation $m = 0$ and at the point $x = \sqrt[4]{4/3f}$ for the perturbation $m = 1$. From the value of Ω one can find the time constant for the growth of the instability,

$$\tau = \frac{r_0\sqrt{4\pi\rho}}{H_0\Omega}.$$

4. Thus, the possibility of development of the instabilities observed in the experiments follows from the theoretical consideration. The case $m = 0$

corresponds to the necking instability, $m = 1$ to the helical instability. Instabilities of higher order (mode $m > 1$) should lead only to a change in the shape of the cross section, without causing curvature of the axial line and while leaving the cross-sectional area unchanged along the axis. These instabilities should not lead to breaks in the conductor and cannot be observed on radiographs.

In the experiments described above, the value of the parameter q lay in the range 0.1—0.8. The parameter f for the molten conductor had the value $0.4 \cdot 10^{-5}$—$7 \cdot 10^{-5}$. The wavelengths of perturbations with $m = 0$, determined from the radiographs, in all cases differ from the calculated values λ_{calc} by no more than a factor of 2-3. The calculated and experimental values of the wavelengths of perturbations with $m = 1$ differ by a factor of 70. Since $\lambda_{\text{exp}} > \lambda_{\text{calc}}$, the discrepancy can be explained by the fact that the helical instability arises and begins to develop before the wire starts to melt. The energy required for bending and stretching a solid cold wire is several times smaller than the energy needed to create the number of necks observed in the experiments, but is substantially greater than E_{th}. The resistance forces in this case are greater than the electrodynamic forces by at least two orders of magnitude. But as the temperature rises, the yield strength of copper drops rapidly (^{7}), and the development of the helical instability at a temperature close to the melting point becomes possible. In specially arranged experiments, when $E_{\text{in}} < E_{\text{m}}$, the wire remained bent after the current had passed. When the wire passes into the liquid phase, the resistance forces decrease sharply and the development of the necking instability becomes possible*. Thus the fact that $E_{\text{th}} > E_{\text{m}}$ is explained.

Experiments on the electrical explosion of a jet of liquid lead confirmed the sequence of instability development described above: at comparatively small E_{in}, the necking instability develops immediately.

5. The necking instability develops and ruptures the conductor in a time of order 10^{-6} sec. After the instability has arisen, the release of Joule heat is concentrated in the necks, and vaporization of the metal may occur in these places. Vaporization occurs locally over a short interval of time. Before the conductor is destroyed, only an insignificant part of the substance has time to vaporize. Consequently, the energy E_{th} must be less than

Fig. 3

Figure 3: Fig. 3

the vaporization energy E_{vap}, as is observed experimentally. Since, with increasing E_{in}, the rate of instability development increases (Ω is proportional to H_0^2), complete vaporization of the substance may fail to occur even in those cases where $E_{\text{in}} \gg E_{\text{vap}}$. This conclusion agrees with the assumption made on the basis of phenomenological data in work (^{1}).

If $E_{\text{in}} \gg E_{\text{th}}$, the energy input is rapid (the initial voltage is large), and the helical instability does not have time to develop before the conductor melts. It is precisely this case that corresponds to the radiographs in Figs. 3b and 3c ($E_{\text{in}} = 800$ J). If, however, E_{in} is greater than E_{th} but close to it, instabilities of both modes should appear, which is confirmed by radiographs of the conductor exploded at $E_{\text{in}} = 290\ \text{J} = 1.2\,E_{\text{th}}$ (Fig. 3a). The wavelength of the helical instability arising after the conductor has passed into the liquid phase is smaller than r_0, and it is difficult to identify it in the presence of the necking instability.

6. Theory, the results of experiments, and the considerations set forth above lead to the conclusion that the appearance of the current pause is the result of the development of the necking magnetohydrodynamic instability. Figure 3 shows radiographs of copper (3b) and lead (3c) wires, obtained at the moment preceding the sharp drop of the current and at the end— the current decay. On the current oscillograms, the moments at which X-ray photographs were taken are marked. It is seen that by the time the current decay begins, the wire is still a regular cylinder and has no breaks. The diameter of the cylinder at this moment is approximately twice the diameter of the wire in its initial state. After less than 6 μsec, at the end of the current decay, the necking instability has already developed so strongly that numerous periodically arranged breaks are clearly visible. The diameter of the liquid "lenses" between the breaks is several times larger than the diameter of the liquid cylinder. The time constant for the growth of the instability, calculated from the formula given above, is, for a copper wire, $\tau = 0.2$ μsec, and for a lead wire, $\tau = 0.1$ μsec. From the radiographs in Fig. 3 it is seen that the experimental values agree well with the calculated ones.

Fig. 3

7. Experiments on the electric explosion of molybdenum and tungsten wires have clearly shown that in this case as well the destruction occurs as a result of the development of the $m = 0$ instability. However, after reaching the maximum value in the first pulse, the current decreases by only a factor

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* It remains as yet unclear why, in a solid heated conductor, the long-wavelength necking instability does not develop, which would require less energy for destruction of the conductor than the observed short-wavelength instability.

of 2–3, remains at this level for some time, and then, after the onset of "restriking," rises again. The development of the instability begins only after the current reaches the amplitude value in the first half-period of the oscillatory discharge. Before this, breaks are not observed, and the drop in conductivity at the end of the first current pulse cannot be explained by the development of the instability.

The authors express their deep gratitude to Academician B. P. Konstantinov for fruitful discussions that stimulated the formulation and execution of this work.

Physico-Technical Institute named after A. F. Ioffe
Academy of Sciences of the USSR

Received
19 V 1965

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Note: Figure translations are in progress. See original paper for figures.