EXPANSION OF THE LUMINESCENCE ZONE IN THE ELECTRICAL EXPLOSION OF THICK WIRES

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ABSTRACT: This paper gives the results of experimental studies of the expansion of the luminescence zone associated with the electrical explosion of copper wires 0.74 mm in diameter and 20 cm long. It is demonstrated that the time dependence of the diameter of the luminescence zone coincides with the law of motion of a self-similar cylindrical shock wave. The energy of hydrydynamic motion has been determined for different energies introduced into the metal. The fraction of vaporized wire is estimated.

The phenomenon of electrical explosion of wires when a capacitor is discharged across them is usually divided into three stages based on the current oscillogram: first current pulse, current pause and second current pulse [1]. During the first current pulse, heating and vaporization of the wire take place; as a result, the current in the discharge circuit is interrupted and a current pause sets in, despite the incomplete discharge of the capacitor (residual voltage). The second current pulse is caused by a discharge in the metal vapor. With increase of the residual voltage the duration of the current pause decreases and at a certain point the second pulse merges with the first, that is, the current pause disappears.

Study of the electrical explosion by the method of high-speed time-resolved photography revealed the presence of a luminescence zone which expands at a velocity greater than 1 km/sec [2]. The exact position of the outer boundary of the luminescence zone is not entirely clear. For example, Bennett [3] points out that in the case of explosion of thin (ϕ < 0.2 mm) copper wires in air the luminescence zone first coincides with the contact boundary between vapor and shock front; then the weakly luminescent shock front separates from the highly luminescent vapor contact boundary. On the other hand, it is clear from [4], a theoretical study of the expansion in air of a shock wave excited by an electrical explosion, that Bennett's highly luminescent zone is not the vapor contact surface, but is situated between that surface and the shock front. This is confirmed by the experimental work of M. P. Vanyukov and V. I. Isaenko [5], in which it is demonstrated that the luminescence is localized between the shock front and the dense cloud of metal vapor, that is, the outer boundary of the luminescence coincides with the shock front. In view of the above and the fact that our experiments were conducted with a low-inductance circuit and rapid energy input, it can be assumed that the outer boundary of the luminescence zone coincides with the shock front. L. I. Sedov [6] and Lin [7] give the radius of a strong self-similar cylindrical shock in air as a function of time for instantaneous input of energy E_0 per unit length of the cylinder axis at time t_0 in the form*

$$r = \left(\frac{E_0}{\alpha\rho}\right)^{1/4} (t-t_0)^{1/2} \left(\alpha = \alpha(\gamma),\ \gamma = \frac{c_p}{c_v}\right). \qquad (1)$$

Here α (in the notation used by Bennett and Lin, $S = \alpha^{-1/4}$) is a function only of the ratio of specific heats γ, and according to [8] is equal to 0.983 for air; ρ is the initial air density. This formula can be applied to the phenomenon of electrical explosion at distances at which the mass of the air enclosed in the cylinder surrounding the wire is greater than its mass.

Bennett demonstrated that the motion of a strong shock and the luminescence zone during an electrical explosion in air are described by these relations, provided t_0 (like Bennett, we will call it the virtual instant of energy input) is understood as the point of intersection of the straight line extrapolating the linear part of the curve $(2r)^2 = f(t)$ and the time axis. Using this curve to determine the slope

$$m = 4\left(\frac{E_0}{\alpha\rho}\right)^{1/2} \qquad (2)$$

and determining the energy introduced into the wire from oscillographic measurements, we can find α, if the energy introduced is so great that the part expended on vaporizing the metal can be neglected. On the other hand, by assigning α and determining m experimentally, it is possible to find the energy E_0 of hydrodynamic motion.

The published studies [3, 9] of the expansion of the luminescence zone of an electrical explosion were made in a pauseless process without measuring the energy released in the discharge gap (wire and plasma); the only known value was the energy stored in the capacitor. This experimental method did not make possible a rapid introduction of energy into the discharge gap nor did it establish what part of the energy released in the gap is transformed into hydrodynamic motion.

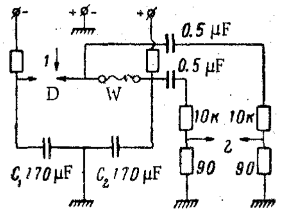

Fig. 1. Schematic of the electrical apparatus, W—wire; D—air discharger.

The purpose of the experiments to be described was determination of the law of expansion of the luminescence zone of the explosion and the energy of hydrodynamic motion when different energies are imparted to the wire under conditions coming close as possible to the concept of instantaneous input. For this reason we used an explosion process with a current pause and allowance was made for the energy introduced into the wire up to the onset of the current pause. An experiment without a current pause was carried out for comparison purposes. As samples we used copper wires in PEL enamel insulation; the wires were 0.74 mm in diameter and 20 cm long. The experiments were conducted in air under normal conditions using the apparatus illustrated in Fig. 1. In the figure, 1 indicates ignition; 2 are the outputs to the oscillograph. The inductance of the discharge circuit was 0.2 μH. A SFR-2m photorecorder was used for recording the expansion of the luminescence zone. The energy introduced into the wire by the time of onset of the current pause was determined from the oscillogram of the residual voltage V_+ using the relation

$$E = C(V_0^2 - V_+^2)/2 . \qquad (3)$$

Here C is the capacity of the capacitors, V_0, V_+ are the discharge and residual voltages, respectively. As an additional check on the energy introduced the wires were exploded in a rugged small-diameter pipe made of a dielectric; this caused the current pause to become infinite and the residual voltage in the capacitors was measured with ordinary instruments. These energy measurements differed from the oscillographic measurements by not more than 7%; this value will be taken as the error of energy measurement.

*It is assumed that air is an ideal gas with γ = 1.4.

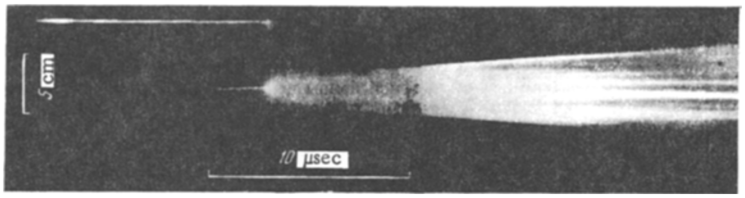

Fig. 2. Photochronogram of the explosion of a copper wire 0.74 mm in diameter and 20 cm long at a discharge voltage of 10 kV. The line at the edge of the photocronogram was produced by an additional discharger triggered at the time of firing of the main discharger D.

Three experiments (1, 2, 3) were made with a current pause and one (4) without it. The duration of the current pause (more than 46 μsec) exceeded the luminescence recording time (less than 15 μsec). The photochronogram of experiment 1 and the oscillogram of experiment 2 are shown in Figs. 2 and 3. The dependence of the square of the diameter of the luminescence zone on time is shown in Fig. 4 from the time of appearance of the luminescence. This figure shows that the curves are well approximated by a linear function, that is, the experimentally determined law of expansion of the luminescence zone coincides with the law of expansion of a self-similar cylindrical shock wave.

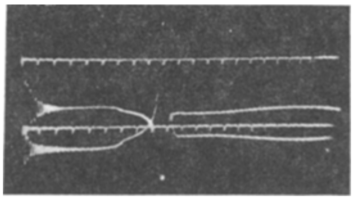

Fig. 3. Oscillogram of the voltage across the wire terminals for a discharge voltage of 15 kV. Time marks: 1 μsec.

The results of determining the slopes m [10^6 $cm^2 sec^{-1}$] from Fig. 4 are shown in the table. For the same experiments this table gives the discharge voltages $2V_0$ (in kV), the lag τ in the onset of luminescence (in μsec) relative to the firing of the discharger, the energies E introduced into the wires (in J/cm) before the current pause, and the virtual instants t_0 of energy input (in μsec). The table shows that m increases with increase of energy. The value of m in experiment 4 (without a current pause) was less than in experiment 3, conducted at a lower discharge voltage, but with a current pause. This probably can be explained as follows: a) the secondary discharge occurred when the energy introduced into the wire was less than in experiment 3, and b) the influence of this discharge on the expansion of the vapor was slight. The values of t_0 in the first three experiments were close to the luminescence lag times, whereas in experiment 4 t_0 was considerably greater than τ; this may be attributed to the delayed input of energy in the latter experiment. Obviously, as the effective energy input time, it is necessary to take the time interval during which the law of motion of luminescence is established. In the first three experiments the effective energy input time was close to the vaporization time for the wires (1.4 μsec), whereas in experiment 4 it was considerably greater (about 8 μsec).

The energy of hydrodynamic motion $E_0 = 1/16 m^2 \alpha\rho$ (in J/cm), that is, the energy transformed into energy of motion of the explosion products of the wire and the surrounding air, is determined from the law of expansion of the shock wave 1. Thus, we substitute into (2) the values obtained for m and the values $\alpha = 0.983$ and $\rho = 1.29 \cdot 10^{-3}$ g/cm^3. The results of this computation are given in column 9 of the table. As indicated by the data presented, in experiments 2 and 3 this energy was somewhat greater than the difference between the energy imparted to the wire and the sublimation energy.*

In many experiments only the rate of expansion of the shock front or the contact surface are determined, not their laws of motion. It therefore makes sense to obtain an estimate of the energy of hydrodynamic motion from these velocities and compare it with the computations. We will estimate the kinetic energy of expansion E_0' (in J/cm) of the products of explosion of the wire on the assumption that their density at any particular time is constant in the radial direction, while the velocity increases linearly from zero on the axis of the wire to the measured value of the rate of expansion v of the luminescence (in km/sec).** In this case the reduced mass M is equal to half the true value. The velocity v (in km/sec) is determined after establishing the law of motion, specifically, for a change of the diameter of the luminescence zone from 2.2 to 3.2 cm. Comparison of this estimate of the expansion energy E_0' with computations based on the theory of an ideal explosion shows good agreement.

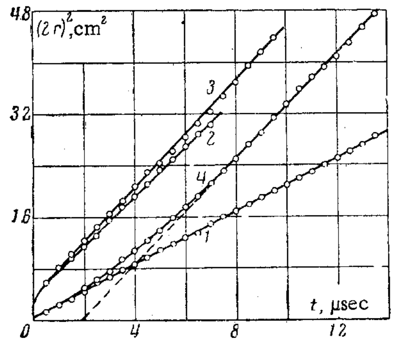

Fig. 4. Square of diameter of luminescence zone as a function of 1, 2, 3, 4 are the experimental curves for discharge voltage of 10, 15, 16, and 18 kV, respectively.

*The value 5.3 kJ/g was used for the sublimation energy E_+ of copper.

**Within the framework of this estimate we neglect the difference between the velocity of the contact boundary and the rate of expansion of the luminescence zone, which is 10–20%.

Experiment	$2V_0$, kV	E, J/cm	$\frac{E}{E_+}$	τ, μsec	t_0, μsec	$m \cdot 10^{-6}$, cm^2/sec	v, km/sec	E_0, J/cm	E_0, J/cm	Vaporized fraction
1	10	183	0.89	11.9	11.6	2.10	1.82	35	31.7	0.72
2	15	297	1.45	8.0	5.9	3.83	3.45	116	123	0.89
3	16	322	1.57	7.4	5.7	4.20	3.85	140	142	0.89
4	18	—	—	6.7	10.2	4.07	—	—	—	—

We will now compute the vaporized fraction. This is determined as the quotient obtained by dividing the difference between the energy introduced into the wire and that expended in hydrodynamic motion by the sublimation energy $\delta = (E - E_0)/E_+$. It can be seen from the table (the energy of the optical radiation emitted is neglected; direct measurements for copper wires [10] revealed that it does not exceed 0.05% of the energy introduced when $E = E_+$) that in experiments 2 and 3, where $E > E_+$, 89% of the metal is vaporized whereas in experiment 1, where $E < E_+$, 28% of the metal escapes in vaporized form. This can be attributed to the fact that in experiment No. 1 a considerable rate of expansion of luminescenece (1.82 km/sec) was recorded for an input of energy less than the sublimation energy.

These results may prove useful in utilizing shock waves from exploding wires, since in such applications it is necessary to know the hydrodynamic energy of the electrical explosion.

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