SOME PROPERTIES OF SHOCK WAVES PRODUCED IN AIR BY EXPLODING WIRES

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The shock wave produced in air during the initial stage of wire explosion was investigated by means of shadow photography; the streak photographs were synchronized with current oscillograms. The experimental wire samples of different metals had diameters from 0.03 to 0.8 mm; the initial electric field strengths varied from 0.1 to 1 kV/mm. The phases: linear expansion of the wire, "stratification," the first and second shock waves, and electric breakdown, were clearly distinguished. The conditions facilitating observation of these phases were determined. It is suggested that the second shock wave results from an increased velocity of metal vapor diffusion that is associated with rapid collapse of the magnetic field at the initiation of the dark pause.

THE electric exploding of wires has interested many investigators as a possible method of exciting shock waves in various ambients including gases, and as a means of producing high temperatures and pressures in a metal vapor. The latter possibility largely determined the direction taken by the investigations and the experimental conditions. In most experiments aiming to produce a maximum spatial concentration of energy very fine wires ($\leq$ 0.08 mm) were subjected to high electric field strengths ($>$1 kV/cm). These conditions shortened the duration of the dark pause or "dwell" phase and led to a rapid development of breakdown in the metal vapor or ambient gas. Under these conditions the gas-dynamical phenomena in the ambient were approximately the same as those accompanying a high-current spark discharge.[1]

Many investigators have studied the influence of the rate of energy delivery on changes in the electric properties of matter and on the gas-dynamical effects accompanying wire explosions. The methods of dimension and similarity theory are customarily employed to analyze the experimental data on shock waves produced in gases by exploding wires.[2] The experimentally observed hydrodynamic flows are usually compared with some analytic solution.[3,4] The simplest solution is that obtained for a strong cylindrical shock wave from a linear source. This solution is sometimes extended to the case of weak shock waves by expanding the solution of the fundamental gas-dynamical equation in powers of $(c/D)^2$, where D is the shock wave velocity and c is the velocity of sound ahead of the shock wave front.

The study of exploding wire shock waves is greatly complicated by prolonged energy release varying with time. Almost all studies of exploding-wire shock waves in gases exhibit complexity in the description and analysis of the initial stage in the development of the gas-dynamical phenomena. We here present the results of our study of shock wave formation in air during the initial stage of wire explosion. We differentiated clearly the phases of linear wire expansion, stratification, first and second shock waves, and breakdown, and determined the conditions facilitating the detection of these phases. Some of the experimentally observed dependences of the shock waves may be useful for determining the nature of their generation.

Our energy source was a 6-μF condenser charged to 30 kV; the inductance of the discharge circuit was $\sim 0.7\mu$H. The current oscillograms were registered by means of a graphite shunt with a time constant $<0.05\mu$sec. Shock waves in air were investigated at 730 mm Hg pressure and $\sim 20°$C. Optical registration was performed by the shadow technique using an SFR-2M instrument with 3× magnification. The light source was an IFP-2000 xenon discharge tube. For the purpose of comparing the current oscillograms with the exploding-wire streak photographs an air spark gap was inserted into the discharge circuit in series with the wire. The onset of current flow corresponds in the photographs to the initiation of luminosity in this gap. The experiments were performed on different metals, using a broad range of wire diameters (0.03–0.80 mm) and initial electric fields (0.1–1 kV/mm).

Figure 1 shows typical streak photographs and oscillograms from several experiments, with an identical time scale. Figure 1e shows the clearest

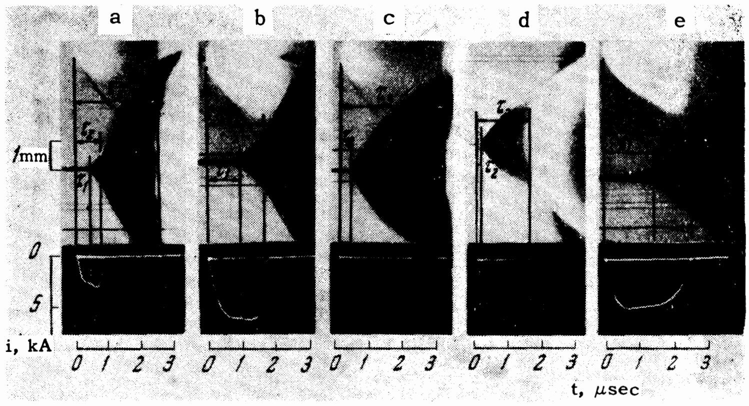

FIG. 1. Synchronized current oscillograms and exploding-wire streak photographs. a – nichrome, d = 0.1 mm, length 5 cm, U_{ch} = 17 kV; b – nichrome, d = 0.2 mm, length 5 cm, U_{ch} = 12 kV; c – copper, d = 0.05 mm, length 5 cm, U_{ch} = 10 kV; d–copper, d = 0.03 mm, length 5 cm, U_{ch} = 15 kV; e–nichrome, d = 0.2mm, length 5 cm, U_{ch} = 10 kV.

discrimination of the first stages in the explosion of a d = 0.2 mm nichrome wire at U_{ch} = 10 kV charged-condenser voltage. Almost instantaneously with the onset of the current the wire begins to expand linearly[5] at the rate ~ 100 m/sec. The expansion terminates with the separation of a layer of metal vapor from the remaining core (clearly observable on the negative). This "stratification" is observed clearly when a large-diameter wire is exploded. The same effect was previously observed by means of pulsed roentgenography.[3] After a time τ_1 more intense outward diffusion of the metal vapor begins; this is the first shock wave. After a time τ_2 the velocity of this flow increases abruptly; this marks the initiation of the second shock wave. After some additional time has elapsed a wave due to electric breakdown is observed (in photographs like Fig. 1, c and d).

The photographs of exploding wire shock waves that are shown in the literature[3, 4 etc.] usually pertain to small wire diameters (hundredths of a millimeter) and a high field strength (> 1 kV/mm). Under these conditions the initial stage is not clearly distinguishable (photographs like Fig. 1c) because the first two waves are combined. Experiments with a nichrome wire (Fig. 1, a, b, e) indicate that the initiation of the first shock wave is simultaneous with a characteristic break in the current oscillogram (at τ_1). The second shock wave appears simultaneously (at τ_2) with the beginning of the "dwell" phase. The chronograms in Fig. 1, a and b, show that the second shock wave is accompanied by nonuniform surface luminosity. In the explosion of fine (≤ 0.05 mm) copper wires (Fig. 1, c and d), the first current pulse is very short and both waves appear almost simultaneously, so that it is impossible to distinguish their properties in the oscillograms and streak photographs. In the photographs Fig. 1a, c, d, at a time τ_3 after current onset a bright glow appears; this is associated with electric breakdown either along the surface of the expanding explosion products or along the axis of the exploding wire. This time τ_3 coincides with the resumption of current flow following the dwell phase.

Figure 2 shows how the propagation rates D of the first and second shock waves depend on the charged-condenser voltage U_{ch} (solid curves) and on the diameter d (dashed curves) of copper wires. The voltage dependence was determined for diameters of 0.17 and 0.38 mm. The diameter dependence was plotted at 20 kV. The curves indicate that with increasing wire diameter accompanied by an appropriate increase of the energy stored in condensers shock wave velocities above 5000 m/sec can be attained.

Figure 3 shows how the period of time between the appearances of the first and second shock waves varies with the wire diameter and the condenser voltage. It is seen that for small wire diameters and high electric fields this period becomes

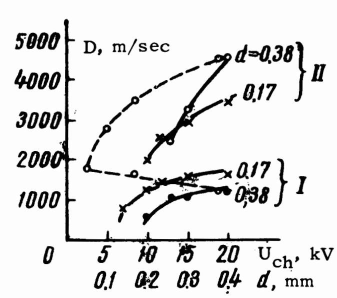

FIG. 2. Rates of propagation of the first (I) and second (II) shock waves versus charged-condenser voltage (solid curves) and diameter of copper wire (dashed curves).

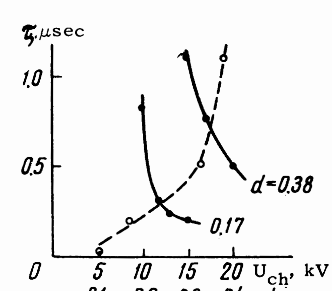

FIG. 3 Time interval between first and second shock waves versus voltage (solid curves) and diameter of copper wire (dashed curves) for U_{ch} = 15 kV.

small, making it very difficult to discriminate the first and second waves.

On the basis of our present results we can state that when a wire of ~0.2-mm diameter explodes in air after a relatively low field is applied (~0.2—0.3 kV/mm) the following phases can appear:

1) Linear expansion at the low speed of 100 m/sec (beginning practically simultaneously with the current).

2) Stratification, which characterizes explosions of large-diameter wires.

3) First shock wave, representing the initiation of intense outward diffusion. (1000–2000 m/sec), simultaneously with a break in the current oscillogram (at τ_1).

4) Second shock wave, at 1000–5000 m/sec, appearing simultaneously with the initiation of the dwell phase (at τ_2).

5) Electric breakdown, coinciding with the resumption of current flow (at τ_3) following the dwell phase.

Clear discrimination of all phases depends on the experimental conditions. In the cases of the high-melting metals tantalum and tungsten the rapidly developing breakdown along the wire surface prevents the discrimination of analogous stages in the explosion.

It was observed in the present work that an abrupt increase of shock wave velocity at the surface of a wire exploding in air (the second shock wave) coincides with the initiation of the dwell phase. Müller[6] postulated that the second shock wave exists in order to account for the breakdown which does not develop along the axis of an exploding wire. The second shock wave is thus associated with gas-dynamical processes accompanying wire explosions. It is known[7] that this wave appears in the solutions of purely gas dynamical problems. On the other hand, the second shock wave could be associated with properties of the equation of state in the poorly investigated density and temperature regions that are involved in wire explosions. The most probable explanation of the second shock wave is associated with the increase in the speed of metal vapor expansion that is made possible by the rapid collapse of the magnetic field as the dwell phase is initiated.

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