MOTION AND CONDENSATION OF PRODUCTS FROM ELECTRICALLY EXPLODED WIRES

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Droplet motion and vapor condensation have been examined in the electrical explosion of wires and foils with various electrode designs in order to separate the explosion products and obtain homogeneous condensates free from droplets. Droplets of diameter in excess of 0.1 μm produce surface defects in the films. The effect is explained in terms of the motion and condensation of the vapor-droplet mixture. The behavior difference between the vapor and droplets allows one to produce gasdynamic separation and obtain mirror-finish condensates.

Electrical explosion provides uncontaminated condensates in comparatively poor vacuums (down to 10^{-5} mm Hg) in 10^{-5} to 10^{-4} sec; for various reasons [1-5], the explosion products are usually inhomogeneous (a mixture of vapor and droplets), and the condensates have surface defects (deformed droplets, pits, and holes), on account of the thermal and kinetic effects of the droplets.

Defect-free films (with mirror finish) are usually produced by providing explosion conditions such that the material evaporates completely [4-7]; on account of the numerous difficulties [1-7], there are only a few papers [8, 9] reporting condensates of homogeneous phase structure (solely under laboratory conditions).

It is therefore of scientific and practical interest to examine the scope for separating the explosion products during motion; for this purpose we examined the motion of the droplet and vapor phases for three modes of explosion as shown in Fig. 1: electrical explosion of a wire 1 or foil between two coaxial electrodes (Fig. 1a) and coaxial electrical explosion of the foil 1 at the end of the coaxial electrodes 3 and 4 (Fig. 1b).

In the latter case, the size of the foil is 5-10 mm greater than the outside diameter of the cylindrical electrode 4. The foil is pressed onto the electrodes by the ring 5 of insulating material. The substrate 2 is 20-150 mm from the material.

The experiments were done with pressure p of about $5 \cdot 10^{-2}$ mm Hg; aluminum and copper wires and foils were used. The energy sources were IM5-140 capacitors, with a maximum stored energy of about 3.5 kJ. The discharge current was recorded with a Rogowski loop. The motion was recorded with an SFR-2M camera. The glass substrates were heated to 150-250°C.

It has been shown [10] that the disruption in the last case differs from that in the case of Fig. 1a [1, 2] in occurring not simultaneously throughout the volume but gradually from the center of the electrode toward the edge. The following equation applies to the propagation of the explosion through the foil:

$$r(t) = A\left[\int_0^t I^2(t)\,dt\right]^{1/2},\quad A = (4\pi^2\delta^2 Q_1\sigma)^{-1/2} \approx \text{const}$$

where Q_1 is the energy sufficient to evaporate unit volume, δ is foil thickness, and σ is specific conductivity.

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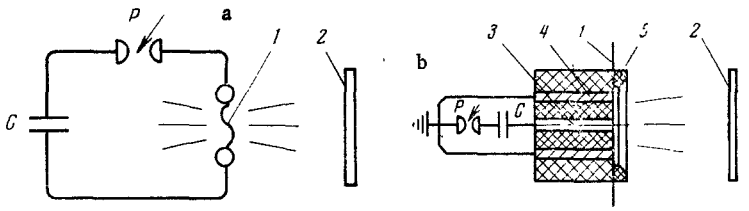

Fig. 1

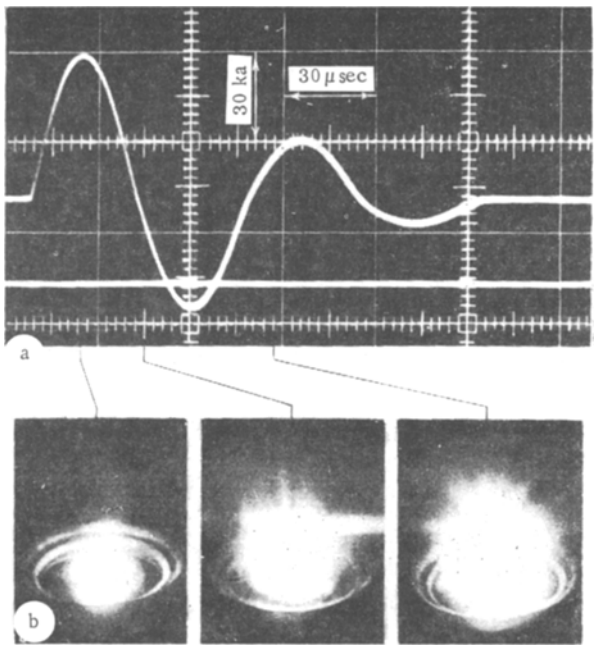

Fig. 2

Figure 2 shows typical current recordings and the sequential stages in the case of Fig. 1b; Fig. 2a shows that there is no current interruption or any other of the characteristic features [1, 2] occurring in bulk specimen disruption.

The various parts of the specimen explode at different times in the case of Fig. 1b (the explosion time T_* may be several half-cycles of the discharge current: $T_* \approx (1\text{-}3)\ T/2$), so the products are produced and displaced continuously. The balance between the vapor and droplet components also varies continuously, since the central zone is the hottest one, and the evaporation conditions there are much better than those at the periphery. The same conclusion can be drawn from the droplets deposited on the substrate; the droplet density and droplet size increase from the center towards the edge. Therefore, the main source of droplets is the edge of the foil, and this splits up later than the central parts, so the droplets follow the metal vapor.

The gradual explosion in the case of Fig. 1b means that there is a spatial and time separation between the droplets and vapor; this becomes even more pronounced during the motion, since the speed of the vapor in all cases is higher than that of the droplets [4, 5, 11].

The specimen geometry and circuit have substantial effects on the motion of the products; for instance, in the case of wires the products move (expand) uniformly in all directions while retaining cylindrical symmetry about the initial position. In the case of the foils in Fig. 1a, the motion is anisotropic; the main body of the material moves off in two opposite directions perpendicular to the flat sides of the foil.

In the case of Fig. 1b, there is directional ejection to one side, and the jet is actually symmetric.

The motion of the particles has features common to all cases. At the start, the particles move at right angles to the initial surface [12], while the vapor always subsequently expands rapidly, while the liquid droplets move along straight lines (they are seen as straight luminous tracts in photographs).

One therefore assumes that the vapor and large droplets move independently.

These features of the motion give an explanation for the general behavior of the products in all cases.

In order to separate the products to get defect-free films, one has to determine whether all the droplets produce defects or only ones of a certain size, and in that case why.

The films were examined with an MIM-8M microscope at a magnification of 2000, but we were unable to observe deformed droplets or traces of impact from droplets less than 0.3-0.5 μm in size.

It is necessary to know the extent of the deformation in order to determine the true droplet size. We assumed that $h/D \approx 1/10$ [11], where h is the thickness of a deformed droplet taking the form of a flat

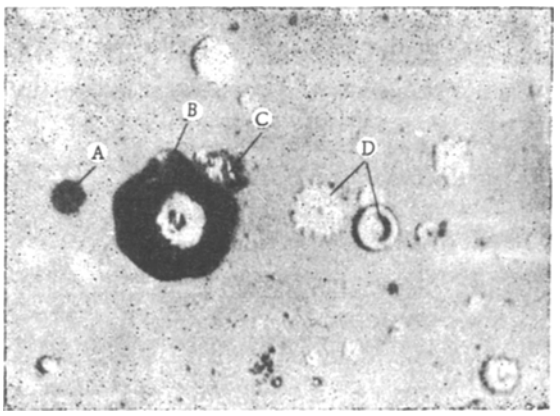

Fig. 3

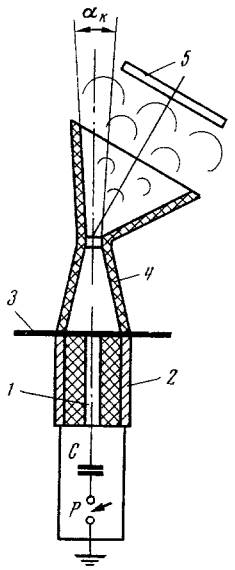

Fig. 4

flake, while D is the diameter of the flake; the calculation is based on equality of the volumes before and after deformation, which gives the true drop diameter as $d \approx 0.5$ D. In our case, the ratio of the thickness of a deformed drop to the diameter varied from 1/10 to 1/100, and with $h/D = 1/100$ we get $d = 0.25$ D, i.e., the relation between the true and deformed diameters is only slightly dependent on the degree of deformation: $d \approx (0.25\text{-}0.5)$ D. We substitute the minimum diameter $D \approx 0.3\text{-}0.5$ μm into this relationship to get that the true size of droplets producing defects is greater than 0.1 μm.

As electrical explosion produces continuous particle-size distribution [13, 14], it would seem that the cause of this is to be sought in the motion and condensation of the media.

Particles of size less than 0.1 μm are entrained by the vapor in such a mixed flow [15], and move at the same speed as the vapor; larger particles are either not entrained at all or only partially so (slip effect). The same occurs in electrical explosion. For instance, particle sizes have been measured [13] for explosions produced over a wide energy range in a neutral gas or air, and a passage of the material through filters reveal the structure of the products. The maximum particle size did not exceed 0.1 μm.

One assumes that droplets less than 0.1 μm in size move with the vapor and condense along with it on the substrate. The high vapor condensation rate (up to 1 cm/sec) goes with the high energy and density to produce considerable heating in the condensate (up to melting point), which facilitates structural perfection in the films [8].

Particles over 0.1 μm lag behind the vapor and arrive later, and they interact with the film already present; these particles differ in initial velocity, and their subsequent motion is essentially inertial (without substantial acceleration by the vapor), so they interact in different ways with the film (Fig. 3).

The detailed values for the velocity and temperature mean that the droplets will crystallize various stages of deformation (C and D in Fig. 3 represent slightly and highly deformed droplets), or else they produce defects in the form of holes (Fig. 3 A) and craters (Fig. 3 B).

The details of the motion and condensation indicate that it is sufficient to eliminate particles over 0.1 μm in size in order to obtain defect-free products with mirror surfaces.

It is possible to separate the products via the features of their motion: rectilinear motion of the defect-producing droplets and rapid vapor expansion (the vapor also entrains droplets below 0.1 μm), if one forces the droplets to move as a narrow beam in one direction while the vapor is capable of expanding in another.

These conditions can be provided in coaxial foil explosion, which shows jet-type escape.

The nozzle of Fig. 4 consists of two cones, which join at their narrow point, and which lie at 30-40° to one another, this system enabling one to alter the direction of vapor motion and to focus the jet of droplets

(α_k is the angle of droplet spread) without altering the initial direction of droplet motion. The spatial and time separation of the products in the case of Fig. 1b facilitates extraction of the vapor from the total flow without droplet entrainment. Substrates placed on the vapor path gave defect-free condensates with mirror finish. For example, we produced aluminum film of thickness 200-500 Å on glass substrates 40 ×60 mm^2.

A deficiency of this separation method is the incomplete use of the material on account of the separation and partial condensation of the vapor on the nozzle walls, while the film can also be contaminated by evaporation products from those walls if they are not made of resistant material.

It has thus been shown to be possible to separate the products from electrical explosion by using the details of the vapor and droplet motion, thereby obtaining defect-free films.

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