# CONDUCTOR DESTRUCTION IN ELECTRICAL EXPLOSION

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Conductor damage has been examined when the current is switched off at various stages in electrical explosion. If the switching is fairly rapid, kink instability growth is accompanied by formation of vapor bubbles at the kinks within the volume of the liquid metal. Later switching results in vapor bubbles uniformly distributed along the conductor. Cumulative ejection occurs under certain conditions. A qualitative interpretation is given.

1. There is considerable debate [1-6] on the nature of the forces causing conductor damage in electrical explosion, because research on the subject is complicated by the simultaneous occurrence of several different effects, such as strong electric and magnetic fields, environmental actions, differences in structural and nonuniformity in the conductors, electrical supply conditions, and so on. It is therefore of interest to examine damage when the effects of some of the factors can be eliminated.

If the current is switched suddenly, the mode of damage is dependent on the switching stage [6-8]. On the other hand, the initial heating rate is not dependent on when the current is interrupted, so one can examine various features of the damage mechanism by switching the current at various stages, since this leaves one of the major factors unchanged, namely the energy supply rate. Also, when the current is interrupted, the subsequent damage occurs at a zero electromagnetic field from the current, so the only magnetohydrodynamic instabilities that can develop are those that arose while the current was flowing. Published evidence [6-8] on current interruption shows that is impossible to treat the observations (in our view) as developing magnetohydrodynamic instabilities of pinch type.

We have examined the conductor damage with a constant initial heating rate and current interruption at a certain stage. These conditions were obtained by tripping the current at various stages in the explosion.

2. The energy store was a capacitor bank type K41I-7 of total capacitance $C = 60$ μF charge to $U_0 = 10$ kV. The maximum stored energy was 2.95 kJ, while the inductance and resistance of the discharge circuit (neglecting the wire) were 1 μH and $1.5 \cdot 10^{-2}$ ohm respectively, with a natural period of $T = 50$ μsec and a maximum short-circuit current of 70 kA at $U_0 = 10$ kV.

The conductor damage was examined by optical recording using an SFR-2M camera with a simultaneous current measurement. A special optical attachment to the SFR-2M provided images of the wires on a 1:4 scale on the film. The light source was an ISPT-6000 flash lamp. The current in the discharge circuit was measured with a Rogowski loop. The optical recordings and current measurements were linked in time using an FÉU-51 photomultiplier by the method described in [9]. The photomultiplier signal was extracted with a narrow mirror set up within the SFR-2M between the focal surface and the lens insert. The electrical signal from the photomultiplier and Rogowski loop were passed to an S1-17 double beam oscilloscope. Then the film recording showed a narrow unexposed part, which corresponded to the beam deflection on the oscilloscope. The setting accuracy was then one exposure. The position of the marker signal on the oscillogram was readily adjusted via the synchronizer in the SFR-2M.

The current-switching element was an accessory wire of smaller diameter $d_l$ in the discharge circuit in series with the main wire of diameter $d_0$. One could adjust $d_l$ within certain limits to switch the current in the main wire. The two wires exploded virtually simultaneously when $d_l$ and $d_0$ were equal.

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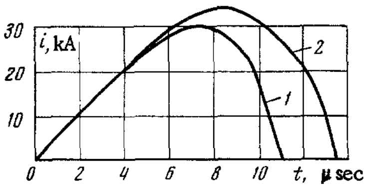

Fig. 1

We used copper wires of diameter 0.5 mm and length 50 mm with explosion in air at normal pressure; the accessory wires were copper ones of length 130 mm and diameters from 0.455 to 0.500 mm, by steps of 0.005 mm. The length of the accessory wire and the minimum diameter were chosen from considerations of preventing secondary breakdown on explosion.

The initial heating rate was kept constant by performing all experiments at the same initial voltage of 7.0 kV.

Figure 1 shows the current as a function of time for two limiting cases: curve 1 corresponds to the earliest current interruption ($d_l$ =0.455 mm), while curve 2 corresponds to no interruption ($d_l$ =0.5 mm); and both cases the main wire had $d_0$ =0.5 mm. Figure 1 shows that the accessory wire with $d_l < d_0$ produces not only earlier current interruption but also some reduction in the current amplitude.

3. The following dimensionless coefficient can be used to characterize the current interruption:

$$k = \frac{\Delta Q_l}{\Delta Q_0}, \ \Delta Q_l = \int\limits_0^{t_l} i_l(t)\,dt, \ \Delta Q_0 = \int\limits_0^{t_0} i_0(t)\,dt$$

where $\Delta Q_l$ is the amount of electricity flowing in the discharge circuit when the current is interrupted and $\Delta Q_0$ is the same without interruption (curve 2 in Fig. 1); $i_l$, $t_l$, $i_0$ and $t_0$ are the corresponding currents and switching instants.

We varied k from 0.77 ($d_l$ =0.455 mm) to 1 ($d_l = d_0$ =0.5 mm); we found that there were five ranges of k in each of which the damage had characteristic features. Typical recordings for each range in k are seen in the current oscillograms in Fig. 2. The marks on the oscillograms correspond to the instants when the shadow pictures were recording, and the times in μsec are stated there; the time origin coincides with the start of the current pulse, and the length of wire used in the recording was 15 mm. The oscillogram scales were as follows: vertical 18.54 kA/dib, horizontal 100 μsec/dib for parts a and b, or 10 μsec/dib for c, d, and e.

The shape of the oscillograms in parts a and b of Fig. 2 requires a special explanation. As the wires were damaged relatively slowly under these conditions, it was necessary to record the current with a large time scale (100 μsec/dib) in order to encompass the start of the current and the characteristic damage stages. However, the k for these conditions were deduced from special oscillograms recorded at 10 μsec/dib.

Figure 2a corresponds to k of 0.77-0.83; there were no visible changes in the wire at the instant of current interruption, but 6-8 μsec afterwards appreciable kinks appeared, which were more or less uniformly distributed along the axis (more careful examination showed that the kinks began to appear at 1-3 μsec after the switching). The kinks increased in amplitude at 10-20 m/sec, and this speed remained constant throughout the recording time of about 500 μsec. Immediately after the kinks had formed, the wire volume began to increase explosively at those points; the value after 200 μsec was 30 times the initial value, for example.

The density in these parts can be estimated from the mass and volume, and the result is much less than the density of copper at its boiling point, which indicates that the wire takes the form of a colloidal foam [10], namely a liquid metal with vapor inclusion. Subsequently, the bubbles burst out and the colloid gives way to an aerosol containing liquid droplets. The mean diameter then falls sharply and one has a thin chain of liquid droplets. The mass remaining after the bursting is less by a factor 1.5-2 and the initial value, so 30-50% of the mass is transformed to vapor.

The amplitudes of the kinks decrease as k increases within each range, while there is an increase in the uniformity of expansion in all parts, as well as in the rate of expansion and number of bubbles.

Figure 2b corresponds to k of 0.83-0.89; the damage occurs much more rapidly and is complete within about 150 μsec. As in the previous case, the appearance of the wire is virtually unaltered at the instant of interruption, except that the diameter has increased somewhat and that a vapor layer has begun to leave the surface. The slight kinks visible at the instant of switching are subsequently completely eliminated by the rapid bulk expansion. The wire diameter increases at the constant speed of about 50 m/sec, and exceeds by a factor 5 the initial value at 40 μsec after interruption. From about 70 μsec onwards a

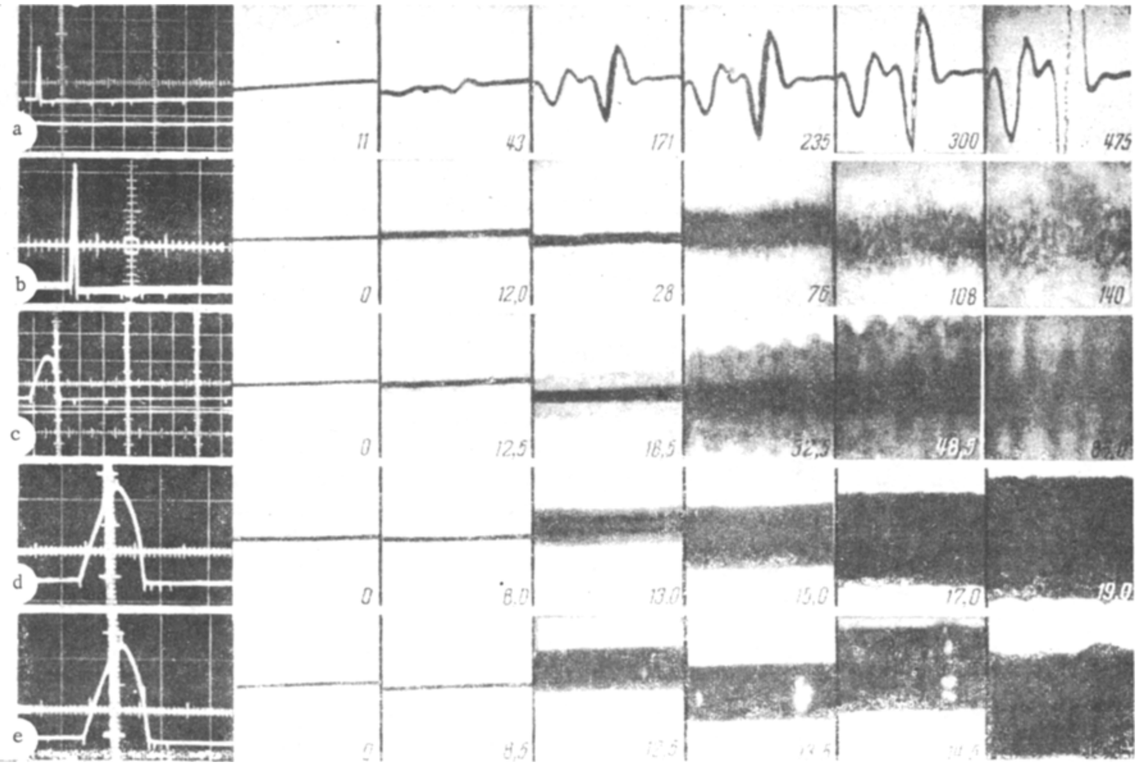

Fig. 2

large number of small gaps appear throughout the volume of the expanding wire, and some 30 $\mu$sec later these products represent essentially a rapidly expanding aerosol in which the gaps between the droplets are filled by vapor.

Figure 2c corresponds to k of 0.89-0.97. There is some kinking at the switching instant together with an increase in wire diameter, which is uniformly surrounded by a small vapor layer. After switching, the wire expands rapidly at a constant speed of about 100 m/sec, while the vapor layer also expands and becomes denser. The expansion rate of the vapor in the concave parts is substantially different from that in the convex parts; the value in the first is 2-3 times larger than the mean and is about 300-500 m/sec. Although the kinks present at the switching instant are subsequently rapidly eliminated by the fast expansion, this difference in the vapour expansion speeds persists. As a result, the vapor layer acquires a wave structure, and the crests of the waves correspond to the concave parts of the previous kinks.

For 20-25 $\mu$sec after current switching, the wire diameter increases uniformly on the length; then the material begins to be redistributed, and narrow jets of material appear at the points corresponding to the concave sides of the previous kinks, these being perpendicular to the axes. These jets rapidly grow and the entire material gradually becomes concentrated in them, and after about 80 $\mu$sec (the end of the recording), the damage products from the wire are seen as isolated narrow patches extended perpendicular to the original wire axis. The number of these condensations corresponds to the number of half-waves in the wire kinking at the switching instant.

Figure 2d corresponds to k of 0.97-0.99; in this range the density of the vapor sheath becomes so great that it is impossible to see the wire within 3-5 $\mu$sec of the switching. However, during the switching and for 2-3 $\mu$sec afterwards it is clear that consolidated material exists within the vapor sheath, and that the boundaries of this expand at about $10^3$ m/sec. Simultaneously, the vapor sheath expands at about $2 \cdot 10^3$ m/sec and becomes denser.

Figure 2e corresponds to k of 0.99-1. The damage picture is not substantially different, except that bright spots appear at isolated points on the wire at the instant corresponding to the characteristic kink on the trailing edge of the current pulse (Fig. 1), whose intensity falls rapidly when the current is interrupted.

4. We consider that the kinks produced at k of 0.77-0.83 (Fig. 2a) arise from three factors acting together:

1) Impulsive electromagnetic forces [3];
2) A large axial pressure in the wire due to the rapid heating (about $10^8$ deg/sec [6]);
3) Nonuniform distribution of the internal stresses along the wire axis on account of nonuniform heating (the heating nonuniformity is clear from the substantial difference in bulk expansion).

The rapid kinking occurs as a rule in parts of the wire that then show bulk evaporation and aerosol production, so it would appear that the third of the above factors is principally responsible for the instability. The subsequent growth of the kinks is due to the inertial hydrodynamic flow of the molten material.

Rapid kinking in exploding wires usually occurs when the energy input lies below the threshold [3]; this value is [3] somewhat greater than the melting energy but substantially less than the evaporation energy. All the same, the rapid kinking was accompanied by a bulk evaporation in the experiments with k of 0.77-0.83; it is possible for vapor to be produced although the metal has not been heated to the evaporation point if the energy is unevenly distributed within the volume on account of structural nonuniformity such as inclusions, microscopic cavities, etc. As a result, some points in the wire can acquire higher temperatures, which lead to earlier melting and evaporation. Microscopic vapor bubbles are produced in the liquid even while the current is still flowing, and the subsequent expansion occurs in response to the pressure of the vapor as the temperatures equalize.

If the current is switched at a later stage (k of 0.83-0.89, Fig. 2b), the number of superheated points is substantially larger, and the distribution along the length becomes more uniform. These points would appear to be evaporation centers, so the subsequent bubbles are formed and expand and ultimately produce the aerosol uniformly along the wire. The rapid volume expansion means that the kinks arising during the current flow do not subsequently develop.

While the wire has a colloidal foam form, there are still layers of liquid between the individual vapor bubbles; even a small current flowing through such a structure could cause rapid explosion of the individual layers to give the transverse structure similar to that observed in electrical explosion above the threshold [3]. Transverse striae of this form have been observed in exploding tungsten wires [11] and were due to emerging bubbles.

At $k > 0.89$ the density of the vapor bubbles becomes so great, and the sizes of them so small, that the individual bubbles cannot be seen (Fig. 2,c-e). We do not propose to discuss here the striation mechanism found at k of 0.89-0.97, and we merely note that the process involves cumulation of the expanding material at the initial kinking points (see [12] for details). The strong flashes from isolated points when the current is not interrupted (Fig. 2e) arise from small arcs resulting from circuit interruption.

Bulk evaporation thus plays an important part in wire damage; even at input energies below the threshold, the uneven volume distribution means that bulk evaporation transforms the wire first to a colloidal foam and then to an aerosol. Against this general background, there may be particular features such as kink development (if the bulk evaporation is weak) or striation (if evaporation is very rapid).

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