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THE ELECTRICAL BEHAVIOR OF FINE WIRES
EXPLODED BY A COAXIAL CABLE
DISCHARGE SYSTEM

by

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and

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May 1959

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ABSTRACT

The characteristic square output current pulse from a discharging coaxial cable has been utilized to explode wires of 1-mil diameter. The primary pulse duration was 3 μ sec and was variable in amplitude to a maximum of 600 amperes. Voltage and current waveforms were recorded on a high-speed oscilloscope. Resolution of the system is better than 10^{-8} sec, thus enabling accurate determination of the resistance history of the material being studied.

A survey of the behavior of various metals is presented and the results of certain parameter studies, such as, geometry, external environment, and current density, are discussed. It is shown that end effects contribute to the measured length of the sample, and that the energy to burst is dependent on current density. The latter effect was previously reported by Russian investigators and is discussed further in the paper by Anderson and Neilson (see abstract of this conference).

A new experimental system capable of producing square current pulses with an amplitude of 2000 amperes is described.

THE ELECTRICAL BEHAVIOR OF FINE WIRES EXPLODED BY A COAXIAL CABLE DISCHARGE SYSTEM

Introduction

In contrast to much of the previous work on exploding wires, in which obtaining a very large energy density is a major goal, the object of the work described in this paper was to measure accurately the electrical behavior of various metals being exploded by large currents. The experimental approach, which is mainly the effort of Dr. Frank Neilson of our laboratory, is thus designed to maximize voltage, current, and time resolution.

Experimental Method

Basically, the entire system is coaxialized, coaxial cable being used for charge storage and the exploding wire sample appearing as a segment of this line. Figure 1 shows a schematic of the circuit used. Current and voltage output waveforms were fed directly to the plates of a Tektronix 517 oscilloscope and were photographically recorded. Specifications of the system are:

1. Maximum charged line voltage - 30 kv
2. Maximum current - 600 amps
3. Main pulse duration 3 μ sec
4. Energy storage - 13.5 joules

The advantages of this type system over the more conventional capacitor storage systems for the problem in which we are interested are:

1. The circuit is purely resistive; thus, the circuit equations are algebraic rather than nonlinear differential equations.
2. The current approximates a step function; thus, voltage and current waveforms show wire behavior independent of RLC circuit behavior.
3. The instrumentation is simpler and more accurate. The system being completely coaxial provides good shielding and frequency response.
4. The coaxial symmetry of the magnetic field around the wire stabilizes the wire mechanically as it bursts.

PHYSICAL CIRCUIT

EQUIVALENT CIRCUIT

FIGURE 1

Results:

Figures 2, 3, and 4 show examples of voltage waveforms obtained under the following initial conditions:

1. Wire diameter - 1 mil
2. Wire length - 50 mils
3. Initial current - 200 amps

It can be seen that resolution is adequate to show the various phase changes in the material as well as the resistance behavior in each phase. The first point at which the slope in the curve changes rapidly is interpreted as a solid-to-liquid transition, modified by the fact that for some time the wire is part solid and part liquid. The second discontinuity is then the start of vaporization, after which, the resistance increases until the voltage gradient is sufficiently high to cause an arc breakdown.

A calculated resistance curve for gold agrees reasonably well with the experimentally determined curve, with the exception of small differences at the liquid-to-vapor transition. This type of investigation has not been applicable for all metals because of the scarcity and sometimes contradictory nature of handbook data for liquid metals.

Of particular interest is bismuth which is one of the few metals having a lower resistance in the liquid than in the solid state. This behavior is clearly shown in the waveform by the double high-resistance spike. To date, 17 pure metals and a number of alloys have been tested and plots made of various parameters, including resistance, voltage, power, and energy, as a function of time, and in the case of resistance, as a function of energy. The pure metals tested were Al, Bi, Cd, Cu, Fe, In, Pb, Mo, Ni, Pa, Pt, Rh, Ag, Sn, W, Zn, and Ti.

Of the pure metals, gold has been most intensively studied. Parametric studies in which both geometry and current density were varied have been made. Two effects are of particular interest and will be discussed in this paper. The first is the energy-to-burst dependency on current density. This effect has been previously reported by Russian observers (Ref. 1) and has been observed by us to occur in both gold and platinum. Figure 5 shows this dependency for gold in the current density range of 10^7 to 10^8 amps/cm². We have not as yet been able to propose a mechanism to adequately explain this effect; thus, the label anomalous effect, as it has been previously called, seems to be still justified.

Preliminary calculations of factors which might affect the resistive behavior have been made, but these, in general, have not been successful in explaining the anomalous effect. Skin effect calculations indicate a penetration time on the order of 1 μ sec and thus is important in only a small fraction of the total cycle time. Inertial confinement times of the liquid column would also seem far too short to produce significant effects. Magnetic pressures for the small wires we are using do not exceed 500 atmospheres, even at

0

Time →

1.1 μ s

Silver

Voltage vs. Time

Max. Volt. 2400 v.

Above: Showing voltage spike

Below: Showing early behavior

FIGURE 2

0

Time

0.5 μ s

Iron

Voltage vs. Time

Max. Volt. 2100 v.

FIGURE 3

Time

0.8 μ s

Bismuth

Voltage vs. Time,

Calibrating Volt. 270 v.

FIGURE 4

O - Obtained by variation of initial cable voltage

△ - Obtained by variation of initial radius

Plot showing the energy-to-burst dependency on current density in gold. Ordinate is energy per unit volume in 10⁻⁴ joules/cir-mil-mil. Abscissa is current density in amps/cir-mil.

FIGURE 5

the center, and it is difficult to see how such a small pressure would produce the large effects observed. From Figure 6 it can be seen that the energy deviation occurs in what we believe to be the liquid and liquid-vapor states. Thus, further studies of pressure and energy in the expanding vapor cloud may provide the answer, and work is continuing in this direction. It is interesting to note that although the energy to the time (t_B) of maximum resistance, equal to the $\int_0^{t_B} i^2 r dt$, is a current dependent variable, another integral (I_n) equal to the $\int_0^{t_B} i^2 dt$ is constant. The constancy of the integral, I_n , which we call action, is shown in Figure 7 and will be discussed further by Anderson and Cnare in their conference papers. A second effect which requires more explanation is shown in Figure 8, in which length was the varied parameter. It can be seen that extrapolation of the energy versus length curve does not show zero energy for zero length. This would indicate that end effects contribute to the measured length of the sample. It is possible that these same effects also contribute to the large terminal blossoms which are generally reported in photographic studies. Further study on end effects is planned and will be conducted when time permits.

In closing, a note about future activities is perhaps not out of place. One disadvantage of the system previously described is the difficulty of accurately mounting the 1-mil-wire samples. To overcome this difficulty, we have now constructed a system operating at 100 kv and producing a 2000-ampere square-current pulse. With this machine we are able to explode wires with diameters up to 5 mils, considerably easing fabrication problems. The system is also adapted to utilize a Kerr-Cell camera we have recently obtained to correlate optical data with the electrical behavior. Work has just begun with this system, and it is hoped we will soon publish some of the information obtained.

Plot of resistance in ohms as a function of energy input in joules

FIGURE 6

○ - Obtained by variation of initial cable voltage.

△ - Obtained by variation of initial radius.

Plot of action to burst $K_{AC} = \int_0^{t_B} \frac{i^2 dt}{A^2}$ in 10^{-3} amp-cou/(cir-mil)²

as a function of current density, J , in amps/cir mil.

FIGURE 7

Plot of U (energy to burst in 10^{-3} joules) and U_v (energy per unit volume to burst in 10^{-4} joules/cir-mil-mil) as a function of length (l) in mils for 1-mil diameter.

FIGURE 8

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