ELECTRON EMISSION UPON EXIT OF A SHOCK WAVE FROM A POWDER INTO A VACUUM

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1. The study of the process of ejection of material upon exit of a shock wave through a free surface is one method of obtaining information on the state of the material behind the shock wave front. In addition, exit of a high-power shock wave is accompanied by a number of interesting physical phenomena: scintillation of the free surface [1, 2], plasma formation [3, 4], and evaporation of material in the unloading wave [5]. There have also been studies of charged-particle emission upon high-speed collision of bodies [6]. The present study is an attempt to detect thermoelectronic emission upon ejection of material as a shock wave exits the free surface of a powder. The formulation of the problem and some results were presented in [7].

2. The experimental equipment (Fig. 1) consisted of a vacuum diode, with cathode formed by a mass of chemically pure iron powder 2, with density 4.6 g/cm^3, placed in a Duralumin container 3. Powder particle size was 0.1-0.5 mm. Container walls were 1 mm thick, with inner diameter of 10 mm and height of 50 mm. A metal grid with 0.1-mm spacing was placed on the free surface of the powder. The distance between the powder free surface and anode 5 varied from 22 to 42 mm in the experiments. Air was exhausted through the Duralumin anode, electrically insulated from the cathode by a Teflon or Plexiglas ring 4, with inner diameter of 20-30 mm. Special care was given to determining the pressure within the vessel immediately before the detonation of explosive charge 1. The pressure varied over the range 0.13-13 Pa in the experiments. The cylindrical explosive charge (1 : 1 mixture of trotyl-hexogene) was placed on top of the container holding the powder. The device was shielded by copper foil during the experiments which recorded signals of $\sim$10 V. A dc voltage of $\sim$200 V of either polarity was placed across the vacuum gap and a series-connected load resistor of $5 \cdot 10^2$-$5 \cdot 10^5$ Ω. The voltage drop across this resistor was recorded by an OK-33 oscilloscope with 1-MΩ input impedance (Fig. 1). In another variant using no bias, the oscilloscope recorded the potential difference between cathode and anode. In some experiments the electrical signal was recorded simultaneously with the scintilation produced upon material ejection, using a high-speed photorecorder. A slit was made in the screening material to observe the scintillation. The recorder slit, 0.1-0.3 mm wide, was located parallel to the device axis; film speed was 3 mm/sec. The accuracy of electrical signal and speed measurements was 10% or better.

3. Detonation of the explosive charge with a velocity of 7.6 km/sec excited a shock wave within the powder in the form of a truncated cone with axis coincident with the device axis. This shock wave configuration moves at the detonation rate [8]. The experiment was arranged so that the lateral portion of this cone exited onto the free surface at the moment that detonation was completed. The main (Mach) shock wave with diameter of 3 ± 1 mm exited 1.2 ± 0.2 μsec later, as determined in individual experiments.

The experiments performed with the arrangement shown in Fig. 1 recorded the signals shown in Fig. 2a (anode positive) and Fig. 2b (anode negative). The arrows indicate calculated exit times for the Mach wave. In a control experiment performed with no powder, the signal level was at least 100 times lower. Simultaneous recording of the scintillation produced (Fig. 3: 1, completion of detonation; 2, forward front of scintillation; 3, trailing edge of scintillation; 4, scintillation reaches anode; display direction, right to left; material travel, upward) and the electrical signal (Fig. 2a, b) shows that the positive signal coincides with the arrival of the scintillating material at the anode to within 0.5 μsec. The maximum current, calculated from the signal amplitude and oscilloscope impedance, was 0.3 A.

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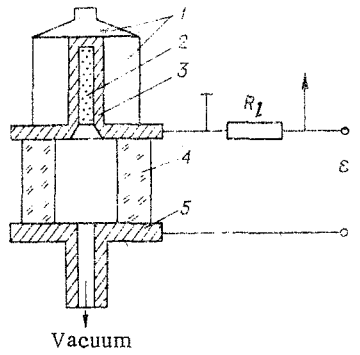

Fig. 1

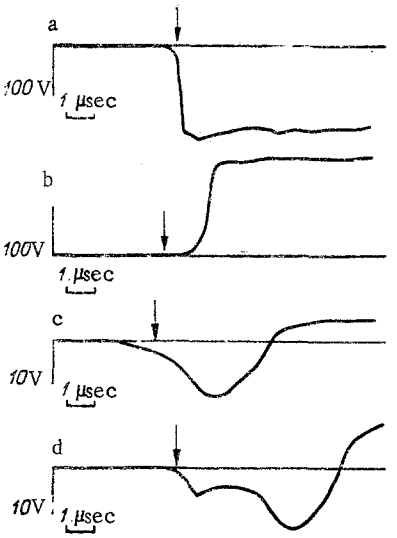

Fig. 2

In another series of experiments with no potential applied to the anode, the diode was connected directly to the oscilloscope input. After exit of the shock wave onto the free surface in this circuit a current appeared, creating a voltage drop across the oscilloscope input impedance. In 1-2 μsec the signal reached a minimum value, then changed sign (Fig. 2c). The duration of the negative-going portion of the signal decreased with decreasing electrode spacing. Simultaneous scintillation recording revealed that the potential minimum corresponded to the appearance of scintillation, while the change in sign corresponds to arrival of the scintillation at the anode. The calculated time of exit of the Mach wave to the surface corresponded to the beginning of the oscilloscope signal. This signal often had a precursor with amplitude of ∿ 0.5 V and duration of 0.5-1.2 μsec. In various experiments the signal amplitude was 8-12 V. Change in residual gas pressure within the diode over the range 0.13-13 Pa had no effect on signal form, amplitude, or duration.

In order to establish what portion of the anode current is produced by electrons, in one of the experiments a metal grid electrically connected to the cathode was installed 25 mm away from the cathode. The grid transmission coefficient was 50%. The signal recorded in this experiment is shown in Fig. 2d. Simultaneous scintillation recording revealed that in this case, within the limits of experimental error, the signal minimum coincided with appearance of scintillation between anode and cathode, while arrival of the forward scintillation front at the anode coincided with the change in signal sign. The signal amplitude was 7 V, only slightly lower than in the experiments without the grid. In all these experiments the anode—cathode distance was maintained at 42 mm. The maximum current recorded in these experiments was ∿20 μA.

The scintillation produced showed the following unique features. Immediately upon completion of detonation (commencement of oblique wave exit to powder surface) no scintillation was observed, or else a weak scintillation propagating toward the anode at a constant velocity of 3-5 km/sec was found. In 3-5 μsec at a distance of 8-15 mm from the powder surface an intense scintillation commenced, which usually moved at a constant rate and showed two distinct fronts — leading and trailing. The leading front moved toward the anode at a rate that varied from 6 to 20 km/sec in the various experiments. Velocities between 7 and 13 km/sec were recorded most frequently. Within these limits residual gas pressure and the voltage applied to the anode had no effect on the form of the scintillation or the propagation velocity.

4. The experimental results indicate that at the moment that the shock wave exits onto the free surface of the powder charge carriers appear in the interelectrode gap. The dependence of the signals observed on applied voltage polarity indicates that the carriers are all of one sign. Appearance of carriers of only one sign cannot be caused by ionization of the residual gas. Considering the polarity of the signals recorded, it is natural to conclude that the carriers are electrons emitted from the cathode as it is heated by the shock wave.

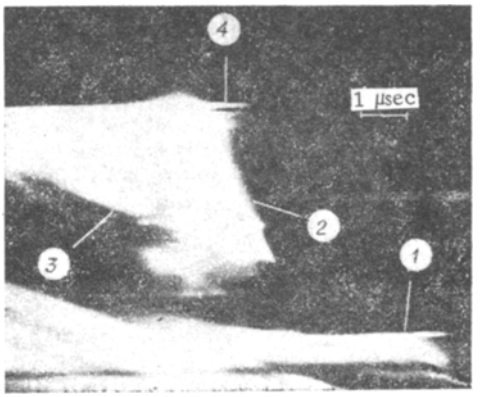

Fig. 3

We will attempt to clarify the conditions necessary for electron emission.

If we use the shock adiabat of iron powder presented in [9], we find that behind the front of the oblique shock wave the pressure and equilibrium temperature comprise 12-16 GPa and 1000-2000°K, while corresponding values in the main Mach wave are 130-140 GPa and (10-12) · 10^3°K. The internal energy of the material is then 30-40 kJ/mole behind the oblique wave front, and 430-470 kJ/mole behind the main wave front (with an elastic component of 90-100 kJ/mole).

The energy required to heat the iron up to the boiling point, as calculated with data of [10, 11], comprises 120 kJ/mole, while the energy required for total sublimation of the iron in a vacuum is 400 kJ/mole [10]. Since upon deloading in a vacuum a portion of the material's internal energy is expended in increasing kinetic energy, according to Zel'dovich's criterion [12] even in the Mach wave the internal energy is insufficient for complete evaporation of the material. However, it is apparently sufficient to cause the deloading curve in p-v coordinates to intersect the line dividing one- and two-phase regions. It has been shown experimentally [5] and theoretically [13, 14] that the process of evaporation in a deloading wave occurs in thermodynamic equilibrium, so that within the deloading wave there must exist a two-phase region consisting of a mixture of liquid and weakly ionized iron vapor. Electron emission into the vacuum apparently occurs from such a system, as indicated by the experimental current values measured. In fact, if emission occurred from the surface of the solid-state iron, then current would be limited by space charge, and by the "three-halves" law would be ∿1 mA for a voltage of 200 V and cathode area of ∿3 cm^2 (which corresponds to the area of the vacuum gap and is undoubtedly larger than the area of the Mach disk). Such a current value is at least two orders of magnitude smaller than that recorded in experiment. In the case of emission by weakly ionized iron vapor, the "three-halves" law does not apply, since the negative space charge is partially compensated by positive ions. If we estimate the degree of ionization of the iron vapor by Sach's formula, and the emission current density with the expression $J = 2 \cdot 10^{-14} n_e T_e^{1/2}$ [15], where n_e is the electron density in cm^{-3} and T_e is the electron temperature, it is evident that the current values observed in experiment could be emitted by a plasma with temperature of (5-10) · 10^3°K and density $n_e \geqslant 10^{14} cm^{-3}$. Such conditions are completely realizable in the deloading wave, since, as has been established experimentally, heating of porous media on shock compression is a nonequilibrium process, and the temperatures achieved can be several times larger than equilibrium values [3, 16]. This unique feature of heating of porous specimens in shock loading may also be responsible for the appearance of the weak precursor signal on the oscilloscope upon exit of the oblique shock wave before the Mach wave exits.

The features of the scintillation observed in experiment are not completely clear: the delay in appearance, presence of two well-defined fronts, and constant propagation rate. It is possible that the beginning of scintillation coincides with the beginning of some phase transition in the deloading wave, or it may be of a different nature. In any case the scintillation region is one of elevated temperatures, and consequently, one of the sources of thermoelectrons. This is indicated by the coincidence of the signal minimum with the appearance of scintillation, and by the change in signal sign as the scintillation reaches the anode.

Thus, the signals recorded are caused by thermoelectronic emission. The thermoelectron source is apparently ionized iron vapor produced by deloading of the shock-compressed powder in the vacuum at a temperature several times exceeding the equilibrium value.

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