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Luminescence accompanying the deformation and fracture of metals

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Experiments are described in which low intensity radiation in the visible region of the spectrum (3000-8200 Å) produced in rapid fracture and deformation of metals is observed and investigated. Two independent recording techniques are employed, one with an electron-optical image converter and the other with a photoelectric multiplier. The light is found to be emitted from fissures and from the most deformed parts. The emission duration is longer than that of the fracture process by approximately an order of magnitude. The emission has a band spectrum with a maximum of 7200–7300 Å. There are all reasons to believe that the radiation has attributes of luminescence.

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A conviction of long standing was that metals do not luminesce in the condensed state (see, e.g., [1]). We have demonstrated[2] in 1965 that the emission produced when a large-density current passes through copper conductors, under conditions when no discharges of any kind exist, is not of thermal origin. In 1969, Muradyan has excited luminescence of a metal by light to produce photoluminescence of copper and gold, while in 1971 photoluminescence came into use for the investigation of the band structure of metals.[4]

An investigation of the radiation produced upon development of neck-type magnetohydrodynamic instability in a liquid copper conductor[5–7] has shown that this radiation has all the attributes of luminescence.[1)] Two physical circumstances in the experimental conditions described earlier[5] could lead to excitation of luminescence, either an electric field or rapid destruction of the (liquid) metal by the instability.

When neck-type MHD instability arises in a cylindrical conductor, the electric field intensity in the metal and the current density are larger at the instant preceding the breaking of the current than those attained in any other experiment by many orders of magnitude. It is therefore natural to assume that electroluminescence of a metal has been registered for the first time. At the same time, the rupture of an MHD conductor by the instability takes place at rather high velocities ($v \geq 100$ m/sec) and it would not be absurd to suggest that this strongly-acting factor could lead to excitation of luminescence.[2)]

We describe here the performance and results of experiments in which we have established the production of nonthermal radiation when metals are deformed in the absence of electric and magnetic fields, as well as the results of an investigation of the temporal and spectral characteristics of the observed radiation. A preliminary communication on this subject was published earlier.[9]

Two series of experiments were performed. In the first we attempted to observe the radiation produced at a metal strain and fracture rate ~7 m/sec. A vertical ram and a reversing mechanism was used to rupture cylindrical samples of 3–4 mm diameter. The radiation detector was a photomultiplier sensitive to the 3000–8200 Å band. The maximum sensitivity of the recording system for an integral light flux was 10^{-8} lum, or in absolute power units 10^{-2} W. The experiments were performed with copper, aluminum, molybdenum, and bismuth. The radiation was not reliably registered but was fixed approximately in $\frac{1}{3}$ of the experiments, i.e., it could not essentially be reproduced in controlled fashion. One cannot exclude the possibility that this was caused by the imperfection of the detecting system (its geometry).

In the second series of experiments we attempted to

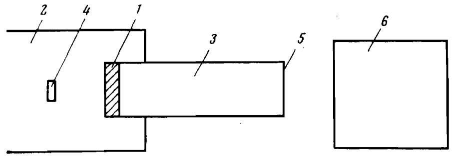

FIG. 1. Experimental setup: 1—sample (diameter 50 mm, thickness 50–25 mm): 2—large chamber; 3—small chamber; 4—striker (diameter 50 mm, thickness 5 mm); 5—transparent glass; 6—FÉU-38 radiation detector, oscilloscope, and photographic camera or UMI-93 image converter and photographic camera or ISP-51, image converter and photographic camera or UM-2 monochromator, photomultiplier, oscilloscope, and photographic camera.

observe radiation at metal strain and fracture rates close to the rate of rupture of a liquid metal by MHD instability.[5–7] To this end we used a contactless method of rupturing a metal surface—by fracture from the rear.[10,11] The radiation detector was the same photomultiplier, and the photographs were obtained with an image converter having the same sensitivity range as the photomultiplier. The experiments were performed in a system consisting of two steel cylindrical chambers, the cavities of which were separated from each other by the sample 1 (Fig. 1). The pressures produced in the large chamber 2 and in the small chamber 3 were 1 and $\sim 10^{-5}$ Torr, respectively. A striker 4 was accelerated in the large chamber to a velocity ~1200 m/sec. When it struck flatly the rear side of the sample, which served as the end cover of the small chamber, the rear fracture caused deformation and destruction of the metal surface (Figs. 2a–c). The radiation was registered through a

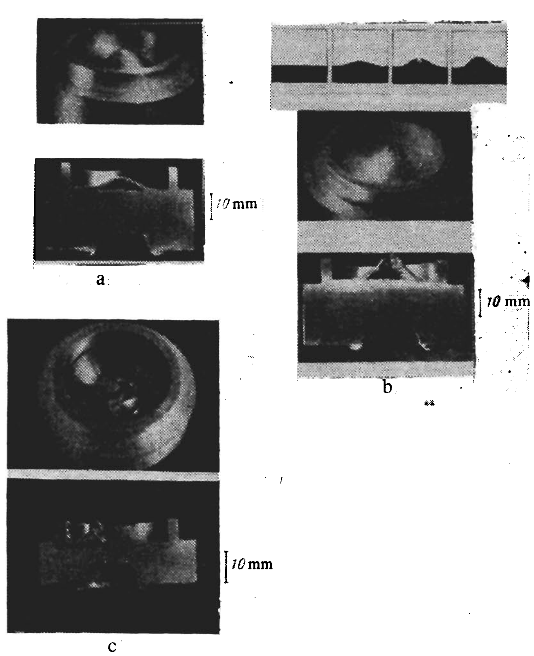

FIG. 2. Photographs of destroyed sample: a) copper sample, deformation without visible breaks; b) copper sample, deformation and break of rear surface; the top section shows shadow photographs obtained at 0.26, 68, and 112 sec after the start of the experiment; c) aluminum sample, deformation and break of rear surface.

transparent window 5 located in the other end cover of the small chamber. The rate of deformation of the rear surface of the metal was determined with the aid of x-ray shadow photography. Four pulsed x ray tubes were circularly arranged in a plane passing through the rear surface of the sample and made it possible to obtain four time-sequence photographs, the exposure time of each being ~100 nsec.[12] The upper part of Fig. 2b shows one of the obtained series of photographs, with the aid of which it was possible to ascertain that the rate of deformation of the copper was ~100 m/sec, and the process of plastic deformation terminates practically after ~100 μsec (these are approximately the rate and time of deformation in the case of rear fracture of aluminum) (Fig. 2c). Radiation was registered in these experiments.

Figure 3 shows oscillograms of the photomultiplier signal. The oscillogram of Fig. 3a was obtained in the case of strong deformation and destruction of the rear surface of the copper, 3b was obtained with deformation but without visible breaks: the irradiation intensity is connected with the magnitude of the deformation. The amplitude of the signal from the photomultiplier is several (3–8) times larger when the metal surface is broken than the amplitude of the signal in the case of deformation without visible breaks. When the sample is thick enough to prevent its rear surface from being deformed, the photomultiplier did not register any radiation (Fig. 3c). Similar results are obtained in experiments with aluminum and duraluminum samples. The radiation lasts 2–2.5 msec. During this time, as can be judged from the oscillograms, two or three bright flashes are produced, and as a rule cannot be resolved in time. In individual cases the peaks corresponding to these flashes on the oscillograms are almost completely separated. In addition, the oscillograms are chopped up apparently by a large number of flashes of lower brightness that follow closely one another. The time constant of the decay of the excited states that cause the observed radiation can presently be determined only very roughly—its

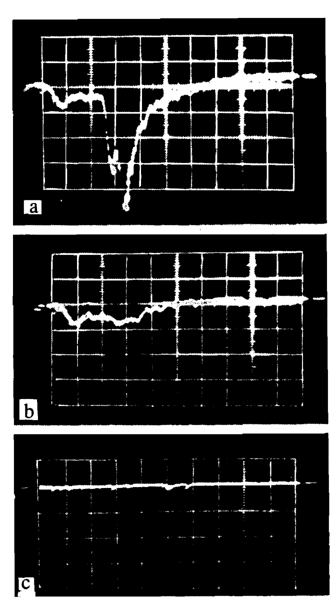

FIG. 3. Photomultiplier-signal oscillograms obtained upon destruction of a metal sample, $t_{sweep} = 0.5$ msec/div $p \approx 10^{-5}$ Torr: a) breaking of rear surface, sample thickness $h = 27$ mm, sensitivity of detecting system $U = 50$ mV/div; b) deformation without visible break, $h = 27$ mm, $U = 50$ mV/div; c) undeformed rear surface, $h = 50$ mm, $U = 10$ mV/div.

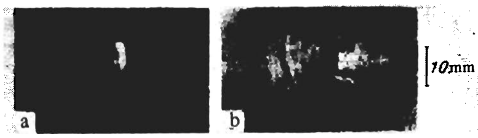

FIG. 4. Photographs: a) crack seen in its own radiation, b) crack seen in reflected light.

value lies between 100 and 500 μsec (see[9] and also below).

To verify that the radiated light is produced in the deformed and ruptured regions of the sample, photographs were obtained of the glowing regions in "its own radiation" with the aid of an image converter. Figure 4a shows a photograph of the radiation produced in the rupture of a copper sample, while Fig. 4b shows a photograph of a crack produced in the sample; the glow contour agrees well with the contour of the crack. Figure 5 shows a photograph of the radiation produced in the case of strong deformation but without visible breaks of the sample, and a simultaneously obtained oscillogram. One can distinguish on the photograph individual glow regions which apparently correspond to the peaks on the oscillogram. The photographs obtained with the aid of the electron optical converter, and certain indirect attributes, allow us to suggest that the different glow regions arise and build up not simultaneously.[3)] Photographs of macroscopic and microscopic cracks were carefully studied under large magnification (200×), and no signs of melting of the edges of the cracks were observed.

Special experiments were performed to verify that the outside film which inevitably exists on the surface of even a very freshly prepared sample does not contribute a noticeable fraction to the observed radiation. By fracture from the rear, a part of the rear surface of the sample was chipped away and destroyed, and this bared a freshly formed metal surface. After 2 or 3 minutes, the sample whose rear side was at a pressure of 10^{-5} Torr during the entire time, was again hit by the striker, as a result of which the freshly formed copper surface was deformed and damaged. It is known that at a pressure of 10^{-5} Torr a freshly formed surface of copper does not oxidize for several hours.[13] This guaranteed that no oxide film could be produced within 2–3 minutes. In these experiments, the slit formed by the first fracture collimates strongly the radiation produced when the freshly produced surface is damaged: the field of view of the photomultiplier turns out to be strictly bounded by the slit. One should therefore expect the duration of the observed flash to amount to 200–300 μsec, and the fixed intensity of the radiation to decrease. The time of the registered pulse turned out to agree with this prediction, but its amplitude changed little. This meant that the radiation brightness was strongly increased by the deformation of the freshly produced surface. In the succeeding experiments, the fresh surface of the sample was subjected to special action of air at atmospheric pressure and was subsequently deformed and damaged: the duration and character of the registered light pulse remained the same as in the case of a surface that was not oxidized. This has made it possible to perform an experiment in which the part of the sample material chipped away in the first fracture was removed and the entire area of the freshly formed surface was bared. The intensity of the registered radiation—the amplitude of the photomultiplier signal—increased by 2.5–3 orders of magnitude in comparison with the radiation following the first fracture (this phenomenon was observed already after the spectra were measured).

The next task was to obtain the spectra of the observed radiation. The dependence of the intensity of the radiation produced by damage of copper samples on the wavelength in the spectral range 3000–8200 Å was investigated by two independent methods. In the first, the investigated radiation was focused on the entrance slit of ISP-51 spectrograph, and the photocathode of a UMI-93 image converter was placed in the image plane of the spectrograph. The image of the spectrum obtained on the converter screen was photographed. Since the radiation intensity was low, it was necessary to accumulate the signals from ten experiments on one photographic film. Curve 1 of Fig. 6 is the result of the reduction of six such spectrograms.

In the second case (Fig. 1), the investigated radiation was focused on the entrance slit of a UM-2 monochroma-

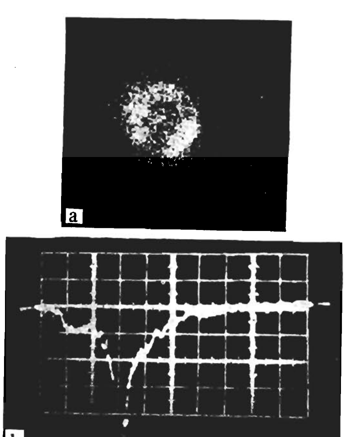

FIG. 5. Radiation of copper sample in the case of strong deformation without visible breaks, $h = 27$ mm, $p \approx 10^{-5}$ Torr: a) photograph obtained with an image converter, b) corresponding oscillogram, $t_{sweep} = 0.5$ msec/div, $U = 50$ mV/div.

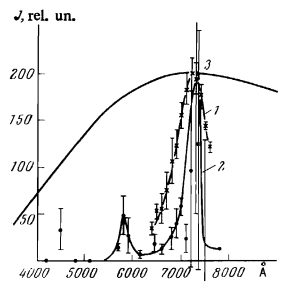

FIG. 6. Spectrum of emission produced when a copper sample is destroyed: 1—results of the reduction of the data obtained with the aid of a spectrograph and an electron-optical converter; 2—results of the reduction of the data obtained with the aid of a monochromator and a photomultiplier; 3—radiation of absolute black body heated to 4000 °K. The error fields were determined from the results of the reduction of six spectra. The probable errors of $\rho = 2\sigma/3$ are indicated.

tor, and the photocathode of an FÉU-38 photomultiplier was placed in the focal plane of the monochromator. In the investigated spectral band, we selected 25 wavelengths at which we measured the radiation intensity. The spectral width of the light flux at the monochromator output was 100 Å. We reduced the data of 5–6 measurements for each wavelength. The results are represented by curve 2 of Fig. 6. The curves obtained by different methods are in good agreement. The same Fig. 6 shows absolute blackbody radiation at 4000 °K ($J_{\lambda\,max}$ = 7200 Å), normalized to the maximum of the intensity (curve 3).

It is seen from Fig. 6 that there is no line spectrum in the registered radiation, the radiation occupies a relatively narrow spectral band with half-width 600–350 Å; the maximum of the intensity occurs at a wavelength 7200–7300 Å (within this band, there the copper, the elements contained in the commerically pure copper used to prepare the samples, and the gases in the air, produce no emission with an intensity exceeding 100 on a scale of 1000[14]). In the experiments in which a photomultiplier was used, we registered one more emission band of shorter wavelength; its intensity was approximately one-seventh the intensity of the main band, and its maximum coincided with the Cu I 5780 Å line (intensity 1000).

The foregoing allows us to conclude with assurance that fracture and rapid deformation excite luminescence in metals.

1) As defined by S. I. Vavilov,[8] luminescence is the excess above thermal radiation at a given temperature, and has an afterglow duration much longer than the period of the optical oscillations.

2) Of course, we do not have in mind here triboluminescence, which is the radiation produced when a dielectric is mechanically destroyed, and is presently regarded as gap-discharge radiation produced as a result of the appearance of opposite electric charges on the opposite surfaces of the break. In well-conducting bodies, where the charge relaxation time is shorter than the crack-formation time, such a process is impossible and, naturally, is never observed in metals. We do not exclude, however, the possibility that the mechanism producing the radiation is connected with phenomena near the surface of the metal.

3) Experiments in which the registration can be simultaneously carried out with image converters and photomultipliers with synchronized sweeps are still only in the planning stage.

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