Change of the Electric Resistance of Laser-Irradiated Beryllium

S. S. AVOTIN, É. P. KRIVCHIKOVA, I. I. PAPIROV, P. I. STOEV, AND V. I. TERESHIN

Physico-technical Institute, Ukrainian Academy of Sciences

Submitted June 29, 1971

Zh. Eksp. Teor. Fiz. **62**, 288–293 (January, 1972)

The change in the electric resistance of beryllium foils during pulsed laser irradiation and also after irradiation and annealing in a temperature range between 77 and 300°K is investigated. The effective heating and cooling rates of the irradiated regions assessed on basis of the change in the electric resistance are $\sim 10^6$ and $\sim 10^5$ deg/sec. The heating occurs in three stages with different time dependences. An anomalous increase of the electric resistance with time is observed in samples irradiated at 77°K. Reversal of the electric resistance after annealing of the samples is studied.

APPLICATION of high-power radiation causes rapid heating of the irradiated region of a solid, accompanied by melting and evaporation of the substance. The nature and the mechanisms of the processes occurring in this case have been analyzed in[1]. The most detailed studies were made on electron emission under the influence of laser radiation, and also on the kinetics of the damage and the structure of the craters. In[2,3] we investigated plastic deformation of beryllium single crystals after irradiation by laser pulses. The study of the electron emission under the influence of laser irradiation has shown that it has a thermal character, and that the surface temperature rises at a rate that reaches 10^{10} deg/sec. The surface temperature increases linearly with the light-flux density[4]. The rate of cooling of the surface is usually several times lower than the rate of heating.

The presence of a thermal effect in irradiation should lead to a noticeable change in the electric resistance of metals both during the irradiation process (as a result of the change of the temperature) and after the cooling (as a result of the change of the shape of the samples and formation of structure defects). The electric characteristics of metals irradiated by laser pulses have not been investigated to this day. Yet such investigations are of considerable interest. Measurement of the resistance during the irradiation process makes it possible to determine the effective temperature of the irradiated volume and its time variation. Rapid cooling of a liquid metal after irradiation leads to an effective "quenching" of structure defects, accompanied by a change in the structure-sensitive characteristics of the investigated objects.

The goal of the present study was to investigate the electric resistance of polycrystalline beryllium directly during the course of laser irradiation, after the irradiation, and as a result of subsequent low-temperature annealing. Owing to a favorable combination of high melting and evaporation heat and considerable electric and thermal conductivity, beryllium is a very convenient object for investigations of this type. It can be subjected to a considerable flux density without appreciable damage and change of shape.

MEASUREMENT PROCEDURE

The investigated samples were beryllium foils obtained by evaporation and condensation in vacuum by a procedure described in [5]. The purity of the samples was 99.9%. Strips of foil 10 mm long, 2 mm wide, and 0.2 mm thick were cut by the electric-spark method, were electrically polished, and electric potential and current contacts were then soldered to them. The samples were irradiated at 77 and 300°K. In the former case, the samples were glued to the internal wall of a cylindrical foamed-plastic vessel opposite the opening for the entrance of the beam. The samples irradiated at room temperature were glued to a bulky brass block through a mica liner. The sample temperature was monitored with a chromel-alumel thermocouple. To obtain temperatures in the 77–300°K range while heating the samples, two procedures were used: lowering the liquid-nitrogen level and keeping the samples in the cooled vapor, or heating the samples by adding alcohol to the nitrogen.

The samples were irradiated by a free-running GOR-100M pulsed laser. The pulse duration was $\sim 10^{-3}$ sec, the radiation energy 40 J, and the average radiation density $\sim 10^7$ erg/cm^2. The beam was focused on the surface of the sample by a lens with focal length 250 mm. The diameter of the irradiated region in the central part of the sample was 2.5 mm. The electric resistance was measured with an oscilloscope and a potentiometer. In direct measurements of the electric resistance of the samples during the irradiation process, the voltage picked off the potential contacts was amplified and fed to an S1-29 cathode-ray oscilloscope, and the oscillogram was traced from the screen. The electric resistance after the radiation was measured with the aid of an R-348 dc potentiometer. All the measurements were performed at constant values of the radiation energy and of the current flowing through the sample (~ 1 A).

Under the indicated irradiation conditions, the change of the electric resistance of the sample, due to shape distortion by melting, was usually comparable with the sensitivity of measurements, and the loss of material due to evaporation did not exceed several per cent. The sensitivity and relative error were 10^{-8} V and 1% respectively in the potentiometric method and 10^{-5} V and 15% in the oscillographic method (at a resolution time $\sim 10^{-6}$ sec).

EXPERIMENTAL RESULTS

The change of the electric resistance of the irradiated zone during the course of irradiation is shown in Fig. 1. Data on the time dependence of the electric re-

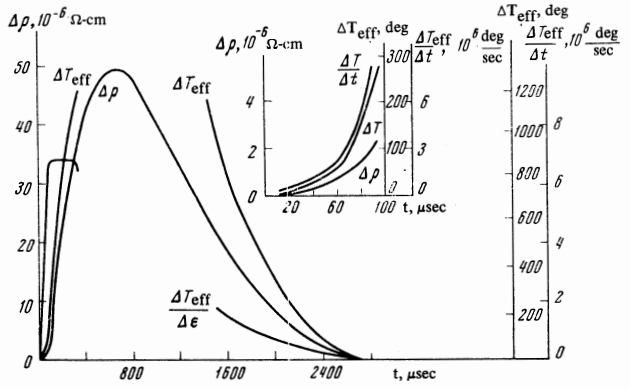

FIG. 1. Variation of the electric resistance, of the effective temperature, and of the rate of heating when beryllium is heated.

sistance can be used to determine the temperature T of the metal and its rate of change dT/dt. However, the solution of this problem encounters two significant difficulties. First, the metal melts when heated, and the electric resistance of a liquid metal and its variation at the melting point are not known. Therefore T and dT/dt can be estimated only when $T < T_m$. Second, the resistance of the irradiated section varies with thickness in non-uniform fashion during the course of irradiation, since the thickness of the heated layer increases with time. Allowance for this factor presents certain difficulties.

The temperature and the heating rate were estimated assuming a homogeneous change of the electric resistance over the thickness. In this case one can determine the effective temperature (or the temperature averaged over the thickness) of the irradiated part at a specified laser pulse waveform. The results of the estimate are shown in Fig. 1. The effective temperature of the irradiated zone were determined only up to the melting point. In addition, the rate of heating was estimated with allowance for the variation of the temperature over the cross section of the sample (without a correction for the jump of the resistance at the melting point). With some simplifications, the problem can be formulated in the following manner (see Fig. 2):

What we have is a parallel connection of two conductors with variable resistances $R_1(t)$ and $R_2(t)$. The resistance R_1 varies because the thickness b of the heated layer increases and the temperature increases at a rate dT/dt:

$$R_1 = \rho_0 \frac{l}{ab(t)}\left(1 + \alpha \frac{dT}{dt} t\right). \quad (1)$$

The resistance R_2 varies only because of the decrease in the thickness:

$$R_2 = \rho_0 l / a[d - b(t)]. \quad (2)$$

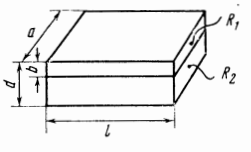

FIG. 2. Diagram of irradiated region.

The total resistance is

$$R(t) = R_1(t) R_2(t) / (R_1(t) + R_2(t)). \quad (3)$$

in (1) and (2), ρ_0 is the resistivity of the metal at room temperature and $\alpha = 10^{-2}$ deg^{-1} is the temperature coefficient of resistivity.

Substituting (1) and (2) in (3) we obtain after simple transformations

$$\frac{dT}{dt} = 1/\alpha t \left[\frac{R(t) b(t)}{R(t) d - \rho_0 k} - 1\right], \quad (4)$$

where $k = l/a$.

To determine the rate of heating from (4), it is necessary to know, besides the function R(t) (Fig. 1), also the character of time variation of the thickness of the heated layer b(t). In the first approximation it can be assumed that the thickness increases like $b \sim h\sqrt{t}$. The coefficient h can be estimated experimentally. The irradiated thin samples (d = 100 μ) are destroyed at the instant when the zone of the molten metal passes through the entire thickness. When measuring the electric resistance at the instant of destruction of the sample, a voltage pip is observed on the oscillogram. From the time elapsed before the destruction of the thin samples, we obtained $h \approx 50$ cm/sec.

The rate of heating can be estimated by means of formula (4) only up to values of t at which $b(t) < d$. In this case this corresponds to $t \sim 100$ μsec. The reduction of the experimental data by means of formula (4) shows that at $t < 100$ μsec the rate of heating is also of the order of 10^6 deg/sec.

It is seen from Fig. 1 that the change of the electric resistance and of the temperature of the samples with heating time goes through three stages which are connected both with the waveform of the pulse and with the properties of the metal:

1) first stage: t = 0—100 μsec, T_{eff} = 20—150°C,

2) second stage: t = 100—300 μsec, T_{eff} = 150—800°C,

3) third stage: t = 300—700 μsec, $T_{eff} > 800$°C.

The electric resistance increases with time like $R \sim t^{5/3}$ during the first stage, linearly in the second, and like $R \sim t^{2/3}$ in the third.

The effective heating rate of the irradiated zone is lower by several orders of magnitude than the surface-heating rate estimated for other metals by studying the electron emission. The rate of cooling turns out to be lower by one order than the rate of heating. This indicates that the heating and cooling of the interiors and of the surfaces of the samples are governed by different mechanisms. The decisive role is played by radiation when the surface is heated, but by the thermal conductivity of the metal when the entire zone is heated. The rate of cooling decreases sharply with time, so that the final recovery of the temperature after irradiation occurs only after several dozen seconds.

Measurements of the electric resistance of beryllium after irradiation was carried out at irradiated-sample temperatures 77 and 300°K. After irradiation at room temperature, an almost complete recovery of the resistance was observed 90 seconds after the irradiation. A different picture was observed in the measurement of the resistance of the samples irradiated at 77°K (Fig. 3). After the jump of the electric resistance at the instant

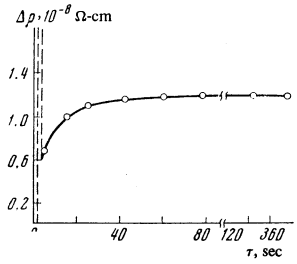

FIG. 3. Change of electric resistance of a sample after irradiation at 77°K.

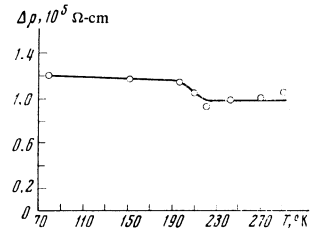

FIG. 4. Recovery of electric resistance of beryllium after isochronic heatings in the region 77–300°K.

of irradiation (which was not registered in the potentiometric measurements and is shown only arbitrarily in Fig. 3), an increase of the resistance is observed for 30–40 seconds immediately after the irradiation, after which the resistance remains practically unchanged. The absolute increase of the resistivity of the irradiated zone amounted in this case to 1.2×10^{-8} ohm-cm, which is 9% higher than the initial value.

The increase of the electric resistance following the quenching of metals from high temperatures is due to the increase of the density of the structure defects[6,7]. The change of the resistance of beryllium after quenching has not been investigated, and the interpretation of the results is therefore difficult. No increase of the resistance was observed when quenched metals were stored at a fixed temperature.

To study the recovery of the electric resistance, the samples irradiated at 77°K were subjected to isochronous (10 min) annealing at 77–300°K. The results are shown in Fig. 4, from which it follows that in the region below room temperature there is one recovery stage, in which ~20% of the resistance is restored. Further storage of the samples at 300°K for 17 hours is accompanied by recovery of ~45% of the electric resistance. The results of the study of the recovery give grounds for assuming that at least 50% of the decrease in the electric resistance of the irradiated samples is due to the formation of point defects. The remaining increment can be ascribed to the formation of microscopic cracks, to an increase of the dislocation density, and to a lesser degree to a change in the shape of the samples. For further analysis of this result, additional information is necessary concerning the behavior of point defects and dislocations in the annealing of the beryllium and their influence on the change of the electric resistance.

CONCLUSIONS

1. A study was made of the change of the electric resistance of beryllium as it was irradiated by laser pulses. The effective rate of heating of the irradiated part was ~10^6 deg/sec, and the rate of cooling was ~10^5 deg/sec. Heating proceeds in three stages governed by three different time dependences.

2. An increase of the electric resistance of beryllium with increasing time was observed after irradiation at 77°K.

3. A noticeable recovery of the electric resistance after the irradiation at 77°K occurs at temperatures near 200 and 300°K.

[1]S. I. Anisimov, A. Ya. Imas, G. S. Romanov, and Yu. V. Khodyko, Deĭstvie oblucheniya bol'shoĭ moshchnosti na metally (Effect of High-power Radiation on Metals), Nauka, 1970.

[2]I. I. Papirov, S. S. Avotiń, É. P. Krivchikova, and L. A. Kornienko, Fizika i khimiya obrabotki materialov (Physics and Chemistry of Working of Materials), 1971 (in press).

[3]I. I. Papirov, S. S. Avotin, and É. P. Krivchikova, ibid.

[4]J. F. Ready, Phys. Rev. 137, A620 (1965).

[5]V. M. Amonenko, A. A. Kruglykh, V. S. Pavlov, and G. F. Tikhinskiĭ, Zavod. Lab. **26**, 625 (1960).

[6]J. W. Kauffman and M. Meshii, translation in: Defekty v zakalennykh Metallakh (Defects in Quenched Metals), Atomizdat, 1969, p. 7.

[7]J. I. Takamura, translation in: Fizicheskoe melallovedenie (Physical Metallurgy), Vol. 3, Mir. 1968, p. 87.

[8]M. Meshii, T. Mori, and J. W. Kaufman, Phys. Rev. **125**, 1239 (1962).

Translated by J. G. Adashko
39