

FORMATION OF A LAYERED STRUCTURE OF A METAL STRENGTHENING ZONE UNDER IRRADIATION WITH THE PULSED HIGH-CURRENT ELECTRON BEAM

Yu.E. Kolyada
Priasovsky State Technical University
Mariupol, Ukraine

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Use of pulsed high-current beams of charged particles finds wide application for hardening the surface of metals and alloys [1, 2].

Modification of surface properties of metals and alloys by concentrated streams of energy, and electron beams, in particular, is stipulated by the following mechanism. As a result of their interaction with a processed material there is a flash heat (up to a melting temperature and higher) of the surface stratum with subsequent cooling at enough high velocity (10^6 - 10^7 K/c), that as a rule, results in essential changes of the structure and properties as compared to the initial state. As a result of a temper the martensite with fine-dispersed grains is formed from a liquid phase of the metal on a surface. The microhardness of the formed stratum in comparison with a starting material is incremented in several times. Thus its operational performances raise: a wear hardness, a corrosion stability etc.

In spite of the fact that the given technologies are widely put into practice, the physics of formation of the modified surface stratum of a material under activity of high-current electron beams is insufficiently investigated. Periodic character of the strengthened stratum deep into a sample (change of a microhardness and structure of a material) [1, 3, 4] in some cases is observed.

In the given paper results of experimental research on interaction of pulsed electron beams in a wide range of energies (from 50 to 500 keV) with iron-based alloys are presented. Requirements for layered structure formation in the strengthened metal band are studied.

As radiants of electron beams used were the following systems. The low-energy high-current beam was shaped in a direct discharge through gases at a low pressure with a cold cathode. Similar systems are described in [5]. Parameters of the beam produced are: current up to $5 \cdot 10^3$ A, energy 30-50 keV, pulse length ~ 2 μ s. The diameter of a beam does not exceed 2 cm. For deriving the high-energy beam the accelerator of a direct action with a cold cathode was used, its detailed schematic layout is given in [6]. Parameters of a used beam are: energy - up to 500 keV, current - up to 10 kA, pulse length 10-15 μ s, diameter of a beam - up to 10 cm. Samples of carbon steel in the annealed state and of alloyed steel in a tempered condition were exposed to irradiation. Dimensions of samples were 10×10×55 mm.

In Fig. 1 (1-3) the photos of the cross metallographic samples are submitted to alloyed steel, undergone single irradiation with a high-energy beam of the 300 keV energy. Photos are obtained at the coefficient of magnification 200. In photos 2 and 3 the layered structure fol-

lowing the surface white stratum is distinctly visible. It is necessary to note, that a spatial period of stratum about depth of a white stratum (~ 10 microns) is obtained as a result of melting and subsequent prompt cooling.

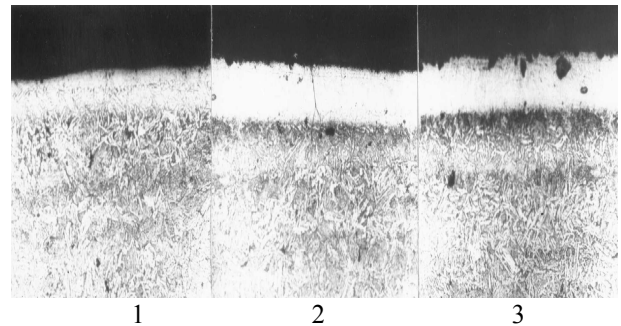


Fig. 1. Cross-sections of metallographic samples of alloyed steel, undergone to single irradiation with a high-energy beam of 300 keV energy.

Periodic character of the strengthened stratum is evidenced also with a microhardness testing deep into a sample, carried out by the Vickers method. The dependence mentioned is shown in Fig. 2.

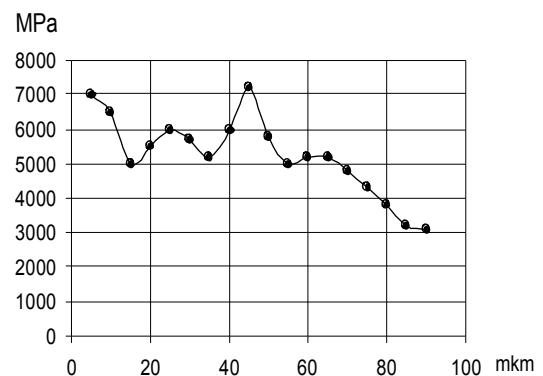


Fig. 2. Distribution of a microhardness of the strengthened stratum deep into a sample.

In a photo presented in Fig. 1 (1) a layered structure, practically, is not observed. The given mode of irradiation differs from previous - 2 and 3 thus in the given experience the requirement of an ablation is not fulfilled. When an ablation develops there is the intensive transpiration of a target that results in an additional impulse of pressure. This appearance takes place, if the energy flux

density exceeds the critical quantity q which is determined from relations [7]:

$$q\sqrt{\tau} = \frac{k}{2} \sqrt{\frac{\pi}{\chi}} T, \delta \ll (\chi\tau)^{1/2}, \quad (1)$$

$$q\sqrt{\tau} = \frac{k\delta}{\chi} T, \delta \gg (\chi\tau)^{1/2},$$

where χ and k are the coefficients of temperature and heat conductivity, respectively, $T \geq 0.1 \lambda/R$ - temperature relevant to a kickoff of intensive transpiration. λ - molar latent heat of vaporization, R - universal gas constant, δ - depth of losses of energy particles of a beam. For alloys of iron it is possible to accept $k = 60 \text{ W/m.K}$, T equals approximately to the temperature of sublimation. For estimation of depth of losses (cm) it is possible to use the known formula [8] down to the energy of a beam $3 \cdot 10^3 \text{ keV}$:

$$\rho \delta = 10^{-5} U^{3/2}. \quad (2)$$

Here ρ - density in g/cm^3 , U - accelerating voltage in kV . In requirements of experience the case is implemented, i.e. for parameters of a beam (energy $\sim 300 \text{ keV}$, a current $\sim 8 \text{ kA}$, a pulse length $\sim 10 \mu\text{s}$) it is necessary to use the inferior expression of relations (1). Quantity q appears equal to $\sim 1\text{-}2 \cdot 10^7 \text{ W/sm}^2$. The used beam can transfer a stream of a power from 10^7 up to $8 \cdot 10^8 \text{ W/cm}^2$. In the given accelerator to control a stream of power in so wide range of values appeared possible due to magnetic squeezing of the aperture of the beam secti. The mode implemented during irradiation of a sample, presented in the photo of Fig.1 (1), is obtained in case of the beam diameter above 10 cm . Thus, the stream of power on a metal surface was below 10^7 W/cm^2 .

The cause of a layered structure formation in case of Fig. 1 (2, 3), most likely, is shaping an intensive standing ultrasonic wave in thickness of a sample (thickness was 1 cm). Really, it is possible, by reaching the considerable pressures up to 10^9 Pa and higher [7] in case of ablation development, to observe beam interaction with a surface of metal in the surface white stratum (a white stratum in the photos presented). It is also confirmed in [9] and in a number of other papers. In the sample thickness under action of an intensive ultrasonic field of a standing wave there is a mechanical hardening of metal which is especially exhibited only in heat areas, since in a cold part of a sample the yield strength of the given alloy is higher than possible accessible quantities of pressure for the given beam parameters. The yield strength for a cold metal is $1.2\text{-}2.8 \cdot 10^9 \text{ Pa}$. As is known, the yield strength decreases with temperature increasing.

Frequency and length of a standing wave, obviously, determine thickness of the fused stratum. It is the resonator which is excited by a particle beam at a natural frequency

$$f_n = \frac{nc}{2l}, \quad (3),$$

where n - the number of harmonics, c - sound velocity, l - cross size of the resonator (thickness of the fused stratum). It is equal to requirements of experience of 10 microns. In this case the normal oscillations are raised in the resonator [10], and the same oscillations are raised also in the remaining sample thickness due to the ultrasonic connection. For a first harmonic the frequency can be equal to $\sim 2 \cdot 10^8 \text{ Hz}$ that is a hypersonic range.

An attempt was undertaken to register these oscillations. For this purpose the ultrasonic waveguide - an iron core of a diameter 0.5 cm and length 0.5 m which fulfilled a role of a line of an acoustic delay, was fastened to the end face of a sample. The lag line was necessary for a time outcome under the relation to time of beam-target interaction. During the impulse of beam-target interaction it is inconvenient to carry out the indicated measuring in connection with a high level of noises. The wave train of the registered ultrasonic oscillations is shown in Fig. 3. The reference frequency of high-frequency oscillations will be as much as 200 MHz . Oscillations are aperiodic. Aperiodicity may be stipulated, as signal attenuation in the used waveguide, and in the sample.

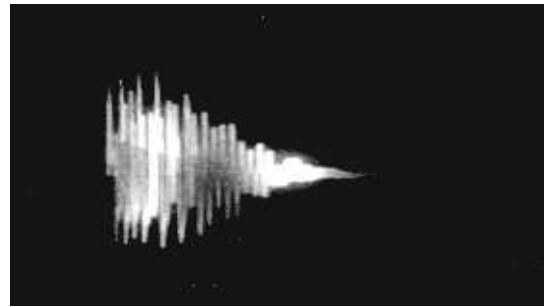


Fig. 3. Wave train of the registered ultrasonic oscillations

With the purpose of checking out the guess that the melting stratum is a ultrasonic system in which elastic oscillations are raised initially with the subsequent distribution to thickness of a sample original, experiments with a low-energy ($\sim 50 \text{ keV}$) beam were carried out. The results of the experiment with carbon steel are given by a number of photos in Fig. 4 (1,2). The photo 4 (1) was obtained at coefficient of magnification 200, and 4 (2) - 450.

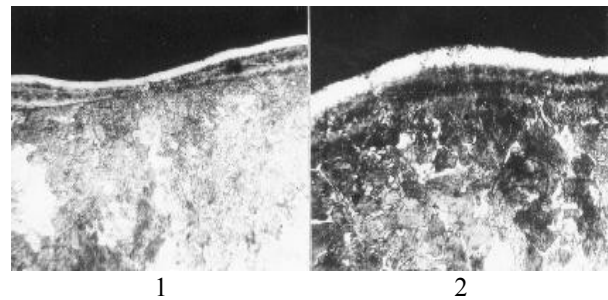


Fig. 4. Cross-sections of metallographic samples of carbon steel, undergone to single irradiation with a beam of 50 keV energy.

The thickness of a white stratum (the fused metal) is about a micron that coincides with a period of a layered structure which is distinctly visible in both photos. The periodic structure is observed only in a depth 5-7 microns. It is explained by that the depth of penetration of heat h during existence of elastic oscillations (this time is equal to a pulse duration of a beam $\tau \sim 2 \mu s$) is determined by the heat conductivity of a material

$$h \sim (\chi \tau)^{1/2}, \quad (4)$$

The depth of the strengthened stratum is about $40-60 \mu m$. Examinations showed the dependence of the microhardness of a sample on the depth (in the paper this dependence is not given).

Thus, the experiments performed allow to get the more complete notion about the mechanism of intense pulsed electron beam interaction with metals and alloys.

If the stream of power beam does not cause an appearance of an ablation, the surface thermal hardening of the metal takes place due to heating (up to a melting temperature and higher) and subsequent cooling at a rather high rate ($10^6-10^7 K/c$), resulting in essential change of the structure and properties as compared to the initial state. As a result of a temper the martensite with fine-dispersed grains is formed from a liquid phase of metal on a surface. The microhardness of the formed stratum in comparison with a starting material increases in several times. This is described in details, for example, in [1, 2].

If the energy flux density of a beam exceeds some critical value there is an appearance of an ablation that leads to the intensive transpiration of a target and to the additional impulse of pressure [7]. As the experiments performed showed, in the fused blanket the normal oscillations at one of the natural frequencies are raised. Due to the ultrasonic communication oscillations are spread deep into the sample in which the standing wave appears. Its length is determined by the depth of the fused blanket. Time of existence of oscillations, obviously, is determined by the beam pulse. Therefore as a result of joint action of a temperature field and a ultrasonic standing wave in the sample there is an appearance of a mechanical hardening. The depth joint action of these factors is determined by the depth penetration of heat during beam pulse. The appearance of a mechanical hardening under action of the excited ultrasonic wave takes place only in enough heated areas. Therefore in deep stratums it is not exhibited. After extinction of a beam action ultrasonic oscillations damp, distribution of a temperature field is prolonged on a greater depth, resulting in deep hardening of a metal sample that is more common for the accepted model. However formation of a layered structure thus does not happen.

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