LONG-RANGE EFFECT AND SELF-ORGANIZATION PROCESSES INDUCED BY LOW-ENERGY ION IRRADIATION IN SOLIDS

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The modification of materials subjected to the bombardment with low-energy ions was investigated. The increase of dislocation density in metal samples was observed up to a depth of 10 mm from the irradiated surface. It is described as a "long-range effect". The low-energy ion irradiation leads to the change of physical and mechanical properties of irradiated materials. This is, actually, a bulk modification. To explain this modification of materials the authors suggest a hypothesis based on the idea of nonlinear oscillation excitations in crystals, which leads to active self-organizing processes in the ion subsystem.

Introduction

A great number of papers are devoted to the investigation of materials modification by ion irradiation [1-4], the energy of ions varying in a wide range from 20 keV to MeV, as a rule. However, only recently it has been shown that the low-energy ion bombardment can lead to the most efficient modification of materials [5-9]. In particular, it has been shown in refs. [5,6] that the process of low-energy (0.5-3 keV) ion bombardment of metals and alloys samples leads actually to their bulk modification. So, the dislocation density of armco-iron exposed to a glow-discharge in plasma increases up to a depth of 10 mm from the irradiated surface. This phenomenon has been described as a "long-range effect" (LRE).

To interpret the LRE, the authors [8,9] assume that it is necessary to take into account the nonlinear effects in crystal lattices. The ion energy was smaller than the threshold energy, which was required for forming the Frenkel's pair. As a result of nonlinear collective oscillations, which are excited in ion subsystems of crystal lattices, new stable structural states were formed. The process of formation and development of ordered structures in nonlinear active medium could be interpreted as the process of self-organization. At present there is no alternative explanation of the LRE based on other assumptions.

The paper presented here is a part of our comprehensive project on materials modification by low-energy irradiation. The goal of this paper is to show the results of experimental studies of the LRE and investigate self-organizing processes that took place herein.

Experimental and Calculation Techniques

Polycrystalline samples of armco- iron, nickel, high-speed steel and metal-ceramics hard alloys consisting of 79% tungsten carbide and 15% titanium carbide TiC were chosen as investigation materials. All samples were placed in a specially constructed plasmagenerator and were exposed to gas discharge plasma under the voltage of 0.8-2.5 kV. The samples were irradiated by ions of residual gases of vacuum (nitrogen, oxygen, and hydrogen) in this process, the ion energy not exceeding 0,8-2,5 keV, accordingly. The time of sample treatment varied from 15 min to 90 min. The

343 K. The fine dislocation structure of armco-iron samples was studied layer by layer using the transmission electron microscopic method. The microhardness of the samples was measured at the irradiated surface and opposite sides of samples using a microhardness tester under different loads. The microhardness of samples was measured during two months after stopping irradiation.

The calculation experiment was made by a molecular dynamics method. We chose Morse potential as the potential of atomic interaction.

$$U(r)=J\cdot\{\exp[-2\alpha(r-r_0)]-2\exp[-\alpha(r-r_0)]\} \quad (1)$$

where J, α are the parameters of the dissociation energy of a couple of atoms and the degree of the potential unharmonicity, respectively; $\Delta r = (r-r_0)$ is the displacement from the equilibrium position. Decomposing the potential (1) into the Taylor row we obtain:

$$F=\frac{dU}{dr}=-2\alpha^2\Delta r+3\alpha^3\Delta r^2- \quad (2)$$
$$-2.3\alpha^4\Delta r^3+1.25\alpha^5\Delta r^4$$

$$K=2\alpha^2 J,\ A=3\alpha^3 J,\ B=2.3\alpha^4 J,\ D=2.7\alpha^5 J \quad (3),$$

where K, A, B, C, D are the coefficients of elasticity, quadratic and cubic nonlinearity and coefficients of nonlinearity of the fourth order, respectively. These coefficients have been calculated using the parameters of Morse potential [1] for armco-Fe. The influence of the surface is taken into consideration when boundary coefficients K', A', B', C', D' different from volume coefficients K, A, B, C, D are introduced.

A special model for calculation of atom displacement after a single ion impact in lattices of different dimensions, using the equations of classical dynamics enabling the description of the evolution of atom ensemble has been developed in [8]. In this paper we studied the atoms displacements after external disturbances by "ion rain – like" bombardment.

Results and discussion

Fig.1 shows the change in the average ... dislocation density in depth from the irradiation are obtained at plasmagenerator voltage of U=0.8 kV, curve 3 at voltage 2 kV. Curve 1 is given to compare a "long-range effect" observed by Yuri Sharkeev [10] for Fe irradiated by Hf ions with energy of 100 keV with the effect observed by us. Thus one can clearly see that a "long-range effect" may take place at a longer distance from the irradiated surface as the ion energy decreases.The dislocation density changes not monotonically, but it is much greater than that on non- irradiated samples

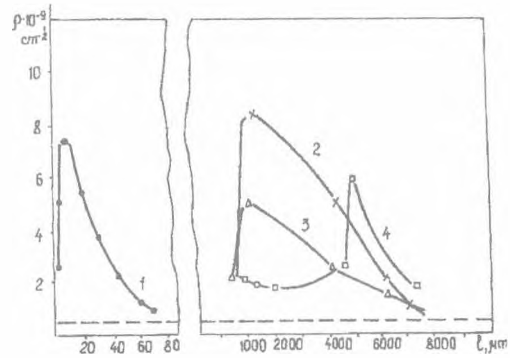

Fig.1. Dependence of the scalar dislocation density on the distance from the irradiated surface: 1 – α-Fe implanted by f ions with ion energy of 100 keV [10]; 2 – armco-Fe, ion energy - 0.8 keV, duration treatment - 90 min.; 3 – armco – Fe, ion energy - 2 keV, duration treatment - 90 min.; 4 – armco-Fe, ion energy- 0.8 keV, duration treatment – 60 min. The dashed line represents the initial state.

Fig.2 shows the dependence of microhardness in high-speed steel irradiated in gas discharge plasma on the time elapsed after stopping the external influence. The time axis is scaled in days. Curves 1 and 2 are for the irradiation of the samples by voltage 2.5 kV for front and back sides of irradiated samples, accordingly. The thickness of samples was 5 mm.

The following particulars should be noted:

1) The magnitude of microhardness for front and back sides of irradiated samples did not differ. This fact confirms the LRE too.
2) Large variations of microhardness with time elapsed after stopping the external influence. Therefore, we obtained a non-equilibrium state of samples after the low-energy ion irradiation.
3) The magnitude of microhardness for high-speed steel after the low-energy ion irradiation is much greater than that on non- irradiated samples

For further studies we have chosen the material having a high degree of heterogeneity. It is a metal-ceramic hard alloy produced by hot sintering of tungsten and titanium carbides (70% WC + + 15% TiC). The binding material is cobalt (6%). These alloys have a complicated character of chemical bonds, with covalent and ion bonds prevailing.

Fig.3 shows the dependence of microhardness in metal-ceramic hard alloys irradiated in gas discharge plasma on the time elapsed after stopping

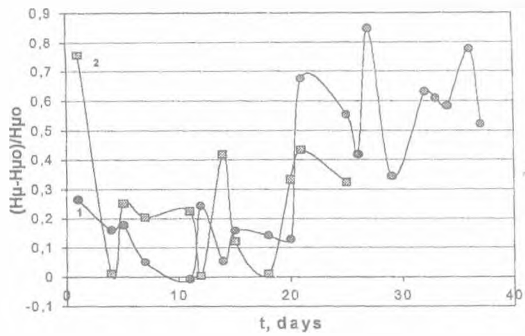

Fig.2. Dependence of the relative change of microhardness for high-speed steel on the time elapsed after stopping the external influence. Curve 1 and curve 2 are for front and back sides of irradiated samples, accordingly. Hμ is the magnitude of microhardness at a given time, $H\mu_0$ is the magnitude of microhardness for non-irradiated samples. The ion energy is 2.5 keV. The duration of treatment is 60 min

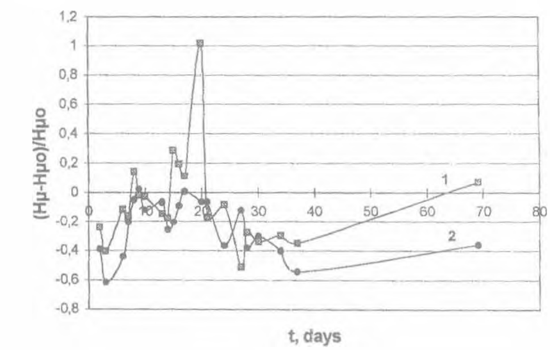

Fig.3. Dependence of the relative change of microhardness for metal-ceramic hard alloys on the time elapsed after stopping the external influence. Curve 1is for ion energy 1 keV, curve 2 is for ion energy 2,5 keV. The duration of treatment is 60 min. Hμ is the magnitude of microhardness at a given time, Hμ is the magnitude of microhardness for non-irradiated samples

The following particulars should be noted:

1) These results are obtained for samples with high initial magnitude of microhardness. Larger variations of microhardness with time have been observed as compared with high-speed steel.
2) The change in ions energy may lead to both strengthening and unstrengthening of the samples. Changing ions energy we can also have the increase in plasticity of brittle samples.
3) The additional investigation shows that the largest increase in microhardness relatively the initial level in non-irradiated samples is observed for samples with the least initial microhardness.

These results cannot be explained by using the traditional radiation condensed [illegible] projected ranges of hydrogen, [illegible] ions in armco-iron, high-speed steel and metal-ceramic alloys were calculated [illegible] code. These projected ranges [illegible] val of energy (1-5 keV) are very small and they do

The above mentioned results can be explained proceeding from general synergetic assumptions.

The process of formation and development of ordered structures in nonlinear active medium can be interpreted as the process of self-organization.

In a nonlinear medium forced out of stable equilibrium the collective effect of atom interaction leads to the formation of new structural states. The specific kind of these new heterogeneous structures depends on the properties of the potential characterizing the atomic oscillator bond between themselves and the magnitude of external influence.

We can see that localized running solitons are formed in crystal lattices as a result of the atoms nonlinear oscillations.

The most interesting is that in separate local areas of the lattice, long-lived (practically non-damped) oscillations of the atoms are formed. We can see that, the localized volume of the lattice is a "breathing" crystal or an "active zone, actually. In the end, the finite state of the atomic lattice irradiated by low-energy ions is a highly fragmented distorted structure

It is very important that the process of nonlinear oscillations covers the overall volume of the irradiated crystal. In fact, we observe a bulk modification of the irradiated samples.

When the energy of external influence is high enough, there occur strong oscillations of the first surface atoms, which leads to the breaking up of the atom bonds and to radiation defects, i.e. to vacancies and displaced atoms. Nonlinear oscillations are not excited in this case and, consequently, self-organization effects do not appear.

Conclusions

1. The glow discharge plasma influence (by low-energy ions) results in a sharp change of the dislocation density and in the type of dislocation structure in a rather large depth from the irradiated surface (up to 10 mm). This action is defined as a "long-range effect"

2. The low-energy ion irradiation leads to a change of physical and mechanical properties of irradiated materials. This is, actually, a bulk modification.

3. Low-energy ion influence on the crystal lattice leads to nonlinear oscillations of atomic oscillators, which result in the formation of the new stable structures of lattices.

4. Low-energy ion irradiation can be used for creating new technologies of strengthening materials and coating tools.

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