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Development of Cascade Processes in Metals

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Abstract

In this work we have performed a systematical investigation of energy dependence of the radiation defects distribution profile in three different materials – tantalum, molybdenum and stainless steel of type 10X18H10T-VD irradiated by high energy protons. It has been shown that in the stainless steel and tantalum, regardless of proton energy, the vacancy complexes similar by configuration appear which are described by the slightly expressed elastic channel. The defects recover in one annealing stage with different migration activation energy. At the same time the molybdenum radiation damageability consists of two components in each of which exists its own mechanism of defects formation. For high energy protons what's important is the inelastic channel of interaction and formation of sub cascades, which are created by primarily knocked-on atoms of considerable energies. However, for low energy protons, the processes of elastic interaction with lattice atoms and emergence of atomic hydrogen in the end of run important.

Keywords: positron annihilation, tantalum, molybdenum, proton irradiation, point defects, vacancy complexes.

1. Introduction

It is known that the effects of nuclear radiation on a matter is accompanied by a number of new phenomena. [1-4] To study the effects associated with changes in the crystal structure of the material in the reactor core, it is often sufficient to conduct simulations of charged particle accelerators. It is very important task of studying the defect distribution profile along the depth of the damaged layer. At one time, for this purpose on the basis of theoretical research has been developed program for computer calculation of the profile distribution of displaced atoms in depth passage of heavy ions in the material. [5] But any program, as it was neither an universal, yet can not take account all aspects of the complex process of the interaction of charged particles with the real crystal lattice, the more it can not be acceptable, when the research objects are multicomponent alloys.

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Charged particles, moving in the matter, lose their energy. The energy loss of the incoming particles can occur in various ways, including on the ionization and excitation of the electron shells, the polarization of the atoms medium, the radiation loss and nuclear stopping, whose role in the formation of structural defects may be different. Consequently, the distribution profile of the defects in depth may also vary, the location, which depends on the species and the parameters of the bombarding particles, target material, the irradiation temperature, etc. In this regard, the experimentally obtained parameters of defect structure can differ significantly from the theoretically calculated.

The average path, which traversed by a charged particle in matter to a full stop, named of his mileage – R. The last depends on the energy of the particle and the properties of the target material. Mileage particles is usually expressed through the length of the path - d and density - r of material:

$$R = d \cdot \rho [\mathrm{g}{*}\mathrm{cm}^{-2}]$$

To assess the interaction of particles with matter in the references given: particle energy - E in the laboratory coordinate system, expressed in MeV; mileage of particles R (E), expressed in g*cm^{-2}. Stopping powers S (E) in MeV $cm^{-2}g^{-1}$; derivatives stopping power in energy D (E),used as a correction factor. To calculate the mileage of a particle whose energy lies between tabular data, follow this formula:

$$R(E)\Delta E) = R(E) + \frac{\Delta E}{S(E)} - \frac{1}{2}\left|\frac{\Delta E}{S(E)}\right|^2 \cdot D(E),$$

where, E - the nearest table value of energy. Conversely, for the calculation of energy corresponding to mileage, the value of which lies between the values given in the table, you can use the formula:

$$E(R + \Delta R) = E(R) + S(E) \cdot \Delta R - \frac{1}{2}S^3(E) \cdot D(E) \cdot (\Delta R)^2$$

To determine the intermediate values of S (E), which absent in the table, used linear interpolation dependence:

$$S(E + \Delta E) = S(E) + D(E) \cdot \Delta E,$$

where S (E) - the closest value stopping power. Similarly, absent intermediate value from the table D (E + DE) can be found on a ratio:

$$D(E + \Delta E) = D(E) + \frac{\delta D}{\delta E} \cdot \Delta E,$$

In these conditions, the accuracy of calculating table data is $\sim$ 1%.

2. Experimental

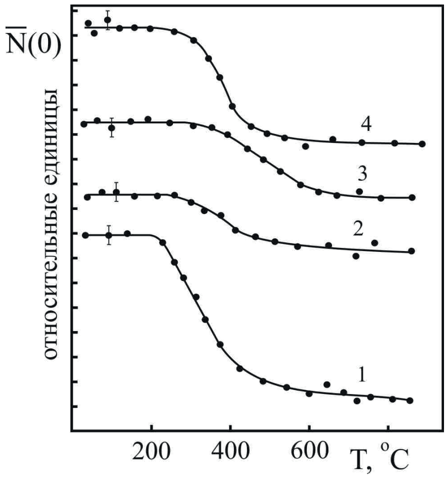
Since at least the passage of charged particles in matter, there is a consistent discharge of its energy, that to study of the profile distribution of defects in depth, in principle is the task of the study energy dependence of radiation damage metal. To solve this problem we can study defect structure of metal by consistently etching the surface or method, which based of alternating thickness absorber. Of course, the most appropriate is the second non-destructive method of investigation, the essence of which consists in irradiating a high energy charged particles and study stack of foils, the total thickness of which is the exceed length of free mileage of the particles in this material. In the result of using this method, each foil is irradiated particles of different energies and contains corresponding structural damage, which characteristics for the depth of the material. For the object of the study were used polycrystalline Mo and Ta, as well as stainless steel 10C18N10T-VD such as foil with the each thickness of 100 mkm and diameter is 17 mm. The initial state of metals was achieved by annealing at T = 1200 °C and steel at 1050 °C during 1.5 hours in a vacuum of 10^{-5} Pa. The thickness of each foil Δd specifies the path element $\Delta x_i = \Delta d_i \rho$, where there is a loss of energy of protons $\Delta E_i = s_i(E)\Delta x_i$; the average energy of the protons on the other side of each foil will be $E_{xi} = E_i$-ΔE_i. Hence, each foil is irradiated with protons of different energies by studying the degree of damage that can be installed its energy dependence. Irradiation was carried out the flow of protons of $1.2 \cdot 10^{13}$sm^{-2}s^{-1} to a fluence of $2 \cdot 10^{17}$ sm^{-2}. The study was conducted by the method of positron spectroscopy by measuring the spectrum of the angular correlation of annihilation radiation.

Irradiation with high-energy protons significantly change the shape of the spectrum of ADAP, narrowing it to the half-width and increasing the maximum intensity as a result of redistribution of the probabilities of positron annihilation with the conduction electrons and the ion core. These factors are reviewed in the annihilation parameter changes. When for annealed sample F = 0.15, as a result of irradiation it increases almost twice. The half-width of the spectrum FWHM for the initial state is equal to 6.1 mrad. Proton irradiation reduces it to an average till 5.6 mrad. However, despite the significant changes in the parameters, clear pattern between them and the energy of the protons in this case is not visible. However, certain trends in behavior of the annihilation parameters can still be set. For example, on average, the relative probability of positron annihilation F with increasing particle energy decreases monotonically. It can serve as a basis that the main contribution to the radiation damage began making low-energy protons that experience with the atoms of the alloy components of elastic collisions [8-10].

3. Results and discussion

Therefore, it is believed that encountered with the structural damage in the samples of steel practically has not difference between other as a configuration, and by the positron capture efficiency and represent one type of trap. Lastly it confirmed by the form of curves of isochronous annealing of the samples from the stack irradiated with protons of different energies.At proton energies E = 29.5 ÷ 13.2 MeV return of the basic properties of materials ends up in the temperature range 350-600 °C, and in $E \leq$ 6 MeV - in the field of 250 - 550°C, ie. there is the existence of a definite connection between the proton energy and temperature annealing of defects. Results of the study according to the changes of the annihilation parameters are summarized in Table 1.

Judging by the size of the migration activation energy of defects, as a result of irradiation of high - energy protons appear dislocation loops with E = 2.1 – 2.2 eV. In the case of low-energy protons, obviously, creates vacancy complexes in the form of small subcascades or related vacancy-impurity complexes with E = 1.7-1.8eV. The most probable is the formation of a bound state of a vacancy - atom of Cr, which is more difficult to break down other during annealing [9].



1. E_P = 4.6 MeV; 2. E_P = 31,2 MeV; 3. E_P = 23,1 MeV; 4. E_P = 29,5 MeV

Figure 1: The energy dependence of the kinetics of annealing steel 10H18N10T - VD irradiated by protons.

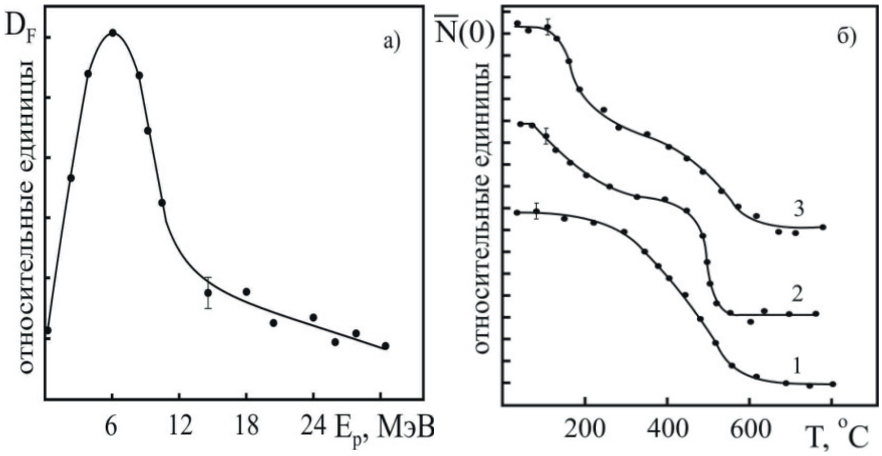
In contrast to stainless steel, tantalum polycrystalline irradiation under the same conditions results in characteristic changes to certain parameters annihilation. For this metal it is very difficult to distinguish the parabolic component of the spectrum due to the small percentage of free charge carriers. That is why, the basic equivalent (instead of F) parameter is the ratio of count rate at the maximum range of N (0) to its value at the angle θ = 8 mrad, those f = N (0) / N (8), which is dependent on the proton energy shown in Fig. 2a. Maximum despreading, respectively,a significant increase in

Table 1: Parameters of annihilation steel on passage depth ofprotons with E_{start} = 30 MeV ($\Phi = 2 \cdot 10^{17}$ cm^{-2}).

№	$E_{P,}$ MeV	X, mkm	$F = S_P/S_g$	$f = N(0)/N(8)$	FWHM, mrad.
anneal.	-	-	0.15	3.1	6.1
19	0	-	0.27	3.9	5.6
18	2.33	1750	0.24	3.9	5.6
17	6.4	1650	0.24	3.8	5.7
16	9.09	1550	0.28	3.4	6
15	11.29	1450	0.25	3.7	5.7
14	13.19	1350	0.31	3.6	5.8
13	14.91	1250	0.26	3.4	5.9
12	16.49	1150	0.23	3.2	5.9
11	17.97	1050	0.27	3.5	5.8
10	19.35	950	0.28	3.8	5.7
9	20.67	850	0.27	3.5	5.7
8	21.92	750	0.29	3.6	5.7
7	23.12	650	0.27	3.5	5.9
6	24.27	550	0.21	3.4	5.9
5	25.39	450	0.25	3.6	5.8
4	26.47	350	0.23	3.3	5.9
3	27.51	250	0.25	3.4	5.9
2	28.52	150	0.24	3.7	5.7
1	29.5	50	0.26	3.7	5.7
Errors ±	0.05	1.00	0.02	0.1	0.1

the parameter f = N (0) / N (8) is observed at low energies ~ 5 - 8 MeV and with increasing particle energy, these parameters have monotonically increasing or decreasing character. Such changes of parameters characterizing the shape of the spectrum, only possible if the corresponding change in the effective capture of positrons by defects, which created with protons.

It is seen that the sample has been irradiated with low-energy protons, is recovered in a single step in the temperature range 250 - 600 °C with an amplitude curve ~ 15% (curve 1), whereas the result of irradiation with high-energy protons is the occurrence of structural defects in Ta return with two stages (curves 2, 3). And with the energy of the particles decrease from 30 MeV to 25 MeV start migration of point defects is shifted towards lower temperatures while increasing the proportion of vacancy defects, thereby confirming a decisive contribution to the elastic interactions in the process of defect. So, when irradiated by protons with E = 30 MeV share vacancy stage is 41% of the total damage level, and with the energy reduction of up to 25 MeV, it increases to 47%. In this second stage recovery takes more than a relief appearance than 1-st case. The migration activation energy for vacancy component has a value E_1 = 1.41–1.45 eV, but for more complex dislocation structures, annealed during the second stage, it takes the value E_2 = 2.33–2.35 eV.



а) б)

1) E_p= 10 MeV; E_P = 25 MeV; 3. E_P = 30 MeV

Figure 2: The energy dependence of damage (a) and the kinetics of annealing (b) That, irradiated by protons.

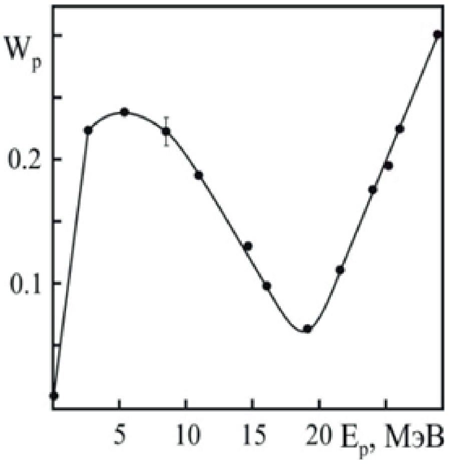


Figure 3: Energy dependence of damageability of Mo, irradiated by protons.

4. Conclusion

Thus, the study of the distribution profile of defects in the depth of the passage of charged particles in three different materials showed that in stainless steel and Ta, regardless of the proton energy, vacancy complexes that are close in configuration are formed, which are reduced in a single annealing step with an activation energy of Ea = 1.7 - 1.8 eV. The total damageability of steel in the entire range of proton energy is mainly determined by one weakly expressed elastic channel, whereas for molybdenum it is composed of two components, each of which has its own specific mechanism of defect formation. The main mechanism for the formation of radiation defects in Ta is clearly expressed elastic interactions. The role of nuclear reactions in the process of creating structural disturbances is weakly expressed here. The defects created by low energy protons are annealed in one stage, whereas high energy particles influence causes emergence of radiation defects.

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