The Influence of the Radiation Dose on the Change of the Mechanical Properties and Surface Composition of the Carbon Steel[1]

P.V. Bykov and V.Ya. Bayankin

Physical-Technical Institute of the UrB RAS, 132, Kirov str., Izhevsk, 426001, Russia
Tel.: +7(3412) 43-06-75, Fax: +7(3412) 72-25-29, E-mail: less@fti.udm.ru

Abstract – An effect of irradiation with N^+ and Ar^+ ions with energy of 40 keV by the radiation dose from 10^{15} to $5 \cdot 10^{16}$ ion/cm^2 and with Mn^+ ions with energy of 45 keV by the radiation dose from $2 \cdot 10^{16}$ to 10^{17} ion/cm^2 on the mechanical properties, the surface morphology, and the composition of surface layers of the carbon steel St.3sp has been studied. The nonmonotonic change of microhardness and fatigue strength in accordance with the type and the dose of irradiation, smoothing of the surface under the action of ion bombardment has been shown.

1. Introduction

One of the trends in modern mechanical engineering is the surface strengthening of moderately cheep steels and alloys for making parts of machines and mechanisms operating under severe conditions. This provides a saving in costly high doped steels and alloys and makes products cheaper. One of the currently evolving methods is the ion- beam and ion-plasma doping of the surface. By choosing purposefully a doping element and irradiation conditions one can provide a vide range of useful properties of surface layers of materials: rise in limits of strength and leakage, toughness, cracking resistance, resistance to corrosion and wear resistance, etc. [1, 2]. Methods of ion and ion-plasma treatment by high-current beams are widely used and studied [3]. But in a number of cases, the use of the intensive ion or ion-plasma treatment causes degradation of properties of the base material because of high temperatures at which this action is realized.

The ion implantation, while increasing the concentration of structural defects of the subsurface layer, promotes the increase of resistance to the movement of dislocations that is one of the mechanisms of an increase of fatigue strength [4]. On the other hand, irradiation of the surface with ions of chemically active elements may give rise to fine-disperse inclusions of new phases which provide higher mechanical properties at the cost of the disperse strengthening of the surface layer [5].

2. Experiment

St3al samples have been plates of length 60 mm and cross-section 8×2 mm which had been cut out from a rolled sheet. The element composition of the samples in their initial states is the follows: C – 0.2%, Mn – 0.4%, and Si – 0.15%, Fe – the rest. The samples are mechanically polished with polishing pastes and cleaned in organic solvents.

Irradiation with N^+ and Ar^+ ions has been performed in an ion-beam unit of the ILU-2 type in NIFTI of the Lobatchevsky State University, Nizhny Novgorod. Parameters of the ion irradiation are as follows: ion energy is 40 keV, ion density current is 10 μA/cm^2, irradiation dose are 10^{15}, 10^{16}, $5 \cdot 10^{16}$, and 10^{17} ion/cm^2. Irradiation with Mn^+ ions has been performed in an accelerated ion source “Diana-2” in PSMI of SB of RAS, Tomsk. Parameters of irradiation are as follows: ion energy is 45 keV, ion current density is ~ 7 μA/cm^2, irradiation dose are $2 \cdot 10^{16}$, $4 \cdot 10^{16}$, $6 \cdot 10^{16}$, $8 \cdot 10^{16}$, and 10^{17} ion/cm^2.

Microhardness of surface layers of samples pre- and post-irradiation has been measured by penetrating the diamond-tipped indenter under a load of 20 g in the unit PMT-3M. Testing for fatigue strength has been carried out according to the scheme of the alternating-sign console bending up to failure at frequency of 22.5 Hz with the coefficient of asymmetry of a cycle $r = -0.1$. Maximum stress across the sample section has varied from 270 to 440 MPa. The relief of the sample surface has been studied with the help of the scanning probe microscope Solver Pro. The chemical composition of surface layers has been studied by the method of the X-ray photoelectron spectroscopy (XPS) on the spectrometer ES-2401 with the use of the MgK_α-irradiation (1253.6 eV). The fractographic analysis has been performed on the raster electron microscopy Philips Quanta 200 in IPM of UrB of RAS, Ekaterinburg.

3. Results and discussion

Steel microhardness in its initial state comprises 520 MPa and increases by 25–150% in the result of irradiation with N, Ar, and Mn ions depending on the irradiation doze and the type of ions. In this case, the maximum increase of microhardness of samples is observed at different doses of irradiation:

– 880 MPa at the dose of irradiation with N ions of $5 \cdot 10^{16}$ ion/cm^2;

– 1220 MPa at the dose of irradiation with Ar ions 10^{15} ion/cm^2;

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– 890 MPa at the dose of irradiation with Mn ions $4 \cdot 10^{16}$ ion/cm^2. It would appear reasonable that the increase of microhardness is connected with the development of radiation defects, especially intensive on irradiation with heavy ions Ar^+, and as a result with the fixation of dislocations. Besides, on irradiation with N^+ and Mn^+ ions strengthening is possible at the cost of the formation of the compound of a new phase.

Fatigue testing has revealed the increase of durability of samples irradiated with Mn, N ions by the dose of 10^{16} and $5 \cdot 10^{16}$ ion/cm^2, and Ar ions by the dose of 10^{15} ion/cm^2. Durability of the rest samples irradiated with Ar ions by the dose of 10^{16} and $5 \cdot 10^{16}$ ion/cm^2 corresponds to durability of initial samples (Fig. 1).

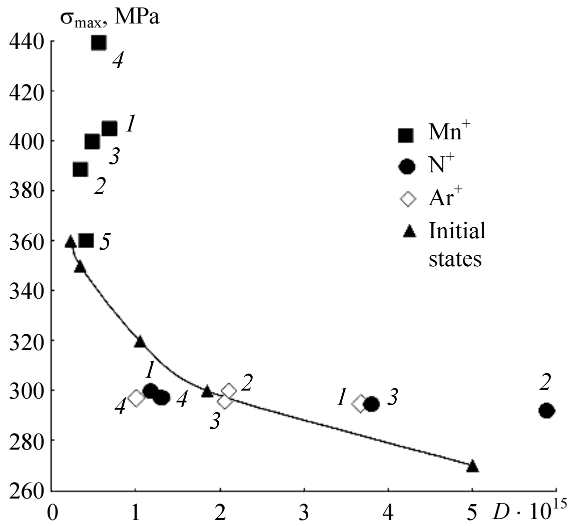

Fig. 1. Results of fatigue testing of samples irradiated with ions of Ar, N (*1* – 10^{15}; *2* – 10^{16}; *3* – $5 \cdot 10^{16}$; *4* – 10^{17} ion/cm^2), and Mn (*1* – $2 \cdot 10^{16}$; *2* – $4 \cdot 10^{16}$; *3* – $6 \cdot 10^{16}$; *4* – $8 \cdot 10^{16}$; *5* – 10^{17} ion/cm^2)

It should be noted that failure of samples irradiated with N ions by the dose of 10^{15} and 10^{17} ion/sm^2 and Ar ions by the dose of 10^{17} ion/sm^2 occurs even more rapidly than that of initial nonirradiated samples.

Analysis of images obtained by the method of the atomic force microscopy suggests that ion implantation results in the change of morphology of sample surfaces. Microdefects on grain surfaces heal, that evidently decreases the probability of nucleating a fatigue crack from the surface [6]. Besides, the parameter of roughness, R_a, decreases considerably with an increase in the dose of irradiation with both N ions and Ar ions (Fig. 2).

Irradiation with Mn ions to an integral dose $4 \cdot 10^{16}$ ion/sm^2 causes the drastic decrease of the parameter of roughness, R_a. As the dose increases, so does the parameter of roughness, R_a, but still remains lower than its initial value.

XPS investigations of samples of the St.3al steel irradiated with N ions have shown that the profile of the N distribution in surface layers has the domal form with the maximum of concentration at a depth of 1–2 nm. The calculation of the penetration depth of N ions into iron, which has been performed by the method described in [7], has shown that the maximum of *N* concentration is bound to be at a depth of about 37 nm. Thus, the profile of N concentration is much shifted to the surface. It presumably occurs on account of a gradient of mechanical stresses arising in the surface layer during the rolling [8].

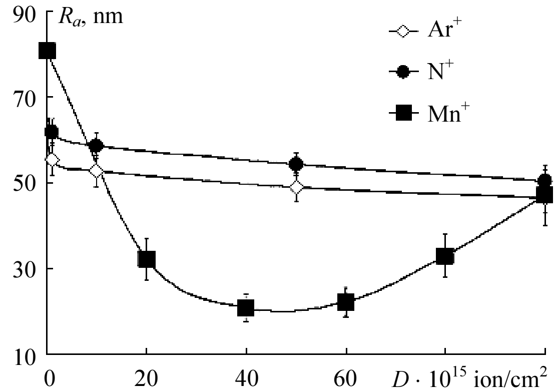

Fig. 2. The change of the parameter of roughness R_a in terms of the dose of irradiation with Mn, N, and Ar ions

XPS investigations of samples of the St.3al steel irradiated with Mn ions have shown that the content of the penetrated impurity is reduced in surface layers with increasing the irradiation dose. Moreover, the correlation between the content of Mn in the layer of 50 nm and the change the microhardness of samples in terms of the irradiation dose that can bear witness to the influence of the dose of implanted Mn on the structure of the changed layer with regard to a "long-range effect" [9] has engaged our attention.

Fractographic studies of sample fracture surfaces have shown the following:

– a line crack of starting samples is initiated from the surface with a great quantity of macrodefects which are concentrator of stresses;

– the subsurface crack initiation is characteristic for samples irradiated with N ions, nucleation sites are located at a depth of about 5–20 μm from the surface. In the surface irradiated with N ions by the dose of 10^{15} ion/sm^2 the crack initiates from the surface;

– the crack in samples irradiated with Ar ions by the dose of 10^{15} and 10^{16} ion/sm^2 initiates beneath the surface also, but at the depth of about 5–10μm, and the crack in the samples irradiated with Ar ions by the dose of $5 \cdot 10^{16}$ and 10^{17} ion/sm^2 initiates from the surface.

4. Conclusions

1. Ion implantation causes the microhardness to increase by 25–150% in terms of the irradiation dose and the type of ions. Microhardness peaks on irradiation with Ar ions by the dose of 10^{15} ion/sm^2, N ions by the dose of $5 \cdot 10^{16}$ ion/sm^2, and Mn ions by the dose of $4 \cdot 10^{16}$ ion/sm^2.

2. The change of the fatigue strength of the St3al carbon steel samples in terms of the irradiation dose

with N^+, Ar^+, and Mn^+ has been revealed. The fatigue strength is maximized on irradiation with N ions by a dose of 10^{16} and $5 \cdot 10^{16}$ ion/sm^2, and with Ar ions by a dose of 10^{15} ion/sm^2.

An increase of the fatigue strength of the studied steel can be connected with the change of the composition and the structure of surface layers of samples and the smoothing of the surface during the ion implantation that is responsible for the process of the change of the mechanism of the crack initiation and the crack propagation.

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