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THE IMPURITY DISTRIBUTION IN IRON AND STEEL UNDER THE ACTION OF COMPRESSION PLASMA FLOW

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Introduction

The treatment of different materials with high-energy nitrogen-based compression plasma flows opens up new opportunities for modification of their surface characteristics aimed at obtaining layers unique in the structure, phase composition, and mechanical properties. Such a treatment is performed using compression plasma flows generated by quasi-stationary plasma accelerators such as a magnetoplasma compressor (MPC).

Previous investigation has shown that exposure of iron samples to compression plasma flows resulted in the formation of deep (up to 60 micrometers) modified layers /1-2/. However, precise identification of impurity concentration has not been performed.

Experimental

Iron (Armco-Fe) and carbon steel (0.8 wt. % C) samples were processed by varied-power compression plasma flows in the Institute of molecular and atomic physics, NAS of Belarus, using gas-discharge MPC of compact geometry /3/. The MPC employing hydrogen and nitrogen as plasma-forming gases, operates in a mode such that a pre-evacuated vacuum chamber is filled with working gas up to a predetermined pressure falling within the range of 400-7000 Pa. According to calorimetric measurements, the value of power density absorbed by a sample surface, depending on the distance from the tip of MPC discharge device, is 5-25 J/cm^2 per pulse.

The study of elemental composition by Auger spectroscopy (AES) has been carried out using Perkin Elmer PHI-660 Auger spectrometer. The setup was equipped with an ion gun both for surface cleaning and for analysing of impurity concentration profiles against depth. Energy of argon ions used for cleaning was 3.5 keV, ion current density — 50 μA/cm^2, incidence angle of ion beam — 60 to 70º. Secondary-Ion Mass Spectrometry investigation has been carried out with Atomica Instruments Ion Microprobe 4100 using a beam of caesium ions. During the implantation, the beam current was kept below 1.5 nA. The nitrogen profiles have been obtained by Rutherford Backscattering Spectrometry (RBS) with a 6 MeV He^{++} beam at a backscattering angle of 170º. The data analysis was performed with the RUMP code /4/.

Results and discussion

When exposing the iron sample to compression plasma flows, a material being processed is saturated by an alloying element (nitrogen) in ε-area that is determined by values of plasma temperature close to the sample surface ($5 \cdot 10^4$ K) and compression flow pressure (10^6 Pa) exerted on a molten layer.

According to AES and RBS data, the iron sample near-surface layers processed in a standard mode (discharge duration — 120 µc; plasma velocity in a compression flow — $6 \cdot 10^6$ cm/s; concentration of the charged particles in a zone of the peak compression — $7 \cdot 10^{17}$ cm^{-3}; plasma temperature — 1-3 eV; energy density absorbed by the sample ~ 15 J/cm^2), contain up to 20 at.% of nitrogen that corresponds to eutectoid composition. With a change in energy of action the nitrogen surface density varies within the limits of ±5 at.% (Fig. 1). More significant nitrogen implantation is observed, when nitrogen initial pressure in MPC standard operating mode is increased up to 7000 Pa. In this case, according to RBS data, nitrogen surface density attains 30 at.%.

Apart from the changes in elemental composition caused by plasma-forming substance implantation into a material, near-surface layers undergo a redistribution of impurities present in the sample before plasma processing. As was shown by RBS-studies of elemental composition of the samples processed by a plasma flow with hydrogen as a plasma-forming substance, redistributed in superficial area 10 µm thick is carbon contained in the initial sample, the carbon concentration decreasing by 3 and 1.5 times in layers up to 0.1 µm and 5 µm thick, respectively. The concentration decrease observed can be explained by dislodging of carbon by high-energy ions of hydrogen present in the compression flow. Such an assumption is confirmed by results of studies of a sample surface using Secondary-Ion Mass Spectrometry, which show a presence of hydrogen in a near-surface area.

Comparison of AES- and RBS-data makes possible a suggestion, that the total penetration depth of nitrogen is more than 7 µm (Fig. 1).

Upon subjecting a surface of carbon steel (0.8 wt. % C) samples to a compression flow whose plasma-forming substance is nitrogen, their near-surface layers contain up to 20 at. % of nitrogen, like those in iron samples. Increasing the energy density in a standard mode obtained by the sample per pulse up to 25 J/cm^2 results in a decrease in surface density of nitrogen by 5 at. %, however the nitrogen total content in a near-surface zone increases essentially (Fig. 2). In particular, at a depth of 5 µm, nitrogen density was ~ 2 at. % at energy density of 15 J/cm^2 and ~ 4 at.% at 25 J/cm^2.

Such regularity can be explained by the replacement of carbon with nitrogen in solid solutions of the first zone of the sample modified layer. As the size of nitrogen atom is less than that of carbon, and concentration of nitrogen at a surface (as well as the initial content of carbon in steel) corresponds to eutectoid

value in the course of crystallization from the melt, the diffusion of nitrogen will proceed more intensely as compared to carbon.
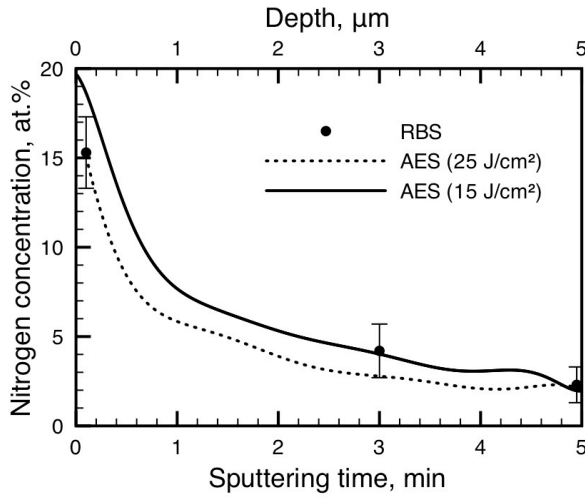

Fig. 1. Concentration profile of nitrogen in the sample of iron processed by compression plasma flow.
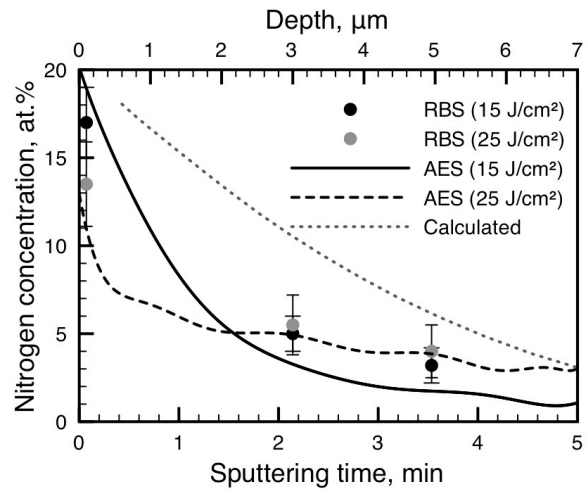
Fig. 2. Concentration profile of nitrogen in the sample of steel (0.8 wt.% C) processed by compression plasma flow.

The process of nitrogen propagation deep into the sample will be analyzed as follows. Let us write down the equation of impurity mass transfer in the melt under condition that the diffusion coefficient D does not depend on the impurity concentration C (Fick's second law):

$$\frac{\partial C}{\partial t} = D\nabla^2 C. \tag{1}$$

The solution of this equation for an impurity constant source is the expression:

$$C(x,t) = C_0[1 - \frac{2}{\sqrt{\pi}}\int_0^{x/2\sqrt{Dt}}\exp(-z^2)dz] = C_0\,\mathrm{efrc}\,\frac{x}{2\sqrt{Dt}}, \tag{2}$$

which is valid when the boundary conditions:

$C(0, t) = 0$; $C(x, 0) = 0$ at $x > 0$; $C(x, t) = C$ with at $x > 0$ and $t > 0$ (3)
are satisfied.

The diffusion coefficient of nitrogen in iron in Eq. (2) depending on the temperature T is defined by the expression /5/:

$$D_N = 6.6\cdot10^{-7}\cdot\exp(-18600/RT)\ \mathrm{m^2/s}, \tag{4}$$

where R is the molar gas constant.

The analysis of process of the compression flow action on a target shows that the boundary conditions (3) are satisfied throughout the life time of surface plasma which is an impurity source, i.e. at $0 < t < 100$ µs. Thus, the nitrogen diffusion depth profile in the sample over the processing duration calculated by means of Eq. (2) (see Fig. 2, "Calculated" curve), is obtained in the following approximation: the temperature of a surface layer 20 µm thick is constant and amounts to 10^3 K /6/, and the corresponding diffusion coefficient D of nitrogen equals $7 \cdot 10^{-8}$ m^2/s.

Reasonable consistency of experimental results and calculation data makes it possible to conclude that nitrogen distribution in a surface layer of the processed samples is governed mainly by the diffusion process.

Thus, as shown by AES and RBS methods, the saturation of a processed material by an alloying element (nitrogen) occurs in ε-area, the analysis of the final surface evidencing that the impurity concentration at the crystal-melt interface is determined mainly by the solubility of both nitrogen and carbon in liquid iron and remains constant for various combinations of processing modes and target materials. The subsequent distribution of nitrogen in a surface layer of processed samples is governed mainly by the diffusion process.

Acknowledgements

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