Experimental measurement methods and data on irradiation of functional design materials by helium ions in linear accelerator

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The experimental research on the irradiation of the functional design materials by the *Helium* ions in the linear accelerator is conducted. The experimental measurements techniques and data on the irradiation of the functional design materials by the *Helium* ions with the energy up to 4 MeV, including the detailed scheme of experimental measurements setup, are presented. The new design of accelerating structure of the *HI*-type such as *POS-4*, using the method of alternate-phase focusing with the step-by-step change of the synchronous phase along the focusing periods in a linear accelerator, is developed with the aim to irradiate the functional design materials by the *Helium* ions. The new design of the injector of the charged *Helium* ions with the energy of 120 KeV at the output of an accelerating tube and the accelerating structure of the type of *POS-4* for the one time charged *Helium* ions acceleration in the linear accelerator are researched and developed. The special chamber for the irradiation of functional design materials by the *Helium* ions is also created. In the process of experiment, the temperature of a sample, the magnitude of current of *Helium* ions beam and the irradiation dose of sample are measured precisely. The experimental measurement setup and techniques are fully tested and optimized in the course of the research on the electro-physical properties of irradiated samples and the thermal-desorption of *Helium* ions in a wide range of temperatures.

PACS numbers: 61.82.Bg, 61.80.Jh, 81.05.Bx, 81.40.-z, 81.40.Wx, 29.17.+w, 29.20.Ej, 29.25.-t, 29.25.Ni, 29.27.Ac, 29.30.-h, 29.85.+c, 29.85.Ca, 29.90.+r, 39.10.+j, 39.30.+w, 44.90.+c, 51.10.+y, 61.18.Bn, 61.43.Bn, 61.46.Bc, 61.72.Hh, 61.72.Ji, 61.72.Mm, 61.72.S+, 61.72.Ss, 61.72.jd, 61.85.+p, 61.90.+d, 63.20.Kr, 63.90.+t, 68.35.bd, 68.43.Vx, 72.15.-v, 72.80.-r, 73.61.At, 79.20.Rf, 84.37.+q.

Keywords: functional design materials for nuclear reactors, electro-physical properties of functional design materials, *Helium* ions irradiation and implantation, thermo-desorption of Helium from functional design materials, thermo-desorption method, electron–phonon interaction, computer modeling, linear accelerator, method of alternating phase focusing with step-by-step change of synchronous phase along focusing periods in accelerating structure, nuclear reactions, fast neutrons nuclear reactor, thermonuclear reactor, nuclear power plant.

Introduction

At the present time, the generated energy at the nuclear power plants (NPP) constitutes more than 50 % from the total energy, developed at the various power generation facilities in the State of Ukraine. However, in the nearest future, a considerable number of nuclear reactors at the NPPs in Ukraine is planned to be taken out of service, because of their operation time resource limitation. There is a similar tendency, as far as the old type nuclear reactors at the NPP is concerned, in many other countries. In this connection, the development of a new generation of nuclear reactors, including the fast neutrons nuclear reactor (FNNR) and the thermonuclear reactor (TNR), is considered. It is a well known fact that there would be a presence of the physical-chemical process of accumulation of considerable amount of *Helium*, which could be created as a result of the different nuclear reactions in the case of the FNNR; and also, it could be directly injected from the plasma in the case of the TNR. It is assumed that the *Helium* accumulation process will take place in the functional design materials of active zone in the FNNR, and especially, in the first wall in the TNR, along with a high degree of the radiation damages of functional design materials structures.

The *Helium* makes a strong influence on the radiation damageability of functional design materials, and it can frequently be a main reason of the considerable deterioration of physical properties of functional design materials, resulting in the service life reduction of designed elements in the nuclear reactors. In this connection, the scientists focus a serious attention to the research problem on the physical behaviour of *Helium* in relation to the various functional design materials at action by the different external conditions. A number of physical features on the *Helium*’s influence in relation to the radiation damages of functional design materials, including the high- and low-temperatures radiation hardening and fragility, the radiation accelerated creep, the erosion of surfaces, in the first wall in the TNR and some other characteristics were researched [1 - 5]. Except the comprehensive knowledge on the influence by the different gases on the radiation damageability of functional design materials, the detailed experimental research data on the physical...
behaviour of different gases, depending on the various internal and external factors, are needed to be considered with the purpose to forecast the radiation damageability of functional design materials in the specified conditions of accumulation of considerable concentration of the gases. The following factors have to be taken to the consideration: the Helium penetration depth, the Helium spatial concentration in the distribution dependencies, the contents of impurities, defects and alloying elements in the metals and alloys with the various crystal grating systems, the processing of functional design materials after the irradiation process. At the present time, there is a considerable lack of obtained experimental research data on the accurate characterization of the physical behaviour of Helium in the functional design materials, depending on the above physical conditions.

At the research on the physical behaviour of Helium in the functional design materials, the special research attention is focused on the Helium influence on the mechanical properties of the functional design materials. It is a well-known fact that a presence of a few tens of ppm of Helium in the austenite steel results in the considerable fragility, which is accompanied by the change in the character of austenite steel destruction: from the trans-crystal cracking to the between-crystals cracking. In the case of the mechanical testing of samples with the known concentration of Helium, the special irradiating devices are needed. These irradiation devices can inject the Helium on the penetration depths from the tens of micrometers to the hundreds of micrometers into the sample; and they must have a dimension of the irradiation beam, without the scanning, up to several centimeters.

The main purpose of given research work is to conduct an experimental investigation on the irradiation of the newly synthesized functional design materials by the Helium ions in the linear accelerator with the energies from 0.12 MeV to 4 MeV, and the testing of this experimental technique at the research on both the Helium thermal desorption and the electrophysical properties of irradiated samples.

2. Experimental research techniques

The linear accelerator of the Helium ions with the energy of 4 MeV was designed at the National Scientific Centre Kharkov Institute of Physics and Technology to make the advanced research on the Helium ions implantation into the samples [6]. The further increase of linear accelerator’s energy up to the magnitude of 34 MeV is planned [6].

2.1. Discussion on Helium ions accelerating structure of type of POS-4 and Helium ions injector

The accelerating section of POS-4 is intended for the He\(^{+}\) ions acceleration up to the energy of 4 MeV (the initial energy is 30 KeV/nucleon), moreover, it can be used for the acceleration of protons. In the accelerating IH-type structure of POS-4, the method of alternating phase focusing with the step-by-step change of the synchronous phase along the focusing periods is used to focus the Helium ions beam [7]. The efficiency of this method depends on the configuration of the focusing period. The choice of synchronous phases has provided an opportunity to capture the ions beam of high intensity in the phase angle of 120°; and also, to reach the radial and phase stabilities of the ions clots along the accelerating structure. The accelerating field had an increasing magnitude at the initial part of accelerating structure, aiming to provide the maximal capture of accelerated particles (120°) in a mode of the stable radial and longitudinal movements. The scheme of accelerating structure of the type of POS-4 and the amplitude of high frequency field, depending on the number of accelerating cells are shown in Fig. 1.

![Fig. 1. Scheme of accelerating structure of type of POS-4 (a) and the amplitude of high frequency field, depending on the number of accelerating cells (b).](image)

In the result of both the computing modeling and the experimental measurements, which were completed in the processes of testing and tuning of the accelerating structure of the type of POS-4, the data on the distribution of electric field in the accelerating structure at the operation frequency of 47.2 MHz is obtained. The main parameters of the accelerating structure of the type of POS-4 are presented in Tab. 1.

The injector of the charged Helium ions with the energy of 120 KeV for the injection of Helium ions beam into the accelerating structure of the type of POS-4 is developed with the purpose to irradiate the functional design materials by the Helium ions. The injector consists a source of the Helium ions, the beam focusing system, and also, the accelerating tube. The double-plasmatron source with the oscillating electrons in the anode region was used to generate the Helium ions beam of specified parameters [8].

2
Operating frequency, MHz | 47,2
---|---
Input impulse current, mA | 30
Output impulse current, mA | 1...0,3
Output normalized rms emittance in plane X, cm-mrad | 0,0584
Output normalized rms emittance in plane Y, cm-mrad | 0,0568
Output normalized 99% emittance in plane X, cm-mrad | 0,7809
Output normalized 99% emittance in plane Y, cm-mrad | 0,7723

**Tab. 1.** Main technical parameters of accelerating structure of type of POS-4.

Such choice has been made, because the Helium, which has an abnormal Pashen curve, is the working gas. In the source, the arc discharge is created to obtain the plasma, which penetrates from the anode region to the slot-hole between the plasma part of a source and the extracting electrode, where the double layer, which is a source of the Helium ions, is formed at the application of extracting potential.

The injector allows to generate the beam of one time charged Helium ions with the current magnitudes of a few tens of milliampere. The main parameters of injector are presented in Tab. 2.

| Working gas | Helium |
|-------------|--------|
| Current of arc discharge, A | 2...4 |
| Current of beam at output, mA | up to 20 |
| Energy of particles at output, KeV | 120 |
| Diameter of beam at output, mm | ~ 8 |
| Pressure of working gas in anode region of source, mm of mercury column | 5·10⁻³ |
| Transmission frequency, Hz | 2...10 |
| Duration of impulse of discharge arc modulator, usec | 500 |
| Magnetic field magnitude in source, Oe | 300...700 |

**Tab. 2.** Main technical parameters of injector.

In Fig. 2, the oscillogram of dependence of the accelerated Helium ions beam current on the time is presented. The arch discharge current is equal to 4 A, the injection current is 1,2 mA, the current of the accelerated Helium ions beam is ~ 300 µA. It can be seen that the accelerated Helium ions beam current has a quasi-squared shape, the deviation of the peak magnitude of current is not more than 5 %.

**Fig. 2.** Oscillogram of Helium ions beam current at output of accelerating structure of type of POS-4 with energy of 4 MeV.

2.2. Discussion on target section in linear accelerator and experimental conditions of samples irradiation

The special chamber within the target section has been developed to irradiate the samples of functional design materials by the Helium ions. The scheme of target section is shown in Fig. 3. The temperature of a sample in the irradiation process was measured by the Chromel – Alumel thermocouple attached to the sample from an opposite side in relation to the incoming Helium ions beam (see Fig. 3). The signal from the thermocouple was amplified by the differential amplifier. The calibration of thermocouple was made by taking into an account the length of measuring wires (~ 30 m).

**Fig. 3.** Scheme of target section: 1 – sample; 2 – heater; 3 – current inputs; 4 – flange.

The special chamber within the target section has been developed to irradiate the samples of functional design materials by the Helium ions. The scheme of target section is shown in Fig. 3. The temperature of a sample in the irradiation process was measured by the Chromel – Alumel thermocouple attached to the sample from an opposite side in relation to the incoming Helium ions beam (see Fig. 3). The signal from the thermocouple was amplified by the differential amplifier. The calibration of thermocouple was made by taking into an account the length of measuring wires (~ 30 m).

The measurements of the magnitudes of currents of the Helium ion beams at the input and output ports of a linear accelerator were made by the induction sensors. During the experimental research, the currents of both the injected Helium ions beam with the energy of 120 KeV and the accelerated Helium ions beam with the energy of 4 MeV were measured. The current of the Helium ions beam was measured by the induction sensors, mounted in front of the sample on the distance of ~ 30 cm. Before the each next irradiation process, the calibration of induction sensors was made, using the Faraday cylinder. The average diameter of Helium ions beam, falling on the sample, was ~ 36 ... 37 mm; and the area of the irradiated sample was around 10 cm². The number of samples, which were irradiated by the Helium ions in the linear accelerator was 10. The irradiated functional design materials and the parameters of irradiation are presented in Tab. 3.
| Number of sample | Sample      | Thickness of sample, µm | Energy of He⁺ ions, MeV | Mean temperature of irradiation, °C | Complete irradiation dose, part./cm² |
|-----------------|-------------|-------------------------|-------------------------|-------------------------------------|-------------------------------------|
| 1               | X18H10T     | 200                     | 4                       | 72                                  | 7.5·10¹⁵                            |
| 2               | Steel-3     | 100                     | 4                       | 78                                  | 1.5·10¹⁶                            |
| 3               | Zr+2.5%Nb   | 250                     | 4                       | 70                                  | 2.3·10¹⁶                            |
| 4               | Zr          | 300                     | 4                       | 58                                  | 5·10¹⁶                             |
| 5               | Zr+1%Nb     | 250                     | 2.42                    | 40-80                               | 5·10¹⁶                             |
| 6               | Zr+1%Nb     | 250                     | (4+0.12)                | 40-80                               | 5·10¹⁶+5·10¹⁶                      |
| 7               | Zr+1%Nb     | 250                     | 0.12                    | 40-80                               | 5·10¹⁶                             |
| 8               | Zr+1%Nb     | 250                     | 0.12                    | 40-80                               | 5·10¹⁶                             |
| 9               | Nb          | 16                      | 4                       | 40-80                               | 5·10¹⁶                             |
| 10              | Nb+1%Zr     | 22                      | 4                       | 40                                  | 5·10¹⁶                             |

Tab. 3. Irradiated materials and parameters of irradiation.

2.3. Discussion on measurement techniques

During the irradiation process, the measurements of the sample’s temperature at the irradiation, the current of Helium ions beam, the irradiation dose were conducted. The analogue-digital converter of the model of ZET 210 «Sigma USB», connected to the computer, was used. The software program was written with the purpose to automate the precise measurements and to save the experimental data. The measurement setup scheme for the measurements of the sample’s temperature at irradiation, the current of Helium ions beam, the irradiation dose are shown in Fig. 4.

The sample’s temperature is measured with the help of the Chromel – Alumel thermocouples with the frequency of 1 Hz, allowing to detect it’s change at the irradiation precisely. The thermocouple is connected to the input of the analogue to digital converter (ADC), which transfers the digitized data on the thermal electromotive force to the constant voltage voltmeter. After the voltmeter, the measured data is shown on the display in the form of the graph with the help of the XYZ-plotter, and also, on the digital indicator (the data at the present time moment), and is saved as a file in the hard disk of computer for the subsequent analysis.

The measurement of Helium ions beam current density is made, using the following scheme. After the analogue data digitization by the ADC, the digital data is transferred to the alternating voltage voltmeter, which is adjusted for the measurement of the peak voltage magnitude. This magnitude is shown on the screen in the form of the graph with the help of the XYZ-plotter) and on the digital indicator (magnitude at the present time moment). The measured data are saved in a file on a hard disk in the computer. The measurements are made at the frequency of 10 Hz, allowing to detect the peak magnitude of Helium beam current most precisely.

The measurement of irradiation dose of a sample is conducted, using the scheme similar to the scheme of measurement of the peak magnitude of the Helium ions beam current. The only distinction is that the integrator is placed after the voltmeter. It allows the direct registering of the irradiation dose of a sample during the experimental works at the linear accelerator.

In Fig. 5, the front panel of the Helium ions beam current measurement device is shown. The temperature measurement device and the irradiation dose measurement device have similar front panels.

Fig. 4. Scheme of measurements of 1) sample temperature at irradiation, 2) current of Helium ions beam, 3) irradiation dose: 1 – input channel; 2 – voltmeter, 3 – on/off switch; 4 – integrator, which is only used for measurement of irradiation dose; 5 – ADC converter; 6 – summation of data; 7 – saving of data in file; 8 – liquid crystal indicator; 9 – data massive; 10 – XYZ plotter.

Fig. 5. Display of measurement device for precise characterization of Helium ions beam current density.
2.4. Discussion on methodical experiments

In the course of the sample’s irradiation experiment, the various operation modes of experimental setup, including both the linear accelerator and the registration devices, were tested firstly. The influence by the on/off switching of power supply of the high frequency accelerating structure block was also tested. The sensitivity is in the limits of 0,5 °С as it follows from the graph in Fig. 6. The temperature of a sample is stabilized after the linear accelerator operation time of 60 ... 90 min.

![Fig. 6. Dependence of temperature of X18H10T sample on time of irradiation.](image)

The measurements of the Helium ions beam current (Fig. 7) have shown that the current of the accelerated Helium ions up to 4 MeV is in 4-6 times smaller than the current of the injected Helium ions. The stability of the Helium ions beam current at the optimal regime of the linear accelerator operation is ± 5 %, and it is also defined by the stability of the power supply systems.

![Fig. 7. Dependence of peak magnitude of Helium ions beam current on time of irradiation](image)

The irradiation dose is registered with the help of the induction sensors of the Helium ions beam current and the program med integrator. The dependence of an irradiation dose of a sample on the time is shown in Fig. 8. The conducted calculations confirm a right experimental techniques approach, which was used to register the irradiation dose of a sample.

![Fig. 8. Dependence of magnitude of irradiation dose of Zirconium sample on time.](image)

During the completion of methodical experiments, the great attention has been paid to the problem of the Helium ions energy detection in the case of the falling Helium ions on the sample. The aluminium foil with the thickness of 10 µm was placed in the front of an induction sensor with the purpose to control the energy of the Helium ions. The measurements of the Helium ions beam current without the foil and with the foil have resulted in the almost identical magnitudes of current (see Fig. 7). It is possible to state that the Helium ions with the energy of 4 MeV reach the sample, because the Helium ions with the energy of 4 MeV with the tracking paths of more than 16 µm can penetrate the Aluminium foil freely.

In Fig. 9, the dependences of the sample’s temperature (the top curve) and the Helium ions beam current (the bottom curve) on the time at the on/off switching of the power supply of the linear accelerator are shown. In this case, the energy of the injected Helium ions is 120 KeV, and the energy of the accelerated Helium ions is 4 MeV. The injected Helium ions beam current is in the 4 times bigger than the accelerated Helium ions current, and the temperature of a sample at the injected Helium ions beam current is smaller, than at the accelerated Helium ions beam current. Thus, an increase of the temperature of a sample is stipulated by the high-energy component of the Helium ions beam (4 MeV). The given conclusion completely coincides with the theoretical calculations and dependences, which are shown in Figs. 7, 9.

![Fig. 9. Dependences of temperature of sample and Helium ions beam current on time at injected and accelerated Helium ions beams currents.](image)
As it follows from the conducted methodical experiments, pursuing the goal to stabilize and increase the Helium ions beam current, it is necessary: 1) to control the change of the high frequency field of the accelerating structure during the sample’s irradiation process, and also, 2) to measure the distribution of the Helium ions current at the target for the purpose of maintenance of its uniformity in the region of the sample. It is also necessary to make the additional vacuum pumping in the position of sample with the purpose to reach the high vacuum in the chamber.

3. Experimental measurement results

In the case of irradiated sample, the computer modeling on the Helium distribution along the thickness of a sample were conducted with the use of the SRIM software. In Fig. 10, the dependences in the researched case of Zr+1%Nb are shown. The full irradiation doses of samples by the Helium ions with the energies of 120 KeV and 4 MeV are $5 \times 10^6$ ions/cm$^2$. The measurements on the thermal desorption of Helium were completed, using the samples no. 1-8 (see Tab. 3).

The electrophysical properties were precisely characterized, using the samples of Nb and Nb+1%Zr (see Tab. 3). The Helium ions with the energy of 4 MeV penetrate into the researched metals on the depths of 7.2 and 7.4 microns correspondingly. The main peaks of distribution of the implanted Helium ions are observed at these depths in the irradiated metal samples.

![Fig. 10. Computed distribution of Helium ions, which are implanted into Zr+1%Nb with energies of 120 KeV (the left graph) and 4 MeV (the right graph); irradiation dose is $5 \times 10^{15}$ 1/cm$^2$.](image)

3.1. Helium thermo-desorption from researched samples

The physical behaviour of Helium in the investigated materials after their irradiation by the Helium ions with energy of 0.12 ... 4 MeV are studied, applying the thermo - desorption (TD) method. The TD technique includes the measurement of partial pressure of Helium, which outgoes from an investigated sample, in the process of post-implantation linear increase of its temperatures. In the experiments, the technique of thermo-desorption in the dynamic mode of operation at which the pressure of gas in the chamber is proportional to the velocity of desorption from the metal. The samples were investigated in the temperatures interval of 0 ... 1500 °C, the velocity of their heating was 5 ... 8 °C/sec.

The TD researches are completed on the experimental setup «Into» [10] with the application of pumping system without the oil, which provides the pressure of residual gases in the target’s chamber at the level of $(2 \ldots 3) 10^2$ Pa. The structural analysis of the gas medium in the experimental chamber of measurement setup was conducted by the mass - spectrometer.

In Fig. 11-13, the Helium thermo-desorption spectrums from the steel of the type of X18H10T and from the alloy of Zr+1%Nb at the various sample’s irradiation parameters are presented.

![Fig. 11. Helium thermo-desorption spectrum in sample of steel of type of X18H10T, which is irradiated by He$^+$ ions with energy of 4 MeV. Heating velocity of sample is 5,5 °C/sec.](image)

There is a narrow range of temperatures with no desorption process in the case of the alloy of Zr+1%Nb at the certain magnitude of the Helium ions irradiation doses and without the dependence on the irradiation energy. There is the notable Helium gas outgo at $T \approx 500$ °C and it proceeds up to $T \approx 1500$ °C. In this range of temperatures, the TD spectrum is characterized by the superposition of several peaks of desorption. The complexity of structure of a spectrum increases at an increase of the irradiation dose (see Figs. 12, 13). The maximum gas outgo is observed in the peak with the temperature of maximum $T \approx 1280$ °C. It makes sense to note that this stage of desorption is observed in the spectrums of samples, which are irradiated up to the dose $\Phi = 5 \times 10^{15}$ 1/cm$^2$ as well as in the samples, which are irradiated to the dose 10 times more bigger.

In Fig. 13, the TD spectrums of the samples of Zr+1%Nb alloy, which are irradiated by the Helium ions with the energy of 2.42 MeV up to the dose $\Phi = 5 \times 10^{15}$ cm$^{-2}$, and also, the TD spectrums of the samples, which are consistently irradiated by the Helium ions with the energies of 0.12 MeV and 4 MeV up to the same irradiation dose of $\Phi = 5 \times 10^{15}$ cm$^{-2}$. Considering the TD spectrums, which are shown in Fig. 12, it is necessary to note that the first spectrum differs by the increased value of the Helium gas atoms at the main high temperature peak.

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Fig. 12. Helium thermo-desorption spectrum in sample of Zr+1%Nb, which is irradiated by He\(^+\) ions with energies of 12 and 120 KeV. Heating velocities of samples: 5 °С/sec – 12 KeV; 7,8 °С/sec – 120 KeV.

The research on the Helium gas outgo process from the Zr+1%Nb samples after their consecutive irradiation by the Helium ions has shown that the structure of spectrums in this case is less complicated, comparing to the spectrums, which are obtained at the irradiation of the Zr+1%Nb alloy by the He\(^+\) ions with the energies of 120 KeV and 2,42 MeV. The notable desorption begins at the temperature $T \approx 600$ °С. The peak of the Helium gas outgo with a maximum at the temperature $T \approx 1200$ °С prevails in the spectrum. At the irradiation of samples of the Zr+1%Nb alloy by the Helium ions with the energies of 0,12 MeV and 4 MeV up to the same irradiation dose $\Phi = 5 \times 10^{15}$ cm\(^{-2}\), the spectrum of thermo-desorption changes slightly. As it is visible in Fig. 13, in this case, the spectrum is also less complicated in comparison with the spectrums, which are obtained at the irradiation of the Zr+1%Nb alloy by the He\(^+\) ions with the energies of 120 KeV and 2,42 MeV. The additional experiments are necessary to precisely characterize the influence by the penetration depths of the implanted particles and the created radiation damages by the implanted particles in the crystal gratings on the mechanisms of the Helium outgo, and hence the structure of the TD spectrum in the volume of sample.

Fig. 13. Helium thermo-desorption spectrum in sample of Zr+1%Nb, which was irradiated by Helium ions (He\(^+\)) ions with energies of:

- a) 2,42 MeV;
b) 4 MeV+120 KeV (top curve), and 120 KeV (bottom curve).

Heating velocity of samples: 5,6 °С/sec – 2,42 MeV;
8 °С/sec – 4 +0,12 MeV; 5 °С/sec – 12 KeV.

An observable absence (or a very small intensity) of the Helium outgo from the steel as well as from the alloy of Zirconium and Niobium at the temperatures much below $T \approx 500$ ... 650 °С confirms that the contents of the Helium atoms in the Zr+1%Nb alloy does not change at the heating in this range of temperatures. Probably, in this range of temperature, there are the complex diffusion processes of the Helium subsystem and the defective structure of a crystal lattice transformations, which result in the multistage processes of the Helium outgo from the implanted Helium volume at the much high temperatures. The presence of several peaks in the TD spectrums points out to an existence of several discrete stages of the Helium outgo with the different thermodynamic characteristics and the Helium outgo mechanisms from
the metal. At the irradiation process, the Helium atoms interact with the defects of crystal grating, which can be considered as the traps for the Helium. During this process, there are the Helium capture by the single vacancies, double-vacancies, and also, aggregations of vacancies (the strong traps for the He atoms); the Helium capture by the dislocations and boundaries of grains, the inter-phase boundaries; and the formation of Helium and Helium-vacancy clusters [3]. In Fig. 13, the TD spectrum of Helium in the Zr+1%Nb alloy is shown by the dashed line. The Helium is implanted by the continuous Helium ions beam with the energy of 12 KeV up to the irradiation dose $\Phi = 5 \cdot 10^7 \text{cm}^{-2}$. Going from the comparison of spectrums, it can be seen that, despite the considerable divergences in the depths of the implanted Helium atoms, the Helium outgo takes place in the peaks with the close temperatures in the high-temperature regions. It allows to make a conclusion that the same physical mechanism is responsible for the process. In the spectrum of samples with the implanted Helium ions with the low energy, there is the low temperature stage of the Helium desorption. Possibly, it is connected with the Helium outgo process from the Helium – vacancy systems, which are created in the subsurface regions of a sample, and have the much high concentration, comparing to the case of the high energy irradiation.

The experimental fact that the Helium TD spectrums in the Zirconium-Niobium alloy are close enough in the range of high temperatures at the various Helium ions saturation mechanisms in the samples apparently has an important meaning at the consideration of the problem about the adequacy of both the technique of impulse implantation of materials and the technique of continuous irradiation (see, for example, [11]).

In our opinion, the innovative research on the Helium atoms TD nature in the functional design materials at the irradiation conditions as well as the research on the existing connections between the Helium atoms TD process and the migration of separate atoms or their systems to the surface, which can be facilitated by the created radiation defects and by the micro holes of gas, have to be continued.

3.2. Discussion on electrophysical properties of irradiated functional design materials

The irradiation of metal samples, which were made of the thin foils of the high pure Nb and the Nb+1% Zr alloy (see no. 9, 10 in Tab. 3) by the He$^+$ ions with the energies of up to 4 MeV and the flouence of $5 \cdot 10^7$ ions/cm$^2$ at the temperature of 40 °C was completed. The thicknesses of samples are 16 and 22 microns correspondingly. The samples were simultaneously exposed to the irradiation during the one experimental stage, and they had the same values of flouences. The mean magnitudes of the specific resistances $\rho$ of the samples were measured before and after the irradiation process at the room and nitrogen (-196 °C) temperatures with the application of the measuring scheme with the four sensors, using the potentiometers of the model of P363-1. After the irradiation, the specific resistance of Nb-sample at the room temperature was on 4,18 % bigger than before the irradiation, whereas in the case of the sample of Nb+1%Zr, the irradiation influence was on an order of magnitude smaller. At the nitrogen temperature, in view of the decrease of the electrons scattering on the phonons, the contribution by the implanted Helium ions in the magnitude of specific resistance appeared to be a little bit bigger and was equal to 5,47 %. The weak influence by the introduced Helium atoms on the magnitude of specific resistance in the sample of Nb+1%Zr alloy follows from the fact that a big enough quantity (〜 1 at. %) of Zr impurities is introduced into the alloy. The Zr atoms represent the main scattering centers for the electrons, because they have the significantly bigger dimensions, comparing to the small sizes of the He atoms. Considering the non-homogeneity in the distribution of the introduced Helium atoms along the thickness of a sample, the magnitudes of electrical specific resistance in the samples represent the averaged magnitudes only, whereas in the region of the main accumulation of Helium in the core of a sample, the changes of electrical specific resistance can probably be much bigger. The technique of the Helium homogeneous implantation along the thickness of a sample is supposed to be developed during our next stage in the research on the electrophysical properties of irradiated metal samples.

Conclusion

The experimental research on the irradiation of the nuclear reactor functional design materials by the Helium ions in the linear accelerator is completed. The experimental measurements methods and data on the irradiation of the nuclear reactor functional design materials by the Helium ions with the energy up to 4 MeV, including the detailed scheme of experimental measurements setup, are presented. The new design of an accelerating structure of the III-type such as POS-4, using the method of alternate-phase focusing with the step-by-step change of the synchronous phase along the focusing periods in a linear accelerator, is developed with the aim to irradiate the nuclear reactor functional design materials by the Helium ions. The new design of the injector of the charged Helium ions with the energy of 120 KeV at the output of an accelerating tube and the accelerating structure section of the type of POS-4 for the one time charged Helium ions acceleration in the linear accelerator are researched and developed. The special chamber for the irradiation of the nuclear reactor functional design materials by the Helium ions is also created. In the process of experiment, the temperature of a sample, the magnitude of current of the Helium ions beam and the irradiation dose are measured precisely. The experimental measurement setup and techniques are fully tested and optimized in the course of the research on the electro-physical properties of irradiated samples and the thermal-desorption of Helium ions in a wide range of temperatures.
Authors are very grateful to a group of distinguished scientists at the National Academy of Sciences in Ukraine (NASU), led by Boris E. Paton, for the numerous encouraging scientific discussions on the reported experimental research results on the irradiation of the nuclear reactor’s functional design materials by the Helium ions in the linear accelerator.

This innovative research is completed in the frames of the nuclear science and technology fundamental research program, facilitating the synthesis of new functional design materials for the fast neutrons nuclear reactors and the thermonuclear reactors at the National Scientific Centre Kharkov Institute of Physics and Technology (NSC KIPT) in Kharkov in Ukraine.

The research is funded by the National Academy of Sciences in Ukraine (NASU).

This research article was published in the Problems of Atomic Science and Technology (VANT) in [12] in 2012.

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