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Phase and structural transformations in metallic iron under the action of heavy ions and recoil nuclei

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HIGHLIGHTS

- We studied the effects of irradiation on the metallic iron.
- The iron were irradiated with $^{12}C^{4+}$ and $^{14}N^{5+}$ ions and recoil nuclei from a ^{228}Th-source.
- The effects of bombardment were studied upon Mossbauer spectroscopy.
- We report on the effect of irradiation on the structure-, phase composition- and corrosion resistance properties of metallic iron.

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ABSTRACT

By the use of various modes of Mössbauer spectroscopy after effects of irradiation of metal iron with $^{12}C^{4+}$ and $^{14}N^{5+}$ ions of medium energies, and alpha-particles and the ^{208}Tl, ^{208,212}Pb, and ^{216}Po recoil from a ^{228}Th-source have been studied. The experimental data obtained in the study enabled various types of external and internal radiation to be compared in regard to the damage they cause, as well as to their effect on the structure-, phase composition- and corrosion resistance properties of metallic iron. Irradiation with $^{12}C^{4+}$ and $^{14}N^{5+}$ ions is accompanied by both structural disordering of the α-Fe lattice, and the appearance of γ-phase in the bulk metal. This is indicated by a single line which is 2 to 3-fold broadened (as compared to the lines of the magnetic sextet). This is a result of a strong local heating of the lattice in the thermal spike area with a subsequent instant cooling-down and recrystallization of this "molted" area. Irradiation of iron foils with $^{12}C^{4+}$- and $^{14}N^{5+}$ ions and with recoil nuclei does provoke corrosion processes (the formation of γ-FeOOH) and is accompanied by an intensive oxidation of the metal.

1. Introduction

At present, a large amount of diverse information has been accumulated on the interaction of ionizing radiations with various types of materials. In the course of numerous studies it was shown that the effects of radiation (causing deep, at times irreversible, and structural changes) determine physico-chemical properties of irradiated metals and alloys (electric- and thermal conductivity, mechanical strength and reactivity), and exercise a significant influence on phase transformations and diffusion processes that occur in irradiated materials (Pompe and Bobeth, 1998; Sickafus et al., 1999; Iwase and Ishino, 2000; Almazouzi et al., 2000; Trinkaus et al., 2000; Morishita et al., 2000; Jung, 2002; Lu and Wechsler, 2007; Schaublin and Chiu, 2007). Nevertheless, until now one of the most important problems of radiation material science, in particular, that of a comparison of the damages caused by various types of radiation has not attracted due attention despite the vast practical significance of the problem.

In the present work, using several modes of Mössbauer Spectroscopy, after-effects have been studied of external and internal irradiation of metallic iron with $^{12}C^{4+}$ and $^{14}N^{5+}$ ions, and heavy recoil nuclei from a ^{228}Th-source.

2. Experimental methods

2.1. Preparation of iron targets

Samples under study were (5–35 μm) thin foils that were made by rolling from α-Fe plates, of natural isotopic abundance and high chemical purity (not less than 99.9%), or isotopically enriched (with ^{57}Fe) materials.

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Prior to irradiation, the targets were pre-heated for two hours in a reducing atmosphere at 1200–1400 K to eliminate the residual deformation stresses. Before irradiation, the matrix condition was checked by Mössbauer spectroscopy.

2.2. Irradiation techniques

2.2.1. Sample irradiation with $^{12}C^{4+}$ and $^{14}N^{5+}$ heavy ions

The irradiation of metal samples of isotopic ^{57}Fe (enrichment, 90%) with $^{12}C^{4+}$ ions (initial energy: 47.2 MeV, beam current: 70 nA) and $^{14}N^{5+}$ ions (initial energy: 58.8 MeV, beam current: 30 nA) was carried out in an accelerator of A.F. Ioffe Physico-technical Institute, Russian Academy of Sciences, St. Petersburg. The range of $^{12}C^{4}$ ion in iron was 23.5 μm while that of ^{14}N was 22.7 μm.

For heat removal during irradiation, the targets were air-cooled from all sides (4π-geometry) and its temperature during irradiation was (295 ± 3) K.

The total yield of nuclear reactions that were used to produce the short-lived ^{66}Ga-, ^{67}Ga-, and ^{69}Ge radionuclides, which were formed in the ^{57}Fe(^{12}C,d), ^{57}Fe(^{12}C,2*n*), ^{57}Fe(^{14}N,^{4}He+n), ^{57}Fe(^{14}N,^{4}He), and ^{57}Fe(^{14}N,2*n*) reaction channels, did not exceed 220 Bq nA^{-1} h^{-1}.

2.2.2. Sample irradiation with alpha-particles and the recoil ^{208}Tl, ^{208,212}Pb, ^{216}Po nuclei of a ^{228}Th-source

Irradiations of iron foils of natural isotopic abundance were carried out in a ^{228}Th-source (radioactivity, $6.7 \cdot 10^{8}$ Bq). The samples were placed at a height of 20 mm above an emanating (^{220}Rn) preparation of thorium, ^{228}Th and ^{224}Ra being in the state of secular radioactive equilibrium (National Nuclear Data Center, Home Page). After that, the source was sealed hermetically. The area of the irradiated sample was 25% of the total inner surface area of the source. The target temperature during irradiation was (295 ± 3) K.

Table 1
Characteristics of the ^{57}Fe Mössbauer Transition (Barb, 1980).

Parent isotope	$T_{1/2}$, days	Gamma-transition energy (keV)	Radiation yield (%)	Level lifetime (ns)	Natural line width (2*Γ*), (mm s^{-1})	ICC[a]
^{57}Co	271.74	14.4	9.16	98.3	0.194	8.18

[a] The internal conversion coefficient.

2.3. Experimental methods used to study products of nuclear reactions and irradiated targets

The study of the products of nuclear reactions has been carried out by the use of precision gamma-ray spectroscopy. To study the radioisotopic composition of irradiated targets, *a HPGe detector (GX1018 manufactured by* Canberra Industries Inc, U.S.A.) was used. Sample measurement results were processed with the Genie-2000 software (developed by Canberra Industries Inc., NC, USA).

The characteristics of the ^{57}Fe Mössbauer transition are given in Table 1. The Mössbauer spectra were measured with an electrodynamic apparatus that operated in a constant acceleration mode. This Commercial Mossbauer Spectrometer CM 2201 was made in

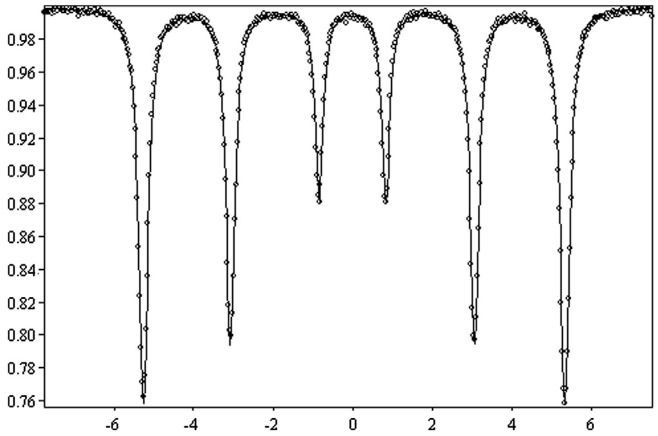

Fig. 1. Absorption spectrum of samples before irradiation measured with a xenon-filled proportional counter. The target was a 25 μm thick foil of natural isotopic abundance with 2.119% ^{57}Fe content. The ^{57}Fe dominated surface density was 0.33 mg cm^{-2}. The measure line width (Γ) is 0.24 mm s^{-1} and magnitude of effect of resonance florescence is 12%.

Table 3
Parameters of Mössbauer Absorption Spectra Measured with natural isotopic α-Fe Absorbers of various thickness.

Absorber thickness, μm(^{57}Fe-determined density, mg cm^{-2})	Experimental line width (mm s^{-1})	Typical magnitude of effect of resonance fluorescence (%)
5 (0.08)	0.21 ± 0.02	3
20 (0.33)	0.22 ± 0.02	10
25 (0.42)	0.24 ± 0.02	12

Table 2
Irradiating conditions and a methodology for studying the targets.

Irradiating conditions					A method for studying[b]
Type of particles	Particle energy	Fluence, particles · (m^{-2})	Target thickness (μm)	Number of displaced atoms within the sample, vacancies/ion (the Kinchin –Pease model)[a] (Particle Interactions with Matter.)	
^{12}C	47.2 MeV(initial)	8.2×10^{19}	35	2630	MSSR
^{14}N	58.8 MeV (initial)	1.6×10^{19}	35	3430	MSSR
^{4}He ^{208}Tl, ^{208,212}Pb, ^{216}Po	6.05–8.8 MeV 0.11–0.17 MeV	4.5×10^{18} (total)	5	14 3660	AMS

[a] Displacement energy – 25 eV.

[b] AMS – Absorption Mössbauer Spectroscopy; MSSR – Mössbauer Spectroscopy of Secondary Radiation; the penetration depth for: (a) X-rays (6.4–7.1 KeV), 20 μm; and (b) conversion- and Auger electrons (5.6 to 14.3 KeV), down to 1.3 μm (Mossbauer Spectroscopy II, 1981; Irkaev et al., 1993).