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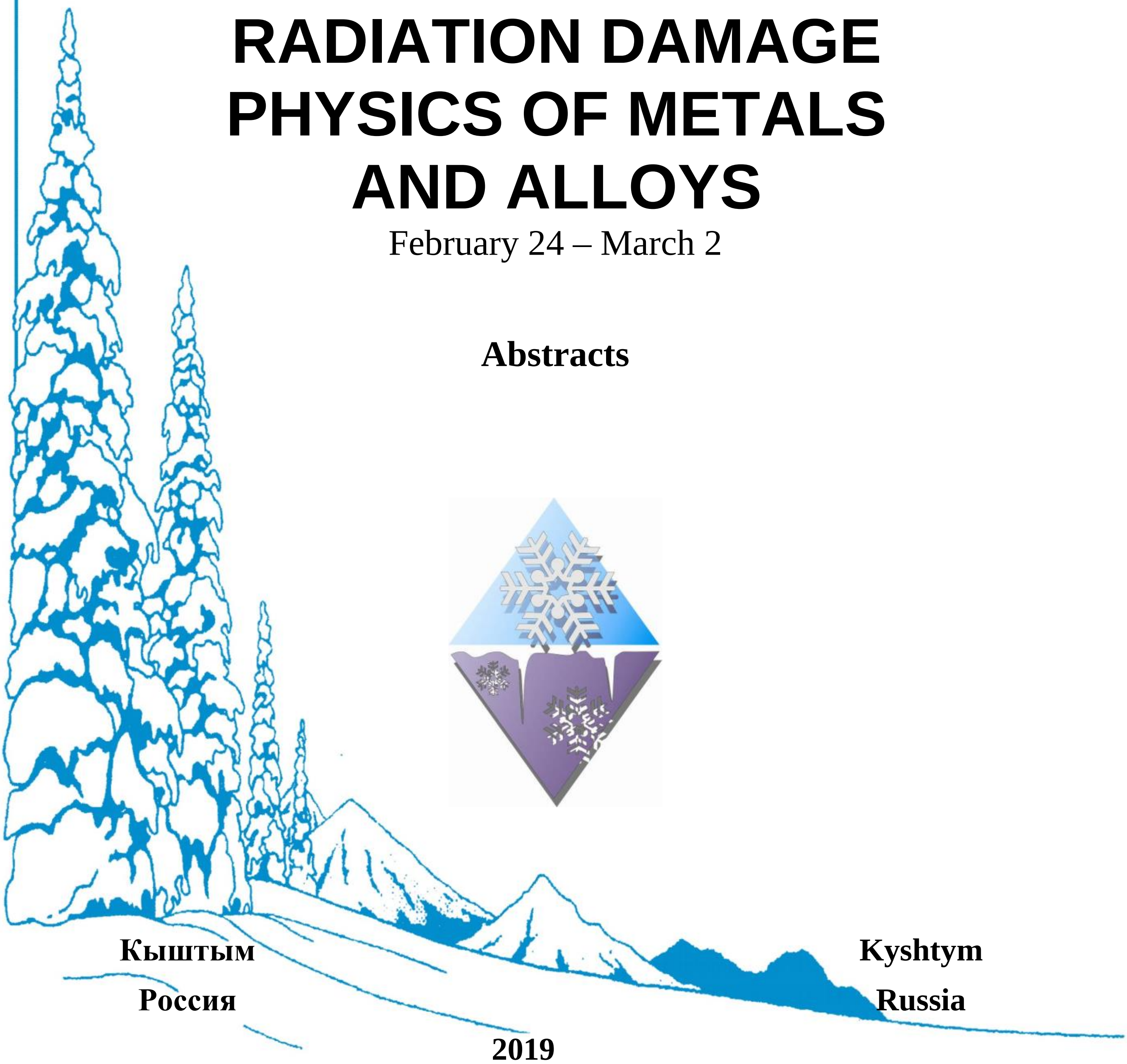
on

RADIATION DAMAGE PHYSICS OF METALS AND ALLOYS

February 24 – March 2

Abstracts



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Kyshtym, Russia
2019

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The Organizing Committee cordially thanks all Sponsors for their support to the Russian science. Special thanks to Celia M. Elliott (USA) and Frank A. Garner (USA), the Russian Foundation for Basic Research, for their financial support to the young scientists, the Seminar attendees. We hope that our meeting in Snezhinsk will serve to promote and expand further scientific contacts.

Compiled by
Denis Perminov

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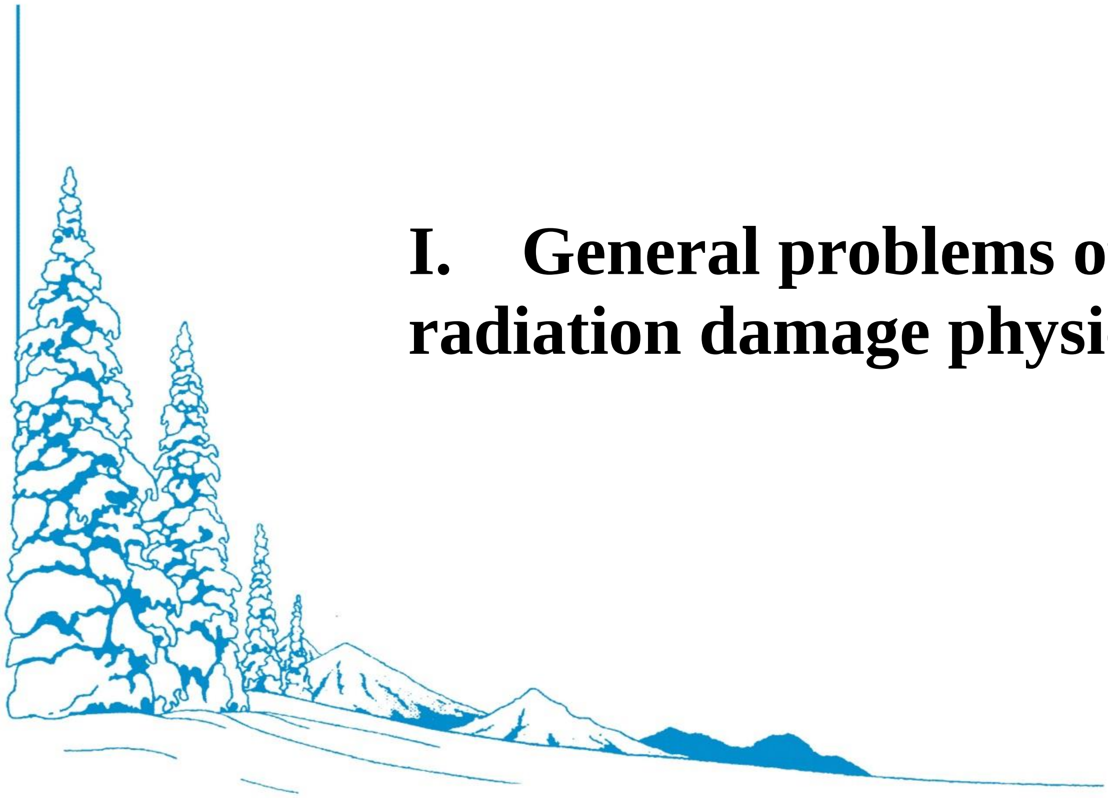

I. General problems of radiation damage physics

This Section is dedicated to most topical, as of now, problems of radiation damage physics of metals and alloys. It includes reports on specific features of the behavior of point defects in various alloys and compounds including Fe-Cr(Ni) systems, which are the basis of many radiation-resistant high-pressure-vessel materials. The program of the Section includes papers dedicated to investigations into specific features of the processes involved in the interaction of radiation- and deformation-induced point defects and their complexes with each other, and with impurity atoms, dislocations, interfaces, and grain boundaries using modern research methods at all stages of the formation of a complicated defect structure in nano- and submicrocrystalline metal systems. Also, the effect of these interactions on deformation- and radiation-induced processes is studied. Much attention is given to multiscale modeling of radiation processes in irradiated materials, analysis of structural and phase transformations, and the behavior of transmutated gas mixtures.

ACCUMULATION OF DEFECTS IN AUSTENITIC STAINLESS STEELS ALLOYED WITH PHOSPHORUS AND TITANIUM DURING ELECTRON IRRADIATION STUDIED BY POSITRON ANNIHILATION

D.A. Perminov, A.P. Druzhkov, V.L. Arbuzov
M.N. Mikheev Institute of Metal Physics of UB RAS, Ekaterinburg, Russia
(perminov@imp.uran.ru)

Austenitic stainless steels and alloys are one of the materials that meet the requirements for structural materials for nuclear reactors in the best way. These alloys offer a well-established process technology, have good performance characteristics, are relatively cheap, their radiation resistance is rather well-studied. However, austenitic steels and alloys are prone to radiation-induced swelling, which is the main factor limiting their use. The swelling of steels can be reduced by doping them with a small amount of alloying additions. Today, phosphorus and titanium are considered as such alloying elements. Interacting with point defects, titanium and phosphorus can affect the mobility of defects and, thus, the swelling of steels. In steels alloyed with titanium at a level higher than 1 at.%, the solid solution decomposition and the formation of second phase precipitates (intermetallic precipitates, titanium carbides) may take place during irradiation. Addition of phosphorus to austenitic stainless steel may lead to the formation of non-coherent needle-shaped Fe_2P and Fe_3P phosphides in the matrix. Doping with phosphorus and titanium together can lead to the formation of complex FeTiP-type phosphides, which are hypothetically more stable than simple phosphides. Precipitates entioned above may serve as effective sinks of point defects or centers of enhanced their recombination.

Thus, the effect of phosphorus and titanium on swelling suppresion may be due to several reasons. At the same time, this effect will depend on the concentration of alloying additions, irradiation temperature, dose and other parameters. Unfortunately, today there are no systematic studies of these effects depending on the content of alloying elements, the initial microstructure of the steels and the irradiation conditions. Such data could facilitate understanding of the mechanisms of the influence of alloying elements on the accumulation of radiation defects. It should be noted that the structural and phase transformations in austenitic steels alloyed with phosphorus and titanium are well-known, but the formation of complex phosphides and their stability have not been practically studied today. In addition, radiation-induced structural and phase transformations in steels containing phosphorus have not been studied. The lack of this knowledge does not allow to choose their optimal structure, as well as to predict their behavior in real operating conditions.

The report presents the results of the study of the accumulation of defects in steels Cr16Ni15Mo3 and Cr16Ni15Mo3Ti at the early stages of irradiation (up to 10^{-4} dpa) at temperatures of 300 K and 573 K, obtained by the method of positron annihilation spectroscopy. The mechanisms of the effect of phosphorus and titanium in a solid solution on the behavior of point defects during irradiation are also discussed.

The work was performed within the framework of the state assignment of the FASO of Russia (theme “Spin” No. AAAA-A18-118020290104-2), according to the project of UB RAS No. 18-10-2-22 with partial support from the Russian Foundation for Basic Research (projects No. 18-02-00270 and 19-02-00719).

CRYSTALLOGRAPHIC, ENERGETIC AND DIFFUSIONAL CHARACTERISTICS OF SELF DI-INTERSTITIALS IN BCC METALS Fe AND V

D.N. Demidov[1], A.B. Sivak[1], P.A. Sivak[1]
[1] NRC "Kurchatov Institute", Moscow, Russia (Demidov_DN@nrcki.ru)

Diffusion of radiation defects generated by neutron radiation and their absorption by sinks leads to the evolution of the microstructure of materials and, as a consequence, to a change of their physical and mechanical properties. To construct phenomenological models of the properties of materials under irradiation changes, it is necessary to know the characteristics of radiation defects. In the process of irradiation, not only self-point defects, but also their clusters are formed. One of the most frequently formed types of clusters are di-interstitials: according to the results of molecular dynamic (MD) simulation of atomic collision cascades in FeC and BCC metals Fe and V, 10 to 20% of the surviving after the end of the cascade self-interstitial atoms are contained in di-interstitials.

In this work, using the interatomic interaction potentials [1] and [2], MD-modeling of the di-interstitials diffusion in Fe and V bcc metals, which are the basis of advanced materials for nuclear engineering (ferritic-martensitic steels, vanadium alloys), was performed. The temperature dependences of the diffusion coefficients of di-interstitials and their analytical approximations in the temperature range of 200–800 K are obtained. This temperature dependence are non-Arrhenius in nature and are realized through several diffusion mechanisms prevailing in different temperature ranges. By the method of molecular statics, the energies of formation of configurations of di-interstitials, which provide various diffusion mechanisms, are determined. Kinetic models of diffusion, explaining the results are constructed.

This work was supported by the Russian Foundation for Basic Research (research project 18-08-01205-a) using the equipment of the collective use center "Complex for modeling and data processing of research facilities of mega-class" of the Kurchatov Institute research center, http://ckp.nrcki.ru/.

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EFFECT OF THE DAMAGE DOSE ACCUMULATION RATE ON THE MICROSTRUCTURE OF Fe-18Cr-10Ni-Ti STEEL IRRADIATED IN THE BOR-60 REACTOR AT 330-350°C

D.E. Markelov, A.V. Obukhov, V.S. Neustroev
JSC "SSC RIAR", Ulyanovsk region, Dimitrovgrad

Most of VVER internals are made of austenitic Fe-18Cr-10Ni-Ti steel. To ensure safe operation of non-removable reactor internals and structures and show the feasibility of their life extension, the data are used from sample irradiation testing and examination of actual items and structures after their long-term operation in fast reactors, since only in fast reactors high damage doses are accumulated required for justifying the service life of VVER internals. High damage doses on the samples can be accumulated in the course of experiments in the reactor core at high accumulation dose rates or in the reactor blanket at low rates but during a much longer time. As it is quite difficult to perform such experiments in the BOR-60 reactor blanket considering a long time period, assemblies made from Fe-18Cr-10Ni-Ti steel can be examined that have been under operation in the reactor blanket for quite long.

It is of interest to examine and compare the microstructure of the samples from Fe-18Cr-10Ni-Ti steel irradiated at different dose accumulation rates up to almost similar damage doses under similar temperatures. For this purpose, two samples were examined. One sample was cut from the duct of a blanket assembly that had been irradiated in the BOR-60 reactor for almost 41 years to accumulate a damage dose of about 100 dpa. Another sample was cut from the sample that had been irradiated for almost 7 years to achieve a damage dose of 100 dpa, as well. These two samples were irradiated at 330-350°C. The damage dose accumulation rate for the duct sample was about 2,5 dpa/year, and for another sample it was 15 dpa/year, which is almost 6 times more. The examination results show that the microstructures of the samples irradiated at different damage dose accumulation rates are very different. There is developed porosity in the sample of a low damage dose accumulation rate and there is no such porosity in the sample of a high rate. Another difference refers to formation of the phase structure of the irradiated samples.

The generated data can be used to justify a gamma-alpha transformation criterion in VVER internals during their long-term operation to achieve high damage doses. These data will be included in the database on radiation resistance of Fe-18Cr-10Ni-Ti steel to demonstrate the possibility of life extension for VVER-type and BOR-60 reactor internals.

ELECTRON-MICROSCOPIC STUDY OF THE FORMATION OF HELIUM POROSITY IN FERRITIC-MARTENSITIC STEELS UNDER POST-IRRADIATION ANNEALING

T.V. Nguyen[1], A.S. Sohatsky[1], V.A. Skuratov[1], K. Kornieieva[1], J.H. O'Connell[2], M. Zdorovet[3], J. Nitling[2]

[1]FLNR, Joint Institute for Nuclear Research, Dubna, Russia (nvtiep@jinr.ru)

[2]CHRTEM, Nelson Mandela University, Port Elizabeth, South Africa

[3]Institute of Nuclear Physics, Astana, Kazakhstan

As shown by numerous studies of the development of helium porosity, obtained as a result of high-temperature ion doping / irradiation, in alloys with dispersed nanoinclusions of secondary phases, introduced into the matrix, in particular, in oxide dispersion-strengthened alloys (ODS), the resulting swelling are usually much less than in alloys similar composition without nanoparticles, for instance [1]. The effect is associated with the heterogeneous nucleation of gas bubbles at the nanoparticles interfaces with the matrix and the further growth of the bubbles already in a fixed state, preventing their coalescence. Radiation vacancies are only the source of the volume for the growth of pinned bubbles. However, it is expected that during high-temperature annealing of helium-doped alloys, the pattern of gas porosity development will be different, since the growth of pores will be controlled by diffusion delivery of thermal vacancies to merging bubbles from vacancies sources: free surface, grain boundaries and unpinned dislocations. Residual internal microstresses, especially strong in ODS alloys, can significantly accelerate self-diffusion in stress gradients, thereby, accelerating pores growth [2].

BCC alloys: model Fe-0.08C-13Cr (AISI410S), experimental Fe-16Cr-2W ODS ("Cr16 ODS") and Fe-0.12C-13Cr-2Mo-Nb-V-B ODS ("EP450 ODS") were chosen as objects for research in this work. The initial state of the samples was characterized by metallography, X-ray diffractometry and TEM. It is established all the alloys have a ferrite structure. In alloys AISI410S and Cr16 ODS, no internal stresses were detected, while in the alloy EP450 ODS residual microstresses were recorded, ranging from 310 to 430 MPa for different crystallographic directions.

Uniform helium doping areas with a concentration of 0.2 and 1 at% were formed in the samples using room temperature ion implantation, after which the samples were annealed at 800 ° C for 30 min. TEM studies performed showed that the porosity develops in the samples AISI410S and Cr16 ODS in the same way during annealing, with large bubbles being observed exclusively in the zones near the grain boundaries, with a gradient to the boundary. The coalescence of pores in the zones occurs according to the mechanism of migration and merge. The middle region of the grain appeares to isolate for the entry of vacancies into it and the coalescence of bubbles does not occur in it. The relative volume of bubbles in the grain body is less than that near the boundary by 6–8 times in samples with [He] = 0.2 at% and 4–5 times at [He] = 1 at%. In annealed EP450 ODS samples with strong microstresses, large bubbles are evenly distributed throughout the volume of the grains. The bubbles decorate mainly dislocations, while there are relatively few bubbles decorating nanooxides. The total gas swelling of EP450 ODS samples is significantly larger than for AISI410S and Cr16 ODS samples. Thus, it was shown that the presence of internal stresses in ODS steels has a significant effect on the thermal growth of helium porosity in them.

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ENERGY OF VACANCY MIGRATION IN STEELS AND ALLOYS

A.V. Kozlov, I.A. Portnykh, O.I. Asiptsov
Institute of Nuclear Materials», Zarechny, Sverdlovsk region, Russia (kozlov_alv@irmatom.ru)

The energy of point defect migration is one of the key characteristics describing diffusion-controlled processes that occur in materials under neutron irradiation. The energy of interstitial migration in reactor materials in most cases is 0.15÷0.30 eV. At operating temperatures in BN reactors (above 600 K) the variation in several hundredths of eV has no significant impact on diffusion-controlled processes, including swelling. The energies of vacancy migration in reactor austenitic steels exceed 1 eV and their variations for hundredths of eV have significant impact on this kind of processes. Therefore their value determination is a topical issue. At the same time a vacancy energy concept in alloys is averaged and its correct utilization is ambiguous.

The paper aims at development of the procedure to measure and use vacancy migration energy in steels and alloys to describe radiation-induced swelling.

The paper gives analysis of the concept of vacancy migration energy in alloys, showing that different kinds of atoms require different energy for transition to the neighbouring vacant interstitial. The procedure of the alloy element migration determination using the results of dilatometric measurements of samples, pre-irradiated in the reactor, is described. The procedure is demonstrated on the previously obtained dilatometric study results for cladding samples made of ChS-68 and EK-164 steels [1]. There vacancy migration energies are defined, when their migration is due to Ni, Fe and Cr atom transition.

The average vacancy migration energy in these steels is calculated so that the total number of vacancy transitions is the same as that for separate elements.

Using the average values of migration energies the quasi-steady vacancy and interstitial concentrations in ChS-68 and EK-164 steels at the initial stage of unsteady-state swelling are calculated.

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GENERATION OF DEFORMATION-INDUCED POINT DEFECTS IN THE ASPECT OF CREATION OF NEW OXIDES STRENGTHENED REACTOR STEELS

V.V. Sagaradze

[1]*IMP UB RAS, Ekaterinburg, Russia (vsagaradze@imp.uran.ru)*

The development of oxide-dispersion strengthened (ODS) heat resistant reactor steels is intensively carried out at the present time in a number of countries such as Japan, France, USA, China, Russia and others. The first stage of production is the mechanical alloying of steels with oxygen in the process of oxygen-containing phases dissolving in the steel matrix during the treatment in mills of the powder mixture. Precipitation of reinforcing oxides of less than 10 nm, occurs during subsequent high-temperature sintering of the mechanical-alloyed powder and leads to significant increasing of heat resistance. In this chain of ODS-steels manufacturing the process of diffusion dissolution of dispersed particles at low temperature deformation remains not fully studied. It is difficult to imagine the deformation-induced dissolution of dispersed phases (consisting entirely or partially of substitution elements such as nickel, titanium, iron, chromium, vanadium, etc.) at low temperatures, since the vacancy diffusion of these elements in steel at room and cryogenic temperatures does not occur. However, the possibility of formation of deformation-induced near-boundary atomic segregation of nickel and anomalous deformation-induced dissolution of a wide variety of dispersed phases (intermetallic, chromium oxides, nitrides, etc.) at 300 K and lower temperature was shown in our work [1]. In particular, the mössbauer method reliably demonstrated the possibility of Ni3Ti and Ni3Al intermetallides dissolution in pre-aged Fe-36Ni-3Ti and Fe-36Ni-5Al alloys during deformation at 77 K. This is explained by the deformation generation of interstitial atoms (despite the high energy of their formation) and their migration from the particle to the matrix after dislocations, for instance. As shown by calculations [1], Nickel atoms in the interstitial position in the crowdion form (the activation energy of migration E~0.1 eV) can move by diffusion (at a considerable distance of ~1 nm or more) in the dislocation field even at a temperature of 77 K, when vacancies are "frozen". Increasing in deformation temperature to 500-600 K, in contrast, activates vacancy diffusion which leads to anomalous enhanced precipitating of intermetallic compounds. We experimentally confirmed the migration of interstitial Nickel atoms at 77-160 K in Fe-Ni austenitic alloys by changing of the electrical resistance during annealing at these temperatures in pre-deformed samples. A similar situation is observed in high-energy electron irradiated Fe-Ni alloys, when the formation of interstitial atoms is not in doubt.

The obtained results on the anomalous dissolution of dispersed phases during deformation allowed to optimize and simplify the process chain of obtaining oxide-dispersion strengthened (ODS) reactor steels. In particular, samples of ODS-steel with high strength properties were obtained as a result of surface oxides dissolution (during processing in the mill of pre-oxidized powder of 13Cr-2W-Y-Ti type reactor steel) and subsequent precipitation of the hardening yttrium-titanium nanooxides (during high-temperature sintering).

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IMPROVEMENT OF ION BOMBARDMENT AS A TOOL TO SIMULATE SWELLING OF AUSTENITIC PWR INTERNAL COMPONENTS USING PREVIOUSLY NEUTRON-IRRADIATED SPECIMENS

F.A. Garner[1], A.J. French[1], H. Kim[1], C. Shiau[1], L. Shao[1], P.D. Freyer[2]
[1]*Texas A&M University*
[2]*Westinghouse Electric Company*

Ion bombardment at highly accelerated atomic displacement rates is being employed to at our laboratory to simulate void swelling of 300 series stainless steels that were used to construct the internal components of PWRs. Most studies of this type use virgin unirradiated specimens as starting material but ion irradiation of virgin material usually produces less-than-neutron-characteristic void densities. More importantly, void swelling of stainless steels under neutron irradiation is preceded by a microchemical evolution than cannot be reproduced at ion-relevant dpa rates. In addition, the densities of voids, Frank loops, precipitates, etc. are strongly affected by the ion-induced dpa rate, requiring a shift in irradiation temperature to maintain defect equivalence.

A proposed partial solution to these shortcomings is to start with neutron-produced microstructures, especially for voids, and then induce additional ion-induced damage, using both shifted and unshifted ion irradiation temperatures. Not only will the starting microstructural densities be characteristic of neutron irradiation, but the microchemical evolution will be either totally or partially complete with a neutron-characteristic behavior before ion damage is introduced.

Two sets of results will be presented. First, previously unpublished "neutron preconditioning" irradiation studies from the 1970 and 1980s will be shown. Second, new ongoing preconditioning studies, incorporating insight derived since the 1980s from both neutron and ion irradiation will be presented, focusing on 304 stainless steel from EBR-II reflector blocks, and 316 PWR flux thimble tubes.

Both sets of studies confirm the utility of using neutron-preconditioned material for ion irradiation, but there are several surprises that require us to reconsider some of the current perceptions of void swelling.

IRRADIATION-INDUCED CREEP OF STEELS X18H10T AND X16H12M3T AT TEMPERATURES 330÷420°C

E.I. Makarov, V.S. Neustroyev
JSC "State Scientific Center – Research Institute of Atomic Reactors", Dimitrovgrad, Russia
(neustroev@niiar.ru)

The paper presents the results of irradiation-induced creep tests conducted for pressurized specimens of various designs [1, 2] made of austenitic steels X18H10T and X16H12M3T. The pressurized specimens were irradiated in the BOR-60 reactor in the temperature ranges 330÷350 and 400÷420°C up to different damage doses.

The purpose is to experimentally define the mechanisms of irradiation-induced creep as well as the effect of different stress conditions on creep strain in austenitic steels X18H10T and X16H12M3T under neutron irradiation in the fast reactor BOR-60.

Examinations of irradiated pressurized specimens shown their diameter to linearly increase as the damage dose rises. The effects of compressing and tensile stresses on the irradiation-induced creep of steel X18H10T were compared. Creep moduli were defined for steels X18H10T and X16H12M3T at the stable creep stage. The creep moduli correlate well with the ones for both Russian X18H9-based austenitic steels and foreign SA 304L and CW316 [3].

The examination results were used in strength calculations of the VVER-1000 baffle and new VVER-1200 design.

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RADIATION DAMAGING OF Y-Ti-O NANOPARTICLES IN ODS ALLOYS WITH HEAVY IONS OF FISSION FRAGMENT ENERGY

E.A. Korneeva[1], V.A. Skuratov[1,2,3], A.S. Sohatsky[1], J. O'Connell[4], M. Zdorovets[5], J. Neethling[4]

[1]Flerov Laboratory for Nuclear Reactions, Joint Institute for Nuclear Research, Dubna, Russia
(skuratov@jinr.ru)
[2]National Research Nuclear University MEPhI, Moscow, Russia
[3]Dubna State University, Dubna, Russia
[4]Centre for HRTEM, Physics Department, Nelson Mandela University, Port Elizabeth, South Africa
[5]Institute of Nuclear Physics, Astana, Kazakhstan

The results of electron-microscopic studies of structural changes in Y-Ti-O nanoparticles in

EP450 ODS steel irradiated with high energy heavy ions as a function of ion fluence, electronic stopping power and the irradiation temperature have been presented in this report. It was found that Kr and Xe ions of fission fragment energy induce formation amorphous latent tracks in $Y_2Ti_2O_7$ particles starting from the specific ionizing energy loss 7.4-9.7 keV/nm in the temperature range 300-1000K [1]. An example of the TEM image of tracks in EP450 ODS steel irradiated with 220 MeV xenon ions at 800K is given in fig. 1. It was shown that ion track region overlapping results in complete amorphization of pyrochlore nanoparticles which crystalline structure is not recovered during post radiation heat treatment. Latent track radius dependence on the electronic stopping power and irradiation temperature may be described the framework of the thermal spike model.

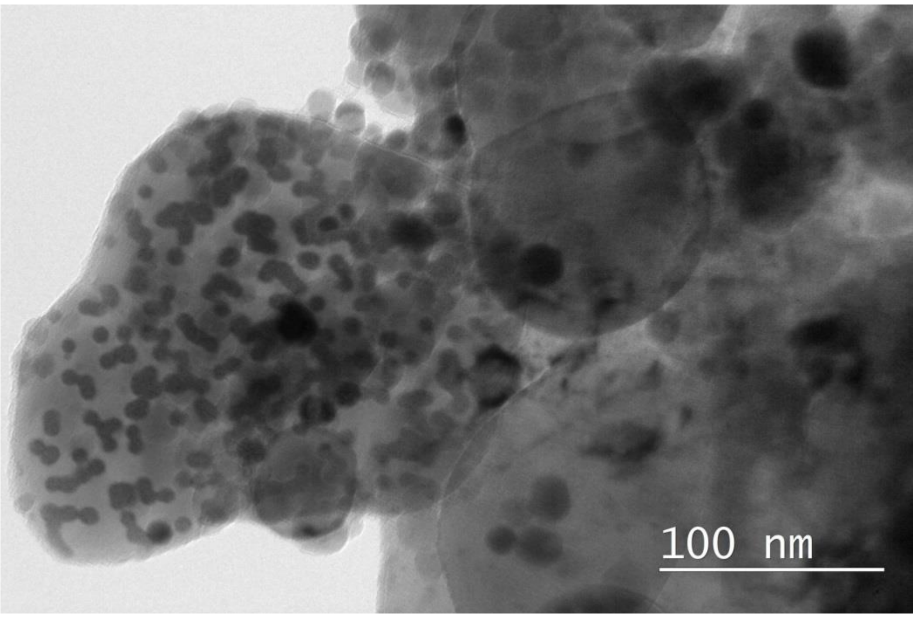

Figure 1. Bright field TEM image of $Y_2Ti_2O_7$ particle in EP450 ODS steel irradiated with Xe(220 MeV) ions at 800 K. Ion fluence $10^{12}cm^{-2}$. Track diameter is 7.2 ± 1.5 nm.

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RECONSIDERING IRRADIATION VARIABLE SHIFTS FOR SOLUTE NANOCLUSTERING

Matthew J. Swenson[1], Janelle P. Wharry[2]
[1]*Department of Mechanical Engineering, University of Idaho, Moscow, Idaho, USA*
[2]*School of Nuclear Engineering, Purdue University, West Lafayette, Indiana, USA*

The objective of this presentation is to review theories of solute nanocluster irradiation evolution, and present their implications on irradiation variable (i.e. temperature and dose rate) shifts. Historically, ion irradiation conditions have been selected to emulate neutron irradiation based on the "invariance theory", which prescribes a positive temperature shift for higher dose rate irradiations. This theory has been proven effective in b.c.c. Fe-based alloys for using ion irradiation to generate void and dislocation loop morphologies resembling those generated by neutron irradiation [1]. However, the invariance theory has not been benchmarked against other nano/microstructural features, including solute nanoclusters. Herein, we present a collection of experiments in a model Fe-9%Cr ODS steel and two commercial ferritic/martensitic (F/M) alloys HCM12A and HT9, irradiated with Fe^{2+} ions, protons, or neutrons at temperatures ranging 400-500°C and to damage doses ranging 1-100 displacements per atom (dpa) [2,3]. The observed irradiation evolution of ODS oxides, Si-Mn-Ni nanoclusters, and Cu-rich nanoclusters, in these three alloys, appear inconsistent with the invariance theory, and suggest that nanocluster evolution mechanisms must consider irradiation damage cascade effects.

This presentation will summarize four theories describing the mechanisms governing nanocluster evolution in irradiated alloys, and compare these theories against experimental data. First, we consider an advanced rate theory model originally developed by Nelson, et al. [4]. The model accurately predicts experimentally observed nanocluster evolution, but when varying the irradiation temperature within the model, a negative temperature shift is required for higher dose rate ion irradiations to simulate nanocluster evolution due to lower dose rate neutron irradiation. This negative temperature shift is corroborated by three other cluster evolution models developed by Martin [5], Wagner (advanced by Chen [6]), and Ribis, et al. [7]. These findings suggest that the irradiation damage cascade morphology (which is ignored in the invariance theory) must be considered in selecting irradiation conditions to properly emulate nanocluster evolution.

Models such as cluster dynamics or phase field, which fully incorporate the influence of irradiation temperature, dose rate, and cascade morphology, are needed to more accurately simulate nanocluster evolution and determine the appropriate temperature shift requirements.

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SHORT-RANGE ORDER AND NON-EQUILIBRIUM VACANCIES IN IRON-BASED BINARY ALLOYS

A.R. Kuznetsov[1,2], Yu.N. Gornostyrev[1], I.G. Shmakov[1]
[1]*IMP UD RAS, Ekaterinburg, Russia (a_kuznetsov@imp.uran.ru)*
[2]*Institute of Physics and Technology, Ural Federal University, Ekaterinburg, Russia*

Substitutional alloys Fe-X (X = Al, Si, Ga, Ge) based on bcc Fe are of considerable interest due to their unusual magnetic and other properties, such as induced magnetic anisotropy (Fe-Al, Si), giant magnetostriction (Fe-Ga), a significant decrease in the elastic moduli (Fe-Ga, Ge). According to the existing concepts, the special physical properties of these alloys are due to the presence of a certain short-range order (SRO), however, the nature and reasons for its formation currently remain the subject of debate.

To clarify the mechanisms of SRO formation, we carried out Monte Carlo simulation of the structure of the alloys under consideration, depending on temperature and magnetic state, using the interatomic interaction energies calculated from first principles (VASP-PAW method). It also took into account the presence of a high concentration of non-equilibrium vacancies generated during intensive treatment of the material (irradiation, large plastic deformation) and/or due to the formation of stable vacancy-impurity complexes (Vac-X) with alloying elements.

It was shown that the energy of the effective X–X interaction in bcc Fe strongly depends on the magnetic state of the matrix. As a result, the B2-type SRO, which is responsible for the enhancement of magnetic anisotropy, is formed at $T > T_C$ and is fixed during quenching, while in the ferromagnetic state ($T < T_C$) the $D0_3$-type SRO is equilibrium. It was shown that the binding energy of a vacancy with an impurity is high in the case of Ga, Ge (~ 0.45 eV) and half as much (~ 0.24 eV) in the case of Al, Si; a similar relationship between the binding energies is retained also during the formation of X-Vac-X complexes. As a result, the formation of B2-type SRO in Fe-X alloys (X = Ga, Ge) is preferable even in the presence of equilibrium vacancies, while in Fe-X alloys (X = Al, Si), additional external treatment is needed.

The results obtained reveal the important role of magnetism in the formation of short-range order in these alloys, as well as the possibility of its significant enhancement due to the presence of vacancies, and allow us to explain the experimentally observed structural features depending on the composition and temperature.

The research was carried out within the state assignment of FASO of Russia (theme “Structure” No. AAAA-A18-118020190116-6), supported in part by RFBR (project No. 18-02-00391). This work has been carried out using computing resources of the federal collective usage center Complex for Simulation and Data Processing for Mega-science Facilities at NRC “Kurchatov Institute”, http://ckp.nrcki.ru/.

STRUCTURAL STATE OF 18CR9NI STEEL AFTER LONG-TERM NEUTRON IRRADIATION AT HIGH TEMPERATURES

V.I. Pastukhov[1,2], V.L. Panchenko[1,3], I.A. Portnykh[1], A.V. Kozlov[1]
[1]Joint Stock Company "Institute of Nuclear Materials", Zarechny, Sverdlovsk region
[2]Ural Federal University named after the first President of Russia B.N. Yeltsin, Yekaterinburg
[3]National Research Nuclear University "Moscow Engineering Physics Institute" (MEPhI), Moscow, Russia

18Cr9Ni-type steels are widely applied in fast and thermal reactors. This is due to a unique combination of structural strength and corrosion resistance, common properties for the structural state formed under relevant heat treatment. Long-term neutron irradiation causes structural changes of the material at micro level, thus affecting macro properties of the material as well. One of the requirements to materials of such a grade comprises predictability and stability of their properties.

Structural state of 18Cr9Ni steel after neutron irradiation for 35 years up to maximum damage dose of 33 dpa has been studied using scanning [1] and transmission electron microscopy. The material was irradiated at temperature in the range between 370 °C and 460 °C at low damage dose rate. The material irradiation lead to formation of radiation-induced voids and stimulated carbide release into the matrix.

The characteristics of a set of 18Cr9ni steel voids were obtained with maximum damage dose after irradiation and at different modes of further heat treatment of the material.

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THE EFFECT OF CHARACTERISTICS OF RADIATION POROSITY FORMED IN AUSTENITIC STEELS ON THE VALUE OF SELF POINT DEFECT CONCENTRATIONS

A.R. Isinbaev, A.V. Kozlov, I.A. Portnykh
JSC "Institute of Nuclear Materials", Zarechny, Russia (isinbaev.a.r@gmail.com)

The issue of radiation resistance of structural materials used for reactor cores is one of the most important scientific and technological issues restraining the development of nuclear energy. The Generation and development of radiation porosity causing the material swelling is the main reason for the instability of structures operated in ionizing radiation fields. It leads to limited service life of structural materials. The investigation of swelling processes will allow learning more about mechanisms, responsible for swelling, and then predicting the service life of fuel assemblies. It will help to find out the ways to improve materials characteristics and extend their service life.

The paper aims at finding out patterns of the effect of radiation porosity characteristics under neutron irradiation on point defect concentration, as well as at investigation of the swelling, induced by vacancy and interstitial concentration imbalance in austenitic steels.

The swelling occurs at the temperature, when vacancies and interstitials are mobile. Point defects in the form of non-cascade Frenkel pairs are generated under material irradiation and, migrating along the crystal, can get on sinks. The point defect migration along the crystal and their absorption by sinks form different vacancy and interstitial flows. Neglecting thermal formation of interstitials, which requires very high energy, vacancy concentration changes over time can be described with the equations [1]:

$$\frac{dc_v}{dt} = (G_v + G_{term}) - (J_{vd} + J_{vg} + J_{vt} + J_{vr} + J_{vv}), \qquad (1)$$

$$\frac{dc_i}{dt} = G_i - (J_{id} + J_{ig} + J_{it} + J_{ir} + J_{iv}), \qquad (2)$$

where G_v is the vacancy generation under irradiation, s^{-1}, G_{term} is the thermal generation of vacancies, s^{-1}, J_{vd} is the vacancy flow to dislocations, s^{-1}, J_{vg} is the flow to grain boundaries, s^{-1}, J_{vf} is the flow to twin boundaries, s^{-1}, J_{vr} is the flow to recombination, s^{-1}, J_{vv} is the flow to vacancies in void, s^{-1} (similar designations for interstitials with *i* index). It should be noted that at the beginning of irradiation the vacancy and interstitial concentration is low, so recombination could be neglected, and there are no voids at all. At this stage the two equations are independent themselves and suggest independent solutions.

Neutron irradiation in the material first leads to sharp increase in vacancy concentration, and in ~ 1 s it becomes quasi-steady [1]. Similar concentration changes occur in interstitials, though for a shorter period of time (about 5-7 orders by magnitude less). After a while the voids grow in the crystal and its swelling therefore happens, caused by unbalanced vacancy and interstitial flow to the void. It allows describing the dependence of the void growth volume rate on these flows [2]:

$$\frac{dV_1}{dt} = (J_{vv+} - J_{vv-} - J_{iv+}) \cdot \frac{a^3}{4} = J_{vv} \cdot \frac{a^3}{4} \quad (3)$$

where J_{vv} is the unbalanced vacancy flow to the void, s^{-1}, J_{vv+} is the vacancy flow to the void, s^{-1}, J_{vv-} is the flow of vacancies vaporizing out of the void, s^{-1}, J_{iv+} is the interstitial flow to the void, s^{-1}, a is the lattice parameter, m, the vacancy volume is accepted equal to elementary volume $a^3 / 4$.

Using these equations the void volume changes have been calculated at certain temperature and neutron flux. This can be used to study the dependence of swelling on neutron irradiation characteristics.

Therefore, the proposed physical model of the effect of vacancy porosity characteristics on void growth rate can be used both for the correct interpretation of the investigated structural materials behaviour in reactors and search for new ways to address the swelling issue.

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THE EFFECT OF HIGH-ENERGY ION IRRADIATION ON THE BEHAVIOR OF HELIUM IN FERRITIC STEELS

A.S. Sohatsky[1], T.V. Nguyen[1], K. Kornieieva[1], V.A. Skuratov[1], J.H. O'Connell[2], M. Zdorovet[3], J. Nitling[2]

[1]*FLNR, Joint Institute for Nuclear Research, Dubna, Russia (nvtiep@jinr.ru)*

[2]*CHRTEM, Nelson Mandela University, Port Elizabeth, South Africa*

[3]*Institute of Nuclear Physics, Astana, Kazakhstan*

The impact of swift heavy ions (SHI) with an energy of more than 1 MeV / a during their deceleration consists in the instantaneous heating of the electronic subsystem of the target material in a cylindrical region around the ion track. Depending on the stopping power and thermal diffusivity of the material large-scale structural changes, produced in the material by each individual ion, are possible as a result of quenching processes. In many dielectrics SHI form amorphous tracks with a diameter of several nm, the overlapping of which, with a sufficient dose of irradiation (no more than 10^{13} cm^{-2}), leads to a continuous amorphization of the target to the depth of ion range. In metals individual ion tracks are not visualized by anything, but their repeated overlapping in fcc metals leads to the formation of stacking fault tetrahedrons, clearly visible in TEM (Cu, Ni). The irradiation of Fe-based bcc alloys with SHI does not produce structural defects visible in TEM. Nevertheless, the formation of invisible clusters of point defects in bcc steels under the irradiation with SHI does not excluded. Helium bubbles obtained as a result of additional ion implantation and following annealing can presumably serve as a detector of the presence of structural changes in the material.

The samples: conventional steel AISI410S (Fe-0.08C-13Cr) and powder oxide dispersion-strengthened (ODS) steel Fe-16Cr-2W ODS (“Cr16 ODS”), after cold-rolling, annealing and normalization were taken for the experiment. The structure of the samples was characterized by metallography, X-ray diffractometry and TEM. It was found that the samples have a ferrite structure, including ferritic-martensitic Cr16 (due to the high content of M23C6 carbides in it) and do not have residual internal stresses. Half of the samples were irradiated with Xe ions with an energy of 200 MeV, a dose of 10^{13} cm^{-2}, at room temperature. Then, using ion implantation at room temperature, a uniform helium doping areas with a concentration of 1 at% were formed in all samples, after which the samples were annealed at 800 ° C for 30 min.

TEM studies have shown that in the samples, not irradiated with SHI Xe, helium bubbles grow during annealing only in zones near the sources of thermal vacancies: grain boundaries and unpinned dislocations, while in samples, pre-irradiated with SHI Xe, bubbles grow nowhere. It is shown that the growth of the observed bubbles occurs by their coalescence according to the mechanism of migration and merge, i.e. due to self diffusion. The absence of pore growth in steels, irradiated with Xe ions, is associated with the formation of a high density of defects clusters, invisible in TEM, that prevent the diffusion of vacancies. This conclusion is indirectly confirmed by x-ray measurements, showing certain structural changes in the ferrite as a result of SHI Xe irradiation.

THE PRIMARY RADIATION DAMAGE IN BCC METALS FE AND V: ANALYSIS OF MOLECULAR DYNAMIC DATA

A.B. Sivak[1], D.N. Demidov[1], P.A. Sivak[1], V.M. Chernov[2]
[1]NRC “Kurchatov Institute”, Moscow, Russia (sivak_ab@nrcki.ru)
[2]JRC “VNIINM”, Moscow, Russia

The analysis of the results of molecular dynamic study of primary damage for various damage energies (1, 5, 10, 20, 50 keV) and temperatures (300, 600, 900 K) have been performed in bcc metals Fe and V which are the basis of advanced materials for nuclear fusion and fission structural materials (ferritic-martensitic steels with accelerated decay of the induced activity, low activation vanadium alloys).

The dependences of the number of survived Frenkel pairs after the passage of atomic collision cascades on temperature and damaging energy have been calculated. An analytic expression has been chosen that accurately describes the calculated data within the statistical uncertainty of the data. The amount of produced Frenkel pairs is ~ 25% of the NRT values at damage energies higher than 10 keV. The temperature increase reduces the number of survived Frenkel pairs (maximal effect is at 2.2 keV: 40%-decrease in the Frenkel pairs number with a temperature increase from 300 to 900 K). Size-distributions of clusters of self-point defects have been obtained.

Possible physical mechanisms underlying the observed features of the obtained energy- and temperature-dependences of the number of Frenkel pairs and the cluster size-distributions have been discussed.

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USE OF PURE IRON AND Fe-15Cr-16Ni MODEL ALLOY TO STUDY THE IMPACT OF DISPLACEMENT RATE AND IRRADIATION TEMPERATURE ON CHARGED PARTICLE SIMULATION OF VOID SWELLING

Aaron J. French, Frank A. Garner, Lin Shao
Nuclear Engineering, Texas A&M University, College Station, TX, United States.

Void swelling of iron-base alloys under neutron irradiation is known to be very sensitive to a wide variety of material and environmental variables. Additional sensitivities arise using charged particle simulation. To enhance the credibility of charged particle simulation of neutron-induced swelling it is necessary to isolate and quantify those variables associated with ion simulation from those that are material-specific or involve segregation and phase stability, especially under the influence of surface effects, injected interstitials and segregation along ion-induced gradients in dpa rates that are characteristic of ion irradiation. Additionally, it is important to assess the impact of the much higher rates of atomic displacement used in ion irradiation compared to neutron irradiation.

Using pure iron the synergistic effects of temperature and displacement rate on swelling, expressed in the well-known "temperature shift" concept, are being studied, using 5 MeV Fe ions at peak dpa rates of $3x10^{-3}$, $1x10^{-4}$, and $3x10^{-4}$ dpa/s, to peak dpa values of 50, 75 and 100 dpa, and at irradiation temperatures of 375, 425, 475, and 525°C. In pure bcc iron there are no microchemical or segregation processes involved in the evolution.

Additionally, we are repeating the temperature shift experiment on a pure annealed fcc Fe-15Cr-20Ni model alloy, using a higher temperature range of 475 to 650°C, based on previous ion studies conducted on this alloy. The specimens used are drawn from the same batch used for dpa-rate studies conducted in the FFTF fast reactor at 420°C where a transient shift was observed with change in dpa rate. The lack of minor solutes (Si, P, C, especially) in this alloy preclude precipitation and minimize segregation of major elements along the ion damage depth profile.

The results provide significant insight on the complexities of using charged particle simulation at accelerated dpa rates to study neutron-induced void swelling, especially with respect to the temperature shift and transient shift phenomena.

VALIDATION OF THEORY OF RADIATION DAMAGE AGAINST EXPERIMENTAL DATA

O.V. Ogorodnikova[1], M. Majerle[2], V.V. Gann[3], J. Cizek[4], P. Hruska[4], S. Simakov[5], M. Stefanik[2], V. Zach[2]
[1]*National Research Nuclear University "MEPHI", Russia,*
[2]*Nuclear Physics Institute of the CAS, Czech Republic,*
[3]*National Science Centre "Kharkov Institute of Physics and Technology", Ukraine,*
[4]*Charles University, Czech Republic,*
[5]*Institute for Neutron Physics and Reactor Technology, Germany*

Tungsten (W) is a leading candidate of plasma-facing material in ITER and DEMO reactors. Reduced activated ferritic-martensitic (RAFM) steels are one of priority candidate materials for advanced fission and fusion structural materials. In this regards, a fundamental understanding of radiation damage in W and Fe is critical for the design of materials in extreme environment, for example, for fusion reactors. However, working on irradiated materials is costly. To simulate neutron-induced damage in nuclear materials, ion beams are widely used. However, it is not always clear if the mechanisms under the ion irradiation are relevant to lower dose rate and the primary knock-on atom (PKA) spectrum under neutron irradiation. In order to simulate the real experimental conditions of irradiation of reactor materials for reliable predictions of radiation damage in fusion reactors, it is necessary to establish the adequacy of the resulting damage produced by different types of irradiation. For this reason, we compare radiation-induced defects in W and Fe created by protons with an energy of 22.5 MeV and neutrons with continuous spectrum up to 35 MeV. Study of different distributions of radiation-induced vacancies and vacancy clusters of different sizes created by different types of irradiation allows us an experimental validation of the value of "displacement per atom" (dpa) when comparing different types of irradiation. Radiation-induced defects have been studied by well-established method of positron-annihilation lifetime-spectroscopy (PALS). New experimental data in combination with data available from the literature provide an evidence that the classical Norgett-Robinson-Torrens (NRT_dpa) model describes well experimental data for W. On the other hand, the recently developed athermal recombination corrected (arc_dpa) model [1] describes well experimental data in the case of Fe. Reasons are discussed.

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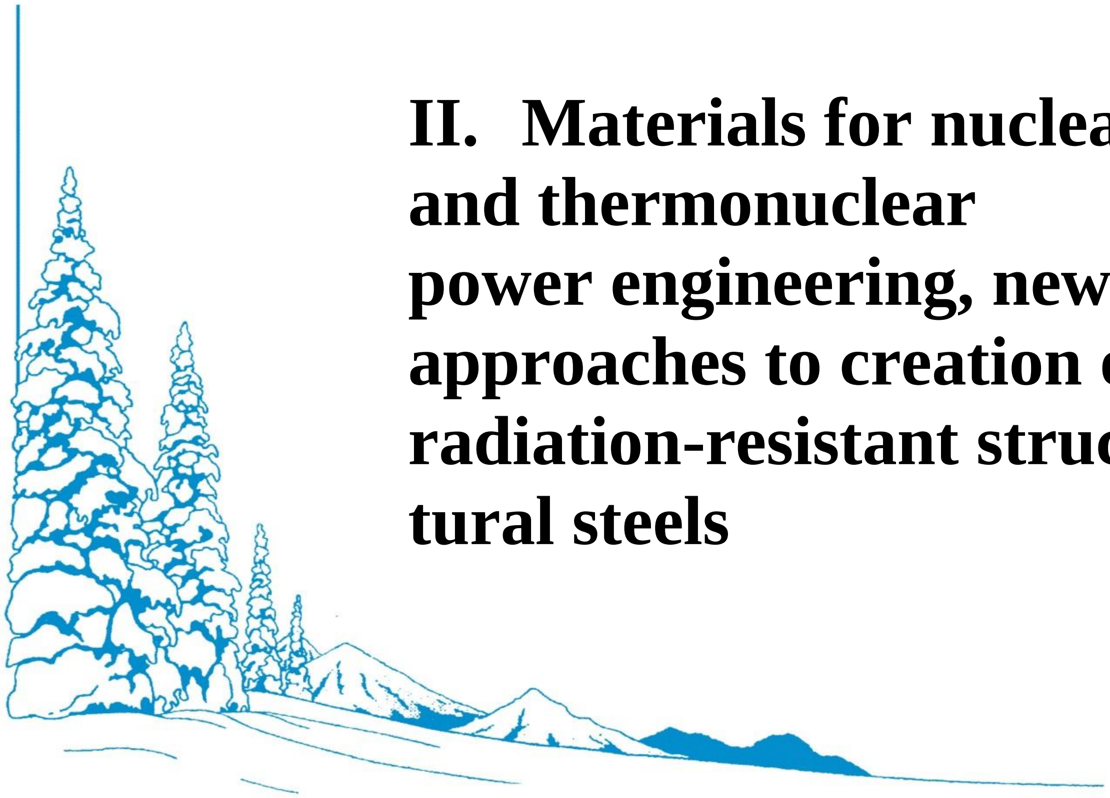

II. Materials for nuclear and thermonuclear power engineering, new approaches to creation of radiation-resistant structural steels

The most topical problem of today is development of new metal materials for fusion and fission-type reactors. Ion particular, the reactors currently under construction (BN-800) and future fast-neutron reactor projects (BN-1800) still expect the constructional materials showing high radiation resistance to withstand the damaging dose of 100-130 dpa, which would ensure the required level of nuclear fuel burnup. The Section includes a great number of material-science presentations on radiation-induced changes in physical and mechanical properties of different high-pressure-vessel materials (those currently in use and showing promise). A consideration will be given to material-science problems of high-temperature creep, swelling of fcc and bcc steels, and the effect of radiation on austenitic high-pressure-vessel steels, including the only "standard" austenitic ChS-68 steel for the BN-600 reactor fuel elements. The results obtained for real high-pressure-vessel materials are analyzed proceeding from the general principles of radiation physics of solids. This Section also includes papers by Russian and foreign investigators reporting the results of studies into the effect of oxide and intermetallic aging on the structure and the mechanical properties of high-alloy constructional steels. Primary emphasis will be on the recently developed steels strengthened with heat-resistant oxides (yttrium, titanium, and thorium).

A NEW APPROACH TO IMPROVING THE THERMAL STABILITY OF CORROSION-RESISTANT CHROMIUM-NICKEL ALLOYS

A.V. Makarov[1], N.N. Soboleva[2], I.Yu. Malygina[2], M.S. Gibzun[1]
[1]*M.N. Miheev Institute of Metal Physics of Ural Branch of the Russian Academy of Sciences, Yekaterinburg, Russia (av-mak@yandex.ru)*
[2]*Institute of Engineering Science, Ural Branch of the Russian Academy of Sciences, Yekaterinburg, Russia*

Coatings made of corrosion-resistant nickel-chromium alloys are widely used to improve the quality of various products, including those operated under conditions of significant heating (rolls and roller tables in hot rolling mills, hot-press dies, walls of crystallizers of continuous casting machines, parts of heat exchangers, turbines, solid fuel boilers and etc.). In this regard, an important task is to find ways to improve the thermal stability of the structure and properties of nickel-chromium alloys.

For NiCrBSi coatings formed by gas-powder laser cladding, a significant decrease in strength and tribological properties was found when heated to 900-950 °C. However, annealing at temperatures of 1000-1075 °C contributes to a sharp improvement in properties to levels corresponding or even exceeding the characteristics of the original coating formed by laser cladding. This is due to the formation in the process of annealing and subsequent cooling of high-strength wear-resistant frame of large chromium carbides and borides. The formed structure is thermally stable and, as a result, has increased hardness and abrasive wear resistance when heated up to the annealing temperature [1, 2]. A decrease in the cooling rate from the annealing temperature can further significantly improve the wear resistance of the alloy. High-temperature annealing of the coating reduces by 1.8 times the wear intensity under sliding friction at sliding speeds of 6.1 and 9.3 m/s, when the temperature of frictional heating of the surface layer reaches ~900 °C and above. The structure with large chromium borides and carbides formed as a result of annealing limits the development of the processes of heat seizure and plastic edging. It provides an increase in the frictional heat resistance of the NiCrBSi alloy.

Based on the discovered effect of increasing the mechanical and tribological characteristics of NiCrBSi laser clad coatings as a result of annealing, a new approach is proposed to improve the thermal stability of chromium-nickel alloys to temperatures of 1000 °C or more, including coating formation and subsequent high-temperature annealing at temperatures of 1000-1075 °C (RF patent No. 2492980) [3]. The proposed new approach expands opportunities for a high-temperature use of chromium-nickel alloys.

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ALLOY DESIGN, MICROSTRUCTURE CHARACTERIZATION AND MECHANICAL PERFORMANCE OF RADIATION-RESISTANT HIGH-ENTROPY ALLOY

Y. Zhang, W.Q. Jiang, Z.W. Zhang

Key Laboratory of Superlight Materials and Surface Technology, Ministry of Education, College of Materials Science and Chemical Engineering, Harbin Engineering University, Harbin 150001, China (zhangyang0115@hrbeu.edu.cn)

In recent years, one kind of new alloys, high-entropy alloy has received more and more attentions due to its unique structure and excellent properties. Promising properties in hardness, wear resistance, oxidation resistance and corrosion resistance, especially irradiation resistence can be obtained by proper composition design. By using a new design philosophy of high-entropy and low-enthalpy, pure and 0.1wt.%C doped $Fe_{30}Cr_{25}Ni_{20}Co_{15}Mn_{10}$ high-entropy alloys were designed to further decrease the free energy and enhance the stability. The alloys were prepared using arc melting method. The effects of carbon element on microstructure and mechanical properties of as-cast and annealed CoCrFeMnNi alloy were investigated. XRD results show that all the alloys were single fcc stucture. The introduction of carbon element into CoCrFeMnNi alloy led to the formation of carbonization, refined grain and increased the mechanical properties. The effect of annealing on the microstructure and mechanical properties were also investigated, and the annealing temperature were 800 ^{o}C and 1000 ^{o}C. After annealing, the anisotropy among RD, ND and TD directions became weaker, and the hardness decreased generally with the increase of annealing temperature. As the annealing temperature increased, the formation of the α-oriented line texture and the randomization of the grain orientation were caused. The addition of C element affects the formation of annealed twins, the tendency of grain orientation randomization during high temperature annealing is discussed.

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DETERMINATION OF CRITICAL BRITTLENESS TEMPERATURE OF THE ALLOY WITH ALTERNATING CHEMICAL COMPOSITION

S.V. Barsanova, M.V. Evseev, V.I. Pastukhov, R.P. Karagergi

Joint Stock Company "Institute of Nuclear Materials"

One of the main tasks during prediction of service life for VVER type nuclear facilities is to assess brittle fracture resistance (BFR) and calculate critical brittleness temperature (T_c) of the reactor vessel material. At the welding joints of the reactor vessel with anticorrosive cladding there is chemical and structural nonuniformity of material, including vessel material, weld, area of welding thermal influence, and anticorrosive cladding metal. Due to nonuniformity these areas become more sensitive to radiation-induced embrittlement, leading to critical brittleness temperature shift to higher temperatures and degradation of mechanical properties. Therefore it is necessary to examine the material of such areas both in its initial state and after irradiation to assess BFR of the metal of base metal and anticorrosive cladding welding properly.

The paper gives experimental data on an electroslag remelting ingot with alternating chemical composition, modelling a welding boundary of the reactor vessel material (15Cr2NiMoVN steel) and anticorrosive cladding material (08Cr25Ni13Mn-U steel). The billet to be examined was made by electroslag remelting of electrodes from dissimilar materials. The bottom part of the ingot is made of pearlitic steel; the top part is made of austenitic steel. Between these regions there is a metal of intermediate composition. The billet was segmented vertically into 10 parts (areas) with alternating chemical composition and structure.

The paper aims at determination of critical brittleness temperature of alloy samples with alternating chemical composition. The electroslag remelting ingot was examined by impact testing of small samples with a Charpy notch, 3.3x3.3x26 mm in size. The tests were carried out with Charpy impact machine at different temperatures (from -130 to 250°C). Serial curves of toughness (KCV), ductile bending fraction (B) and relative sample widening (δ_B), depending on testing temperature, were obtained for samples from different areas. Fractographic studies were carried out to determine ductile fracture. Based on these data the values of critical brittleness temperature were calculated for the material in its initial state (T_{c0}). Also short-term mechanical tests were carried out and hardness variation along the ingot was determined.

The paper concludes that this technique to determine critical brittleness temperature can be applied for samples with alternating chemical composition after irradiation and prediction of working capacity of vessel steels.

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EFFECT OF HIGH-DOSE NEUTRON IRRADIATION ON MICROSTRUCTURE AND PROPERTIES OF TITANIUM BERYLLIDE

R. Gaisin[1], V. Chakin[1], R. Rolli[1], M. Klimenkov[1], P. Vladimirov[1], A. Fedorov[2], L. Magielsen[2]
[1]Karlsruhe Institute of Technology, Institute for Applied Materials, Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen, Germany (ramil.gaisin@kit.edu)
[2]Nuclear Research and Consultancy Group, Westerduinweg 3, Postbus 25, Petten, 1755 ZG, the Netherlands

Beryllium was planned to be used as a neutron multiplier material for the Helium Cooled Pebble Bed (HCPB) blanket concept in the DEMO fusion reactor. However, recent investigations of beryllium pebbles irradiated at high neutron doses show that beryllium demonstrates high swelling, low corrosion resistance in air and steam, high tritium retention behavior. This significant degradation of the properties raises doubts on the use of beryllium in the DEMO blanket. Intermetallic compounds of beryllium such as beryllides show much less swelling under irradiation. Titanium beryllide has higher working temperatures, corrosion resistance and strength as well as lower tritium retention. However, the effect of irradiation at high temperatures with high neutron doses on the structure and properties of titanium beryllide was not sufficiently studied.

In the present study, two kinds of titanium beryllide were investigated. The first kind of Be-7 at.%Ti alloy was received from JAEA, Japan. It was fabricated using the conventional argon melting process. The second kind of $Be_{12}Ti$ was fabricated in KIT, Karlsruhe, Germany using powder metallurgy methods such as the hot extrusion and the hot isostatic pressing (HIP). The melted titanium beryllide and the melted pure beryllium were irradiated at temperatures of 438-768°C and neutron damage doses of 23-37 dpa in the HFR, Petten, the Netherlands. Microstructure and microhardness of both irradiated materials were studied using an optical microscope, scanning and transmission electron microscopes. Thermal desorption tests of these irradiated materials were performed with a quadrupole mass-spectrometer and an ionization chamber. In case of titanium beryllide fabricated by powder metallurgy methods, the effect of HIP temperature on microstructure and properties of this material was also investigated.

Microstructure investigations showed, that as-cast irradiated Be-7 at.%Ti has two phases such as pure beryllium and $Be_{12}Ti$. The volume fraction of beryllium in the titanium beryllide, produced by powder metallurgy, is much lower compared to the as-cast beryllide. With increasing HIP temperature, the amount of residual beryllium decreases.

The microstructural studies of the irradiated cast titanium beryllide showed that helium bubbles are mainly located in the beryllium phase, and titanium beryllide has almost no bubbles even after irradiation at the highest temperature. Experiments on thermal desorption showed that the titanium beryllide samples irradiated at temperatures of 525–768°C contain negligible amounts of tritium in comparison with the beryllium phase which has a much higher tritium retention. The possible advantages of the use of titanium beryllide fabricated by powder metallurgy compared to the as-cast beryllide under irradiation are discussed.

EFFECT OF LOW-TEMPERATURE ION IRRADIATION ON THE NANOSTRUCTURE OF CHS-139 STEEL

N.A. Iskandarov, S.V. Rogozhkin, A.A. Nikitin, A.A. Bogachev, A.A. Khomich, V.V. Khoroshilov, A.A. Lukyanchuk, O.A. Raznitsyn, A.S. Shutov, P.A. Fedin, T.V. Kulevoy
NRC «Kurchatov Institute» - ITEP, Moscow, Russia (nasib.iskandarov@itep.ru)

Heat resistant ferritic-martensitic steels are the most promising structural materials for new generation of fusion and fast breeder power plants. Taking into account that ferritic-martensitic steels demonstrate the low-temperature radiation embrittlement (LTRE), information about behavior of the micro- and nanostructure of these materials under low-temperature irradiation is important.

Specimens of ChS-139 steel were irradiated by Fe ion beam at 250 °C, 300 °C, and 400 °C up to few dpa. The atom probe analysis of irradiated samples revealed radiation-induced clusters and Cottrell atmospheres enriched in Ni, Si, and Mn. The typical sizes of these clusters in all irradiated states were about few nm, and their number density was ~ 10^{24} m^{-3}. In unirradiated ChS-139 steel, a large amount of nanoclusters (~10^{23} m^{-3}) enriched in Cr, V, Nb, and N was found out in previous work [1]. In ChS-139 steel irradiated to 6 dpa, the concentrations of enriching elements in Cr-V-Nb-N clusters decreased noticeably, while the size of clusters did not change. The typical sizes and the number density of Cr–V–Nb–N clusters were 7 ± 4 nm and $10^{22}\div10^{23}$ m^{-3}. The magnitude of detected radiation induced effects indicates evident contribution of them to LTRE of ChS-139 steel.

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FEATURES OF THE FORMATION OF THE SURFACE OF NEUTRON-ABSORBING COATINGS ON THE BASIS OF TITANIUM BORIDE WHEN THE MAGNETRON SPUTERRING A COMPOSITE CATHODE TARGET WITH THE B-TI SYSTEM

A.S. Larionov[1], L.V. Chekushina[1], S.B. Kislitsin[1,2], A.S. Dikov[1,2]
[1]*NRP RK, Almaty, Kazakhstan (gaskonets@list.ru)*
[2]*NRNU MEPhI, Moskow, Russia*

Current volumes of accumulated radioactive waste and their growth forecasts force a transition to a higher level of organization of the process of handling radioactive waste (RW) and spent nuclear fuel (SNF) - transfer them to a safe state throughout the entire period of potential radiation danger [1]. SNF contains fissile materials that are sources of neutron radiation, which leads to the regeneration of part of the fuel and an increase in overall activity. It is possible to increase radiation safety by reducing the number of neutrons. Neutron-absorbing materials are used for this. Boron has the largest absorption cross section for thermal neutrons, which makes it the most promising element for creating neutron-absorbing coatings [2].

The paper presents the results of studies of the structure and phase composition of neutron-absorbing coatings of titanium boride, applied by magnetron sputtering from a target of complex composition on a steel substrate. Target for magnetron sputtering made by sintering powders of titanium and boron carbide. Studies of the structure and elemental composition of the coating performed by X-ray diffractometry, SPM, SEM and EMF. The applied method of forming this coating made it possible to obtain a sprayed layer characterized as a mixture of two phases: the hexagonal phase of Ti_2B_5 and the orthorhombic phase of TiB_{12}. The first is a matrix, the second is represented as an implementation phase — evenly distributed in a matrix particles with a diameter of up to 0.5 μm. The matrix has a grain structure with a grain size of ~ 10 nm. The total content of boron is ~ 80 at.%, which is 4 times higher than the concentration of boron in coatings obtained by plasma spraying of B_4C powder. The use of titanium boride coatings synthesized by magnetron sputtering as neutron-absorbing materials will reduce the thickness of the coating as compared to boron carbide coatings synthesized by plasma spraying [3].

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IMPROVEMENT OF THE SURFACE MECHANICAL PROPERTIES OF STRUCTURAL MATERIALS BY ULTRASONIC IMPACT–FRICTION TREATMENT

S.N. Luchko[1], N.V. Lezhnin[1], A.V. Makarov[1], M.S. Gibzun[1]
[1]*Mikheev Institute of Metal Physics, Ural Branch, Russian Academy of Sciences, Ekaterinburg, Russia (serojaluchko@gmail.com)*

Nanostructuring surface treatments with indenters from solid materials are modern methods of severe plastic deformation for local change of the structure and hardening of materials. Known is a method of standard ultrasonic treatment with a lubricating material (industrial oil) at the normal (perpendicular to the machined surface) exposure to the indenter oscillating with ultrasonic frequency. This treatment does not provide the maximum degree of plastic deformation of the surface layer. The objective of this work is to study and comparison of ultrasonic impact and ultrasonic impact-friction treatments [1] for hardening flat samples of steel 09G2S.

The microhardness measurement was carried out according to the restitutedindentation method by the Vickers pyramid when the indenter load of 100 g. It was established that the initial microhardness of the samples was ~ 200 HV0,1. After the standard ultrasonic impact treatment with the lubricant in the normal exposure indenter, the hardness increased to ~ 263 HV0,1. When replacing industrial oil with argon, hardness increased to ~ 370 HV0,1 under normal exposure. This indicates an increase in the coefficient (force) of friction and, as a consequence, an increase in the deformation of the surface layer. Argon is used as protective gas atmosphere to prevent oxygen embrittlement of the diffusion active highly dispersed surface layer formed by ultrasonic treatments.

The introduction of the friction component when using the inclination of the indenter to the treated surface increases the shear component of the plastic deformation. Treatment of the steel surface with the use of a lubricant and the subsequent inclination of the indenter to the angles of 10, 20, 30 and 40° from the vertical to the surface allows increasing the hardness of the material to ~270, 370,400 and 435 HV0,1, respectively. Ultrasonic impact-friction treatment in argon showed more effective hardening of steel to ~380, 395, 485 and 732 HV0,1.

Increasing the angle of inclination of the indenter to the surface and the exclusion of lubricants leads to a significant increase in strength by increasing the coefficient of friction in the pair "processed material – indenter, and as a consequence, the formation on the surface of a highly dispersed layer of greater thickness.

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ION IRRADIATION EFFECTS ON NANOCLUSTER PRECIPITATION IN STEELS

Z.W. Zhang[1,2], Y. Zhang[1], C.T. Liu[3], X-L. Wang[3], J.R. Williams[2], B.A. Chin[2]
[1] *Harbin Engineering University, Harbin 150001, China*
[2] *Auburn University, Auburn, AL 36849, USA*
[3] *City University of Hong Kong, Kowloon, Hong Kong*

Newly-developed precipitate-strengthened ferritic steels with and without pre-existing nanoscale precipitates were irradiated with 4 MeV protons to a dose of ~5 mdpa at 50 °C and subsequently examined by nanoindentation and atom probe tomography (APT). Irradiation-enhanced precipitation and coarsening of pre-existing nanoscale precipitates were observed. Proton irradiation induces the precipitation reaction and coarsening of pre-existing nanoscale precipitates, and these results are similar to a thermal aging process. The precipitation and coarsening of nanoscale precipitates are responsible for the changes in hardness. The observation of the radiation-induced softening is essentially due to the coarsening of the pre-existing Cu-rich nanoscale precipitates. The implication of the precipitation on the embrittlement of reactor-pressure-vessel steels after irradiation is discussed.

MICROSTRUCTURE, DEFORMATION AND IRRADIATION CHARACTERISTICS OF OXIDE DISPERSION STRENGTHENED ALLOYS FOR NUCLEAR APPLICATIONS

Yinbin Miao[1], Xiang Liu[2], James Stubbins[3]
[1]*Materials Scientist, Chemical and Fuel Cycle Technologies Division, Argonne National Lab, Lemont, IL 60439, USA*
[2]*Research Associate, Advanced Post-Irradiation Examination Department, Idaho National Lab, Idaho Falls, ID 83402, USA*
[3]*Donald Biggar Willett Professor, Department of Nuclear, Plasma and Radiological Engineering, University of Illinois at Urbana-Champaign, Urbana, IL, 61801, USA*
(jstubbin@illinois.edu)

There has been a continuing effort to develop enhanced versions of several types of engineering alloys by strengthening them with a very high number density of very small oxide particles. Most of the recent work has concentrated on ferritic/martensitic ODS alloy development and performance. It is clear that the addition of a fine distribution of nano-oxide dispersoids will provide major improvements in material strength especially at very high temperatures and extend the application temperature range to levels appropriate for advanced nuclear systems. Since the oxide particles are actually ceramics, they should maintain their stability and strengthening capabilities even at very high temperatures. For nuclear applications where atomic displacement damage takes place, the particles also offer a very large amount of internal surface area which can potentially absorb irradiation-induced defects to reduce radiation damage effects.

This process of making metal alloys with dispersed oxide particles has been attempted in a wide variety of metal systems with some success. The current heavy emphasis on developing ODS F/M steels has resulted in a nearly negligible interest in the development of ODS stainless steels. This talk will discuss the possibilities for the development of ODS austenitic steels. Since austenitic stainless steels are currently used for a wide variety of applications in current nuclear reactors and are slated for use in a number of advanced nuclear fission and nuclear fusion reactor systems, the development of ODS austenitic alloys should be of considerable interest. The research work discusses the oxide dispersoid microstructure and mechanical behavior of this class of new alloys for nuclear applications [1,2]. The talk will also cover recent results on the irradiation behavior of ODS particles and other microstructural features in the ferritic alloys [3,4].

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NEW DATA AND INSIGHTS ON PREDICTION OF VOID SWELLING IN AUSTENITIC PRESSURE VESSEL INTERNALS

F.A. Garner
Texas A&M university, College Station TX

It is well known that void swelling is an issue that must be addressed for austenitic pressure vessel components, particularly for extended lifetimes of 60 years or more. While there are currently available predictive correlations for swelling of 304 and 316 stainless steel, their applicability to pressure vessel internals of PWRs has not been established, especially as all observed swelling levels in PWRS are somewhat scattered but are less than 1% at the highest doses examined.

The major problem is that these correlations were developed using data from the EBR-II fast reactor which operated at temperatures above 370°C, while most of PWR internals will operate at lower temperatures and with an inherently different type of temperature history, as well as operating under quite different neutron-flux spectra and atomic displacement rates.

The current predictive equation for 304 stainless steel was developed from out-of-core regions in EBR-II fast reactor where the atomic displacement rates are comparable to that of PWR baffle plates, but at very much lower generation rates of helium and hydrogen, which are known influencers of void swelling. Additionally, there is significant scatter in the EBR-II 304 stainless steel data base from which the swelling correlation was derived and the low temperature portion of these data has not been adequately examined since they exist at lower dose levels obtained near the core lower boundary.

The major unresolved question concerning the existing swelling correlation is:

While it is well-known that austenitic stainless steels will eventually swell at a post-transient swelling rate of ~1%/dpa over temperatures and dpa rates characteristic of fast reactors, as assumed in the current swelling correlation, is it reasonable to assume that a similar high swelling rate must occur under PWR-relevant conditions?

This activity involves reanalysis of many earlier data sets involving components of 304 stainless steel. Not all of these data sets have been previously published. Additional data from Russian and British variants of 300 series steels irradiated in fast reactors at lower PWR-relevant temperatures are also used to assess the generality of the derived conclusions concerning low temperature swelling behavior.

The major conclusion of this effort is that while the post-transient onset of ~1%/dpa swelling rate, a rate sometimes referred to as a "crystal constant", eventually develops over a wide range of temperatures in austenitic steels, there appears to be another previously unrecognized, much lower swelling rate of ~0.06 to 0.07%/dpa that precedes the 1%/dpa regime. This second crystal constant often persists to very high doses, especially at lower irradiation temperatures characteristic of PWR internals.

It therefore appears that the 1%/dpa swelling rate mandated in the current swelling correlation is not destiny and may not apply to most of the steel in PWR internals operating at lower temperatures. This is a very exciting possibility that swelling may not as large an issue in PWRs as previously anticipated.

RADIATION PHENOMENA IN IRRADIATED AUSTENITIC STEELS AFTER LONG IRRADIATION IN BOR-60 REACTOR

V.S. Neustroev, S.V. Belozerov, E.I. Makarov, D.E. Markelov, A.V. Obukhov, D.A. Sokolowsky
JSC "State Scientific Center – Research Institute of Atomic Reactors", Dimitrovgrad, Russia
(neustroev@niiar.ru)

To assess the state of the material after long-term irradiation, it is necessary to conduct studies of elements and structures that have been operated for a long time at different temperatures in the BOR-60 reactor. However, it is impossible to do without special experiments on samples of various types with the maintenance of sufficiently stable temperature conditions of irradiation, determining a particular radiation phenomenon.

This report presents some results of recent studies of radiation phenomena, such as radiation swelling, low-temperature radiation hardening and embrittlement of austenitic steels. The influence of irradiation duration (dose rate) on the properties and structure of irradiated steels is discussed. The influence of microstructure formation features on the physical and mechanical properties of neutron-irradiated steels is also considered.

REMOTE ELECTRIC POTENTIAL TESTING OF THIN-WALLED TUBES IN HOT CELLS

V.S. Shikhalev, S.V. Bryushkov
Joint Stock Company "Institute of Nuclear Materials"

The effect of radiation and technological defects on variation of electrical resistance of thin-walled tube claddings is discussed. Electric potential non-destructive testing of materials (EPT) and metrological performance of the equipment are described. Theoretical dependence and experimental results connecting vacancy swelling of the cladding material, austenitic stainless steel, with its electrical resistance variation.

In order to apply EPT for thin-walled tubes, INM has developed and manufactured experimental inchamber devices and assessed the technique as a cladding quality criterion.

Claddings of standard and experimental thin-walled tubes were examined with electric potential testing after operation in the reactor. The patterns and kinds of material damages were investigated; new data on irradiation effect on electric resistance variation of the cladding material were obtained. Vacancy swelling degree and cladding reduction due to corrosion were assessed, and the effect of structural and technological peculiarities of fuel pins on EPT results was demonstrated in terms of fuel pins of experimental fuel assemblies.

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SURFACE MICRORELIEF FEATURES OF CONSTRUCTION STEEL STRENGTHENED BY ULTRASONIC IMPACT–FRICTIONAL TREATMENT

M.S. Gibzun[1], N.V. Lezhnin[1], A.V. Makarov[1,2], S.N. Luchko[1]
[1]*Mikheev Institute of Metal Physics, Ural Branch, Russian Academy of Sciences, Ekaterinburg, Russia (nlezhnin@bk.ru)*
[2]*Institute of Engineering Science, Ural Branch, Russian Academy of Sciences, Ekaterinburg, Russia*

The parameters of the surface layer have a significant impact on the performance of materials, such as wear resistance, friction coefficient and fatigue properties. The advantages of surface deformation treatments are the possibility of combining with the finishing treatment of parts, ease of implementation on an industrial scale, low cost and environmental friendliness.

The objective of this work is to assess the influence of regimes and the environment on the surface roughness and processing efficiency of ultrasonic impact-frictional treatment [1].

The steel 09G2S after normalization 950ºC was subjected to ultrasonic impact-friction treatment with 6 mm hemispherical carbide indenter under static load 147 N (15 kg) at angles 90º, 80º, 70º, 60º, 50º to the surface. The treatment was carried out a single scan of indenter on the surface with a 0.1 mm feed per pass and a tool speed of 600 mm/min.The roughness parameters were determined with the help of optical profilometer Wyko NT-1100 using5 surface images in random places at magnifications of 5 and 100 times.

According to the results of the study, the macropattern in the form of parallel “protrusions” and “troughs” with a step of 0.2 mm and a microrelief formed when the instrument contacts the surface to be processed can be distinguished on the treated surface.

After ultrasonic impact-friction treatment with the lubricant, the average roughness value R_a of the macrorelief remains approximately at the same level (1.7-1.9 μm) in the range of processing angles from 90 ° to 70 ° degrees, then R_a increases to ~ 2.4 μm at processing angles of 60 ° and 50º.At the same time, for the microsites, the Ra surface remains approximately at the same level (0.20-0.25 μm) for all the processing angles.

Ultrasonic impact-friction treatment in an oxide-free environment of argon gives an average roughness value R_a of the macrorelief at a level of 1.4-1.6 μm in the range of processing angles from 90 ° to 70 °, then it grows to ~ 2.2 μm at an angle of 60 ° and up to ~ 3.5 μm at an angle of processing 50º.At the same time, the opposite is observed: R_a microrelief is maintained at a level of 0.23–0.29 μm in the range of processing angles from 90 ° to 70 ° degrees, then decreases to about 0.13 μm at a processing angle of 60 ° and below 0.1 μm at a processing angle of 50 °.An increase in the macrorelief indicates an increase in the shear component of plastic deformation during processing with smaller angles.

Thus:

1. Ultrasonic impact-frictional treatment can give a potential surface finish of the order of R_a = 0.2 μm, which was established at the micro-sites, despite the deterioration of the surface relief obtained in this work.

2. The use of argon as a protective medium makes it possible to achieve large degrees of plastic deformation while ensuring parameters comparable to the roughness parameters obtained when conducting ultrasonic impact-friction treatment with the use of a lubricant.

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SURFACE STRENGTHENING OF CONSTRUCTIONAL STEELS FOR NUCLEAR POWER INDUSTRY BY ULTRASONIC IMPACT–FRICTIONAL TREATMENT

N.V. Lezhnin[1], A.V. Makarov[1,2], S.N. Luchko[1], M.S. Gibzun[1], M.A. Chalina[1]
[1]*Mikheev Institute of Metal Physics, Ural Branch, Russian Academy of Sciences, Ekaterinburg, Russia (nlezhnin@bk.ru)*
[2]*Institute of Engineering Science, Ural Branch, Russian Academy of Sciences, Ekaterinburg, Russia*

One of the most important tasks of materials science is to ensure the reliability and service life of products by improving the performance of materials.Today, widespread technologyto locally modify the properties of the finished part, while maintaining the structure of the product as a whole.Deformation surface treatments are an affordable and environmentally friendly method of hardening the material, which allows a significant influence on the mechanical and operational characteristics of products and welded joints due to the formation of ultrafine and nanostructures.Strain hardeningis also an effective method for thermally non-refractory materials such as austenitic stainless steels.Another important feature of the deformation treatment is the formation of a gradient structure, providing a smooth transition from a hardened surface to a softer core.

The aim of this work was to compare ultrasonic impact-friction treatment[1]proposed by the authorswith the traditional methods of surface strain hardening treatment: frictional treatment with a sliding hemisphericalindenter and ultrasonic impact treatment (application of static load normal to the treated surface). The idea of ultrasonic impact-friction treatment is to combine significant degrees of plastic deformation of the metal due to high pressures under high-energy ultrasonic impact, and the activation of the rotational mode of plastic flow, due to shear deformation under friction action. Thus, the implemented conditions are similar to high-pressure torsion process and lead to grain refinement down to the nanoscale. The application of the load at different angles to the treated surface made it possible to estimate the contribution of normal and shear deformation components to the depth and hardening of the surface layer.

The treatments were carried out onsed in nuclear industry structural steel grades 04Kh17N8GMT in the quenched state and 09G2S in the normalized condition. The initial hardness of both materials was ~200 HV0.1. The methods of metallography, microdurometry and 3D profilometry have established:

1. Ultrasonic impact-friction treatment allows to significantly increase the depth and hardness of the deformed surface layer in comparison with traditional ultrasonic impact treatment.

2. At the same time, an increase in strength is accompanied by a deterioration in the surface quality due to the formation of a deformation macrorelief at small loading angles and an increase in the arithmetic average deviation of the surface profile R_a. The solution to this problem is the subject of further research.

Therefore, ultrasonic impact-friction treatment can be considered as a promising method for surface modification of structural materials, allowing to increase the degree and depth of hardening while maintaining high surface quality.

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STABILITY EVALUATION OF MULTICOMPONENT ALLOYS VIA ACCURATE ON-LATTICE MODEL

E.A. Meshkov, I.I. Novoselov, A.V. Yanilkin
Dukhov Research Institute of Automatics (evgenij.meshkov@gmail.com)

High-entropy alloys are the promising class of metal materials (HEA). These materials contain four or more major components with concentrations ranging from 5 to 35 at.% [1]. It was shown that some HEAs have excellent mechanical properties (high ductility, high tensile strength, hardness), as well as high resistance to radiation-induced degradation processes (low swelling, hardening, segregation of components) [2]. Therefore, HEAs are considered as promising radiation-resistant materials.

In this paper, we investigated the local ordering of atoms in a high-entropy alloy CoCrFeNi via machine learning interatomic potential (MLIP) [3] in a wide temperature range. The *ab-anitio* calculations were used to parameterize MLIP, which was later used in kinetic Monte-Carlo calculations. The results of the study of local ordering in CoCrFeNi are presented in Fig. 1. In this figure, the y-axis shows the order parameter (SRO), which numerically characterizes the formation of random solid solution (SRO ≈ 0), sublattices

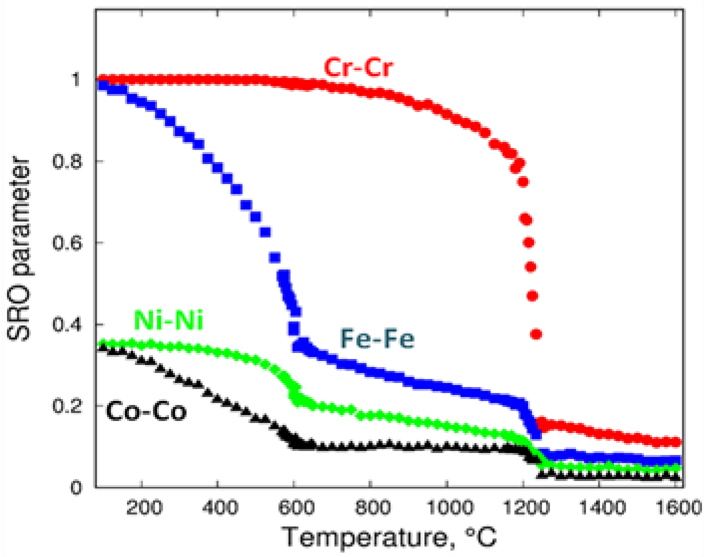

Fig.1 Temperature dependence of SRO parameter of CoCrFeNi componenets

(SRO ≈ 1) or clusters (SRO < 0) in the system. According to the obtained data, simple cubic sublattices of iron (blue squares) and chromium (red circles) are formed at temperatures up to 600 °C and 1230 °C, respectively, in the investigated system with FCC lattice.

The obtained results are consistent with previously published experimental and theoretical data [4]. However, the temperature range of existence of iron and chromium sublattices was determined for the first time. These results can be used to identify the causes of radiation resistance of alloys of this class.

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STUDY OF STEEL 12Cr18Ni10Ti CORROSION RESISTANCE IN PROCESS AND MODEL SOLUTIONS OF RADIOACTIVE SUSPENSIONS CONTAINED IN HLW STORAGE TANKS

M.A. Litvinova, V.P. Lelikov, A.A. Maltsev
FSUE Mayak PA, Ozyorsk, Russia (cpl@po-mayak.ru)

The research objective was to study corrosion resistance of steel 12X18H10T that in terms of composition, physical and chemical properties and corrosion resistance is the closest to steel 08X18H9T used for lining HLW storage tanks at the RT-1 Plant. Studies were conducted in process solutions and in solutions, which simulated the process medium of storage tanks in terms of composition.

Chemical composition of all model solutions corresponded to the average composition of contents of storage tanks. In the course of testing steel 12X18H10T under model conditions and studying impact of concentration of chloride ions and hydroxide ions, temperature and test duration: mass concentration of NaOH varied in solution from 0 to 150 g/dm^3 and that of NaCl varied from 1 to 6 g/dm^3; temperature influence was studied at 20, 60 and 95 °C at the test duration of 25 hours for each temperature.

Studies performed in model solutions demonstrated that, under the given conditions, steel 12X18H10T corrosion resistance is high. Only at first cycles, for some samples, increased corrosion rate was observed. However, these weight losses related to existence of sample surface defects. Later on, corrosion rate of steel 12X18H10T remained at an insignificant level.

Study of corrosion resistance of steel 12X18H10T in real process media of the RT-1 Plant storage tanks was carried out using witness samples with the total exposure period of 15,520 hours (730 days).

Study of corrosion resistance of steel 12X18H10T undertaken in the process media of storage tanks demonstrated that the average corrosion rate of witness samples made of steel 12X18H10T in contact with the process media of storage tanks was not more than 0.44 µm for the period from 2014 to 2016.

Taking into account peculiarities of the test procedures, the obtained corrosion rate was insignificant as applied to operating conditions of the process equipment made of corrosion-resistant steels contacting with radioactive media.

The results of undertaken studies demonstrated high corrosion resistance of steel 12X18H10T in model and process solutions of storage tanks. For the given reasons, it follows that the constructional material used for lining the RT-1 Plant storage tanks (i.e. steel 08X18H9T, which is similar in its physical and chemical parameters to parameters of steel 12X18H10T) also keeps its stable passive state under real operating conditions in the course of HLW storage.

SWELLING OF BERYLLIUM UNDER HIGH-DOSE NEUTRON IRRADIATION

V. Chakin[1], M. Klimenkov[1], A. Fedorov[2], L. Magielsen[2]
[1]Karlsruhe Institute of Technology, Institute for Applied Materials, Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen, Germany (vladimir.chakin@kit.edu)
[2]Nuclear Research and Consultancy Group, Westerduinweg 3, Postbus 25, Petten, 1755 ZG, the Netherlands

Beryllium possesses unique nuclear physical properties which allow its use as a reflector or moderator in research nuclear reactors and as plasma-facing and neutron multiplier materials in future fusion reactors such as ITER and DEMO. Beryllium transmutes under neutron irradiation into helium and tritium that causes its swelling. The first evidence of beryllium swelling dates back to the late 1950s and to the early 1960s. However, even presently, there are no enough results to describe the swelling phenomenon from the point of view of designers, i.e. to predict the swelling behavior of beryllium under high-dose neutron irradiation. In this study, new experimental results and appropriate correlations of beryllium swelling versus irradiation temperature at 343-1041 K and neutron dose after high-dose neutron irradiation ($(0.5\text{-}8)\times10^{22}$ cm^{-2} (E>0.1 MeV)) in the SM, BOR-60, and HFR nuclear research reactors are presented. Four kinds of beryllium materials were investigated including two Russian grades TE-56 and TE-400, and the cast beryllium and the beryllium pebbles with 1 mm diameter produced by the rotating electrode method both delivered by NGK, Japan. Swelling was measured using immersion, geometrical, helium pycnometry, and transmission electron microscopy methods.

The type of dose dependence of beryllium swelling depends on the irradiation temperature. After irradiation at 343 K, the swelling increases with different rate depending on the neutron dose, i.e. it has an irregular behavior. However, even at the highest neutron fluence of 7.7×10^{22} cm^{-2} (E>0.1 MeV), the maximum swelling is not higher than 2.6 %. The increasing irradiation temperature up to 473 K leads to the linear dose dependence of beryllium swelling. The maximum swelling is between 2.6 and 3.4 % at the highest dose of 6.5×10^{22} cm^{-2} (E>0.1 MeV). After irradiation at 673-713 K, also the linear dose dependence of beryllium swelling occurs. In this case, the maximum swelling reaches 5 % at the maximum neutron fluence of 8×10^{22} cm^{-2} (E>0.1 MeV). Considering the higher irradiation temperatures of 641-923 K within the fast neutron fluence ranges of $(0.57\text{-}1.81)\times10^{22}$ cm^{-2}, the beryllium swelling demonstrates an almost equal swelling rate for four different irradiation temperatures from this temperature interval. A remarkable increase of the swelling takes place with increasing irradiation temperature from 696 to 1041 K within dose intervals of $(0.73\text{-}1.82)\times10^{22}$ cm^{-2}. At 1041 K, the beryllium swelling is almost 22 %. It can be concluded that beryllium swells with highest rate starting since 800 K. The beryllium swelling shows the similar behavior in the case of low-temperature irradiation (343 K) with the following high-temperature annealing (up to 1073 K), i.e. the sharp increase of swelling starts at 900-1000 K.

The obtained dose and temperature dependences of beryllium swelling can be used by nuclear and fusion reactors designers in the indicated ranges of neutron doses and irradiation temperatures. The use of these dependences outside these ranges is problematic and can be applied only for a rough estimate of the beryllium swelling behavior.

THE EFFECT OF DEFORMATION TEMPERATURE DURING SHEAR UNDER PRESSURE ON CHANGES OF STRUCTURAL−PHASE STATE AND MECHANICAL PROPERTIES OF HIGH-NITROGEN AUSTENITIC STEEL AFTER HIGH-TEMPERATURE AGING

S.N. Luchko[1], A.V. Makarov[1], V.A. Shabashov[1], K.A. Kozlov[1], V.V. Sagaradze[1], A.E. Zamatovskii[1], E.G. Volkova[1], A.L. Osintseva[2]
[1]*Mikheev Institute of Metal Physics, Ural Branch, Russian Academy of Sciences, Ekaterinburg, Russia (serojaluchko@gmail.com)*
[2]*Institute of Engineering Science, Ural Branch, Russian Academy of Sciences, Ekaterinburg, Russia*

The development of high-nitrogen steels of ferritic and austenitic classes is the actual direction of modern metallurgy of high-strength materials. The effect of large plastic deformation realized by the shear under pressure (SP) on structure, phase composition and mechanical properties of high-nitrogen steel 08Kh22GA1,24 after quenching and various modes of high-temperature aging at 650°C, forming a ferrite (α-BCC) structure of the metal matrix with chromium nitrides has been investigated [1]. The objective of this work is to study of the effect of deformation temperature (−196°C, 20°C и 200°C) on structure, phase composition and mechanical properties of high-nitrogen steel after quenching and high-temperature aging at 650°C (2,5h).

Mossbauer spectroscopy and transmission electron microscopy methods were [established] that steel has pearlite-like structure with interlayers α-phase (ferrite) and thin extended secondary nitrides Cr2N after high-temperature aging at 650°C (holding 2,5h) due to release of nitrogen and chromium from austenite, which stabilizing γ - phase. Under the conditions of cold deformation at room temperature, an increase is observed in the nitrogen content in the state of the interstitial solid solution in the matrix of the aged steel with the austenite structure; in the structure of ferrite, an increase in the chromium content in the substitutional solid solution in the α-phase is observed [2]. In the ferrite of the steel aged at 650°C and containing Cr_2N chromium nitrides, there is an increase in the chromium content in the bcc matrix from the initial values of 18.5 at % to 19.3, 19.8, and 21.9 at % with a decrease in the temperature of the SP from 200 to 20 and -196°C, respectively because of the dissolution of chromium nitrides and a decrease in the activity of the competing deformationinduced aging.

The microhardness measurements by the restitutedindentation method using a tetrahedral Vickers pyramid, it was also established that with an increase deformation temperature from −196°C to 200°C, a more effective strengthening occurs (from ~854 to ~988 HV0,025, respectively). Measurements of the micromechanical properties of high-nitrogen steel also showed a slight increase in the hardness of indentation: from H_{IT}=8,7 GPa for deformation SP at -196°C to H_{IT}=10,3 GPa for deformation SP at 200°C.

This work was performed according to the State Task of the Federal Agency of Scientific

Organizations of the Russian Federation (theme "Structure," no. 01201463331) and was supported in part by the project of the Ural Branch of the Russian Academy of Sciences (no. 15-9-12-45).

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THE EFFECT OF SHORT-TERM TREATMENT BY HIGH-FREQUENCY CURRENTS ON THE ALUMINUM COATINGS EMBRITTLEMENT

M.V. Lapin, A.A. Sushchev, V.N. Matviyenko, V.A. Gornova, A.A. Zotikov
RFNC – VNIITF, Snezhinsk, Russia (suschev.and@yandex.ru)

At present, a significant amount of parts made of radioactive materials is stored in the plants of the nuclear industry. It is impossible to transfer parts for recycling as there are coatings on their surfaces. In particular, these parts may have coatings based on titanium or aluminum, deposited by the method of condensation with ion bombardment [1] or similar methods. To remove coatings from the surface of parts from radioactive materials, various methods for removing coatings are currently most widely used. The part is based on the use of acids, alkalis and organic solvents. The other part is based on mechanical processing with the formation of large volumes of chips containing radioactive materials. Attempts have been made to develop a technology for removing thin metal films from parts made of radioactive materials. However, this problem still remains relevant and does not have a sufficiently effective solution.

The report discusses the results of the implementation of the technology of removing aluminum coating from the surface of parts from radioactive metals and alloys. The technology includes heating of parts in a vacuum chamber with high-frequency pulsed currents before the formation of intermetallic compounds [2], and supersonic flow of an inert gas with corundum powder [3].

A significant advantage of the developed method is the small amount of solid radioactive waste generated. In a production environment provides a high level of environmental safety. The task of creating a universal "dry" method for removing metallic coatings from parts made of radioactive metals has been solved. The method provides a reduction in energy costs and processing time of each part [4]. For more favorable conditions for the removal of thin coatings pre-applied additional metal coating, similar to remove.

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THE EFFECT OF SHOCK-WAVE LOADING ON THE STRUCTURAL-PHASE TRANSFORMATIONS IN AUSTENITIC STEEL

N.V. Kataeva[1], V.V. Sagaradze[1], V. Pavlenko[2]
[1]*Institute of physics of metals named after M. N. Mikheeva, Ural branch of RAS, Ekaterinburg, Russia (kataeva@imp.uran.ru)*
[2]*FSUE "RFNC-VNIITF them. Academ. E. I. Zababakhin", Snezhinsk, Russia*

Austenitic steel 04Cr20Ni6Mn11Mo2NWNb with 0.4 wt.% of nitrogen after quenching from rolling heating, as well as after quenching from 1100 °C and cold deformation by 15 %, has high mechanical properties, increased characteristics of wear resistance and resistance to stress corrosion cracking (SCC), which indicates the possibility of its use as a cladding material of hull steels of Arctic vessels.

Methods of metallography, transmission electron microscopy and EBSD analysis were used to study structural-phase transformations at different speeds and temperatures of shock-wave loading in austenitic steel 04Cr20Ni6Mn11Mo2NWNb.

In the absence of recrystallization during heating of the samples in the conditions of deformation with velocities 471 and 904 m/s. In the process of impact deformation in the investigated steel there was an increase in the dislocation density and the development of direct martensite transformation with the formation of ε-martensite with the HCP lattice. If in the process of shock-wave loading the samples were heated above 150-300 °C, the steel should develop reverse martensitic transformation $\varepsilon \rightarrow \gamma$ with the disappearance of crystals ε-phase. The appearance in austenitic grains of dark well-bounded bands with high dislocation density, which have the same FCC lattice and orientation as the austenitic matrix, indicates the development of cyclic transformation $\gamma \rightarrow \varepsilon \rightarrow \gamma$ in the process of impact. The formation inside the austenitic grains of elongated areas with high dislocation density (up to 8×10^{10} cm^{-2}), which have the same FCC lattice as the austenitic matrix, indicates the development of the reverse $\varepsilon \rightarrow \gamma$ transformation under impact with the appearance of sites, hardened phase rivet. The increase in the shock-wave loading velocity from 471 to 904 m / s at the initial room temperature leads to additional heating of the samples and causes activation of the inverse $\varepsilon \rightarrow \gamma$ transformation with the inheritance of dislocations.

The work was done on the topics "Structure", № AAA-A18-118020190116-6 and "Pressure" № AAA-A18-118020190104-3. Electron microscopic studies were carried out in the OEM of the SUC IFM UB RAS.

THE INFLUENCE OF CARBURIZATION IN A PLASMA ELECTRON BEAM ON THE HARDENING AND THE QUALITY OF THE SURFACE OF METASTABLE AUSTENITIC STEEL

P.A. Skorynina[1], A.V. Makarov[1,2], A.I. Men'shakov[3], N.V. Gavrilov[3], A.L. Osintseva[1]
[1]*Institute of Engineering Science, Ural Branch of the Russian Academy of Sciences, Yekaterinburg, Russia (polina.skorynina@mail.ru)*
[2] *M.N. Mikheev Institute of Metal Physics, Ural Branch of the Russian Academy of Sciences, Yekaterinburg, Russia*
[3] *Institute of Electrophysics, Ural Branch of the Russian Academy of Sciences, Yekaterinburg, Russia*

The significant disadvantages of austenitic Chromium-Nickel steels are low strength properties and a tendency to friction adhesion, which are not improved by heat treatment. This limits the possibility of using austenitic steels in areas where, in addition to providing corrosion resistance, high strength properties and wear resistance are required. Low-temperature (below 500 °C) plasma carburization allows to combine the improvement of mechanical and corrosion properties of austenitic Chromium-Nickel steels [1]. The paper considers the effect of carburization in the electron beam plasma in the temperature range 350-500°C on the carbon concentration, phase composition, hardening and surface roughness of Chromium-Nickel austenitic steel 04Kh17N8T.

The carburization at all temperatures provides the same level of hardening (1100-1110 HV 0.025) of the surface layer of austenitic steel. The effective hardening is due to the increased carbon content in the γ-phase at all carburization temperatures and the formation of the Fe_3C phase at T_C=350-450 °C, chromium carbides $Cr_{23}C_6$ at T_C=350, 450, 500 °C, Cr_7C_3 at T_C=400 and 500 °C. with a decrease in the carburization temperature, the depth of the hardened layer also decreases due to a decrease in the speed of carbon diffusion. After carburization, the carbon concentration in the layer with a depth of ~60 μm reaches 1.28-2.23 wt. %.

The optical profilometry method was used to determine the deterioration of the electropolished surface with initial roughness Ra=40 nm as a result of carburization at T_C=400-500 °C: the roughness parameter Ra increases to 755-1420 nm. The carburization at TC = 350 °C does not lead to a significant deterioration in the quality of the electropolished surface: the values of the roughness parameter increase only to Ra=195 nm. However, carburization of hardened austenitic steel at this temperature provides the lowest depth of the hardened layer. To increase the rate of diffusion of carbon into the volume of the modified material and, accordingly, to increase the depth of the hardened layer, at T_C=350 °C, it may be promising to conduct a deformation nanostructuring of the surface layer before chemical modification.

The work was supported by RFBR, grant No. 18-38-00561_mol_a. It was done within the state assignment for IES UB RAS, theme No. AAAA-A18-118020790148-1, and the assignment of FASO Russia, theme "Structure" No. AAAA-A18-118020190116-6 (project No. 18-10-2-39).

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THE INFLUENCE OF LANTHANUM-CONTAINING MODIFIERS ON MELT OVERCOOLING TENDENCY

M.V. Lapin[1], O.Yu. Sheshukov[2], I.V. Nekrasov[2]
[1]RFNC – VNIITF, Snezhinsk, Russia (Max2046@yandex.ru)
[2]Institute of Metallurgy, RAS, Ural Branch, Ekaterinburg, Russia

High requirements for mechanical properties and radiation resistance of materials used in nuclear power engineering require new approaches to production [1]. It is necessary to take into account a number of aspects that are missed in traditional technological processes at metallurgical factories, but with proper implementation they allow uncovering the potential for improving product quality without a profound change in the technological scheme. One of such aspects is the process of modifying the cast structure of the metal by introducing alkaline earth and rare earth elements immediately prior to casting. The main disadvantage of this technology is the contamination of the melt with the materials that make up the modifying additives. The temperature of the cast metal is not optimal for effective modification, and the time before the solidification of the melt is not enough to remove non-metallic inclusions introduced by modifiers.

The report examines the influence of lanthanum-containing modifiers on melt overcooling tendency, reviews modifiers proposed by manufacturers, and discusses the results of introducing the technology of high-temperature metal treatment before evacuating [2]. In addition, prospects for the application of technology for the manufacture of steel for the nuclear industry are considered.

In this work, the main focus of attention is on silicocalcium alloys with the addition of Ba, Ce and La, as one of the most actively used in factories. Chemically similar modifiers made using standard technology and fast-cooling chips alloys were used. The analysis of the fractional, phase and chemical composition of the modifiers. To determine the effect of modifiers on the degree of supercooling, a series of experiments aimed at identifying the optimal amount of modifier injected per ton of steel was carried out. The main method for studying the tendency of the melt to overcooling was to determine the hysteresis of the kinematic viscosity in heating and cooling modes. Viscosity is one of the most characteristic structural-sensitive characteristics of a liquid, and its study, along with the study of other physicochemical properties, opens up possibilities for establishing the structure of metal melts, the nature and interaction forces between components in alloys [3].

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THE RESULTS OF STRUCTURAL AND CRACK RESISTANCE INVESTIGATION OF ZIRCONIUM TUBES OF CPS DEFECTIVE CHANNEL AFTER 32 YEARS OF OPERATION IN RBMK REACTOR

D.N. Velmogin, V.A. Tsygvinstev, S.A. Averin, M.V. Evseev, M.V. Chernetsov, V.I. Pastukhov
JSC "INM", Zarechny, Russia (irm@irmatom.ru)

CPS channel, operated for 32 years in the third unit of Kursk NPP since 1983 and removed out of the reactor due to loss of operating capacity (leakage detected), was an object of the study. The defects were detected during ultrasonic testing. When a defective channel section was being cut out, the channel fractured along the nipple in the heat effect zone of electron-beam welding (EBW).

The paper aims at investigation of structural behaviour of zirconium part of the channel and its crack resistance.

Post irradiation examination of CPS channel was carried out at INM Hot Laboratory.

Metallographic studies showed that local hydride stacks (blisters), formed at the internal surface of the channel, as well as high concentration of hydrides under blisters are observed in nipple structure and tube regions adjacent to EBW welds. Blister distribution along the channel is non-uniform. Most blisters are at the upper and bottom parts of the channel, they rarely appear in the channel centre and their size is much smaller.

X-ray diffraction analysis of blisters showed that the following phases are present: δ-$ZrH_{1.66}$, γ-ZrH, α-Zr. β-Zr with high hydrogen solubility was detected in EBW heat effect zones. According to SEM results, β-Zr is registered close to boundaries of initial high-temperature β-grain, at the monotectoid pack joints and between lamels in monotectoid packs at a rate of ~ 3 vol.% and with Nb concentration in β-Zr of ~ 27.7-27.9%.

Crack resistance studies showed that operating fracture happened in the area with minimum fracture toughness level and critical crack opening value. Crack resistance characteristics changed due to significant hydrogen absorption of the material.

It was noted that deposit distribution in the channel was non-uniform: there were less deposits in the middle part than in the upper and bottom ones. It was suggested that hydrogen concentration increases due to: high hydrogen concentration in cooling liquid, deposits at the internal surface and different phase composition of the material.

No significant temperature effect was detected. Hydrogen concentration in regions with operating temperature of ~40° and ~ 80° reaches 700-1000 ppm, and at temperature of ~ 60° it does not exceed 160 ppm. It was also noted that sample fluence has no impact on hydride formation at low temperatures.

Therefore, changes in crack resistance characteristics were caused by hydration absorption, and non-uniform hydrogen absorption can be caused by irradiation temperature and deposits, formed at the internal channel surface. β-Zr with high hydrogen solubility was detected, which also can lead to non-uniform distribution of hydrogen concentration.

TOMOGRAPHIC ATOM PROBE STUDY OF OXIDE DISPERSION STRENGTHENED 12CRODS STEEL UNDER HEAVY ION IRRADIATION

A.A. Khomich, N.N. Orlov, A.A. Nikitin, A.S. Shutov, O.A. Raznitsyn, A.A. Lukyanchuk, S.V. Rogozhkin

Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of National Research Centre «Kurchatov Institute», Moscow, Russian Federation

(artem.khomich@gmail.com)

One of the important problems for advanced fission and fusion power plants is the development of structural materials for the reactor core. Operational5 characteristics of new materials should be considerably better in comparison with the existing ones. Radiation resistance is expected to be up to 200 dpa, mechanical properties must be stable at high temperatures (> 700°C), and new materials also have to be corrosion resistant in coolant. Prospective candidates to meet these requirements are oxide dispersion strengthened (ODS) ferritic-martensitic steels. The development of these materials is currently underway in many research centers (ORNL, KIT, KAERI, VNIINM etc.). Mechanical properties of ODS steels significantly depend on the nanostructure of the material: size and spatial distribution of dispersed inclusions (oxide particles and clusters). It is known that Ti and V affect the formation of nanoscale particles by reducing their size and increasing the number density. In this context, it is important to study ODS steels with different alloying systems. This approach allows a deeper level of understanding the processes of nanostructure formation of ODS materials, depending on the initial composition. Moreover, studying of inclusion stability behavior under irradiation, including a variety of simulated impacts, such as heavy ion irradiation is important issue, because of ODS steels application in nuclear reactors. In this work ferritic-martensitic ODS steel 12Cr-1.1W-0.2V-0.3Ti-0.3Y_2O_3 produced in Korea Atomic Energy Research Institute (KAERI) was irradiated by Fe^{2+} heavy ions to 8 dpa at room temperature and investigated by atom probe prototype with laser evaporation (APPLE-3D) designed at ITEPh (Moscow). The 3D-distribution of chemical elements in the bulk of the material has been obtained. Clusters enriched in Ti, O and Y, have been found in both states. It was observed an increasing of average cluster size from 4 nm in initial state to 5 nm in irradiated state without significant change in number density (~10^{23} m^{-3}). Ratios of Y/Ti, Y/(Ti+V), (Ti+V+Y)/O in clusters are the same within the error for irradiated and non-irradiated states indicating that the clusters are stable to the heavy ion irradiation at room temperature up to 8 dpa.

This study is supported by the Russian Science Foundation under grant 17-19-01696.

UPDATE OF THE DOSE-TEMPERATURE DEPENDENCE OF THE SWELLING OF Fe-18Cr-10Ni-Ti STEEL TO CALCULATE THE SWELLING OF THE LONG-IRRADIATED ELEMENTS OF THE BOR-60 REACTOR

D.A. Sokolovsky, V.S. Neustroev

JSC "State Scientific Center – Research Institute of Atomic Reactors", Dimitrovgrad, Russia

(neustroev@niiar.ru)

At present, an empirical dose-temperature formula mainly used to calculate swelling *S* of austenitic Fe-18Cr-10Ni-Ti steel is as follows [1]:

$$S\,(\%) = C \cdot D^{1,88} \exp[-1{,}83 \cdot 10^{-4}(T - 470)^2],\ C = 1{,}04 \cdot 10^{-2}. \qquad (1)$$

To calculate components under long-term irradiation, coefficient C was specified based on swelling data of two irradiation rigs IR-1 and IR-2; the coefficient was set to $C = 5{,}6 \cdot 10^{-3}$.

The specified formula was used to evaluate swelling of duct of BOR-60 blanket assembly E-169 irradiated in one and the same cell for 27 years to a maximal damage dose of 81 dpa. The correctness of specified formula was confirmed by a good fit of calculated and experimental [2] results that makes the formula applicable.

The specified formula was also used to calculate swelling of one of BOR-60 critical components, namely biological protection pin. From the viewpoint of this component, it allowed the extension of the BOR-60 lifetime till 2023. Additional data will be obtained in future on swelling of Fe-18Cr-10Ni-Ti steel used for manufacturing IR-1 and IR-2 components to increase the statistical relevancy of swelling dose-temperature dependence at high temperatures.

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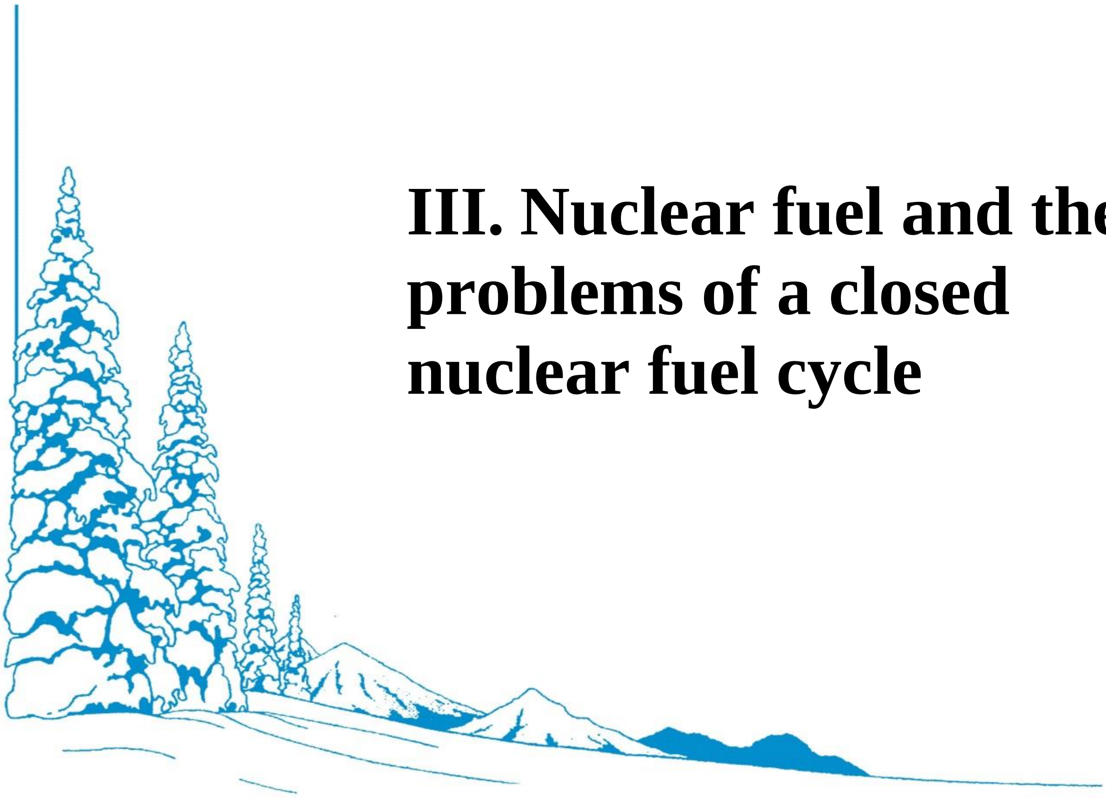

III. Nuclear fuel and the problems of a closed nuclear fuel cycle

The universal processes for the reprocessing of spent nuclear fuel of various types are hydrometallurgical and gas fluoride ones, which make it possible to obtain refabricated fuel with a high purification rate from fission products. For promising fuels (metal, nitride, carbide), alternative pyrochemical processes for the processing of spent nuclear fuel in molten salts have been developed: electrochemical (electrolysis, electrorefining), reductive extraction, deposition of oxides, and others.

The field of application of pyrochemical methods is the reprocessing of spent nuclear fuel with a short holding time, when high cleaning coefficients of refurbished fuel from PD are not required. These developments have not yet emerged from the stage of pilot plants, however, interest in their industrial implementation is still high due to the urgency of creating large-scale atomic energy with fast neutron reactors.

INFLUENCE OF ENRICHMENT ON THE PHYSICAL AND MECHANICAL CHARACTERISTICS OF URANIUM GRAPHITE FUEL

A.S. Dikov[1,2], A.S. Larionov[1], S.B. Kislitsin[1,2], V.V. Firsova[1]
[1]INP RK, Almaty, Kazakhstan (lexa_edji@mail.ru)
[2]NRNU MEPhI, Moskow, Russia

Recently, an increase in the safety level in the operation of nuclear reactors has been achieved by conversion them from highly enriched fuel to low-enriched fuel [1]. To assess the risks of converting pulsed uranium-graphite reactors, it is necessary to discover the difference in the physicomechanical characteristics of fuel cell materials with different enrichment [2].

Results of compression and bending mechanical tests for samples with high enriched uranium-graphite fuel (HEU) and low enriched uranium-graphite fuel (LEU) are given. Enrichment with 235-uranium for HEU is 90% and for LEU - 19.75%. The destruction character of the samples is brittle. The average value of σ_{comp} for LEU fuel is 34.1 ± 3 MPa, for HEU 57.64 ± 5 MPa..

Measurement of thermal expansion in three directions showed the presence of anisotropy properties for both HEU and LEU fuel. In the case of HEU fuel, anisotropy is more pronounced.

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SELECTION OF OPTIMAL MODE FOR MOX FUEL EXAMINATION THROUGH THE USE OF SCANNING ELECTRON MICROSCOPY, RESEARCH RESULTS

A.A. Maltsev, M.A. Litvinova
FSUE Mayak PA, Ozyorsk, Russia (cpl@po-mayak.ru)

The research objective was to find the optimal mode for examining MOX fuel pellets (hereinafter pellets) through the use of a scanning electron microscope Mire 3 LMH manufactured by TESCAN (hereinafter SEM) and an automated system of energy dispersive x-ray microanalysis with a detector X-MAX 80 manufactured by Oxford Instruments (hereinafter EDS).

There is a need to examine pellets with the help of SEM and EDS to determine the area of sections with increased Pu content (which differs from the rated value by a factor of two) in comparison to the area of pellet section slice under study and to identify their linear characteristics in pellets of mixed oxide uranium – plutonium fuel. Sections with increased Pu content (which differs from the rated value by a factor of two) are understood as slice sections with Pu mass content of more than 36%. Linear characteristics of sections with increased Pu content (which differs from the rated value by a factor of two) are understood as a number of sections, linear dimensions of which exceed 100 μm.

The result accumulation rate and the result quality in the “Quant Map” mapping mode, which allows accumulating quantitative maps of elements with the visualization of spatial distribution of concentration of elements on the surface of the sample under study, depend on a number of factors, the primary of which are resolution and number of elements in a list of quantitative analysis. It is also very important to accumulate sufficient amount of impulses for spectral data in each pixel.

In the course of selection of optimal method for examination of pellets using SEM and EDS in the mapping mode “Quant Map”, some problems were identified which hamper obtaining accurate results and relate to pellet self-radiation that are:

- Possible damage of EDS window and its quick failure;
- Significant dead time of ESD detectors and, as a result, insufficient number of desired signals coming from the surface of the sample under study;
- Substantial time spent on the adjusted analysis of the pellet areas (3 zones of 1 mm^2 each).

As a result of the research, the analysis layout was optimized and the time required for examination of one pellet was reduced by a factor of three.

As of now, studies of possibilities of pellet examination using SEM and EDS are underway. It is planned to attain the optimal mode for analyzing the pellet surface all over the controlled sample area with the most accurate quantitative result for the element distribution analysis.

STUDY OF COLD CRUCIBLE INDUCTION-SLAG REMELTING OF METAL HLW RESULTED FROM SNF REPROCESSING

P.V. Kozlov[1,2], M.B. Remizov[1], T.V. Smelova[3], D.Yu. Suntsov[3], I.N. Shestoperov[3]
[1]*FSUE Mayak PA, Ozyorsk, Russia (cpl@po-mayak.ru)*
[2]*OTI MEPHI, Ozyorsk, Russia (kozlov_pavel@inbox.ru)*
[3]*VNIINM, Moscow, Russia (tvs@bochvar.ru)*

In the course of spent nuclear fuel dissolution at Mayak PA Radiochemical Plant solid HLW is generated, which consists of fuel element cladding fragments that are sent for storage in a specialized storage facility. The mentioned waste contains fission products including long-lived radionuclides (REE, Cs, Sr, Ru, U, Pu etc.) and activation products (radioactive isotopes, such as Fe, Co, Ni etc.). Claddings could be contaminated with fissile materials and radioactive substances due to the presence of:

- activation products of cladding structural materials;
- surface contamination in the form of thin films the isotope content of which is similar to the isotope content of the solution resulted from SNF reprocessing;
- fine insoluble sediment particles, which precipitated on the fuel element claddings during SNF dissolution and contain insoluble fuel fragments and insoluble compounds of uranium, TRU and fission product.

This storage approach is environmentally hazardous and economically unviable. The problem can be solved by decontamination and compaction of irradiated claddings of fuel elements. This will help to downgrade the mentioned radioactive waste, to reduce the amount of high-level solid radioactive waste resulted from SNF reprocessing, to bring it to compliance with acceptance criteria in terms of further disposal, as well as to reprocess the fuel element cladding fragments accumulated over decades of Radiochemical Plant operation.

Comparison of various options of steel and zirconium material melting investigated in research centers in Japan, France and Russia demonstrated that the best results in zirconium re-melting were obtained for induction-slag re-melting in cold crucible.

Analysis of experimental investigations related to the induction-slag re-melting of alloys based on zirconium and stainless steel demonstrated the capability of fissile materials and fission products to move with sufficiently high efficiency to the slag that comprises Fe, Ca, Si oxides and calcium and magnesium fluorides. Upon that, extraction degree of stainless steel amounted to 68%, of stainless steel and zirconium alloy it was 74% and of zirconium alloy it was 52.5%. In the course of melting, melted flux contacts with zirconium alloy and oxide film on the surface of fuel element claddings which results in formation of slags containing ZrO_2. Melting continues for about 15 minutes and temperature is 1650 to 1900°C. The process is carried out in argon environment.

The obtained results have proven the very possibility of applying the induction-slag melting for decontamination and compaction of irradiated fuel element claddings and allowed generating initial data for experimental (lab-scale) facility based on cold crucible melter with the metal output of 20kg/day.

THERMONUCLEAR BURNING OF A DENSE PLASMA IN MIF DEVICE

Zh.B. Seksembayev[1], V.I. Kukulin[2], S.K. Sakhiyev[3]
[1]L.N.Gumilyov Eurasian National University, Astana, Kazakhstan (jandos_s90@mail.ru)
[2]Skobeltsyn Institute of Nuclear Physics, Moscow, Russia
[3]Abai Kazakh National Pedagogical University, Almaty, Kazakhstan

For traditional types of thermonuclear fuel, the main reactions that take place and determine the nature of burning can be found in [1]. In [2], the concept of one of the schemes for implementation of magnetic-inertial fusion (MIF) is shown. There, the authors propose to use a combination of Z-pinch with laser pulse to ignite fuel for a self-sustaining fusion process. In this type of device, the fuel is confined in extreme conditions that contribute to the active run of nuclear reactions. The temperature of the plasma due to acting strong shock waves and compressing electromagnetic forces is brought to several tens of keV. Within these values, the rate of fusion reactions is very high.

In the report the results of thermonuclear burning simulation of fuels DD, DT, D^3He in such devices, where extreme conditions (temperature and density) are achieved, are presented, with use of the updated data on rates of the main nuclear reactions. The temperature increase of local burning zone due to the energy of exothermic reactions is taken into account. As the initial conditions, plasma temperature was set at 10–30 keV and particle concentration of each fuel component was set at $5*10^{23}$ cm^{-3}.

In the result of calculations, it was found that the burning of the DD fuel is not accompanied by temperature increase, since the radiation loss exceeds the energy released in nuclear reactions and which increases the kinetic energy of the plasma particles. Therefore, it has been determined that such fuel is not applicable as a fuel for the effective implementation of such fusion device. While simulating the burning of DT and D^3He fuels, the process is accompanied by an increase in temperature, which increases the rate of reactions, and, accordingly, the fuel burns out faster.

The half-burning times of fuel components, which is about 3-4 ns for DT [3] are found. For D^3He, the resulting times are approximately 6 and 13 ns, respectively. These parameters determine the time criteria for plasma confinement for efficient burning.

This simulation model of thermonuclear burning can be used to design an experimental setup for the implementation of thermonuclear fusion based on magnetic inertial confinement.

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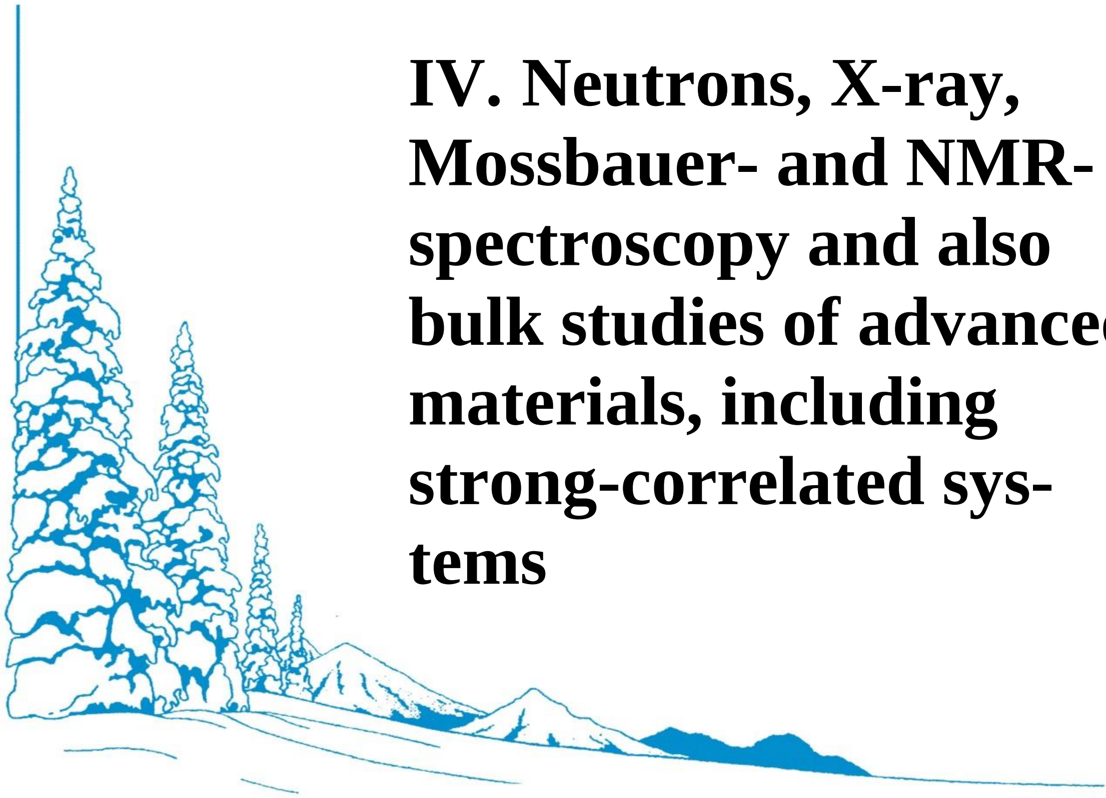

IV. Neutrons, X-ray, Mossbauer- and NMR-spectroscopy and also bulk studies of advanced materials, including strong-correlated systems

The development of advanced technologies, including new generation nuclear techniques, make a strict requirement to structural and functional materials on the basis of which the element base for progressive computer, information and monitoring systems will be created. From this point of view, the perspective materials for it are materials based on d- and f-elements, having unique physical properties and known as systems with strong electron correlations. The spectroscopic investigations by neutron and X-ray scattering methods play the outstanding role in studying of physical properties of these materials. For this reason, in the Seminars' Programme is included reports, devoted to examination of perspective materials - new generation superconductors, frustrated magnets, valence-unstable systems, ferroelectrics, quantum magnets and hybrid nanostructures - by mean of inelastic neutron scattering, X-ray spectroscopy and measurements of microscopic parameters.

ACCELERATED DISSOLUTION AND PRECIPITATION OF PHASES IN IRON ALLOYS UPON MEGA-DEFORMATION. COMPARISON WITH RADIATION EFFECT

V.A. Shabashov
[1]*IMP UB RAS, Ekaterinburg, Russia (shabashov@imp.uran.ru)*

In present-day materials science, the scientific direction of deformation nanostructuring and abnormal phase transitions induced by large plastic deformation has been actively developing. The subject of the present review consists in the summing up of our previous results on the study of the relaxation of structure along the way (i) of the atomic redistribution – in the form of short-range clustering in binary iron alloys, – induced by megaplastic deformation (i.e., of super large value), and (ii) of the dissolution and precipitation of the disperse nitrides and carbides in steels and intermetallics in ageing alloys. In the capacity of the main method of executing megaplastic deformation, along with the practically important milling in ball mills and friction-providing external action, we have employed high pressure torsion (HPT) in Bridgman anvils, which permits to control the degree, rate, and temperature of deformation action. At the local level of two nearest neighbors (of the one or two coordination shells in relation to an iron atom) we have studied atomic mass transfer that is stipulated by the generation of a large number of point defects of deformation origin and conducted a comparison with the case of irradiation by high-energy electrons. We have established the change in the direction of phase transformations, as well as the anomalous acceleration of the ordering and precipitation disperse phases upon altering the temperature ($T < 0.3\ T_{melt}$) and rate (from $2{\cdot}10^{-2}$ to $8{\cdot}10^{-2}$ s^{-1}) of deformation. We also demonstrated the possibility of regulating ultra-fine-grained structure with the solid-solution strengthening and dispersion hardening.

This work was performed under the state assignment of the Federal Agency for Scientific Organizations of Russia (theme “Structure” No. AAAA-A18-118020190116-6) supported in part by the Russian Foundation for Basic Research (project No. 18-03-00216).

ANISOTROPY OF MAGNETIC EXCITATIONS IN HIGH-TEMPERATURE SUPERCONDUCTORS

A.S. Ivanov
Institut Laue-Langevin, Grenoble, France (aivanov@ill.fr)

Magnetic response in unconventional superconductors remains to be attractive subject in attempts to reveal clues to high-temperature superconductivity. A particular attention was given to the phases with oriented electronic arrangements in real space, stripes, as possible competitors to the superconducting state. We used inelastic neutron scattering in order to characterize the magnetic excitation spectra in single crystals of different superconductors with orthorhombic distortions of the base tetragonal structure. Such distortions that may create a specific pinning potential for the stripes are observed in different families of copper- and iron-based superconductors. The measurements of the orientation anisotropy in the magnetic spectra should be performed with material samples that contain a singled out orientation of the orthorhombic domains. In the as-grown crystals these elastic domains with different orientation of orthorhombic axes exist in practically equal fractions what makes it impossible to discern the anisotropy. Our cuprate samples are obtained in a special procedure when a single crystal is cooled down to ambient temperature through the tetra-ortho structural transition being subject to a uniaxial mechanical compression. The domain population ratio achieved in such a way can be as high as 20:1 on small, a-few-mm^3 size, crystals. The samples for neutron scattering experiments have been composed from several tens of such small crystals mutually co-oriented with a precision of 1-2 degrees. The crystals of the iron-based pnictide superconductors undergo the tetra-ortho structural transitions well below the room temperature so that detwinning procedure had to be performed "*in situ*" in a cryostat. We give examples of the anisotropy of magnetic excitation spectra measured with such detwinned single crystals.

ANOMALOUS PHASE TRANSITIONS IN THE SURFACE OF AUSTENITIC STAINLESS STEELS NITRIDED IN ELECTRON BEAM PLASMA AT LOW TEMPERATURES

V.A. Shabashov[1], K.A. Kozlov[1], A.V. Makarov[1], N.V. Gavrilov[2], S.G. Titova[3]
[1]*IMP UB RAS, Ekaterinburg, Russia (shabashov@imp.uran.ru)*
[2]*Institute of Electrophysics UB RAS, Ekaterinburg, Russia*
[3]*Ural Federal University, Ekaterinburg, Russia*

The structure of "expanded" austenite in Fe-18Cr-8Ni-Ti and Fe-17Cr-8Ni-Mn-Ti metastable stainless steels nitrided in the electron beam plasma was studied by Mossbauer spectroscopy in the transmission geometry and on the surface (by CEMS) in combination with X-ray analysis. The CEMS analysis of the plate (with thickness of 600 μm) surface of Fe-17Cr-8Ni-Mn-Ti steel nitrided at 350 °C indicates an almost complete $\gamma \rightarrow \alpha$ phase transition in the surface layer with a thickness of a few tenths of a micron and the preservation of chromium in the ferromagnetic α-phase. The formation of the α-phase is explained by the shear transformation due to the relaxation of high elastic tensile accommodation stresses between nitrogen-supersaturated austenite and nitrogen-free austenite. According to X-ray analysis and CEMS in the layer located at a depth of 1-5 μm in Fe-17Cr-8Ni-Mn-Ti steel nitrided at 350 °C the structure of "expanded" austenite is formed, with substantial alteration in depth of concentration and phase compositions. The structure consists of the mixture of nitrogen-saturated austenite and nonstoichiometric, defective nitride phases of iron (with predominant iron configurations surrounded by three nitrogen atoms). Nitriding a 20-μm-thick Fe-18Cr-8Ni-Ti steel foil at 500 °C changes the phase and concentration composition of the steel over the entire depth and causes the formation of the chromium-depleted α-phase, CrN and Fe_4N nitrides, and nitrogen-supersaturated austenite. The decrease in the nitriding temperature to 200–400 °C does not change the concentration and phase composition over the main volume of the foil. This is supposedly attributed to a limited capacity of the nitriding and an absence of stress gradients.

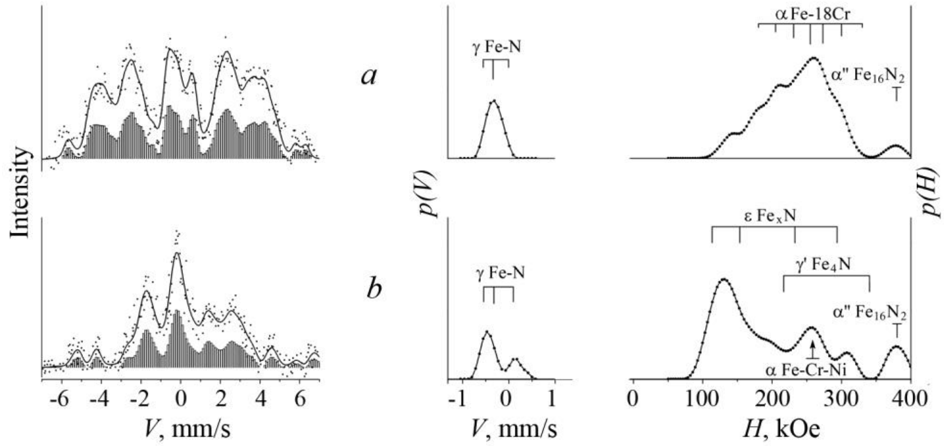

Fig. CEMS Mössbauer spectra of layer-by-layer analysis of Fe-17Cr-8Ni-Mn-Ti steel plate after one-side nitriding at 350 °C: *a* – outer layer; *b* – 5 µm thinning. The spectra show the distributions of *p(V)* over the entire velocity range; to the right of the spectra, the distributions of *p(V)* and *p(H)* show the positions of γ- and α-solid solutions and iron nitrides.

This work was performed under the state assignment of the Federal Agency for Scientific Organizations of Russia (theme "Structure" No. AAAA-A18-118020190116-6) supported in part by the Russian Foundation for Basic Research (project No. 18-03-00216).

ATOMIC ORDERING IN FCC Fe-Ni ALLOYS INDUCED BY ULTRA-HIGH PLASTIC DEFORMATION

V.A. Shabashov, V.V. Sagaradze, K.A. Kozlov, A.E. Zamatovskii, N.V. Kataeva, K.A. Lyashkov, S.E. Danilov

[1]*IMP UB RAS, Ekaterinburg, Russia (shabashov@imp.uran.ru)*

The effect of severe plastic deformation and high-energy electron irradiation in invar $Fe_{100-x}Ni_x$ (x = 34.2..35.5 at. %) binary alloys investigated by means of Mossbauer spectroscopy. After high pressure torsion (HPT) in Bridgman anvils of the quenched and aged alloys at 298 K the decrease in degree of homogeneous short-range ordering occurred in consequence of disordering by moving dislocations. The rise of high pressure torsion temperature from room up to 473 K reduces disordering process and at 573 K in contrast increases homogeneous short-range ordering. The process characterized by growing of Fe and Ni atoms neighborhoods and appearing of the stage similar to radiation-enhanced ordering controlled by formation of FeNi superstructure. The kinetics of short-range ordering is determined by competition between the dislocation disordering and the short-range ordering accelerated by point defects. The prime factor of deformation-induced temperature dependence of short-range ordering is the vacancy concentration and mobility as well as proposed boundaries motion speed of dynamic recrystallization. Short-range ordering enhanced by warm deformation is similar to radiation-enhanced ordering and attributed to continuous generating of nonequilibrium mobile point defects during deformation.

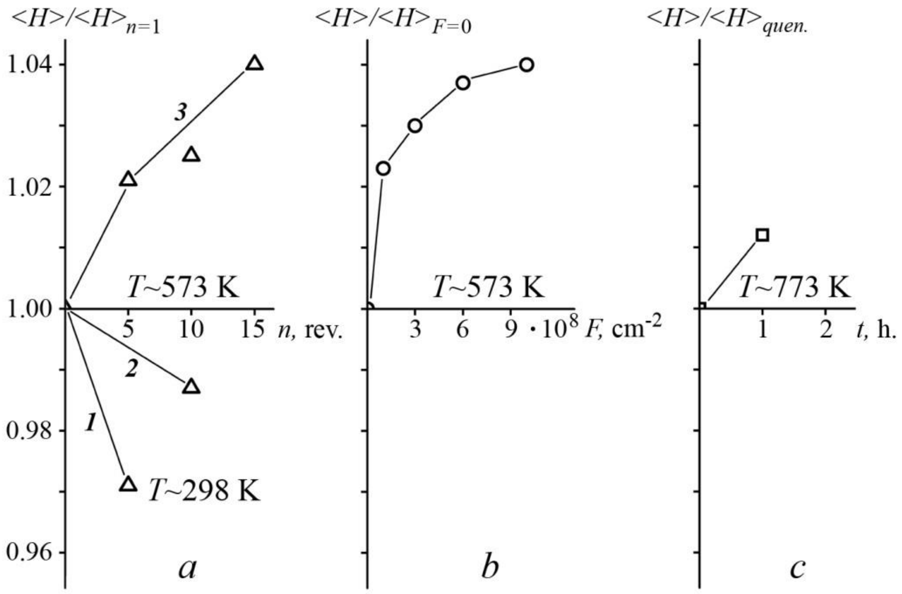

Fig. Relative hyperfine magnetic field of $Fe_{65.8}Ni_{34.2}$ and $Fe_{64.5}Ni_{35.5}$ alloys after influence: *a* – $\langle H\rangle/\langle H\rangle_{n=1}$ of quenched $Fe_{64.5}Ni_{35.5}$ alloy after HPT at 298 K (*1*), aged alloy after HPT at 298 K (*2*), quenched alloy after HPT at 573 K (*3*); *b* – $\langle H\rangle/\langle H\rangle_{F=0}$ of $Fe_{65.8}Ni_{34.2}$ alloy after electron irradiation at 573 K; *c* – $\langle H\rangle/\langle H\rangle_{ann..}$ of $Fe_{64.5}Ni_{35.5}$ alloy after aging at 773 K, 1 h.

This work was performed under the state assignment of the Federal Agency for Scientific Organizations of Russia (theme “Structure” No. AAAA-A18-118020190116-6) supported in part by the Russian Foundation for Basic Research (project No. 18-03-00216).

ATOMIC REDISTRIBUTION IN Fe-Cr ALLOYS UNDER LARGE PLASTIC DEFORMATION AND ELECTRON IRRADIATION

K.A. Kozlov[1], V.A. Shabashov[1], A.E. Zamatovskii[1], V.V. Sagaradze[1], A.L. Nikolaev[1]
[1]*IMP UB RAS, Ekaterinburg, Russia (kozlov@imp.uran.ru)*

In number of studies devoted to investigating the influence of severe plastic deformation on the structural-phase transitions and properties of alloys it has been noted a fundamental difference between the structure of materials in the equilibrium state and after severe plastic deformation including diffusive atomic redistribution at low temperatures. This is seen, for example, in anomalous dissolution and precipitation of phases in the metallic matrices [1] or in changes in the short-range atomic order of the alloys [2]. In this work, the data of deformation-enhanced short-range clustering in low-concentrated supersaturated BCC alloy Fe-Cr are shown. The short-range clustering is found in annealed and aged $FeCr_x$ (x = 12, 20) alloys. After cold deformation (at 80-298 K) the decrease in degree of short-range clustering occurred in the annealed and aged alloys. On the contrary, after deformation at 473-573 K the increase in the degree of short-range clustering is observed. The alteration in the direction and the enhancement of short-range clustering is determined by the competition between the dislocation disordering and the short-range ordering accelerated by point defects owing to the continuous generation of mobile nonequilibrium point defects such as the interstitial atoms and vacancies. The principal importance for the accelerating of clustering in supersaturated BCC Fe-Cr alloys is the maintain of high concentration of point defects under continuous deformation.

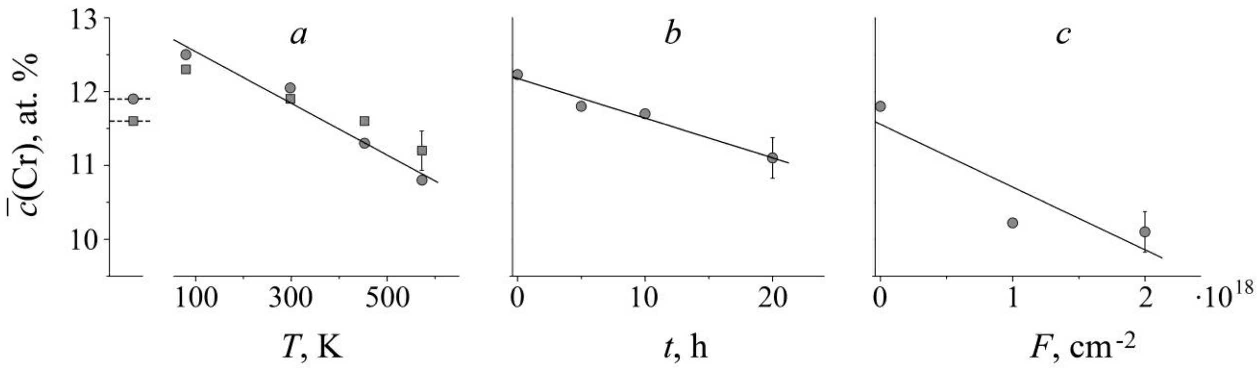

Fig. The dependence of c(Cr) in the matrix of the alloys (a), (b) $Fe_{86.8}Cr_{13.2}$, and (c) $Fe_{88}Cr_{12}$ on the temperature of high pressure torsion, duration of ball milling (BM), and fluence of electrons at 423 K. Round symbols correspond to the values for the state “annealed at 1073 K (as-received)”; square symbols, for the state “annealed at 773 K, 50 h (aged)”.

This work was performed under the state assignment of the Federal Agency for Scientific Organizations of Russia (theme “Structure” No. AAAA-A18-118020190116-6) supported in part by the Russian Foundation for Basic Research (project No. 18-03-00216).

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COMPARATIVE STUDY OF MAGNETIC AND RESONANCE PROPERTIES OF $PbMn_{1-X}Fe_XBO_4$(X=0, 0.1) SINGLE CRYSTALS

M.I. Kolkov[1], A.I. Pankrats[1,2], A.D. Balaev[1], S.E. Nikitin[3,4]

[1]*Институт Физики им. Киренского, Федеральный исследовательский центр КНЦ РАН, Krasnoyarsk, Russia*

[2]*Siberian Federal University, Krasnoyarsk, Russia*

[3] *Max Planck Institute for Chemical Physics of Solids, Dresden, Germany*

[4]*Institut für Festkörper- und Materialphysik, Technische Universität Dresden, Dresden, Germany*

$PbMn_{1-x}Fe_xBO_4$ single crystals (x = 0, 0.1) were first obtained by flux technic and belong to the orthorhombic space group Pnma. Magnetic, resonance, and thermophysical properties were studied on these single crystals. The $PbMnBO_4$ single crystal is a highly anisotropic ferromagnet with a light axis that coincides with the orthorhombic axis a and Curie temperature of 30.3 K [1, 2]. An anomalously large value of the gap in the FMR spectrum ν = 112 GHz is caused by strong anisotropy in $PbMnBO_4$.

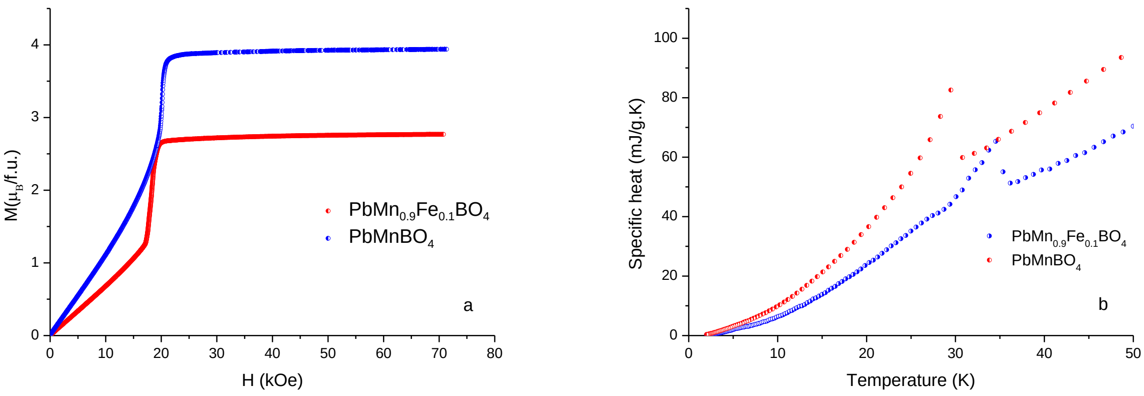

Fig. 1. a – Field dependences of magnetization along the axis b at T = 4.2 K, b – Temperature dependences of heat capacity at zero magnetic field

Ferrimagnetic type of magnetic ordering, as well as the magnitude of the saturation magnetization M_s has a value 2,67 Bohr magnets on formula unit in a substituted the $PbMn_{0.9}Fe_{0.1}BO_4$ single crystal, in contrast to unsubstituted PbMnBO4, is connected with the fact that the structure of this compound apparently consists of two sublattices formed by Mn and Fe ions, whose magnetic moments are antiparallel. The nature of the magnetization in the figure 1a indicates a structural phase transition of the first type, in the region of 20 kOe. Analysis of the temperature dependence of the $PbMn_{0.9}Fe_{0.1}BO_4$ heat capacity in a zero external magnetic field allowed to set the transition temperature T_c equal to 35 K (Fig. 1b), which is associated with an increase in the average exchange interactions in this single crystal.

This work was done with grant support by Kraifoundation - RFBR, project No. 18-42-240008.

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DEPENDENCE OF PHONON SPECTRUM OF NARROW-GaP SEMICONDUCTOR FeSi FROM ATOMIC VOLUME

P.P. Parshin

National Research Centre «Kurchatov Institute», 123182, Moscow, Russia

(Parshin_PP@rrcki.ru, neupar45@yandex.ru)

The analysis of experimental data on the evolution of the spectrum of thermal vibrations of iron atoms in the FeSi monosilicide is presented as function of two external parameters – temperature (range T= 46 – 297 K, at P= 0.1 MPa) and pressure (P= 0.1 MPa – 43 GPA, at T=297 K). The spectra are measured by nuclear inelastic scattering of synchrotron radiation with high energy resolution [1, 2, 3]. It was found that the decrease the atomic volume, resulting from decreasing temperature as well as increasing pressure causes a strong modification of the phonon spectrum. The modification is manifested particular, in splitting of the low-energy phonon peak, and in increasing of the energies of all spectral peaks. The dependences of the mean energy of the vibrational spectrum of iron atoms and Debye energy on decreasing of the atomic volume have been obtained and analyzed. Two possible scenarios of changes in the electron spectrum of FeSi are proposed, which allow us to explain the observed phonon anomalies. Under normal conditions, the compound behaves like a metal and turns into a narrow-gap semiconductor upon a decrease of the atomic volume. According to the first scenario, a further decrease of the atomic volume leads to metallization of the compound, while in the second scenario, this decrease broadens of the bandgap in the electron spectrum and, hence, leads to the formation of a semiconductor state with a broad bandgap. In any case, FeSi ceases to be a narrow-gap semiconductor, and all anomalies associated with the presence of a narrow gap disappear. The results obtained generally allow us to distinguish the electron-phonon interaction in the iron sublattice as a physical mechanism linking the change in the atomic volume with the manifestations of anomalies in the phonon spectrum of FeSi.

The work was partially supported by grant RSF 16-12-10065.

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ELASTIC CHARACTERISTICS AND THERMOCHEMICAL STABILITY OF MIXTURE NITRIDE URANIUM AND PLUTONIUM FUEL

V.G. Subbotin, V.A. Shelan, V.A. Gorohov, I.V. Sannikov
FSUE «RFNC-VNIITF», Snezhinsk, Russia (shelan1987@gmail.com)

One of the most promising of nuclear fuel for fast breeding reactors (FBR) is mixture nitride uranium and plutonium fuel, which in consider with oxide fuel has higher density and thermal conductivity. However, data of thermophysical and thermochemical properties, using for justification efficiency for TVEL FBR with mixture nitride uranium and plutonium, doesn't enough.

There were carried out investigation of elastic characteristics and thermochemical stability of mixture nitride uranium and plutonium specimens (U,Pu)N in RFNC-VNIITF. Thermal dependencies of elastic moduli nitride specimens with porosity from 10 to 20 % and concentration of plutonium nitride (PuN) from 0 to 20 % of mass. There were obtain temperatures of beginning thermal dissociation UN and (U,Pu)N in vacuum, the degradation rates in vacuum and argon with nitrogen additive in interval of temperature from 1800 to 2100 °C.

Investigations carried out with nitride specimens, fabricating in RFNC-VNIITF by approach powder metallurgy from nitrides, producing from metals. Ultrasound facility, which was fabricating by NRNU MEPhI and located in glove box, used to measurements of elastic moduli nitride specimens. Researches of thermochemical stability were obtained on special facility, which was fabricating by RFNC-VNIITF, located in glove box and sealed with quadrupole mass-spectrometer with dimension 300 a.u.m.

Our experiments were provided in accordance in [1] by technical specification and financial

support by SC «VNIINM».

We express our gratitude to Belyaev Dmitrii, Toropov Ilya, Lekomtcev Sergei, Nedosviti Alexander for conduction of structural analysis of specimens.

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HARDNESS AND DAMAGE OF THE U-Fe-Ge ALLOY SPHERE UNDER EXPLOSIVE LOADING

D.A. Belyaev, A.S. Aleksandrov. Yu.N. Zuev, E.A. Kozlov, S.A. Lekomtsev, A.S. Nedosviti, I.L. Svyatov, E.A. Levi

Russian Federal Nuclear Center- Zababakhin All-Russia Research Institute of Technical Physics, Snezhinsk (bad1331@mail.ru)

The paper presents the metallography analysis results for the structural state of the three-phase U-Fe-Ge alloy sphere (Figure 1) recovered under the symmetrical explosive loading by converging shock waves (Figure 2). The sphere initial geometry and the loading conditions are identical to that of the unalloyed plutonium sphere studied in [1]. The analysis was carried out using light microscopy and scanning electron microscopy, microhardness testing combined with digital mapping of the observed physical magnitudes [2].

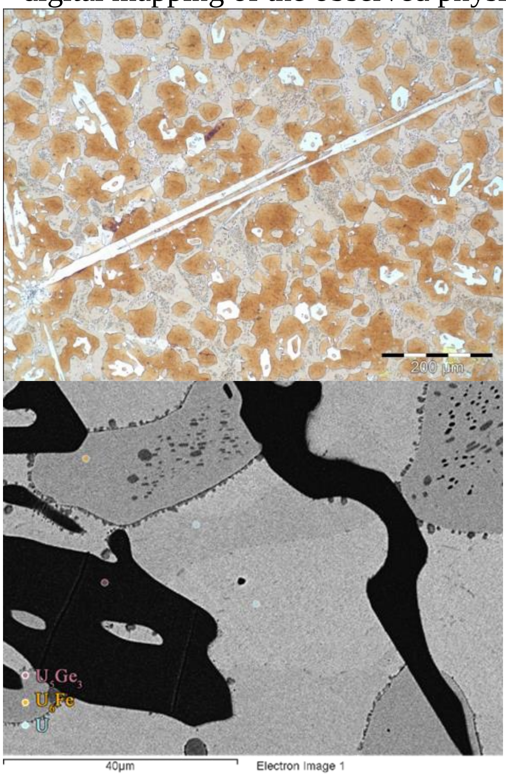

Figure 1 — Three-phase microstructure of the alloy U-Fe-Ge

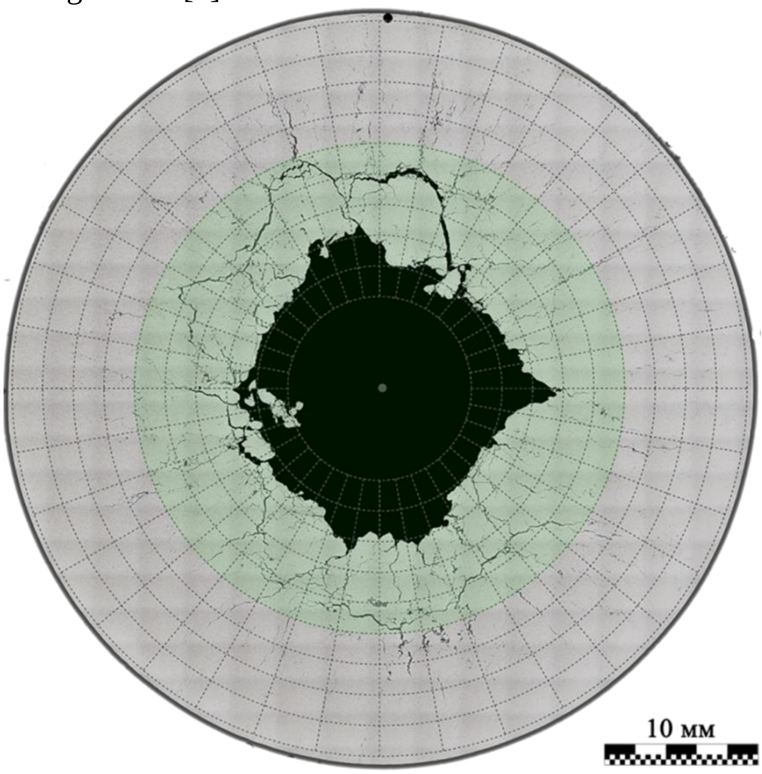

Figure 2 — Damage in the meridional section of the sphere due to the explosive loading

Statistic and spatial distributions of damage, microhardness and hardness in the meridional section of the sphere, as well as changes in the microstructural state were obtained and analyzed. The material fracture behavior was determined and the pattern of its localization along the radius was identified.

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INTRIGUING PROPERTIES OF ε-Fe_2O_3 – RARE POLYMORPH OF IRON OXIDE

D.A. Balaev[1], A.A. Dubrovskiy[1], S.V. Semenov[1], Yu.V. Knyazev[1], O.A. Bayukov[1], A.A. Krasikov[1], V.L. Kirillov[2], S.S. Yakushkin[2], O.N. Martyanov[2]
[1]*Kirensky Institute of Physics, Federal Research Center KSC SB RAS, Krasnoyarsk, Russia,* (*dabalaev@iph.krasn.ru*)
[2]*Boreskov Institute of Catalysis SB RAS, Novosibirsk, Russia*

The polymorphic modification of trivalent iron oxide ε-Fe_2O_3 exists in nanoscale form only. This magnetic material possesses unique properties, since nanoparticles ~ 20 nm in size exhibit a large coercive force (~ 20 kOe) at room temperature [1-3], and also effectively absorb electromagnetic radiation in the millimeter wavelength range. There is a magnetic transition in ε-Fe_2O_3 in the range of 80-150 K, which accompanied by a drastic change in the magnetic properties [2-4]. This iron oxide has a high temperature of magnetic ordering, about ~ 850 K [5], while in the vicinity of ~ 500 K another magnetic transition takes place. The non-centrosymmetric structure of ε-Fe_2O_3 with the space group Pna21 suggests the presence of ferroelectricity, which results in the presence of magnetodielectric effect in ε-Fe_2O_3. In the report the main results obtained earlier on ε-Fe_2O_3 oxide, as well as the results obtained by the authors [6–9] will be reviewed. Special attention will be paid to the surface effects manifested in the magnetic properties of systems of ultrafine particles (~ 3-6 nm) [7,9].

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MAGNETIC EXCITATION SPECTRUM AND BULK MODULUS BEHAVIOR OF δ-PHASE PLUTONIUM

A.V. Mirmelstein, V.N. Matvienko
FSUE "RFNC-VNIITF" Snezhinsk, Russia (mirmelstein@mail.ru)

It is well known that metallic plutonium is characterized by a whole number of unique physical properties thanks to which it acquired reputation of the most mysterious element in the periodic system. Despite significant progress, both in the field of experimental research, and in theory, physics of metallic plutonium continues to be widely discussed. In particular, the problem of the elastic properties of plutonium has not been sufficiently developed. It has long been known that the δ-phase of pure (unalloyed) plutonium contracts with increasing temperature. This effect is usually explained in terms of the so-called "Invar" mechanism [1,2]. However, physical nature of the two-level system of the "Invar" model is rather vague. Unusual softening of the bulk modulus with increasing temperature is also challenging since this effect in the δ-phase of Pu-Ga alloys is observed within the same temperature interval where the crystal

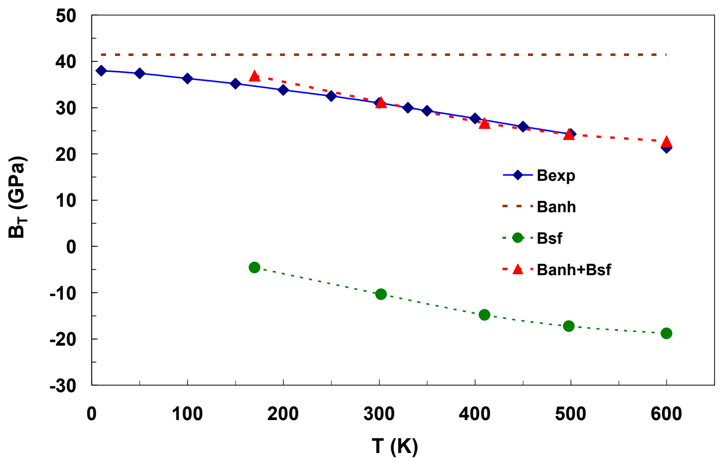

Figure 1. Isothermal bulk modulus B_T vs. temperature calculated in this work (B_{sf}, green circles). Experimental values are shown by blue diamonds. The normal anharmonic contribution B_{anh} = 41.5 GPa (brown dashed line) is assumed to be T-independent. Red triangles show the sum of B_{sf} and B_{anh}.

lattice compresses or has almost zero thermal expansion coefficient [3]. Most likely, the anomalous behavior of bulk modules is related to the peculiarities of the magnetic degrees of freedom, but the interpretation proposed in [4] raises serious questions (see, for example, [5]). Here we suggest another approach based on the results of inelastic scattering experiments [6]. Considering δ-Pu as a Kondo system and using the thermodynamic relations [7] we demonstrate that this approach allows, in principle, to explain the anomalous softening of the δ-Pu bulk modulus (Figure 1). However, to prove this approach additional experimental investigations of the magnetic excitation spectrum of plutonium are required.

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MAGNETIC IMPURITY EFFECTS IN KONDO-INSULATOR

P.A. Alekseev[1,2], W.T. Fuhrman[3], J.-M. Mignot[4], K.S. Nemkovski[5], E.S. Clementyev[6], V.N. Lazukov[1]

[1]*National Research Centre "Kurchatov Institute", Moscow, Russia (pavel_alekseev-r@mail.ru)*

[2]*National Research Nuclear University "MEPhI", Moscow, Russia*

[3]*The Johns Hopkins University, Baltimore, Maryland 21218 USA*

[4]*Laboratoire Leon Brillouin, CEA-CNRS, CEA/Saclay, France*

[5]*Forschungszentrum Julich GmbH, Lichtenbergstrae 1, 85747 Garching, Germany*

[6]*I. Kant Baltic Federal University, REC "Functional Nanomaterials", Kaliningrad, Russia*

The influence of the impurity magnetic moment on the specific thermodynamic and electron spectral characteristic are analyzed for the Kondo insulators like SmB_6 and YbB_{12} along with heavy fermion $CeAl_3$ system. It was Gd impurity for SmB_6 [1], Tm impurity for YbB_{12} [2] and Gd impurity for the $CeAl_3$ [3]. For the $Sm(Gd)B_6$ the heat capacity and magnetization data are analyzed in wide range of low concentrations of Gd (from 0.04% taken as the case of "pure" SmB_6, up to 5%). For the latter two systems as well as for the pure SmB6 in the strong (up to 24T) external magnetic field [4], inelastic magnetic neutron scattering data are analyzed for a low temperature regime corresponding to the formation of the spin gap and the resonance mode in typical Kondo insulators.

The detailed study of $Sm(Gd)B_6$ has realized that introduction of Gd-magnetic moment impurity results in an appearance and grow of the electronic specific heat contribution along with suppression of the Gd magnetic moment on the increase of its concentration. These results discover the origin of the long leaving state for the resonance mode at low temperature (intrinsic line width order of 0.1 meV below 20K) and its fast relaxation on the temperature increase in pure SmB_6. These observations also sheds light on the "puzzling" disappearance of the resonance mode and modification of the spin gap due to magnetic impurity in $Yb(Tm)B_{12}$ Kondo-insulator. Such kind of effects can be considered as the "Kondo-undercompencation" phenomenon.

As concerns the $Ce(Gd)Al_3$ system the measured neutron spectra show no remarkable difference between Gd- (magnetic) and Y-(nonmagnetic) impurity effects in energy and intensity of inelastic magnetic excitations which is quite different from Kondo-insulators presented above. This fact could be interpreted as a consequence of the difference in character of the cooperative ground state for a Kondo-insulator and the single site one for a heavy fermion compound.

The application of the magnetic field to the SmB6 single crystal shows an energy splitting of the resonance mode but in not expected way and this observation needs in more theoretical efforts.

The work is supported by the RSF Grant #18-12-00133.

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MÖSSBAUER ANALYSIS OF MECHANICAL ALLOYING ^{238}U WITH ^{57}Fe

K.A. Kozlov[1], V.A. Shabashov[1], V.V.Sagaradze[1], Yu.N. Zuev[2]
[1]*IMP UB RAS, Ekaterinburg, Russia (kozlov@imp.uran.ru)*
[2]*FSUE "RFNC-VNIITF", Snezhinsk, Russia*

The problem of thermal stability and swelling of uranium-based radioactive fuel is extremely important. It is known that the introduction of a small amount of iron increases the thermal stability of uranium. The solubility of iron in uranium at 650 °C is less than 0.014 %, and solubility of uranium in α-Fe is practically absent. For the purpose of increasing the iron content in the uranium, the study was undertaken to find out the ability of mechanical alloying (MA) of uranium by iron.

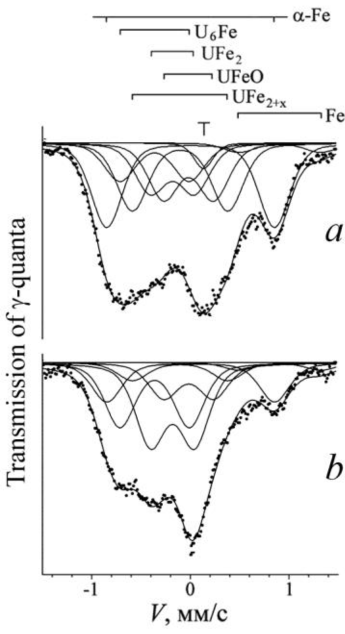

Fig. Mössbauer spectra of samples obtained as a result of mechanical alloing by high pressure torsion of foils α-U + ^{57}Fe (*a*) and subsequent annealing at 300 °C, 1 h (*b*).

α-^{238}U containing the natural iron (~3 wt. %) and α-Fe, enriched to 95.78 wt. % by resonant isotope ^{57}Fe was taken as an initial substance for MA. The deformation was carried out by the method of shear under pressure at 9 GPa in rotating Bridgman anvils according to the "sandwich" scheme: uranium foil/iron foil (or powder).

It was shown that in shear conditions with the deformation degree ε = 6.2 (5 revolutions.) and ε = 7.0 (10 revolutions of anvils) Mossbauer spectra of the samples corresponded to superposition of α-Fe ferromagnetic sextet with α-Fe(U) satellite as well as the doublets of U_mFe_n precursor and UFe_2, U_6Fe paramagnetic intermetallics [1]. Low isothermal annealing at 300 °C, 1 hour led to significant increase in the number of UFe_2 and U_6Fe intermetallic compounds at the expense of the metastable UmFen and α-Fe(U). The phase composition of mechanically alloyed samples after deformation and thermal annealing corresponded to the equilibrium diagram of the U-Fe system on the uranium and iron sides [2].

Thus, using mechanical alloying and subsequent thermal annealing, a structure containing a mixture of α-U, α-Fe and intermetallic compounds UFe_2 and U_6Fe was formed.

This work was performed under the state assignment of the Federal Agency for Scientific Organizations of Russia (theme "Structure" No. AAAA-A18-118020190116-6) supported in part *by the Russian Foundation for Basic Research (project No. 18-03-00216).*

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PHOTOVOLTAIC PHENOMENA IN MIS STRUCTURES

I.A. Bondarev[1,2], M.V. Rautskii[1], A.V. Lukyanenko[1,2], A.S. Tarasov[1], I.A. Yakovlev[1], L.V. Shanidze[1,2], S.N. Varnakov[1], S.G. Ovchinnikov[1], N.V. Volkov[1]
[1]*Kirensky Institute of Physics, Federal Research Center "Krasnoyarsk Scientific Center SB RAS", Krasnoyarsk, 660036, Russia (bia@iph.krasn.ru)*
[2]*Siberian Federal University, 660041, Krasnoyarsk, Russia*

Metal/insulator/semiconductor (MIS) structures are actively studied, due to such phenomena as giant magnetoresistance effect (GMR), spin injection, spin accumulation etc. Such structures combine the electrical properties of metals and the magnetic properties of semiconductors, which is widely used in spintronics devices. Studies of the lateral photovoltaic effect (LPE) are applied for creation of sensitive positional detectors and solar cells.

This paper is devoted to the study of LPV in MIS structures. The main sample was the $Mn/SiO_2/n\text{-}Si$ structure. On a Si(100) substrate, thin SiO_2 (1,5 nm) layer was formed by chemical etching. A manganese film with thickness of 15 nm was deposited by the molecular beam epitaxy.

Figure 1 demonstrates the field dependence of magnetoresistive effect. The value of MV is calculated according the formula MV = [V(H) – V (0)] / V(0) × 100%; where V(H) – is voltage in magnetic field H and V(0) – voltage in zero field. The measurements were performed in the diode mode (the top contact was located on the film, and the bottom one was on the substrate side), when the structure was irradiated with a laser with λ = 809 nm. A strong dependence of the photovoltage on the magnetic field and the laser power is observed, which is partly due to the presence of the surface states localized at the insulator/semiconductor interface.

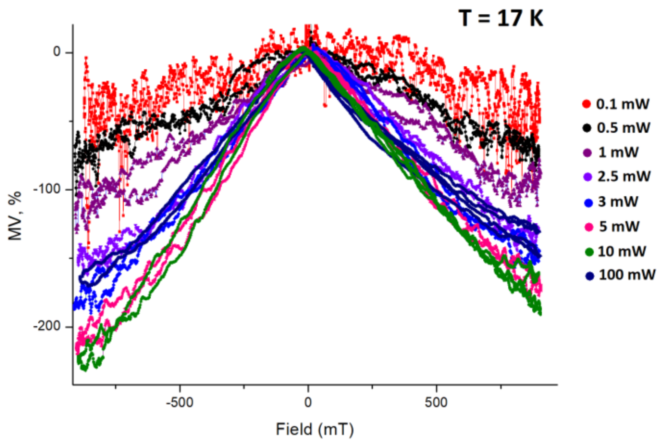

Figure 1. Field dependence of the magnetoresistive effect in the $Mn/SiO_2/n\text{-}Si$ structure, under laser irradiation with λ=809 nm at different irradiation power.

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SPIN-WAVE DYNAMIC AND EXCHANGE INTERACTIONS IN MULTIFERROIC $NdFe_3(BO_3)_4$ EXPLORED BY INELASTIC NEUTRON SCATTERING.

I.V. Golosovsky[1], A.K. Ovsyanikov[1], D.N. Aristov[1], P.G. Matveeva[1], A.A. Mukhin[2], M. Boehm[3], L-P. Regnault[3], L.N. Bezmaternykh[4]
[1]*NRC "Kurchatov Institute", B.P. Konstantinov Petersburg Nuclear Physics Institute, 188300, Gatchina, Russia (golosovsky_iv@pnpi.nrcki.ru)*
[2]*Prokhorov General Physics Institute, RAS, 119991, Moscow, Russia.*
[3]*Institut Laue Langevin, 6 rue Jules Horowitz, BP 156, F-38042 Grenoble, France.*
[4]*Kirenskii Institute of Physics, Siberian Division, RAS, 660038, Krasnoyarsk, Russia.*

The inelastic neutron scattering experiments were performed to reveal the magnetic excitations and to obtain the exchange parameters in phase with collinear antiferromagnetic structure.

Rich picture of spin excitations and strong hybridization and anticrossing of Fe and Nd-subsystems were observed. The experimental spectra were analyzed in a frame of spin-wave theory. The model, which includes the exchange interactions up to 8 coordination spheres, satisfactory describes the observed dispersion curves up to ~ 5.5 meV. It was shown that the spin-wave dynamic is defined by the strongest antiferromagnetic intra-chain interaction along the Fe chains and three nearly inter-chain interactions. Other interactions, including ferromagnetic exchange, appeared to be insignificant. The overall energy balance of the three antiferromagnetic inter-chain exchange parameters, which couple moments from the adjacent ferromagnetic layers, stabilizes parallel moments in the layer. It demonstrates that the pathway geometry plays a crucial role in the forming of the magnetic structure [1].

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SYNTHESIS AND SPIN-DEPENDENT TRANSPORT IN HYBRID STRUCTURES BASED ON THE IRON SILICIDE

A.S. Tarasov, M.V. Rautskii, A.V. Lukyanenko, D.A. Smolyakov, I.A. Bondarev, I.A. Yakovlev, I.A. Tarasov, S.N. Varnakov, S.G. Ovchinnikov, N.V. Volkov
[1]*Kirensky Institute of Physics, Federal Research Center "Krasnoyarsk Scientific Center SB RAS", Krasnoyarsk, 660036, Russia (taras@iph.krasn.ru)*

Study of spin-dependent transport phenomena in semiconductor and ferromagnetic based structures is perspective for further integration of spin functionality to the traditional silicon

CMOS and SOI technology [1]. In this work we present the results of the study of electric transport in the epitaxial Fe_3Si/*p*-Si hybrid structures.

Fe_3Si films were grown by the molecular beam epitaxy under ultrahigh vacuum conditions on the low-doped *p*-Si substrates with carrier concentration of 2×10^{15} cm^{-3}. For study of spin-dependent transport properties, we fabricated the Schottky diode and the 3-terminal microdevice with the distance between the closest contacts of 10 μm (inset for Fig.1 (a)). Measurements were performed using the KEITHLEY 2634b and Agilent E4980A precision devices.

In the 3-terminal Fe_3Si/*p*-Si device, by the Hanle method, spin accumulation effect was observed (Fig.1 (a)). Approximation of experimental curves by Lorentz function allowed calculating spin lifetime in silicon, which turned out to be comparable with the literature data for structures with heavily-doped silicon. To explain the observed effect in our structure with low-doped silicon, the electrical properties of the ferromagnet/semiconductor interface were studied. The value of the Schottky barrier was determined, and the presence of surface states localized at the interface was shown, which allowed proposing a scheme of spin-dependent electrical extraction. (Fig.1 (b)). Holes with spin parallel to Fe_3Si tunnel from the valence band into the ferromagnetic electrode through the localized states. It leads to the spin accumulation in the valence band of silicon.

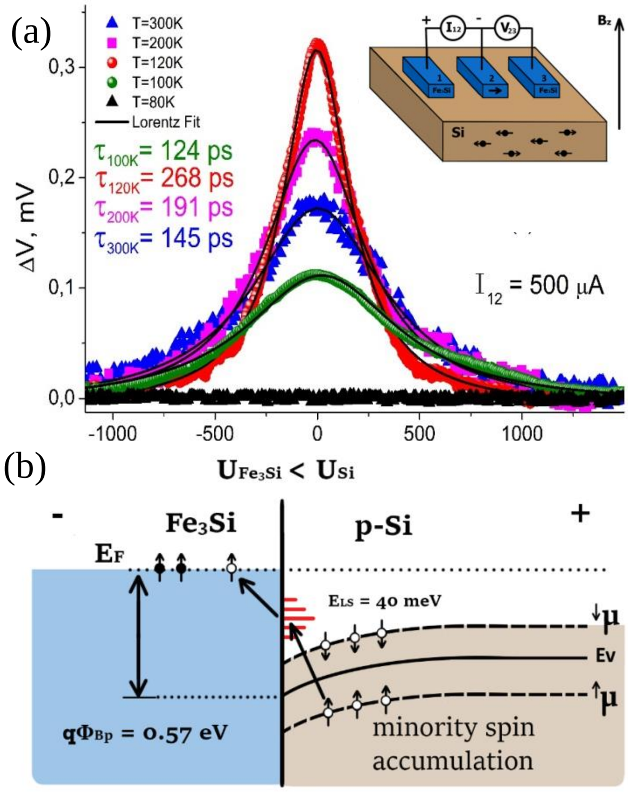

Figure 1. (a) Field dependences of local voltage ΔV measured for the 3-terminal Fe_3Si/p-Si device in perpendicular magnetic field and approximation by Lorenz curve. Inset shows the microdevice. (b) Energy band diagram of Fe_3Si/p-Si transition with the scheme of spin-dependent hole transport.

The study was supported by RFBR, the government of Krasnoyarsk region and Krasnoyarsk Regional Fund according to the research project № 18-42-243022.

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SYNTHESIS OF CHEMICAL ELEMENTS AT ELECTRIC CURRENT PULSES IN WATER WITH NaCl 0.1G / L CONCENTRATION AND TRANSMUTATION OF A PART OF EXTRACTED MATERIAL OF BRASS ELECTRODES

M.P. Kashchenko[1,2], V.F. Balakirev[3], M.B. Smirnov[1], Yu.L. Chepelev[1], V.V. Ilyushin[1], N.V. Nikolaeva[4], V.G. Pushin[2,4]

[1]*Ural State Forestry University, Yekaterinburg, Russia (mpk46@mail.ru)*

[2]*Ural Federal University, Yekaterinburg, Russia*

[3]*Institute of Metallurgy, Ural Branch of the RAS, Yekaterinburg, Russia*

[4]*Institute of Metal Physics, Ural Branch of the RAS, Yekaterinburg, Russia*

According to the data of chapter 4 in [1], with a specific variant of the electrolysis of water and aqueous solutions of salts, there is a synthesis of a fairly wide range of chemical elements. A possible explanation of the mechanism of synthesis requires the expansion of traditional concepts [2, 3]. At the same time, it is advisable to build up the experimental data base, systematize and analyze them, both with the goal of independently confirming known facts of synthesizing elements and establishing new options for forming elements and clarifying the conditions for their formation. To solve some of the tasks, according to [4], a simplified experimental set-up compared to [1] was assembled, which allows performing pulsed electrical discharges in water and aqueous salt solutions using an oscillating circuit tuned to resonance with the supply voltage (220V, 50Hz) . In particular, in the first experiment, NaCl solution with a concentration of 0.1 g / l was used to increase the initial conductivity. Brass (63.77 at % Cu, 37.23 at % Zn) was used as the material of the hollow tubular electrodes. The starting potential difference was 560V. The gap between the electrodes was 0.7-1 mm. The electrodes were arranged vertically. Between the upper and lower vessels, the water moved by itself. Each series of discharges was accompanied by the appearance of a portion of a liquid with a dark (black) color with subsequent precipitation. Analysis of the sediment using energy dispersive techniques showed that along with products of simple erosion of electrodes (Cu and Zn) there are synthesized elements (Mg, Si, S, Fe and several others) which confirms the data [1, 4].

In addition, spherical particles (with diameters to several microns) have been identified as the main component of which is Fe. The appearance of such particles most likely indicates the possibility of extracting material from the region of local melting of electrodes accompanied by copper and zinc transmutations. This means that with the erosion of electrodes, not all iron is synthesized from water as suggested in [4].

The authors are grateful to V.A. Pan'kov and B.P. Kuz'min for initiating the production of experimental studies confirming the synthesis of elements.

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THERMAL CREEP OF NITRIDE FUEL

V.G. Subbotin, M.V.Stepanov, V.A. Gorokhov
FSUE Zababakhin RFNC-VNIITF, Snezhinsk, Russian Federation (step74h3@mail.ru)

Creep is one of important nuclear fuel characteristics that determines its behavior in reactor under the conditions of elevated temperatures and the character of fuel interaction with fuel cell shell. As applied to nitride uranium-plutonium fuel, the data about its thermal creep is almost not available in open literature.

At RFNC-VNIITF, specialists performed a series of experiments on investigation into thermal creep of nitride fuel pellets in the range of temperatures from 1050 up to 1450 °C and stresses in pellets from 10 up to 50 MPa. We built diagrams of creep for pellets with various porosity (from 10 up to 23 %) and various plutonium nitride content (from 0 up to 20 % mass.) We obtained the dependences of established creep rate of the samples on the temperature under constant stress, and dependences of established creep rate of the samples on the stress under constant temperature.

Investigations were conducted on fuel pellets that were fabricated at RFNC-VNIITF by method of powder metallurgy from nitrides that were obtained by direct synthesis from corresponding metals. Investigations were conducted by method of uniaxial compression of the samples on special blimped stand developed at RFNC-VNIITF.

The work was performed according to reference [1] upon technical project and financial support of JSC "VNIINM".

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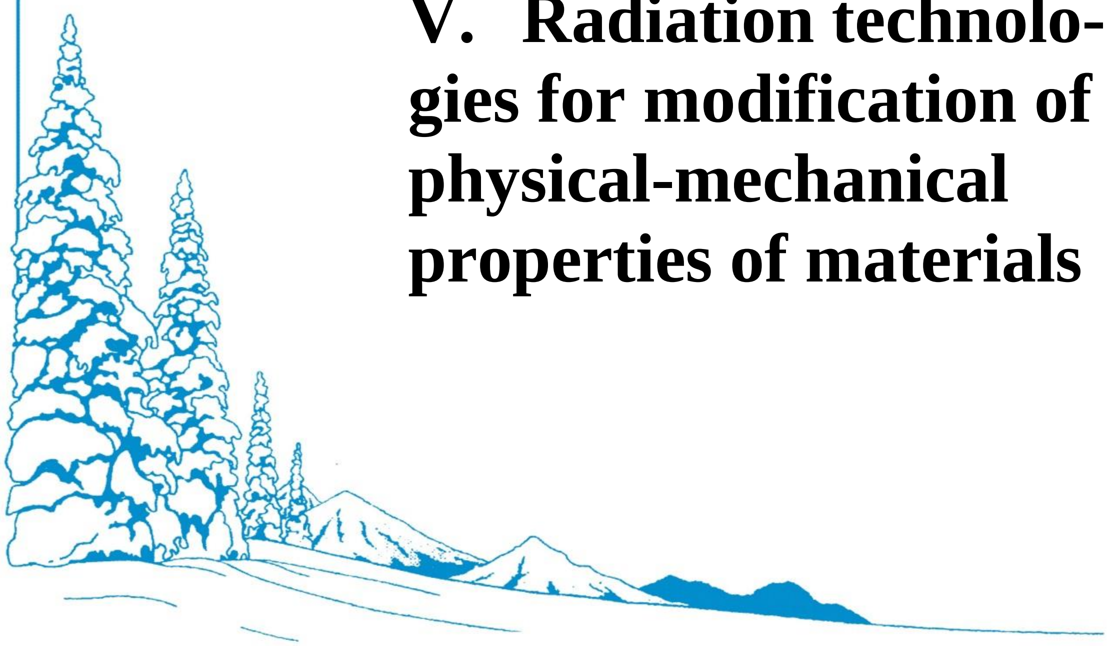
V. Radiation technologies for modification of physical-mechanical properties of materials



This section is introduced in the Seminar's Program in order to exchange information about the latest achievements in the field of radiation material science associated with the development of physical bases and the use of electron- and ion-beam and ion-plasma methods for modifying the structure and properties of materials at the macro-, micro-, meso- and nanoscale level. The section program includes presentations devoted to the consideration of the fundamental aspects of the impact of accelerated ion beams with matter, that are determined their corpuscular nature and are general for both continuous and pulsed ion beams.

The powerful pulsed beams of electrons, ions, plasma flows and laser irradiation (P> 10^7 W / cm^2) cause instant melting and even evaporation of surface layer material. Modification of the properties at the same time is a result of the formation and propagation of powerful thermo-elastic waves. The combination of ion implantation with other methods, such as ion-beam mixing of films deposited previously on the surface of the target (Ion Mixing) or ion-assisted deposition of elements in vapor or plasma (Ion Beam Assisted Deposition) in order to increase the depth of exposure, which at normal conditions is only a percentage of a micron, leads to considerable complication and rise in price of the process. In connection with this, the intensively investigated recently long-range effects occur during ion bombardment, which allow to significantly increase the depth of the modified zone, become urgency, that is particularly important to develop methods for the modification of surface properties of construction materials.

The most promising is currently studying of nanoscale dynamic effects caused by corpuscular irradiation. Nanoscale regions of dense cascades of atomic displacements, warmed up for about 10^{12} seconds to temperatures of 3000-5000 K and higher, are zones of explosive energy release and the source of the post-cascade solitary shock waves, which can rebuild the metastable environment. The rate of energy release is comparable to that for a nuclear explosion. Radiation-dynamic effects, which are not taken into account in the classical radiation physics of condensed matter, play an important role also under neutron irradiation and self-irradiation of fissile materials. They should be considered in connection with the nuclear safety issue in the development of new materials for use in the internals of nuclear power plants, as well as materials for use in outer space.

ANALYSIS OF THE CHEMICAL STATE OF THE COMPONENTS OF THE Cu-Ni, Cu-Mn ALLOYS AFTER IMPLANTATION OF N^+ IONS

T.S. Kartapova, O.R. Bakieva, F.Z. Gil'mutdinov, V.L. Vorobyov
Udmurt Federal Research Center, Ural Branch of the Russian Academy of Sciences, Izhevsk, Russia

Alloys of Cu-Ni, Cu-Mn systems are widely used in various fields of engineering and technology. Their physical and physico-chemical properties are largely determined by the composition and structure of the surface and near-surface layers. Their modification in order to achieve the specified properties is an urgent task, and the methods of ion-beam processing are of scientific and practical interest in connection with the possibility of forming structural-phase states in non-equilibrium conditions that are not realizable by traditional processing methods.

In this work, we studied the features of the formation of the chemical state of the surface layers of the CuNi, CuMn alloys under conditions of low-dose implantation of N^+ ions. The considered copper-based alloys have as the second component elements with different chemical activities. In this regard, we should expect the contribution of the selectivity of the interaction of implantable ions with the components of the alloys to the formation of the chemical composition of the modified layers, along with radiation-stimulated segregations.

The irradiation was carried out in a repetitively pulsed mode in an ion beam installation with a PION-1M source with an energy of 30 keV with doses of $5 * 10^{16}$ and 10^{17} ions / cm^2. Separation of singly charged N^+ ions was performed using a Wien filter. Analysis of the chemical composition and interatomic interaction was performed by X-ray electron spectroscopy using an SPECS electronic spectrometer. The analysis of the chemical state of manganese was carried out using the spectra of Mn2p and the parameters of the multiplet splitting of the spectrum of Mn3s. The chemical state of copper and nickel was carried out on the basis of a joint analysis of the spectra of the core levels and the LVV-Auger spectra.

The results of irradiation with nitrogen ions are analyzed in comparison with the results obtained with the implantation of ions of chemically inert argon, as well as oxygen ions under the same experimental conditions and exposure parameters. It is shown that irradiation with all types of ions of Cu-Mn alloys leads to enrichment of the surface layers with manganese and its compounds, which can reach up to 100% at high doses of exposure. The features of the formation of manganese oxides, nitrides, and oxynitrides were studied depending on the irradiation parameters and the type of the implanted ions. Based on the results for both the considered systems (Cu-Ni, Mn), conclusions were made about the joint contribution of segregation processes and the selectivity of interatomic interaction to the formation of the composition of ion-modified surfaces.

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CHANGES IN THE COMPOSITION OF SURFACE LAYERS AND STRUCTURE IN AMORPHIC MATERIALS IN THE CONDITIONS OF ION IRRADIATION

A.A. Kolotov, V.L. Vorobev, D.V. Surnin, V.Ya. Bayankin
*Udmurt Scientific Center of the Ural Branch of the Russian Academy of Sciences, Izhevsk, Russia (**less@udman.ru**)*

Metal alloys that are in an amorphous state - amorphous metal alloys, have a number of unique characteristics - such as special magnetic, corrosive, mechanical properties not typical of ordinary metal materials. The main characteristic of amorphous alloys is the absence of long-range order and the presence of short-range order in the arrangement of atoms. Despite the prospects of amorphous alloys, their practical application is limited. The main reason for this is the insufficient knowledge of the processes of glass formation of metals and crystallization of amorphous alloys. The issue of thermal stability of amorphous alloys today remains one of the current areas of applied and basic research. The analysis of the structure and segregation processes is especially important here, especially in the early stages of crystallization, since the crystallization of amorphous alloys proceeds through a sequence of metastable states, and the properties of the alloy change so much that we can speak of two different materials of the same chemical composition. Hence the task of managing crystallization, as a method of creating new materials.

In the framework of the work, the laws governing the evolution of the structure and composition of the surface layers of amorphous alloys subjected to ion-beam processing are investigated. It was shown that as a result of ion bombardment of amorphous materials, the amorphous phase disintegrates with a release of a set of metastable phases, and the speed and number of new phases depend on both the irradiation parameters and the type of irradiated ions. In this work, a comparative analysis of samples of amorphous alloys of the Fe – P, Fe – B, and Ti – Cu system irradiated with boron ions is carried out. Irradiation was carried out with a variation of energy and current density. It is shown that the structural changes of the amorphous phase and surface crystals of an amorphous alloy are determined by the modes of ion-beam processing — the dose and energy of the primary ions. In this work, the features of component rearrangements in the surface layers under various processing conditions are investigated - in particular, the accumulation of implantable atoms in the surface layers, which determine the direction of segregation processes, is shown.

Comparing the results of X-ray structural analysis and data on the composition of the surface region, it can be assumed that as a result of irradiation, metastable phases are actively formed in the surface layers, the composition of which varies depending on the irradiation parameters. In this case, the phase formation process is actively developed in the amorphous matrix until complete crystallization. It is noted that crystallization of the amorphous phase during ion implantation occurs at lower temperatures (lower by more than 200-300 degrees) than in the case of thermal crystallization. From this we can conclude that the microscopic processes of development of cascades of atomic-atomic collisions play a decisive role in the process of diffusion and phase formation.

CHANGE OF STRUCTURE AND PROPERTIES OF AMORPHOUS ALLOY UNDER THE INFLUENCE OF LASER RADIATION

A.V. Zhikharev, V.Ya. Bayankin, S.G. Bystrov
Physical- technical Institute of the Udmurt federal research center Ural branch of RAS, Izhevsk, Russia (less@udman.ru)

In work results of a research of influence the focused pulse laser radiation on $FeSi_6B_{16}$ amorphous alloy depending on power density of laser radiation are considered.

Laser irradiation on the amorphous alloy was performed by a focused laser beam at the natural atmosphere. A laser radiation source was the precision laser marker "Betamarker-2010" operating on the basis of a solid-state Nd-YAG laser with a lamp-pumped system and Q-switching. The variable parameter during the irradiation was the pump lamp current. The main parameter determining the efficiency and quality of the laser irradiation process is the laser radiation power density in the focal spot. In order to determine the power densities of the laser transmitter in the chosen irradiation regimes, we carried out approximate calculations. At the same time the number of the impulses falling on a point equaled to one. Pulse duration was set in 1000 nanoseconds. The focal length equaled 210 mm.

The analysis of alloy state before and after laser influence is carried out by means of the methods of atomic power microscopy, x-ray photoelectronic spectroscopy, x-ray diffraction analysis and measurements of microhardness.

As a result of the conducted researches it is established that in all cases of laser influence amorphous metal $FeSi_6B_{16}$ alloy was exposed to strong thermal influence. Heating of alloy to high temperatures led to melting of a samples surface and to distribution of the front of a thermal wave from strongly heated surface in inside layers of material. The warmed layer of material which resulted from heating had more time for cooling and education of crystal germs. Crystallization process glory could be a consequence of diffusive redistribution of the making alloy elements at aspiration of a system to stabilization of structure that led to emergence in an amorphous matrix of the areas with concentration heterogeneity providing origin of germs of a crystal phase in these areas. At the same time mobility of elements of the Fe-Si-B system, most likely, was a consequence of a strong warming up, pro-melting and softening of the alloy layers which were affected by the laser. However, apparently, because of fast cooling of a radiation zone of samples after cancellation of the laser there was "freezing" of growth of the formed germs of a crystal phase. Therefore samples in volume remained all also X-ray amorphous.

It is supposed according to literary data that amorphous $FeSi_6B_{16}$ alloy with education in α-Fe the crystal phase Fe_2B which increases strength properties of material will crystallize. Data of measurements of microhardness recorded growth of values of microhardness for all samples of rather initial state, and RFES-profiles of concentration of elements on depth of alloy showed decrease in its contents in blankets.

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COMPARATIVE STUDY OF INFLUENCE OF ION BOMBARDMENT AND LOW-TEMPERATURE ANNEALING ON THE STRUCTURE AND PHASE COMPOSITION OF THE 1441 (Al-Li-Cu-Mg) ALLOY EXPOSED TO SEVERE PLASTIC DEFORMATION

N.V. Gushchina[1], V.V. Ovchinnikov[1,2], F.F. Makhin'ko[1], L.I. Kaigorodova[3], D.Y. Rasposienko[3]
1Institute of Electrophysics, Ural Branch, Russian Academy of Sciences, Yekaterinburg, Russia (guscha@rambler.ru)
2Ural Federal University, Yekaterinburg, Russia
2Institute of Metal Physics, Ural Branch, Russian Academy of Sciences, Yekaterinburg, Russia

The effect of severe plastic deformation (SPD), and also subsequent low-temperature annealing, and irradiation with argon ions on structural and phase transformations in alloy 1441 based on the Al-Li-Cu-Mg system was studied by transmission electron microscopy.

The samples of the 1441 alloy 2 mm thick were deformed at room temperature and a pressure of 4 GPa in Bridgman anvils to 5 revolutions (angle of the anvil rotation $\varphi = 10\pi$ rad). The thickness of the samples after deformation was 400 μm. Some samples after SPD were annealed at a low temperature of 160°C for 15 h, the rest samples were irradiated in a continuous mode using an ILM-1 ion implanter with a PULSAR-1M source. The ion energy E = 10, 20 keV, the ion current density j = 100, 300 $\mu A/cm^2$, and the ion fluence $F = 1\cdot10^{15}$–$5\cdot10^{16}$ cm^{-2} during irradiation were varied.

Electron microscopic analysis showed that after SPD in the 1441 alloy, a predominantly mixed grain structure consisting of submicrocrystals with an average diameter of ~ 0.3-0.4 μm and nanocrystals with a diameter of less than 100 nm was observed. In addition, fragments of deformation bands were detected.

After annealing of the 1441 alloy subjected to SPD, a predominantly homogeneous recrystallized structure with an average grain size of 0.3-0.5 μm was observed. In some parts of the sample after annealing, the fragments of the banded structure with low-contrast boundaries of the bands formed during SPD were preserved.

It was found that extremely short-term exposure to argon ions with an energy of 20 Kev at a sufficiently high ion current density j = 300 $\mu A/cm^2$ (for 1 s, $F = 1.9\cdot10^{15}$ cm^{-2}, T ≤ 160°C) contributes to the formation of an equilibrium recrystallized structure in an extended surface layer (at least up to 200 μm in depth at an average projective run of argon ions ~ 20 nm) of the 1441 alloy subjected to SPD. There is a heterogeneity of the microstructure in grain size: from 0.4-0.5 to 0.8-1 μm.

In the case of irradiation in the regime with lower ion energy (10 Kev), ion current density (100 $\mu A/cm^2$), the submicrostructure dispersion and dimensional uniformity increase (the range of grain size change is 0.5-0.7 μm).

Unlike low-temperature annealing (T = 160 °C, 15 h), irradiation for 1 s (T ≤ 160°C) leads to the complete disappearance of the deformation bands available after SPD. In addition, during irradiation, the dissolution of S_1 (Al_2LiMg) and T_2 (Al_3CuLi_5) phase particles existing in a strongly deformed state are occurs, and the natural aging process with the formation of the δ (Al_3Li) metastable phase is suppressed.

The study suggests a significant role of fast nanoscale dynamic processes in cascade-forming irradiation [1].

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DEPOSITION OF DIELECTRIC COATINGS Al_2O_3 BY THE METHOD OF REACTIVE MAGNETRON SPUTTERING

L.R. Khlabystina, M.V. Lapin, V.N. Matvienko
RFNC – VNIITF, Snezhinsk, Russia (lyubov_tihomirova@mail.ru)

The widespread use of aluminum oxide films in various fields is due to their properties such as chemical inertness in a variety of corrosive media, hardness, wear resistance, good dielectric strength [1]. Due to the high radiation resistance of aluminum oxide is considered as a potential material of the first wall of fusion reactors and containers for hydrogen content. The method for producing thin (about 500–1000 nm) aluminum oxide films using reactive magnetron sputtering is well known and well described in the literature [2, 3]. However, the production of dielectric films in the process of reactive magnetron sputtering creates a lot of problems associated with the occurrence of a large number of breakdowns in the discharge system. In addition, with increasing film thickness, the target cathode is poisoned by oxygen, the film begins to lose transparency, the stoichiometric ratio is disturbed, and the transparency and density of the film decrease.

A number of experiments have been carried out to determine the optimum parameters for the deposition of an aluminum target in a reaction medium of argon gas with 7, 10, 13% oxygen, in terms of the deposition rate and uniformity of the coating.

In addition to the quartz thickness gauge, measurements on witness samples using a calotest in accordance with ISO 26423 [4] were used to determine the coating thickness. According to the results of studies of the surface of the samples by scanning electron microscopy, it was found that the coating is continuous and has almost the same chemical composition for each spraying process. Analysis of the films obtained using a powder X-ray diffractometer in the characteristic copper radiation showed that the structure of the coatings is amorphous. It is shown that the coating films obtained with the content of 10 and 13% oxygen in the composition of the reaction mixture have a high electrical resistance.

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EFFECTS OF IRRADIATION ON DEFORMATION MECHANISMS IN 304L STAINLESS STEEL

Janelle P. Wharry[1], Keyou S. Mao[1,2], Cheng Sun[2], Paula D. Freyer[3], Frank A. Garner[4]
[1]*College of Engineering, Purdue University, West Lafayette, IN 47907, USA*
[2]*Materials and Fuels Complex, Idaho National Laboratory, Idaho Falls, ID 47907, USA*
[3]*Westinghouse Electric Company LLC, Pittsburgh, PA 15235, USA*
[4]*Department of Nuclear Engineering, Texas A&M University, College Station, TX 77843, USA*

This presentation will describe recent advancements in micro-mechanical testing that inform how deformation mechanisms in 304L stainless steels (SS) are affected by the presence of irradiation-induced defects. Austenitic 304L SS is one of the most widely utilized structural alloys in nuclear energy systems, and aptly, the influence of irradiation on the mechanical integrity of these alloys has been studied extensively. However, the role of irradiation on the underlying mechanisms of mechanical deformation remains relatively poorly understood. Now, the recent advancement of micro-scale mechanical testing in a scanning electron microscope (SEM), coupled with site-specific transmission electron microscopy (TEM), enables us to precisely determine deformation mechanisms as a function of plastic strain and grain orientation.

The example to be presented focuses on specimens of AISI 304L stainless steel reflector blocks irradiated in EBR-II. We select a plate from these blocks, which has been irradiated to 20 displacements per atom (dpa) at 415°C, and which contains ~3 atomic parts per million (appm) He amounting to 1.5% swelling. An archival specimen of the identical alloy heat is also studied as a control. We use nanoindentation to determine the anisotropy of hardness and modulus along the principal crystallographic directions [100], [110], and [111]. Low anisotropy is observed in both the irradiated and unirradiated specimen. Comparing the nanoindentation loading curves, there is evidence of a pop-in in the irradiated specimen, which is not present in the unirradiated specimen. This pop-in suggests that irradiation promotes activation of alternative deformation mechanism(s) in addition to dislocation slip. Site-specific focused ion beam (FIB) milling is used to prepare TEM lamellae from the nanoindentation volume. The subsequent TEM investigation confirms the nucleation of deformation-induced martensite needles in the irradiated specimen. On the other hand, the unirradiated control specimen exhibits evidence only of dislocation slip; this is unsurprising given that alternative deformation mechanisms such as twinning and martensitic transformation are typically observed only near cryogenic temperatures in austenitic SS. SEM-based micropillar compression testing is also used to observe the deformation mechanisms in real time. Micropillar compression tests reveal confirmatory evidence of twinning and martensitic transformations in the irradiated specimen.

We conclude that surfaces available from irradiation-produced voids provide sufficient free energy to accommodate the martensitic transformation. Results from this study suggest that irradiation damage could provide a new pathway to conduct fundamental, mechanistic study of deformation mechanisms that are typically only accessible at extremely low temperatures.

ELECTROCHEMICAL PROPERTIES OF ION-MODIFIED THIN CARBON FILMS

T.S. Kartapova, O.R. Bakieva, F.Z. Gil'mutdinov, V.L. Vorobyov, A.A. Kolotov
Udmurt Federal Research Center, Ural Branch of the Russian Academy of Sciences, Izhevsk, Russia

We have previously shown that carbon-nitrogen CNx films on the surface of armco-iron in general have protective properties in aggressive media [1-3]. It was also shown that, despite some similarity in the chemical state and the concentration of nitrogen embedded in the carbon layers, the films obtained by magnetron sputtering in an argon-nitrogen mixture have worse properties compared to the coatings obtained by magnetron sputtering in argon followed by implantation of nitrogen ions. A significant difference in the second case is the additional disordering of the entire film and the formation of a transition layer consisting of non-stoichiometric carbonitride compounds with nitrogen penetration deeper than the film / iron interface.

In this regard, in this work, comparative thin 20-22 nm carbon films on Armco iron with subsequent nitrogen implantation are carried out. The XPS method showed that such a thin layer is a region of variable composition and can be considered as a model of the transition carbonitride layer between a 30 nm thick carbon-nitrogen film and the metal to be coated.

This work was supported by the RFBR project 16-43-180765.

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EVIDENCES OF THE SHOCK-WAVE NATURE OF LOW-TEMPERATURE ATOMIC REDISTRIBUTION PROCESSES UNDER ION BOMBARDMENT

E.V. Makarov[1], V.V. Ovchinnikov[1.2]
[1]*Ural Federal University named after the first President of Russia B.N. Yeltsin, Yekaterinburg, Russia (efre-m@yandex.ru)*
[2]*Institute of Electrophysics UB RAS, Yekaterinburg, Russia*

From the condition of the free energy minimum $F = E – T \cdot S$ it follows that at 0 K only pure components and stoichiometric compounds or their mixtures are thermodynamically stable. With temperature drop the diffusion mobility of atoms falls, the interatomic distances decrease, the role of covalent bonds increases. This determines the predisposition of binary and multicomponent media to the formation of low-temperature phases, including those with reduced symmetry. At the same time at temperatures $T < (0.3 – 0.4)\ T_{melt}$, diffusion processes in condensed media are actually frozen and the equilibrium states are unattainable for actually imaginable time intervals.

In the IEP UB RAS studies (see review [1]) nanoscale dynamic effects were found in condensed media under cascade-forming types of irradiation that remained outside the field of view of classical radiation physics. They are associated with the processes of explosive energy release in areas of dense cascades of atomic displacements with the formation for trillionths of a second of nanoscale zones (thermal spikes) heated to 3000 – 6000 K and higher with thermal pressures of 5 – 40 GPa, which in some cases exceed the theoretical yield point of materials. This leads to the formation of post-cascade shock waves capable of provide liquid type flow of condensed media at their front, initiating structural phase transformations. In this case, radiation shaking can play the role of temperature.

In metastable environments post-cascade solitary waves can become undamping, feeding on the energy of phase transformations initiated on their front.

To prove the significant, and in some cases the prevailing role of shock-wave processes (but not radiation-enhanced diffusion), it is necessary to reduce the exposure time of the ion beam for eliminating the role of migration processes. In study [2], it was shown that the diffusion path length of vacancies in pure aluminum $l = (D / \tau)^{1/2}$ for 1 s is only 0.4 μm. The path of interstitial atoms in an ideal lattice is 2 – 3 orders of magnitude greater, and in non-ideal crystals it decreases only due to the presence of traps and sinks. By limiting the exposure time to $\tau \leq 0.001$ s, one can completely eliminate the role of thermal and radiation enhanced diffusion for objects with a thickness of more than several tens of micrometers.

In these experiments using the temporal diaphragms, which set the exposure to 0.001; 0.01 and 0.1 s, it was shown that the formation of short-range atomic order in alloys, iron with 6.25 at. % Si, 6.25 and 8.25 at. % Mn during their low-temperature irradiation ($T < 300$ °C) by Ar^+ and Xe^+ ions is due exclusively to the post-cascade dynamic (shock-wave) effects. The values of the short-range order parameter were determined as a result of processing the Mössbauer spectra of samples ~ 25 μm thick initially disordered by cold plastic deformation. In samples subjected to similar thermal effects, but in the absence of irradiation, atomic ordering processes are not detected.

This work was performed as part of State Task.

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LOCAL ATOMIC STRUCTURE OF THE IONMODIFIED SURFACE OF Fe

I.K. Averkiev[1,2], O.R. Bakieva[2], T.S. Kartapova[2], S.M. Reshetnikov[1,2], F.Z. Gil'mutdinov[2]

Udmurt State University, Izhevsk, Russia

Udmurt Federal Research Center, Ural Branch of the Russian Academy of Sciences, Izhevsk, Russia

A series of experiments on the irradiation of iron surface with argon and oxygen ions with various parameters of ionic modification was carried out. The electrochemical study of the ionmodified surface of Fe was carry out. There are shown the irradiation of iron surface with oxygen ions leads to increased corrosion properties of the metal. The ion exposure parameters, allowing to achieve an increase in corrosion resistance of 10 points were determined. The chemical composition and local atomic structure of the samples with high electrochemical parameters were studied to determine the mechanism of formation of the passivation layer. The local atomic structure of ionmodified iron surface were studied by EELFS spectroscopy (Electron Energy Loss Fine Structure). It is XAFS-like method (X-ray Absorption Fine Structure). The experimental $M_{2,3}$ EELFS spectra of Fe and K EELFS spectra of O were obtained before and after ion irradiation (by argon and oxygen ions). The parameters of the local atomic structure (partial interatomic distances, coordination numbers, parameters of the thermal dispersion of atoms) of the ion-modified iron surface are determined.

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MOLECULAR - DYNAMIC STUDY OF THE CARBON SURFACE UNDER ION IRRADIATION

N.M. Sozonova, A.Yu. Drozdov, V.Ya. Bayankin, V.L. Vorob'ev
Udmurt Federal Research Center of the Ural Branch of the Russian Academy of Sciences, Izhevsk, Russia (Sozonova@udman.ru)

Modification of materials is an important issue of scientific and technological progress. Of great importance is the change in the surface of solids. Surface properties are responsible for many characteristics, such as wear resistance, corrosion and fatigue strength. One of the promising areas of surface modification of materials is ion-beam mixing.

At the first stage, an experiment was carried out with carbon deposition on a titanium substrate and subsequent irradiation of the obtained film with argon ions with an energy of 30 keV, a current density per pulse of 3 mA/cm^2 and doses of 10^{17} and $4\cdot10^{17}$ ions/cm^2. It is revealed that the sprayed film in front of the transition layer with titanium is amorphous carbon. The beginning of the transition layer corresponds to a depth of ~ 50 nm. The ion beam leads to a further increase in the degree of disordering of the carbon layer and a shift of the transition region to the surface. It is assumed that the disordering of the carbon layer is one of the reasons for the increase in the microhardness more than 2 times. The beginning of the transition layer after mixing is 40 nm. Experimental study of the process in short periods of time is a difficult task, since the physical state of the material during and after irradiation varies. Therefore, the results of ion implantation and immediately after its completion are of the greatest interest. This is possible using computer simulation of ion implantation.

The study of the surface layer of disordered carbon was carried out using a computer experiment using the molecular dynamics method using the LAMMPS software package. Created by a disordered system of carbon atoms. Radial distribution functions of the obtained sample were constructed. Then the implantation of argon ion in the direction perpendicular to the surface of the material was modeled. The energy of the incident ion was chosen to be 30 keV.

The collision cascades resulting from ion irradiation are analyzed. Atoms are sputtered on the surface and voids are formed. To analyze the studied structure, the functions of the radial distribution were constructed at different points in time. It was found that the degree of carbon disordering increases.

The work was performed as part of the state assignment of the FANO of Russia AAAA-A17-117022250040-0

NEW PROTECTIVE CASING OF MANIPULATORS: EXPERIENCE IN DEVELOPMENT AND IMPLEMENTATION

M.R. Khusainov[1], A.I. Berezyuk[1], S.A. Komaristov[1], V.M. Shagin[1], S.S. Zyryanov[2], A.V. Kruzhalov[2], O.V. Ryabuhin[2], F.G. Neshov[2]
[1]*FSUE «PO «Mayak», Ozyorsk, Russia (cpl@po-mayak.ru)*
[2]*FSAE HE «UrFU», Ekaterinburg, Russia*

Electrically-driven manipulators MEM-10 are used at Mayak PA for remote handling operations carried out in the course of SNF reprocessing. To protect the manipulators were used covers of radiation-resistant polymer – polyethylene terephthalate. The experience of their operation showed that in hot cells, where work is performed with α-active nuclear materials in open form, the life of protective covers is about one month. In these chambers the material changes color from white to dark brown, the pockets quickly lose their elasticity and are destroyed. After the destruction of the protective covers, small fragments of nuclear materials begin to fall into the open places of articulation of the hand, elbow and arm of the manipulator, which leads to disruption of their mobility and, consequently, to the need to replace expensive manipulators.

Working with α-active nuclear materials in an open form is associated with an intense effect of α-radiation. The impact of this operational factor, as shown by the results of research conducted in the FSAEI HPE «UrFU», is the main cause of rapid destruction of covers.

Mayak PA conducted research on the selection of materials suitable for fabrication of protective covers for MEM-10 manipulators. In a laboratory environment and under hot cell conditions of the radiochemical plant, it was determined what strengths various polymeric materials had when exposed to different operational factors. Based on the results of the first stage of the research, at which samples of industrial textiles of Russian and of foreign origin, as well as elastomers and regular plastic protective covers of manipulators of foreign origin were studied, materials with the best strength characteristics in terms of exposure to operational factors were chosen. At the second stage, prototype covers were fabricated using the selected materials and their testing under hot cell conditions was performed at the radiochemical plant.

To date, prototype samples of protective covers of different designs have been manufactured using the polymeric material selected on the basis of the research results. Hot cell testing of these samples is underway to identify optimal design of the protective cover.

RADIATION-INDUCED CHANGES IN THE MORPHOLOGY OF THE PARTICLES OF POWDERED POLYTETRAFLUOROETHYLENE

M.A. Arsent’ev[1], E.D. Politova[1], A.Yu. Rashkovskii[2], A.S. Smolyanskii[1,3]
[1]*Branch of joint-stock company “Karpov Institute of Physical Chemistry”, Moscow, Russia (secretary@cc.nifhi.ac.ru)*
[2]*Limited liability company “Systems for microscopy and analysis”, Moscow, Russia*
[3]*D. Mendeleev University of Chemical Technology of Russia, Moscow, Russia*

Traditionally used technology of synthesis of powdered polytetrafluoroethylene (PTFE) by emulsion polymerization allows to obtain crystalline polymer particles of different shapes [1], which can destroy or interact with each other in the process of γ-irradiation [2]. In this study, by means of transmission electron microscopy (TEM) and electron back diffraction, the changes of PTFE powder particles morphology occurring under the action of γ-radiation ^{60}Co-source in air at room temperature in the range of absorbed doses of 10 - 500 kGy at a dose rate of 1.5±0.3 Gy/s were studied. In the studies, samples of powdered PTFE grade F-4D (State Standard 14906-77) were used. FEI Tecnai G2 F20 S-Twin TMP (manufactured by FEI Company (USA)) was used in PEM measurements at an accelerating voltage of 200 kV in a light field. The resolution of the device is 0.14 nm (line resolution).

It was found that at a dose of 10 kGy PTFE powder consists of two types of particles: a) filamentous crystals (FC) up to 1 μm long and up to 0.1 μm thick; b) granules, which are an agglomerate of several folded crystals. Increasing the dose to 50 kGy or more leads to the disappearance of FC. An appearance of the numerous helical structures with a height of 3 to 8 nm, growing at the exit of screw dislocations on the surface of the granules observed at the same time on the surface of the granules. Helical structures are no longer observed in doses exceeding 100 kGy. In samples of PTFE powder irradiated to 500 kGy, granular particles consist of numerous microcrystals and pores of sizes 100 – 150 nm.

These data are consistent with the results of the previous x-ray phase analysis of the irradiated PTFE powders under consideration [2]. According to the results of the described studies, it is suggested that both radiation-induced homogeneous processes of crystal lattice transformation (isomorphism, topochemical reactions, dislocation formation, etc.) and heterogeneous processes developing as a result of the destruction of polymer chains, which lead to the formation of pores and microcrystals formed from fragments of the destructed PTFE chains, proceed simultaneously.

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STRUCTURE AND PROPERTIES OF TITANIUM-BASED COATINGS PREPARED BY PLASMA AND ION BEAM TECHNOLOGIES

I.A. Tsyganov[1], A.I. Tsyganov[1], A. Kolitsch[2], A. Lode[3], M. Gelinsky[3]
[1]*Lipetsk State Technical University, Lipetsk, Russia (zyganov.igor@gmail.com)*
[2]*Helmholtz-Zentrum Dresden-Rossendorf, Dresden, Germany*
[3]*Technische Universität Dresden, Dresden, Germany*

Plasma-based and ion beam technologies as ion implantation, ion beam assisted deposition (IBAD) or plasma immersion ion implantation (PIII) have been proven to be effective approaches for modification of surface properties of different materials [1]. The relation between structure and biocompatibility in form of the biomineralization of the titanium-based layers (pure Ti, titanium nitride TiN, titanium oxide TiO_2, titanium oxynitrides TiN_xO_y, Ca-implanted TiN_xO_y) deposited by metal plasma immersion ion implantation and deposition (MePIIID) technique has been studied in our experiments [2].

In this work structure, phase composition, microhardness, Young's modulus and hydrophilicity of titanium oxynitride $TiN_{0.4}O_{1.6}$, and pure and phosphorus ions implanted TiO_2 coatings produced by MePIIID were investigated. To evaluate the correlation between the structure of the layers and their cytocompatibility, the influence of the surfaces on the behavior of osteoblast-like SaOS-2 cells was studied *in vitro*. The good mechanical properties and biocompatibility of titanium oxynitride $TiN_{0.4}O_{1.6}$ and P-implanted titanium oxide TiO_2 without any toxic elements make these Ti-based layers interesting candidates for long-term studies *in vivo*.

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THE CHEMICAL COMPOSITION OF THE SURFACE LAYERS OF NICKEL FOIL WITH A DEPOSITED LAYER OF ALUMINUM, AFTER MIXING BY ARGON IONS

P.V. Bykov, V.L. Vorobiev, I.N. Klimova, A.A. Kolotov, V.Ya. Bayankiv
UdmFRC UrB RAS, Izhevsk, Russia, (less@udman.ru)

Intermetallic phases, in particular Ni-Al and Ti-Al systems, have unique physical and mechanical properties [1]. They retain the structure and strength at high temperatures, have good anti-corrosion and anti-friction properties, what is much superior to conventional materials. The formation of intermetallic structures in the nanocrystalline state in the surface layers of metal materials can be successfully implemented when exposed to the surface of high-intensity metal ion beams [2]. In addition, ion mixing, based on the introduction of the required admixture from the surface layers in the transmission of the kinetic energy of the primary beam, has great prospects for obtaining new structures and compounds with desired properties [3, 4].

The aim of this work was to study the effect of the dose of argon ions on the formation of the composition of the surface layers, Nickel foil with a sprayed layer of aluminum.

The study sample was a Nickel plate having a size of 10×10 mm^2 and a thickness of about 40 microns. A film of aluminum with a thickness of 20 nm on the surface of Nickel samples were deposited by magnetron sputtering method on the "Cathode-1M". Ion-beam mixing of aluminum films was carried out by bombarding with Ar^+ ions in the pulse-periodic mode with an ion energy of 40 KeV, a current density in the pulse of 3 μa/cm^2, in the dose range $5\cdot10^{15}$ - 10^{17} ion/cm^2. Chemical composition studies were carried out on x-ray photoelectron spectrometers ES-2401 and SPECS using Mg K_a-radiation.

The study by the XPS method showed that under the conditions of ion-beam mixing with the used irradiation parameters, an intermetallic compound corresponding to Ni_3Al stoichiometry is formed in the surface layers of the Nickel-aluminum system. Moreover, under the studied irradiation regimes, the highest percentage of such a compound in the modified layer is present at a dose of $5\cdot10^{16}$ ion/cm^2.

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THE COMPOSITION, STRUCTURE AND PROPERTIES OF NANOSIZED LAYERS ON THE SURFACE OF TITANIUM ALLOY DOPED WITH CARBON BY ION-BEAM MIXING

V.L. Vorobyov[1], F.Z. Gilmutdinov[1], P.V. Bykov[1], V.Ya. Baynkin[1]
[1] *Udmurt Federal Research Center Ural Branch of the Russian Academy of Sciences, Izhevsk, Russia (Vasily_L.84@mail.ru)*

Films and coatings based on carbides and nitrides of transition metals are widely used in mechanical engineering, microelectronics, medicine and other fields to improve the strength characteristics of materials, protect the surface from corrosion, improve product design, etc. [1-2]. A promising method for the formation of coatings and films with desired properties are ion-beam treatment methods [3]. In particular, the effect of high-energy ion flow on the pre-deposited, magnetronically, on the target surface of the nanolayers of the alloying substance, which allows the formation of coatings with high adhesion to the substrate [4]. Despite the research in this direction, the processes of formation of nanoscale carbon and carbon-carbide coatings on metal surfaces with ion-beam mixing have not been studied enough.

In this regard, the aim of this work was to study the surface morphology, chemical and phase composition, interatomic chemical bonds, atomic structure and mechanical properties (microhardness) of nanoscale layers on the surface of titanium alloy doped with carbon by ion-beam mixing.

When performing the work, it was revealed that under the conditions of ion-beam mixing in the transition layer of the film/substrate system, the formation of titanium carbides occurs, both with stoichiometric ratio and with non-stoichiometric ratio of components, the content of which increases with the radiation dose and at a dose of 4•1017 ion/cm2 reaches 20 at.%. However, a thin surface layer about 20 nm deep remains, mainly composed of carbon atoms. It is shown that carbon atoms in this layer are in disordered state with both sp2 and sp3 hybridization of C-C bonds. Formation of titanium carbides in the transition layer and disordered carbon structure on the surface of the film under ion-beam mixing causes hardening of the surface layer and, as a consequence, an increase in the microhardness of the samples by 100% or more. It is shown that the growth of microhardness is associated with the layer formed as a result of mixing, rather than the effect of irradiation on the titanium alloy substrate.

The work was performed within the framework of a task set AAA-A17-117022250040-0.

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THE SPECTRAL COMPOSITION OF THE GLOW OF PURE METALS (Fe, Zr, W, Ta) IN UNDER IRRADIATION BY INERT GASES IONS (Ar^+, Kr^+ AND Xe^+). THERMAL SPIKES TEMPERATURE MEASUREMENT

K.V. Shalomov[1,2], V.V. Ovchinnikov[1,2], S.O. Cholah[1]
[1]*Ural Federal University named after the first President of Russia B.N. Yeltsin, Yekaterinburg, Russia (icsartf@gmail.com)*
[2] *Institute of Electrophysics UB RAS, Yekaterinburg, Russia*

In the course of the process of ion irradiation, each heavy ion, penetrating into the target, creates one or several dense cascades of atomic displacements. At energies of 5-25 keV, these are usually single cascades. According to the data of numerical simulation using molecular dynamics and Monte Carlo (SRIM) methods [1], the typical cascade diameter is 10–20 nm, and the heating temperature of the cascade region as a result of energy transfer to atoms of the cascade of 3000-6000 K and higher. Such areas, thermalized for about one trillionth part of a second, are called thermal spikes. The surface temperature of the sun, about 6000 K, determines the spectrum of the sunlight. Visible light of the same range of wavelengths is observed by the emission of targets in the course their ion irradiation. In [2, 3], it was first suggested that this is an equilibrium (thermal) radiation (but not some other kind of radiation) associated with the presence of "thermal spikes". The latter was substantiated by the features of the observed glow. As a result of analyzing the emission spectra of targets from pure metals: Fe, Zr, W, Al, during their irradiation with Ar^+ ions, temperatures were determined and thermal pressures in the region of thermal spikes were estimated. These results are not only of theoretical, but also of practical interest in order to increase the depth of the modified layer under ion bombardment (from fractions of microns to several mm) using explosive energy release effects (for ~ 10^{-11} s) in areas of thermal spikes with emission of powerful post-cascade elastic and shock waves.

In this paper, the results of [2, 3] were reproduced, and new data were obtained relating to the irradiation of these and other metals (in particular, pure Ta) not only with argon, but with three types of ions: Ar^+, Xe^+, Kr^+. We took into account the wide band of the Planck thermal glow of thermal spikes, and the “tail” of the infrared radiation of the target, uniformly heated as a result of resorption of heat from thermal spikes. The temperature corresponding to IR line was determined by thermocouple readings and was considered known, and the initial estimate of the temperature of the thermal spikes was obtained from the Wien displacement law. All unknown parameters were determined as a result of fitting the experimental emission spectra with Planck curves. The results of the approximation indicate that the width of the experimental bands is noticeably smaller than the width of the peaks of the equilibrium Planck radiation. The latter is most likely due to the fact that the regions of dense cascades in the process of their evolution reach only a quasi-equilibrium state. Nevertheless, the use of the concept of temperature, rather than the average energy of a particle, is more illustrative. It is shown that the measured temperatures are determined to the greatest extent by the metal type and to a lesser extent by the type of ion and ion energy (Ar^+, Kr^+, or Xe^+). In general, there is good agreement with the results of numerical simulation. The estimated pressures in the areas of thermal spikes of the irradiated metals reach 5-40 GPa and are several times higher than the yield strength of these metals. The obtained data confirm the possibility of emission of post-cascade shock waves, which cause structural-and-phase transformations in metastable media.

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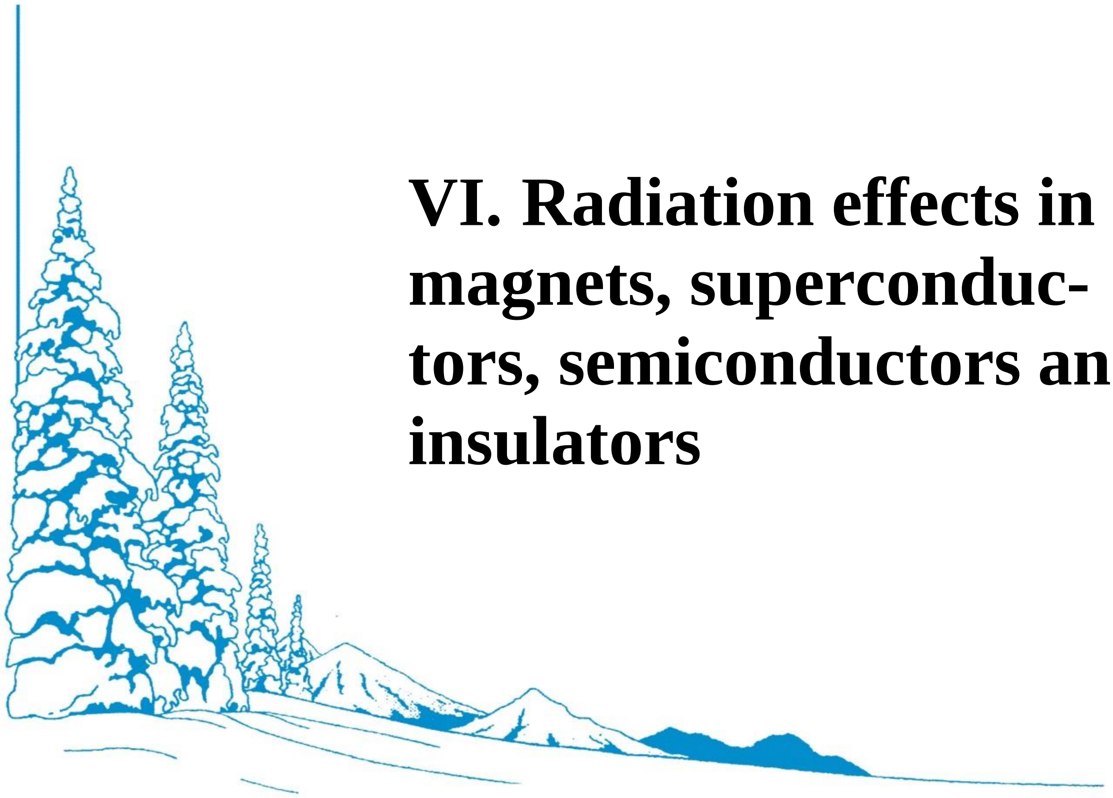

VI. Radiation effects in magnets, superconductors, semiconductors and insulators

The subject of this Section is traditionally formulated with a view to introduce the Seminar attendees (mainly metal physicists) to the results of the latest research into radiation effects in superconductors, semiconductors and dielectrics (magnetic dielectrics including). In the case of the first two materials, their physical properties change significantly upon exposure even to rather low fluences of high-energy particles. Therefore, investigation of the causes of damage and the impairment of the physical and mechanical properties of the materials of this group has always been - and is today - a topical task. The Seminar Program includes papers on physics of radiation effects in semiconductors and insulators. The behavior of radiation defects and changes in the physical and mechanical properties of materials such as manganites, oxides, etc. are analyzed. The amorphization of silicon upon exposure to ion beams, the dielectric effect in HTSC ceramics, principles underlying the radiation modification of semiconductors and dielectrics, and the influence of radiation-induced disordering on semiconductor radiation detectors are discussed.

CHARGE NEUTRALITY IN SEMICONDUCTORS

V.N. Brudny
National Research Tomsk State University, Tomsk, Russia (brudnyi@mail.tsu.ru)

Irradiation exposure leads to a change in the electronic properties of semiconductors, which is used to modify their parameters. Despite the large amount of researches on a wide range of semiconductor materials, starting with the pioneering work of Lark-Horowitz (1946), they did not answer the question of why some semiconductors upon irradiation transform in a high-resistance state, while other materials obtain *n*-type or *p*-type conductivity. Meanwhile, studies under high-dose irradiation revealed the effect of the Fermi level pinning in the limiting position F_{lim} characteristic of each semiconductor. This allowed us to develop prognostic models suitable for an apriority quantitative assessment of the electronic properties of the irradiated semiconductor, which do not require a detailed information about the nature and parameters of the radiation-induced defects (RIDs). This model is based on the equation of the neutrality of a defective crystal and the features of its screening. In contrast to metals, where screening is purely electronic (Thomas – Fermi radius), in semiconductors there is a mixed electronic and electrostatic (dielectric) screening. In this case, under conditions of a high degree of material compensation, electrons provide for only large-scale potential fluctuations, whose dimensions are comparable to the radius of electronic screening. In this case, the screening of local potential fluctuations is provided by charges bound on the defect states. This allows, along with the global chemical potential (Fermi level), to introduce a local chemical potential, which historically received the term charge neutrality level (CNL) in the study of metal/semiconductor interfaces. An analytical model for estimating the position of a CNL at such boundaries was proposed by Tersoff [1] as the branch - point (BP) of the complex band structure of a crystal. Although this model was developed for tunneling states induced by a metal in a semiconductor, it corresponded well to the F_{lim} - values in irradiated semiconductors. The following model for estimating of the CNL in a defective semiconductor was developed from the condition of local neutrality of the model amphoteric gap state of a crystal [2]. Later, a model of the deepest (most localized) defective state of a semiconductor was proposed to obtain the CNL value in the semiconductors [3]. These models give good agreement with the experimental of F_{lim}- values in irradiated semiconductors. In general, the calculations show that the CNL is located near the middle of the dielectric gap (Penn's gap) of the semiconductor. Moreover, its correspondence with the BP energy position of semiconductor is due to the fact that it meets the condition of maximum partial neutrality of the gap states of the crystal. It is the driving force for shifting the Fermi level to a position close to the CNL upon irradiation exposure. This parameter averagely takes into account the effect of self-compensation of the material for the entire spectrum of the RIDs of crystal. Depending on the irradiation conditions, the semiconductor forms such a set of defect states, which always ensures the fulfillment of the condition F_{lim} = CNL at a strong supersaturation of the crystal with radiation - induced defects.

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DYNAMIC EFFECTS IN RADIATION PHYSICS

V.V. Ovchinnikov[1,2]
[1]*Ural Federal University named after the first President of Russia B.N. Yeltsin, Yekaterinburg, Russia (viae05@rambler.ru)*
[2]*Institute of Electrophysics UB RAS, Yekaterinburg, Russia*

The presentation is devoted to a brief overview of the model, taking into account the nanoscale dynamic effects during cascade-forming irradiation. We are talking about explosive energy release in the areas of dense cascades of atomic displacements (thermal spikes), emitting powerful post-cascade solitary waves, which theoretically can initiate structural-phase transformations in metastable media over unlimited long distances. The distances at which the experimentally observed effects of accelerated ions with energies in the range of 10^4 - $k\times10^5$ eV (in continuous irradiation mode) sometimes exceed several tens or even hundreds of micrometers (with ion ranges of specified energies in a substance less than 1 micron). The depth of exposure to ion beams, can reach 1-10 mm.

The fundamentals of the theory of undamped propagation of plane and spherical post-cascade waves in metastable media are presented. It is noted that the most probable energy of the recoil atoms generated by reactor neutrons and fission fragments also belongs to the above energy range, which indicates the need to take into account nanoscale dynamic effects regardless of the type of cascade-forming radiation.

Examples of recent studies by the author and his colleagues are presented, which confirm the main features of low-dose processes caused by nano-scale dynamic effects during cascade-forming (in particular, ion) irradiation. We are talking about (1) reducing the temperature of structural and phase transformations by 100-300 K in pure metals and alloys, which were initially in a non-equilibrium (amorphous, strongly deformed, quenched) state; (2) multifold (by 2-3 and more orders of magnitude) increase in the speed of processes in comparison with the thermo-activated processes; (3) the propagation of transformations over distances that are many times greater than the projected ranges (R_p) of ions (or primary recoil atoms under neutron irradiation). Theoretically, these distances are not limited, in practice they reach (10^3 -10^5)$\times R_p$ and more (up to several mm in aluminum alloys).

In the near future, the observed effects can provide a breakthrough in basic researchs of low-temperature processes initiated by irradiation in metastable media, as well as in the processing and creation of new functional materials.

This work was performed as part of State Task № 0389-2015-0025.

FORMATION OF LIGHT-EMITTING STRUCTURES BASED ON THE SILICON BY ION BEAMS

D.I. Tetelbaum
Lobachevsky University, Nizhny Novgorod, Russia, (tetelbaum@phys.unn.ru)

One of the most impotent problems of modern electronics is the creation of efficient light-emitting structures on the basis of silicon. The problem is associated with the need of using to optical signal transmission channels to increase the rate of electronic systems (integrated circuits) and with the undesirability of refusing silicon as the main material of such systems. This problem is hampered by the fundamental property of this semiconductor - the indirect gap of the electronic structure.

The report presents some results of investigation aimed solving this problem: improving the light-emitting properties of the system of dislocations in silicon and formation of regions with a hexagonal syngony in silicon, this has better light-emitting properties. The radiation aspect of this investigation is that in both cases ion irradiation is used as a technological method, which is most compatible with traditional silicon technology.

The system of dislocations with luminescence at a wavelength of ~ 1.55 μm (line D1) is formed by implantation of Si^+ ions with subsequent annealing at 1100 °C. It has been established that additional implantation of boron ions helps to eliminate the main drawback of dislocation luminescence (DL) - a sharp decrease in intensity with increasing temperature (starting from cryogenic one). Ion doping by boron made it possible to increase the temperature range with dislocation photoluminescence at least to 200 K. The operation of aluminum gettering leads to a further improvement of the light-emitting properties.

It was found that under ion implantation of Kr^+ ions into SiO_2 film on a silicon substrate with subsequent annealing, regions of the 9R-Si hexagonal phase are formed inside the substrate near the border with the film. The irradiated samples have luminescence at a wavelength of ~ 1.24 μm. A theoretical calculation of the electronic band structure of the 9R-Si phase showed that the energy of photons with such a wavelength is close to that expected for the interband transition for this phase. The dependences of the luminescent properties on the thickness of the SiO_2 film and the conditions of ion synthesis of the 9R-Si phase were studied.

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INVESTIGATION OF ELECTRONIC AND STRUCTURAL PARAMETERS OF GaN FILMS GROWN ON Al_2O_3 SUBSTRATE

P.A. Brudnyi[1], V.M. Boiko[2]
[1]*National Research Tomsk State University, 36 Lenin Ave., Tomsk 634050, Russia*
[2]*Karpov Institute of Physical Chemistry, Kiev Highway, 109 km, Obninsk 249033, Russia*

The effects of fast neutron up to 1.75×10^{20} f.n/cm^2 and fast plus thermal neutron up to 3.5×10^{20} f.t.n/cm^2 irradiations on the electrical properties and crystal lattice parameters of *wz*-GaN films have been studied [1]. It is revealed that high-dose neutron irradiation induces a transition of *n*-type conductivity samples into a semi-insulating state with resistivity of ~10^{10} Ω cm at room temperature, while *p*-type GaN films undergo a *p*-to-*n* conversion and high resistivity too. An intense neutron bombardment leads to the formation of such a set of the defects that ensures the stabilization of Fermi level near the charge neutrality level (CNL) of GaN. The calculations place the CNL position in *wz*-GaN crystal at about 2.7 eV relative to the valence band maximum [2, 3]. The subsequent irradiation of these semi-insulating samples leads to a decrease of resistivity up to ~ 10^5 Ω·cm (RT) at the final neutron fluence, as a result of the hopping conductivity of carriers under the defective states of the irradiated crystasl. The significant role of thermal neutrons ($E \leq 0.1$ MeV) in the damage build-up in GaN is shown. The isochronal annealing of irradiated samples reveal some annealing stages of the donor- and acceptor-type defects in the temperature range of (100 -1000)^{0}C.

X-ray diffraction measurements reveal an expansion of GaN *c*-lattice parameter up to a saturation level of 0.42% at the final fluences, while the *a*-lattice parameter remains nearly unchanged upon neutron irradiation. The initial value of *c*-parameter restores at 1000 °C annealing temperature, with the main annealing stage in the temperature range of 150–400° C. The Raman scattering measurements were performed to study the lattice damages in *wz*-GaN film after neutron bombardment and at subsequent isochronal annealing.

The presented work was carried out under the financial support of the project "Research and development of manufacturing technology for ultrahigh-frequency monolithic integrated circuits based on InAlN/GaN heterostructures for space applications" (Agreement No. 14.578.21.0240, 26.09.2017). An unique identifier of the project RFMEFI 57817X 240.

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LATENT TRACKS INDUCED BY SWIFT HEAVY IONS IN SILICON NITRIDE

A.D. Ibrayeva[1,2], A. Janse van Vuuren[3], J. O'Connell[3], V.A. Skuratov[4], M.V. Zdorovets[1,2]
[1]*L.N.Gumilyov Eurasian National University, Astana, Kazakhstan (a.d.ibrayeva@gmail.com)*
[2]*Institute of Nuclear Physics, Astana, Kazakhstan*
[3]*Centre for HRTEM, Physics Department, Nelson Mandela Metropolitan University, Port Elizabeth, South Africa*
[4]*Flerov Laboratory for Nuclear Reactions, Joint Institute for Nuclear Research, Dubna, Russia*

The radiation resistance of silicon nitride, as one of the candidate materials for the inert matrix fuel hosts for the transmutation of minor actinides [1], has been intensively researched using various types of ionizing radiation. The least studied one is the structural response of Si_3N_4 to the influence of high-energy (E ≥ 1 MeV/nucleon) heavy ions simulating the fission fragment bombardment. Currently, there are only a few literature data on the morphology of specific radiation damages in this material, formed in the electronic power stopping regime and called as latent tracks [2].

This paper presents the results of electron microscopic researches of the parameters of latent tracks in Si_3N_4 irradiated with 220 MeV Xe ions at fluences in the range from 3×10^{11} cm^{-2} to 2×10^{14} cm^{-2} at 80K, 300K and 1000K. Amorphous tracks, which radius changes insufficiently at the different irradiation temperatures, are established to start overlapping at ~ 10^{13} cm^{-2}, that leads to the complete amorphization of the surface layer of ceramics, as shown in Fig. 1. At the fluence of 2×10^{14} cm^{-2} the tracks in the amorphized material are observed with a lower density than the density of the surrounding matrix. Based on the data obtained, the applicability of the thermal spike model to describe the parameters of latent tracks in Si_3N_4 is considered.

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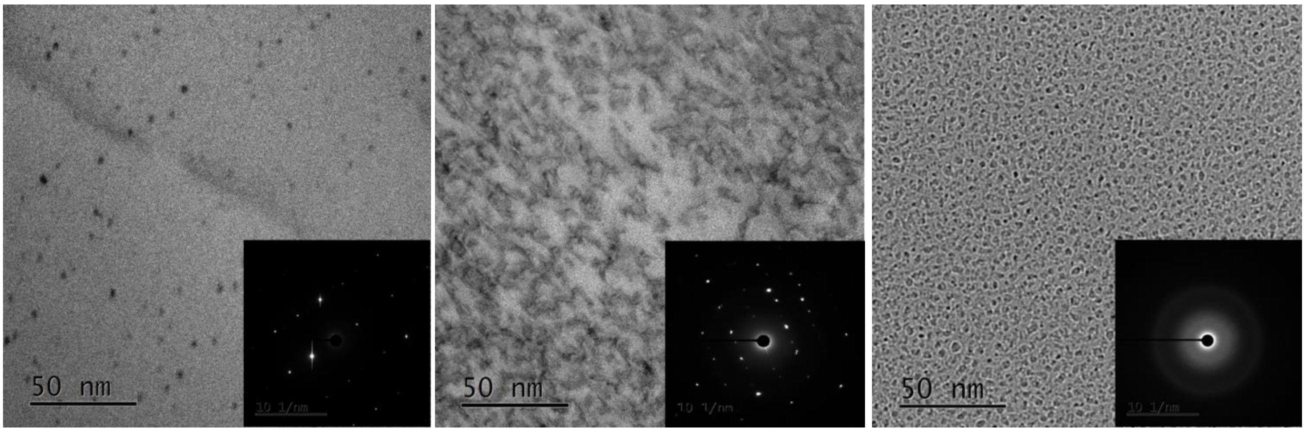

a) b) c)

Figure 1. Bright field TEM micrographs and selected area diffraction patterns of Si_3N_4 irradiated with 220 MeV Xe to fluences of (a) 5×10^{11} cm^{-2}, (b) 1×10^{13} cm^{-2}, (c) 2×10^{14} cm^{-2}.

SILICON BASED HYBRID STRUCTURES: FROM MAGNETORESISTANCE TO SPIN ACCUMULATION EFFECT

N.V. Volkov[1], A.S. Tarasov[1], M.V. Rautskii[1], A.V. Lukyanenko[1], I.A. Bondarev[1], I.A. Yakovlev[1], I.A. Tarasov[1], S.N. Varnakov[1], S.G. Ovchinnikov[1]
[1]*Kirensky Institute of Physics, Federal Research Center "Krasnoyarsk Scientific Center SB RAS", Krasnoyarsk, 660036, Russia (taras@iph.krasn.ru)*

Silicon hybrid nanostructures have tremendous potential for the development and improvement of traditional electronic devices, since they demonstrate new diverse electron transport effects of interest both for basic research and for practical use. In this work, we present the results of the study of hybrid structures in which several types of magnetoresistance were found, as well as the spin accumulation effect. By the method of thermal evaporation in ultrahigh vacuum, *Me*/*p*-Si structures have been synthesized, where *Me* – Mn, Fe, Fe_3Si. For studies of the magnetic spin-dependent transport properties, a Schottky diode was fabricated from each structure (inset in Fig. 1 (a)). For the structure of Fe_3Si/Si, a three-terminal microdevice was prepared with a distance between the nearest contacts of 10 µm (see in Fig. 1 (c)). The measurements were performed using precision instruments KEITHLEY 2634b and Agilent E4980A on the experimental setup, which includes an optical helium cryostat and an electromagnet. In the Mn/SiO_2/*p*-Si diode effects of giant magnetoimpedance and magnetoresistance were observed (Fig. 1 (a)). The effect of magnetic field is associated with the suppression of impact ionization, and is realized through several mechanisms, which leads to an increase in the threshold energy required to start the process of impact ionization. During the study of the photovoltaic effect in the Fe/SiO_2/p-Si structure a high sensitivity to a magnetic field was observed, which is mostly pronounced at temperatures below 12 K (Figure 1 (b)). In a specially manufactured three-terminal Fe_3Si/*p*-Si device the Hanle method was used to detect the spin accumulation effect (Fig. 1 (c)). The study and analysis of the electrical properties of the ferromagnet/semiconductor interface suggests that the device implements spin-dependent electrical extraction of holes by tunneling from the valence band to the ferromagnetic electrode through localized states. This leads to spin accumulation in the valence band of silicon.

The study was supported by RFBR according to the research project № 17-02-00302.

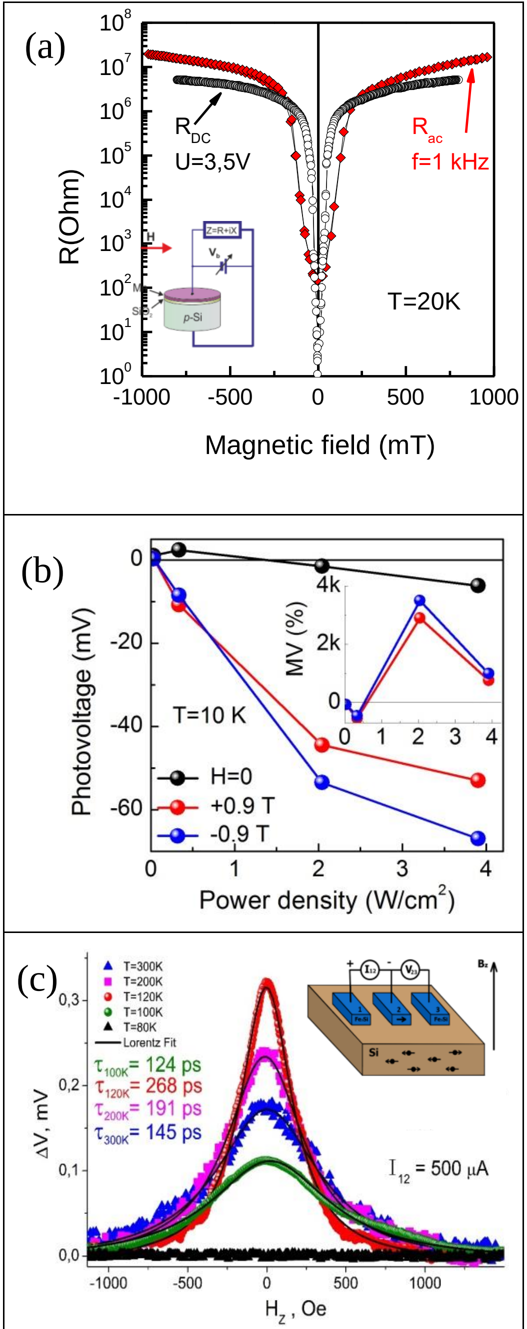

Figure 1. (a) Magnetoresistance for the Mn/Si diode. Optically induced magnetoresistance in the Fe/Si structure (b). Electrical Hanle effect in the Fe_3Si/p-Si microdevice.

STUDY OF THE RADIATION - INDUCED THIN FILM MATERIALS PHASE AND PROPERTIES TRANSFORMATIONS UNDER ION BEAM IRRADIATION

M.M. Dementyeva[1], K.E. Prikhodko[1,2], B.A. Gurovich[1], L.V. Kutuzov[1], D.A. Komarov[1]
[1]*National Research Center «Kurchatov Institute», Moscow, Russia (dementyeva_mm@nrcki.ru)*
[2]*National Research Nuclear University «MEPhI», Moscow, Russia*

This paper presents the experimental study of the radiation techniques applications for directed modifications of thin-film materials atomic composition and properties under ion beam irradiation. The radiation technology was developed in the NRC «Kurchatov Institute» and used to create a various types of functional elements on nanoscale level. It is known, that various thin-film materials (superconductors, metals, insulators) demonstrate different electrophysical and optical properties depending on their phase composition. Consequently, the problem of low-energy (0.1–4 keV) ion beam irradiation influence on selected areas of materials with different ion beam composition (protons, oxygen ions, nitrogen, etc.) and different radiation doses becomes actually. The radiation technology includes three methods of thin-film atomic compositions changes: method of selective removal of atoms (SRA) [1], methods of selective displacement of atoms (SDA) and method of selective associations of atoms (SAA)[2]. The main advantages of these methods are: the ability to produce functional elements with preassigned shapes and minimum sized 3-10 nm; the parallel transformation possibility of the local composition and properties in several layers of multilayer thin-film structures; high productivity of the process.

In this work the kinetics of metal oxide thin film recovery process during the selective removal of oxygen atoms under proton irradiation was studied by analytical transmission electron microscopy techniques on CuO, WO_3, Co_3O_4 thin films. It was experimentally shown that metals oxide recovering was characterized by non-monotonic target depth-trend due to radiation nature of SRA process. In addition, we obtained the experimental data for the development of SRA process kinetic model. The activation energy value of the radiation-stimulated diffusion process was obtained from Co_3O_4 recovery data under proton irradiation at different temperatures and irradiation doses.

The SDA process was studied by irradiation of superconductive NbN thin films with composite ion beams and beams consisting of oxygen ions. Technological conditions to create cryogenic resistive, capacitive elements, Josephson junctions, etc. using SDA method were identified.

The SAA process was studied by irradiation of metallic aluminum thin films with oxygen ions at various energies and irradiation doses. Dose dependences concentration changes of elements in depth of the film were obtained by electron energy loss spectroscopy (EELS) on the transmission electron microscope. It was found the irradiation conditions that allow to create a high-quality aluminum oxide Al_2O_3 to the full depth of the film at room temperature .

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SYNERGETICS IN RADIATION-ENHANCED CASCADE PROCESSES IN SOLIDS

N.N. Turaeva[1], B.L. Oksengendler[2], Yu.V. Pakharukov[3]
[1]*Webster University, USA*
[2]*Arifov Institute of Ion-Plasma and Laser Technologies, Uzbekistan*
(oksengendlerbl@yandex.ru)
[3]*Tumen Industrial University, Russia*

In synergetics, there are two concepts to enhance the formation of chemical reaction products [1,2], that shift the system far from the equilibrium state: (1) autocatalytic reactions, in which the reagent increases its quantity in interaction with another reagent and (2) cooperative binding in the synthesis on the substrate, when initial binding of reagents leads to facilitated binding of other reagents. Those concepts are valid for biological systems [2], although in recent years they have being applied to many other processes, including non-equilibrium nonlinear processes under the intense irradiation [3,4]. In the present work, radiation enhanced cascade processes are considered within the framework of the theory of autocatalytic reactions. The nature of cascade of atomic collisions is important for solid states since they initiate the processes such as radiation damage, sputtering and ionic implantation.

In the model, the cascade of atomic collisions is considered as an autocatalytic reaction between the “hot” interstitial atom, displaced from its site by irradiation and a regular atom of the crystal until the transfer energy is larger than the threshold energy of displacement. The kinetics of the process can be described within the synergetic theory of autocatalytic reactions. The analysis of the distribution function of displaced atoms at stationary conditions shows that the number depends upon the radiation intensity, the concentration of regular atoms of the crystal and the ratio of coefficients of direct and reverse chemical reactions, corresponding to the processes of defect production and recombination. Moreover, the fluctuations of the number of displaced atoms in the cascade exhibit a non-Poisson character.

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THE EFFECT OF LONG-RANGE ACTION CAUSED BY THE GENERATION OF ACOUSTIC WAVES UPON THE IRRADIATION OF MATERIALS BY IONS OR LIGHT AND THE PROPAGATION OF WAVES ALONG SOLID STATE–WATER INTERFACE: EXPERIMENT AND MODEL

D.I. Tetelbaum[1], V.S. Tulovchikov[1], A.V. Stepanov[2], E.V. Kuril'chik[1], A.A. Nikolskaya[1], R.A. Shuisky[1]
[1]Lobachevsky University, Nizhny Novgorod, Russia, (tetelbaum@phys.unn.ru)
[2]Chuvash State Agricultural Academy, Cheboksary, Russia

It's generally accepted that, under ion irradiation of solids, the structure and properties are changed at the depths to which implanted atoms reach either directly during irradiation, or as a result of post-implantation annealing. However, the so-called long-range effect (ED), which consists in changing the structure and properties at much greater distances from the irradiated surface, has been known long ago [1]. In fact, this name means phenomena that differ in their mechanism. In [2], two types of ED are indicated – “large - dose ED”, related with static stresses causing displacement of dislocations, and “low-dose” one, related with local heating (“thermal peaks”), causing the generation of a shock wave.

Since 1971 [3], we have studied the third type of ED (later called also “low-dose ED” [4]), which is caused by the excitation of acoustic (hypersonic) waves in natural oxide (EO) on the sample surface [5]. This type of ED is inherent not only to ion irradiation, but also to other types of exposure that can cause self-oscillations in EO (electron beams, light, ultrasound, etc.).

The report provides a brief overview of the basic laws of this type of ED and sets out the model for understanding of its mechanism. These modes are supported by molecular dynamics calculations [5]. Experimentally the role of acoustic waves in ED is recently confirmed phenomenon of ultra-long-range transmission of the influence of light or ion irradiation of Si samples in the case when super far propagation of these waves was provided, namely of Na along the solid / water solution of NaCl interface. Molecular dynamics modeling showed that the presence of Na ions leads to a sharp increase in the amplitude of acoustic (hypersonic) waves as they propagate along the indicated interface. The interdisciplinary feature of these studies, in particular, their importance for biology, biomedicine and neurophysiology, is noted.

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THE EFFECT OF RADIATION ON THE BIPOLARANE PSEUDOGAP IN HTS MATERIALS

B.L.Oksengendler[1], Z.I. Karimov[2], Yu.V. Pakharukov[3], N.N.Turaeva[3]
[1]*Institute of ion-plasma and laser technologies, Uzbekistan Academy of Science, Tashkent, Uzbekistan (il: oksengendlerbl@mail.ru)*
[2]*NUUz Nanotechnology Development Centre, Tashkent, Uzbekistan*
[3]*Tyumen, Russian Federation*
[3]*Webster University, 470E / Lockwood Ave., Webster Grover, 63119 USA*

The idea of a pseudogap (PG) structure of the electronic spectrum in HTSC materials has been current for many years / 1-3 /. However, we are not aware of systematic effects of radiation on PG. At the same time, it is possible that it may become the basic test for the mechanism of the formation of PG.

In this work, the effects of energetic radiation on a PG have been analyzed in the case it is formed by bipolarons.

According to the methodology / 4,5 /, we theoretically investigated the radiation kinetics of the defective composition of HTSC with different degrees and types of initial heterogeneity, which is divided according to the scale: “small” (local) type of close Frenkel pairs and more “large” (nano), in fact the last one may have fractal properties.

The existence of the effect of “small doses” of two types, specifically affecting the structure of a PG of bipolaron origin, was discovered: at very low dose rates, “dumping-recombination” of close Frenkel pairs occurs and the characteristics of the sample are improved; after that, further as the irradiation proceeds, the processes caused by fractality will prevail: the fractal dimension of the sample decreases, the characteristics of the sample deteriorate — the usual accumulation of stable radiation defects occurs.

The theory allows us to formulate tests for the mechanism of formation of PG.

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VII. Facilities and techniques of experiment

The Seminar Program traditionally includes a methodological section. Its purpose is to acquaint the attendees with the latest methodological developments in the sphere of radiation physics and radiation material science, and inform them about new radiation sources and application of the new methods for condensed matter investigation.

ATOM PROBE TOMOGRAPHY DEVELOPMENT AT ITEP

A.A. Lukyanchuk, O.A. Raznitsyn, A.S. Shutov, A.A. Aleev, S.V. Rogozhkin
[1] *FSBI Institute for Theoretical and Experimental Physics named by A.I.Alikhanov of NRC «Kurchatov Institute» (Anton.Lukyanchuk@itep.ru)*
[2] *National Research Nuclear University "MEPhI"*

At the present time there is a significant need for the application of ultramicroscopy methods, since the functional and mechanical properties of materials depend not only on microscale features, but also on features on a scale from a few angstroms to tens of nanometers. In the last decade, a unique method of studying the nano-structure of the material – Atom Probe Tomography (APT) has been intensively developing. APT provides information on the three-dimensional distribution of atoms in a specimen with chemical nature of each atom. The APT technique is based on the principle of atomic disassembly of materials and projection magnification used earlier in field-ion microscopy, as well as time-of-flight mass spectrometry applied to each evaporated ion. Due to the projection geometry of the evaporation of atoms of the material, the technique allows obtaining a depth resolution about 1-2 Å, and the lateral resolution is about 2-4 Å.

At the Kurchatov Institute - ITEP, the nanostructures of reactor structural materials are studied (ex. [1,2]). To control the size and chemical composition of impurities in materials, the APT technique is used. In 2014, it was decided to develop APT instrument using a modern delay-line detection system and a femtosecond laser evaporation system - the Atom Probe Prototype with Laser Evaporation (APPLE-3D) [3]. To monitor and control the setup, own software was developed. Also, a full package of software tools for the reconstruction and analysis of APT data KVANTM-3D [4] has been implemented. Different materials were studied with APPLE-3D: ferritic-martensitic steels, alloys (nickel, titanium, aluminum, zirconium, vanadium, high-entropy, neodymium-iron), Fe-Cr model systems, pure metals: tungsten, aluminum and molybdenum. The possibility of studying materials based on silicon is also shown.

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4. Certificate of Software Registration №RU2018661876, Date of Registration 20.09.2018

IN SITU MEASUREMENT OF RADIATION DAMAGE WITH TRANSIENT GRATING SPECTROSCOPY

M.P. Short[1], C.A. Dennett[1], S.E. Ferry[1], A. Kushima[1], K.P. So[1], P. Cao[1], K. Hattar[2], D. Buller[2]
[1]*Massachusetts Institute of Technology, Cambridge, MA, USA (hereiam@mit.edu)*
[2]*Sandia National Laboratory, Albuquerque, NM, USA*

Materials issues are the main factors holding back life extension of light water reactors and deployment of advanced reactors. Radiation damage still limits the lifetime of current and future nuclear reactors, but our ability to quickly gauge its extent is severely limited. In this talk, we will introduce our improvement [4] and application of transient grating spectroscopy (TGS) [1-5] to study how materials behave during irradiation on the mesoscale. Changes in thermal diffusivity are linked to defect clustering and radiation induced segregation (RIS) in both pure metals and neutron-irradiated steels, while changes in stiffness correlate strongly to the onset of void swelling. This technique reduces the time to acquire key knowledge of material property changes under irradiation from months to hours, greatly speeding up our ability to better understand radiation resistant materials, and gauge their lifetimes in nuclear applications.

A number of studies will be presented along this theme, demonstrating the utility of this new technique for radiation materials science. We will specifically show how changes in surface acoustic wave (SAW) speed, which directly link to Young's Modulus and Poisson's ratio, can identify the radiation dose in DPA to the onset of void swelling in single crystal copper and nickel. Radiation-dependent changes in thermal diffusivity help show the saturation of radiation-induced dislocations and defect clustering in single-crystal niobium irradiated with Si ions, while the same thermal diffusivity changes reveal the onset and saturation of radiation induced segregation in neutron-irradiated 304 stainless steel to 28 DPA. Finally, a number of studies, ranging from deducing thermal properties of irradiated carbon nanotube coatings, MAX phase materials, tungsten fuzz development for fusion applications, and illustrating temperature-dependent radiation effects in SiC will be shown to show the broad applicability of TGS.

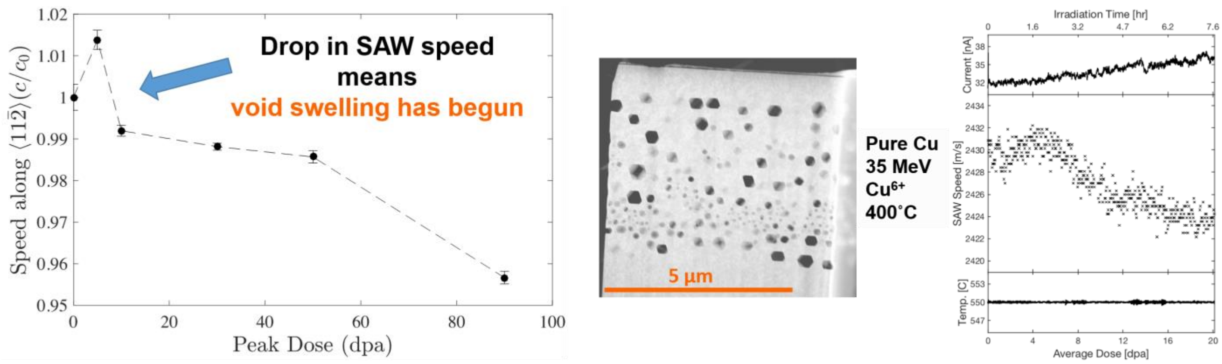

Figure 1: Drop in SAW speed (left) corresponding to the onset of void swelling in single crystal copper (center, [1]), and in-situ detection of the same in single crystal nickel (right, submitted for publication)

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MODERN POSSIBILITIES OF SCANNING PROBE MICROSCOPYFOR PROCESS CONTROL AND RESEARCH OF MATERIALSOF NUCLEAR AND THERMONUCLEAR TECHNOLOGIES

B.A. Loginov
JSC "Zavod PROTON", MIET-University, Moscow, Russia (b-loginov@mail.ru)

The history of the use of Nobel prize-winning 1986 scanning probe microscopes (SPM) in the nuclear and thermonuclear fields in Russia was started in 1999 in ITEF together with MIET [1, 2]. World's first was developed, patented [3] and made of radiation-resistant SPM-s for glove (VNIINM, RFNC-VNIITF) and hot (RIAR, SCK) cameras. They gave three-dimensional images of the surface of different materials with a resolution of up to 1 *nm* with visualization of the dynamics of the structure during decay or irradiation. For the thermonuclear industry, a unique SPM of 3 *cm* x 3 *cm* x 3 *cm* was made, which worked at the front wall of the TOKAMAK T-10 (Kurchatov Institute) and gave a picture of the dynamics of its atomization-deposition at a temperature of about 1 million degrees [4], which contributed to the development of the necessary plasma modes that do not spoil the front wall.

It should be noted that all of the above-mentioned Russian developments still not only hold the brand "for the first time in the world", but are the only SPM of this kind, although 10 years have passed and it is known about attempts to repeat them outside Russia. The uniqueness of the situation is also in the fact that over the past 10 years SPM has made great progress, and can be applied at a new level to solve the problems of materials science in the above areas.

If earlier SPM gave a three-dimensional surface relief with a resolution of up to 1 nm, now they give a resolution up to atomic. If earlier they gave only relief, now at each point of relief can give the value of many physical parameters of the material: electrical conductivity, electrical potentials, particle capacity, magnetization, electroluminescence, photosensitivity, electron density, concentration of dopants and other semiconductor properties, thermal conductivity, friction, adhesion, elasticity, viscosity, acoustic properties, a wide range of piezoelectric and magnetic properties, including coercive force and saturation field. Moreover, now SPM can give the value of physical characteristics not in a number of points selected by the operator, but immediately give a full map of the distribution of this characteristic over the area with a resolution of up to 1 *nm*. It has also become available to study materials and the dynamics of their phase transformations in the natural atmosphere, vacuum and gases in a wide temperature range from helium 4,2 *K* to 1500 ° *C* and above.

A distinctive feature of SPM from other microscopes is that they may adapted for implementation in a variety of conditions in a wide range of temperature, pressure, chamber volume, composition of gas media and associated electromagnetic and radiation backgrounds. SPM can give a film as a set of images measuring the morphology and properties of materials. It is possible to use SPM also as emergency sensors.

Based on the above, it is possible and promising to start a new round of development of the application of SPM for nuclear and thermonuclear materials science, with Russia's significant advance and priority.

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THE METHODICAL APPROACH OF MASS TRANSFER INVESTIGATION FOR STEEL CORROSION PRODUCTS IN LIQUID LEAD

O.A. Golosov, V.N. Nikolkin, A.V. Barybin, S.S. Khvostov, D.S. Butakov
Joint Stock Company “Institute of Nuclear Materials”, Zarechny, Russia
(den.butackov@yandex.ru)

The experimental results of outlow of EP-823 steel elements into lead investigated using neutron activation method is presented. EP-823 steel samples, irradiated in IVV-2M reactor to neutron fluence of $1.1 \cdot 10^{19}$ n/cm^2, unoxidized and thermally oxidized in the air to reach oxide film thickness of 0.3 and 1.2 µm have been exposed to static corrosion tests in lead at the temperature of 720 °C during 55 h. It has been shown that corrosion itself and corrosion product outflow into lead are selective in terms of steel elements. It has been established that the maximum rate of the release into molten lead was registered for iron atoms, which by ~20 times exceeds that of chromium under dissolution of an unoxidized sample with metal surface. Iron diffusion flow for samples with oxide films when dissolved in lead approximately by 60-65 times exceeds chromium diffusion flow. However, oxide thickness increased by four times almost has no effect on this ratio. Along with increasing oxide film thickness, chromium atom flow rate decreases by ~2 and ~5.6 times with the oxide 0.3 and 1.2 µm thick, respectively. Diffusion flow of iron atoms into lead increases by ~30 % with the oxide 0.3 µm thick, and when the oxide is 1.2 µm thick it decreases by ~2 times as compared with unoxidized steel. Iron outflow into lead is at the level of 5-15 % from its concentration in the oxide film formed during testing. Chromium outflow does not exceed 1 % and decreases with the increasing thickness of the initial oxide film. Iron concentration in lead volume is at the level of solubility limit; that of chromium is by 20-200 times lower.

USE OF ANALYTICAL TEM AND STEM TECHNIQUES TO MICROSTRUCTURE ANALYSIS OF IRRADIATED MATERIALS

K.E. Prikhodko[1,2]

[1]*National Research Centre «Kurchatov Institute», Moscow, Russia (prihodko_ke@nrcki.ru)*

[2]*National Research Nuclear University «MEPhI», Moscow, Russia*

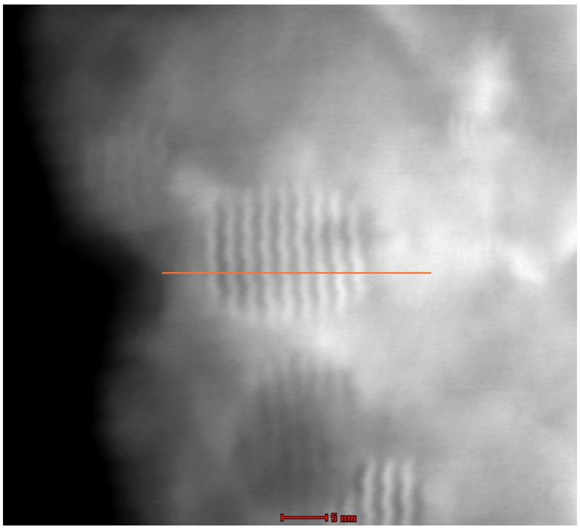
In this work the review of experimental studies results of modern analytical TEM and STEM electron microscopy techniques to find out the microstructure of irradiated nuclear power plants constructive materials is presented.

In the frame of transmission electron microscopy (TEM) the following items are discussed:

- Use of high resolution bright field imaging (HRTEM) to identify the crystal structure if nano-size particles while the traditional selected area electron diffraction (SAED) technique is unable to get the information due to the size effect reciprocal space spots blurring.
- Chemical elements energy filtering mapping (EFTEM) using electron energy loss spectroscopy (EELS)

Different examples of TEM techniques implementation for pressure water reactor PVS and internals materials microstructure investigation are shown.

In the frame of scanning transmission electron microscopy (STEM) the item of chemical elements STEM line profiles and area mapping by using EELS spectra is discussed. Examples of irradiation-induced structural changes in austenitic steels are shown [1] (figure 1). We have demonstrated the ability to use this technique for helium identification inside the materials pores after neutron and imitation irradiation on the accelerator.



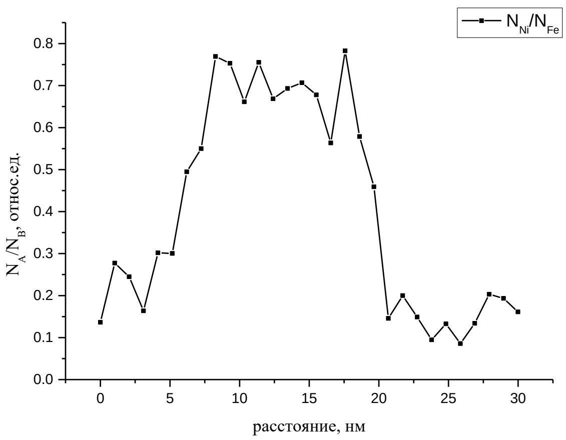


Fig.1 STEM DF image of radiation-induced G-phase particle in irradiates austenitic steel and corresponding Ni/Fe concentration line-profile obtained by ELLS spectra analysis.

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