THE THERMAL STABILITY OF METAL MULTILAYER SYSTEMS

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1. INTRODUCTION

The progress in present-day techniques makes the construction of novel materials operating under extreme conditions of high temperatures, intensive mechanical loads, aggressive and contacting environments, external irradiation possible. Because of various requirement to surface and volume properties the employment of traditional technologies of production of the material with depth-homogeneous composition and structure are not perspective. For instance, a great amount of chromium atoms (5-10 at.%) are to be introduced into the high-temperature ($\gamma+\gamma'$) nickel superalloys to provide heat-resistance, however, their high-temperature strength and durability decreased in this case. The creation of protective coatings on industrial materials was the next stage in technology development. Nowadays the progress in the production of high-qualitative coatings is associated with ion-beam technologies (ion implantation, ion-plasma deposition and others).

For a comparatively short time ago ion-beam methods were developed from laboratory tests to perspective and well-competitive technologies. Increasing of wear resistance, variation of frictional properties of materials, hardening of tools are the application sphere, where the ion treatment can give the maximal effect.

Analyzing the numerous publications on ion-beam methods of surface layer modification we have come to the conclusion that only specific metastable surface states were the main subjects of interest for many investigators, whereas the principal aspects, such as thermal and chemical stabilities of surface layers were ignored. In this context it is not surprising that ion technologies could not find appropriate application for hardening of industrial products being exploited at high temperatures, when specific properties of ion-implanted surface due to inherent metastable phases are being lost.

In the present report we propose the physical foundations of ion technologies of stable multilayer metallic material production for the construction of novel high-temperature many-functional materials.

2. THE PROBLEM OF HEAT-RESISTANCE ENHANCEMENT OF HIGH-TEMPERATURE NICKEL SUPERALLOYS

To satisfy hard requirements to high-temperature alloys for air-cosmic techniques it is necessary to develop new approaches to their construction and production within the frameworks of National Programmes. According to the USA National Air-Cosmic Programme that was accepted fifteen years ago, 70-80% of materials used for aircrafts are expected to be produced from new composite materials by the year 2005. In Japan the National Project "Moonlight" was realized in 1978-84. The aim was to produce high-temperature nickel superalloys using the technology of a directional crystallization. At present the second National Project "Advanced Alloys With Controlled Crystalline Structure" using the single-crystal technology is being performed in Japan. The physical foundations for the construction of perspective materials in both projects is the design-method (i.e. the computer design of materials based on the data bases on thermodynamic properties and phase equilibria of multicomponent alloys). High temperature nickel superalloys produced by the Japanese scientists have a time of life till failure 3-5 times longer than American alloys prepared by the traditional methods. Thus the application of the design-method for the development of alloys has led the investigators to considerable successes. In the design-method the regressive dependence for a long-time strength (σ) of an alloy at 982°C (exposure time is about 100 h) depending of γ'-phase composition (on the base of Ni_3Al) was obtained, as:

$$\sigma^{982^\circ C} = 13.32 + 0.4357\,X_{Al} + 0.946\,X_W + 0.762\,X_{Mo} - 0.238X_{Cr} + 132.36\,\nu \quad [\mathrm{kg/mm^2}], \qquad (1)$$

where X_{Al}, X_W, X_{Cr}, X_{Mo} are concentrations of Al, W, Cr, Mo in the γ'-phase; ν is a fraction of the γ'-strengthening phase. The regressive dependence for durability (τ) at 1000°C (load is 117.6 N/mm^2) depending on the γ'-phase composition is, as

$$\lg\tau[h] = -1.426 + 0.164Y_W + 0.092Y_{Mo} + 0.102Y_{Ta} - 0.11Y_{Cr} + 9.5\nu - 5.5\nu^2, \qquad (2)$$

where ν is a molar fraction of the γ' -phase; Y_i is a molar fraction of the i-component in the γ'-phase. From these formulas it follows that such alloying components as tungsten, molybdenum and tantalum increase both strength and durability. At the same time, the enhancement of the chromium content decreases both high-temperature strength and durability of an alloy. Nevertheless, chromium is added to provide heat-resistance of alloys. In such a way lowering the chromium content in a bulk of alloys would result in an increase of the high-temperature strength and durability, whereas heat-resistance could be provided in principle by the chromium surface deposition. However, the main factor limiting the heat-resistance for any protective coatings is their instability due to diffusion from the surface into the bulk of a material.

Thus it is necessary to obtain an optimal combination of volume and surface properties of a material. It can be made by the construction of surface layers chemically compatible with a bulk material by means of ion beam technologies.

3. PHYSICAL BASES OF ION-BEAM TECHNOLOGIES OF STABLE MULTILAYER METALLIC MATERIAL PRODUCTION

Previously we have proposed a thermodynamical approach to solve a problem of chemical compatibility of heat-resistant coatings with a high-temperature substrate. The main idea of this approach consists in the determination of compositions and phase-structural states for a substrate and a coating that provide zero-gradients of chemical potentials for all components of an alloy at a given temperature. The following illustration will make this clear. A schematic phase diagramme of an alloy A-B is represented in Fig. 1a.

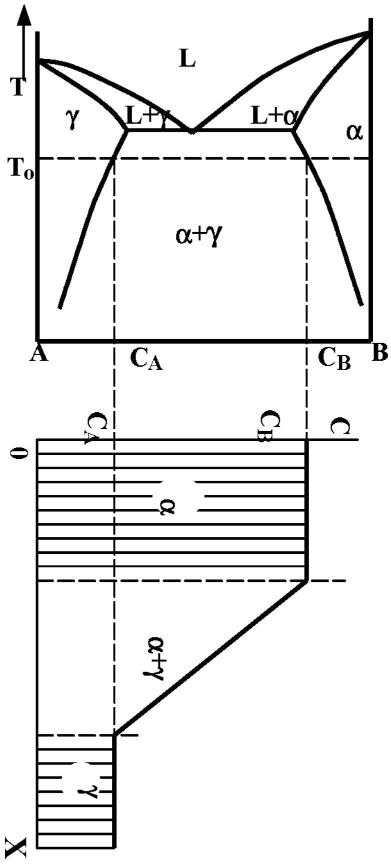

Fig. 1. Schematic phase diagramme of alloy A-B (a) and thermo-dynamically equilibrium depth-distribution of phases and component composition at temperature T_0 (b).

Suppose that this alloy is exploited at temperature T_0 , which corresponds to two equilibrium phases with various phase-structural states γ and α and chemical concentrations (C_A and C_B). Then creating the surface with the structure of the α-phase and chemical composition C_B on the matrix with a γ-phase structure and a chemical composition C_A we will obtain a thermodynamically equilibrium two-layer system, where alloy component diffusion is absent (see Fig. 1b). Ion technology, as active method for formation of surface layers with high adhesion and the required chemical composition permit to realize this idea in principle. In contrast to the traditional methods of chemical heat treatment the presence of a two-phase intermediate region ($\alpha + \gamma$) in ion-implanted layers can provide not only chemical compatibility between coating and matrix but also physical compatibility. The proposed technology for the production of multilayer many-functional metallic materials consists of the following stages:

(1) determination of the working temperature T_0 for many-functional multilayer alloy;

(2) performing self-consistent thermodynamical calculations of a phase diagram for a system, including all chemical components of both the substrate and the coating;

(3) chemical potential calculation for all the components in various phase diagram regions at temperature T_0;

(4) selection of chemical compositions and phase-structural states for both the substrate and the coating on the base of calculated and experimentally obtained phase diagrammes;

(5) melting of alloys for substrate and coating materials and heat-treatment at temperature T_0;

(6) control of phase states and chemical compositions of heat-treated alloys to provide chemical compatibility of the prepared materials;

(7) selection of ion-beam (plasma) method for surface layer production with the given chemical composition;

(8) heat treatment of the produced multilayer material and depth-control of its phase state and chemical composition;

(9) testing of thermal and chemical stability of surface layers at temperature T_0 followed by the control of their composition.

4. THERMAL STABILITY OF NI-CR SYSTEM

It is known that high-temperature superalloys working in an oxidizing atmosphere contain a great number of components, at least six: Ni, Al, W, Mo, Ta, Cr. Oxygen needs to be added to the above listed components. Therefore the seven-component system Ni-Al-W-Mo-Ta-Cr-O is required to be considered. That makes it a very difficult system to describe. So to test the above mentioned stages of the technology proposed we shall consider the simplest subsystem Ni-Cr. Nickel is a base for high-temperature alloys, and chromium increases the heat-resistance. Besides that the commercial alloy IN-671 contains 50 at.% Cr + 50 at.% Ni.

Two aspects caused the selection of a working temperature range: the low limit was defined as the temperature of about 950°C, being the working temperature for gas turbine blades prepared from high-temperature nickel alloys, and the high limit corresponded to temperature 1055°C above which there is a sharp chromium content decrease in the projected α-coating. In this way we selected the working temperature equal to 1050 °C .

4.1. Selection of chemical compatible alloys in the Ni-Cr system

The experimentally obtained compositions are about 47 at.% of Cr and 86.5 at.% of Cr corresponding to $\gamma/(\alpha+\gamma)$ and $\alpha/(\alpha+\gamma)$ boundaries at T= 1100°C. Our thermodynamical calculations yielded $X^{\gamma/\alpha+\gamma} = 47.9$ at.% of Cr and $X^{\alpha/\alpha+\gamma} = 89.2$ at.% of Cr. Averaged experimental and theoretical compositions are equal to $X^{\gamma/\alpha+\gamma} = 47 \pm 0.5$ at.% of Cr and $X^{\alpha/\alpha+\gamma} = 87.5 \pm 1$ at.% of Cr. The minor precipitations of the α-phase (inclusions of α-phase) in the γ-phase and minor precipitations of the γ-phase in the α-phase need to guarantee chemical compatibility of the coating (α-solution) with the substrate (γ-solution). Therefore, four Ni-Cr samples with the compositions 47.5 at.% of Cr, 48.5 at.% of Cr, 86.0 at.% of Cr and 88.5 at.% of Cr were chosen near the solvus $(\gamma+\alpha)/\gamma$ and $(\gamma+\alpha)/\alpha$ (from two sides) of the phase diagramme for the Ni-Cr alloy. These alloys were melted and annealed for homogenization for 250-800 h in vacuum at 1150°C. Then these alloys were quenched and their phase compositions were investigated by micro X-ray spectral analysis. The phase-structural states and sizes of phase inclusions were studied using Cameca. The criterion of chemical compatibility between the coating and the substrate in practice is that: the compositions of the main phases must correspond to $(\gamma+\alpha)/\gamma$ and $(\gamma+\alpha)/\alpha$ solvus at T= 1100°C, the composition of the α-phase inclusions in the substrate must correspond to that of the coating main phase and the composition of the γ-phase inclusions in the coating must correspond to that of the substrate main phase. The results given in Table 1 demonstrate, that chemical compatibility of the substrate and the coating was reached for two of the chosen alloys at 800 h sample annealing.

Table 1 Phase composition for chemical compatible substrate and coating materials

Material	Phase and composition		Size of inclusions [μm]
	for matrix	for impurities	
Substrate	γ; 47.3 at% Cr	α; 90.7 at% Cr	3×5
coating	α; 91.3 at% Cr	γ; 50.5 at% Cr	2×8

The advantage of ion technologies is a possibility to create the depth-inhomogeneous alloy with needed chemical composition and phase-structural state (including multi-phase regions). The multilayer cohesion is provided by ion mixing in this case.

For surface layer production we applied the following methods: vacuum thermal evaporation, pulsed ion implantation with ion-plasma compensation of target sputtering and ion-plasma deposition. The small thickness of modified surface layers reduces the time of heat treatment to achieve thermodynamical equilibrium. The vacuum thermal evaporation method does not make a layer with a sufficient adhesion and a special purity of substrate surface is needed. There is not an adhesion problem in the case of ion implantation, but high (more than 50%) concentrations of implanted ions in the surface layers can not be realised because of sputtering. The last problem can be solved by means of an ion-plasma compensation method of target sputtering during implantation. The method of ion-plasma magnetron deposition allows to deposit on the surface substrate the coating with phase-structural state and chemical composition of the sputtered material. This method provides high adhesion due to the prior ion etching of the substrate.

Vacuum evaporation was made using the industrial unit "VUP-5m". We used the accelerator "RADUGA-4" for implantation with ion-plasma compensation of sputtering.

The ion-plasma magnetron deposition was made using the designed installation "Argamak". It has the following technical characteristics: the deposition rate of metallic coatings - 0.3-1.8 μm/min; sample heating during the deposition process - 70-100°C; volume of the chamber - $1500 \times 1000 \times 1500$ mm^3. This installation was completed with two magnetrones (diameter of working surface – 40 mm).

The accelerating recharging complex UKP-2-1 of the Institute of Nuclear Physics of Republic of Kazahkstan is applied for high energy implantation and ion-beam analysis of materials. This accelerator is quite a precise tandem system with 1 MV accelerating voltage. It allows to produce beams of a wide ion spectrum (including inert gas ions) with currents in the μA range. The acceleration of inert gas ions was realized on the tandem systems for the first time. The main feature of the accelerator is the presence of two crossed beam tracts using the same source of accelerating voltage. The first tract is used for heavy ions acceleration, the second one - for hydrogen ions and inert gases. UKP-2-1 has four channels for beams transporting. Two beams (heavy ion and proton) can irradiate one target simultaneously. The acceleration of heavy ions and protons permits to study implanted materials in situ. The basic technical characteristics of UKP-2-1 are the following: beam energy 0.4-2.0 MeV; energy spread 0.03% for the beam energy of 1 MeV; current of beam -to 50 μA; accelerated ion masses range from 1 to 250 amu; beam size 2-5 mm; beam scanning area 50×50 mm^2. The methods of nuclear resonance reaction, Rutherford backscattering spectroscopy and channeling have been developed with UKP-2-1 using.

4.2. Special methods of surface layer investigations

Processes of formation and decomposition of phases in ion implanted massive specimens were investigated deficiently. The reason for this are the following high requirements to methods used to study these: they need to be nondestructive and to enable thin surface layers to be studied separately from the matrix. In contrast to thin films the systematical investigations of thermal stability of implanted alloys were not carried out on massive specimens.

The investigation of phase state and chemical composition of a coating was made by glancing angle X-ray diffractometry with the use of synchrotron radiation (SR) and nuclear resonance reactions (NRR) correspondingly.

The studies of material surface layers by the glancing angle X-ray diffractometry method are well-known. However, the sensitivity of this method essentially falls, when we analyze thin layers with the use of standard X-ray tubes. The advantages of SR as compared with the traditional sources of X-ray radiation are the high spectral intensity, the continuity of the radiation spectrum in a wide range of energy, small beam divergence and others. Therefore, there is a preference for studying of phase formation in irradiated surface layers by the glancing angle SR diffractometry method.

The experiments using SR were carried out on the channel "diffraction movie" of the electron-positron storage ring (VEPP-3) of the Institute of Nuclear Physics of the Siberian Branch of the Russian Academy of Sciences under the following conditions: the crystal monochromator is germanium; the wavelength of X-ray irradiation λ is 1.6081 Å (K is an edge of cobalt absorption); monochromatization extent $\Delta\lambda/\lambda = 10^{-3}$; the sample-detector distance = 220 mm; diffraction angle interval covered by the detector = 20°; detector space resolution ≥ 0.1 mm; the detector resolution = 0.02°; the calculation was made using the computer "ODRA-1325".

The method NRR was used to determine the depth-distribution profiles of surface layer elements. It has a high sensitivity to impurities in the surface (10^{-7}-10^{-8} at.%) and high depth resolution (a few tens of Å), if narrow resonances are available in the excitation function. Such a resonance was found for the reaction (p, γ) on the Cr isotope at a proton energy equaled to 1005 keV. The experiments were carried out using the accelerator recharging complex UKP-2-1.

We have compared the stability regions represented in temperature-annealing time coordinates for the chromium coatings produced by various methods on the substrate of pure nickel and nickel-chromium alloy. The results of experimental investigations of chromium implanted surface layers with ion-plasma compensation of matrix sputtering are given in Fig. 2. The experimental points represent the temperature, at which the surface layer does not dissolve yet during isochronous annealings for given time. The disappearance of the α-phase on diffraction diagrams and the reduction of the chromium concentration down to its matrix content in experiments by the NRR-method was evidence of the whole chromium dissolution. The chromium coatings prepared with ion-plasma deposition are more stable than those with ion implantation, and thermally evaporated in vacuum ones are less stable.

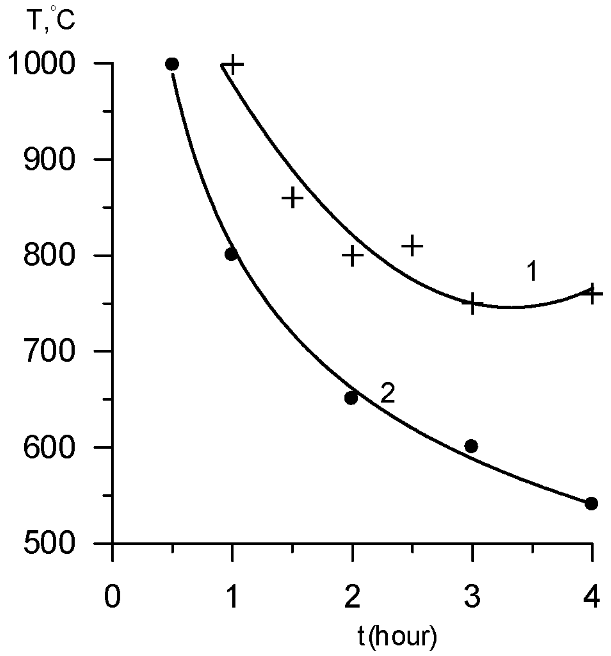

Fig. 2. Experimental data of dissolution temperature of chromium coating (α-phase), produced on the accelerator "RADUGA-4" from annealing time for Ni—Cr alloy (+) and for pure Ni (•). Curves 1, 2 are the results of a mathematical treatment.

Using the simplified model for the process of coating dissolving ($X \sim \sqrt{Dt}$, $D = D_o \exp(-E/kT)$, where X is the thickness of a coating, D is the diffusion coefficient, t is time, T is the temperature, E is the activation energy for migration) we are able to reproduce the obtained experimental results (curve 1 and 2 in Fig. 2). The activation energy for curve 1 is equal to 1.05 eV and 0.41 eV for curve 2. The diffusion coefficients ratio in pure Ni and Ni-Cr alloy at a temperature of 800°C equals 3, and at 900-1000°C ranges from 1.8 to 2.0.

Thus, for a specially prepared alloy at a given temperature, slowing down of the chromium diffusion process is observed as compared with pure nickel. The best result on increasing the thermal stability of surface layers is obtained when the method of ion-plasma deposition is used (4-10 times). In such a way the obtained results for the system Ni-Cr confirm the proposed principles of the production of surface layers chemically compatible with the substrate material.

5. THE THERMAL STABILITY OF IMPLANTATION IRON-METALLOID SYSTEMS STUDIED BY THE MÖSSBAUER SPECTROSCOPY METHODS

There are two reasons of interest to the implantation metal-metalloid systems. Firstly, the implantation phases forming in the sub-surface layers of an irradiated metal can improve substantially its mechanical properties. Secondly, compared to irradiation of a metal by metal ions, due to high activity of metalloid atoms in a metal, both simple and complex compounds are formed. Despite a large number of published works on the implantation of metal-metalloid systems, only few works are devoted to investigation of phase formation and phase transformation in massive specimens by means of non-destructive methods. The few studies concerning iron implanted by the boron or carbon atoms, performed by the Mössbauer spectroscopy methods, are seemingly, insufficient for making general conclusions on the implantation Fe-metalloid systems

In this section the implantation systems Fe:B^+, Fe:C^+ and Fe:0^+ are studied by the Mössbauer spectroscopy methods in order to reveal general regularities and peculiarities in formation and disintegration of the stable and metastable phases in the implantation metal-metalloid systems.

For irradiation by B^+, C^+ and O^+ ions and Mössbauer studies, α-Fe enriched by ^{57}Fe isotope up to 95% has been used as a target. The fraction of other elements does not exceed 0.05at.%. Primary samples with a size of 5x5mm^2 and a thickness of 50µm have been obtained by rolling and homogenisation annealing in vacuum at 800°C during 3 hours.

Irradiation has been carried out at the accelerator ILU-4. As the implanted ions are of different masses, their energies have been chosen such that the average projected range is the same and comprises 50nm.ion beam of rectangular section of 8x30 mm^2 is scanned with the frequency 50 Hz over the area 30x30 mm^2. The total current comprises 30 to 40 µA - for carbon, 15 to 25 µA - for boron and 10 to 15 µA - for oxygen.

The irradiation dose is $5 \cdot 10^{17}$ cm^{-2}. Heat removal during irradiation is provided by means of mechanical contact of the sample with the target holder. Evaluation of the thermal power released in the target under implantation has shown that the sample temperature doesn't exceed 100°C.

Isochronous annealing series, each having duration 30 minutes, have been carried out in vacuum of $5 \cdot 10^{-6}$ mm Hg within the temperature range from 200 to 700°C with the 100°C interval. The time required to reach a given temperature is about a half of hour. After annealing, the samples cooled slowly along with the furnace during several hours.

For the ion implantation technique the thickness of modified sub-surface layer comprising is typically 0.1µm. This value is substantially lower than the specimen thickness, and the experimental technique has to be surface-sensitive. The conversion electron Mössbauer spectroscopy (CEMS) method is one of a few non-destructive methods for investigation thin subsurface layers. Such parameters of the Mössbauer spectra as the isomer shift δ, the quadrupole displacement ε, hyperfine magnetic field H_n, the intensities I and the widths Γ of the spectrum components allow to assess the structure, the phase composition and the properties of implanted layers. It is true even when amorphous phases and small-size modified regions are available in them.

The technique of the performed Mössbauer experiment is described here.

Peculiarities of the phase and structural state of the modified layer have required not only to use the combined approach but also to develop a special strategy for application of the software package MSTools when processing and analysing the Mössbauer spectra.

The Mössbauer spectra processing and analysing have been performed in three steps.

(1) The model-based spectrum processing is carried out. The goal of this step obtaining the Mössbauer spectrum of the modified region without contribution from the α-Fe matrix atoms.

(2) The restoration of the distribution function $p(H_n)$ of the hyperfine magnetic field H_n is performed for the spectra obtained as a result of the first step processing. The goal of second step is obtaining additional *apriori* (for third step) information on the formed phases.

(3) The final model-based spectrum processing is carried out using *apriori* information. The step goal is to perform quantitative phase analysis of the sample-modified layer.

The schematic physical picture of the phase transformation succession in the implantation systems under thermal annealing is represented in Fig.3 for visual demonstration. The areas of concentric regions in this figure correspond to the relative fraction of the iron atoms in formed phases.

As a result of the CEMS analyses of the implantation systems Fe:B^+, Fe:C^+ and Fe:O^+, a general physical picture that reflects both the qualitative and quantitative characteristics of the phase transformation processes is given. The following general regularities in the phase formation and transformation have been revealed for the implantation- induced metal-metalloid systems.

1) It is possible to form both stable and metastable metal-metalloid phases by ion implantation; the produced compounds in the modified layers can be the dominant phases.

2) The concentration of metalloid atoms in the formed metal-metalloid phases decreases as the temperature of thermal annealing increases (the process can be followed by modified region expansion, segregation and migration of metalloid atoms).

3) In the case of slow migration of metalloid atoms out of the implanted layer, the temperatures of the phase transformations in this layer correlate with the temperature phase boundaries in the phase diagram for the metal-metalloid system.

4) Despite the non-equilibrium character of implanted ions embedded into the matrix, the tendency of phase transformation in the implanted layer with increasing annealing temperature can be predicted by the phase diagram.

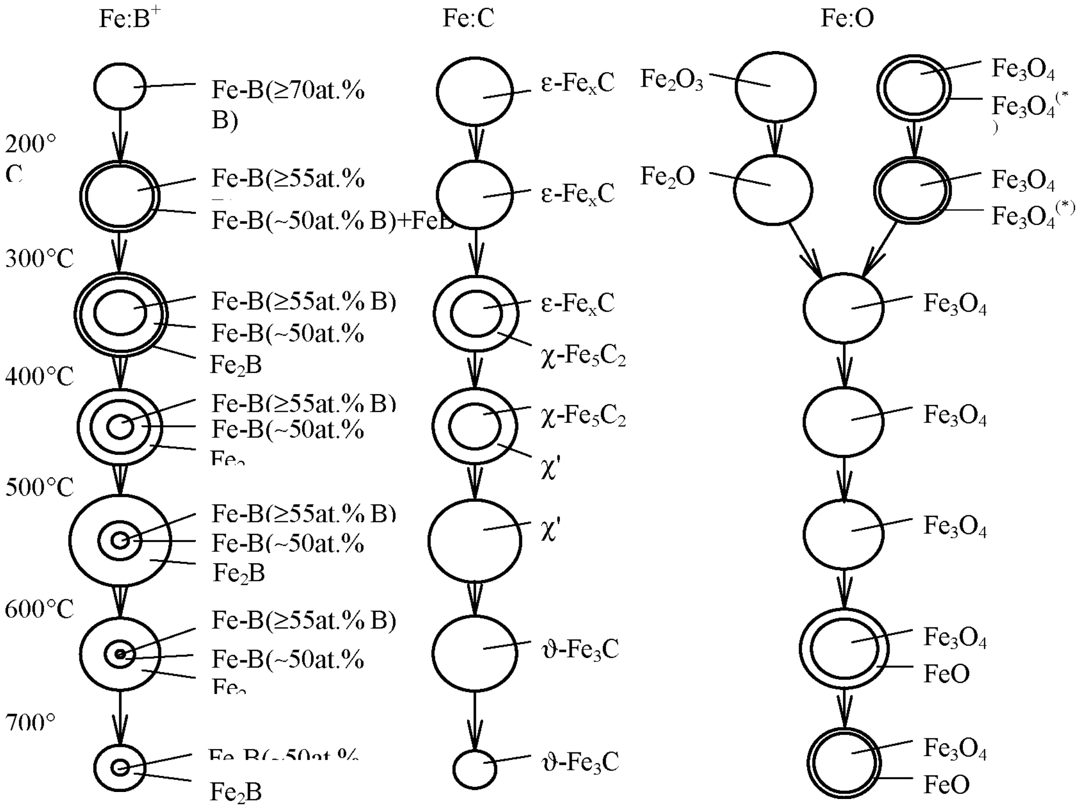

Fig.3 The schematic pictures of phase transformation successions in the studied implantation systems under isochronous thermal annealing

5) When the implantation system trends towards thermodynamic equilibrium, the two-phase precipitates playing roles of high-temperature steady elements can be produced. The process of phase transformation deceleration can be analysed on basis of the phase diagram for the case when two two-phase regions exist with different average concentrations within the temperature range covering the annealing temperature values.

6. THE THERMAL STABILITY OF BE-FE-BE THREE-LAYER SYSTEMS STUDIED BY THE MÖSSBAUER SPECTROSCOPY METHODS

The α-Fe foils with the beryllium coatings, produced by magnetron sputtering, is studied here. This system is considered as a good candidate for thermonuclear application. The specimens are made from α-Fe foils (enriched by ^{57}Fe isotope up to 89 at.%), rolled to the thickness 11μm and subject to homogenization annealing in vacuum at 800°C for 2 hours. The deposition of Be onto the iron foil from both side is carried out by magnetron sputtering at "Argamak" installation. The beryllium coatings are equal 0.5μm thicknesses. Isothermal annealing series are carried out at temperatures 720°C. The annealing vacuum was of $5\cdot10^{-6}$ mm Hg.

The Mössbauer studies are performed at a room temperature by means of two registration techniques: the technique of conversion electrons Mössbauer spectroscopy (CEMS), from both sides of a specimen in back scattering geometry and the γ-ray technique in absorption geometry. In the first case, information is obtained about a phase state of subsurface layers with the thickness values that depend on their chemical composition.

In the frames of thermodynamic approach for obtaining of high temperature $FeBe_2$ stable coating in multilayer Fe-Be system we need to obtain the concentration Be in a bulk that exceeds a solubility limit after thermal annealing. It was realised in system Be(0.5μm)- Fe(11μm)-Be(0.5μm) see Fig.4. The dissolution of $FeBe_2$ phase in subsurfase layers of such system occurs considerably slowly then in system Be(0.5μm)- Fe(11μm). These investigations are carried out now.

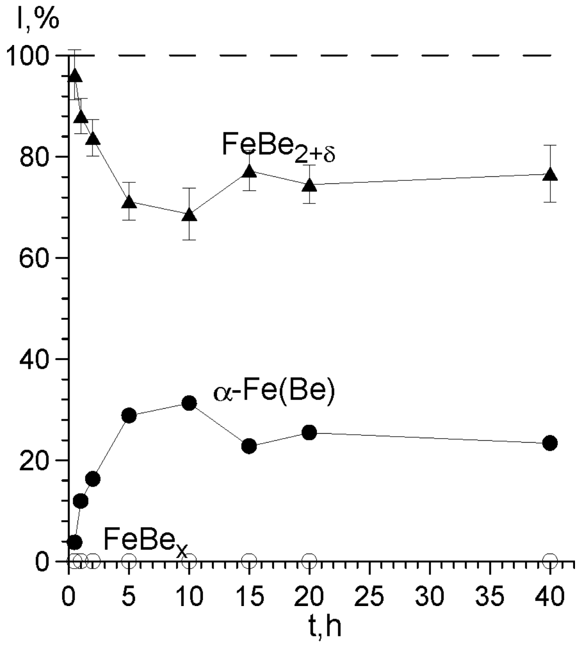

Fig.4. The relative intensities of the partial CEMS-spectra of ^{57}Fe nuclei in binary system Be(0.5μm)- Fe(11μm)-Be(0.5μm)- versus the time of isothermal 720^0C annealing.

7. CONCLUSIONS

At the present time ion-beam technologies have no alternatives in obtaining surface layers with required component composition by variation of irradiation regimes, ion energies, type of ions. However, the sphere for industrial applications of these technologies is not wide enough. Mainly, they are applied to improve mechanical properties for materials working at low temperatures. For the exploitation of modified layers under high temperatures it is necessary to provide their chemical compatibility with the matrix material. We developed the physical bases of the technology for the production of chemically compatible heat-resistant coatings on high-temperature nickel alloys and demonstrated its correctness on the example of the Ni-Cr system.

The technology of many-functional multilayer material production consists of some stages, beginning from the collection of experimental data for thermodynamical properties of multicomponent multiphase alloys, calculations of phase diagrams and chemical potentials, optimal choice for the method of surface layer deposition and regimes of heat treatment for matrix and surface materials to the creation of implanted devices and new equipment including the precision methods for surface control. Therefore, to completely develop scientific foundations for this technology it is necessary to cooperate with specialists working in such fields of science and techniques as: ion implantation and ion-beam technology, theories and simulations of phase diagrams, thermodynamics of multicomponent systems, and computer design-method.

REFERENCES

1. Thermodynamic Approach to Thermostable Metallic Surface Layers Production by Ion Implantation, Abst.Int.Conf. «Ion Beam Modification of Materials», Heidelberg, Germany, P099 (1992);
2. The application of thermodynamical approach and ion-beam technology to solving of problem of chemical compatibility of heat-resistance layers with high temperature materials on the example of nickel-chromium alloys, Doklady of Russian Academy of Science, **331**, 434 (1993) (in Russian);
3. Physical and chemical base of stable multilayer metals obtaining. Application to nickel-chromium-aluminium alloys, Doklady of Russian Academy of Science, **338**, 477 (1994) (in Russian);
4. Ion-beam technology for stable multilayer metals obtaining, Izvestiya of Russian Academy of Science, **58**, 199 (1994) (in Russian);
5. The application of CALPHAD method to the creation of chemically stable high temperature resistance coating on nickel-based superalloys, CALPHAD, **18**, 362 (1994);
6. The thermodynamical approach for obtaining of high temperature stable multilayer materials", Nucl.Instr.Meth. **B103**, 38 (1995);
7. Mossbauer study of iron surface implanted by oxygen ions, Poverhnost, **7-8**, 28 (1995) (in Russian);
8. Mossbauer study of iron surface implanted by boron ions, Poverhnost, **11**, 80 (1996) (in Russian);
9. Mossbauer study of iron surface implanted by carbon ions, Poverhnost, **4**, 27-33 (2000)(in Russian);
10. Phase transformation studies in implantation induced iron-metalloid system studied by Mossbauer spectroscopy", Nucl.Instr.Meth., **B170**, 85-97 (2000).