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ELECTRON BEAMS TRANSPORT AND ENERGY DEPOSITION IN HETEROGENEOUS ASSEMBLIES OF THE HASTELLOY SAMPLES EMBEDDED INTO THE MOLTEN FLUORIDES MIX

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By means of the Monte Carlo computer modeling technique the depth dependencies of energy deposition and concentration of radiation induced point defects have been calculated in heterogeneous assemblies of Hastelloy plates embedded into the melt of fluoride salts and irradiated by 8–10 MeV electron beams. For assemblies of various designs the beam penetration depth dependencies of energy spectra, angular distributions and energy fluxes of electrons and secondary gamma quanta had been studied in great details. As a result of these investigations the optimization of the target assembly design for the imitating experiment at the LUE-10 linac has been accomplished. It has been shown that for the optimized target ampoule design at the experimental conditions (700 hrs long 10 MeV electron irradiation) different surfaces of the Hastelloy plates contacting with molten fluorides are characterized by substantially different values of specific energy deposition (from ~5 keV/atom down to ~60 eV/atom) arising from inelastic ionization energy losses of primary and secondary charged particles. The concentration of point defects produced in elastic collisions of charged particles with target atoms decreases by ~500 times along the assembly thickness. Therefore the single imitating experiment opens up the possibility to study the radiation and corrosion stability of Hastelloy irradiated in the molten fluorides medium in a wide range of doses of electron beam energy deposition and radiation damage of alloy.

INTRODUCTION

The accelerated electrons irradiation test bench based on the 10 MeV LUE-10 linac has been recently created in NSC KIPT and the imitating experiments are carried out on this bench in order to study the effects of irradiation on the corrosion stability and mechanical properties of the Hastelloy Nickel-Molybdenum-Chromium alloy in aggressive medium of molten fluorides. These investigations are of great importance for the development [1] and the choice of optimal structural materials for the new-generation accelerator driven transmutation reactors with molten-salt blanket.

In imitating experiments the efficient utilization of the electron beam energy stimulates the application of thick heterogeneous targets (assemblies) with total thickness comparable with the range of primary electrons (controlled by the rate of their energy losses). Relativistic electrons intensively lose their energy in substance due to inelastic collisions and radiative processes of interaction. In turn the secondary bremsstrahlung photons emitted by electrons produce secondary electrons of rather high energies as well as the electron-positron pairs. All these processes give rise to complex radiation fields of charged particles and gamma quanta in matter that become strongly non-uniform at penetration distances comparable with the range of electron beam. For heterogeneous targets additional complexity of the radiation fields takes place due to certain fine scattering effects near the interfaces of materials.

The radiation stimulated chemical reactions are determined by the rate and the density of the radiation energy deposition in the area of the contact of the material with the melt. The locally deposited energy of some electronvolts is enough to activate a chemical reaction or diffusional replacements of atoms.

The surface and bulk radiation damage effects are mainly due to the energy transferred by electrons in elastic collisions with atoms. To induce a displacement of atom the locally transferred energy has to be larger then the Frenkel pair production threshold, $E_d \approx 25\ldots30$ eV.

Due to the beam slowing down processes the energy locally deposited by radiation essentially depends on the beam penetration depth. Therefore the energy deposited in surface layers of specimens in molten fluorides is dramatically depending on the specimen location and thickness. For this reason the target assembly design can be chosen in such a way that provides irradiation of many specimens with different irradiation rates and doses. If the assembly thickness is comparable with the primary electrons slowing down range, and the assembly contains N specimens, then we have $2\times N$ surfaces of contact of alloy with the molten salt. Consequently we obtain the possibility to investigate the irradiation impact on the corrosion in wide range of the deposited energy values. On the other hand, the specimen thickness has to be large enough to get representative information on the irradiation impact on mechanical properties.

To elaborate such an optimal experimental setup and to facilitate the adequate interpretation of experimental data the very detailed calculations of the electron beam deposited energy distributions in irradiated assemblies are required. Due to the complexity of the radiation fields in thick heterogeneous targets the interrelated problems of quantitative prediction of the electron beam energy deposition and the optimization of target design are non-trivial and stimulate the application of advanced methods of mathematical modeling for adequate description of secondary effects of primary electrons transport in matter.

In the present work the 8…10 MeV electron beams radiation fields and the associated deposited energy profiles in the various designs of containers (ampoules) that hold the irradiated alloy samples embedded into the melt of fluorides are calculated by means of the Monte

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Carlo computer modeling method. The main objective of these calculations consists in the substantiation of the choice of the ampoule design optimal form the point of view of investigation of the dependence of irradiation effects on the surface and in the bulk of samples on the electron beam energy deposition rate.

1. MODELING SETUP AND METHODS

1.1. EXPERIMENTAL GEOMETRY

The overall design and dimensions of ampoules to be used in experiments on the irradiation of the Hastelloy samples in liquid medium of molten fluorides are illustrated by the sketch depicted in fig. 1. The ampoule thickness is chosen to be comparable with the slowing down length (the range) of the primary electrons.

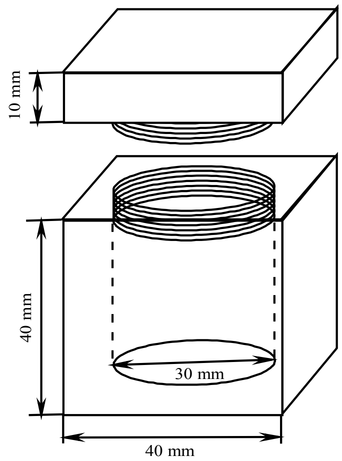

Fig. 1. The general view of target ampoule for irradiation of Hastelloy in the medium of molten salts

The leakproof container is a rectangular parallelepiped with the centered cylindrical cavity. In experiment the cavity holds the assembly of thin Hastelloy plates periodically arranged orthogonally to the electron beam axis and is filled by the melt of fluoride salts. The flat single-layered set of 16 such containers in the irradiation chamber is irradiated by the scanning beam of electrons. The accelerator scanning system forms the quasi-parallel broad electron beam and provides uniform conditions of irradiation of all target containers. Because of the flat geometry of the target assembly the beam attenuation and energy deposition is essentially depending on the beam penetration depth only.

1.2. MATERIALS

The target ampoule is made from the Carbon-Carbon (C-C) composite material with density $\rho = 1.5$ g/cm^3.

The molten fluorides liquid mix used in experiments contains (by molar fractions) 50% of ZrF_4 and 50% of NaF salts and has the density 3.3 g/cm^3.

Different versions of the Hastelloy brand Ni/Mo/Cr alloys are slightly varying by elemental composition and density. In the present work, as well as in the imitating experiments under consideration, the manufactured in NSC KIPT [1] Hastelloy Type A alloy with density 8.9 g/cm^3 was investigated (see Table 1).

One should note that the variation of chemical composition of different sorts of Hastelloy-type alloys have only weak effect on the slowing down of energetic electrons because major contribution to the stopping power is determined by Ni and Mo components that do not vary significantly from one sort to another.

Table 1

The elemental composition of the Hastelloy A alloy used in experiments and modeling

ELEMENT	*Z*	FRACTION	
		at%	wgt%
Al	13	0.83	1.85
Si	14	0.15	0.32
Ti	22	0.47	0.59
Cr	24	6.70	7.74
Mn	25	0.50	0.55
Fe	26	1.50	1.61
Ni	28	78.15	80.01
Mo	42	11.70	7.32

The total ranges of electrons in the target materials of interest calculated using the continuous slowing down approximation (CSDA) by means of the U.S. NIST supplied reference computer code *ESTAR* [2] are depicted in fig. 2 as functions of electron energy.

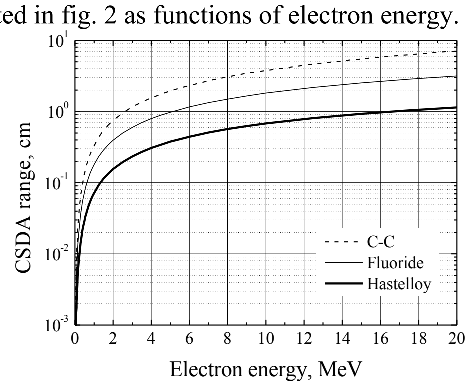

Fig. 2. Energy dependencies of the continuous slowing down approximation ranges of electrons in the target materials used in experiments and modeling

It is clear from this figure that for energies up to 10 MeV the ranges do not exceed 1…2 cm in fluorides and 5…8 mm in Hastelloy. It means that for such energies the total range of electrons in the target assembly is comparable with the size of containers, and the complete absorption of primary electrons should occur.

Due to the rapid decrease of ranges with the decrease of electron energy the ranges of scattered and secondary electrons that spread in lateral directions of the target assembly are typically much smaller then the ranges of primary electrons. Therefore taking into account the actual shape and dimensions of the target ampoule the influence of fringe effects determined by the transversal heterogeneity of the target assembly can be neglected in the first approximation. In this approximation the problem of the energy deposition calculation can be considered in the one-dimensional geometry that is described only by the strong heterogeneity along the beam penetration depth.

The results of the *ESTAR*-based calculations of the stopping power of electrons in the materials under consideration are shown in fig. 3.

These calculations testify that for the energy region peculiar for imitating experiments the slowing down of electrons becomes to be influenced by the radiative energy losses. Consequently the irradiation of ampoules would be accompanied with the noticeable rate of production of secondary bremsstrahlung photons having high penetration capability.

Thus the radiative energy losses, along with ionization ones, have to be taken into account in the energy deposition calculations.

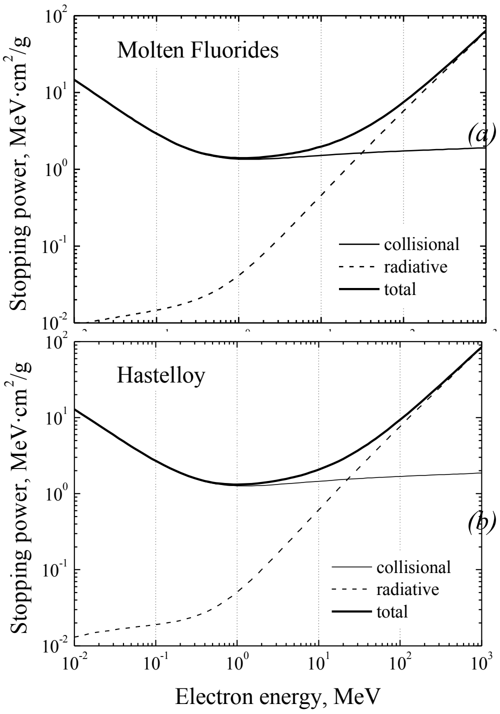

Fig. 3 Ionization (collisional), radiative and total stopping power ($\rho^{-1}\cdot dE/dx$) of electrons in the melt of fluoride salts (a) and in the Hastelloy alloy (b)

1.3. METHODS OF CALCULATIONS

For one-dimensional geometry the energy E_{dep} deposited per one atom of a medium at depth z during the time t of electron irradiation can be estimated using the following expression:

$$\int_0^{E_0} \varphi_e(E,z)\cdot\left|\left(\frac{dE}{dx}(E,z)\right)_{ion}\right| dE +$$

$$E_\gamma ¿ \varphi_\gamma(E_\gamma,z) ¿ \mu_{en}(E_\gamma,z)\ dE_\gamma ¿ \quad , \qquad (1)$$

$$E_{dep}(z,t)=\frac{t}{n(z)}\cdot ¿\{¿\}¿\{\}$$

where n is the atomic concentration of the material at depth z, φ_e and φ_γ are the energy spectra of the electron and photons flux density at this depth, $(dE/dx)_{ion}$ is the ionization stopping power of electrons with energy E for the material at depth z, μ_{en} is the linear energy absorption coefficient of the photons with energy E_γ in this material, E_0 is the energy of primary electrons.

To estimate the point defects (Frenkel pairs) production in elastic collisions of electrons with atoms the following method can be used. The number of displacements per atom (dpa) including the secondary displacements produced by primary knocked atom (PKA) is expressed by the following formula:

$$C(z,t)=t\cdot\int_{E_d(z)}^{E_0} \nu(T,z)dT \int_{E_d(z)}^{E_0} \varphi_e(E,z)\frac{d\sigma(T;E,z)}{dT}dE \quad , \qquad (2)$$

where $d\sigma/dT$ is the differential cross-section of the transfer of energy T in elastic collision of electron with atom, ν is the radiation damage function describing the secondary atoms displacements in the collision cascade produced by a PKA with energy T, E_d is the displacement threshold energy. The dependencies of these quantities on depth z emphasize the layered structure of the heterogeneous target.

The differential cross-section $d\sigma/dT$ is derived from the relativistic Mott cross-section of elastic scattering (see, *e.g.*, Ref. 3):

$$\frac{d\sigma(T,E)}{dT}=4\pi\left(\frac{Za_0E_R}{mc^2}\right)^2\cdot\frac{1-\beta^2}{\beta^4}\cdot\frac{T_m}{T^2}\times ¿$$

$$¿\times\left[1-\beta^2\frac{T}{T_m}+\frac{\pi\alpha}{\beta}\cdot\left(\sqrt{\frac{T}{T_m}}-\frac{T}{T_m}\right)\right] \quad , \qquad (3)$$

where Z is the target atomic number, a_0 and E_R are the Bohr atomic radius and the Rydberg energy, m is the electron mass, $\beta = v/c$ is the ratio of electron velocity v and the speed of light c, α is the fine structure constant, and T_m is the maximal energy of a recoil atom of mass M in elastic collision with an electron of energy E:

$$T_m(E)=\frac{2E\cdot(E+2\ mc^2)}{Mc^2} \ . \qquad (4)$$

The radiation damage function for rather low PKA energies peculiar for electron irradiation can be estimated using the Kinchin-Pease model [3]:

$$\nu(T)=\begin{cases} 0, & T<E_d \\ 1, & E_d\le T<2\cdot E_d \\ T/2E_d, & T>2\cdot E_d \end{cases} \ . \qquad (5)$$

For multicomponent targets, such as Hastelloy, the calculations according to Eqs. 3 to 5 have take into account different probabilities of electron impact with each sort of atom (determined by its atomic fraction) as well as the perturbation of the radiation damage function due to the multicomponent nature of the atomic collision cascade.

The calculations according to Eqs. 1 and 2 require the knowledge of the depth dependencies of the electrons and photons flux densities energy spectra. These functions can be calculated analytically only in certain degenerated cases (*e.g.* for thin target with the thickness much less then the range of primary electrons). However such simplifications are not adequate for our case of thick heterogeneous targets and the problem requires the application of numerical methods of calculations, or the computer modeling methods.

For calculations we have used the Monte Carlo method implemented in the specially developed computer code based on the *Geant4* toolkit [4] that provides the modeling of radiation transport in heterogeneous multicomponent media with complex geometries.

The modeling code takes into account all major physical processes of electromagnetic interactions. For charged particles (electrons and positrons) they include ionization energy losses, multiple scattering, elastic (Möller or Bhabba) scattering and δ-electrons production, the annihilation of positrons and the bremsstrahlung photons emission. For secondary photons the photoabsorption, incoherent (Compton) scattering and gamma conversion ($e^{\pm}$ pairs production) are taken into account. Hadronic processes such as nuclear reactions initiated by electron and photons were neglected in our calculations because their contribution into the energy deposition is marginal for the beam energies of interest.

The code simulated the electron-photon cascades initiated by primary electrons and calculated the particles' and energy fluxes, the particles' energy and angular distributions as well as the deposited energies by means of the statistical averaging of the physical quantities of interest over a large ($\sim 10^7$) number of cascades.

The histories of primary and secondary particles transport were followed down to the energies at which the ranges of electrons and positrons as well as the mean free-path lengths of photons fall down to 10 µm. At these cut-off energies (that are different for each material and a sort of particle) the particles trajectories were interrupted and their energy was locally deposited in the material correspondent to the particle's path endpoint.

The heterogeneous layered media were modeled that simulate different versions of the target designs and consist of alternate layers of fluorides melt and Hastelloy enclosed by the outer layers of C-C material representing the container walls.

The modeling was carried out for broad parallel beam of electrons. In different calculations the beam energy varied from 8 to 10 MeV. Angular and energy spreads of primary beam were neglected. However the filtration and scattering of electrons by 0.3 mm thick steel foil at beam entrance was taken into account.

The spatial resolution of the modeling results in Hastelloy and molten fluorides was 0.05 mm. The statistical errors of Monte Carlo averaging procedures was typically better then 0.5%.

2. MODELING RESULTS AND DISCUSSION

In our calculations the parameters of optimization of the target design were the number, the values of thickness and the positions of Hastelloy plates in the melt as well as the thickness of surrounding C-C walls.

2.1. PRELIMINARY TARGET DESIGN

The preliminary estimations have been made for the target design depicted in fig. 4 at primary electrons energy 8 MeV.

According to this preliminary design 1.5 mm thick Hastelloy plates are embedded into the melt so that the width of each layer of fluorides equals to 7.5 mm. For this case the depth dependencies of electrons and photons energy fluences (calculated per one primary electron fallen on the unit of target surface area) and the profile of deposited energy are shown in fig. 5.

As it is clear from fig. 5,a, the front C-C wall of the target ampoule attenuates the energy flux of electrons very weakly. It is due to the low atomic number and density of Carbon.

In contrast, due to the high stopping the layers of the melt, and especially of the Hastelloy alloy, strongly affect the flux. In the design considered primary electrons are practically completely absorbed in the first layer of Hastelloy that is characterized by strong gradients of both energy fluence and deposited energy.

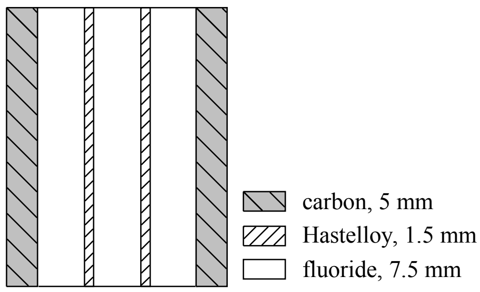

Fig. 4. The transversal section of the preliminary target design with thick layers of Hastelloy and fluorides melt

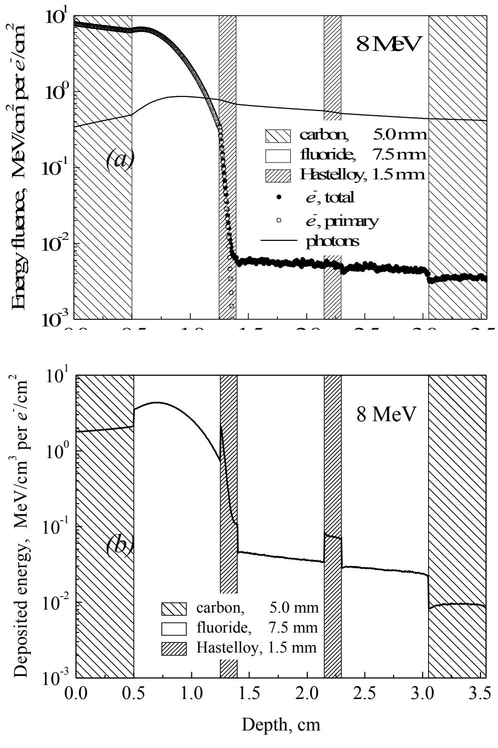

Fig. 5. Penetration depth dependencies of the energy fluences (a) of electrons and photons (incl. the energy

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fluence of primary electrons) and the deposited energy profile (b) for 8 MeV irradiation of the target of preliminary design (see fig. 4). The quantities are normalized per unit of primary electrons fluence

Inside the carbon wall and especially in the first layer of the molten fluorides the considerable production of bremsstrahlung gamma quanta by high-energy primary electrons takes place. Then the gamma radiation is rather slowly attenuated in the subsequent layers of the target. As a result the energy deposited in the second plate of Hastelloy is completely due to secondary electrons produced mainly by the bremsstrahlung photons incoherent scattering process and weakly depends on the penetration depth within the plate and the melt layer.

Thus the preliminary design of fig. 4 is far from optimality: in fact it allows to study the dependence of surface irradiation effects on the deposited energy only for two “melt-Hastelloy” interfaces of four available.

2.2. TARGET DESIGN OPTIMIZATION

The evident way for target optimization consists in the increase of beam energy, the decrease of thickness of the molten fluorides layers and the increase of the Hastelloy plate number in the target assembly.

Basing on the preliminary data of fig. 5 one can conclude that the total thickness of the irradiated system “melt-Hastelloy” should not exceed 1 cm. It is fairly consistent with the ranges estimations shown in fig. 2. Within the scope of the overall geometry of the target ampoule (see fig. 1) it can be provided by means of the insertion of the C-C half-liners (shaped as cylindrical segments) into the container’s cavity.

This method accompanied by the decreasing of Hastelloy plates thickness down to 0.6 mm and the increasing of their number to 5 is implemented in the target design depicted in fig. 6.

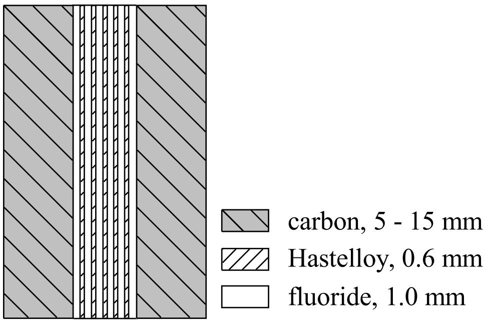


Fig. 6. The section of the target design with Carbon-Carbon insertions and 5 equidistant plates of Hastelloy

The depth profiles of energy fluences and deposited energy for 10 MeV irradiation of this target at different thicknesses of beam entrance/exit carbon layers are shown in figs. 7 and 8.

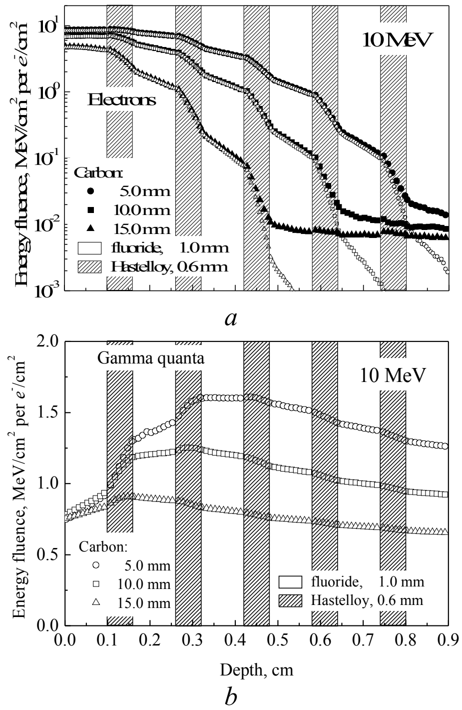


Fig. 7. Depth dependencies of normalized energy fluences of electrons (a) (open markers — the contribution of primary electrons) and gamma quanta (b) for different thicknesses of C-C layers at entrance and exit of 10 MeV electron beam. The target design of fig. 6

It is clear from fig. 7 that the variation of the thickness of the entrance carbon wall allows to control efficiently the evolution of radiation energy fluxes over the penetration depth.

The analysis of data depicted in fig. 8 shows that inside the assembly containing five Hastelloy plates the overall range of the depth dependency of deposited energy is practically the same for all thicknesses of carbon layers under consideration. The significant gradient of the energy deposition is obtained for three (of five) Hastelloy plates while the opposite surfaces of two other plates are in the same conditions of energy deposition. It means that it is sufficient to irradiate three layers of Hastelloy to obtain optimal information on the interfaces irradiation effects.

The increase of the C-C layer thickness increases the gradient of fluxes in the region of the front Hastelloy layers that are described by the high level of energy deposition. At the same time the production rate of gamma quanta (that leads to the smoothing of depth dependencies) is decreased because of stronger decrease of primary electron energy in thicker layers of carbon.

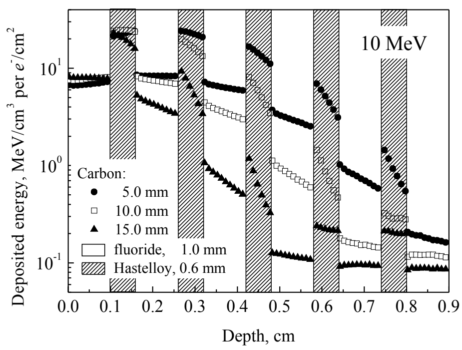


Fig. 8. Depth dependencies of deposited energies for different thicknesses of C-C layers. The target design of fig. 6, beam energy 10 MeV

Maximal gradients inside the Hastelloy layers take place for 15 mm thick C-C layer. It is due to the overall softening of electron energy spectrum in course of the beam slowing down in carbon.

2.3. OPTIMIZED EXPERIMENTAL DESIGN

In accordance with the obtained computer modeling data for actual experiments the target design depicted in fig. 9 has been chosen. This design and the correspondent results of computer modeling of radiation transport and beam energy deposition are discussed below.

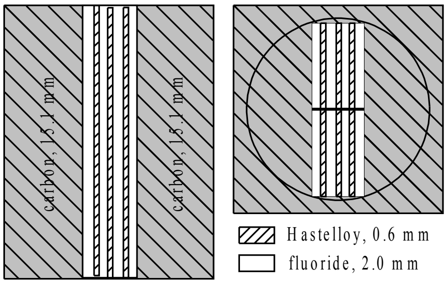


Fig. 9. The optimized design of target for the experiment: sectional and top views

Within the scope of this target design appropriate C-C insertion segments provide the thickness of front and back carbon walls of target container equal to 15.1 mm.

Three pairs of the 0.3 mm thick Hastelloy plates are tightly put together (in pairs) forming three 0.6 mm thick Hastelloy layers embedded into the molten salt. The inside surfaces of the Hastelloy specimens are closely contacting but evidently certain small amount of salt can penetrate between them. In our simulation this minor amount is ignored. The chosen thickness and size of the Hastelloy samples is considered to be enough to conduct mechanical tests after irradiation.

Three layers of Hastelloy are separated with 2 mm thick layers of melt. Such a thickness also allows to prevent the exhaustion of the molten salt chemical activity during the rather long-term irradiation experiment.

For the target design under consideration the depth dependencies of normalized energy fluences and deposited energies depicted in fig. 10 show that all layers of Hastelloy are characterized by strong gradients of both flux density and deposited energy.

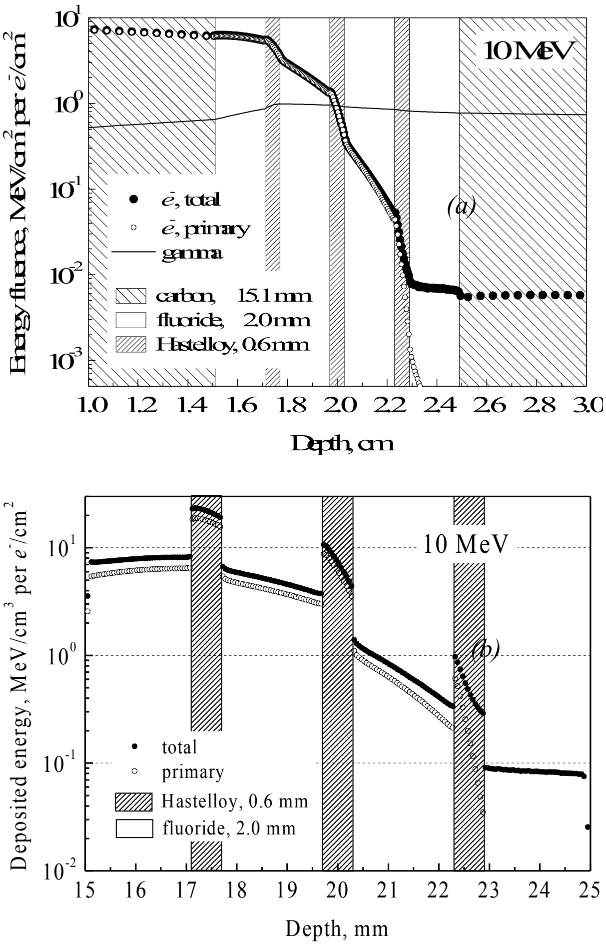


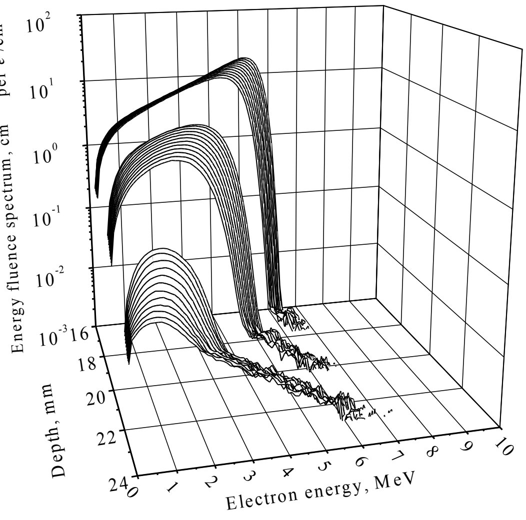
Fig. 10. Depth dependencies of the particles normalized fluences (a, incl. primary electrons and produced gammas) and the deposited energy profile (b) for optimized target design of fig. 9. Primary electron energy 10 MeV

The overall range of provided deposited energies in the near-surface regions of Hastelloy is about two orders of magnitude. Thus all samples of alloy can be efficiently used for the analysis of the dependency of corrosion and mechanical properties of Hastelloy on the value of deposited energy.

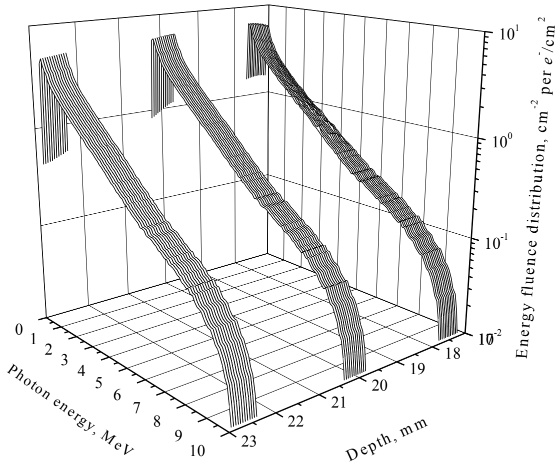
In the first two layers of Hastelloy the major contribution into the energy deposition is formed by the primary electrons. In the last layer (and especially in the last Hastelloy plate) the main yield to the energy deposition is due to the secondary electrons produced by the Compton scattering of bremsstrahlung photons.

The data shown in fig. 11,a testify that the energy spectrum of electrons (that includes both primary and secondary charged particles) considerably changes with the beam penetration depth. Typical energies of electrons are 4…6 MeV inside the first layer of Hastelloy and 3…4 MeV in the second one. In the third layer the electron energies fall down to 2 MeV and lower.

The photons energy spectra are typical for incoherent bremsstrahlung (see fig. 11,b) and only weakly depend on penetration depth. In the low energy region the weak annihilation photons peak (E_γ = 511 keV) has been found at modeling that testifies the existence of certain contribution of the $e^{\pm}$ pairs production processes into the energy deposition in the target.



a



b

Fig. 11. Energy spectra of energy fluences of electrons (a) and photons (b) inside the Hastelloy layers

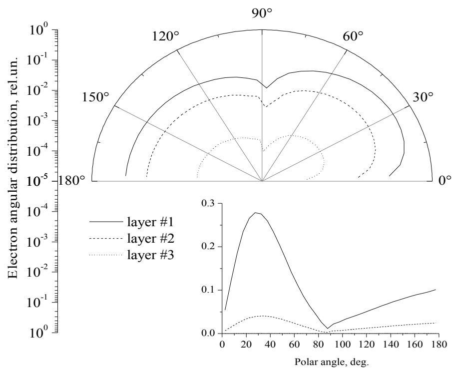
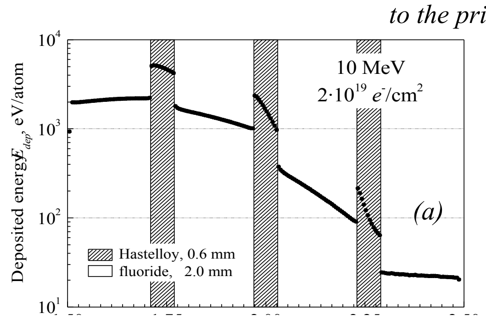


Fig. 12. Angular distributions of electrons inside three sequential layers of Hastelloy. Zero polar angle corresponds to the primary beam direction



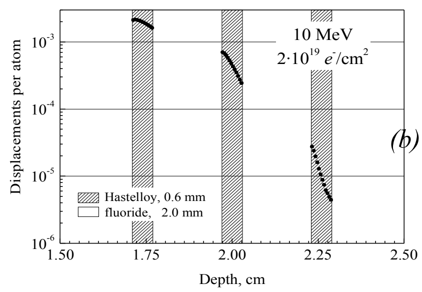


Fig. 13. The penetration depth dependency of the deposited energy (a) and the total number of atomic displacements (b) in Hastelloy at experimental conditions for optimized target design

The modeling of angular distributions of electrons in the Hastelloy layers (see fig. 12) has shown that electrons experience considerable scattering in the target. As a result the deposited energy depth dependency is formed by complex broad angular distribution of fast charged particles that incorporates the significant fraction of scattered and secondary electrons that propagate in the direction opposite to the primary beam direction.

2.4. DISCUSSION

The final data of the Monte Carlo computer modeling of the deposited energy depth profile in the "melt-Hastelloy" system at 700 hours long target irradiation by the electron beam with energy 10 MeV and current density 1.25 μA/cm^2 are depicted in fig. 13a. The data have been obtained by means of appropriate scaling of normalized data of fig. 10b. The correspondent Hastelloy radiation damage profile calculated at the displacement threshold energy E_d = 25 eV for all sorts of atoms in the alloy is presented in fig. 13,b.

For interface regions of all Hastelloy plates the deposited energies and the atomic concentrations of point defects are summarized in Table 2 both in absolute (per atom) and relative units.

Table 2

Deposited energies in the interface (near-surface) regions of the Hastelloy plates and the melt

SAMPLE	SAMPLE SURFACE	MATERIAL	DEPTH	DEPOSITED ENERGY		POINT DEFECTS	
			cm	eV/atom	percentage	dpa	percentage

		fluoride	1.7075	2221.52					
1	1-1	Hastelloy	1.7125	5066.72	100.0	100.0	2.12×10^{-3}	100.0	100.0
	1-2		1.7375	4906.46	96.84	96.84	2.01×10^{-3}	94.44	94.44
2	2-1		1.7425	4815.29	95.04	95.04	1.95×10^{-3}	91.94	91.94
	2-2		1.7675	4208.23	83.06	83.06	1.62×10^{-3}	76.20	76.20
		fluoride	1.7725	1794.76					
			1.9675	1010.82					
3	3-1	Hastelloy	1.9725	2347.23	46.33	100.0	7.00×10^{-4}	32.96	100.0
	3-2		1.9975	1698.40	33.52	72.36	4.80×10^{-4}	22.59	68.54
4	4-1		2.0025	1563.33	30.85	66.60	4.33×10^{-4}	20.37	61.80
	4-2		2.0275	969.88	19.14	41.32	2.44×10^{-4}	11.48	34.83
		fluoride	2.0325	375.17					
			2.2275	90.93					
5	5-1	Hastelloy	2.2325	214.55	4.23	100.0	2.75×10^{-5}	1.30	100.0
	5-2		2.2575	107.01	2.11	49.88	1.06×10^{-5}	0.50	38.64
6	6-1		2.2625	95.04	1.88	44.30	8.83×10^{-6}	0.42	32.07
	6-2		2.2875	63.82	1.26	29.74	4.42×10^{-6}	0.21	16.07
		fluoride	2.2925	24.39					

The accelerator irradiation up to high electron fluences leads to the significant values of specific deposited energies that in average amounts to 2 keV per atom. At such levels of deposited energy one can expect the considerable effects of irradiation on the corrosion processes at the contact of Hastelloy with molten fluoride salts and on the degradation of mechanical properties of alloy under irradiation in aggressive environment.

At the same time one should mention that the level of the Hastelloy radiation damage (see fig. 13b) for electron irradiation is considerably lower then that for neutron irradiation in reactor. However its depth dependence is even more strong then that of deposited energy: it decreases by 500 times from the front surface of the first specimen to the back surface of the last Hastelloy plate.

Thus the chosen optimal design of target provides the capability to clarify the dose dependencies of irradiation effects of interest using the results of single imitating experiment because the surface layers of irradiated samples are described by the considerably different rates of energy deposition and radiation damage.

CONCLUSIONS

The detailed Monte Carlo modeling performed in the present work has allowed to select from the variety of possible versions the optimal design of the target for imitating experiments on the investigation of corrosion and mechanical properties of Hastelloy contacting with molten fluorides under electron irradiation. Within the scope of the experimental geometry proposed basing on the modeling results the maximal variability of energy deposition on different interfaces of Hastelloy and fluorides is obtained that provides the information on the dose dependencies of the corrosion stability and the mechanical properties degradation.

The modeling of such complex multicomponent heterogeneous system that is presented by the irradiated assemblies taking into account all valuable physical processes that determine the relativistic electrons energy deposition in substance has been provided both the obtainment of important information on the kinetics of development of electron-photon processes in this system and the quantitative calculation data on depth profiles of energy deposition necessary for adequate analysis of the results of imitating experiments.

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ТРАНСПОРТ И ПОГЛОЩЕНИЕ ЭНЕРГИИ ЭЛЕКТРОННЫХ ПУЧКОВ В ГЕТЕРОГЕННЫХ СБОРКАХ ОБРАЗЦОВ ХАСТЕЛЛОЯ, ПОГРУЖЕННЫХ В СМЕСЬ РАСПЛАВЛЕННЫХ ФТОРИДОВ

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Путем математического моделирования методом Монте-Карло рассчитаны профили энерговыделения и концентраций образуемых точечных дефектов в гетерогенных сборках тонких пластинок сплава хастеллой, погруженных в расплав фторидных солей, под облучением пучками электронов с энергиями 8…10 МэВ. Детально исследована эволюция энергетических спектров, угловых распределений и плотностей потока энергии электронов и вторичных гамма-квантов по глубине проникновения пучка в сборки различных конструкций.

На этой основе выполнена оптимизация конструкции сборки-мишени для имитационного эксперимента на электронном ускорителе ЛУЭ-10. Показано, что для оптимизированной конструкции ампулы мишени в условиях эксперимента (700-часовое облучение электронами с энергией 10 МэВ) на различных поверхностях пластинок хастеллоя, контактирующих с расплавом, достигаются существенно различные значения удельного энерговыделения (от ~5 кэВ/атом до ~60 эВ/атом), связанного с неупругими ионизационными потерями энергии первичных и вторичных заряженных частиц. Концентрации точечных дефектов, образуемых в упругих столкновениях заряженных частиц с атомами, на толщине сборки спадают приблизительно в 500 раз. Таким образом, единственный имитационный эксперимент открывает возможность исследовать радиационную и коррозионную стойкость хастеллоя, облученного в среде расплавленных фторидов, в широком интервале доз энерговыделения электронного пучка и радиационного повреждения сплава.

ТРАНСПОРТ ТА ПОГЛИНАННЯ ЕНЕРГІЇ ЕЛЕКТРОННИХ ПУЧКІВ В ГЕТЕРОГЕННИХ ЗБІРКАХ ЗРАЗКІВ ХАСТЕЛОЯ, ЗАНУРЕНИХ У СУМІШ РОЗПЛАВЛЕНИХ ФТОРИДІВ

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Шляхом математичного моделювання методом Монте-Карло розраховані профілі енерговиділення та концентрацій точкових дефектів, що утворюються в гетерогенних збірках тонких платівок сплаву хастелой, занурених у розплав фторидних солей, під опроміненням пучками електронів с енергіями 8…10 МеВ. Детально досліджена еволюція енергетичних спектрів, кутових розподілів та густин потоку енергії електронів та вторинних гамма-квантів з глибиною проникнення пучка у збірки різних конструкцій. На цій основі виконана оптимізація конструкції збірки-мішені для імітаційного експерименту на електроннім прискорювачі ЛПЕ-10. Показано, що для оптимізованої конструкції ампули мішені за умов експерименту (700-годинне опромінювання електронами з енергією 10 МеВ) на різних поверхнях платівок хастелою, що контактують з розплавом, досягаються суттєво різні значення питомого енерговиділення (від ~5 кеВ/атом до ~60 еВ/атом), пов’язаного з непружними іонізаційними втратами енергії первинних та вторинних заряджених частинок. Концентрації точкових дефектів, що утворюються у пружних зіткненнях заряджених частинок з атомами, на товщині збірки спадають приблизно у 500 разів. Таким чином, єдиний імітаційний експеримент відкриває можливість дослідити радіаційну та корозійну стійкість хастелою, опроміненого у середовищі розплавлених фторидів, в широкому інтервалі доз енерговиділення електронного пучка та радіаційного пошкодження сплаву.