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Original Article

A model for calculating the irradiation swelling of AgInCd absorber in nuclear control rods

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ABSTRACT

The actual swelling of AgInCd absorber might exceed the predicted swelling value after years of service in pressurized water reactors, and the chemical and microstructural changes of AgInCd absorber induced by transmutation reactions are the main reason for the swelling acceleration of AgInCd absorber. In the present study, a model for calculating the irradiation swelling of AgInCd absorber in nuclear control rods is developed according to chemical and microstructural changes of AgInCd absorber. In this model, the chemical compositions of AgInCd absorber as a function of the thermal neutron fluence are firstly calculated, and then the volume of AgInCd absorber after irradiation is obtained on the basis of the crystallographic parameters of phases in the AgInCd absorber, and the irradiation swelling of AgInCd absorber is finally calculated. The crystallographic parameters can be obtained by preparing the simulated AgInCd alloys and fitting the experimental data. The model calculating results of irradiation swelling are in good agreement with the actual swelling data in literature. More importantly, the present model can well explain the EPRI results of the acceleration in the diametral swelling rate above 6–8 $\times$ 10^{20} n/cm^2 and the decrease in the diametral swelling rate above about 2 $\times$ 10^{21} n/cm^2.

1. Introduction

The safety of nuclear reactors is of great significance to public health and national economy. Nuclear control rods are a critical component of nuclear reactors, which can inhibit, release and regulate the reactivity of nuclear reactors. Therefore, the normal operation of nuclear control rods is an important barrier for the safety of nuclear reactors. For obtaining higher control rod worth, the absorber materials of nuclear control rods are usually composed of many chemical elements with high capacity for absorbing neutrons. AgInCd absorber with 80 wt% Ag, 15 wt% In and 5 wt% Cd is widely used in the nuclear control rods of pressurized water reactors because of their superior neutron absorption performance and better structural stability under neutron irradiation [1–7]. However, during the operation of nuclear power plants, the actual swelling of AgInCd absorber might exceed the predicted swelling value after years of service, resulting in the sticking phenomenon of the nuclear control rods [8–10]. It was estimated that the swelling rate of the stuck control rods after years of service was more than four times of the expected swelling rate for the F06 rod bundle of Cruas nuclear power plant, which indicated that there was a swelling acceleration of AgInCd absorber in the later stage of service. The sticking of AgInCd absorber caused by swelling acceleration might seriously affect the normal operation of nuclear power plants, which not only brought danger to the safety of reactors, but also could cause huge economic losses for the nuclear power plants.

It is generally believed that there are two physical processes that possibly cause the swelling of AgInCd absorber in nuclear control rods [9,11,12]: one is the creep deformation of AgInCd absorber under the compressive force of pretension spring at both ends of control rods and its own gravity; the second is the irradiation swelling of AgInCd absorber. For creep deformation, since the compressive force and gravity suffered by AgInCd absorber will not change significantly during the whole service process, the swelling rate induced by creep deformation should be relatively stable during service. Therefore, the irradiation swelling is particularly important for the swelling acceleration of AgInCd absorber. Generally speaking, there are three reasons for the swelling of metal materials under neutron irradiation [13,14]: the crystal damage produced by fast neutron, the pores formed by gas products, and the chemical and microstructural changes induced by transmutation reactions. For the AgInCd system, the two former reasons

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are of less importance, because the (*n, α*) and (*n, p*) reactions (producing the gas products) cannot occur in the AgInCd alloy during the irradiation process in the nuclear pile, and the crystal damage caused by fast neutrons can be annealed and annihilated quickly at the temperature of 300~350 °C. Therefore, the chemical and microstructural changes of AgInCd alloys induced by transmutation reactions are likely to be the main reason for the swelling acceleration of AgInCd absorber.

During the neutron irradiation process, Ag element will transform into Cd and In will turn into Sn by transmutation reactions in the AgInCd alloys, thus this Ag–In–Cd ternary alloy becomes the Ag–In–Cd–Sn quaternary alloy [12,15]. The unirradiated AgInCd alloy is a single-phase solid solution with face-centered cubic (*fcc*) structure, while the transmutation products Sn and Cd can promote the formation of a low-density second phase with hexagonal close packed (*hcp*) structure, because Sn has a low solid solubility in the AgInCd alloys [3,12,16]. Bourgoin believed that the precipitation of the second phase with transmutation products was an important reason for the swelling of AgInCd absorber in the later stages of service [16]. In a previous study, a swelling acceleration of AgInCd absorber was also found when the neutron dose exceeded approximately 6×10^{20} n/cm^2 [17]. Desgranges believed that the swelling of AgInCd absorber was mainly caused by two factors (chemical swelling and structural swelling), and the swelling acceleration was primarily related to the structural swelling induced by the transformation from *fcc* structure into *hcp* structure [17]. However, there is no quantitative and physically interpretable model for calculating the irradiation swelling of AgInCd absorber in nuclear control rods at present. In this paper, a physically interpretable model is attempted to be developed for calculating the irradiation swelling of AgInCd absorber based on the chemical and microstructural changes of AgInCd alloys.

2. Calculating model of irradiation swelling

The main reason for the radiation swelling of AgInCd absorber in pressurized water reactors is the chemical and microstructural changes of AgInCd alloys during the irradiation process, resulting in the formation of *hcp* phase with lower density. For calculating the irradiation swelling of AgInCd absorber, it is firstly necessary to calculate the chemical compositions of AgInCd alloys during the irradiation process. In fact, multiple nuclides in the AgInCd alloys change simultaneously due to transmutation reactions under the neutron irradiation conditions. In our previous study, we have established a model to calculate the chemical compositions of AgInCd absorber under neutron irradiation [12]. In this model, the change rate ($\frac{dN_i(r,t)}{dt}$) of one nuclide with irrdiation time at position *r* can be described by the following differential equation [12,18]:

$$\frac{dN_i(r,t)}{dt} = \sum_{j=1}^{m} l_{ij}\lambda_j N_j(r,t) + \Phi(r,t)\sum_{k=1}^{m} f_{ik}\sigma_k N_k(r,t) - (\lambda_i + \Phi(r,t)\sigma_i)N_i(r,t) \tag{1}$$

where $N_i(r,t)$, $N_j(r,t)$ and $N_k(r,t)$ are the contents of nuclides ***i***, ***j*** and ***k*** at the irrdiation time (t) in the AgInCd absorber, respectively; r is the radial distance from the center of AgInCd absorber; λ_i and λ_j are the radioactive decay constant of nuclides ***i*** and ***j***, respectively; σ_i and σ_k are the neutron cross sections of nuclides ***i*** and ***k***, respectively; l_{ij} is the fraction of radioactive decay of parent nuclide ***j*** to generate nuclide ***i***; f_{ik} is fraction of neutron absorption of other nuclide ***k*** to generate nuclide ***i***; $\Phi(r,t)$ is the neutron flux at a radial position (r) of AgInCd absorber. Since the AgInCd absorber will absorb and consume thermal neutrons by transmutation reactions, the thermal neutron flux in the AgInCd absorber will gradually decrease from the outer region to the interior. Assuming that the thermal neutron flux in the AgInCd absorber is axisymmetrically distributed, the thermal neutron flux at the radial distance (r) can be described by following formula [12]:

$$\frac{d\Phi(r,t)}{dr} = -\sum_{i=1}^{m} \Phi(r,t)\sigma_i N_i(r,t) \tag{2}$$

The boundary condition of formula (2) is that the thermal neutron flux on the surface of the AgInCd absorber is equal to the typical environment flux in the reactor core (approximately 10^{13} n/cm^2/s). Given the initial conditions of AgInCd absorber, and the chemical compositions of AgInCd absorber as a function of the thermal neutron fluence can be calculated by above formulas. In our previous study, the chemical composition distribution along the radius of AgInCd absorber and the average chemical compositions was calculated as a function of neutron fluence [12].

During the neutron irradiation process, the AgInCd absorber absorbs neutrons and undergoes transmutation reactions, and its total mass will change. Due to the uncertainty of transmutation reactions, the mass change of AgInCd absorber is not easy to calculate. Therefore, the irradiation swelling of AgInCd absorber cannot be calculated simply by measuring the density of the simulated AgInCd alloys. As mentioned above, Ag and In will transform into Cd and Sn by transmutation reactions, and the microstructure of AgInCd absorber changes correspondingly from a single *fcc* phase into a mixture of *fcc* and *hcp* phases. Based on the fact that the total number of heavy atoms in the AgInCd absorber remains unchanged during the transmutation process, the present paper will first calculate the volume fraction and lattice parameters of different phases (*fcc* and *hcp* phases) in the AgInCd absorber, and then calculate the volume of AgInCd absorber after neutron irradiation, and finally obtain the irradiation swelling of AgInCd absorber.

According to the fundamentals of materials science [19], the volume of a single unit cell of the *fcc* phase is a_{fcc}^3 (a_{fcc} is the lattice parameter of *fcc* phase), and the number of atoms in the single unit cell of *fcc* phase is 4. Similarly, the volume of *hcp* unit cell is $\frac{3\sqrt{3}}{2}a_{hcp}{}^2c_{hcp}$ (a_{hcp} and c_{hcp} are the lattice parameters of *hcp* phase), and the number of atoms in *hcp* unit cell is 6. For the AgInCd absorber with diameter (D_x) and length (L), the total number of atoms (N_x) contained in the AgInCd absorber can be obtained by following formula:

$$N_x = \frac{4\pi\left(\frac{D_x}{2}\right)^2 L\varphi_{fcc}}{a_{fcc}{}^3} + \frac{6\pi\left(\frac{D_x}{2}\right)^2 L\varphi_{hcp}}{\frac{3\sqrt{3}}{2}a_{hcp}{}^2c_{hcp}} \tag{3}$$

where φ_{fcc} and φ_{hcp} are the volume fraction of *fcc* and *hcp* phases in the AgInCd absorber during the irradiation process, respectively.

For the unirradiated AgInCd absorber (diameter D_0), the microstructure is completely composed of *fcc* phase, the total number of atoms (N_0) contained in the unirradiated AgInCd absorber can be calculated:

$$N_0 = \frac{4\pi\left(\frac{D_x}{2}\right)^2 L}{\left(a_{fcc|x=0}\right)^3} \tag{4}$$

where $a_{fcc|x=0}$ is the lattice parameter of *fcc* phase when the thermal neutron fluence or irradiation time is zero.

The two ends of AgInCd absorber are fixed by the pretension springs. It can be considered that the length (L) of AgInCd absorber will not change with the changes of chemical composition and microstructure during the irradiation process. Since the total number of heavy atoms in the AgInCd absorber remains unchanged during the transmutation process (i.e., $N_x = N_0$), the diametral expression of AgInCd absorber during the irradiation process can be obtained by combining formula (3) and formula (4):

$$D_x = D_0\left(a_{fcc|x=0}\right)^{-\frac{3}{2}}\left(\frac{\varphi_{fcc}}{a_{fcc}{}^3} + \frac{\varphi_{hcp}}{\sqrt{3}a_{hcp}{}^2c_{hcp}}\right)^{-\frac{1}{2}} \tag{5}$$

Consequently, the diametral irradiation swelling rate (φ) of AgInCd absorber induced by the chemical and microstructural changes of

AgInCd alloys during the irradiation process can be calculated, as follows:

$$\varphi = \left(a_{fcc|x=0}\right)^{-\frac{3}{2}} \left(\frac{\varphi_{fcc}}{{a_{fcc}}^3} + \frac{\varphi_{hcp}}{\sqrt{3}{a_{hcp}}^2 c_{hcp}} \right)^{-\frac{1}{2}} - 1 \quad (6)$$

For quantitatively calculating the irradiation swelling of AgInCd absorber, it is also necessary to obtain the relationships between the crystallographic parameters (φ_{fcc}, φ_{hcp}, a_{fcc}, a_{hcp} and c_{hcp}) and the thermal neutron fluence. In the next section, we will obtain these parametric relationships by preparing and characterizing a series of simulated AgInCd alloys.

3. Model parameters obtained by experiment

The relationship between the average chemical compositions of AgInCd absorber and the thermal neutron fluence can be calculated by the chemical composition model, and the detail calculation process and the data of cross sections and radioactive decay can be found in our previous study [12]. For the initial chemical composition of AgInCd absorber (80 wt% Ag, 15 wt% In and 5 wt% Cd) and the typical neutron flux of 10^{13} n/cm^2/s in the reactor core, the average chemical compositions of the irradiated AgInCd absorber as a function of the thermal neutron fluence can be calculated, as shown in Fig. 1. These calculation results of average chemical compositions are similar to the results in our previous study [12]. In general, when the thermal neutron fluence is within the level of 8.0 × 10^{21} n/cm^2, there is an approximately linear relationship between the content of each element and the thermal neutron fluence.

For achieving the relationship between the crystallographic parameters and the thermal neutron fluence, the simulated AgInCd alloys were firstly prepared according to the calculated chemical compositions of AgInCd absorber shown in Fig. 1. We chose six chemical compositions of the simulated AgInCd alloys which corresponded to the thermal neutron fluence of 0, 9.5 × 10^{20} n/cm^2, 1.85 × 10^{21} n/cm^2, 2.85 × 10^{21} n/cm^2, 6.3 × 10^{21} n/cm^2 and 7.9 × 10^{21} n/cm^2, respectively. The nominal chemical compositions of the six simulated AgInCd alloys with different thermal neutron fluences are shown in Table 1. These simulated AgInCd alloys were fabricated by the sealed vacuum melting in the seal-welded vessels by using pure Ag, In, Cd and Sn raw metals with different weight ratios on the basis of the calculated chemical compositions. The melting processes were conducted at 980 °C for 3 h in a furnace, the seal-welded vessels kept rotating to promote the chemical homogenization of the simulated AgInCd alloys during the isothermal melting process, followed by the cooling process with furnace. By mechanically removing the seal-welded vessels, cylindrical AgInCd samples with size of φ 20 mm × 80 mm can be obtained.

Table 1
The chemical compositions (wt.%) and densities of the six simulated AgInCd alloys corresponding to different thermal neutron fluences.

Neutron fluence (× 10^{20} n/cm^2)	Ag	In	Cd	Sn	Average density
0	80	15	5	0	10.175
9.5	77.5	13.5	7.5	1.5	10.030
18.5	74	12	11	3	9.956
28.5	71	10.5	14	4.5	9.834
63	61	6.5	24	8.5	9.641
79	55	5	30	10	9.521

The average densities of the six simulated AgInCd alloys were measured by using the Archimedes method and the density results are present in Table 1. For obtaining the volume fractions of *fcc* and *hcp* phases in the simulated AgInCd alloys as a function of the thermal neutron fluence, the microstructural characterization of the prepared AgInCd alloys was conducted by using a scanning electronic microscopy (FEI, NOVA NanoSEM400) in the backscattered electron imaging mode after the conventional metallographic preparation. Because the *hcp* phase contains more Sn and Cd elements in the simulated AgInCd alloys [16], the contrast of this phase is brighter than the *fcc* phase in the backscattered electron imaging mode. According to the contrast difference of *fcc* and *hcp* phases, the volume fractions of *hcp* phase in the simulated AgInCd alloys were measured by using an area measurement software (Mias, developed by Sichuan University). In order to obtain accurate volume fraction of the phases, the microstructural characterization was conducted at least three different regions for each simulated AgInCd alloy. Fig. 2 shows the volume fraction of *hcp* phase in the simulated AgInCd alloys as a function of the thermal neutron fluence. It can be seen that the volume fraction of *hcp* phase firstly increases slowly with the increase of thermal neutron fluence when the thermal neutron fluence is lower than 9.5 × 10^{20} n/cm^2, then increases faster between the neutron fluence range of 9.5 × 10^{20} n/cm^2 and 2.85 × 10^{21} n/cm^2, and finally increase slowly again after the thermal neutron fluence is higher than 2.85 × 10^{21} n/cm^2.

Through the logistic regression analysis, the relationship between the volume fraction of *hcp* phase in the simulated AgInCd alloys and the thermal neutron fluence can be well fitted:

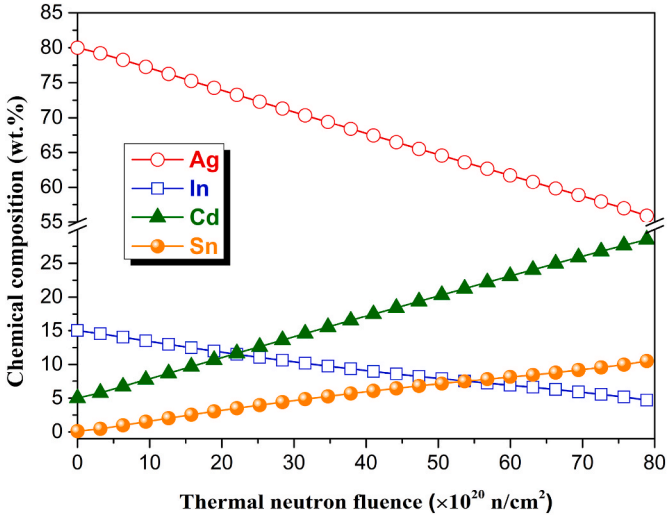

Fig. 1. The relationship between the average chemical compositions of AgInCd absorber and the thermal neutron fluence. These calculation results are adapted from Ref. [12].

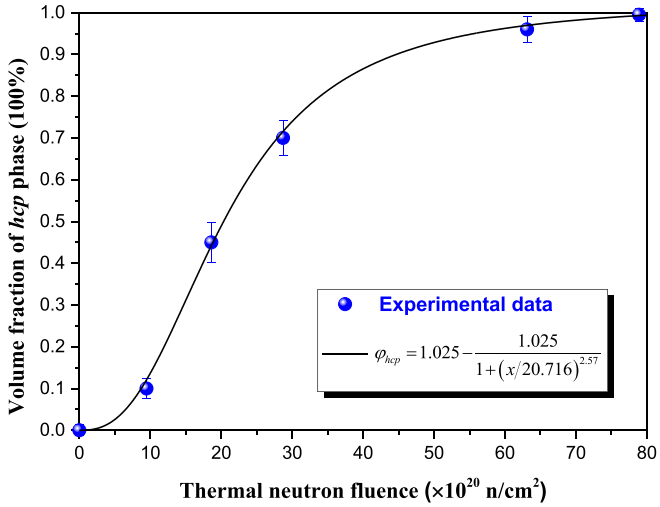

Fig. 2. The volume fraction of *hcp* phase in the simulated AgInCd alloys as a function of the thermal neutron fluence.

$$\varphi_{hcp} = 1.025 - \frac{1.025}{1 + (x/20.716)^{2.57}} \quad (7)$$

where x is the thermal neutron fluence, $\times 10^{20}$ n/cm^2. Since there are only two phases in the simulated AgInCd alloys, the sum of volume fractions of *fcc* and *hcp* phases equals unit. Thus, the volume fraction of *fcc* phase can be expressed as:

$$\varphi_{fcc} = 1 - \varphi_{hcp} \quad (8)$$

For achieving the lattice parameters of *fcc* and *hcp* phases in the simulated AgInCd alloys as a function of the thermal neutron fluence, the X-ray diffraction (XRD, Philips X'Pert Pro MPD) tests were conducted for the six simulated AgInCd alloys in the diffraction range of 30°~85° and at least three different regions were examined for each AgInCd alloy to ensure the repeatability of lattice parameters. After the XRD testing, a fitting software (MDI Jade 5.5) was used to achieve the lattice parameters of *fcc* and *hcp* phases. During the fitting process, the *fcc* and *hcp* phases were indexed and their phase peaks could be extracted in the Jade software, then the lattice parameters could be fitted by using the function of WPF Refinement and Cell Refinement. Fig. 3 shows the fitting lattice parameter of *fcc* phase in the simulated AgInCd alloys as a function of the thermal neutron fluence. Generally, the lattice parameter a of *fcc* phase increases linearly with the increase of thermal neutron fluence. Through the linear fitting, the relationship between the lattice parameter of *fcc* phase and the thermal neutron fluence can be obtained:

$$a_{fcc} = 4.1486 + 2.153 \times 10^{-4}x \quad (9)$$

Similarly, the lattice parameter a and lattice parameters c of *hcp* phase also increase linearly with the increase of thermal neutron fluence, as shown in Fig. 4. The relationship between the lattice parameters of *fcc* phase and the thermal neutron fluence can be fitted by the linear fitting:

$$a_{hcp} = 2.9567 + 6.433 \times 10^{-4}x \quad (10)$$

$$c_{hcp} = 4.7891 + 2.2422 \times 10^{-4}x \quad (11)$$

4. Calculating results and verification of model

According to the developed model for calculating the irradiation swelling of AgInCd absorber and the crystallographic parameters obtained by experiment, the diametral irradiation swelling rate of AgInCd absorber in nuclear control rods can be quantitatively calculated. Fig. 5 shows the calculating results of diametral irradiation swelling rate of AgInCd absorber as a function of the thermal neutron fluence, and the actual swelling data in literature are also presented in this figure for comparison. It can be found that the calculation results of irradiation swelling rate is located in the middle region of the actual swelling data in Refs. [20–25], indicating that the calculating model of irradiation swelling of AgInCd absorber has a good accuracy.

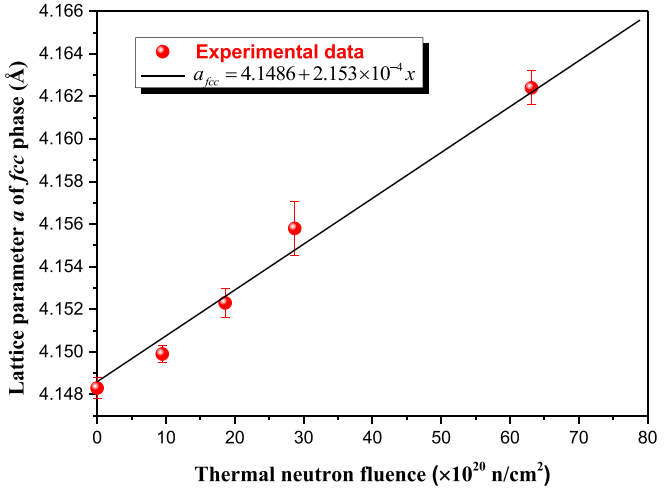

Fig. 3. The lattice parameter of *fcc* phase in the simulated AgInCd alloys as a function of the thermal neutron fluence.

In general, the irradiation swelling rate of AgInCd absorber increases gradually with the increase of thermal neutron fluence. The increase of irradiation swelling can be mainly attributed to two reasons. Firstly, as mentioned above, the total number of heavy atoms in the AgInCd absorber remains unchanged during the transmutation process, the atomic number density (number of atoms per unit volume) of phases in the AgInCd absorber directly determines the volume of AgInCd absorber. According to the fundamentals of materials science [19], the atomic number densities of *fcc* and *hcp* phases are $\frac{4}{a_{fcc}^3}$ and $\frac{4\sqrt{3}}{3a_{hcp}^2 c_{hcp}}$, respectively. Combining with formulas (9)~(11), the atomic number densities of *fcc* and *hcp* phases in the AgInCd absorber as a function of the thermal neutron fluence can be graphed, as presented in Fig. 6. Obviously, the atomic number densities of both *fcc* and *hcp* phases decrease linearly with the increase of thermal neutron fluence. As a result, the volume of AgInCd absorber increases accordingly with the thermal neutron fluence.

Secondly, it can also be seen from Fig. 6 that the atomic number density of *hcp* phase is notably smaller than the *fcc* phase, and the atomic density differences are further enhanced with the increase of thermal neutron fluence. On the other hand, the volume fraction of *hcp* phase increases and the *fcc* phase decreases with the increase of thermal neutron fluence, as shown in Fig. 2. Consequently, the irradiation swelling rate of AgInCd absorber increases gradually with the increase of thermal neutron fluence.

In previous studies [2,26], the irradiation swelling rate of AgInCd absorber was generally considered to be a linear relationship with the thermal neutron fluence. For example, Strasser and Yario [2] recommended that the swelling rate of AgInCd absorber was 0.5% per 1×10^{21} n/cm^2 of neutron fluence, as presented by the dashed line in Fig. 5. However, the calculation results of the present model do not have a linear relationship with the thermal neutron fluence, especially when the thermal neutron fluence is within 3.0×10^{21} n/cm^2, as shown in Fig. 5. The main reason for this discrepancy is due to the fast increase in the volume fraction of *hcp* phase in the AgInCd absorber when the thermal neutron fluence is in the range of 9.5×10^{20} n/cm^2 to 2.85×10^{21} n/cm^2, as shown in Fig. 2. In fact, the nonlinear relationship between swelling rate and the thermal neutron fluence is in better agreement with the actual swelling data in literature than the linear relationship.

In addition, Electric Power Research Institute (EPRI) report [27] presents that there is an acceleration in the diametral swelling rate of AgInCd absorber with the thermal neutron fluence above 6–8 $\times 10^{20}$ n/cm^2, and then a decrease in the diametral swelling rate above about 2 $\times 10^{21}$ n/cm^2. EPRI researcher took the attitude that the acceleration of the diametral swelling rate of AgInCd absorber was mainly ascribed to the absorber thermal creep [27]. As mentioned previously, the swelling rate induced by creep deformation should be relatively stable during service, because the compressive force and gravity suffered by the AgInCd absorber will not change significantly during the whole service process. Therefore, attributing the acceleration of diametral swelling rate above 6–8 $\times 10^{20}$ n/cm^2 to the thermal creep of AgInCd absorber is relatively far-fetched.

It is exciting that the present model can well explain the EPRI results of the acceleration in the diametral swelling rate above 6–8 $\times 10^{20}$ n/cm^2 and then the decrease in the diametral swelling rate above about 2 $\times 10^{21}$ n/cm^2. Fig. 7 illustrates the second order derivative of diametral irradiation swelling rate of AgInCd absorber with respect to the thermal neutron fluence, i.e. $\frac{d^2\varphi}{dx^2}$. It can be seen that the value of $\frac{d^2\varphi}{dx^2}$ is positive when the thermal neutron fluence is below about 1.8×10^{21} n/cm^2 and

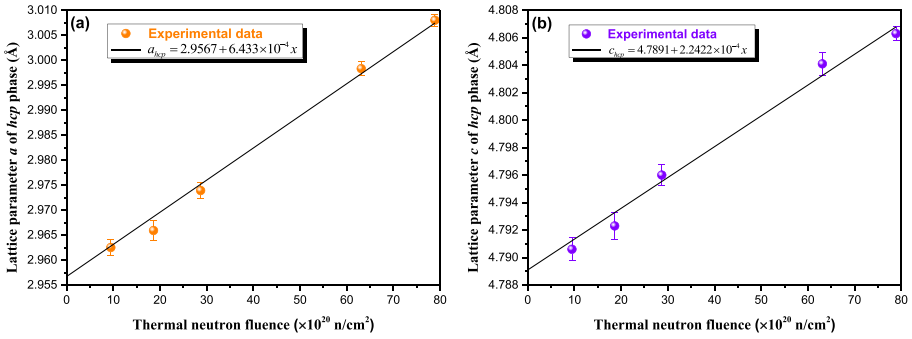

Fig. 4. The (a) lattice parameter *a* and (b) lattice parameter *c* of *hcp* phase in the simulated AgInCd alloys as a function of the thermal neutron fluence.

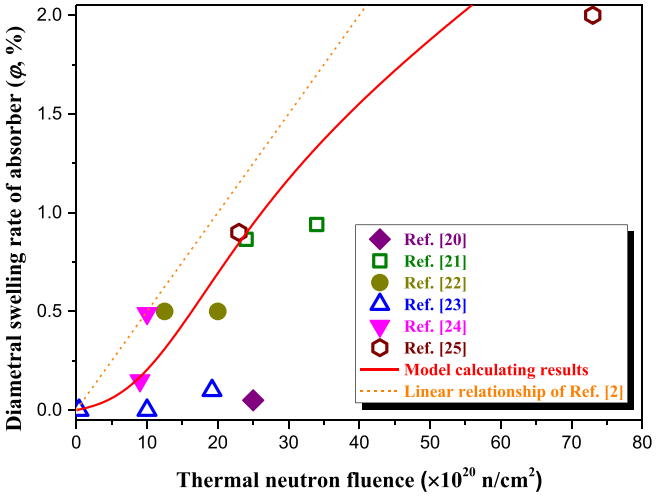

Fig. 5. The calculating results of diametral irradiation swelling rate of AgInCd absorber and the actual swelling data in literature. Noting that some diametral swelling data ($\Delta\varphi$) are converted from the volume swelling data (ΔV) in literature by the approximate double relationship for the restrained swelling ($\Delta V \approx 2\Delta\varphi$) or the triple relationship for the unrestrained swelling ($\Delta V \approx 3\Delta\varphi$).

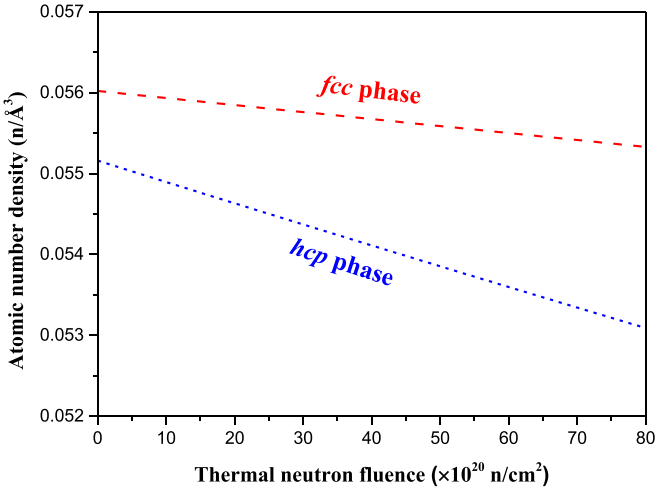

Fig. 6. The atomic number densities of *fcc* phase and *hcp* phase in the AgInCd absorber as a function of the thermal neutron fluence.

this value reaches the maximum value at a neutron fluence of ~7.5 × 10^{20} n/cm^2. These calculated results are in well accordance with the acceleration in the diametral swelling rate with the thermal neutron fluence above 6–8 × 10^{20} n/cm^2. When the thermal neutron fluence is

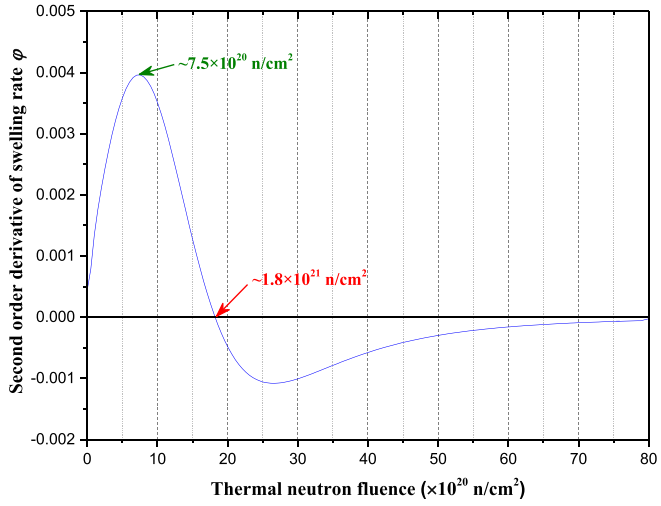

Fig. 7. The second order derivative of diametral irradiation swelling rate of AgInCd absorber with respect to the thermal neutron fluence.

higher than about 1.8 × 10^{21} n/cm^2, the value of $\frac{d^2\varphi}{dx^2}$ turns negative, indicating the curve of diametral irradiation swelling rate is convex upward above about 1.8 × 10^{21} n/cm^2, This result also coincides with the decrease in the diametral swelling rate above about 2 × 10^{21} n/cm^2. Considering the fact that the lattice parameters of *fcc* and *hcp* phases increase almost linearly with the change of thermal neutron fluence in the present model, the first acceleration and subsequent decrease in the diametral swelling rate should be mainly related to the volume fraction of *hcp* phase. As shown in Fig. 2, the volume fraction of *hcp* phase increases rapidly when the neutron fluence exceeds ~7 × 10^{20} n/cm^2 and its increase rate slows down when the neutron fluence exceeds ~2 × 10^{21} n/cm^2, resulting in the acceleration in the diametral swelling rate above 6–8 × 10^{20} n/cm^2 and the decrease in the diametral swelling rate above about 2 × 10^{21} n/cm^2.

Overall, both the calculating swelling rate results and their trend transition values of the present model are in good agreement with the actual swelling data of AgInCd absorber. It can be expected that this model is conducive to the accurate understanding the relationship between the irradiation swelling of AgInCd absorber and the thermal neutron fluence, which can be adopted to predict the service lifetime of AgInCd control rods. It is worth noting that the chemical compositions of AgInCd absorber are inhomogeneous and change along the radius of absorber in the real control rods due to the neutron flux attenuation from absorber surface to interior [12,16], while we prepare the simulated AgInCd alloys with homogeneous compositions according to the average chemical compositions of AgInCd absorber in the present model. There must be a certain difference between the present established model and the real situation. Considering the complexity of the

real situation in pile, including but not limited to the real-time changes of thermal neutron flux and the redistribution of chemical compositions of AgInCd absorber drove by the irradiation-enhanced diffusion, it is difficult to establish a model that is fully consistent with the real situation to calculate the swelling of AgInCd absorber. The calculating model that takes into account the inhomogeneous compositions of AgInCd absorber can be further developed in the future.

5. Conclusions

In the present study, a model for calculating the irradiation swelling of AgInCd absorber in nuclear control rods is developed according to the chemical and microstructural changes of AgInCd absorber during the irradiation process.

(1) The present model is established on the basis of that the total number of heavy atoms in the AgInCd absorber remains unchanged during the transmutation process. The volume fraction and lattice parameters (crystallographic parameters) of *fcc* and *hcp* phases in the AgInCd absorber are firstly obtained, then the volume of AgInCd absorber after neutron irradiation and the irradiation swelling of AgInCd absorber can be calculated.
(2) For achieving the relationship between the crystallographic parameters and the thermal neutron fluence, the simulated AgInCd alloys are prepared according to the calculated chemical compositions of AgInCd absorber. Subsequently, the crystallographic parameters of *fcc* and *hcp* phases in the simulated AgInCd alloys as a function of the thermal neutron fluence are obtained by fitting the experimental data of the simulated AgInCd alloys.
(3) The model calculating results of irradiation swelling are in good agreement with actual swelling data in literature. More importantly, the present model can well explain the EPRI results of the acceleration in the diametral swelling rate above 6–8 $\times$ 10^{20} n/cm^2 and the decrease in the diametral swelling rate above about 2 $\times$ 10^{21} n/cm^2. Both of the actual swelling data and EPRI results can effectively verify the reliability of the present model of irradiation swelling.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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