Research paper

Boron-10 stimulated helium production and accelerated radiation displacements for rapid development of fusion structural materials

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1. Introduction

Harnessing fusion power is the holy grail of energy science and engineering and may be the key to space explorations and climate adaptation. Deuterium-tritium fusion in a burning plasma, the most promising route, produces 3.5 MeV helium ions and 14.1 MeV neutrons. Neutrons are much more deeply penetrating in materials than ions and electrons, which is both a blessing and a curse. On one hand, this allows (a) energy transfer to a coolant and (b) neutron capture in fusion reactor core. On the other hand, this fast neutrons streaming through such vacuum vessel (VV) would cause not only massive displacement damages for rapid development of fusion structural materials

Boron doping, combined with neutron capture in fission reactors, has been used to simulate the helium effect on fusion structural materials. However, inhomogeneous helium bubble formation was often observed due to boron segregation to grain boundaries. The excess radiation displacements due to $^{10}$B(n, α) reaction, the high-energy lithium and helium ions, also were not accounted for, which can significantly accelerate the displacements-per-atom (dpa) accumulation alongside helium production (appm). Hereby an isotopically pure $^{10}$B doping approach is proposed to simulate the extreme environment inside fusion reactors with a high He appm-to-dpa ratio of about 10, which is about $10^2$ larger than in fission reactors. Computational modeling showed that ~13% of total radiation displacement was induced by $^{10}$B(n, α)$^7$Li in the case of 1 000 appm $^{10}$B doped Fe samples, which becomes even greater with increasing $^{10}$B loading. Spatially homogenous radiation damage and helium generation are predicted for grain sizes less than 1 μm, even if the boron partially formed precipitates or segregates on grain boundaries. Feasibility studies with various $^{10}$B doping (and $^{235}$U-codoping) levels in research reactors showed the estimated helium generation and radiation damage would significantly mimic fusion conditions and greatly expedite fusion materials testing, from many years down to months. © 2023 Published by Elsevier B.V. on behalf of The Chinese Ceramic Society. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/)
qualify novel structural materials that can survive thousands of appm (He) [7] and hundreds of dpa of radiation displacements, in order to ensure a few years of full-power-operations—the minimum for economic fusion power generation. However, the lack of high-flux fast neutrons for materials testing leads to a chicken-and-egg problem. On one hand, we do not yet have full confidence that any materials available today can survive thousands of appm (He) with hundreds of dpa at ≥600°C in contact with corrosive coolants. On the other hand, the lack of such materials also impedes the establishment and safe operation of such sources. As background, fast-neutron sources are difficult to come by. At present, Russia operates BN-600 and BN-800 fast neutron reactors, China operates China Experimental Fast Reactor (CEFR), all liquid sodium cooled, but there is no fast neutron fission reactor operating in Europe and the Americas. Currently, there is no facility anywhere in the world that can provide a neutron energy spectrum and fluence close to economic fusion power reactor conditions. The test facility for fusion neutron sources, such as the proposed International Fusion Materials-Irradiation Facility (IFMIF) and Advanced Fusion Neutron Source (A-FNS) are not expected to be available for more than 10 years. To simulate the 14.1 MeV-neutron effects on fusion reactor materials, experimental techniques such as multi-ion beam irradiation [8,9], spallation neutron sources [10,11], boron doping [12–19], and nickel doping [20–22] have been proposed.

The boron doping approach has been used to accelerate helium production by boron-neutron capture \(^{10}\text{B}(n, \alpha)\) reactions using softer-spectrum neutrons, which are much more broadly available at fission reactors around the world, for example, the MIT Nuclear Research Reactor (MTR), the High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory, and commercial fission power reactors. \(^{10}\text{B}\) has an exceptionally high thermal neutron capture cross-section of 3,840 b, thus \(^{10}\text{B}\) produces helium 10\(^5\) times faster under thermal neutrons than Fe under fast neutrons. Chemically pre-doping of material under investigation by \(^{10}\text{B}\) can greatly boost radiation damage and helium concentrations induced by \(^{10}\text{B}(n, \alpha)\) reactions in pure iron were estimated based on computer simulations using the Stopping and Range of Ions in Matter (SRIM-2013) code with the full cascades damage energy method, which provides the highest accuracy for vacancy production [26,27]. The vacancy production was calculated using the damage energy method given in Eqn. (1) with recommended displacement threshold energy (40 eV for Fe and 90 eV for W) and lattice binding energy (5.8 eV for Fe and 13.2 eV for W) [27,28].

\[
\rho_{\text{NRT}} = 0.87 \frac{T_{\text{damp}}}{E_d} \quad T_{\text{damp}} = E_{\text{ioniz}} - E_{\text{recoil}}
\]

where \(\rho_{\text{NRT}}\) is the Norgett, Robinson, and Torrens (NRT) displacements, \(T_{\text{damp}}\) is the damage energy, \(E_d\) is the displacement threshold energy, \(E_{\text{recoil}}\) is the energy absorbed by recoils, and \(E_{\text{ioniz}}\) is the ionization energy loss of the recoil ions.

3. Results and discussion

3.1. Radiation damage and helium distribution induced by \(^{10}\text{B}(n, \alpha)\) \(^{7}\text{Li}\) reactions

The usage of \(^{10}\text{B}(n, \alpha)\) \(^{7}\text{Li}\) reactions can accelerate not only helium production but also radiation damage induced by highly energetic Li and He product nuclei, as shown in Fig. 1. Unlike nickel doping which produces long-lived radio-isotopes, no long-lived radioactive elements are produced from boron transmutation, which makes it relatively easy to handle after the neutron irradiation (One does need to consider the effect of thermal neutron transmutation on the base material, for example, \(^{13}\text{C}(n, \gamma)\) \(^{14}\text{C}\), as the natural abundance of carbon-13 is ~1% and carbon-14 has a half-life of 5,730 years). There are two types of \(^{10}\text{B}(n, \alpha)\) \(^{7}\text{Li}\) reactions that emit MeV-scale Li and He ions as given in Eqn. (2).

\[\text{Neutron} \rightarrow \text{Li} \rightarrow \text{He} \quad \text{He} \rightarrow \text{Li} \rightarrow \text{He} \]

\[\text{Li} \rightarrow \text{He} \rightarrow \text{Li} \rightarrow \text{He} \]

\[^{10}\text{B}\] has a negligible thermal neutron capture cross-section of 0.005 b. \(^{10}\text{B}\) and \(^{11}\text{B}\) has natural abundance of 19.8% and 80.2%, respectively, thus using enriched \(^{10}\text{B}\), which is commercially available, would give 5 × speedup and dose rate. This way, we can shorten the radiation campaign to much less than a year, while still reaching thousands of appm (He) and hundreds of dpa, thus allowing greatly accelerated fusion structural materials selection and optimization.

![Fig. 1. Schematic illustration of \(^{10}\text{B}\) doping methodology to simulate helium production and dpa accumulation (Not to scale). Note that the outgoing Li (blue) and He (red) ions have spherically random momenta, unlike the energetic ions produced by ion accelerators, thus mitigating potential polarization artifacts [29].](image-url)
benefit of the dpa generation by Eqn. (2) is that the radiation damages are isotropic, unlike that created with accelerator-driven ion beam where the high momentum monodispersity can create polarization artifacts and vacancy-interstitial imbalances in the typical 1D geometry [29].

\[
\begin{align*}
5^{10}\text{B} + ^{1}\text{n}_{\text{thermal}} & \rightarrow (94\%) \ 2\text{Li}^{3+} (0.840 \text{ MeV}) + 4\text{He}^{2+} (1.470 \text{ MeV}) + \gamma (0.48 \text{ MeV}) \\
& \rightarrow (6\%) \ 3\text{Li}^{3+} (1.015 \text{ MeV}) + 4\text{He}^{2+} (1.777 \text{ MeV})
\end{align*}
\] (2)

The depth-dependent vacancy production in pure iron was calculated using the full cascades damage energy method as shown in Fig. 2. Since 94% of \(^{10}\text{B} (n, \alpha)^{7}\text{Li}\) reactions emit 0.84 MeV Li and 1.47 MeV He ions, the radiation damage was mostly induced by 0.84 MeV Li ions below 1.5 \(\mu\)m penetration radius, and 1.47 MeV He ions (Fig. 2(a)) in the region from 1.5 \(\mu\)m to 2.5 \(\mu\)m, where the peak radiation damage was below 40% of that of Li ions. The radiation damage in tungsten (Fig. 3) was lower than that of iron due to higher displacement energy \((E_d = 40 \text{ eV for Fe and 90 eV for W})\) and lattice binding energy \((5.8 \text{ eV for Fe and 13.2 eV for W})\).

Note that Figs. 2 and 3 are produced from SRIM simulation which assumes a 1D geometry where the “Depth” \(x\) is aligned with the initial ion (\(^4\text{He} or \ ^7\text{Li}\)) momentum, and the distribution of Frenkel pair, helium deposition, etc. are described by a 1D distribution \(dP = \rho(x) dx, x = [0, \infty]\) shown in these figures. As illustrated in Fig. 1, however, since the initial ion momenta are spherically random within 4\(\pi\) solid angle, the actual distribution of vacancy concentration etc. will be a spherical distribution, \(dP = \rho_{\text{radial}}(r) 4\pi r^2 dr, r = [0, \infty]\). Even though numerically \(r = x\), the radial fan-out would induce a transformation:

\[
\rho(x) dx = \rho(r) dr = \rho_{\text{radial}}(r) 4\pi r^2 dr
\] (3)

so we obtain

\[
\rho_{\text{radial}}(r) = \rho(r) \sqrt{4\pi r^2}
\] (4)

and therefore if there is a single emission source embedded in the 3D matrix like a stationary boride particle, the \(\rho_{\text{radial}}(r)\) distribution can have two peaks, one at \(r = 0\) where \(\rho_{\text{radial}}(r = 0)\) turns singular as \(r^{-2}\) due to finite \(\rho(x = 0)\) shown in Figs. 2 and 3, and the other peak will occur at \(r_{\text{peak}}>0\) but with \(r_{\text{peak}} < r_{\text{peak}} \equiv \text{argmax} \rho(x)\). That is, the peak damage and helium concentration will occur closer to the boride particle than the standard “Bragg peak” in 1D geometry. This effect is illustrated in Fig. 4.

\[
\begin{align*}
\text{Fig. 2. SRIM-calculated vacancies production induced in iron (a) by 94\% of } ^{10}\text{B}(n, \alpha)^{7}\text{Li reactions (b) by 6\% of } ^{10}\text{B}(n, \alpha)^{7}\text{Li reactions.}
\end{align*}
\]
Fig. 3. SRIM-calculated vacancies production induced in tungsten (a) by 94% of $^{10}\text{B}(n, a)^7\text{Li}$ reactions (b) by 6% of $^{10}\text{B}(n, a)^7\text{Li}$ reactions.

Fig. 4. Peak damage region of 1D ($x_{\text{peak}}$) and 3D ($r_{\text{peak}}$) geometry induced by $^{10}\text{B}(n, a)^7\text{Li}$ reactions in (a) iron (b) tungsten.

Fig. 5. Ion distribution of He and Li ions emitted from $^{10}\text{B}$ particles in iron with an average grain size of 1 $\mu$m.

Fig. 6. Phase diagram of Fe-B [32] (taken with permission from the publisher).
at 910 °C and 200 wppm in γ-iron at 1149 °C, corresponding to 418 appm and 1,032 appm, respectively (Fig. 6) [30]. The relatively low boron solubility in iron is considered due to its atomic diameter of 1.8 Å, which is not only too small for the substitutional position in iron (2.52 Å) but also too large for the interstitial site (octahedral interstitial site in α-iron = 0.38 Å and octahedral interstitial site in γ-iron = 1.085 Å) [31].

There are several ways for enhancing boron solubility in Fe-based alloys. Using metallic alloying elements such as chromium, vanadium, and molybdenum can expand the iron lattice to allow boron atoms to occupy the interstitial sites [33]. Since reduced activation ferritic/martensitic (RAFM) steels, one of the candidate structural materials for fusion reactors, have 8%–9% (in mass) Cr and 0.15%–0.25% (in mass) V, the boron solubility of RAFM will be expected to be higher than that in pure iron. Out-of-equilibrium effects in irradiated materials such as radiation-induced mixing, vacancy production, and vacancy-induced precipitate dissolution could also enhance the “dynamic” boron solubility and allow homogeneous helium and radiation damage generation during neutron irradiation [34,35].

### 3.3. Neutron irradiation at HFIR

Since 10B has an extremely high neutron capture cross-section of 3840 b for thermal neutron, neutron irradiation in a thermal reactor such as the HFIR and Petten High Flux Reactor will result in complete transmutation of 10B within ~1 dpa [17,36]. The vacancy productions per each ion (Li and He) were calculated in iron and tungsten, considering the reaction probability as shown in Table 1. For example, each Li and He ion would knock out 210 and 76 iron atoms from their original lattice site, respectively. A single 10B(n, α)7Li reaction in the iron, therefore, would produce 286 displacements and one helium gas atom, corresponding to 3,491 He appm/dpa. This could be used to control the ratio of helium production to radiation damage (appm/dpa) in neutron irradiation by changing the 10B concentration.

The neutron irradiations of Fe and W doped with various 10B concentrations at HFIR were computationally designed to mimic fusion conditions as shown in Table 2. The calculation was conducted based on one-cycle neutron irradiation (25 days) with a fast neutron flux of 1.2 × 10^{15} (n/(cm^2-s)) and a thermal neutron flux of 2.4 × 10^{15} (n/(cm^2-s)) [37]. The radiation damage induced by fast neutron (>0.1 MeV) was calculated based on the previous studies [38,39]. The radiation damage induced by 10B(n, α)7Li reactions was almost negligible at the low 10B concentrations well matched to previous studies. However, considerable radiation damage was produced with increasing 10B concentration (~13% of total radiation damage was induced by 10B(n, α)7Li reactions in case of 1,000 appm 10B doped Fe), which becomes even greater with increasing 10B loading. These results showed that the radiation damage induced by He and Li ions should be considered to reduce errors in the dpa estimation.

Simulations of 10B-doped iron showed the possibility of massive helium production, but additional radiation source is necessary to expedite radiation damage to hundreds of dpa, appropriate for fusion conditions. To maximize the radiation damage during neutron irradiation with ppm-level concentration, 235U co-dopants could be added to 10B doped iron. The radiation damage induced by fission reaction was estimated using SRIM simulations with following assumptions. The vacancies induced by gamma ray, fission neutron, and beta particles from 235U fission were ignored, considering low energy (<10 MeV) compared to fission fragments (~168 MeV). The fission fragments were assumed to be 95Kr and 137Ba, the most probable fragment masses. The fissions per initial fissile atoms (FIFA) was estimated to be 14.5% during one-cycle neutron irradiation in HFIR considering the fission cross section of 235U (ENDF/B-VIII.0). The SRIM simulation on 235U-codoped iron showed that each 95Kr and 137Ba ion would knock out 24,374 and 45,243 iron atoms, respectively. For example, the radiation damage of iron doped with 1,000 appm 235U could achieve ~10 dpa after the one-cycle neutron irradiation in HFIR. The radiation damage (~100 dpa) and helium production (~1,000 appm) for Fe-based fusion structural materials could be achieved by the neutron irradiation of iron doped with 1,000 appm 10B and 9,700 appm 235U as shown in Table 2. The irradiation tests for W-based fusion materials were also computationally designed to mimic the fusion conditions (~26 dpa, ~13 He appm) [40].

Fig. 7(a) shows the total radiation damage and helium generation of neutron-irradiated iron at HFIR with various 10B concentrations after the one-cycle irradiation. It should be noted that 10B does not produce radiation damage and He continually during the neutron irradiation. The half-life of burnt 10B was estimated to be 0.9 days, which suggests that most helium and radiation damage generation will occur at the very beginning of neutron irradiation. This initial concentrated generation could be mitigated by using a thermal neutron shielding such as a EuO2-shield capsule that can slow down the transmutation closer to a fusion reactor condition as maintaining the amount of radiation damage and helium generation after the neutron irradiation [35]. The boron-10 doping combined with 235U co-doping can shorten the radiation campaign to less than 2 months as shown in Fig. 8(a), while still reaching thousands of appm (He) and hundreds of dpa. Therefore, our proposed methodology can greatly reduce the time and cost of neutron irradiation tests for fusion reactor materials, which can greatly accelerate fusion structural materials selection and optimization.

### 3.4. Neutron irradiation at MITR

The fast neutron (E > 0.1 MeV) flux and thermal neutron flux of MITR are 1.3 × 10^{14} n/(cm^2-s) and 3.4 × 10^{13} n/(cm^2-s), respectively. The thermal neutron fluence of MITR (1.3 × 10^{20} n/cm^2) is much lower than that of HFIR (5.2 × 10^{21} n/cm^2), which would not transmute all 10B after the one-cycle irradiation (45 days). The burn-up of 10B isotope under neutron irradiation (F) was estimated to be ~0.4 using Eqn. (3) [41].

\[
F = 1 - \exp(-\sigma_t \phi_{th} t)
\]  

where \(\sigma_t\) is the thermal neutron capture cross-section of 10B, \(\phi_{th}\) is the thermal neutron flux at MITR, and \(t\) is the irradiation time.

The radiation damage induced by both neutron and 10B(n, α)7Li reactions for one cycle in MITR is relatively low than HFIR, which suggests higher 235U and 10B dopant concentrations is required as shown in Table 3. The 10B and 235U doping methodology can greatly enhance the irradiation capability of MITR by 500 times (from 0.008 dpa/day to ~4 dpa/day) with hundreds appm of helium production, as shown in Fig. 8(b), which allows rapid investigation of helium effect on fusion structural materials.

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**Table 1**

<table>
<thead>
<tr>
<th></th>
<th>Fe</th>
<th>W</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vacancies per Li ion</td>
<td>210</td>
<td>84</td>
</tr>
<tr>
<td>Vacancies per He ion</td>
<td>76</td>
<td>26</td>
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<tr>
<td>Total displacements</td>
<td>286</td>
<td>110</td>
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<tr>
<td>He appm/dpa</td>
<td>3,491</td>
<td>9,072</td>
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</table>
Table 2
Helium generation and radiation damage of $^{10}$B-doped Fe and W irradiated at HFIR for 25 days.

<table>
<thead>
<tr>
<th>Material</th>
<th>Dopant concentration (appm)</th>
<th>He generation (appm)</th>
<th>Radiation damage (dpa)</th>
<th>He appm/dpa</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$^{10}$B</td>
<td>$^{235}$U</td>
<td>Neutron (&gt;0.1 MeV)</td>
<td>$^{10}$B(n, α)$^7$Li Fission reaction</td>
</tr>
<tr>
<td>Fe</td>
<td>1,000</td>
<td>0</td>
<td>1,000</td>
<td>1.9</td>
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<td></td>
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<td></td>
<td>10.0</td>
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<td>98.0</td>
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<tr>
<td>W</td>
<td>13</td>
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<td>13</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
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<td>13</td>
<td></td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>4,000</td>
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<td>25.0</td>
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</table>

Fig. 7. Radiation damage production and helium production of iron doped with various $^{10}$B (a) neutron irradiation at HFIR (the half-life of burnt $^{10}$B was ~0.9 days) (b) neutron irradiation at MITR (the half-life of burnt $^{10}$B was ~61.4 days).

Table 3
Helium generation and radiation damage of $^{10}$B-doped Fe and W irradiated at MITR for 45 days.

<table>
<thead>
<tr>
<th>Material</th>
<th>Dopant concentration (appm)</th>
<th>He generation (appm)</th>
<th>Radiation damage (dpa)</th>
<th>He appm/dpa</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$^{10}$B</td>
<td>$^{235}$U</td>
<td>Neutron (&gt;0.1 MeV)</td>
<td>$^{10}$B(n, α)$^7$Li Fission reaction</td>
</tr>
<tr>
<td>Fe</td>
<td>2,600</td>
<td>0</td>
<td>995</td>
<td>0.4</td>
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<tr>
<td></td>
<td>2,600</td>
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<td></td>
<td>32</td>
<td>11,000</td>
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<td>26.0</td>
</tr>
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</table>

Fig. 8. Radiation damage production and helium production of iron doped with $^{10}$B and $^{235}$U (a) neutron irradiation with 9700 appm $^{235}$U at HFIR (b) neutron irradiation with 26,000 appm $^{235}$U at MITR.
3.5. Design of doping methodology

Fig. 9 shows the envisioned flow chart of the boron doping technique to investigate the effects of helium concentration on material properties. First, the $^{10}$B concentration will be determined based on the ratio of helium production to radiation damage. Since the radiation damage induced by neutron and $^{10}$B$(n, \alpha)^7$Li reactions in the research reactor is not enough to emulate the fusion environment, additional sources for radiation damage such as $^{235}$U will be necessary to achieve the target radiation damage.

The fabrication of uniformly dispersed $^{10}$B in iron and tungsten is the key step to simulating the homogenous helium production and radiation damage since discrete halos were often observed around $^{10}$B rich precipitates after neutron irradiation [17]. Arc melting could be utilized, which showed no B precipitates observed even though the B concentration exceeds the solubility limit in the iron (500 appm at the 1,050 °C annealing temperature) [11]. Other methods such as 3D printing can also be considered. The microstructure of fabricated alloys will be observed to confirm the presence of boron precipitates. Mechanical properties will be measured not only to investigate the dopant effect but also to compare the properties before and after the neutron irradiation.

420 stainless steel (420 SS) powders were provided from Höganäs. The particle size ranges from 20 to 63 μm. $^{10}$B powders with average particle diameter 200 μm were purchased from American Elements. Large $^{10}$B particles were ball-milled in a Fritsch Pulverisette 7 using 5 mm diameter of stainless steel balls and vials (ball to powder ratio of 5) for 15 h in order to reduce their particle size before blending them with 420 SS powders. Afterwards, $^{10}$B powders were mixed with 420 SS powders to form a mixture of 2 600 appm $^{10}$B and blended in batches of 500 g in a high-speed blender (VM0104, Vita-Mix, USA) for 90 min. $^{10}$B doped 420 SS composite powders were printed via laser powder bed fusion (LPBF) using a commercial system (EOS M290) as shown in Fig. 10. The parameter set was determined based on data from previously published LPBF study of AISI 420 [42].

$^{10}$B-doped samples and $^{11}$B-doped samples will be irradiated at thermal research reactors to separate the effect of chemistry modification from irradiation effects. Since the thermal neutron flux of HFIR is high enough to transmute all $^{10}$B at the very beginning of neutron irradiation, thermal neutron shielding capsules for samples could be utilized to slow down the transmutation, closer to the fusion reactor environment [34].

The microstructure of the irradiated sample will be characterized using transmission electron microscopy (TEM) and atom probe tomography (APT) to confirm the homogenous helium bubble formation. The size and density of helium bubbles will be measured after the irradiation [43]. Tensile tests will be also conducted to investigate the effect of helium on strength or ductility. By this approach, we should be able to shorten the irradiation campaigns to achieve rapid helium generation and expedite fusion materials testing from many years down to months or even days.

4. Conclusion

The isotopically pure $^{10}$B doping methodology on iron and tungsten was proposed to simulate the extreme environments inside fusion reactors with a high He appm-to-dpa ratio. Computational modeling of the radiation damage showed that a single $^{10}$B$(n, \alpha)^7$Li reaction can produce 286 displacements in iron and 110 displacements in tungsten corresponding to 3,491 He appm/dpa and 9,072 He appm/dpa, respectively. Considerable radiation displacement was induced by $^{10}$B$(n, \alpha)^7$Li reactions (>10% total radiation displacements in 1,000 appm $^{10}$B doped Fe samples), which becomes even greater with increasing $^{10}$B concentration. Therefore, the radiation damage induced by Li and He ions should be considered to minimize the errors in the dpa estimation.

The boron segregation to grain boundaries, the main problem of previous boron doping, could be overcome by more homogenous distribution of $^{10}$B. Spatially homogenous radiation damage and helium generation were expected for grain sizes less than 1 μm, even if the boron partially formed precipitates or segregates on grain boundaries. Several factors such as metallic alloying, radiation-induced mixing, and vacancy-induced precipitate dissolution could also suppress boron segregation in iron and tungsten.

Feasibility studies on neutron irradiation with various $^{10}$B concentrations in fission research reactor were performed to estimate helium generation and radiation damage. One-cycle neutron irradiation at HFIR showed that a complete burn-up of $^{10}$B could be achieved, although the burn-up after the one-cycle at MITR was estimated to be ~40%. The simulation results showed that the $^{10}$B and $^{235}$U doping methodology in both HFIR and MITR can simulate
the extreme environment of fusion structural materials with high displacement rate (~4 dpa/day) and helium production rate (hundreds of appm/day). This proposed method would closely mimic fusion conditions and can greatly expedite fusion materials testing from many years down to months or even days, which can accelerate the design and qualification of fusion structural materials.

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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