Post-irradiation moderate-temperature annealing achieves synergistic recovery of microstructure and mechanical properties of the white bright band in SA508-3/52(M) dissimilar joints

Authors: Li, Mr. Chuanzong, Tian, Miss Ziyu, Chen, Prof. Junmei, Xu, Prof. Jijin, Chen, Prof. Jieshi, Yu, Prof. Chun, Lu, Prof. Hao, Lu, Prof. Hao

Date: 2026-01-22T01:34:29+00:00

Abstract

Regarding the irradiation damage issue of dissimilar metal joints in nuclear power systems during long-term service, this study achieved synergistic recovery of microstructure and mechanical properties of the white bright band (WBB) in SA508-3/52(M) joints through post-irradiation moderate-temperature annealing. The evolution characteristics of helium bubbles in the WBB region were analyzed, and the regulatory mechanism of moderate-temperature annealing on the mechanical properties of the WBB was revealed. The results indicate that differences in the microstructure at the SA508-3/52 and SA508-3/52M joint interfacial region exhibit a pronounced influence on the evolution behavior of helium bubbles. Moderate-temperature annealing significantly reduces the hardness of the WBB by promoting dislocation annihilation, minimizing the irradiation defect density, and relieving residual stresses, effectively mitigating irradiation hardening. Simultaneously, the decreased number density resulting from helium bubble coarsening reduces brittle fracture sources at grain boundaries. Combined with the mechanism of crack propagation path complexification, it markedly lowers the swelling rate and enhances the fracture toughness of the WBB.

Full Text

Preamble

Post-irradiation moderate-temperature annealing achieves synergistic recovery of microstructure and mechanical properties of the white bright band in SA508-3/52(M) dissimilar joints Chuanzong Lia, Ziyu Tiana, Junmei Chena, Jijin Xua,

Jieshi Chena,b, Chun Yua, *Hao Lua* a Shanghai Key Laboratory of Materials Laser Processing and Modification, School of Materials Science and Engineering, Shanghai Jiao Tong University, Shanghai 200240, China b School of Materials Science and Engineering, Shanghai University of Engineering Science, Shanghai 201602, China *E-mail: yuchun1980@sjtu.edu.cn (Chun Yu); shweld@sjtu.edu.cn (Hao Lu)

Abstract

Regarding the irradiation damage issue of dissimilar metal joints in nuclear power systems during long-term service, this study achieved synergistic recovery of microstructure and mechanical properties of the white bright band (WBB) in SA508-3/52(M) joints through post-irradiation moderate-temperature annealing. The evolution characteristics of helium bubbles in the WBB region were analyzed, and the regulatory mechanism of moderate-temperature annealing on the mechanical properties of the WBB was revealed. The results indicate that differences in the microstructure at the SA508-3/52 and SA508-3/52M joint interfacial region exhibit a pronounced influence on the evolution behavior of helium bubbles. Moderate-temperature annealing significantly reduces the hardness of the WBB by promoting dislocation annihilation, minimizing the irradiation defect density, and relieving residual stresses, effectively mitigating irradiation hardening. Simultaneously, the decreased number density resulting from helium bubble coarsening reduces brittle fracture sources at grain boundaries. Combined with the mechanism of crack propagation path complexification, it markedly lowers the swelling rate and enhances the fracture toughness of the WBB.

Keywords: Dissimilar joint; White bright band; Helium ion irradiation; Moderate-temperature annealing; Helium bubbles; Nanoindentation

1. Introduction

In critical components such as the main piping, steam generators, and the safe end of the pressure vessel in the nuclear reactor, there are typically numerous dissimilar-metal joints [1-3]. These joints typically utilize SA508-3 low-alloy steel and 316L stainless steel, with 52/52M nickel-based alloy serving as the transition material for welding [4, 5]. During service, dissimilar joints are subjected to prolonged exposure to harsh conditions such as high temperatures, high pressures, and irradiation, their performance directly determines the operational safety of nuclear power plants. In reality, due to the significant differences in chemical composition and thermophysical properties among various welding materials, their bonding interface region tends to become the weakest link in dissimilar joints. It has been found that within a range of several tens of micrometers on the nickel-based alloy side of the SA508-3/52(M) interface, there often exists a band-like region parallel to the fusion line. This region, due to its excellent corrosion resistance, usually exhibits a smooth, bright white appearance under optical microscopy (OM), and it is therefore vividly referred to as the "white bright band (WBB)" [6-8]. The WBB, with its unique morphology and its special position at the joint interface, is generally regarded as a critical region that influences the overall performance of dissimilar joints.

In nuclear engineering, equipment exposed to long-term high-energy particle irradiation will undergo various microstructural changes and corresponding performance degradation [9].

Helium embrittlement and swelling at high temperatures, particularly helium bubbles formed directly through transmutation reactions (n, α), have been confirmed as the primary pathways for material irradiation degradation [10, 11]. For dissimilar metal joints in nuclear power plants that have already sustained irradiation damage, effectively repairing this damage to extend their service life poses a practical challenge in current engineering applications.

It is well known that heat treatment is an effective method for restoring material properties [12]. Post-irradiation annealing significantly alters the microstructure of irradiation damage, thereby inducing corresponding changes in the material' s mechanical behavior [13-15]. At different temperature ranges, the regulatory mechanisms of heat treatment on irradiation damage exhibit distinct variations. At temperatures below 300℃, the thermal activation energy is low and insufficient to drive long-range migration of helium atoms.

Helium bubbles and dislocation loops remain in a metastable state, exhibiting limited changes in size and number density, while mechanical property degradation induced by irradiation persists [11]. As temperatures rise to the intermediate range of 300-600°C, vacancy migration activity increases, helium bubbles tend to aggregate and grow, and partial dislocation loops are reduced through vacancy recombination [16, 17]. This process significantly alleviates irradiation hardening of the material, and the plasticity and toughness are restored to a certain extent. When the annealing temperature exceeds 600℃, most radiation-induced dislocation loops are absorbed via point-defect diffusion and rapidly reduced [18]. Helium bubbles grow rapidly at high temperatures [19, 20]. Although defect density and irradiation hardening are markedly reduced, enlarged helium bubbles cause volume swelling and form brittle fracture sources at grain boundaries [21]. Therefore, while high-temperature annealing improves plasticity and toughness, it also carries the risk of embrittlement due to helium bubble aggregation. Compared to the potential embrittlement risks of high-temperature annealing, moderate-temperature annealing after irradiation offers a more balanced performance optimization solution. However, for the two most common types of dissimilar metal joints at the safe end of nuclear reactor pressure vessels—with and without transition layers—the impact mechanisms of moderate-temperature annealing heat treatment on irradiation damage and mechanical properties in their interfacial regions, particularly within the WBB, remain poorly understood. Given that the WBB is a critical region affecting the overall performance of dissimilar joints, in-depth research on the repair mechanisms of its microstructure and mechanical properties after irradiation via moderate-temperature annealing is of profound scientific importance and engineering application value for enhancing the safety of nuclear power equipment.

This study primarily investigates the repair effect of moderate-temperature annealing on irradiation damage in the WBB of SA508-3/52(M) dissimilar joints following He ion irradiation. The interfacial region and WBB were comprehensively characterized using OM, scanning electron microscopy (SEM), electron backscatter diffraction (EBSD), and transmission electron microscopy (TEM). The repair mechanism of the microstructure of the WBB after irradiation through moderate-temperature annealing was analyzed in detail.

Additionally, nanoindentation tests were conducted on the WBB and its adjacent regions before and after heat treatment, and the effect of moderate-temperature annealing on the mechanical properties of the dissimilar joint WBB region was discussed. The results of this study provide reliable experimental and theoretical support for improving the service performance and damage repair of dissimilar metal joints in key components of nuclear power plants.

2.1 Joint preparation

The dissimilar metal welding used in this study involves multiple materials, including SA508-3 low-alloy steel, 52 nickel-based alloy, 52M nickel-based alloy, and 316L austenitic stainless steel. The above materials were provided by Shanghai Electric Nuclear Power Equipment Co., Ltd. Their chemical compositions are shown in Table 1 .

Table 1 Chemical composition of base and filler metals (wt.%).

Alloy SA508-3 Joints without transition layers (SA508-3/52) directly join SA508-3 low-alloy steel and 316L stainless steel using 52 nickel-based alloy welding wire. For joints with a transition layer (SA508-3/52M), first build up the SA508-3 base metal surface with 52M nickel-based alloy, then use 52 welding wire to join the transition layer to the 316L stainless steel.

Schematic diagrams of SA508-3/52 and SA508-3/52M are depicted in Fig. 1 Figure 1: see original paper.

2.2 He ion irradiation and moderate-temperature annealing

The He ion irradiation experiments were conducted at the Shanghai Institute of Applied Physics, Chinese Academy of Sciences (SINAP-CAS), using a 4 MV pelletron accelerator.

The SA508-3/52(M) joints were irradiated by 4 MeV He+ with a fluence of 3$×$1016 ions/cm2 at 300℃. The irradiation direction was parallel to the thickness of the specimens, as shown in Fig. 1(c, d). Following irradiation, the specimens were annealed at 550°C for 3 hours in a vacuum tube furnace.

2.3 Microstructure characterization and nanoindentation test

The OM and TESCAN GAIA3 SEM equipped with an energy dispersive spectrometer (EDS) was used to observe the morphology and elemental distribution of WBB and its adjacent regions. The microstructure of the dissimilar joint interfacial region was determined by EBSD. TEM samples were prepared using the focused ion beam (FIB) lifting technique.

The irradiation damage characteristics in the WBB feature region were investigated using a Tecnai G2 F20S-TWIN TEM (Fig. 1(e)), and the size and distribution of helium bubbles were characterized and statistically analyzed under under-focused and over-focused conditions in bright-field mode. Nanoindentation testing was performed on the WBB region using a G200 nanoindenter (Fig. 1(f)). To ensure the accuracy of test results, the indentation test was repeated at least 8 times for each sample.

Fig. 1. (a, b) Schematic diagram of SA508-3/52 and SA508-3/52M joints; (c, d) irradiation direction; (e) characteristic regions observed in TEM specimens; (f) location of nanoindentation sampling points.

3.1 Microstructure characteristics in WBB before moderate-temperature annealing

Fig. 2 [Figure 2: see original paper] displays the microstructure of the SA508-3/52(M) joint interfacial region. It can be observed that the microstructure on the SA508-3 side is predominantly ferritic (body-centered cubic), while the WBB retains the face-centered cubic characteristics of the 52(M) alloy (Fig. 2(a-c, h-k)). The EDS results of Fig. 2(d-g) indicate that there is a certain area of element gradient variation near the fusion line of the joint on the 52 and 52 M sides, with ranges of approximately 30 μm and 20 μm, respectively, which corresponds to the width of WBB. However, it is noted that although the WBB exhibits considerable width, the dramatic elemental variations occur primarily within an extremely narrow range of 0-6 μm from the fusion line. Therefore, this study focuses on the microstructural evolution of the WBB within the corresponding specific region.

Fig. 2. (a, b) OM image of the WBB region; (c) schematic diagram of the WBB position; (d-g) SEM images (d, f) and EDS line scan distributions (e, g) of the WBB region; (h-k) inverse pole figures (IPF) (h, j) and phase maps (i, k) of the SA508-3/52(M) joint interfacial region.

Fig. 3 [Figure 3: see original paper] shows the TEM images of the WBB in the SA508-3/52(M) joint before irradiation.

Different characteristic regions within the WBB are named using the format "distance from fusion line-filled material-unirradiated (u)/irradiated (i)/heat-treated (h)". Compared to the SA508-3/52M joint, the WBB of the SA508-3/52 joint contains a large amount of black precipitate phases. As observed in Fig. 3(i-m), the precipitate mainly exhibits enrichment of Cr and C elements. Based on previous research, it is reasonable to infer that these precipitates are mainly $Cr_{23}C_6$ phases [22, 23]. After irradiation, the precipitate phase characteristics in WBB persist. Consequently, the significant distinction in precipitate phase characteristics between SA508-3/52 and SA508-3/52M joints primarily stems from the differing chemical compositions of the 52 and 52M alloys. The analysis area within the WBB of the irradiated joint is indicated in Fig. 4 [Figure 4: see original paper]. According to SRIM simulation results and TEM data, the significant irradiation damage regions of the SA508-3/52(M) joint WBB are all located within the depth range of 1600-1900 nm below the surface. Therefore, subsequent irradiation damage analysis targeting the marked locations will primarily focus on the corresponding depth range.

Fig. 3. TEM images of SA508-3/52(M) joint WBB before irradiation. (a-d) Characterization positions of FIB specimens for the SA508-3/52 joint WBB (a) and TEM bright-field images at 1, 3, and 6 μm distances from the fusion line (b-d); (e-h) characterization positions of FIB specimens for the SA508-3/52M joint WBB (e) and TEM bright-field images at 1, 3, and 6 μm distances from the fusion line (f-h); (i) precipitate phase morphology in the SA508-3/52 joint WBB; (j-l) element distribution of the precipitate phase; (m) high-resolution TEM image of the precipitate phase, with the inset showing the fourier transform (FT) image of the precipitate phase.

3.2 Helium bubble evolution in WBB after moderate-temperature annealing

TEM images the WBB region in SA508-3/52(M) joints after 550°C moderate-temperature annealing are presented in Figs. 5-7. The characteristic positions of the WBB selected before and after heat treatment remain consistent. Fig. 6 Figure 6: see original paper display the TEM images of characteristic locations within the SA508-3/52 joint WBB after heat treatment.

There is still a large amount of Cr23C6 precipitate phases dispersed in the SA508-3/52 joint WBB after moderate-temperature annealing. It has been demonstrated that during irradiation, these precipitate phases can serve as preferred nucleation sites for helium bubbles. By lowering the nucleation energy barrier and providing vacancy sources, they substantially facilitate the nucleation and initial growth of helium bubbles [24, 25]. Simultaneously, the precipitate phase can also act as a rigid barrier to impede migration driven by surface diffusion of helium bubbles [24]. During the moderate-temperature annealing stage, the precipitate phase continues to exert the aforementioned effects. To quantify the effect of post-irradiation moderate-temperature annealing on the distribution characteristics of helium bubbles in the WBB region, quantitative statistics of helium bubbles in TEM images were obtained using the Nanomeasure software. Fig. 6(g-i) show the statistical results of helium bubble sizes at 1, 3, and 6 μm distances from the fusion line in the SA508-3/52 joint WBB before and after heat treatment. It can be observed that the average helium bubble sizes at positions 1-52-h, 3-52-h, and 6-52-h are 1.58 nm, 1.49 nm, and 1.55 nm, respectively, representing increases of 5.33%, 10.37%, and 6.89% compared to the joints before heat treatment. The peak sizes of helium bubbles at the corresponding positions also increased by 1.93%, 0.98%, and 1.78%, respectively. This indicates that the size of helium bubbles throughout the WBB has been significantly enhanced after moderate-temperature annealing.

Fig. 4. (a, b) Characterization positions of SA508-3/52 (M) joint FIB specimen after irradiation; (c) ion range profile of He concentrations and profile of the irradiation damage; (d-i) TEM bright-field images of the WBB region at 1, 3, and 6 μm distances from the fusion line for SA508-3/52 (d-f) and SA508-3/52M (g-i) joints.

Fig. 5 [Figure 5: see original paper]. Characterization locations of SA508-3/52 (a) and SA508-3/52M (b) joint FIB specimens after moderate-temperature annealing.

Fig. 6. (a-f) TEM bright-field images of the WBB region in SA508-3/52 joints at 1, 3, and 6 μm distances from the fusion line after moderate-temperature annealing; (g-i) statistical results of helium bubble sizes at 1, 3, and 6 μm distances from the fusion line in the WBB region of SA508-3/52 joints before and after moderate-temperature annealing.

Fig. 7 Figure 7: see original paper present the TEM images of different positions of the SA508-3/52M joint WBB after moderate-temperature annealing. There is still no precipitate phase distribution within the WBB, but the helium bubbles and dislocation loops remain clearly discernible.

Due to the absence of precipitate phase constraints, the migration resistance of helium bubbles and dislocation loops in the SA508-3/52M joint WBB has significantly decreased.

Comparing the WBB regions before heat treatment reveals that moderate-temperature annealing exhibits a similar trend in its effect on irradiation damage within the WBB of the SA508-3/52M joint. From the quantitative statistics of helium bubble sizes in Fig. 7(g-i), it can be seen that the average helium bubble sizes at positions 1-52M-h, 3-52M-h, and 6-52M-h are 1.68 nm, 1.45 nm, and 1.61 nm, respectively, representing increases of 2.73%, 2.72%, and 3.25% compared to the joints before heat treatment. The peak sizes of helium bubbles at these three characteristic positions increased by 4.63%, 2.09%, and 5.41%, respectively. Compared to the SA508-3/52 joint, the effect of moderate-temperature annealing on the evolution of helium bubbles in the SA508-3/52M joint WBB is more significant.

Fig. 7. (a-f) TEM bright-field images of the WBB region in SA508-3/52M joints at 1, 3, and 6 μm distances from the fusion line after moderate-temperature annealing; (g-i) statistical results of helium bubble sizes at 1, 3, and 6 μm distances from the fusion line in the WBB region of SA508-3/52M joints before

and after moderate-temperature annealing.

It has been reported that the phenomenon of helium bubble coarsening is primarily driven by two mechanisms: "Migration and Coalescence" and "Ostwald Ripening" [26, 27].

The former primarily results from the random rearrangement of helium bubbles on the surface due to diffusion of matrix atoms (Fig. 8 Figure 8: see original paper); the latter is caused by the thermal reactivation and redissolution of small-sized helium bubbles, as well as the reabsorption of He atoms (Fig. 8(d)). Under moderate-temperature annealing conditions, the precipitate phases and grain boundaries serve as vacancy sources and rapid diffusion channels, promoting the preferential formation of large-sized helium bubbles in these regions.

Specifically, helium bubbles at the interface nucleate and grow through vacancy enrichment, whereas those within the crystal can only achieve localized aggregation due to their limited diffusion capacity. The migration and coalescence of helium bubbles require overcoming a surface diffusion energy barrier. However, solute atoms such as Cr adsorb onto the surface of helium bubbles. By reducing the interfacial energy and pinning helium bubble motion, they cause the helium bubbles to coarsen in situ only through inhibited migration and coalescence, rather than undergoing long-range migration [28]. During annealing at 550°C, some helium atoms acquire sufficient thermal activation energy, enabling them to diffuse through the matrix and migrate to larger helium bubbles, thereby causing an increase in helium bubble size. Nevertheless, since 550℃ has not yet reached the critical threshold required for the Ostwald ripening mechanism to dominate, the number of helium bubbles grown through this mechanism remains limited [19]. Consequently, the overall coarsening process continues to be primarily driven by the migration and coalescence mechanism.

Fig. 8. Schematic diagram of the helium bubble coarsening mechanism in the WBB region of SA508-3/52(M) joints during moderate-temperature annealing.

Fig. 9 Figure 9: see original paper illustrates the statistical results of helium bubble number density at positions 1, 3, and 6 μm from the fusion line in the SA508-3/52(M) joint WBB. Since the coarsening process of helium bubbles under moderate-temperature annealing conditions is primarily governed by the migration coalescence mechanism, this leads to numerous small helium bubbles coalescing into larger helium bubble aggregates through migration collisions.

Therefore, based on this mechanism, the helium bubble number density in the WBB is theoretically expected to exhibit a decreasing trend. The helium bubble number density in the WBB decreased significantly after moderate-temperature annealing. The average number densities at three characteristic locations of the SA508-3/52 joint were 6.31\$$\times 10^{\{23\}/m}\{3\}, 4.43\times 10^{\{23\}/m}\{3\}, and 5.61\times 10^{\{23\}/m}\{3\}$\$, respectively, representing reductions of 60.19%, 62.30%, and 67.21% compared to the joint before heat treatment. Similar to SA508-3/52 joints, the coarsening process of helium bubbles in the SA508-3/52M joint WBB is also primarily governed by the migration and coalescence mechanism. After heat treatment, the average number density of helium bubbles at positions 1-52M-h, 3-52M-h, and 6-52M-h in SA508-3/52M decreased by 51.38%, 48.05%, and 43.40%, respectively. Fig. 9(g-l) presents the calculated swelling rates induced by helium bubbles at the corresponding positions of the SA508-3/52(M) joint WBB. Relevant studies indicate that the swelling rate of materials exhibits the following quantitative relationship with helium bubble size and number density [29]: where v is the initial volume of the material, Δv is the volume increment, is the average radius of the helium bubble, and is the number density. According to the above equation, the increase in volume resulting from the enlargement of helium bubbles is insufficient to compensate for the reduction caused by the decrease in number density, ultimately leading to a significant decline in the swelling rate of the irradiated region within the WBB. Compared to before annealing, the average and peak swelling rates at positions 1-52-h, 3-52-h, and 6-52-h in the SA508-3/52 joint WBB decreased by 49.16%, 42.66%, and 56.46%, as well as by 36.37%, 21.84%, and 48.34%, respectively. It is noteworthy that, in contrast to the overall downward trend, the peak swelling rate for the SA508-3/52M joint WBB exhibits an upward trend. This increase against the overall trend is partly attributed to the absence of precipitate phases that could serve as diffusion channels in the SA508-3/52M joint WBB. On the other hand, it is primarily attributed to the pinning of helium bubbles by the higher Cr content in the 52M alloy.

Fig. 9. Statistical results of helium bubble number density (a-f) and swelling rate (g-l) at 1, 3, and 6 μm distances from the fusion line in the WBB region of SA508-3/52 (a-c, g-i) and SA508-3/52M (d-f, j-l) joints before and after moderate-temperature annealing.

3.3 Mechanical properties of WBB region

The microhardness of the WBB region in the SA508-3/52(M) joint is depicted in Fig. 10 Figure 10: see original paper. It can be observed that the hardness of the WBB region in SA508-3/52(M) joints is significantly higher than that of surrounding areas, both before and after moderate-temperature annealing, reaching a peak at a distance of 6 μm from the fusion line.

However, it is noteworthy that the SA508-3/52 joint WBB exhibits a distinctly higher hardness distribution, primarily attributable to the dislocation pinning effect of precipitates such as $Cr_{23}C_6$. This hardness distribution persists even after moderate-temperature annealing.

Before heat treatment, the peak hardness values in the WBB regions of SA508-3/52 and SA508-3/52M joints were 11.95 GPa and 8.72 GPa, respectively, with average hardness values of 9.53 GPa and 7.11 GPa. After heat treatment, the corresponding peak hardness decreased to 9.25 GPa and 7.68 GPa, respectively, while the average hardness decreased to

7.84 GPa and 6.53 GPa. Moderate-temperature annealing reduces dislocations and irradiation

defects, thereby diminishing the pinning effect of irradiation defects on dislocation motion.

Simultaneously, it relieves lattice distortions and residual stresses generated during welding and ion irradiation.

Fig. 10. Microhardness (a, b) and fracture toughness (c, d) of the WBB and its adjacent regions in SA508-3/52 (a, c) and SA508-3/52M (b, d) joints before and after moderate-temperature annealing.

In addition, it has been pointed out that the extent of irradiation damage in materials can also be effectively evaluated through fracture toughness [30]. Nevertheless, due to the extremely limited width of the WBB region at the joint interface, conventional fracture toughness testing methods struggle to yield reliable data. Therefore, this study achieved a precise characterization of fracture toughness in the WBB region by analyzing the elastic-plastic strain energy ratio within the load-displacement curve from nanoindentation testing. The specific calculation method is detailed in the Supplementary file. Fig. 10(c, d) depict the calculated results of fracture toughness in the WBB region before and after moderate-temperature annealing. Prior to moderate-temperature annealing, the fracture toughness trough values in the WBB regions of SA508-3/52 and SA508-3/52M joints were

82.10 $\mathrm{MPa}\cdot\mathrm{m}^1/^2$ and 98.03 $\mathrm{MPa}\cdot\mathrm{m}^1/^2$, respectively, with average values of 108.48 $\mathrm{MPa}\cdot\mathrm{m}^1/^2$

and 129.13 $\mathrm{MPa}\cdot\mathrm{m}^1/^2$. After heat treatment, the corresponding fracture toughness trough values increased to 84.11 $\mathrm{MPa}\cdot\mathrm{m}^1/^2$ and 109.75 $\mathrm{MPa}\cdot\mathrm{m}^1/^2$, respectively, while the average values rose to 110.75 $\mathrm{MPa}\cdot\mathrm{m}^1/^2$ and 132.36 $\mathrm{MPa}\cdot\mathrm{m}^1/^2$. After moderate-temperature annealing, the fracture toughness of the WBB region generally increases, which is mainly influenced by the following mechanisms. First, the reduction of irradiation defects. Based on migration and coalescence coupled with the Ostwald ripening mechanism, helium bubble size increases while their number density decreases significantly. The internal pressure of helium bubbles is partially released through vacancy migration, reducing local stress concentration and making residual stress distribution more uniform, thereby diminishing the driving force for microcrack initiation [31]. Second, the strengthening of grain boundaries. The migration and coalescence of helium bubbles at grain boundaries consume a significant number of small helium bubbles, leading to a marked decline in the number density at grain boundaries and thereby reducing the tendency for intergranular fracture [32]. Third, the complexification of crack propagation pathways. The coarsened and uniformly distributed helium bubbles and dislocation network form multiple obstacles, forcing cracks to frequently change their propagation direction and consume more energy [14]. Furthermore, due to the absence of precipitate phases such as $Cr_{23}C_6$, which form weak points in the mechanical properties within the SA508-3/52M joint WBB, it exhibits higher fracture toughness than the WBB region of the SA508-3/52 joint.

4. Conclusion

This study focused on SA508-3/52(M) dissimilar metal joints irradiated with He ions, thoroughly analyzing the effects of 550℃ moderate-temperature annealing on the repair of irradiation damage in the WBB. Moderate-temperature annealing exhibits a significant repair effect on irradiation damage in the SA508-3/52(M) dissimilar joint WBB, but the evolution behavior of helium bubbles induced by heat treatment is simultaneously influenced by the microstructure of the WBB region. Moderate-temperature annealing reduces the hardness of the WBB in SA508-3/52 and SA508-3/52M joints by 22.59% and 11.93%, respectively, by promoting dislocation annihilation, lowering the irradiation defect density, and relieving residual stress, thereby effectively mitigating irradiation hardening. Meanwhile, moderate-temperature annealing substantially reduced the swelling rate in the WBB, achieving maximum reductions of 56.46% and 40.42% in SA508-3/52 and SA508-3/52M joints. Based on mechanisms such as irradiation defect reduction, grain boundary strengthening, and crack propagation path complication, the fracture toughness of the SA508-3/52(M) joint WBB was notably enhanced. This study provides systematic theoretical guidance and technical support for the irradiation damage management of nuclear power equipment.

CRediT authorship contribution statement Chuanzong Li: Investigation, Methodology, Data curation, Writing -Original Draft, Writing -review & editing. Ziyu Tian: Conceptualization, Formal analysis, Writing -review & editing. Junmei Chen: Conceptualization, Supervision. Jijin Xu: Conceptualization, Formal analysis. Jieshi Chen:

Supervision. Chun Yu: Project administration, Investigation, Supervision. Hao Lu: Project administration, Funding acquisition, Supervision.

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.

Acknowledgments

The authors acknowledge the support given by the National Natural Science Foundation of China [Grant No. 52275354].

References

[1] H. Ming, Z. Zhang, J. Wang, E.H. Han, P. Wang, Z. Sun, Microstructure of a safe-end dissimilar metal weld joint (SA508-52-316L) prepared by

narrow-gap GTAW, Mater. Charact. 123 (2017) 233-243. http://doi.org/10.1016/j.matchar.2016.11.029 [2] T. Sarikka, M. Ahonen, R. Mouginot, P. Nevasmaa, P. Karjalainen-Roikonen, U. Ehrnstén, H. Hänninen, Effect of mechanical mismatch on fracture mechanical behavior of SA 508 –Alloy 52 narrow gap dissimilar metal weld, Int. J. Pres. Ves. Pip. 157 (2017) 30-42. http://doi.org/10.1016/j.ijpvp.2017.08.003 [3] W.C. Dong, D.B. Gao, S.P. Lu, Numerical investigation on residual stresses of the safe-end/nozzle dissimilar metal welded joint in CAP1400 nuclear power plants, Acta Metall. 32(5) (2018) 618-628. http://doi.org/ 10.1007/s40195-018-0803-8 [4] H. Ming, Z. Zhang, J. Wang, E.H. Han, Microstructure of a domestically fabricated dissimilar metal weld joint (SA508-52M-309L-CF8A) in nuclear power plant, Mater. Charact. 148 (2019) 100-115. http://doi.org/10.1016/j.matchar.2018.12.011 [5] H. Ming, R. Zhu, Z. Zhang, J. Wang, E.H. Han, W. Ke, M. Su, Microstructure, local mechanical properties and stress corrosion cracking susceptibility of an SA508-52M-316LN safe-end dissimilar metal weld joint by GTAW, Mater. Sci. Eng. A 669 (2016) 279-290. http://doi.org/10.1016/j.msea.2016.05.101 [6] Q. Wang, M. Zhang, W. Liu, X. Wei, J. Xu, J. Chen, H. Lu, C. Yu, Study of type-II boundary behavior during SA508-3/EQ309L overlay weld interfacial failure process, J. Mater. Process. Tech. 247 (2017) 64-72. http://doi.org/10.1016/j.jmatprotec.2017.04.009 [7] B.T. Alexandrov, J.C. Lippold, J.W. Sowards, A.T. Hope, D.R. Saltzmann, Fusion boundary microstructure evolution associated with embrittlement of Ni-base alloy overlays applied to carbon steel, Weld. World 57(1) (2012) 39-53. http://doi.org/10.1007/s40194-012-0007-1 [8] G. Rogalski, A. Świerczyńska, M. Landowski, D. Fydrych, Mechanical and microstructural characterization of TIG welded dissimilar joints between 304L austenitic stainless steel and Incoloy 800HT nickel alloy, Metals 10(5) (2020) 1-19. http://doi.org/10.3390/met10050559 [9] Z. Zhu, W. Ji, H. Huang, Distinct He-induced damage evolution in nickel-based alloys irradiated at elevated temperatures, J. Nucl. Mater. 560 (2022) 153506. http://doi.org/10.1016/j.jnucmat.2022.153506 [10] H.F. Huang, W. Zhang, M. De Los Reyes, X.L. Zhou, C. Yang, R. Xie, X.T. Zhou, P. Huai, H.J. Xu, Mitigation of He embrittlement and swelling in nickel by dispersed SiC nanoparticles, Mater. Des. 90 (2016) 359-363. http://doi.org/10.1016/j.matdes.2015.10.147 [11] J. Liu, H. Huang, R. Liu, Z. Zhu, Q. Lei, A. Liu, Y. Li, In situ TEM observation of the evolution of helium bubbles in Hastelloy N alloy during annealing, J. Nucl. Mater. 537 (2020) 152184. http://doi.org/10.1016/j.jnucmat.2020.152184 [12] C. Xu, W.Y. Chen, X. Zhang, Y. Wu, M. Li, Y. Yang, Effects of neutron irradiation and post-irradiation annealing on the microstructure of HT-UPS stainless steel, J. Nucl. Mater. 507 (2018) 188-197. http://doi.org/10.1016/j.jnucmat.2018.04.043 [13] C. Konkati, N. Gayathri, P. Mukherjee, A. Chauhan, Proton-irradiation and post-irradiation annealing behavior of a CoCrFeMnNi-based multi-principal element alloy, Mater. Sci. Eng. A 945 (2025) 148968. http://doi.org/10.1016/j.msea.2025.148968 [14] T. Petit, C. Ritter, J. Besson, T.F. Morgeneyer, Effects of neutron irradiation and post-irradiation annealing on pop-in crack propagation instabilities in 6061 aluminium alloy, J. Nucl. Mater. 569 (2022) 153909.

http://doi.org/10.1016/j.jnucmat.2022.153909 [15] X. Yi, Y. Du, D. Geng, Z. Li, W. Han, P. Liu, J. Chen, K. Yabuuchi, K. Yoshida, S. Ohnuki, Q. Zhan, F.

Wan, Y. Nagai, Heavy-ion irradiation and post-irradiation annealing effects in explosion-welded CuCrZr/316LN joints application, Mater.

Charact. (2021) http://doi.org/10.1016/j.matchar.2021. 111252 [16] H. Liu, S. Min, M. Jiang, F. Chu, Y. Li, Z. Chen, K. Zhang, J. Hou, A. Huang, Helium bubble growth in He+ ions implanted 304L stainless steel processed by laser powder bed fusion during post-irradiation annealing at 600 °C, Acta Metall. 35(9) (2022) 1509-1518. http://doi.org/10.1007/s40195-022-01391-w [17] K.i. Fukumoto, T. Mabuchi, K. Yabuuchi, K. Fujii, Irradiation hardening of stainless steel model alloy after Fe-ion irradiation and post-irradiation annealing treatment, J. Nucl. Mater. 557 (2021) 153296. http://doi.org/ 10.1016/j.jnucmat.2021.153296 [18] F.G. Charles A. Hirst, Boopathy Kombaiah, Penghui Cao, Scott Middlemas, R. Scott Kemp, Ju Li, Kai Nordlund, and Michael P. Short, Revealing hidden defects through stored energy measurements of radiation damage, Sci. Adv. 8(31) (2022) 1-9. http://doi.org/10.1126/sciadv.abn2733 [19] J. Gao, H. Huang, X. Liu, C. Wang, J.F. Stubbins, Y. Li, A special coarsening mechanism for intergranular helium bubbles upon heating: A combined experimental and numerical study, Scripta Mater. 147 (2018) 93-97. http://doi.org/10.1016/j.scriptamat.2018.01.006 [20] J. Gao, L. Bao, H. Huang, Y. Li, J. Zeng, Z. Liu, R. Liu, L. Shi, Evolution law of helium bubbles in hastelloy N alloy post-irradiation annealing conditions, Materials 9(10) (2016) http://doi.org/10.3390/ ma9100832 [21] S.H. Li, J.T. Li, W.Z. Han, Radiation-induced helium bubbles in metals, Materials 12(7) (2019) 1-32. http://doi.org/10.3390/ma12071036 [22] F. Vodopivec, D. Steiner-Petrovič, B. Žužek, M. Jenko, Coarsening rate of M23C6 and MC particles in a high chromium creep resistant steel, Steel Res. Int. 84(11) (2013) 1110-1114. http://doi.org/10.1002/ srin.201200150 [23] Y. Yang, Y. Gao, C. Liu, J. Dong, L. Lou, Synergistic evolution of MC/M23C6 carbides in a polycrystalline Ni-based superalloy during long-term aging: Elemental diffusion and interaction mechanisms, Mater.

Charact. 229 (2025) 115462. http://doi.org/10.1016/j.matchar.2025.115462 [24] J. Gao, H. Huang, J. Liu, Z. Zhu, Y. Li, Irradiation-induced hexagonal precipitates and their coupling with the evolution of helium bubbles, J. Appl. Phys. 125(5) (2019) 1-7. http://doi.org/10.1063/1.5081987 [25] W. Qin, A.K. Chauhan, M. Song, D. Gu, T.L. Li, W.L. Zhu, J.A. Szpunar, Microstructure criterion for the preferential locations of helium bubble precipitation in a polycrystal, J. Nucl. Mater. 577 (2023) 154332. http://doi.org/10.1016/j.jnucmat.2023.154332 [26] H. Trinkaus, B.N. Singh, Helium accumulation in metals during irradiation –where do we stand?, J. Nucl.

Mater. 323(2-3) (2003) 229-242. http://doi.org/10.1016/j.jnucmat.2003.09.001 [27] H. Trinkaus, The effect of internal pressure on the coarsening of inert gas bubbles in metals, Scripta Metal. 23(10) (1989) 1773-1778.

http://doi.org/10.1016/0036-9748(89)90359-1 [28] J. Liu, H. Huang, A. Liu, Y. Li, The effects of post-irradiation isochronous annealing on defects evolution and hardening in Hastelloy N alloy, J. Nucl. Mater. 548 (2021) 152855. http://doi.org/10.1016/j.jnucmat. [29] L.K. Mansur, Theory and experimental background on dimensional changes in irradiated alloys, J. Nucl.

Mater. 216 (1994) 97-123. http://doi.org/10.1016/0022-3115(94)90009-4 [30] Q.B. Chu, L. Sun, Z.F. Tong, Q. Wang, Development of a new irradiation-embrittlement prediction model reactor pressure-vessel steels, Nucl.

Tech. 35(11) (2024) http://doi.org/10.1007/s41365-024-01538-7 [31] Z. Zhu, H. Huang, J. Liu, Z. Zhu, Helium-induced damage behavior in high temperature nickel-based alloys with different chemical composition, J. Nucl. Mater. (2020) http://doi.org/10.1016/j.jnucmat. 2020.152419 [32] Z. Yan, T. Yang, Y. Lin, Y. Lu, Y. Su, S.J. Zinkle, Y. Wang, Effects of temperature on helium bubble behaviour Fe–9Cr alloy, Nucl.

Mater. (2020) http://doi.org/10.1016/j.jnucmat.2020.152045

Note: Figure translations are in progress. See original paper for figures.