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The neutron irradiation effect on mechanical properties of HIP joint material

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Abstract

Dispersion strengthened copper (DSCu) and stainless steel are the candidate material for the heat sink and the structural material of the ITER shielding blanket and these materials are joined by hot isostatic pressing (HIP). In this study, the neutron irradiation effect on mechanical properties of HIP joint material was examined by tensile and impact tests using specimens with irradiation damage of about 1.5 dpa. The results of tensile tests show that tensile strength of HIP joint material was about the same as that of DSCu base material, and this trend did not change after neutron irradiation. On the other hand, the impact value of HIP joint material was smaller than that of DSCu base material because of the diffusion of main elements at joint boundary. It was shown that embrittlement by the neutron irradiation effect is smaller than that of the effect by HIP joint.

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1. Introduction

Dispersion strengthened copper (DSCu) is a promising heat sink material for the shielding blanket of the International Thermonuclear Experimental Reactor (ITER), due to its high strength [1] and high thermal conductivity at high temperature. Stainless steel such as SS316LN-IG is a promising structural material [2]. These materials are joined for fabrication of the shielding blanket. The hot isostatic pressing (HIP) joint method is the candidate fabrication method of the shielding blanket in ITER.

However, neutron irradiation effects on mechanical properties of the HIP joint material have not been clarified under the irradiation condition of the primary wall in the ITER. Therefore, this issue has been investigated intensively in some recent studies [3–5]. A main objective of the present study is to clarify the neutron irradiation effect on mechanical properties of HIP joint materials in comparison to the effect on those of the base material.

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The objective of this study is estimation of neutron irradiation effects on mechanical properties of HIP joint material.

2. Experiment procedures

2.1. Materials and specimens

In this study, Al-25 and SS316LN-IG were adopted as copper material and stainless steel, respectively because these are candidate materials for the shielding blanket of ITER [6]. Al-25 is a kind of DSCu fabricated by OMG Americas Ltd. On the other hand, SS316LN-IG is the structural material for ITER and it was fabricated by the Japan Steel Works, Ltd. The chemical compositions of Al-25 and SS316LN-IG are shown in Tables 1 and 2, respectively.

Table 1
Chemical composition of SS316LN-IG material (wt%)

Fe	Balance
C	0.029
Mn	1.64
Si	0.44
P	0.012
S	0.009
Cr	17.48
Ni	12.11
Mo	2.56
Nb	0.067
Cu	0.02
Co	0.02
N	0.067
B	0.0003

Table 2
Chemical composition of Al-25 material (wt%)

Cu	Balance
Al	0.25
B	0.02
(ppm)	
Pb	6
Fe	13
Bi	3
As	1
Zn	15
Sn	6
Cd	1
He	1
Te	1
P	1
S	3
Sb	2
Mn	1

Processing procedure for the HIP joint in this study is shown below.

HIP temperature	1050 °C
HIP pressure	150 MPa
Holding time	2 h
Roughness of joint boundary surface (R_{max})	<1 μm

This is a candidate HIP joint condition of the Japanese blanket fabrication method and this condition was optimized in earlier studies by using un-irradiated materials [7]. Al-25 base material and SS316LN-IG base material were heat-treated with this processing procedure for the HIP joint. Tensile and impact specimens were fabricated from Al-25/SS316LN-IG HIP joint material and also from Al-25 and SS316LN-IG base material. Dimensions of the specimens are shown in Fig. 1.

2.2. Irradiation test

These specimens were irradiated for four operation cycles (100 days) at the first layer position with the beryllium reflector in the Japan Materials Testing Reactor (JMTR), which is located in the Oarai Research Establishment of the Japan Atomic Energy Research Institute (JAERI). The fast neutron fluence of the specimens was determined by iron fluence monitors, and the maximum value was 1.4×10^{25} m^{-2} ($E > 1$ MeV), which corresponds to a displacement dose of approximately 1.5 displacements per atom (dpa). The helium generation was calculated by the MCNP code [8], and it was about 16.0 atomic ppm (appm). The thermal neutron fluence was determined by Al–Co monitors, and it was 2.5×10^{25} m^{-2} ($E < 0.68$ eV) at maximum. Irradiation temperature of specimens was calculated by the ABAQUS code and it was between 240 and 250 °C.

2.3. Post irradiation examinations

Tensile properties and impact value were measured at post-irradiation examinations (PIE). Tensile tests were performed in air at two temperatures: i.e. 25 °C (room temperature) and 250 °C (the same as the irradiation temperature). The crosshead speed of tensile test was 0.1 mm/min (which corresponds to a strain rate of about 0.33%/min) before the 0.2% yield stress (0.2%YS), and it changed to 1.0 mm/min (about 3.3%/min) after the 0.2%YS. Total elongation (TEL) was measured by the crosshead moving. After tensile tests, fracture surfaces of each specimen were observed by scanning electron microscope (SEM).

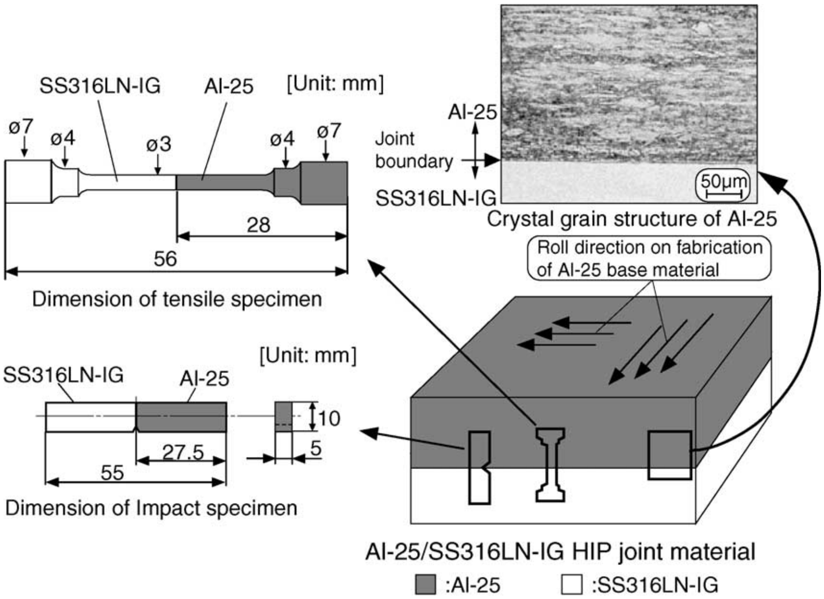

Fig. 1. Detail of tensile specimen and impact specimen.

Charpy impact tests were performed for both irradiated and un-irradiated Al-25/SS316LN-IG HIP joint material. The test temperatures of impact tests were 25 °C (room temperature) and 250 °C (the same as the irradiation temperature). Additionally, impact values of irradiated Al-25/SS316LN-IG HIP joints were measured at 100 and 400 °C for reference.

3. Results and discussion

3.1. Tensile properties

Specimens after tensile test are shown in Fig. 2. Fracture positions of all specimens of Al-25/SS316LN-IG HIP joint material were not located in the joint

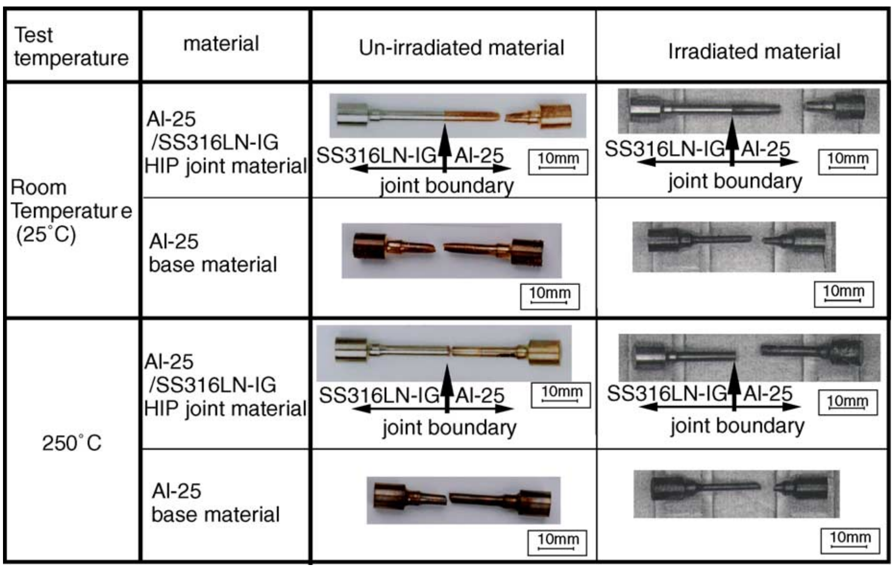

Fig. 2. Photographs of Al-25/SS316LN-IG HIP joint material specimens and Al-25 base material specimens after tensile test.

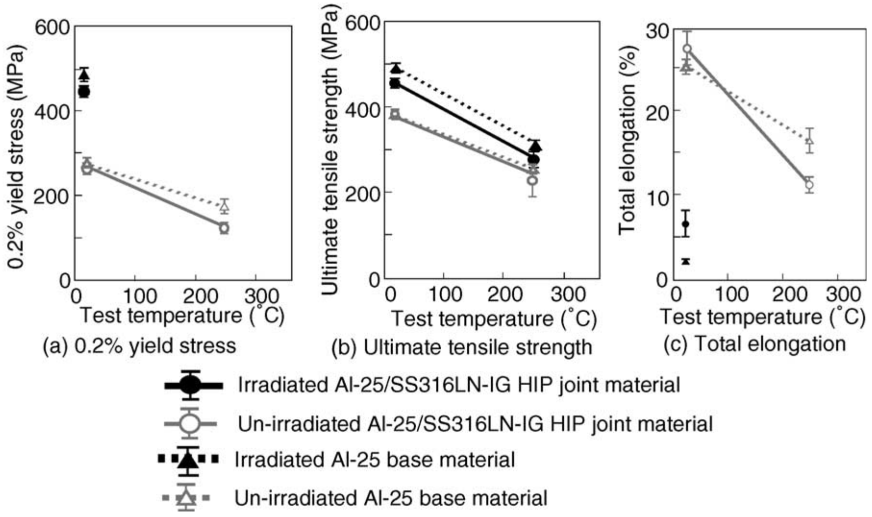

Fig. 3. Tensile properties of Al-25/SS316LN-IG HIP joint material and Al-25 base material.

boundary but these were located in the part of Al-25 base material. Therefore, it is considered that Al-25 and SS316LN-IG would be able to be joined tightly by the HIP condition adopted in this study.

Tensile properties of Al-25/SS316LN-IG HIP joint material and Al-25 base material are shown in Fig. 3. At test temperature 25 °C, ultimate tensile strength (UTS) of Al-25/SS316LN-IG HIP joint material increased from 400 to 460 MPa, and the total elongation of Al-25/SS316LN-IG HIP joint material decreased from 28% to 8% by neutron irradiation effect. The neutron irradiation effect on tensile properties of

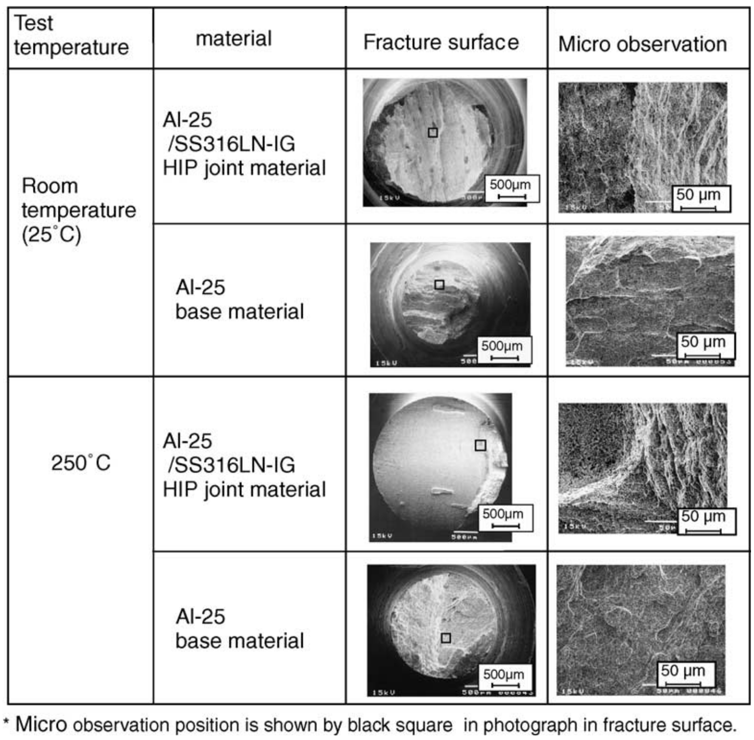

Fig. 4. Fracture surface of Al-25/SS316LN-IG HIP joint material and Al-25 base material after tensile test.

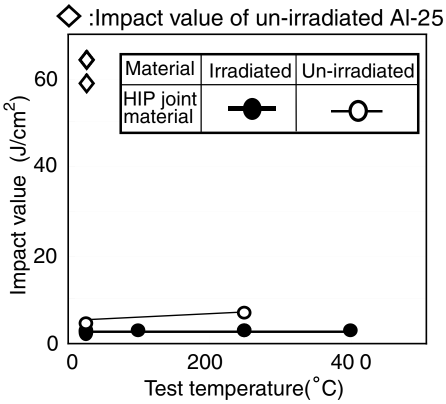

Fig. 5. Impact values of irradiated and un-irradiated Al-25/SS316LN-IG HIP joint material.

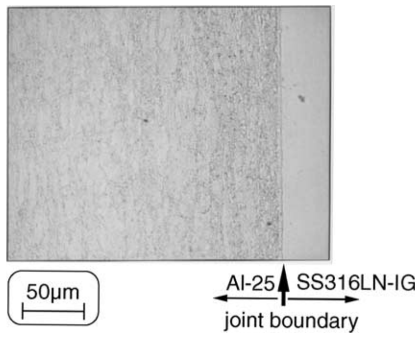

Fig. 6. Metalographical observation at the joint boundary of Al-25/SS316LN-IG HIP joint material.

Al-25/SS316LN-IG HIP joint material was much the same as that of Al-25 base material. It caused that Al-25/SS316LN-IG HIP joint material broke at the part of Al-25 base material. Therefore, tensile properties of Al-25/SS316LN-IG HIP joint material depend on that of Al-25 base material.

On the other hand, irradiated Al-25/SS316LN-IG HIP joint material and irradiated Al-25 base material broke by the brittle fracture at test temperature 250 °C. SEM observations of fracture surface after tensile test are shown in Fig. 4. These observations show that no dimple pattern and detachment of stratified crystal were observed at the fracture surface at test temperature 250 °C. It is considered that this cause was the fabrication method of Al-25 base material. Al-25 base material was fabricated by powder metallurgy and hot rolling. Therefore, the crystal grain structure of Al-25 base material was extended in the rolling direction. When a tensile load acts vertically to the rolling direction,

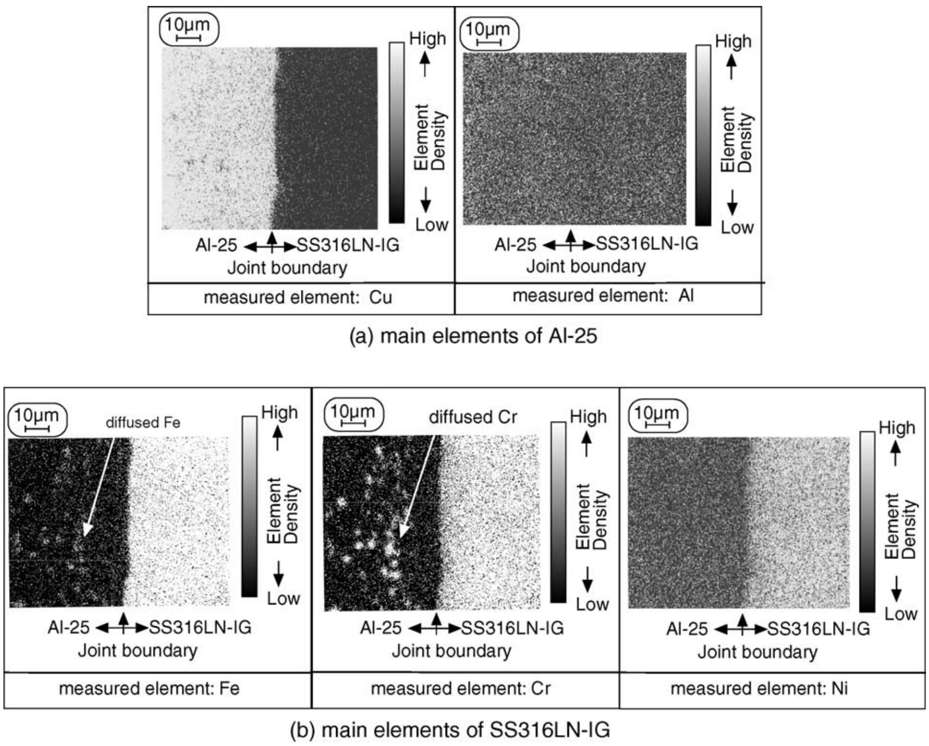

Fig. 7. XMA observation at the joint boundary of Al-25/SS316LN-IG HIP joint material.

fractures progress by the detachment of crystal grain boundaries before the extension of crystal grains. Thus, Al-25/SS316LN-IG HIP joint material and Al-25 material broke without plastic deformation.

Therefore, it is concluded that the neutron irradiation effect on Al-25/SS316LN-IG HIP joint material is much the same as that of Al-25 base material on irradiation damage 1.5 dpa.

3.2. Impact properties

Results of impact tests are shown in Fig. 5. Impact values of Al-25/SS316LN-IG HIP joint material were very much smaller than those of Al-25 base material. This cause is regarded as the influence by the effect of HIP joint. Then, the metallurgical state and the diffusion state of main elements were observed at the joint boundary of irradiated Al-25/SS316LN-IG HIP joint material. The result of metalographical observation at joint boundary is shown in Fig. 6. The metalographical structure of Al-25 base material near the joint boundary was thin and parallel to the joint boundary by the effect of rolling at the Al-25 base material fabrication. It is considered that this metallurgical structure influenced to the impact value of Al-25/SS316LN-IG HIP joint material, because each impact specimen broke near the joint boundary.

The diffusion state of main elements at joint boundary were observed by XMA (X-ray Micro Analyzer) and it was shown in Fig. 7. Cu and Al were selected as main elements of Al-25 and Fe, Cr and Ni were selected as main elements of SS316LN-IG. Most Cu and Al were observed in the part of Al-25 material side mainly. On the other hand, Cr and Fe were distributed over the part of Al-25 in addition to the part of SS316LN-IG. Fe is impurity material in Al-25 composition and Cr is not included in Al-25 base material. It is considered that Fe and Cr diffused to the part of Al-25 from SS316LN-IG material in the HIP joint process. The compound of Cu and Cr was more brittle than Al-25 base material and fracture positions of each impact specimen concentrated around this place. Therefore, it is considered that Fe and Cr in the part of Al-25 functioned as the starting point of fracture and the impact value of Al-25/SS316LN-IG HIP joint material became lower than that of Al-25 base material.

Impact value of Al-25/SS316LN-IG HIP joint material was changed to be lower by the embrittlement of the neutron irradiation effect. As for the decrease in the impact value, it is clearly recognized that the influence of the HIP joining is much bigger than the that of the neutron irradiation effect.

4. Conclusion

This study estimated the neutron irradiation effect on mechanical properties of Al-25/SS316LN-IG HIP joint material. The following points are concluded from the results of the tensile and impact test.

(1) Tensile properties (i.e., the 0.2% YS, UTS, and TEL) of Al-25/SS316LN-IG HIP joint material were about the same as those of the Al-25 base materials. These features were basically common to the irradiated and un-irradiated materials.
(2) Impact value of Al-25/SS316LN-IG HIP joint material was reduced by the neutron irradiation effect. However, this effect was smaller than that of diffusion by HIP joint.
(3) The state of the crystal grain structure of Al-25 material strongly relates to mechanical properties and the fracture mechanism of Al-25/SS316LN-IG HIP joint materials. In particular, the impact values fall remarkably in the case that any brittle interposition objects are formed by diffusion elements.

Thus, this study clarified the neutron irradiation effect on the tensile and impact properties of Al-25/SS316LN-IG HIP joint material for the case of irradiation damage of 1.5 dpa.

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References

[1] R. Aymar, J. Nucl. Mater. 258–263 (1998) 56.
[2] A.A.F. Tavassoli, J. Nucl. Mater. 258–263 (1998) 85.
[3] A.S. Pokrovsky, S.A. Fabritsiev, D.J. Edwards, S.J. Zinkle, J. Nucl. Mater. 283–287 (2000) 404.
[4] A. Lind, U. Bergenlid, J. Nucl. Mater. 283–287 (2000) 451.
[5] S.A. Fabritsiev, A.S. Pokrovsky, D.J. Edwards, S.J. Zinkle, J. Nucl. Mater. 283–287 (2000) 523.
[6] F. Elio, K. Ioki, P. Barabaschi, L. Bruno, A. Cardella, M. Hechler, T. Kodama, A. Lodato, D. Loesser, D. Lousteau, N. Miki, K. Mohri, R. Parker, R. Raffray, D. Williamson, M. Yamada, W. Daenner, R. Mattas, Y. Strebkov, H. Takatsu, Fusion Eng. 46 (1999) 159.
[7] S. Sato, T. Hatano, T. Kuroda, K. Furuya, S. Hara, M. Enoeda, H. Takatsu, J. Nucl. Mater. 258–263 (1998) 265.
[8] J.F. Briesmeister (Ed.), MCNP-A General Monte Carlo N-Particle Transport Code, Version 4B, LA-12625-M, 1997.