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Strength of copper alloys in high temperature environment

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Abstract

The first wall of ITER is expected to be hot isostatic pressing (HIP) bonded structure of copper-alloy/SS316. Firstly, fracture toughness and crack propagation tests were performed on DS-Cu and DS-Cu/SS316 HIP joints at ambient temperature and 573 K [T. Yamada, M. Uno, M. Saito, Fall Meeting of the Atomic Energy Society of Japan, vol. I, 1998, p. 187 (in Japanese)]. J_{IC} values of DS-Cu and DS-Cu/SS316 decreased significantly at 573 K. In crack propagation test, DS-Cu lost its ductility at 573 K. Secondly, we performed fracture toughness tests on CuCrZr and CuCrZr/CuCrZr, CuCrZr/SS316 HIP joints at ambient and 573 K. CuCrZr base metal had higher J_{IC} values than DS-Cu. Concerning CuCrZr/CuCrZr and CuCrZr/SS316 HIP joint, its J_{IC} value decreased to less than that of CuCrZr base metal.

1. Introduction

The first wall of ITER consists of copper-alloy heat sink, SS316 cooling pipes through heat sink, which are bonded by hot isostatic pressing (HIP) which is one of the candidate fabrication methods. It is anticipated that the differences in thermal expansion ratio and in mechanical properties between heat sink and cooling pipes cause thermal stresses and stress concentrations near the joint interface where cracks may grow easily in reactor operation. We need to insure structural integrity and reliability of the interface. The objective of this paper is to evaluate fracture strengths of two copper alloys against initial cracks at ambient temperature and 573 K.

2. Experimental procedure

Chemical compositions of DS-Cu, CuCrZr, and SS316 are shown in Table 1. HIP conditions and thermomechanical treatments of DS-Cu, DS-Cu/SS316, CuCrZr/CuCrZr, CuCrZr/SS316, HIP heat treated and non-heat treated CuCrZr are shown in Table 2. Fracture toughness tests were carried out for DS-Cu, DS-Cu/SS316, CuCrZr/CuCrZr, CuCrZr/SS316, HIP heat treated CuCrZr and non-heat treated CuCrZr following ASTM E813. In this test, multiple-specimen technique was employed and two types of CT specimen sizes shown in Fig. 1 are used. Procedures of this test are the following: firstly, initial crack was introduced to each specimen by mechanical fatigue. Specimens were loaded to a selected displacement level, and unloaded. During this loading process, we recorded loads and load-line displacements (load-line displacements were measured by clip gage). After breaking each specimen by mechanical fatigue, we measured slow-stable crack extension (Δa) and calculated J-integral from load, load-line displacement. Fatigue crack propagation test was carried out for DS-Cu and DS-Cu/SS316 following ASTM E 647. CT specimen size used in this test was shown in Fig. 2. Procedures of this test are the following: firstly, initial crack was introduced to each specimen by mechanical fatigue. Each specimen was loaded at a constant range so that fatigue crack propagated. In this test, we suitably changed load range to mark 'beach marks' on the fracture surface. After breaking the specimen by mechanical fatigue, we measured crack length a using

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Table 1
Chemical compositions of DS-Cu, CuCrZr and SS316

DS-Cu							
Cu	Al	Fe	Pb	B	O		
99.51%	0.25%	0.0023%	0.0006%	0.017%	0.05%		
CuCrZr							
Cu	Cr	Zr	O	Fe	Ni		
99.13%	0.8%	0.07%	0.0004%	<0.03%	<0.03%		
SS316							
C	Si	Mn	P	S	Ni	Cr	Mo
0.018%	0.46%	0.84%	0.027%	0.001%	12.22%	17.43%	2.13%

Table 2
HIPing conditions and thermomechanical treatments of DS-Cu, DS-Cu/SS316, CuCrZr/CuCrZr, CuCrZr/SS316, HIP heat treated and non-heat treated CuCrZr

	HIPing conditions			Thermomechanical treatments	
	Pressure (MPa)	Temperature (K)	Hold time (h)	Solution treatment	Aging
DS-Cu	None	1323	2	None	None
DS-Cu/SS316	150	1323	2	None	None
CuCrZr/SS316	150	1323	2	[a]	[b]
CuCrZr/CuCrZr	150	1323	2	[a]	[b]
HIP heat treated CuCrZr	None	1323	2	[a]	[b]
Non-heat treated CuCrZr	None	None	None	None	None

[a] Temperature 1253 K, Hold time 30 min.
[b] Temperature 828 K, Hold time 2 h.

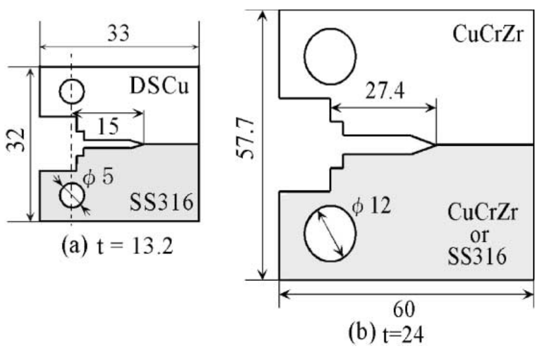

Fig. 1. Dimensions of test specimens of fracture toughness test: (a) DS-Cu and DS-Cu/SS316 (b) HIP heat treated and non-heat treated CuCrZr, CuCrZr/CuCrZr and CuCrZr/SS316.

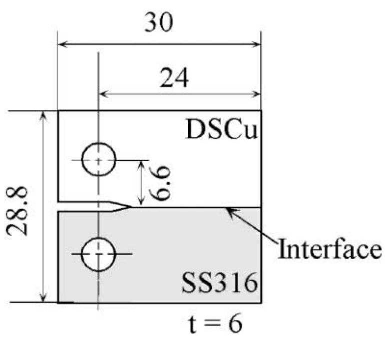

Fig. 2. Dimensions of test specimen of fatigue crack propagation test.

beach marks, and calculated stress intensity factor range ΔK and fatigue crack growth rate $da/dN = (a_{i+1} - a_i)/(N_{i+1} - N_i)$ where N is the number of the cycle. Both test were preformed in air at ambient temperature and 573 K.

3. Results

3.1. DS-Cu and DS-Cu/SS316 joints

Mechanical properties of DS-Cu, CuCrZr and SS316 are shown in Table 3. J–R curves and J_{IC} values of DS-Cu and DS-Cu/SS316 joint obtained by fracture toughness tests are shown in Fig. 3. Fracture toughness

Table 3
Mechanical properties of DS-Cu, CuCrZr and SS316 (HIP bonded with DS-Cu) at ambient/high temperature

	Young's modulus (GPa) (ambient/573 K)	Ultimate tensile strength (MPa) (ambient/573 K)	Elongation (%) (ambient/573 K)
DS-Cu	118/110	398/294	34/24
CuCrZr	118/113	291/220	24/7
SS316	185/196	567/429	71/45

Note: all specimens are HIP heat treated.

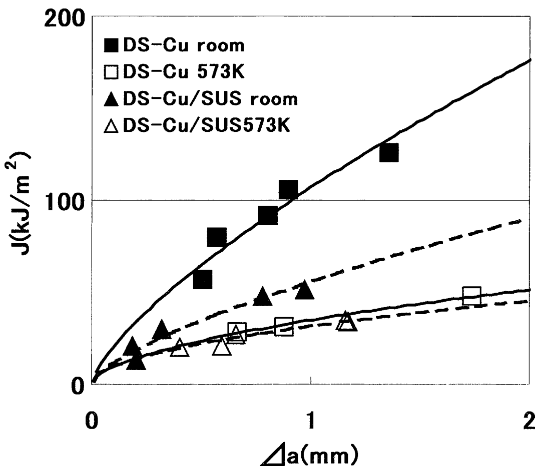

Fig. 3. *J–R* curves of DS-Cu and DS-Cu/SS316.

J_{IC} (kJ/m^2) values of DS-Cu (38.3 and 15.3), DS-Cu/SS316 HIPed joint (25.2 and 14.4) were obtained at ambient temperature and 573 K respectively. The relationships between ΔK and da/dN obtained by fatigue crack propagation tests are shown in Fig. 4. Each fatigue crack propagation ratio da/dN (m/cycle) as a function of ΔK MPa $(\sqrt{m})$ is the following: DS-Cu ($da/dN = 3.33 \times 10^{-11}(\Delta K)^{2.91}$ and $da/dN = 1.40 \times 10^{-10}\ (\Delta K)^{2.71}$), DS-Cu/SS316 ($da/dN = 1.52 \times 10^{-12}\ (\Delta K)^{4.48}$ and $da/dN = 9.58 \times 10^{-12}\ (\Delta K)^{4.45}$) at ambient temperature and 573 K, respectively.

3.2. HIP heat treated and non-heat treated CuCrZr, CuCrZr/CuCrZr and CuCrZr/SS316 joint

J–R curves and J_{IC} values of HIP heat treated and non-heat treated CuCrZr, CuCrZr/CuCrZr and CuCrZr/SS316 joint obtained by fracture toughness tests are shown in Fig. 5. Fracture toughness J_{IC} (kJ/m^2) values of HIP heat treated CuCrZr (1281 and 655), non-heat treated CuCrZr (450 and 704), CuCrZr/CuCrZr (81 and 32) and CuCrZr/SS316 (155 and 79) were obtained at ambient temperature and 573 K respectively.

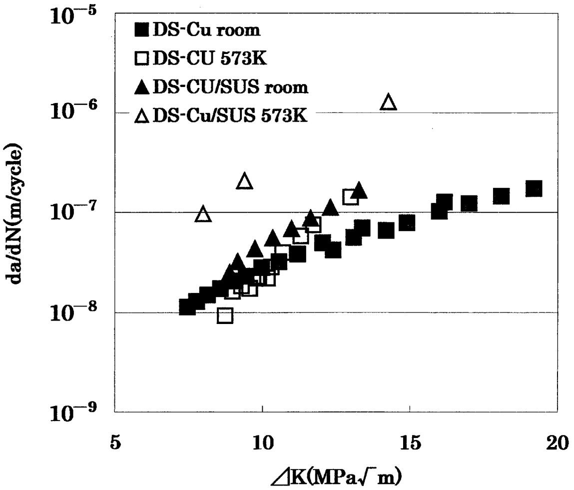

Fig. 4. da/dN versus ΔK for crack propagation test.

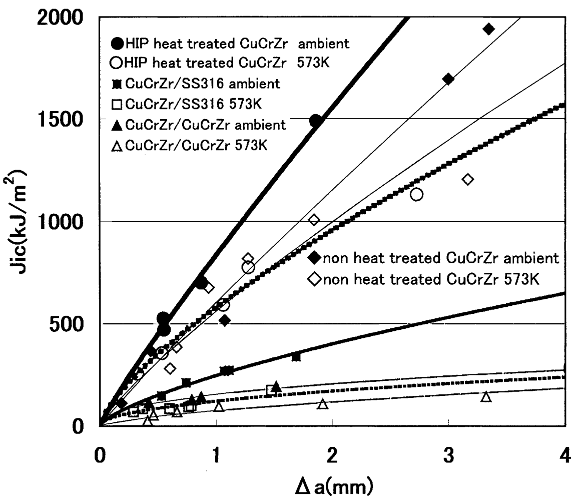

Fig. 5. *J–R* curves of CuCrZr, CuCrZr/CuCrZr and CuCrZr/SS316.

4. Discussions

4.1. Fracture toughness

J_{IC} values of all types of specimens decreased as environmental temperature increased. In CuCrZr/CuCrZr HIP joint specimens crack propagated along HIP joint interface while it was confirmed that copper alloy layer with about 10 μm in thickness covered the SS316 side of the fracture surface of all copper-alloy/SS316 HIP bonded specimens. It has been reported that the intermediate layer form between copper alloy and SS316 and that crack propagate in copper alloy along the new layer [1]. At 573 K the *J–R* curve of DS-Cu/SS316 HIP joint was similar to that of DS-Cu which indicates that

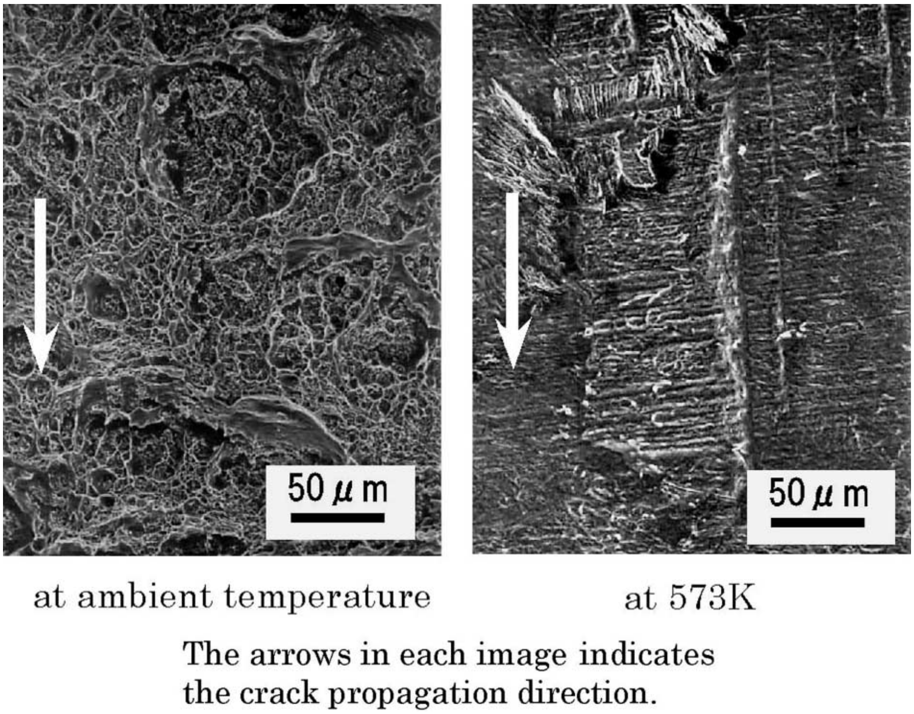

Fig. 6. SEM images of the fracture surfaces of CuCrZr/CuCrZr at ambient temperature and 573 K.

fracture toughness of DS-Cu governs that of the HIP boundary at 573 K. HIP heat treated CuCrZr has high enough J_{IC} values and tearing modulus to justify structural design at ambient temperature and 573 K. J_{IC} values of CuCrZr/CuCrZr and CuCrZr/SS316 are very low in comparison with those of heat treated CuCrZr. In the CuCrZr base metal, although recrystallization was caused by HIP heat treatment, there was no large difference in J_{IC} values and fracture surfaces between HIP heat treated and non-heat treated CuCrZr. The first wall finally consists of three kinds of alloys including beryllium armor; it is difficult to find out the most suitable aging heat treatment for them. Therefore, if each three alloys have sufficient mechanical properties without specific aging heat treatment after HIP heat treatment, we want to apply them as they are. It is observed from fracture surfaces of CuCrZr/CuCrZr in Fig. 6 that CuCrZr/CuCrZr HIPed interface lost its ductility at 573 K: many dimples indicating 'ductile fracture' are found on the fracture surface at ambient temperature while no one at 573 K. Based on J_{IC} values and fracture patterns, it is concluded that it is still possible to improve the CuCrZr/CuCrZr HIP conditions.

4.2. Fatigue crack propagation ratio

The crack growth rate became greater at 573 K. The crack growth rate on DS-Cu/SS316 HIP joint was higher than that of DS-Cu. Also after fatigue tests, a thin DS-Cu layer covered the SS316 side of the fracture surface in all HIP bonded specimens. Two conclusions can be drawn: the initial crack in the DS-Cu/SS316 propagates between the new layer and DS-Cu base metal and the DS-Cu/SS316 interface dose not have high strength against crack propagation. DS-Cu changes into less ductile at 573 K as shown in Fig. 7. The SEM image of Fig. 7 illustrates the fracture surfaces of DS-Cu/SS316 HIP joint at constant load range at two different temperatures so that at first crack was propagated at 573 K and then at ambient temperature (the difference of the

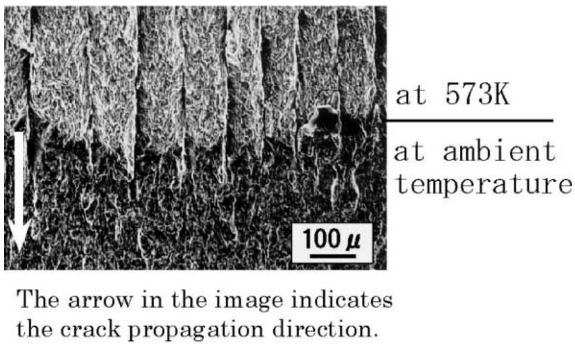

Fig. 7. SEM image of the fracture surface of DS-Cu at constant load at two different temperatures.

surface color caused by the oxidation at 573 K was clearly appeared). Vertical cracks at about equal intervals are appeared up to the end of fatigue crack propagation at 573 K in the upper half of the SEM image. At ambient temperature, in the lower half of the image, there is no crack like features on the fracture surface.

5. Conclusions

Fracture toughness and fatigue crack propagation tests on DS-Cu, DS-Cu/SS316, CuCrZr, CuCrZr/CuCrZr and CuCrZr/SS316 were performed at ambient temperature and 573 K. Based on the present test results the following conclusions can be drawn.

(1) Fracture toughness J_{IC} (kJ/m^2) values of DS-Cu (38.3 and 15.3), DS-Cu/SS316 HIPed joint (25.2 and 14.4), HIP heat treated CuCrZr (1281 and 655), non-heat treated CuCrZr (450 and 704), CuCrZr/CuCrZr HIPed joint (81 and 32) and CuCrZr/SS316 HIPed joint (155 and 79) were obtained at ambient temperature and 573 K, respectively. J_{IC} values of each specimen at 573 K decreased comparing with those at ambient temperature. CuCrZr base metal had a much larger J_{IC} value than the DS-Cu and DS-Cu/SS316. The J_{IC} value for CuCrZr/CuCrZr HIP joint was less than one tenth of that of the CuCrZr base metal value. It is necessary to investigate the more suitable HIP heat treatment for CuCrZr/CuCrZr HIP joint. The J_{IC} value of the DS-Cu/SS316 HIP joint was similar to that of the DS-Cu at 573 K. From the viewpoint of fracture toughness, it is concluded that this HIP conditions is most suitable for CuCrZr/SS316 joint.

(2) Crack propagation rates of DS-Cu and DS-Cu/SS316 joint at 573 K were higher than those at the ambient temperature.

(3) The new layer in the copper alloy side next to the HIP joint interface was found in copper-alloy/SS316 specimens, and the crack propagated in the copper alloy along the length of the new layer.

Reference

[1] T. Hatano, M. Kanari, S. Sato, M. Gotoh, K. Furuya, T. Kuroda, M. Saito, M. Enoeda, H. Takatsu, J. Nucl. Mater. 258–263 (1998) 950.