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先進炉に跨がる材料開発の現状と課題

Present status and issues for material development for advanced reactor

Diffusion Bonding of Austenitic Alloys for High Temperature Nuclear Systems

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1. Introduction

Recently, there has been interest in application of compact type heat exchangers in generation-IV reactors like a sodium-cooled fast reactor (SFR) and high temperature gas-cooled reactors (HTGR) to utilize higher better heat transfer capability with pressurized gas coolant such as supercritical-CO_2 (S-CO_2) [1,2] and high temperature He [3,4]. In manufacturing of compact heat exchangers, diffusion bonding is considered the critical joining process for austenitic alloys like stainless steels and Ni-base alloys [5]. Therefore, the quality and performance of diffusion bond region of such alloys are of great concern for the safety and integrity of generation-IV reactors. In this study, diffusion bonds were made using several austenitic alloys, and the microstructure of the bond region was observed. Then, the tensile properties of diffusion bond region were evaluated. Finally the effect of long-term exposure to high temperature S-CO_2 on tensile properties of austenitic alloys was investigated.

2. Materials and experiments

2-1. Materials, diffusion bonding, and microstructure observation

Fe-base austenitic stainless steels (SS 316H, SS 347H and Alloy 800HT) and Ni-base alloys (Alloy 600, Alloy 690, Alloy 617, and Haynes 230) were diffusion bonded. The typical diffusion bonding was performed at near solution annealing temperature with applied compressive stress below the yield stress. Duration of diffusion bonding was limited to one or two hours to prevent excessive grain growth. The diffusion bonded region was observed under scanning electron microscope (SEM) to identify the quality of bonding and presence of grain boundary migration across bond line. The presence and identity of precipitates along the bond line were also investigated.

Table. 1 Austenitic alloys used diffusion bonding evaluation (in wt-%)

Alloy		Fe	Cr	Ni	C	Ti	Mo	Mn	Al	Si	Other
Fe-Ni-Cr	800HT	Bal.	21.03	33.64	.06	.55	.20	.93	.48	.48	.003B .05Co
	316H	Bal.	17.3	10.7	0.05	-	2.1	0.8	-	0.6	0.25Cu 0.16Co
	347H	Bal.	18.3	8.6	0.07	-	-	1.2	-	0.8	0.43Nb
Ni-Cr-Fe	600	9.33	16.16	Bal.	.077	.20	-	.30	.16	.30	.04Co
	690	8.34	28.36	Bal.	.02	.28	-	.18	.30	.24	.002B <.01Nb
	617	1.58	22.1	Bal.	.09	.35	9.57	.12	1.41	.42	.07W 11.6Co
	230	1.03	20.0	Bal.	.10	.18	1.66	.63	.64	.02	5.12Co 14.0W

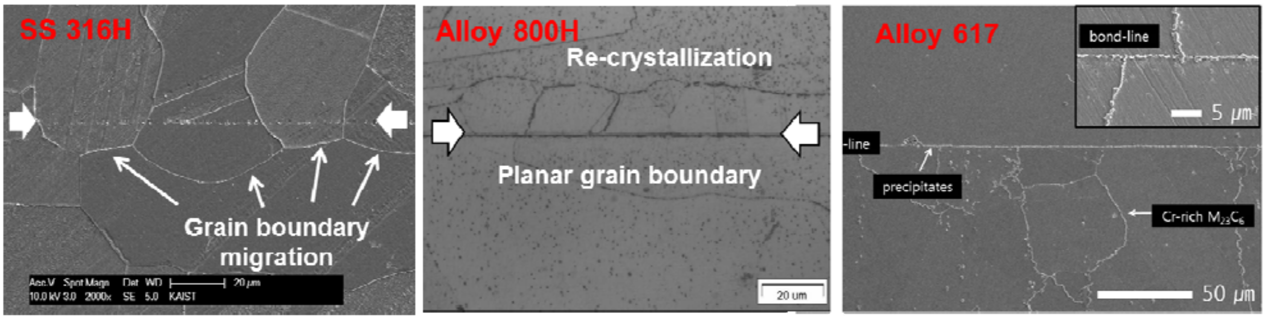
2-2. Tensile property evaluation

The tensile properties of diffusion bonded coupons were evaluated at room temperature and high temperatures expected in various nuclear applications. Then, diffusion bonded coupons were long-term exposed to various high temperature environments such as helium, S-CO_2, and air to assess the effects of long-term exposure to tensile properties and microstructure of diffusion bond region.

3. Results and discussion

3-1. Microstructure and tensile properties of diffusion bonding

Fig. 1 shows the typical microstructure of diffusion bond region of austenitic stainless steels and Ni-base alloys. As shown in the figure, extensive grain boundary migration was observed for austenitic stainless steel 316H, despite the presence of fine precipitates along the bond line. In both Alloy 800HT and Alloy 617, grain migration was virtually not present. On the other hand, diffusion bond line decorated with fine precipitates was clearly visible. The tensile properties of diffusion bonded samples were measured at high temperature and the results of SS 316H and Alloy 600 are summarized in Fig. 2. Tensile ductility of the as-bonded SS 316H and SS 347H was comparable to that of parent materials up to 550 °C while that of as-bonded Alloy 800HT was lower in all temperature ranges. In case of Alloy 600 and Alloy 690, loss of ductility was also observed due to the presence of the precipitates formed along the bond-line.



a) SS 316 H b) Alloy 800HT c) Alloy 617

Fig. 1 Microstructure of diffusion bond region of several austenitic alloys.

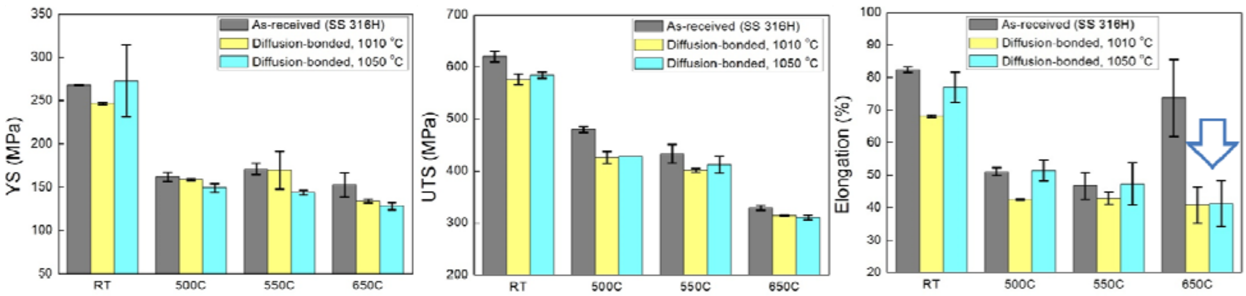


Fig. 2 Tensile properties of diffusion-bonded SS 316H at various temperatures [2]

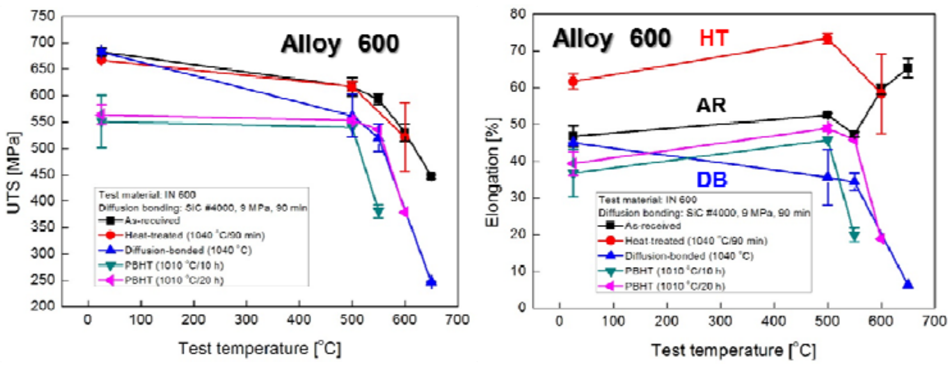


Fig. 3 Tensile properties of diffusion-bonded Alloy 600 at various temperatures [6]

3-2. Effect of long-term exposure on tensile properties

The tensile properties after long-term exposure to relevant high temperature environments were measured and the results are summarized in Fig. 4. As shown in Fig. 4, as exposure time in S-CO_2 increased, tensile strength changes were relatively small, especially for Ni-base alloys. The large increase in tensile stress for Alloy 800HT seems related to precipitation of secondary phases due to the presence of Al and Ti. Loss of ductility was observed for austenitic stainless steels after long-term exposure to S-CO_2 environment, while ductility was almost the same for Ni-base alloys. Also, the location of final fracture was at the bond-line for most austenitic stainless steels, which suggested that diffusion bond-line became the weakest region after S-CO_2 exposure.

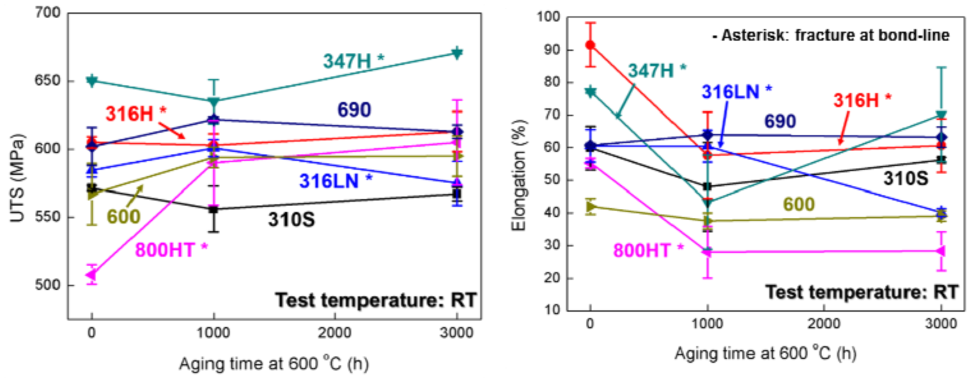


Fig. 4 Tensile properties of diffusion-bonded Alloy 600 after up to 3000 h exposure to 600 °C S-CO2 environment

4. Summary and conclusions

For the application to generation-IV reactors, diffusion bonding of austenitic alloys was performed and the microstructure and mechanical properties were evaluated. For austenitic stainless steels, grain migration across the bond-line was observed. While, grain migration was virtually not present for Ni-base alloys which showed clear bond-line decorated with fine precipitates. Both alloy groups showed good ductility at lower temperature, but loss of ductility was observed at higher temperature. Exposure to S-CO2 caused relatively small change in tensile strength, but large decrease in ductility for austenitic stainless steels associated with failure at bond-line. However, the loss of ductility was little for Ni-base alloys.

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