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Solid-state Diffusion Bonding of Candidate Fe-base and Ni-base Alloys for the Application of S-CO_2 Cycle Heat Exchanger

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1. Introduction

To improve the inherent safety of sodium-cooled fast reactor (SFR), super-critical CO_2 (S-CO_2) Brayton cycle is being considered as an alternative power conversion system to steam Rankine cycle [1]. To achieve efficient heat transfer, compact type heat exchangers, such as printed circuit or plate fin type heat exchanger, are considered for intermediate heat exchangers (IHXs). Solid-state diffusion bonding (DB) is one of key issues for joining the thin metal sheets with flow passages that are either machined or photo-chemically etched.

In this study, diffusion bonding was performed for the candidate Fe-base and Ni-base alloys. Tensile properties of the as-bonded were compared with the as-received and characteristics of the aged in high temperature S-CO_2 environment were discussed.

2. Methods and Results

2.1 Experimental procedure

Test materials used in this study are ferritic-martensitic steel (F91), austenitic stainless steels (SS 316H, SS 347H), Fe-Ni-Cr alloy (Incoloy 800HT), and Ni-base alloys (Alloy 600, Alloy 690). Diffusion bonding was performed by a contractor (TNP Co.) following the diffusion bonding conditions suggested by the authors (Table I).

Small-size plate type specimens were prepared to evaluate tensile properties at RT, 500, and 550 ^oC with the cross-head speed of 3.33×10^{-4}/s. To evaluate the performance of diffusion-bonded structure in super-critical CO_2 cycle, both as-received and as-bonded specimens were exposed to 550 ^oC up to 1000 h.

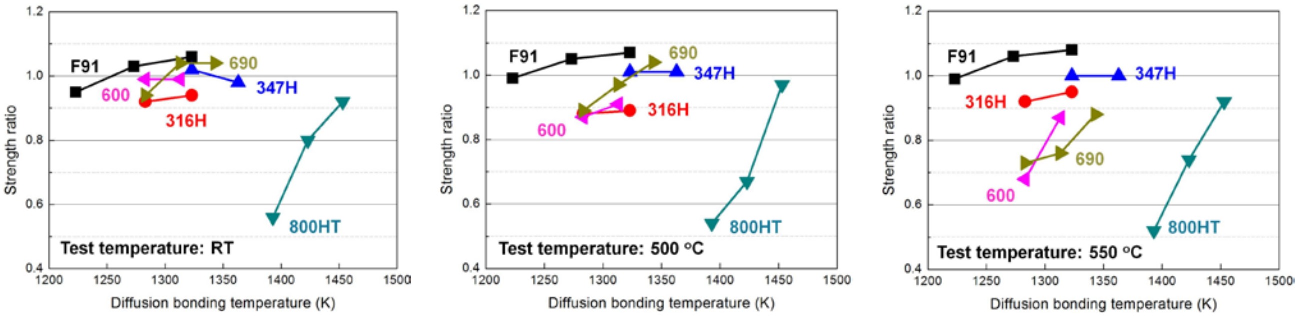
2.2 Characteristics of the as-bonded

Fig. 1 shows the strength ratio of the as-bonded specimens compared to the as-received ones at RT, 500, and 550 ^oC. As shown in the figure, strength ratio increased as the diffusion bonding temperature increases. In all test temperature ranges, strength of the as-bonded F91, SS 316H, and SS 347H was approaching to that of the as-received materials (> 0.9). Also, the location of final failure was in the gauge section off the bond-line. Through the electron microscopic analysis, grain boundary migration across the bond-line was observed. Therefore, the performance of diffusion bonding for these alloys is judged to be sound up to 550 ^oC.

However, for Ni-base alloys, the strength ratio was close to 1 up to 500 ^oC, but decreased to about 0.8 at 550 ^oC. Poor joint quality is thought to be caused by the planar grain boundary and the formation of the precipitates along the bond-line. Such microstructures were previously reported by other researchers on the diffusion bonding of precipitation hardening Ni-base alloys [2-4]. The presence of the precipitates hinders the grain boundary migration between the mating surfaces and could reduce the mechanical properties. Thus, the location of failure was near/at the bond-line at 550 ^oC.
The influence of diffusion bonding temperature on the strength ratio is clearly observed for Incoloy 800HT. While the strength ratio is only about 0.5 if bonded at 1120 ^oC, it increased to above 0.9 at 1180 ^oC. However, the location of failure is still near/at the bond-line even for diffusion-bonded at 1180 ^oC.

Table I: Diffusion bonding conditions

Alloy	Temperature (^oC)	Pressure	Duration time	Surface condition	Remark
F91	950	6 MPa	Hold (10 min) + Pressure (60 min)	SiC #4000	Without interlayer, tempered (720 ^oC/60 min/air cooling)
	1000				
	1050				
SS 316H	1010	8 MPa		SiC #1200	Without interlayer
	1050				
SS 347H	1050	8 MPa		SiC #4000	Without interlayer
	1090				
Incoloy 800HT	1120	10 MPa		SiC #1200	Without interlayer
	1150				
	1180				
Alloy 600	1010	9 MPa		SiC #4000	Without interlayer
	1040				
Alloy 690	1010	9 MPa		SiC #1200	Without interlayer
	1040				
	1070				



(a) (b) (c)

Fig. 1. Influence of the diffusion bonding temperature on the strength ratio at (a) RT, (b) 500 °C, and (c) 550 °C.

2.3 Tensile properties of the as-bonded specimens exposed to S-CO_2 environment

Fig. 2 shows the tensile test results of both the as-received and as-bonded specimens after aged in high temperature S-CO_2 environment. After exposure to the environment up to 1000 h, mechanical properties were somewhat increased or decreased depending on the alloys. However, the changes were not significant, which implies that the bond-line is not severely corroded or carburized at 550 °C.

For the austenitic stainless steels and Ni-base alloys, the resistance to the corrosion and carburization was well recognized by the previous studies [5,6]. Furukawa et al. found that the weight gain of 316FR was significantly lower than that of 12Cr steels, while carbon penetrated slightly into the base metal caused precipitation of $M_{23}C_6$ type carbides [5]. Firouzdor et al. observed discontinuous islands of carburized regions underneath the surface oxide layers which appear to promote delamination of oxide layers from the substrate [6]. However, the depth affected by the carburizing environment was not more than a few μm, so it was thought that the bond-line would not have been degraded severely. For the specimens tested in this study, further microscopic analysis near the bond-line is in progress. The results will be compared to the grain boundaries of the parent matrix.

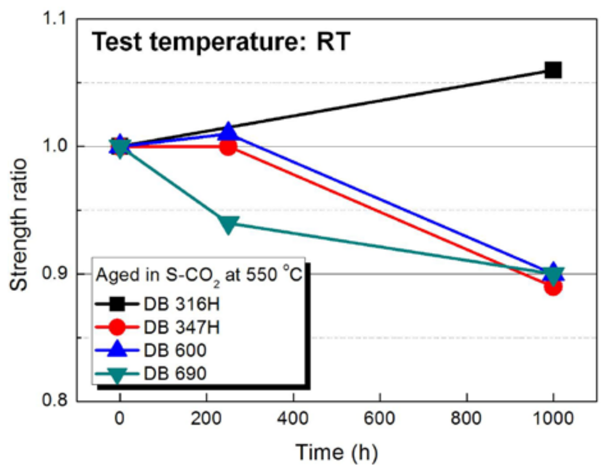


Fig. 2. Strength ratio of the ultimate tensile strength of the as-bonded and the aged in S-CO_2 at 550 °C.

3. Conclusions

Studies on diffusion bonding of candidate alloys for the application of super-critical CO_2 cycle were carried out. Strength ratios were close to 1 for Fe-base alloys (F91, SS 316H, and SS 347H), while those of Ni-base alloys (Alloy 600, Alloy 690) and Fe-Ni-Cr alloy (Incoloy 800HT) were somewhat decreased to about 0.8 due to the planar grain boundary and precipitates formed along the bond-line. After exposure in high temperature S-CO_2 environment for 1000 h, mechanical properties were not changed substantially and the location of the failure was still in the gauge section away from the bond-line for most alloys. Thus, bond-line which plays a role as grain boundary is thought to have superior corrosion and carburization resistance comparable to that of parent matrix.

Acknowledgements

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REFERENCES

[1] V. Dostal M.J. Driscoll, and P. Hejzlar, A Supercritical Carbon Dioxide Cycle for Next Generation Nuclear Reactors, MIT Annual and Progress Reports, MIT-ANP-TR-100, 2004.
[2] D. S. Duvall, W. A. Owczarski, D. F. Paulonis, and W. H. King, Methods for Diffusion Welding the Superalloy Udimet 700, Welding Research Supplement, Vol.51, p.41s, 1972.
[3] G. Zhang, R. S. Chandel, and H. P. Seow, Solid State Diffusion Bonding of Inconel 718, Science and Technology of Welding and Joining, Vol.6, p.235, 2001.
[4] B. Ravisankar, J. Krishnamoorthi, S. S. Ramakrishnan, and P. C. Angelo, Diffusion Bonding of SU 263, Journal of Materials Processing Technology, Vol.209, p.2135, 2009.
[5] T. Furukawa, Y. Inagaki, and M. Aritomi, Compatibility of FBR Structural Materials with Supercritical Carbon Dioxide, Progress in Nuclear Energy, Vol.53, p.1050, 2011.
[6] V. Firouzdor, K. Sridharan, G. Cao, M. Anderson, and T. R. Allen, Corrosion of a Stainless Steel and Nickel-based Alloys in High Temperature Supercritical Carbon Dioxide Environment, Corrosion Science, Vol.69, p.281, 2013.