Effect of Ni-foil Interlayer on Diffusion Bonding of Austenitic Stainless Steels

Ji-Hwan Cha, Sung Hwan Kim, Changheui Jang*
Korea Advanced Institute of Science and Technology (KAIST), Daejeon 34141, Republic of Korea
**Corresponding Author: chjang@kaist.ac.kr*

1. Introduction

The Sodium-cooled Fast Reactor (SFR) is one of the next generation nuclear reactor designs with an operation temperature expected to be 500–550°C utilizing supercritical carbon dioxide (S-CO_2) as the power conversion coolant [1]. Micro-channel heat exchangers with high heat transfer area such as the printed circuit heat exchanger (PCHE) are likely to be adopted to ensure high thermal efficiencies [2]. Such heat exchangers would be fabricated by diffusion bonding of stacked millimeter-thick metal plates having flow channels. Thus, the quality of the diffusion-bond joint is critical to assure heat exchanger performance and integrity.

In terms of materials, SS 316L and Alloy 800H are considered as candidate materials for the heat exchangers. Authors previously found that diffusion bonded austenitic alloys exhibit good bonding properties compared to the base material below 550 °C [3]. However, at higher temperatures, premature failure along the bond-line was observed. This was attributed to formation of precipitates along the bonding interface, which prevented grain boundary migration and resulted in a planar bond-line. Grain boundary migration occurred after diffusion bonding at solid solution temperature. In the cooling procedure of diffusion bonding, solution atoms reconstruct the grain boundary.

In this study, Ni-foil interlayer was applied to diffusion bonding of SS 316L and Alloy 800H in order to remove precipitates and induce grain boundary migration at the bond line to obtain better bond quality and tensile properties. The mechanical integrity of the diffusion bond joints was evaluated by tensile testing at both room temperature and 650 °C. Moreover, the mechanical integrity of the diffusion bond joints will be discussed using results of microstructural analyses.

2. Experimental methods

The chemical compositions of SS 316L and Alloy 800 used in this study as analyzed by inductively coupled plasma (ICP) spectroscopy are listed in Table 1. Blocks of SS 316L, and Alloy 800 were machined with 25 mm in length, 20 mm in width, and 10 mm in thickness (Fig. 1). Prior to diffusion bonding, these blocks were mechanically ground on bonding side with 5000 grit SiC paper and ultrasonically cleaned in ethanol.

Diffusion bonding of these blocks were conducted by a local contractor, TNP Corporation, in the following procedure. The two blocks are installed with the mechanically treated surfaces in contact between uniaxial presses. The chamber is made into a vacuum and heated to the target temperature. The target temperature is held for 10 min for homogenization of the blocks. Then, pressure is applied to the joining pieces, which establishes the joint. Vacuum is maintained during the cooling of the bonded piece to room temperature. The conditions used for diffusion bonding in this study are listed in Table 2.

For evaluation of bonding properties, tensile testing was conducted using mini sized tensile specimens. The mini sized tensile specimens were fabricated from the diffusion bonded blocks with the bond-line located at the center of the gauge length (Fig. 1). Tensile tests were conducted at both room temperature and high temperature (650 °C) at a strain rate of 3.33×10^{-4} s^{-1}. Meanwhile, it should be mentioned that the specimen geometry was not in full accordance with ASME method E8/E8M-13a. In the section 3, bonding conditions were abbreviated as follow, As-received=AR, As-bonded=AB, bonded with Ni-foil interlayer=NB.

For microstructural analyses of the bond-line, analytical methods such as scanning electron microscopy (SEM, FEI Magellan400) equipped with energy dispersive X-ray spectroscopy (EDS) were utilized.

Table 1. Chemical composition of SS 316L, and Alloy 800H.

wt.%	Fe	Cr	Ni	C	Ti	Mo	Al
SS 316L	Bal.	15.74	10.09	0.016	-	2.04	0.03
Alloy 800H	45.79	20.12	31.85	.07	.51	-	.49

wt.%	Mn	Si
SS 316L	1.28	0.34
Alloy 800H	.87	.17

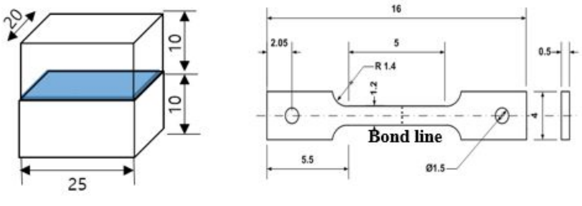

Fig. 1.Geometry and dimensions of diffusion bonded blocks and mini sized tensile specimens (in mm).

Table 2. Diffusion bonding conditions

Alloy	**Temperature**	**Pressure**	**Bonding duration**	**Surface condition**	**Interlayer**
316L	1050 °C	8 MPa	1 h	5000 grit SiC	None
					5 µm Ni-foil
800H	1150 °C	10 MPa	1 h	5000 grit SiC	None
					5 µm Ni-foil

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3. Results and discussion

The bond efficiency of the diffusion bonded specimens was evaluated by comparison of tensile properties to that of the base metal (AR). Fig. 2 shows the result of tensile testing at room temperature and 650 °C. At room temperature (RT), the ultimate tensile strength (UTS) and elongation of AB, and with 5 µm NB specimens are lower than AR for SS 316L. Especially, the elongation of AB and with 5 µm NB specimens are 70 %, 62 % of AR, respectively. At 650 °C, even though the UTS and elongation also have lower values than those of AR, the UTS and elongation values were more similar to those of AR than RT condition.

Fig. 3 shows the resulting microstructures after diffusion bonding of SS 316L for AB and with 5µm NB. The AB condition showed migration of grain boundaries, despite it having many precipitates at the bonding interface. The remaining precipitates at the bonding interface may be responsible for deteriorating tensile properties of diffusion bonded joints. EDS line scanning was conducted around the bond line. The result of scanning showed that the Cr, Mn peaks had high value than other contents. Meanwhile, the very small size of the precipitates made clear identification difficult.

In case of with 5 µm NB condition, migration of grain boundaries was observed. There were no precipitates around the bonding interface unlike the AB condition. However, Ni foil could clearly be found at the bonding interface. EDS line scanning across the bond-line showed high Ni contents at the bonding interface, indicating that the Ni foil did not diffuse completely into the matrix. This chemical inhomogeneity may be responsible for deteriorating tensile properties. Meanwhile, it could be seen that Cr of the base metal also diffused into the Ni-foil. This implies that the Ni-foil interlayer would not deteriorate corrosion resistance at the bond-line.

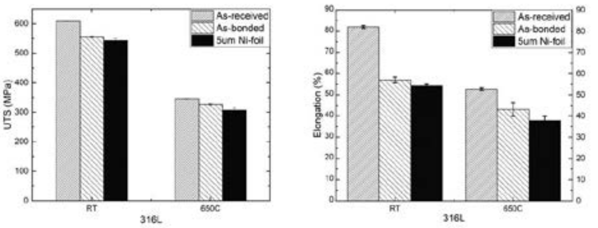

Fig. 2. Ultimate tensile strength (UTS) and elongation of SS 316L at room temperature and 650 °C.

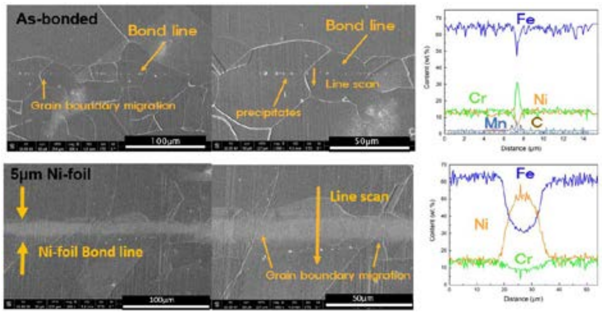

Fig. 3. SEM micrographs and EDS line scanning of diffusion bonded SS 316L (AB, and with 5 µm NB)

Fig. 4 shows the result of tensile testing at room temperature and 650 °C for Alloy 800H. At room temperature (RT), the ultimate tensile strength (UTS) and elongation of AB, and with 5 µm NB are similar to AR. The UTS and elongation of AB and with 5 µm NB specimens were almost same value compared to AR specimens. At 650°C, the UTS and elongation AB condition had lower value than of AR. In case of with 5 µm NB condition, the UTS, and elongation were similar to those of AR. It showed that the elongation of with 5µm NB condition significantly improved at 650 °C.

Fig. 5 shows the resulting microstructures after diffusion bonding of Alloy 800H for AB and with 5µm NB. In the case of AB condition, there were precipitates at the bonding interface and no migration of grain boundaries beyond the interface. EDS line scanning across the bond-line showed that Cr, Ti, C, and O peaks occupied a high portion near the bonding interface. In previous works, these precipitates were reported as Ti (C, N) and $Cr_{23}C_6$ precipitates [3]. Duvall et al. also found the existence of Ti-rich precipitates to deteriorate bond quality and utilized Ni interlayer to prevent their formation [4].

In case of with 5 µm NB condition, it is difficult to distinguish the interlayer unlike SS 316L at bond interface. Although some precipitates were formed at the Ni-foil and matrix interface, the size and amount of the precipitates were much smaller than those of AB. More importantly, insertion of Ni-foil interlayer resulted in migration of grains at the bonding interface. EDS line scanning showed that the Ni diffusion to the base metal is greater for Alloy 800H compared to SS 316L. This may be associated with differences of the base metal composition, or simply as diffusion bonding temperature was higher for Alloy 800H. Nonetheless, it should be noted that chemical inhomogeneity remains, which indicate the necessity to optimize the interlayer thickness and bonding temperature for a sound diffusion bond.

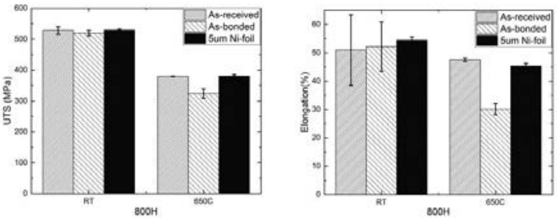

Fig. 4. Ultimate tensile strength (UTS) and elongation of Alloy 800H at room temperature and 650 °C.

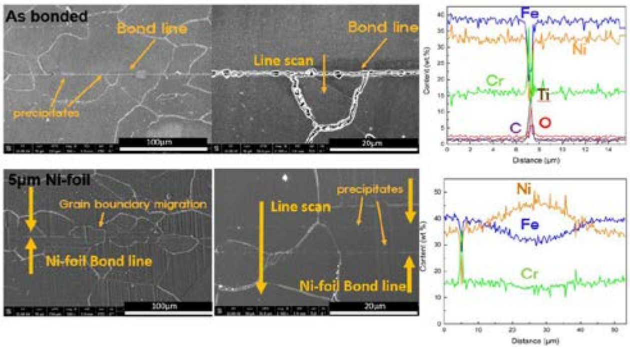

Fig. 5. SEM micrographs and EDS line scanning of diffusion bonded Alloy 800H (AB, and with 5 μm NB)

4. Conclusion

In this study, Ni-foil interlayer was applied to SS 316L and Alloy 800H before diffusion bonding in order to remove precipitates and induce grain boundary migration at the bond line to obtain better bond quality. Based on the tensile tests and microstructural analyses, the following conclusions could be drawn.

(1) Diffusion bonding without Ni-foil interlayer resulted in precipitate formation across the bond interface for both alloys. Still, migration of grain boundaries across the bond-line occurred for SS 316L. On the other hand, a planar bond-line could be observed for Alloy 800H, as the extent of precipitate formation was more severe for Alloy 800H.

(2) Ni-foil interlayer seems to be an effective method for removing precipitates and recovering tensile properties, given that appropriate bonding temperature and thickness are selected. However, the small amount of precipitates still remains, despite using Ni-foil interlayer.

(3) For a good diffusion bond, achieving appropriate Ni interlayer thickness for each material and chemical composition homogeneity were crucial. Inhomogeneity between bonding interface and base metal of SS 316L caused premature fracture at the bond line during tensile testing.

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