Effect of post-bond heat treatment on the diffusion bonding properties of Alloy 800H with Ni-foil interlayer

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1. Introduction

A supercritical carbon dioxide (S-CO_2) power conversion system is considered for a sodium-cooled fast reactor (SFR) with operating temperatures of 500 – 550 ℃ [1]. Micro-channel heat exchangers with high heat transfer areas, such as printed circuit heat exchanger (PCHE), are likely to be designed for higher heat efficiencies in S-CO_2 cycle [2]. The heat exchanger is fabricated by stacking and diffusion bonding of millimeter-thick metal plates with flow channels. Therefore, the quality of the diffusion-bond joint is important for ensuring structural integrity of heat exchangers.

Alloy 800H is considered as structural materials for the PCHEs. Below 550 ℃, the tensile properties of diffusion bonded austenitic alloys are comparable to that of base materials [3]. However, the tensile property, especially ductility decreased considerably above 550 ℃ due to the presence of precipitates on the bond-line. Recently, the application of Ni-foil interlayer to diffusion bonding moderately prevented the formation of precipitates on the bond-line, and showed better bond quality and tensile properties [4]. Nevertheless, the chemical inhomogeneity due to Ni enrichment and precipitation along the bond-line would affect the integrity of joint. In this study, post-bond heat treatment was applied to diffusion-bonded 800H with Ni-foil interlayer to induce the dissolution of precipitates and Ni homogenization at the bond-line to obtain better bond quality. The mechanical property of the joints was evaluated by tensile testing at room temperature and 650 ℃. Furthermore, the effects of post-bond heat treatment will be discussed using the microstructural changes.

2. Experimental methods

The chemical composition of Alloy 800H used in this study as analyzed by the inductively coupled plasma (ICP) spectroscopy is given in Table I. Blocks of as-received Alloy 800H were fabricated with a dimension of 25 mm in length, 20 mm in width, and 10 mm in thickness (Fig. 1). The bonding side of the blocks were mechanically ground with 5000 grit SiC paper and ultrasonically cleaned in ethanol. The diffusion bonding of blocks was carried out by TNP Corporation, Changwon. The two blocks were installed with mechanically polished surfaces facing each other and a thin Ni-foil of 5 μm thickness was placed in-between. The conditions used for diffusion bonding in this study are listed in Table II. After diffusion bonding, post-bond heat treatments (PBHT) were applied in a high temperature air furnace followed by air-cooling. The details of the PBHT conditions (HT-A, HT-B) used in this study are listed in Table III, based on the solution annealing and carbide dissolution temperatures for Alloy 800H.

Tensile test was conducted using mini sized tensile specimens for evaluating the bonding properties. 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 ℃) 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. The tensile properties of the Ni-foil interlayer diffusion bonded (DB) and PBHT (HT-A and HT-B) specimens were compared with as-received (AR) and as-bonded (AB) Alloy 800H. DB and PBHT (1200 ℃, 1 h) = HT-B. For microstructural analyses of the bond-line, analytical methods such as scanning electron microscopy (SEM, FEI SU5000) equipped with energy dispersive X-ray spectroscopy (EDS) was utilized.

Table I: Chemical composition of Alloy 800H (in wt.%).

Fe	Cr	Ni	C	Ti	Al	Mn	Si
Bal.	20.12	31.85	.07	.51	.49	.87	.17

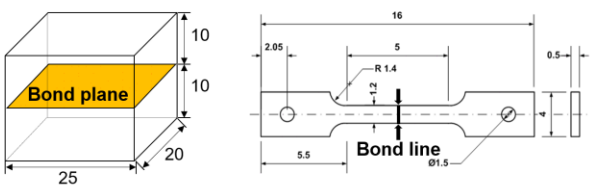

Fig. 1. Geometry and dimensions of diffusion bonded blocks and mini sized tensile specimens (in mm).

Table II: Diffusion bonding condition for Alloy 800H.

Alloy	Temperature	Pressure	Duration time	Interlayer
800H	1150 ℃	10 MPa	1 h	5 μm Ni foil

Table III: Post-bond heat treatment (PBHT) conditions for Alloy 800H

Heat treatment	Temperature	Dwell time	Cooling method
HT-A	1100 °C	10 h	Air cooling
HT-B	1200 °C	1 h	

3. Result and discussion

Fig. 2 shows the results of tensile tests performed at room temperature (RT) and 650 °C for Alloy 800H for the evaluation of bond quality. At RT, the ultimate tensile strength (UTS) of DB is similar to that of AR condition, while the PBHT specimens show decreased UTS, particularly for HT-B. The decrease in tensile strength can be attributed to the coarsening of grains and dissolution of precipitates during PBHT. Meanwhile, the elongation of the AB 800H dropped considerably at 650 °C, which was recovered by the presence of Ni-foil interlayer (DB). The PBHT specimens further increased the elongation of Alloy 800H, in which the HT-B condition exhibited significant improvement with an elongation of 60 %.

Fig. 3 shows the results of SEM microstructural analysis of DB and PBHT specimens. In case of DB condition, a pair of bond-lines can be observed from the Ni-foil placement in-between the blocks during diffusion bonding. At higher magnifications, several Ti-rich carbide and Al-rich oxide precipitates were noticeably present along the bond-lines. Ni was enriched at the bond-line corresponding to the presence of Ni-foil interlayer, while some instance of grain boundary migration was present around the bond-lines. It suggests that the homogenization of Ni was not complete during the diffusion bonding process.

For the HT-A condition, the grain growth was more pronounced leading to increased occurrences of grain boundary migration. The bond-lines in HT-A were less clearly noticed compared to the DB condition, attributed to the reduction of thickness of the Ti-rich carbides at the bond-line. The reduction in thickness suggests the dissolution or lower stability of those precipitates from the PBHT. In addition, the EDS line scan shows that the Ni enrichment reduced to some extent compared to the DB condition. For the case of HT-B, the grain growth was significant compared to previous conditions, leading to increased grain boundary migration. The bond-lines were also less clearly noticed from the reduction of Ti-rich carbides along the bond-line. The extent of reduction in Ni enrichment is comparable to that of HT-A condition, indicating that increased PBHT duration is required for reducing the chemical inhomogeneity.

Fig. 4 shows the Thermo-Calc phase stability calculation of the TiC precipitates in Alloy 800H. It can be observed that the fraction of TiC precipitates decreases with increasing temperature, similar to the observation from PBHT conditions. However, complete dissolution of TiC precipitates is feasible only at temperatures closer to the solidus temperature. The reduction of Ti-rich carbides along the bond-line can be attributed for the improved tensile ductility at 650 °C for PBHT specimens. Previously, Duvall et al. reported that Ti-rich precipitates play a considerable role in degrading the bond quality [5]. Based on the observations, the shorter PBHT at 1200 °C (HT-B) contributed to higher elongation than longer PBHT at 1100 °C (HT-A), suggesting that exposures to increased temperature for shorter durations can be an effective method for recovering the tensile ductility. It must be also noted that the PBHT temperature and duration must be optimized to avoid excessive grain growth leading to decreased tensile strength.

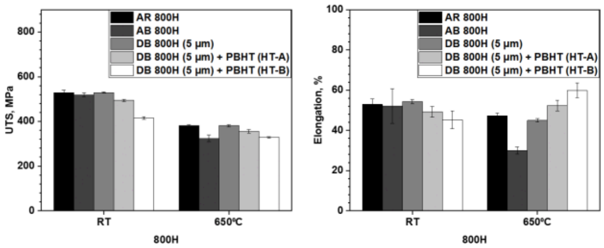

Fig. 2. Ultimate tensile strength (UTS) and elongation of Alloy 800H at room temperature and 650°C.

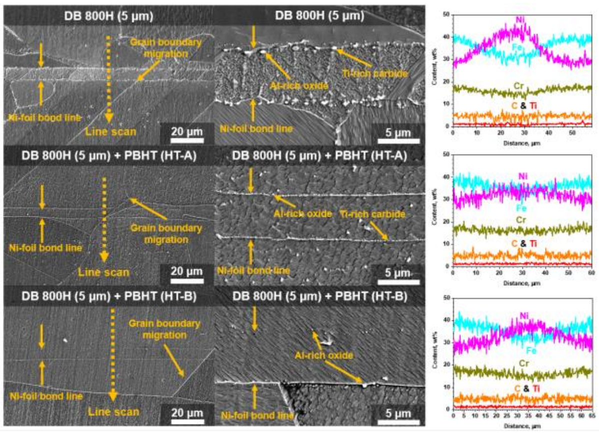

Fig. 3. SEM micrographs and EDS line scanning of diffusion bonded Alloy 800H (DB, HT-A, and HT-B).

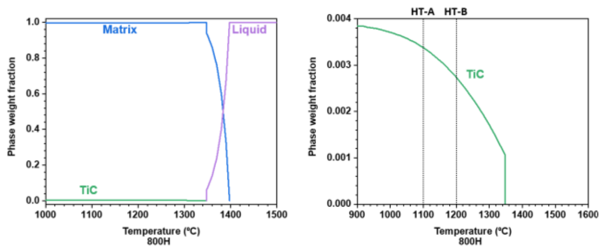

Fig. 4. Thermo-Calc (TCFE9 database) phase stability calculation for Alloy 800H.

4. Conclusions

This study aims to improve the bonding efficiency by applying PBHT to the diffusion-bonded Alloy 800H with Ni-foil interlayer. Two PBHT conditions: HT-A (1100 °C for 10 h) and HT-B (1200 °C for 1 h) were evaluated in this study. Based on the tensile tests and microstructural analysis, the following conclusions could be drawn.

(1) The Ni-foil interlayer recovered the tensile ductility at 650 °C for the diffusion bonded Alloy 800H. However, several Ti-rich carbide and Al-rich oxide precipitates along with the enrichment of Ni were present along the bond-line.

(2) The PBHT treatment further increased the tensile ductility, while slightly decreased the tensile strength, with increased effect in HT-B condition. The microstructural analysis showed reduction in the Ti-rich carbide precipitation along the bond-line and several occurrences of grain boundary migration. The increased ductility was attributed to the dissolution of Ti-rich carbides and the decreased strength from the grain coarsening. The enrichment of Ni decreased to some extent from the PBHT.

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