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Microstructure and mechanical property change of dissimilar metal welds Alloy 600 – Alloy 182 – A508 Gr. 3 according to thermal aging effect at 400ºC

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1. Introduction

Nowadays, Korean nuclear power plants (NPPs) are getting older. Especially primary circuit of pressurized water reactor (PWR) has a severe problem related with stress corrosion cracking (SCC).

Among several key components in primary circuit, special attention should be paid to head penetration nozzles and associated dissimilar metal weld (DMW) joints between nickel based alloy and low-alloy steel in control rod drive mechanism (CRDM) of reactor pressure vessel since a number of cracking and coolant leakage incidents occurred in recent years. [1-2]

For CRDM, penetration nozzles consist of several materials such as DMWs. Austenitic Alloy 600 has been used as a material of reactor pressure vessel (RPV) penetration nozzle and steam generator (SG) nozzle at primary circuit. Alloy 182, which has similar chemical composition with that of Alloy 600, has also been used as a filler metal joining Alloy 600 with low-alloy steel A508 Gr.3. [1]

As time goes by, material degradation under the challenging conditions causes many issues, for examples, accidently shutting down or crucially economical loss.

To prevent such critical matters above mentioned, investigation about degradation mechanism of materials by thermal aging should be conducted. However, there are no sufficient studies on this field. Therefore, the final goal of this study is to investigate microstructure along the DMW undergone thermal aging process.

Firstly, in order to get a reference data for further comparison analysis which is expected to show degradation mechanism of the weld joint, un-heated weld joint was investigated with several instruments, Vickers hardness tester, scanning electron microscope (SEM), and an energy-dispersive X-ray spectrometer (EDS).

2. Experimental Procedure

2.1 Materials and specimens

By joining Alloy 600 and A508 Gr. 3 with Alloy 182 serving as dissimilar filler metal, representative mock-up sample was fabricated with welding process which was qualified by the American Society of Mechanical Engineers (ASME) [3].

Alloy 600 and buttered A508 Gr. 3 block were joined by Alloy 182 filler. Chemical compositions of each metal is shown in Table 1. Welded bulk sample was cut to prepare as-welded and heat treated samples.

In this study, investigation was conducted with as-welded sample. Further study will be done by using heat treated sample. For this future plan, thermal aging process is now ongoing.

$$\frac{t_{aging}}{t_{ref}} = exp\left[-\frac{Q\left(\frac{1}{T_{ref}} - \frac{1}{T_{aging}}\right)}{R}\right]$$

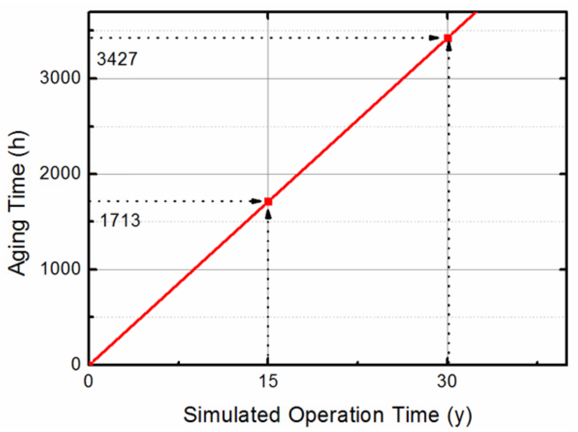
t_{aging} = Aging time [hr]
t_{ref} = Simulated operation time [hr]
T_{aging} = Aging temperature [K]
T_{ref} = Simulated operation Temperature (320ºC) [K]
R = Gas Constance [kJ/mol]
Q = Activation Energy for Cr diffusion (about 125kJ./mol)

Figure. 1. Diffusion equation for calculate the relation between temperature and time of reference case and aging case.

Heat treatment simulates aged DMWs which are used during 15-y and 30-y in the nuclear power plant (operating at temperature about 320°C). Aging temperature and aging time are calculated under diffusion equation in Fig. 1.

Table 1. Chemical composition (in wt. %) of dissimilar metal welds used in this study

Material	Composition									
	C	Si	Mn	P	S	Fe	Cu	Ni	Cr	etc
Alloy 600	0.06	0.30	0.07	-	0.001	8.13	0.01	74.9	15.6	-
Alloy 182	0.05	0.37	7.42	0.01	0.01	4.48	0.01	70.9	14.9	1.77Nb+Ta 0.03Ti
A508 Gr.3	0.19	0.22	1.33	0.008	0.002	Bal.	0.02	0.91	0.19	0.47Mo, 0.02Al, 0.003V



Specimen I.D.	t_{ref}	t_{aging}, T_{aging}
As-welded	-	-
HT400_Y15	15-yr	1713-hr at 400°C
HT400_Y30	30-yr	3427-hr at 400°C

Figure. 2. Aging time at the temperature 400°C to simulate 15-y and 30-y at the temperature 320°C in nuclear power plant respectively.

This formula is started from the idea if the diffusion lengths are equal, the aging effects will be also same. For the target component to be applied, chromium is selected since it has a significant role to form SCC. Therefore, the activation energy (Q) is chosen as 125kJ/mol, was used in the Ni based weld metals [4].

The aging temperature is limited to 450°C since unwanted microstructure phases – such as sigma phase – can be formed when temperature becomes higher than that much. To verify effect of long-term thermal aging, the temperature of thermal aging was selected to 400°C.

According to the abovementioned values for the diffusion equation, the finally calculated aging time for 15-y at 320°C is 1713-hr at 400°C and the aging time for 30-y at 320°C is 3427-hr at 400°C.

2.2 Experimental procedure

The specimens cut from as-welded mock-up sample were grounded and polished with emery paper up to 800 grit, diamond paste up to 1 μm, and finally 0.02 μm colloidal silica to make flat surface with minimal mechanical deformation.

Micro-hardness was measured by Vickers micro-hardness tester using a load of 1.0 kgf (i.e. $HV_{1.0}$). Hardness measurements were conducted from Alloy 600 to A508 Gr. 3.

The specimen for microstructure analysis was etched in solution of 20% HNO_3 + 80% HCl about 3 min. Microstructural characterization was conducted by using FEI Nanonova 230 field emission SEM with attached EDS.

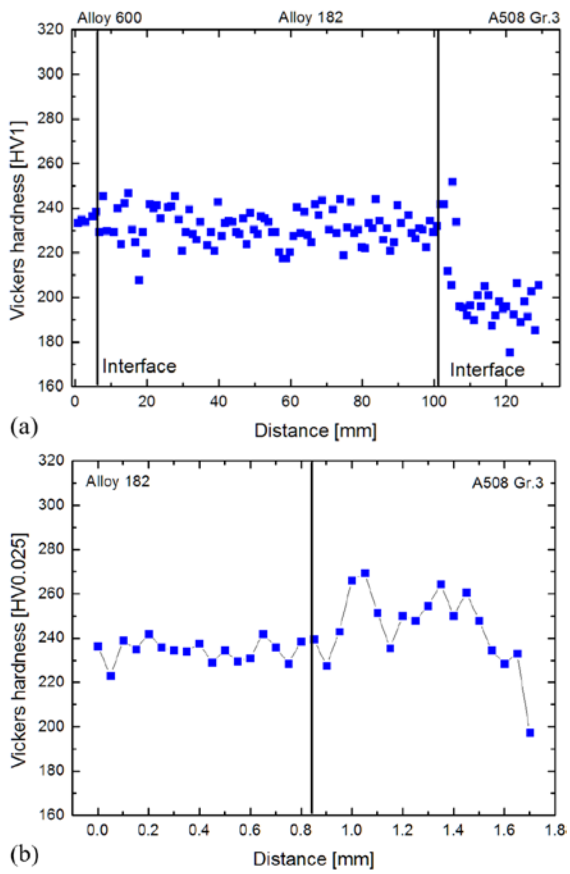


Figure. 3. Distribution of Vickers hardness on (a) whole range of DMW, (b) narrow range at the interface between Alloy 182 and A508 Gr.3

3. Results and Discussions

3.1 Microhardness

Fig. 3 (a) shows the distribution of measured Vickers microhardness values on whole region of DMW, it is observed that the microhardness of Alloy 600 and Alloy 182 are generally larger than that of A508 Gr. 3 base metal. Also, the very right side of the interface between Alloy 182 and A508 Gr. 3 has higher peak of hardness compared with remained part of A508 Gr.3. Vickers hardness on Alloy 182 is around $232HV_{1.0}$, and that of A508 Gr. 3 base metal is around $197HV_{1.0}$.

To observe the tendency of hardness change on the interface, more precise measurement was done. Fig. 3 (b) is the microhardness of narrow region of the interface between Alloy 182 and A508 Gr.3 by using lighter load of $HV_{0.025}$. The largest peak of A508 Gr. 3 is around $270HV_{0.025}$. This value is larger than that of Alloy 182 and A508 Gr.3 near the interface.

This result can give an insight of general material properties about ductility. Moreover, the highest hardness part near the fusion boundary (FB) can be possibly degraded by thermal aging with combination of weld thermal history. Local loss of ductility judged from hardness is more problematic in terms of structural integrity, synergistically combined with effect of thermal aging near FB. Therefore, it is considered that thermal aging can cause degradation on high hardness region.

3.2 Microstructure

Fig. 4 shows SEM images of four distinguished regions between FB and heat affected zone (HAZ) in A508 Gr. 3; coarse-grained HAZ having larger lath martensite, fine-grained HAZ having smaller lath martensite, intercritical HAZ having partial transformation to austenite, and subcritical HAZ having almost similar structure with base metal. Larger lath martensite structure is changed into bainite (base metal) consisting of ferrite and cementite. Comparing profile of microhardness measurement shown in the previous section, peak of microhardness corresponds to coarse-grained HAZ and very fine grains (allotriomorphic or idiomorphic ferrite) in Martensite/Upper bainite mixture [5], and relatively low microhardness region is bainite structure in HAZ.

Fig. 5 (a) is the basic microstructures of Alloy 600, the interface between Alloy 600 and Alloy 182, and Alloy 182.

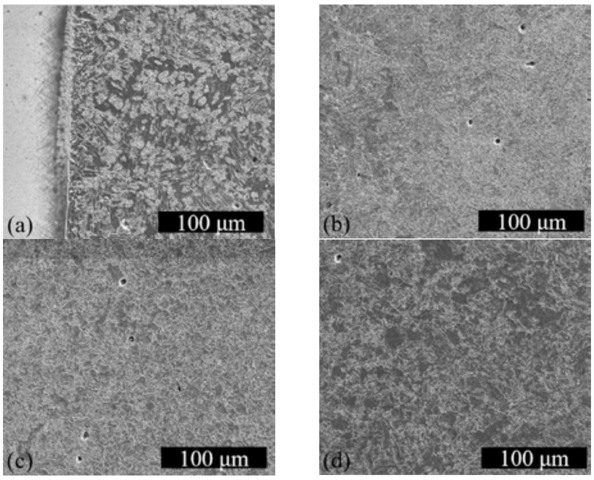


Figure. 4. Microstructures of A508 Gr. 3 which have (a) coarse-grained HAZ, (b) fine-grained HAZ, (c) intercritical HAZ, and (d) subcritical HAZ structure respectively

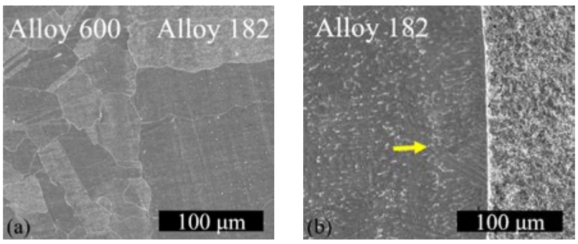


Figure. 5. Microstructure of (a) the interface between Alloy 600 and Alloy 182 weld metal, (b) the interface between Alloy 182 and A508 Gr.3 weld metal. The yellow arrowed line is Type-II boundaries.

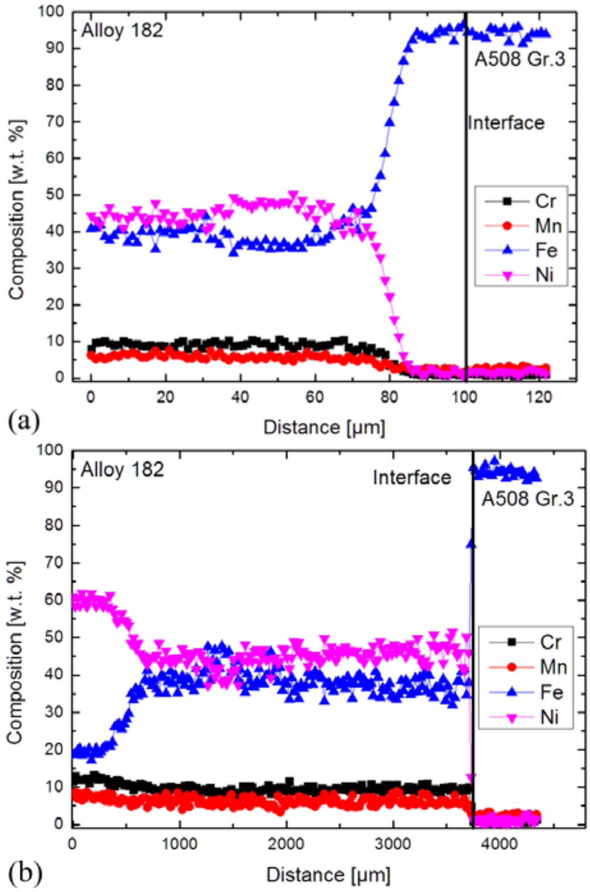


Figure. 6. EDS linear profile along the interface between Alloy 182 and A508 Gr. 3 at (a) high magnification and (b) low magnification.

Alloy 600 has austenitic structure with large grain size, and Alloy 600 HAZ has almost same grain size and microstructure with that of base metal. Alloy 182 weld metal has austenitic dendrite structure which is observed at distant point from FB, and no certain characteristics were observed up to the interface between Alloy 182 and Alloy 600.

Fig. 5 (b) shows the interface between Alloy 182 and A508 Gr. 3. Alloy 182 weld metal has austenitic dendrite structure which is common structure of weld metal. And the pointed line by yellow arrow is Type-II boundaries, parallel to FB, which are observed within 100 μm. Type-II boundaries are known as more susceptible to material degradation because of several factors, such as grain boundary misorientation and high lattice distortion energy [2].

Fig. 6 shows EDS elemental analysis across weld joint. Significant compositional gradient for whole elements including chromium, iron and nickel was observed at the interface between Alloy 182 and A508 Gr. 3. However, in Fig. 6 (a) there are some difference between EDS result and the chemical composition of the material used in this experiment shown on Table 1. In Fig. 6 (b) the chromium dilution zone was observed about 3000 μm from the FB to Alloy 182.

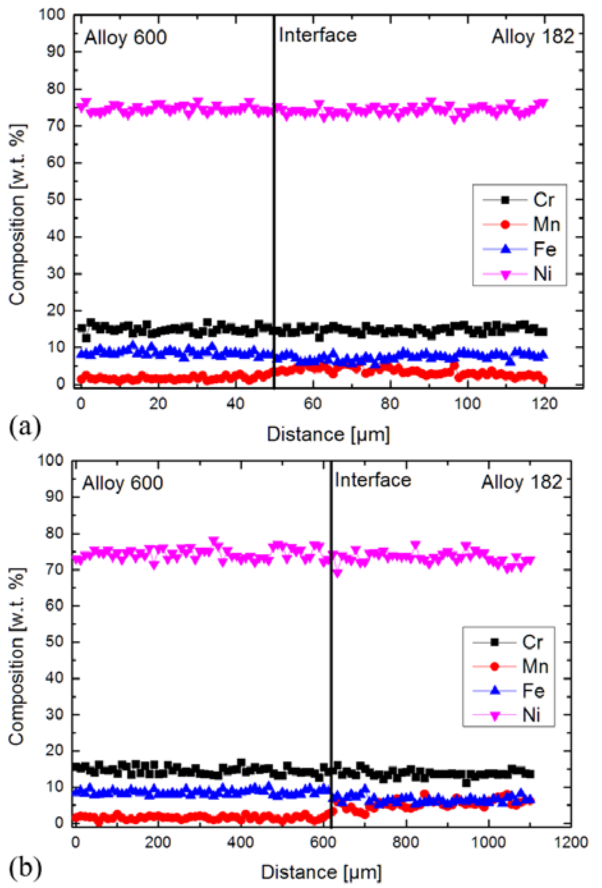


Figure. 7. EDS linear profile along the interface between Alloy 600 and Alloy 182 at (a) high magnification and (b) low magnification.

After that zone, the chemical composition becomes same with the value of Table 1.

In Fig. 7, on the other hand, the interface between Alloy 600 and Alloy 182 has no such a change in chemical composition like that of Alloy 182 and A508 Gr. 3. Since Alloy 600 and Alloy 182 have almost same composition as shown in Table 1.

This study investigates some basic properties of dissimilar metal weld Alloy 600 – Alloy 182 - A508 Gr. 3 as a reference data for further experiments which will consider long-term thermal aging effect on each results.

4. Conclusions

Detail instrumental analysis in Alloy 600 – Alloy 182 - A508 Gr. 3 DMW joint were performed in order to investigate microstructure and mechanical properties of material. Following conclusions can be drawn from this study. Alloy 182 has austenitic dendrite structure which is formed by heat flow during welding process. Type-II boundaries were observed at the interface between Alloy 182 and A508 Gr. 3. Chemical composition shows rapid transition at the interface which makes 3000 μm of chromium dilution zone.

Microstructure of A508 Gr. 3 was investigated from the interface between Alloy 182 to base metal. HAZ were observed near the interface and this was classified by phase and grain size which were vary by distance from the interface. Coarse-grain and fine-grain HAZ seems to have highest hardness at A508 Gr. 3.

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