Journal of Nuclear Materials 471 (2016) 8–16

Contents lists available at ScienceDirect

Journal of Nuclear Materials

journal homepage: www.elsevier.com/locate/jnucmat

Fusion boundary precipitation in thermally aged dissimilar metal welds studied by atom probe tomography and nanoindentation

Kyoung Joon Choi [a], Taeho Kim [a], Seung Chang Yoo [a], Seunghyun Kim [a], Jae Hyuk Lee [b], Ji Hyun Kim [a, *]

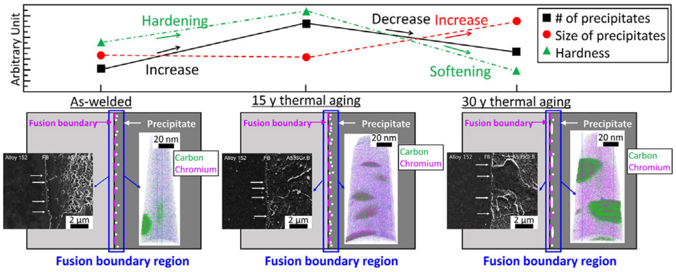
[a] *School of Mechanical and Nuclear Engineering, Ulsan National Institute of Science and Technology (UNIST), UNIST-gil 50, Banyeon-ri, Eonyang-eup, Ulju-gun, Ulsan, 44919, Republic of Korea*

[b] *Institute for Nanomaterials Technology (NINT), Pohang University of Science and Technology (POSTECH), Cheongam-ro 77, Nam-gu, Pohang, Gyeongbuk, 37673, Republic of Korea*

HIGHLIGHTS

- Effects of long-term thermal aging was investigated in fusion boundary.
- Mechanical and microstructural change by long-term thermal aging was investigated.
- Thermal aging and chemical gradient cause Cr diffusion and Cr rich precipitation.
- In early stage of thermal aging, increased number of precipitates induces hardening.
- In later stage of thermal aging, coarsened size of precipitates causes softening.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 2 December 2015
Received in revised form
28 December 2015
Accepted 31 December 2015
Available online 4 January 2016

Keywords:
Dissimilar metal weld
Thermal aging
Precipitation
Atom probe tomography
Nanoindentation

ABSTRACT

In this study, microstructural and mechanical characterizations were performed to investigate the effect of long-term thermal aging on the fusion boundary region between low-alloy steel and Nickel-based weld metal in dissimilar metal welds used in operating power plant systems. The effects of thermal aging treatment on the low-alloy steel side near the fusion boundary were an increase in the ratio of Cr constituents and Cr-rich precipitates and the formation and growth of $Cr_{23}C_6$. Cr concentrations were calculated using atom probe tomography. The accuracy of simulations of thermal aging effects of heat treatment was verified, and the activation energy for Cr diffusion in the fusion boundary region was calculated. The mechanical properties of fusion boundary region changed based on the distribution of Cr-rich precipitates, where the material initially hardened with the formation of Cr-rich precipitates and then softened because of the reduction of residual strain or coarsening of Cr-rich precipitates.

1. Introduction

In recent years, stress corrosion cracking (SCC) of nickel-based weld metal in commercial power plants has been reported, and the initiation and growth of SCC have been acknowledged in the nickel-based weld metal of dissimilar metal welds (DMWs). The

---

* Corresponding author.
E-mail address: kimjh@unist.ac.kr (J.H. Kim).

http://dx.doi.org/10.1016/j.jnucmat.2015.12.047
0022-3115/© 2016 Elsevier B.V. All rights reserved.

corrosion resistance of welds composed of weld metal may be inferior to that of a properly annealed base metal for reasons such as microsegregation, precipitation, and the formation of an unmixed zone [1]. To prevent SCC incidents, the Cr concentration of the nickel-based weld metal can be increased. In the manufacture of DMWs for high-energy systems, high-Cr weld metal is frequently used as a dissimilar weld metal to join low-alloy steel pressure vessel nozzles and steam generator nozzles to nickel-based wrought alloy or austenitic stainless steel components. The thermal expansion coefficient of the weld metal lies between those of the substrates, i.e., a nickel-based wrought alloy and a low-alloy steel. This feature also significantly retards C diffusion from the ferrite base metal to the weld metal [2–4]. No SCC has occurred in DMWs where a high-Cr weld metal is used as the weld metal in the weld between the nickel-based alloy and a low-alloy steel.

However, current operational experience is thought to be too short to justify the conclusion that high-Cr weld metals are perfectly immune to SCC. Because of dilution effects in the dilution zone and in the fusion boundary (FB) region near the low-alloy steel, the reduced Cr content can increase the corrosion and SCC susceptibility of the bulk weld metal [5–8].

Although serious cracking issues may not occur in as-welded materials, thermal aging may change the local microstructure and decrease the cracking resistance or strength. In particular, among weld joints, the FB region is expected to be the most susceptible to thermal aging effects owing to the chemical gradient formed during welding. For these reasons, thermal aging effects in the FB region were previously investigated with an as-welded and aged weld joint, which was treated at 400 °C and 450 °C for times equivalent to 15 y and 30 y service times of power plants [6,9,10]. In thermal aging, the basic principle is to ensure the same diffusion length of Cr (or the same Cr concentration) in the aged specimens at different temperatures. Cr-rich precipitates in the FB region were observed to form and grow by the thermal aging heat treatment in weld joints treated at the two different temperatures. However, the effects of thermal aging seemed to be more dominant in the aged weld joint at 450 °C than in the one treated at 450 °C.

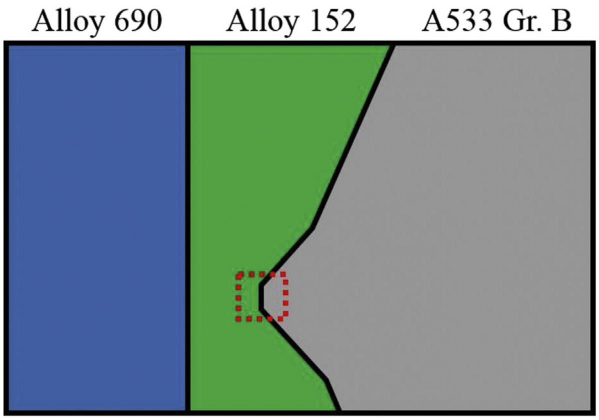
Thus, this study aims (a) to evaluate the simulation of thermal aging effects, which cause an increase in Cr and the formation and growth of Cr-rich precipitates in the FB region between Alloy 152 Ni-based weld metal and A533 Gr. B low-alloy steel, and (b) to investigate the effects of thermal aging heat treatment on the material properties of the FB region with nanoindentation. Additionally, the activation energy for Cr diffusion in the FB region was calculated based on 3D atom probe tomography (3D APT) results.

Ultimately, such data will be important for assessing the effects of aging on structural components and for evaluating the long-term operation of commercial power plants.

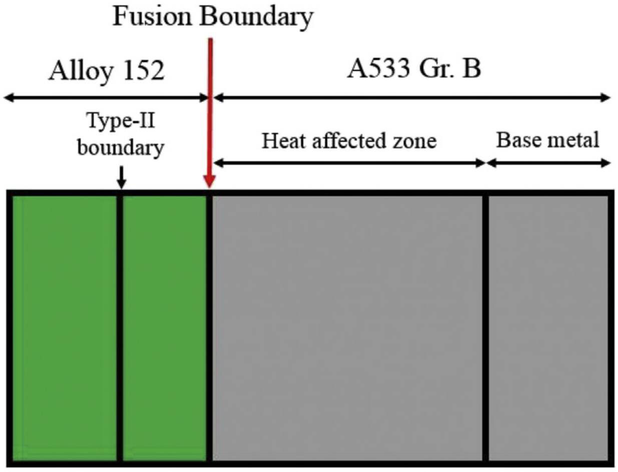
2. Experimental

2.1. Materials and sample preparation

Some of the DMW joints used in the earlier study were used in this study [6,9–15]. By joining Alloy 690 and A533 Gr. B with Alloy 152, which served as the dissimilar filler metal, a representative mockup sample was fabricated at Argonne National Laboratory (ANL), based on ASME Section IX. First, A533 Gr. B was coated with Alloy 152 weld metal, which formed three buttering layers. Once the low-alloy steel block was buttered with Alloy 152, a post-weld heat treatment was performed at 607–635 °C for 3 h. Next, Alloy 690 and the buttered low-alloy steel block were joined by Alloy 152 weld metal (Fig. 1). The chemical compositions of both metals are shown in Table 1.



(a) Cross section of a dissimilar metal weld



(b) Analysis area (magnification of the red dotted region in (a))

Fig. 1. Representative dissimilar metal weld consisting of Alloy 690, Alloy 152, and A533 Gr. B steel.

The bulk sample of the weld joint was cut to prepare the sample for thermal aging heat treatment. This treatment was applied to the partial samples to simulate aged DMWs during the typical 15 and 30 y lifespans of a power plant system (operating at a temperature of about 320 °C). The aging temperature is limited to a maximum of 450 °C because unwanted microstructure phases, such as the sigma phase, can be formed above that temperature. To verify the effects of temperature and time on thermal aging and evaluate the simulation of the thermal aging effects, the heat treatment temperatures selected were 400 and 450 °C.

An activation energy of 125 kJ/mol was used in the Ni weld metals, which had a chemical composition similar to that of the materials in the region near the FB [3,9,10]. The aging time was determined using the following Arrhenius equation of thermal diffusion [16,17].

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

t_{aging} = Aging Time [h]
t_{ref} = Service Time at Operation Temp. [h]
T_{aging} = Aging Temp. [K]