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Effect of neutron irradiation on the mechanical properties of weld overlay cladding for reactor pressure vessel

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ABSTRACT

This study investigates the effects of high fluence neutron irradiation on the mechanical properties of two types of cladding materials fabricated using the submerged-arc welding and electroslag welding methods. The tensile tests, Charpy impact tests, and fracture toughness tests were conducted before and after the neutron irradiation with a fluence of 1×10^{24} n/m^2 at 290 °C. With neutron irradiation, we could observe an increase in the yield strength and ultimate strength, and a decrease in the total elongation. All cladding materials exhibited ductile-to-brittle transition behavior during the Charpy impact tests. A reduction in the Charpy upper-shelf energy and an increase in the ductile-to-brittle transition temperature was observed with neutron irradiation. There was no obvious decrease in the elastic–plastic fracture toughness (J_{Ic}) of the cladding materials upon irradiation with high neutron fluence. The tearing modulus was found to decrease with neutron irradiation; the submerged-arc-welded cladding materials exhibited low J_{Ic} values at high temperatures.

1. Introduction

Reactor pressure vessels (RPVs) in the nuclear power plants are typically constructed using low-alloy steel. The inner surface of an RPV, which is susceptible to the corrosive environment caused by the reactor coolant, is protected by overlay cladding with several millimeters thick layer of austenitic stainless steel. This process is referred to as "weld overlay cladding." Pressurized thermal shock (PTS) is one of the most severe events that may lead to the failure of the pressurized water reactor (PWR). For the structural integrity assessment of an RPV during a PTS event, the Japanese code on the method for fracture toughness testing and evaluation, JEAC 4206-2007 [1], postulates the formation of an axial semi-elliptical crack of depth 10 mm and length 60 mm on the inner surface of the beltline region of the RPV base metal or weld metal. According to the Japanese fitness-for-service code, JSME S NA1-2012 [2], the clad thickness should be added to the detected crack depth. Weld overlay cladding is not considered a structural material in RPVs. The properties of weld overlay cladding are considered only for evaluating the stress generated during a PTS transient, including the calculations of temperature distribution and thermal stress. In contrast, the U.S. NRC code considers the welding residual stress of the cladding in evaluating the generated stress [3]. Furthermore, the French RSE-M code takes into account the yield stress and the Young's modulus of the cladding for calculating the stress intensity factor of the under-clad crack [4]. Understanding the mechanical properties, particularly the elastic–plastic fracture toughness, of cladding materials after neutron irradiation is necessary to improve the structural integrity assessment of RPV.

The cladding material has a duplex phase structure, comprising net-like structures of δ-ferrite phase [5] in the austenitic matrix. It was reported that the δ-ferrite phase in the cladding tends to harden with neutron irradiation and thermal aging, causing an increase in the ductile-to-brittle transition temperature (DBTT) and a decrease in the Charpy upper-shelf energy [6–11]. To this end, several studies have investigated the effects of neutron irradiation and long-term thermal aging on the fracture toughness of the cladding materials. Horsten and Belcher [12] and Bethmont et al. [13], the effects of neutron irradiation and thermal aging on the mechanical properties of submerged-arc strip cladding are relatively insignificant; hence, the cladding retains sufficient fracture toughness after irradiation. In contrast, Haggag et al. [8–10] reported the low resistance to ductile crack initiation at 290 °C for the neutron irradiated three-wire series-arc cladding materials. However, to the best of our knowledge, there are no experimental data to elucidate the effects of high-fluence neutron irradiation on the mechanical properties of cladding materials or those of the electroslag strip cladding material.

Therefore, the objective of this study is to investigate the effects of high-fluence neutron irradiation on the mechanical properties of the cladding materials fabricated by the submerged-arc welding

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(SAW) and electroslag welding (ESW) methods. This paper presents the results of the tensile tests, Charpy impact tests, and fracture toughness tests before and after irradiation with a fluence of 1×10^{24} n/m^2 at 290 °C.

2. Experimental

2.1. Materials

The cladding materials analyzed in this study were fabricated by the SAW and ESW methods. Stainless steel strips of width 50 mm and 75 mm were used for SAW and ESW, respectively. The main difference between the SAW and ESW cladding pertains to the method adopted for melting the strip. The arc melts the strip in SAW, whereas the resistance heat from the molten slag melts the strip in the case of ESW. The solidification rate of the ESW weld metal is typically lower than that of SAW weld metal. Consequently, the ESW weld metal has superior degasification, low slag inclusion, and resistance to porosity.

In this study, cladding was performed by multilayer depositions on 200-mm-thick SQV2A plates [11]. This provided a cladding thickness of approximately 25 mm, to machine the mechanical test specimens. The cladding layers were welded along the rolling direction of the base metal. The direction of cladding materials are defined as follows: the longitudinal direction (*L*), transverse direction (*T*), and short transverse direction (*S*) correspond to the rolling direction parallel to the welding direction, perpendicular to the welding direction, and along the thickness direction of the cladding, respectively. The thickness of a single layer was approximately 5 mm. The first layer was formed using 309 L electrode, whereas the subsequent layers were formed using 308 L electrodes.

Fig. 1 shows the microstructure of the SAW cladding material, which contains δ-ferrite in the austenitic matrix. The chemical composition of the cladding material is listed in Table 1. Comparing the composition of the cladding material formed by SAW and ESW, it can be observed that the SAW weld metal has higher carbon content than the ESW weld metal. This can be attributed to the fact that the SAW cladding requires higher heat input and more dilution by the base plate than the ESW cladding, resulting in the weld metal having higher carbon content. In addition, the SAW weld metal has higher sulfur and molybdenum contents than the ESW weld metal. The contents of other elements in the weld metal did not significantly differ between the two welding methods. The cladding was subjected to post-weld heat treatment (PWHT) at 615 °C for 7 h with subsequent furnace cooling. The δ-ferrite contents of the SAW cladding and ESW cladding were observed to be 10.5% and 8.5%, respectively.

2.2. Specimens

Fig. 2 shows the schematic of the tensile and fracture toughness specimens, indicating the corresponding dimensions. Fig. 3 shows the sampling locations of specimens from the cladded base metal. The specimens were machined such that the parallel part of the tensile specimens, the notch of the Charpy specimen, and the fatigue pre-crack tip of the fracture toughness specimen (0.4T-CT) were located in the second layer of cladding. The tensile specimens were oriented parallel to the welding direction. The Charpy and the 0.4T-CT specimens were machined in the *L–S* orientation such that the crack extended in the direction of the surface. All the fracture surfaces were perpendicular to the welding direction, i.e., parallel to the direction of the dendrite structure.

2.3. Neutron irradiation

The neutron irradiation was performed by the Japan Materials Testing Reactor (JMTR). In the typical process, irradiation capsules filled with helium gas and instrumented with thermocouples, along with Fe and Al(Ti)–Co dosimetry wires, were prepared for the irradiation experiments. The irradiation temperature was controlled using an optimized combination of γ-ray and electric heating, maintaining the specimen temperature in the range of 290 ± 5 °C. The fast neutron fluence irradiated on each specimen was calculated to be in the range of 1.0×10^{24}–1.5×10^{24} n/m^2 ($E > 1$ MeV), with the fast neutron flux of approximately 2.0×10^{17} n/m^2/s ($E > 1$ MeV).

2.4. Testing procedure

In this study, tensile tests were conducted from room temperature up to 290 °C. During the tensile test, the crosshead speed was maintained as 0.2 mm/min. The Charpy impact test was performed on a 300-J Charpy impact testing machine with an International Organization for Standardization (ISO)-type tup in the temperature range from −130 °C to 150 °C.

The *J*-integral versus crack extension (*J–R*) curves and the elastic–plastic fracture toughness (J_{Ic}) tests were conducted according to ASTM E1820-11e [12] using the unloading-compliance technique. In the typical process, the 0.4T-CT specimens were precracked by fatigue at room temperature such that the ratio of crack length to specimen width (a/W) was approximately 0.5. The obtained specimens were then side-grooved on each side to approximately 10% of their thickness. Subsequently, the J_{Ic} tests were conducted in the temperature range from −50 °C to 270 °C. The tearing moduli corresponding to the crack extension of 1 mm were calculated using the following equation [15].

$$T_{mat} = (E/\sigma_{fs}^2)(dJ/da) \quad (1)$$

where E is the Young's modulus, σ_{fs} is the flow stress, and dJ/da is the slope of the *J–R* curve corresponding to the crack extension of 1 mm.

3. Results and discussion

3.1. Tensile test

Fig. 4(a and b) shows the temperature dependence of tensile properties for SAW and ESW cladding materials, respectively. The corresponding tensile test results are summarized in Table 2. In case of both the SAW and ESW cladding materials, neutron

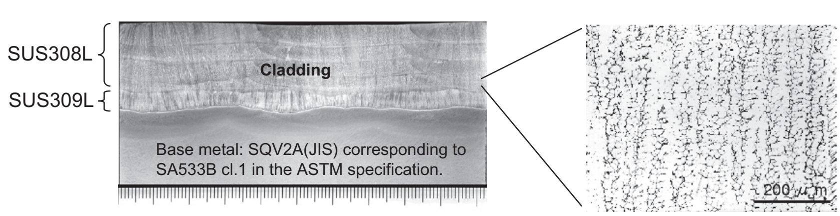

Fig. 1. Microstructure of SAW cladding.