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Original Article

Identification of nonregular indication according to change of grain size/surface geometry in nuclear power plant (NPP) reactor vessel (RV)-upper head alloy 690 penetration

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ABSTRACT

During the fabrication process of reactor vessel head penetration (RVHP), the grain size of the tube material can be changed by hot or cold work and the inner side of the tube can also be shrunk due to welding outside of the tube. Several nonregular time-of-flight diffraction (TOFD) signals were found because of deformed grains. In this paper, an investigation of nonregular TOFD indications acquired from RVHP tubes using experiments and computer simulation was performed in order to identify and distinguish TOFD signals by coarse grains from those by Primary Water Stress Corrosion Crack (PWSCC). For proper understanding of the nonregular TOFD indications, microstructural analysis of the RVHP tubes and prediction of signals scattered from the grains using Finite Element Method (FEM) simulation were performed. Prediction of ultrasonic signals from the various sizes of side drilled holes to find equivalent flaws, determination of the size of the nonregular TOFD indications from the coarse grains, and experimental investigation of TOFD signals from coarse grain and shrinkage geometry to identify PWSCC signals were performed.

From the computer simulation and experimental investigation results, it was possible to obtain the nonregular TOFD indications from the coarse grains in the alloy 690 penetration tube of RVHP; these nonregular indications may be classified as PWSCC. By comparing the computer simulation and experimental results, we were able to confirm a clear difference between the coarse grain signal and the PWSCC signal.

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1. Introduction

Since there were Primary Water Stress Corrosion Crack (PWSCCs) found in the reactor vessel head penetration (RVHP) weld of the Oconee and Davis-Besse nuclear power plants (NPPs) in 2001 and 2002, the Nuclear Regulatory Commission (USNRC) issued US NRC Bulletin 2002-01, US NRC Order EA-03-009, and US NRC Order EA-03-009 (Revison 1). According to the recommendation of the Korean Regulatory Body and the Korea Institute of Nuclear Safety, inspections of RVHP have been performed since the early 2000s. In addition, Korean utilities have inspected the RVHP of Korean NPPs in accordance with the American society of Mechanical Engineers (ASME) Code Case N729-1, which requires periodic inspection as to the susceptibility represented by the effective degraded year parameter [1].

Recently, the penetration tubes of the upper reactor head have been manufactured using alloy 690 to replace alloy 600 in order to improve corrosion resistance [2]. However, PWSCCs can be initiated in the contact area of the primary water at high temperature and pressure. Thus, in the contact area, the time-of-flight diffraction (TOFD) technique, which is claimed to have a high probability of detection to detect cracks, has been periodically applied to ensure material integrity. During the fabrication process of RVHP, the grain size of the tube material can be changed by hot or cold work and the inner side of the tube can also be shrunk due to welding outside of the tube. Thus, nonregular TOFD signals can be acquired during

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tube inspection from the deformed grains (coarse grain) and shrinkage geometry. Therefore, it is necessary to investigate those nonregular TOFD signals in order to discriminate them from flaw signals and to evaluate those flaws correctly. With that purpose in mind, nonregular signals are classified into two types in terms of formation mechanisms and signal patterns: (1) nonregular surface geometry indication, very similar to surface geometry indication (SGI), obtained from the inner surface of the tubes, which have big curvatures; and (2) nonregular penetration tube indication (NPTI), obtained from big volumetric flaws such as cracks, which are one kind of penetration tube indication (PTI).

The effects on TOFD-image pattern and size of nonregular TOFD signals (nonregular surface geometry indication and NPTI) were experimentally evaluated using mock-ups with simulated artificial defects used to generate these nonregular signals. Also, in order to properly understand the nonregular TOFD signals (NPTI), a scattered signal from the coarse grains in the tube was simulated using a computer.

For the experimental investigation, one SGI and three PTI mockups and a computer controlled ultrasonic testing (UT) system with transducer module of PCS-24 TOFD were prepared. The material, dimensions, and configurations of these mock-ups are the same as those of Korean NPPs. The major purpose of the SGI mock-up is to investigate the effect on detection and sizing of internal flaws, which depend on the shape of the inner surface. One SGI mockup of a penetration tube made of alloy 690 was fabricated using gas tungsten arc welding (GTAW) to induce weld shrinkage. Then, several Electric Discharge Machining (EDM) notches were machined in the axial and circumferential directions with 10% and 25% of tube thickness, respectively, in the shrinkage region. Three PTI mock-ups were selected from the fabricated penetration tubes made using forged alloy 690 materials; it was found that there were nonregular TOFD signals in the penetration tubes before they were installed in the reactor vessel (RV) head. Using electron microscopy, it was found that the PTI mock-ups cut out for microstructural analysis and evaluation of grain size of the areal region produced nonregular signals. The measured grain size and shape are used as the input values of the Finite Element Method (FEM) simulation for an ultrasound beam model to characterize the ultrasonic beams, including backscattering noise, attenuation, and propagation of ultrasound, and to predict ultrasonic signals from the grains, etc.

For the computer simulation, the microstructure of the major components of the NPPs was modeled to determine the effect of the grain size on the ultrasound testing. In order to describe the geometry of the grain boundary, the Voronoi method [3] was used to generate the grain pattern. The coordinates of the generating points are generated by a random number generator in MATLAB (The Mathwork, Natick, MA, USA). Using the simulated ultrasonic signals, we investigated the relationship between the ultrasonic signals and the grain size. Then, using TOFD B-scan images, ultrasonic scattering signals with coarse grains were analyzed.

In the computer simulation and experimental results, for the alloy 690 penetration tube of the reactor pressure vessel (RPV) head, the changes of weld shrinkage and microstructure grain size were investigated by TOFD signal evaluation.

2. Materials and methods

2.1. Mock-up

The SGI mock-up block was fabricated using J-groove welding, which penetrated the tube to 16.91 mm thickness, as shown in Fig. 1 and Fig. 2; block was then cut out from the base metal of the RV with some remaining part outside of the tube. Then, using a modified dial gage, the inner surface of the mock-up block was used to measure the area of shrinkage due to welding deformation. Finally, machining notches were added to the mock-up block at suitable positions for acquisition of ultrasonic signals.

The applied welding method is GTAW, as shown in Fig. 1 and Table 1. GTAW is widely used to obtain stable arc and high quality weld metal. And the mock-up was designed with 5 degrees of groove angle to minimize the welding amounts in the J-Groove.

Fig. 3 shows the shape of the shrinkage of the SGI mock-up. As shown in Fig. 3, compared to healthy penetration nozzle, the measured shrinkage of the penetration tubes was 1.2–1.6 mm. Artificial EDM notches in the inner and outer shrinkage areas of the welding surface deformation area were fabricated. Positions and sizes of the EDM notches are shown in Fig. 4 and Table 2. The depths of A, B, and D EDM notches were 25% of the penetration tube thickness; in cases F, G, J, and M, the notches were 10% of the penetration tube thickness.

PTI is the most general indicator during any inspection of the penetration nozzle material. Therefore, destructive testing of an area in which a nonregular signal has been detected is one common method to analyze the nozzle with PTI. A PTI mock-up block was therefore prepared using the same material and size of the SGI mock-up block, as shown in Fig. 5. The PTI mock-up was cut out of the area that had acquired nonregular TOFD signals from the installed RPV head. Specifications of the probe used for the inspection are provided in Table 3.

2.2. Experimental set-up

The mock-up blocks were inspected using a TOFD transducer assembly (WesDyne International, Madison, PA, USA) with a computer-controlled scanner, as shown in Fig. 6. The TOFD

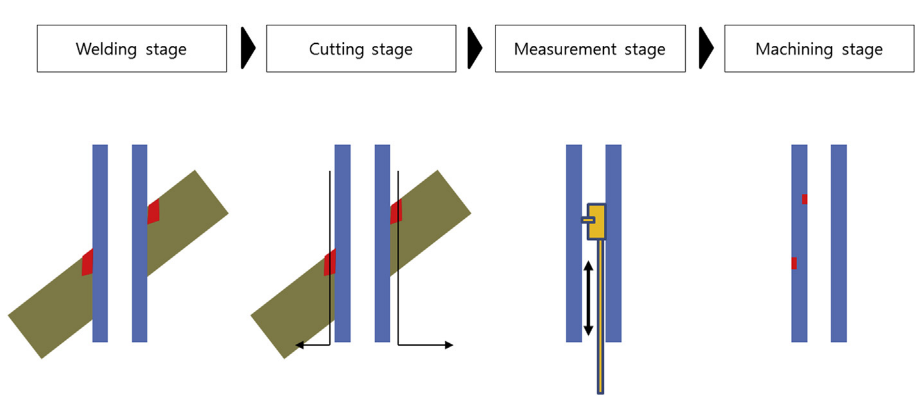

Fig. 1. Manufacturing stages of surface geometry indication (SGI) mock-up.

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