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Residual stress assessment of nickel-based alloy 690 welding parts

Sang-Hwan Lee [a], Yoon-Suk Chang [a,*], Sung-Woo Kim [b]

[a] Department of Nuclear Engineering, Kyung Hee University, 1732 Deogyeong-daero, Giheung, Yongin, Kyounggi 446-701, Republic of Korea
[b] Nuclear Material Safety Research Division, Korea Atomic Energy Research Institute, 989-111 Daedeok-daero, Yuseong, Daejeon 305-353, Republic of Korea

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ABSTRACT

Failures of welding parts in nuclear power plants have increased significantly. One of main degradation mechanisms was initiation and growth of primary water stress corrosion cracking accelerated by residual stress at dissimilar metal welds of piping, reactor head penetrations and nozzles connecting major components. Therefore, estimation of the welding residual stress became an important issue for ensuring reliability of them. The present study deals with verification of welding simulation techniques through sensitivity analyses of bottom-mounted instrumentation nozzle mock-up and control rod drive mechanism (CRDM) nozzle mock-up, examination of residual stress effects for a welded cylindrical block and application of the residual stress evaluation method to real penetration nozzles of CRDM made of nickel-based alloy 690.

1. Introduction

Austenitic stainless steels and nickel-based alloys have been widely used for the reactor coolant pressure boundary (RCPB) components of nuclear power plants (NPPs) with respect to corrosion resistance and mechanical characteristics. For instance, the main piping of reactor coolant system and connected safety-related systems were manufactured with the stainless steels or sheathed with corrosion resistant materials. Also, the nickel-based alloys were used for heat-transfer tubes, penetration nozzles and dissimilar metal (DM) welding parts. However, during the last three decades, primary water stress corrosion cracking (PWSCC) was continuously reported at the RCPB components so that lots of studies have been carried out by industrial research institutes as well as regulatory authorities around the world [1]. It is well-known that the PWSCC occurs when three conditions were fulfilled: susceptible materials, corrosive environments and high tensile stresses. If we assume that key features of the nickel-based alloys and reactor coolant environments are similar in a broad sense, the only distinguishing factor of PWSCC is the tensile stress caused by welding [2]. Particularly, determination of the residual stress comes into the re-spotlight as the increase of repair welding of aged nuclear components. Hence, it is crucial to predict and control the tensile welding residual stress distributions of major components for reliable design, construction and operation of NPPs.

Historically, the PWSCC was firstly recognized in 1976 at a steam generator tube support plate and U-bends of Turkey Point and Surrey power plants in United States. Thereafter, successive failures such as a coolant leak due to cracks at control rod drive mechanism (CRDM) nozzles of the Bugey unit 3 in France and a small crack indication on the internal surface area

* Corresponding author.
E-mail address: yschang@khu.ac.kr (Y.-S. Chang).

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of a bottom mounted instrumentation (BMI) nozzle of Thuruga unit 1 in Japan [3,4] have increased so rapidly as to become an worldwide issue. Similar phenomena were also observed at the CRDM nozzles of Davis-Besse power plant, the BMI nozzles of South Texas and the pressurizer nozzle-to-safe end DM butt welds of Wolf Creek power plants et cetera [5–8]. Since the residual stresses are inevitable in the welding process [9,10] and greatly influence upon the PWSCC [11–13], the DM welds have to be managed appropriately to prevent unanticipated coolant leakage out of the RCPB.

Prediction of the welding residual stress was initially performed by analytical methods but recently advanced through numerical ones in accordance with rapidly progressing computational technologies and softwares for thermal and non-linear structural analyses [14]. Dong [15] employed shell element models to carry out systematic analyses of a typical multi-pass girth weld in Type 316L stainless steel pipe and examined effects of part-circumferential repair length to a pipe girth weld [16]. Also, a mechanics-based approach was introduced to generalize residual stress profiles under a wide range of geometry and girth welding conditions [17]. Residual stress effects on fatigue life and fracture of welded structures were numerically examined [18–20]. Bouchard [21] identified some of the origins of apparent innate scatters and surveyed how structural integrity evaluation codes and procedures characterize the welding residual stresses for defect assessment purpose. Although other research activities were not included due to the lack of space, independent studies expanded into several collaborative researches to properly resolve the PWSCC issue. For instance, Electricite de France (EDF) organized an international program for better understanding of the cracking behaviors [22]. Also, according to Bugey-like events identified at the vicinity of the J-groove welding/buttering regions in Oconee, Arkansas and North Anna pressurized water reactors, a series of materials reliability program (MRP) was launched in order to prepare technical bases for root cause evaluation [23].

In practice, an incipient nickel-based materials such as alloys 600 and 82/182 were used for construction of steam generator tubes, reactor pressure vessel (RPV) penetration nozzles and DM welding parts of piping in NPPs. However, due to aforementioned failure histories, the material is currently being replaced by new materials such as alloys 690 and 52/152 having better resistance and mechanical features under stress corrosion cracking (SCC) and high-temperature environments [24]. Despite of the corrective action, there was a little operating experience of the alloy 690 and filler metals, and their stability against PWSCC has not been proven yet. Also, there are several limitations to apply welding residual stress measurement. In this context, the present study is to investigate verification of welding simulation techniques through sensitivity analyses of BMI nozzle mock-up and CRDM nozzle mock-up, examination of residual stress effects for a welded cylindrical block and application of the residual stress evaluation method to real CRDM penetration nozzles made of the alloy 690.

2. Welding simulation methods

2.1. Welding characteristics and heat transfer analysis

During a multi-layered welding process, the material undergoes expansive loads by applied heats and compressive loads by natural cooling repeatedly. Because the volume change of the welded zone is restrained by the adjacent base metals as well as the phase transformation occurs due to rapid cooling, generation of the welding residual stress is inevitable. However, the welding residual stress amounts to the yield strength of material is not considered explicitly in design stage so that it has been rise on an important factor affecting to degradation of welded components in operating NPPs. Particularly, in case of a DM welding, due to the difference of mechanical and thermal properties among materials, the residual stress is much higher and its distribution becomes more complicated [25]. In order to estimate the residual stress in the DM welded zone, several numerical analysis methods with diverse procedures have been proposed. A typical procedure is based on a sequential finite element (FE) analyses; at first, heat transfer analysis is carried out to simulate the heating and cooling processes by considering the welding heat source. Subsequent elastic–plastic residual stress analysis is performed by using the temperature profiles and, then, further mechanical and thermal stress analyses taking into account post weld heat treatment as well as normal operating and hydrostatic test conditions are optional [26].

With regard to the heat transfer analysis, there are two representative methods for attaching weld beads such as the prescribed temperature method and volumetric flux method. The former is to apply heat to each weld bead by keeping the set temperature as more than a melting point (T_m + 10 °C) for a designated time whereas the latter is to apply volumetric heat flux (Q) to the ith bead calculated by the following equation.

$$Q_i\left(\frac{w}{m^3}\right) = \eta\frac{V_iI_i}{A_i v \Delta t} \tag{1}$$

where η is the welding efficiency that has a value of 0.7–0.8 in case of shield metal arc welding (SMAW), V is the voltage, I is the current, A is the cross-sectional area of weld bead, v is the welding speed and t is the welding time.

In this study, mainly the prescribed temperature method was adopted according to the previous research [27] because it showed not only efficiencies in preparing input deck and computational time but also little difference in heat transfer analyses results between two methods. Especially, the set temperature and sustaining time were determined from repeated FE analyses as the optimum one to provide equivalent temperature distributions at the location of 4 mm apart from the fusion line based on the previous research. The phase transformation was not incorporated in the present FE analyses from the view point of conservative PWSCC evaluation and computational time saving. The interesting regions of this study were the