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The effect of heat treatments on the constituent materials of a nuclear reactor pressure vessel in hydrogen environment

J. Toribio[a,*], D. Vergara[a], M. Lorenzo[a]

[a]Fracture & Structural Integrity Research Group, University of Salamanca, Spain

Abstract

A nuclear reactor pressure vessel (NRPV) wall is formed by two layer of different materials: an inner layer of stainless steel (*cladding material*) and an outer layer of low carbon steel (*base material*) which is highly susceptible to corrosion related phenomena. A reduction of the mechanical properties of both materials forming the wall would appear due to the action of the harsh environment causing hydrogen embrittlement (HE) related phenomena. As a result of the manufacturing process, residual stresses and strains appear in the NRPV wall, thereby influencing the main stage in HE: hydrogen diffusion. A common engineering practice for reducing such states is to apply a *tempering heat treatment*. In this paper, a numerical analysis is carried out for revealing the influence of the heat treatment parameters (*tempering temperature* and *tempering time*) on the HE of a commonly used NRPV. To achieve this goal, a numerical model of hydrogen diffusion assisted by stress and strain was used considering diverse residual stress-strain states after tempering. This way, the obtained hydrogen accumulation during operation time of the NRPV provides insight into the better tempering conditions from the structural integrity point of view.

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Keywords: nuclear reactor pressure vessel; hydrogen embrittlement; heat treatments; residual stresses and strains.

1. Introduction

A nuclear reactor pressure vessel (NRPV) wall is composed by a bi-material of low carbon steel (*base material*) and stainless steel (*cladding material*), the first one being highly susceptible to corrosion-related phenomena, such as

* Corresponding author. Tel.: +34 980 545 000 (ext. 3673); fax: +34 980 545 002.
E-mail address: toribio@usal.es

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hydrogen embrittlement (HE). During operation time, the stress state undergone by the NRPV can be estimated as the combined action of in-service stress caused by (i) the existing gradient of temperature in the NRPV wall and (ii) the remaining residual stress states after tempering heat treatment.

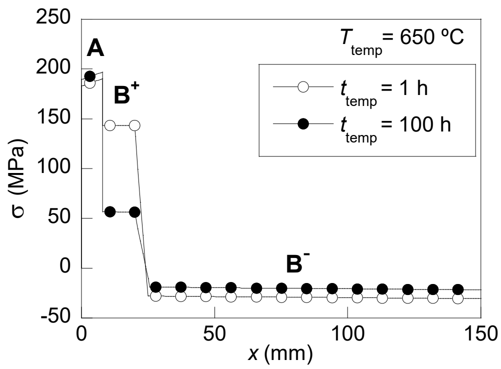
The aim of this paper is to analyze the effect of residual stresses and plastic strains generated after tempering on the HE susceptibility of a NRPV. To achieve this goal a model of hydrogen diffusion assisted by stress and strain previously developed by Toribio et al. (2010) is applied to determine the best conditions of the tempering process from the structural integrity point of view to avoid HE damage.

2. Stress-strain state in the vessel

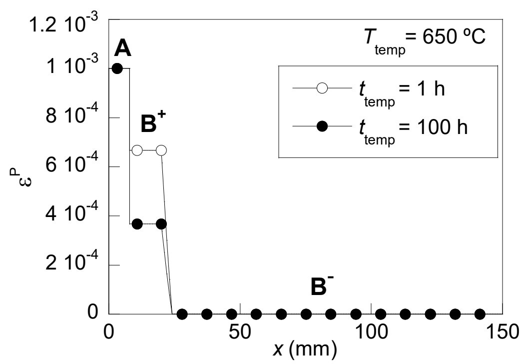
To perform the analysis, a real cylindrical vessel of a nuclear reactor WWER-440 was considered according to the data previously given by Kostylev and Margolin (2000): inner radius (r_{in} = 1.77 m), width of the stainless steel first layer (w_A= 8 mm), and width of low carbon steel second layer (w_B= 142 mm), and consequently the outer radius must be r_{out} = 1.92 m. According to the results presented by Kostylev and Margolin (2000), the residual stress-strain state is uniformly distributed along the cladding width (w_A) whereas, in the case of second layer of low carbon steel (w_B), it is divided into two intervals: the first one is extended over a zone of width $2w_A$ with tensile stresses (zone B^+) while the second one ($w_B - 2w_A$) with compressive stresses is denoted as B^-. In addition, the in-service thermal-origin stress can be estimated by considering the constraint caused by the own vessel geometry and the different deformation of both layers due to different thermal expansion coefficients of each material. Such deformations are caused by the in-service gradient of temperature ($T_{in} \approx 300$ºC; T_{out} (environment) = 25ºC).

To go further in the analysis of HE, the values of the variables governing the hydrogen diffusion process, namely, the *hydrostatic stress* (σ) and the *equivalent plastic strain* (ε^P), were obtained from the results given by Kostylev and Margolin (2000) in terms of the components of the stress tensor. In Fig. 1 the distributions of both variables σ and ε^P through the vessel width w are shown as a function of the depth from the outer surface, defined as $x = r_{out} - r$, r being the common radial cylindrical coordinate. Thus, $x = 0$ represents the outer surface exposed to the environment whereas $x = w_A + w_B$ = 150 mm represents the inner surface of the NRPV wall exposed to the hydrogenating environment.

To evaluate the influence of the tempering heat treatment on the stress-strain state of the NRPV wall, two different tempering temperatures (T_{temp}), 650 ºC and 670 ºC, and two different tempering times (t_{temp}), 1 and 100 hours, were considered. Although a slightly higher residual stress was obtained for T_{temp} = 650 ºC, obtained results showed that σ distributions are quite similar for the two T_{temp} considered. Regarding the distribution in Fig. 1a, three intervals can be observed: (i) positive gradient of σ through wall A –stainless steel–; (ii) slight gradient of σ through wall B^+; (iii) slight negative gradient of σ in the zone B^-. On the other hand, the lower the t_{temp}, the higher the residual stress σ, mainly in zone B^+ (Fig. 1b).



(a)



(b)

Fig. 1. Distribution of total residual hydrostatic stress σ (a) and equivalent plastic strain ε^P (b) through the vessel width, for different tempering times (t_{temp} = 1 and 100 hours) for a given tempering temperature (T_{temp}= 650 ºC).