Transactions of the Korean Nuclear Society Autumn Meeting
Gyeongju, Korea, October 25-26, 2012

Comparison of Rate Theory Based Modeling Calculations with the Surveillance Test Results of Korean Light Water Reactors

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1. Introduction

Neutron irradiation to reactor pressure vessel (RPV) steels causes a decrease in fracture toughness and an increase in yield strength while in service. It is generally accepted that the growth of point defect cluster (PDC) and copper-rich precipitate (CRP) affects radiation hardening of RPV steels. A number of models have been proposed to account for the embrittlement of RPV steels [1-3]. The rate theory based modeling mathematically described the evolution of radiation-induced microstructures of ferritic steels under neutron irradiation. In this work, we compared the rate theory based modeling calculation with the surveillance test results of Korean Light Water Reactors (LWRs).

2. Methods and Results

The details of the mathematical model for PDC evolution are described in other references [3,4]. A number of time-dependent differential equations were established and integrated numerically, which contained the interstitial and vacancy concentrations, the number density of interstitial and vacancy clusters with varying sizes, and the size of CRP in matrix. The amount of radiation hardening caused by PDC and CRP was calculated using Orowan's model.

Microstructural studies have revealed that CRPs in RPV are distributed with high density ranging from 10^{17} to 10^{18} n/cm^3, and the size of CRP is very small (2-6 nm) [1]. In this work, the density of CRP was fixed in the calculations from the beginning, and growth of CRP is dominated by diffusion of vacancies. The detailed description of the CRP size calculation can be found elsewhere [5].

2.1 Basic model parameters

It is very crucial to determine the kinetic and material parameters as accurately as possible in order to solve the rate equations. The basic parameters used in this work are listed in Table 1. These are reference values for ferritic steels in our modeling [6]. Although the parameters are less than ideal, it seems that the calculation results are useful to expect a trend for a quantitative prediction of the amount of radiation hardening.

Table I: Kinetic and material parameters

Parameter	Value
Vacancy migration energy (E_v^m)	1.25 eV
Vacancy formation energy (E_v^f)	1.55 eV
Vacancy pre-exponential factor (D_o^v)	0.5 cm^2/s
Effective grain diameter (d_g)	0.001 cm
Interstitial migration energy (E_m^i)	0.25 eV
Interstitial pre-exponential factor (D_o^i)	0.05 cm^2/s
Dislocation density (ρ_{dis})	1×10^{11}/cm^2
Dislocation interstitial bias (z_i^{dis})	1.25
Dislocation vacancy bias (z_v^{dis})	1
Lattice constant of Fe (a_L)	2.87×10^{-8} cm
Cascade efficiency (η)	0.1
Vacancy clustering fraction (f_{vcl}^1:f_{vcl}^7: f_{vcl}^8)	0.7:0.1:0.07
Interstitial clustering fraction (f_{icl}^1:f_{icl}^2:f_{icl}^3:f_{icl}^4)	0.7:0.15:0.1 :0.05
Interstitial cluster binding energy (E_2^B:E_3^B:E_4^B)	0.5:0.75:1.25 eV
Copper migration energy (E_{Cu}^m)	2.8 eV
Copper pre-exponential factor (D_o^{Cu})	300 cm^2/s

2.2 Calculation results

Fig. 1 shows the comparison of the yield strength changes between calculated value and surveillance test data of Kori 1 as an example. The yield strength increase included incremental changes from the PDC and CRP contributions. The tendency of the calculation and surveillance data shows rather good agreements. The weld of Kori 1 unit shows a high yield strength change because of its high Cu concentration of 0.22 wt%. The other units show rather low yield strength changes of welds, because they have very low Cu contents.

Fig. 2 shows the comparison between calculated yield strengths and measured yield strengths of Korean LWRs. Blue dots represents the base materials and red dots represent the weld materials. The relationship between calculated and measured values shows a reasonable trend. The proportional coefficient is 0.99. The base points are mainly located below the trend line, and it means that the calculation shows an overestimated value.

The weld points are located mainly over the trend line, it means an underestimated value.

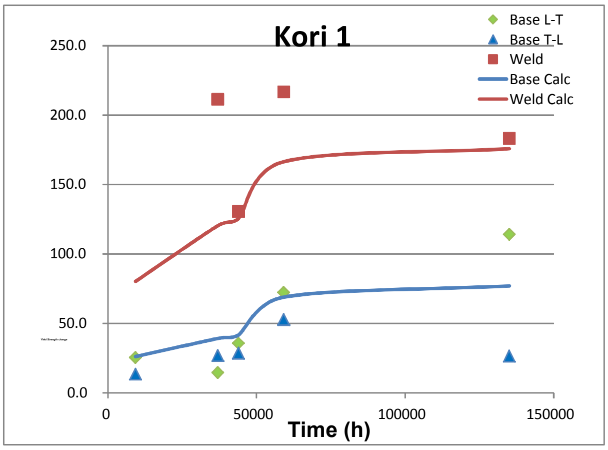

Fig. 1. Calculated and measured values of yield strength change in Kori 1 unit.

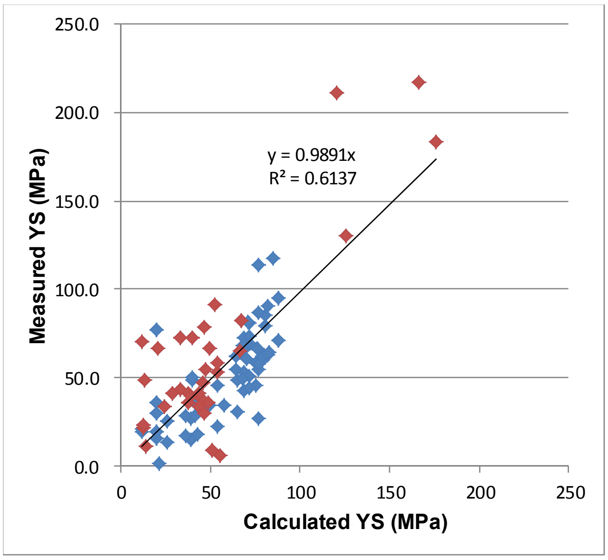

Fig. 2. Comparison of calculated and measured yield strengths of Korean LWRs.

3. Conclusions

A rate theory based modeling of radiation hardening in RPV steels were carried out and compared to the measured surveillance test results in Korean LWRs. These results were very sensitive to model parameters; however, the calculated yield strengths show a fair agreement with the measured yield strengths. Even though there are many limitation of rate theory based modeling, the application of modeling yielded an acceptable estimation of the mechanical property changes in RPV. It is essential to determine the accurate parameters related to displacement cascade and to develop an elaborate model in the future.

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