Transactions of the Korean Nuclear Society Autumn Meeting
Gyeongju, Korea, October 24-25, 2013

Radiation induced defect flux behaviors at zirconium based component

Sang Il Choi[a], Jun hyun Kwon[b], Gyeong-Geun Lee[b] and Ji Hyun Kim[a*]
[a]*Ulsan National Institute of Science and Technology (UNIST)*
100 Banyeon-ri, Eonyang-eup, Ulju-gun, Ulsan, Republic of Korea 689-798
[b]*Korea Atomic Energy Research Institute*
1045 Daedeok-daero, Yuseong-gu, Daejeon, Republic of Korea 305-353,
**Corresponding author: kimjh@unist.ac.kr*

1. Introduction

Zirconium is one of the most favorable core materials because of its excellent properties (radiation and corrosion resistant) compared to other structure materials in light water reactor. Hence vast amount of experiment and theoretical performance test has been done in various points of view such as corrosion and change of mechanical properties and dimension.

In commercial reactor core, structure materials are located in high temperature and high pressure environment. Therefore, main concern of structure materials is corrosion and mechanical properties change than radiation effects on materials.

However, radiation effects on materials become more important phenomena because research reactor condition is different from commercial reactor. The temperature is lower than 100 ℃ and radiation dose is much higher than that of commercial reactor.

Among the radiation effect on zirconium based metal, radiation induced growth (RIG), known as volume conservative distortion, is one of the most important phenomena.

Recently, theoretical RIG modeling based on radiation damage theory (RDT) and balance equation are developed. However, these growth modeling have limited framework of single crystal and high temperature.

To model theoretical RIG in research reactor, qualitative mechanism must be set up. Therefore, this paper intent is establishing defect flux mechanism of zirconium base metal in research reactor for RIG modeling. After than theoretical RIG work will be expanded to research reactor condition.

2. Radiation damage theory

RDT is the mathematical expression of radiation induced defect quantity and quality. Hence quantification of radiation induced defect (RID) concentration is the essential part of theoretical RIG modeling. RDT is must needed to RIG modeling.

2-1 Primary radiation damage

The RID generation sequence could be classified by two parts. The first part is composed with cascade generation and relaxation phenomena. In these phenomena, atom behavior was explained by kinetics and atomic fluctuation. This phenomena occurs so quickly (< 10^{-11}). Therefore, in this time region, atom diffusion dose not considering. The mathematical expression is

$$R_d = N\int_{\check{E}}^{\hat{E}} \Phi(E_i)\sigma_D(E_i)\mathrm{d}E_i \qquad (1)$$

Where N = *lattice atom density*
$\Phi(Ei)$ = *energy-dependent particle flux*
$\sigma_D(Ei)$ = *energy-dependent displacement cross section.*

2-2 Rate Theory & balance equation

After cascade generation and relaxation time region, atom diffusion is main effect of RID concentration. These phenomena could be mathematically expressed by balance equation from chemistry. From balance equation it could know defect concentration at any given time.

$$\frac{dC_v}{dt} = K_o - K_{iv}C_iC_v - K_{vs}C_vC_s^T \qquad (2)$$

$$\frac{dC_i}{dt} = K_o - K_{iv}C_iC_v - K_{is}C_iC_s^T \qquad (3)$$

Where K_0= *defect production rate*
K_{iv}= *vacancy–interstitial recombination*
C_i = *interstitial concentration*
K_{vs}= *vacancy–sink reaction*
K_{is} = *interstitial–sink reaction*
C_s^T = *the total sink strengths of all the extended defects in the material*

3. Defect flux behavior in zirconium base metal

The fundamental mechanism of RIG is atom rearrangement by defect flux behavior of RID. Historically, defect flux behavior established at 1979 by Holt [1]. Most recently, Woo expanded Holt work by establishing defect flux mechanism on zircaloy [2]. However until now, sink (grain boundary, dislocation loop, dislocation line, precipitate, defect cluster) effect on zircaloy is not unclear.

Therefore, this paper intends to reveal defect flux behavior at zirconium alloy in research reactor. Fortunately defect flux mechanism of single crystal and zircaloy was briefly revealed by many researchers [3, 4].

Prior to modeling defect flux in research reactor condition, these model need to be reviewed. After that, defect flux to sink will be researched at low temperature.

3-1 Single crystal defect flux behavior

In case of single crystal, major sink is only dislocation and dislocation loop. Therefore, RIG begins from developing of dislocation and dislocation loop. Before breakaway region, interstitial loop in prism plane is main reason of <a> -axis elongation. However after breakaway region, vacancy loop on basal plane is also main reason of <c> -axis construction.

At first stage of RIG, dislocation and dislocation loop are bias sink because interstitial diffusion coefficient is much higher than vacancy diffusion coefficient i.e. $D_iC_{1i} >> D_vC_{1v}$ (where $D_i >> D_v$). Therefore interstitial loop generated and growth.

At middle stage, dislocation and dislocation loop became neutral sink because vacancy concentration is rapidly increasing. While interstitial, which have to recombination with vacancy, disappear at matrix i.e. $D_iC_{1i} = D_vC_{1v}$ (where $C_{1v} >> C_{1i}$). Therefore growth strain will be saturation.

At last stage, <c> dislocation loop is formed on the basal plane. Therefore, dislocation loop and dislocation on prism plane once again absorb interstitial. While interstitial concentration is increasing by vacancy loop. Therefore, RIG increases proportionately with radiation dose.

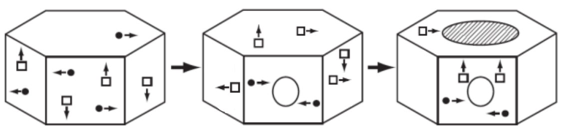

Fig.1. Defect flux of single crystal schematic

3-2 Annealed zircaloy

Annealed zircaloy have low dislocation density cause grain boundary play major role of sink. Therefore, RIG behavior is controlled by defect flux to grain boundary before dislocation loop generated.

At first stage, grain boundaries perpendicular to the basal plane are preferential sinks for SIAs. In contrast, grain boundaries parallel to the basal plane constitute preferential sinks for vacancies. Therefore, first growth occurs by grain boundary

At middle stage, dislocation loops are generated but interstitial is already absorbed by grain boundary. It will make dislocation loop become neutrally sink. Also, growth shows saturation tendency.

At last stage, same tendency of single crystal case, vacancy loops are generated and growth behavior shows linear increasing with radiation dose.

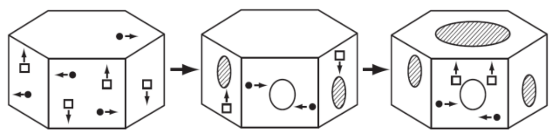

Fig.2. Defect flux of annealed zircaloy schematic

3-3 Cold worked zircaloy

In case of cold worked zircaloy, dislocation density is sufficiently high. Therefore dislocation as sink is dominant effect of defect flux on matrix. Growth strain increases linearly in proportion to the radiation dose.

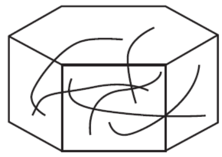

Fig.3. Defect flux cold worked zircaloy schematic

4. Summary

The mechanism of RIG is briefly reviewed. The sink effect on RIG could be analyzed by defect flux mechanism.

1. Initial sink has high influence because initial sink strength is so strong. Therefore, other sinks become weak. Cold worked zircaloy-2 did not show saturation region.
2. Defect flux to initial dislocation density is the most dominant parameter on growth. Therefore, it can be analyzed that increasing temperature leads to increasing defect flux to initial dislocation sink.

5. Acknowledgement

This work was financially supported by the Korean Nuclear R&D program organized by the National Research Foundation (NRF) in support of the Ministry of Science, ICT and future Planning (MSIP).

6. Reference

[1] R.A. Holt, and E.F. Ibrahim, Factors affecting the anisotropy of irradiation creep and growth of zirconium alloys. Acta Metallurgica, 27(8) pp. 1319-1328 (1979)

[2] C.H. Woo, Theory of irradiation deformation in nono-cubic metals: effects of anisotropy diffusion, Journal of Nuclear Materials, 159, pp. 237-256 (1988)

[3] F. Christien and A. Barbu, Effect of self-interstitial diffusion anisotropy in electron-irradiated zirconium: A cluster dynamics modeling. Journal of Nuclear Materials, 346(2-3), pp. 272-281 (2005)

[4] S.I. Golubov, A.V. Barashev, and R.E. Stoller, Radiation growth of HCP metals under cascade damage conditions, Material Research Society, 1383, pp 55-60 (2012)