Investigation of dislocation density in pressure vessel steels by positron annihilation lifetime measurements

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1. Introduction

A positron is the probe that is able to selectively detect open-type defects in metals. Positrons tend to be trapped and annihilated with electrons since they are positively charged particles. Positron annihilation spectroscopy (PAS) is a sensitive method for the study of open-type defects which include vacancies, vacancy agglomerates, and dislocations [1]. This technique has been widely used for detecting point defects in various materials irradiated by high-energy particles. The measured positron annihilation lifetimes of a sample are linked to the size of the defects and the relative intensities of each defect are related to the defect concentrations. Thus, PAS can provide information on the size of open-type defects and their number density.

Pressure vessel steels intrinsically include various types of open-volume defect, which are point defects, dislocations, grain boundaries etc. In particular, the presence of dislocations in metals significantly affects the mechanical property changes in irradiated materials. Although we can observe the dislocations in metals through an electron microscopy and X-ray diffraction topography, it is difficult to measure the amount of dislocations in a quantitative way. In order to investigate the intrinsic dislocation density in commercial steels, we measured the positron lifetimes and relative intensities of pressure vessel steels for three nuclear power plants, which include Younggwang units 4 and 5 (denoted by YG4 and YG5), and Uljin unit 4 (U4). Then, the absolute dislocation density of these pressure vessel steels was determined by applying the positron trapping models. This study provides a convenient way of measuring the dislocation density of alloys by PAS.

2. Experimental

The materials used for this study are commercial-grade steels of which the reactor pressure vessels (RPV) for the nuclear power plants were made. The chemical compositions of the steels are listed in Table 1. No differences were found in the chemical compositions between the samples. Each steel was, however, made with different methods which were slightly modified from the vacuum carbon deoxidization processes.

Table 1. Chemical compositions of test samples

element \ steel type	YG4	YG5	U4
C	0.2	0.21	0.19
Mn	1.42	1.24	1.35
P	0.007	0.007	0.006
S	0.003	0.002	0.002
Si	0.07	0.24	0.008
Ni	0.79	0.92	0.82
Cr	0.15	0.21	0.17
Mo	0.57	0.49	0.51
V	0.005	0.005	0.002
Cu	0.06	0.03	0.03
Al	0.005	0.022	0.009
Fe	Bal.	Bal.	Bal.

The PAS measurements for samples were performed at room temperature by means of a fast-fast coincidence timing spectrometer. We employed a ^{22}Na β^+-source of about 1 MBq. The positron lifetime can be measured by detecting the time difference between the birth γ-radiation of the ^{22}Na β^+-source and one of the annihilation γ-quanta with an energy of 511 keV. The scheme of the positron lifetime measurement is shown in Fig. 1. The time resolution of the system is 260 ps in full width at half

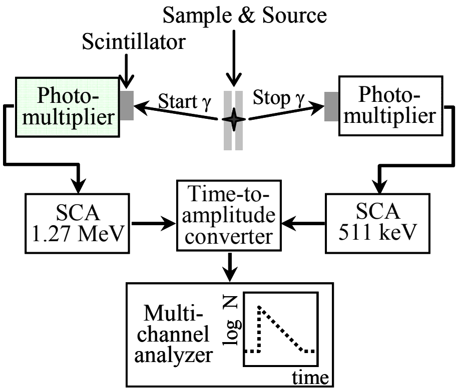

Fig. 1. Scheme of the positron annihilation lifetime spectroscopy (SCA: single-channel analyzer).

`maximum. The positron lifetime data was analyzed by using the PALSFIT program [2]. All the spectra were decomposed into two lifetime components, which were denoted by τ_1 (shorter) and τ_2 (longer).

3. Results

The positron lifetime spectra for three kinds of RPV steels and well-annealed pure Fe are shown in Fig. 2. We can not see a big difference in the spectra between the three RPV samples. The results for the positron annihilation lifetime data, analyzed by PALSFIT, are listed in Table 2. The τ_1 component corresponds to an annihilation of free positrons non-localized in a lattice. We observed a relatively long lifetime component of τ_2 (~150 ps). It is probable that a certain amount of positrons are trapped at dislocations. The characteristic value of the positron lifetime at dislocations is about 150 ps.

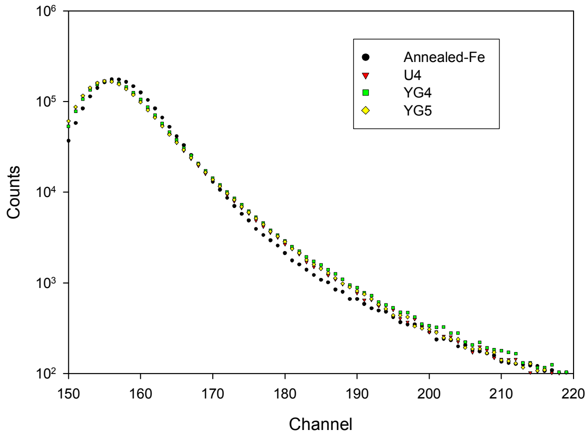

Fig. 2. Experimental positron annihilation lifetime spectra for three RPV steels (YG4, YG5, U4) and pure Fe.

Table 2. Positron annihilation lifetime data for the three RPV steels

	YG4	YG5	U4
Lifetime τ_1 (ps)	64.8	63.7	70.2
Intensity I_1 (%)	35.55	34.1	39.6
Lifetime τ_2 (ps)	150	151.1	150.3
Intensity I_2 (%)	64.45	65.94	60.4
Average τ_{avg} (ps)	119.7	121.4	118.6
Dislocation density ρ_{dis} (cm^{-2})	9.42×10^9	9.98×10^9	7.64×10^9

A positron capture in defects is characterized by the trapping rate which is proportional to the defect density. There is a linear relationship between the positron trapping rate and the defect density. For dislocations, the positron trapping rate κ_{dis} can be expressed by the dislocation density ρ_{dis} as:

$$\kappa_{dis} = \mu_{dis} \cdot \rho_{dis} \qquad (1)$$

where the proportionality constant μ_{dis} is the trapping co-efficient. The average trapping coefficient for dislocations in pure Fe is ~0.6 cm^2s^{-1} [3]. The positron trapping rate κ_{dis} can be obtained from the lifetime data by an application of the two-state trapping model, which is given as:

$$\kappa_{dis} = I_2\left(\frac{1}{\tau_1} - \frac{1}{\tau_2}\right) \qquad (2)$$

By combining Eqs. (1) and (2), the dislocation density of each steel was estimated, which was listed in Table 2. The dislocation density of U4 RPV steels is relatively lower than those of YG4 and YG5 steels.

4. Conclusions

The PAS method was applied to estimate the dislocation density for the commercial RPV steels. It has been shown that it is possible to determine the dislocation density quantitatively by applying the trapping model. The calculated dislocation density for the steels was close to 10^{10} cm^{-2}. The PAS method is useful for investigating dislocations, as well as open-type defects such as a vacancy and its cluster.

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