RADIATION EFFECT OF HOME–MADE STAINLESS STEEL STUDIED BY POSITRON ANNIHILATION

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ABSTRACT

The heavy ion irradiation is used for the first time to simulate the radiation damage produced by reactor neutrons in home-made modified stainless steels. The produced radiation damage is investigated by the positron annihilation spectroscopy. No detectable radiation damage is observed in the home-made modified stainless steels irradiated by 81.6 MeV carbon ions to a total dose of $3.3 \times 10^{16}\ cm^{-2}$, indicating that the home-made modified stainless steel of this type has good radiation resistant properties.

Keywords: Modified stainless steel Radiation damage Radiation resistant property Heavy ion simulation Positron annihilation lifetime

1 INTRODUCTION

Stainless steels have been widely used as structural and cladding materials in fast and fusion reactors. Radiation damage is induced in stainless steels during the reactor operation. After years of operation radiation damage causes structure and property alterations of reactor materials, such as swelling, creeping, hardening and embritlement, which migt lead to a reactor accident. The investigation of radiation damage in reactor materials is one of the most stimulating topics in the research of nuclear reactor materials. A great effort has been put into stainless steels in order to understand the production mechanism of radiation damage and to develop radiation resistant stainless steels for use in nuclear reactors. It is known that the cold work and the addition of minor impurities to stainless steels can enormously improve radiation resistant properties of stainless steels. The disastrous radiation damage occurs at the accumulated neutron fluence of $10^{23}\ cm^{-2}$ after some years of reactor operation. No neutron source is available to simulate the radiation damage produced at such a high neutron fluence. The production rate of radiation damage could be 10^7 order higher by heavy ion irradiation than by neutron irradiation. Therefore, the present work was motivated to simulate the radiation damage in the home-made stainless steel induced by neutrons in a reactor after some years operation by heavy ion irradiation and to examine its radiation resistant property by the positron annihilation spectroscopy.

2 EXPERIMENTAL

The samples used in the experiment were the home-made modified austenitic stainless steel, which is composed of C-0.07 %, Mn-1.53 %, Si-0.73 %, S-0.05%, P-less than 0.01 %, Ni-13.5 %, Cr-17 %, Mo-2.3 %, Ti-0.25 % and Fe balanced to total 100 % and cold-worked to 20 %. The samples were polished to a mirror-like surface. The size of the sample was 1 mm thick and 14 mm in diameter.

Two samples were irradiated by 81.6 MeV carbon beam from the HI-13 tandem accelerator in China Institute of Atomic Energy. The irradiation energy was chosen on the basis of the available terminal voltage of accelerator and high damage rate. The irradiation was performed at room temperature, which was obtained by cooling the sample holder with water and limiting the beam current to about 100 nA. The temperature was monitored and stable during the irradiation of 35 h. The total amount of irradiation dose was $3.3 \times 10^{16}\,cm^{-2}$ for each sample, which is corresponding to 5 dpa[1].

The positron annihilation lifetime measurement was conducted at room temperature before and after the irradiation, using a BaF_2 detector positron lifetime spectrometer with a fast-fast coincidence circuit[2]. The positron lifetime spectrometer has a time resolution of 203 ps for ^{60}C γ rays. Two samples irradiated by carbon ions were arranged as a sandwich with a 1.11 MBq ^{22}Na source in the center. The measured lifetime spectra were analysed by means of a PATFIT program[3]. Besides the source component, the lifetime spectra were well fitted in terms of two lifetime components with a fit variance of less than 1.2.

3 RESULTS AND DISCUSSION

Fig.1 shows the damage distribution calculated by a TRIM-88 program in the stainless steel irradiated by 81.6 MeV carbon ions. It illustrates that the damage produced in the sample is distributed over the range of about 65 μm with a peak at 60 μm. The positrons emitted from a ^{22}Na source can penetrate into the sample of stainless steel to a depth of about 100 μm. Therefore, the obtained results are a range average of the radiation induced defects. The range of positrons in the sample is longer than the distribution range of the induced damage. This does not lead an overestimation of the matrix component because of the trapping effect of positrons in the damaged region. The trapping effect results in a fraction of positrons actually annihilating in the damaged range which is much higher than that simply deduced from the ratio of the damaged range to the positron penitration range. This is an advantage of using positrons to study the radiation damage induced by heavy ion irradiation[4].

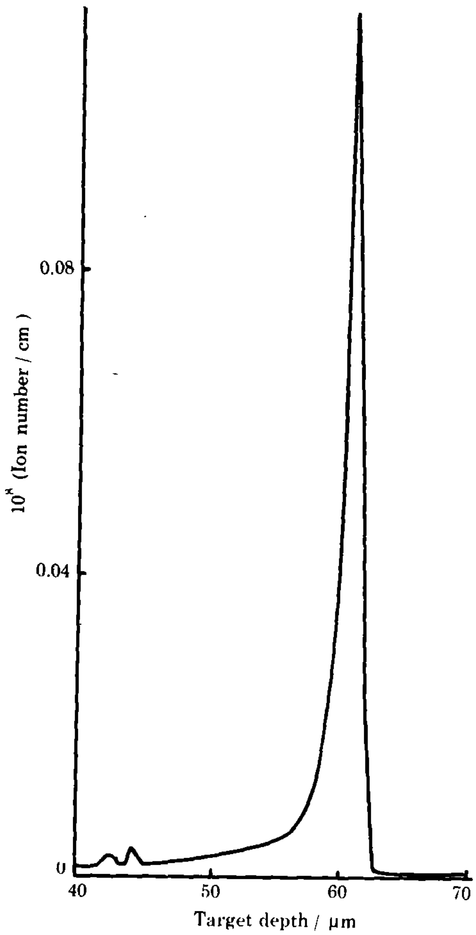

Fig.1 Damage distribution calculated by TRIM−88 program for home−made modified stainless steel irradiated by 81.6 MeV carbon ions to a total dose of 3.3×10^{16} cm^{-2}

The lifetime spectra before and after the irradiation by 81.6 MeV carbon ions are shown in Fig.2. Table 1 lists the numerical results of the lifetimes τ_1 and τ_2 and their relative intensities I_1 and I_2 obtained by fitting. The lifetimes τ_1 and τ_2 are the lifetimes of positrons annihilated in the stainless steel sample and τ_3 is the source component. From Fig.2 and Table 1 it can be clearly seen that both lifetimes τ_1 and τ_2 and their intensities are almost exactly the same before and after 81.6 MeV carbon ion irradiation. This strongly indicates that no detectable radiation damage is produced in the home-made modified stainless steel bombarded by 81.6 MeV carbon beam to a total dose of 3.3×10^{16} cm^{-2}.

Void swelling is one of the most serious radiation effects for the reactor structural and cladding materials, which might cause a disastrous reactor accident. For safe and economical operation it is of great importance to develop new materials with good radiation resistance of void swelling. Great effort has been attached to the study of void swelling and the development of void swelling resistant materials. There are two ways to suppress void swelling, which is generally considered to be one of the life limiting properties of structural materials in fission and fusion reactors. One is the cold work[5−7] which increases the compactness of the reactor materials and creates a high dencity of dislocations acting as defect sinks. The created dislocations can reduce void swelling. In general, 20 % cold work is adopted. Austenitic stainless steels cold-worked to 20 % have a much smaller swelling effect than those solute-annealed. The other is the addition of minor impurities to stainless steels[8-10]. The additions of e.g. P, Si, Ni and Ti can effectively result in suppression of void swelling under irradiation. The formation of precipitates of iron and added impurities is thought to enhance point defect recombination at the precipitate-matrix interfaces. These interfaces are effective traps for gaseous impurities produced by neutrons. The α atoms which would

Table 1

Positron lifetimes and their intensities for home-made modified stainless steel before and after 81.6 MeV carbon irradiation of 5 dpa

	τ_1 / ps	τ_2 / ps	τ_3 / ps	I_1 / %	I_2 / %
Before	152	276	1393	17.1	82.9
After	155	273	1393	17.0	83.0

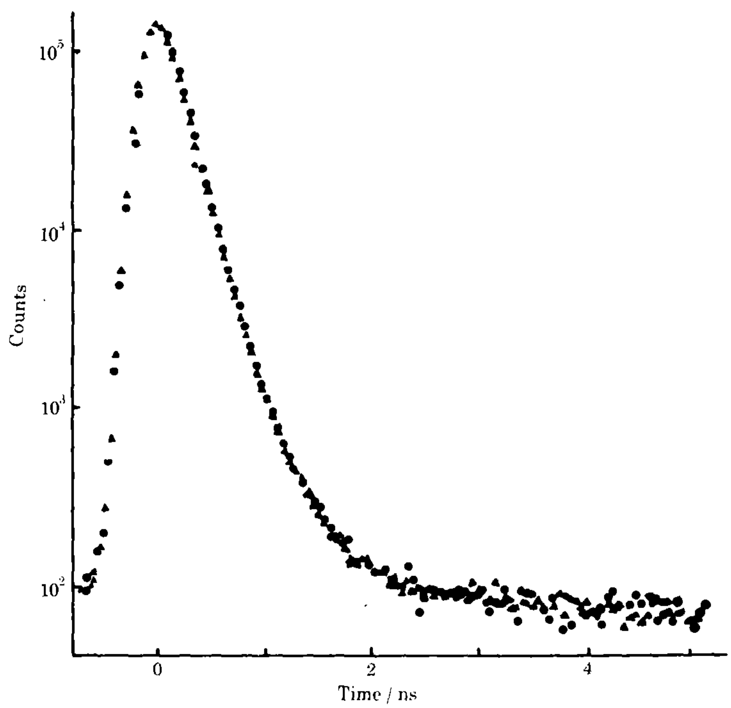

Fig.2 Positron lifetime spectra for home-made modified stainless steel before and after 81.6 MeV carbon irradiation

●- Irradiated ▲- Unirradiated

otherwise assist void nucleation, are scavenged. The addition of fast diffusing elements such as P, Si etc. causes an increase of effective vacancy diffusion coefficient, which results in the reduction in void swelling. The home-made modified stainless steel samples used in the experiment were prepared by adding Si, Ni, P, Ti etc. and cold working to 20 %. Therefore, the radiation resistance of void swelling is expected to be greatly improved. To prove it, the radiation resistant property of the modified stainless steel samples were examined by the 81.6 MeV carbon particle irradiation to a dose of 3.3×10^{16} cm^{-2}. Following the irradiation, the induced radiation damage was inspected through the positron annihilation lifetime measurement. No detectable radiation damage was observed, indicating that the modified stainless steel of this type is able to withstand an irradiation to a total dose of 5 dpa without showing any damage in it. The induced radiation damage in stainless steels depends on the irradiation temperature and irradiation dose. A high temperature and much higher dose irradiation experiments are under way.

In summary, heavy ion irradiation has been used for the first time to simulate the radiation damage in stainless steels produced by neutrons in reactors. The induced radiation damage has been investigated by the positron annihilation spectroscopy. The experimental results show that the radiation resistant properties of stainless steels are modified by the addition of minor impurities and the cold work. No radiation damage was observed in the home-made stainless steels irradiated by 81.6 MeV carbon ions to a dose of 5 dpa.

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