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VOID SWELLING BEHAVIOUR OF AUSTENITIC STAINLESS STEEL DURING ELECTRON IRRADIATION

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摘　要

利用高压电子显微镜研究了 00Cr17Ni14Mo2 奥氏体不锈钢（AISI 316L）的辐照空洞肿胀行为。结果表明，在固溶状态下几乎不存在肿胀孕育期，在离位损伤量大约为 40 dpa 时发生了转折，从肿胀过渡期转入了稳态期；在冷轧状态下不仅出现了明显的孕育期，而且直到离位损伤量为 84 dpa 时也还处于肿胀过渡期内，此外，还测定了两种状态下的空洞尺寸和密度，并讨论了影响辐照肿胀的因素。

VOID SWELLING BEHAVIOUR OF AUSTENITIC STAINLESS STEEL DURING ELECTRON IRRADIATION

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ABSTRACT

The irradiation swelling behaviour of 00Cr17Ni14Mo2 austenitic stainless steel (AISI 316L)was investigated by means of high voltage electron microscope. Results showed that in solution annealed condition almost no swelling incubation period existed, and the swelling shifted from the transition period to the steady-state one when the displacement damage was around 40 dpa. In cold rolled condition there was evidently incubation period, and when the displacement damage was up to 84 dpa the swelling still remained in the transition period. The average size and density of voids in both conditions were measured, and the factors, which influenced the void swelling, were discussed.

INTRODUCTION

The first wall structural material facing the plasma in fission-fusion hybrid reactor will be for long subjected to high fluence irradiation of 14 MeV neutrons. In this condition void swelling and helium embrittlement will become two important factors restricting the use of material. In short-term engineering the operation temperature will not be high, so that void swelling becomes more important. In China's hybrid reactor developing program 00Cr17Ni14Mo2 austenitic stainless steel has been selected as the primary candidate alloy. As is known to all, austenitic stainless steels possess poor swelling behaviour, so it is indispensable to get swelling data of 00Cr17Ni14Mo2 austenitic stainless steel and to understand its swelling regularity. Based on it some improving methods have been developed.

For lack of powerful source of fusion neutrons, other irradiation methods have been usually used in order to simulate irradiation of fusion neutrons. Electron irradiation is one of the methods. Its advantages are high damage rate, possibility of in situ observation and no activation. In this paper the void swelling behaviour of 00Cr17Ni14Mo2 austenitic stainless steel during electron irradiation was investigated.

1 EXPERIMENTAL METHOD

The chemical composition of the tested material was 0.025 C, 17.22 Cr, 14.14 Ni, 2.25 Mo, 1.24 Mn and 0.53 Si (wt%). The material was solution annealed in vaccum for 1 h at 1323 K and air cooled. Then some specimens were cold rolled, and strain was 20%. Their microstructure has been reported[1].

Irradiation was carried out in high voltage microscope. Electron energy was 1 MeV, the incident orientation of electron beam was <110>, and irradiation temperature was 823 K, which was determined to be the temperature of swelling maximum[2]. The highest displacement damage in the experiment was around 86 dpa. Microstructural change was observed in situ during irradiation.

2 RESULTS AND DISCUSSION

2.1 Void swelling analysis for solution annealed condition

Observation showed that in solution annealed condition many small voids can be found even at very low displacement damage (around 2 dpa). As displacement damage developed, the average size of voids increased (Fig. 1) and their density decreased (Fig. 2). The growth of voids brought about development of irradiation swelling. From experimental data it can be seen that this development can be divided into two stages (Fig. 3). In the first stage, transition period, the swelling amount increased slowly, then turning point appeared and afterwards the swelling rate was steeply raised. It meant that swelling entered the second stage, steady-state period. When the displacement damage was 86 dpa the swelling amount exceeded 15%. By linear regression analysis for experimental data of the transition period, the following equation can be given

$$\Delta V/V = 0.067 \times (D + 0.78) \qquad (1)$$

where D is the displacement damage, [dpa]. Physical meaning of the last numeral (-0.78) in the above-mentioned equation was the incubation period. The negative incubation period showed that almost no incubation period existed in swelling process, i. e. voids rapidly appeared as soon as irradiation started. From experimental data of the steady-state period the swelling amount can be illustrated by the following equation

$$\Delta V/V = 0.251 \times (D - 39.9) + 2.73 \qquad (2)$$

From the equation it can be seen that the swelling rate of this period was 4 times of that of the transition one and the turning point corresponded to about 40 dpa. Compared with the data of neutron irradiation, the sweling rate of the steady-state period during electron irradiation was lower than the data, given by reactor neutron irradiation (about 0.7%/dpa), and the turning point was close to the data from reactor neutron irradiation (about 30 dpa)[3]. The difference between swelling rate of electron and neutron irradiation related to disparity of two types of particles.

The microstructure of solution annealed condition after irradiation was characterized by voids with large size and high density. From experimental data of the transition period the average size of voids can be expressed by the following equation

$$d(\mathrm{m}) = 0.361 \times (38.77 + D) \times 10^{-9} \qquad (3)$$

and for the steady-state period the equation was

$$d(\mathrm{m}) = 0.603 \times (8.10 + D) \times 10^{-9} \qquad (4)$$

Both periods had the same equation for density of voids

$$\rho(\mathrm{m}^{-3}) = 0.017 \times (179.07 - D) \times 10^{21} \qquad (5)$$

From the equations it can be seen that in the transition period the growth rate of voids was only about 60% of that in the steady-state one, but there was little difference between void density of both periods. It meant that the swelling turning came from change of growth rate of voids. During electron irradiation new small voids continuously appeared and void density would increase. But experimental results indicated decrease of void density with displacement damage. It meant that voids grew through coalescence besides continuous entrance of new vacancies into them, and the coalescence of voids developed more rapidly than production of new small voids. The coalescence included two types of mechanism, direct join and ripening process. The former was induced by direct contact of two voids in their growth process. The latter was attributed to the effect of surface energy. If void was regarded as a second phase in a broad sense, stability of small voids was lower than that of large voids. Small voids dissolved in matrix and supersaturation of vacancies in matrix increased. Oppositely, large voids grew by the increased supersaturation.

Electron irradition of AISI 316 austenitic stainless steel, which contained more carbon than the material in this work, was studied[4,5]. In the same irradiation condition (823 K and 50 dpa), with increased carbon content the swelling amount was raised (Fig. 4). It meant that austenitic stainless steel with lower carbon content possessed better resistance to irradiation swelling. When the average size of voids in steels with different carbon content was compared, it can be seen that the void size increased with carbon content. In 0.07%C steel the void size was 190 nm[4], in 0.05%C steel it was 90 nm[5], and in 0.025%C steel it was smaller than 40 nm. The difference of void size was the reason for different swelling behaviour. Carbon promoted diffusion of voids, the effect of carbon can be explained by its effect on atomic bond[6].

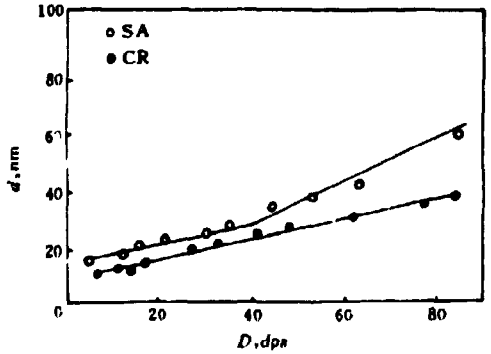

Fig. 1 The effect of displacement damage on void size

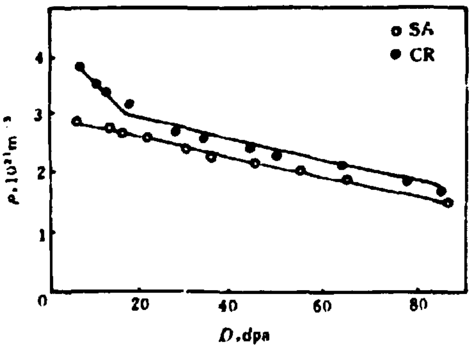

Fig. 2 The effect of displacement damage on void density

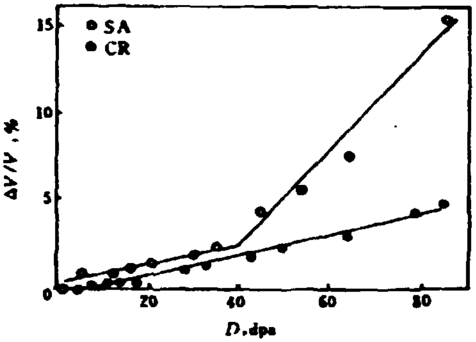

Fig. 3 Development of swelling during electron irradiation

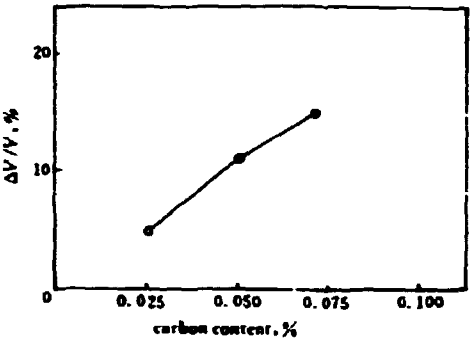

Fig. 4 The relationship between swelling amount and carbon content

2.2 Void swelling analysis for cold rolled condition

Cold work can improve swelling behaviour of materials and it is true for 00Cr17Ni14Mo2 austenitic stainless steel. In cold rolled condition appeared a distinct incubation period during electron irradiation (around 5 dpa). The regularity of the average size and density of voids in cold rolled condition was the same as that in solution annealed condition. As displacement damage was raised, the average size of voids increased (Fig. 1) and their density decreased (Fig. 2). Swelling amount increased too, but it was fewer than that of solution annealed condition (Fig. 3). It was more important that no turning point was found up to 84 dpa, it meant that the transition period was extended and the steady-state period not appeared. Swelling amount was fewer than 5% at 84 dpa. The equation for it was as follows

$$\Delta V/V = 0.058 \times (D - 6.13) \qquad (6)$$

It can be seen that the swelling rate in cold rolled condition was nearly equal to that in solution annealed condition. The improvement can be attributed to appearence of the incubation period and prolongation of the transition period, not to swelling rate. The average size and density of voids were expressed by the following equations

$$d(\mathrm{m}) = 0.335 \times (28.47 + D) \times 10^{-9} \qquad (7)$$

$$\rho(\mathrm{m}^{-3}) = 0.018 \times (179.08 - D) \times 10^{21} \qquad (8)$$

Compared with experimental data of the transition period of solution annealed condition, the growth rate of voids was decreased and their density a little increased in cold rolled condition. So its microstructure was characterized by small size and high density of voids. It meant that the coalescence process of voids in cold rolled condition developed slowly. The microstructural observation showed that cold work produced a lot of defects, including deformation induced structures and dislocation lines[1]. In 20% cold rolled condition the dislocation density was higher than that of solution annealed one in 4 order of magnitude. Dislocation was strong sink for point defects. It can promote recombination of point defect, so the degree of vacance supersaturation decreased. Dislocation hindered vacance clusters from migrating and merging each other, so the incubation period appeared and it was difficult for them to grow to critical size. Dislocation retarded coalescence process of voids, so the voids were dispersive and their density became high.

3 CONCLUSIONS

(1) Almost no swelling incubation period existed in solution annealed condition of 00Cr17Ni14Mo2 austenitic stainless steel during electron irradiation. Initially the swelling developed slowly. The turning appeared at about 40 dpa of displacement damage, then the swelling entered the steady-state period from the transition one, and swelling amount rapidly increased. The mechanism of void coalescence were direct join and ripening. Its microstructure was characterized by large size of voids.

(2) A distinct swelling incubation period appeared in cold rolled condition of 00Cr17Ni14Mo2 austenitic stainless steel during electron irradiation. Up to high displacement damage (84 dpa) no turning point was found and swelling still remained in the transition period. It meant that the swelling behaviour was improved. The improvement was attributed to the sink effect of dislocation, which retarded coalescence of voids. The microstructure was characterized by small size of voids.

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