ELSEVIER

Journal of Nuclear Materials 283–287 (2000) 278–281

journal of nuclear materials

www.elsevier.nl/locate/jnucmat

Role of α_2/γ and γ/γ phase boundaries in cavity formation in a TiAl intermetallic compound irradiated with He-ions

K. Nakata [a,*], K. Fukai [b], A. Hishinuma [b], K. Ameyama [c]

[a] *Hitachi Research Laboratory, Hitachi Ltd., Hitachi-shi, Ibaraki 317-0073, Japan*
[b] *Department of Material Science and Engineering, JAERI, Tokai-mura, Ibaraki 319-1195, Japan*
[c] *Faculty of Science and Engineering, Ritsumeikan University, Kusatsu-shi, Shiga 525-0028, Japan*

Abstract

A Ti–48at.%Al intermetallic compound has been irradiated with 200 keV He-ions at 623 and 773 K. The helium cavity density decreases with decreasing α_2 and γ lamella width. A plot of the cavity density and lamella width reveals a linear relationship after irradiation to 15 dpa. Cavity density in regions with 300 nm wide lamella is about half of that in large γ grains of the specimen. The α_2/γ lamellar boundaries supply a preferential nucleation site for cavities. Although the cavities are also formed on the γ/γ lamellar boundaries, the nucleation is limited to misfit dislocations on the boundaries. Defect-free zones are in the regions of about 50 nm width immediately adjacent to the lamellar boundaries at 773 K. These results suggest that the lamellar boundaries are effective sinks for radiation defects and contribute to the suppression of radiation-induced defect cluster development in TiAl alloys.

1. Introduction

TiAl alloys have been considered as fusion reactor materials because of their small neutron-induced radioactivity compared with stainless steels [1]. A problem, however, which adversely affects their use as engineering materials, is their low ductility at low temperatures. Many investigations have indicated that the two-phase lamellar microstructure consisting of γ-TiAl and α_2-Ti_3Al layers induces good ductility in the TiAl compound [2].

Radiation effects in TiAl alloys have been studied mainly through observation of radiation-induced microstructural development. According to these studies, the TiAl alloys are considered to have good radiation resistance above 773 K, since the growth rate of defect clusters, such as interstitial loops and cavities, is much smaller than that in stainless steels [3–5]. The radiation behavior is also somewhat different between α_2 and γ phases. Diffusion paths of radiation-induced defects are restricted in the (0 0 1) planes in γ-TiAl, in order to keep its $L1_0$-ordered structure [4,5].

These radiation studies were carried out using TiAl alloys with equiaxial grains, but few studies have been performed in materials with a lamellar structure. The radiation behavior in the lamellar structure may be different from that in the equiaxial grains. The lamellar spacing in TiAl alloys is generally less than 1 μm, and the lamellar boundaries seem to play an important role in defect cluster formation. In this study, development of radiation-induced defect clusters is investigated by using He-ion irradiation and TEM observations in the lamellar structure of a TiAl alloy. The role of lamellar boundaries in the formation and growth of helium cavities is discussed.

2. Experimental

The material used was a Ti–48at.%Al intermetallic compound produced by vacuum melting processing. The main impurity was oxygen (430 appm). The material was

* Corresponding author. Present address: Tokyo R&D Center, JAPEIC, 1-9-2 Mihama, Urayasu, Chiba, 279-0011 Japan. Tel.: +81-47 380 8797; fax: +81-47 380 8556.
E-mail address: kiyotomo@msn.com (K. Nakata).

0022-3115/00/$ - see front matter
PII: S 0 0 2 2 - 3 1 1 5 (0 0) 0 0 2 0 8 - 7

annealed at 1603 K for 14.4 ks and then hot isostatic pressed (HIP) at 1373 K for 14.4 ks. The treatment provided a fine mixed structure of γ/γ and α_2/γ lamellar grains and equiaxial γ grains.

The disks ($3\mathrm{mm}^{\varnothing}, 0.25\mathrm{mm}^{t}$) were electropolished into foils by a twin-jet technique in a solution of 5% perchloric acid and 95% methyl alcohol at about 268 K. The He-ion irradiation was performed by a Cockcroft ion accelerator operating at 200 kV. The irradiation was continued up to a fluence of 3×10^{21} ions/m^2 with a flux of 6×10^{17} ions/m^2 s at temperatures of 623 and 773 K. Damaged and stopped ions were peaked at about 760 and 820 nm from the ion bombarded surface, respectively, as calculated by the TRIM85 code [5]. After sectioning by Ar-ion sputtering, a microstructure observation was carried out around the damaged peak region by using a 200 kV TEM: the average damage in the observed area was estimated to be 15 dpa, assuming a threshold displacement energy of 25 eV [4], and helium concentration of 1×10^5 appm (10 at.%).

The density and the average size of cavities in the lamella were determined using micrographs as follows. A rectangular area of (500–1000) $\mathrm{nm}^{l} \times 50\ \mathrm{nm}^{w}$, which was parallel to the lamella, was set in the central part of the lamella, and the number and size of cavities included in the area were measured. If the lamella width was less than 50 nm, the lamella width was applied to the width of the measured area. The cavity density distribution was also determined from narrower rectangular areas of (500–1000) $\mathrm{nm}^{l} \times 30\ \mathrm{nm}^{w}$, from a lamellar boundary to the center of a lamella.

3. Results

Cavity structure is shown in Fig. 1 for the α_2/γ lamellar region in the specimen irradiated to 3×10^{21} ions/m^2 (about 15 dpa in this area) at 773 K. The cavities are observed in the matrix and as a row on the lamellar boundaries. Since the observed area contains a high helium concentration, these cavities are considered to correlate with injected helium atoms [4]. While most of the cavities in the α_2 lamellas are spherically shaped, the cavities in the α_2 lamellas are elliptical or rectangular: they were confirmed by crystallographic analysis to have formed on an (0 0 0 1) plane. The cavity density in the central part of the α_2 and γ lamellas and near the α_2/γ lamellar boundaries is shown in Fig. 2. The density near the lamellar boundaries is two to several times higher than that in the central part of the lamellas.

Comparing the number of cavities in the lamellas with each other, higher cavity densities are observed in wider lamellas. The lamella width dependence of cavity density in α_2 and γ lamellas is shown in Fig. 3 after irradiation to 15 dpa at temperatures of 623 and 773 K. In the γ lamellas irradiated at 773 K, the cavity density decreases linearly with the lamella width, and few cavities are formed in the lamellas with less than a 100 nm width. The average cavity density in large γ grains (>10 μm in diameter) of the specimen irradiated at 773 K is also shown in Fig. 3(b). The density in the lamellas with less than a 300 nm width is much lower than that in the large γ grains. A similar linear relationship is seen in the α_2 lamellas at 623 and 773 K.

Cavity formation in the γ/γ lamellar region is shown in Fig. 4 for the specimen irradiated to 15 dpa at 773 K. Cavities are seen both in the matrix and near the γ/γ lamellar boundaries. The latter cavities are in a row on the boundaries. From the observation by dislocation contrast, a one-to-one correspondence between the cavity rows and dislocation images was confirmed. Therefore, the cavities are preferentially formed along the dislocations on the γ/γ lamellar boundaries. Details of the cavity distribution are shown in Fig. 5 for the γ/γ lamellar region after irradiation to 15 dpa at 773 K. The cavity density is high at the γ/γ lamellar boundaries, but

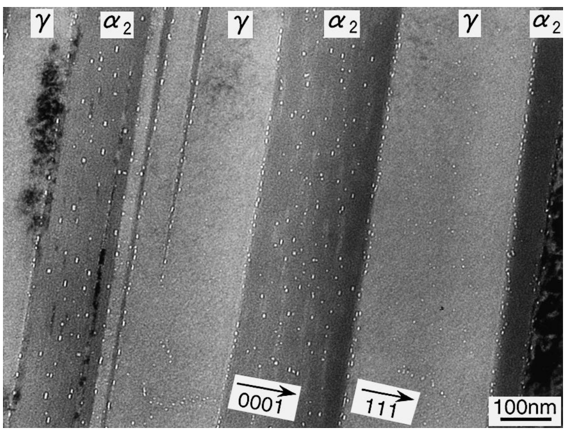

Fig. 1. Cavities in the α_2/γ lamellar region of Ti–48at.%Al irradiated with helium ions up to 15 dpa at 773 K.

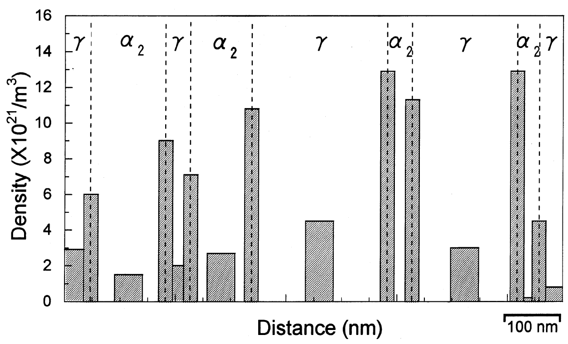

Fig. 2. The cavity density in the central part of the lamellas and near α_2/γ lamellar boundaries in the α_2/γ lamellar region irradiated to 15 dpa at 773 K.

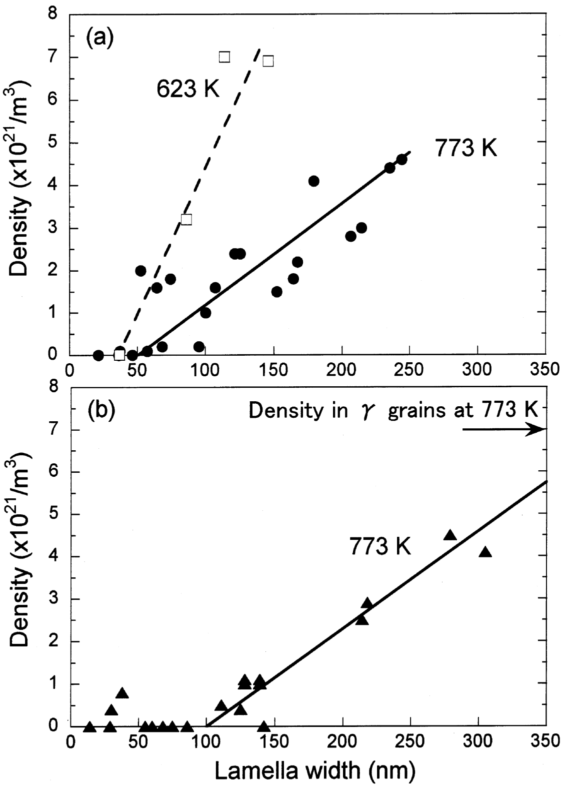

Fig. 3. (a) Lamella width dependence of cavity density in α_2; (b) γ lamellas in the specimen irradiated to 15 dpa at 623 and 773 K. No cavities are observed in γ lamellas at 623 K.

the density increase is not as apparent as that at the α_2/γ lamellar boundaries. Lower cavity density areas are found on both sides of the boundary.

Fig. 6 shows the loop structure in the lamellar region for a specimen irradiated to about 3 dpa at 623 K. Most of the loops are interstitial-type, identified by an inner–outer contrast method. Defect-free zones are found in areas with about 50 nm width immediately adjacent to the α_2/γ and γ/γ lamellar boundaries, where the loops are absent. This observation suggests that the lamellar boundaries act as sinks for radiation defects, as well as a preferential nucleation site for helium cavities.

4. Discussion

The crystallographic orientation between α_2 and γ phases in lamellar structure of Ti alloys is $\{1\,1\,1\}\gamma//(0\,0\,0\,1)\alpha_2$ and $\langle 1\,\bar{1}\,0\rangle\gamma//\langle 1\,1\,\bar{2}\,0\rangle\alpha_2$. In γ-TiAl, the crystal structure is fct, not fcc and $c/a \cong 1.02$, while α_2-Ti_3Al is hcp. So, since the $\langle 1\,\bar{1}\,0\rangle\gamma$ is not completely parallel to the $\langle 1\,1\,\bar{2}\,0\rangle\alpha_2$, misfit dislocations are present on the α_2/γ lamellar boundaries [6]. On the other hand,

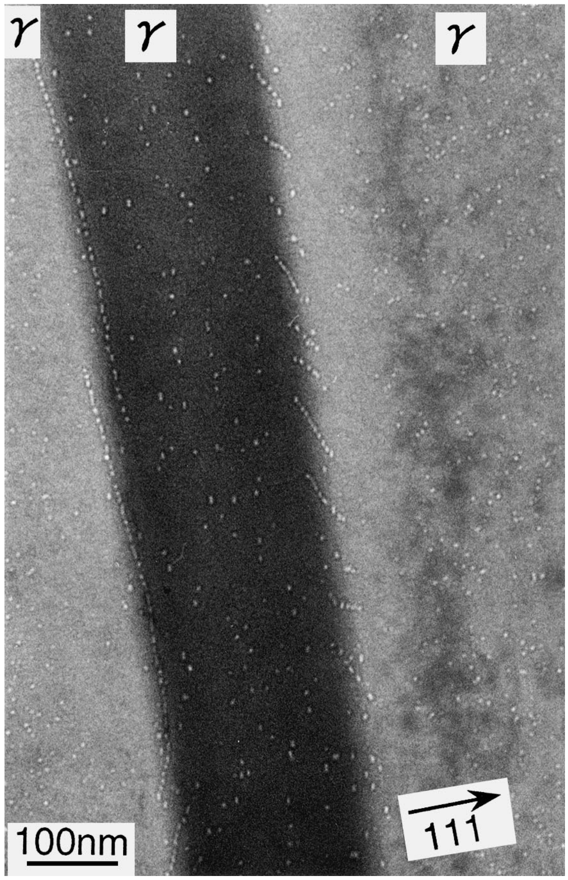

Fig. 4. Cavities in the γ/γ lamellar region of the specimen irradiated to 15 dpa at 773 K.

three types of γ/γ lamellar boundaries have been reported: twin, pseudo-twin and 120°-rotated boundaries [7]. These boundaries show better coherency compared with the α_2/γ lamellar boundaries [8], but misfit dislocations have also been observed on the boundaries [9,10]. The number of cavities formed by irradiation

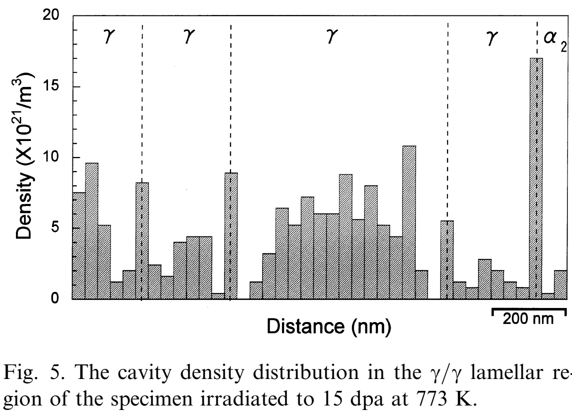

Fig. 5. The cavity density distribution in the γ/γ lamellar region of the specimen irradiated to 15 dpa at 773 K.

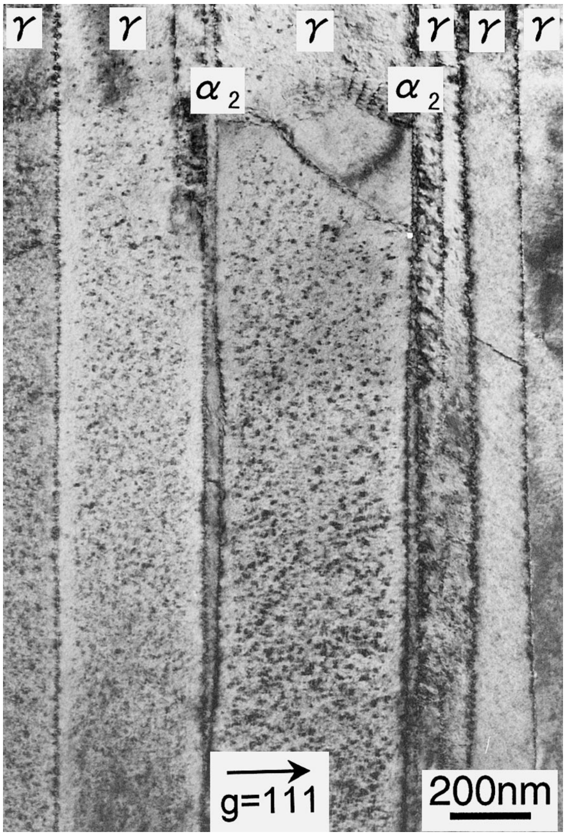

Fig. 6. Dislocation loops formed in the lamellar region of the specimen after irradiation to 3 dpa at 623 K.

depends on the density of misfit dislocations on the lamellar boundary, because the cavities are nucleated on the misfit dislocations, as typically shown in Fig. 4. The larger effect of cavity nucleation on α_2/γ lamellar boundaries seems attributable to the higher misfit dislocation density on the boundaries.

Cavity density decreases linearly with decreasing lamella width, and the density in the lamella of 300 nm width is about half of that in large γ grains (Fig. 3). This observation indicates that lamellar boundaries influence cavity formation in the areas of, at least, 150 nm from the boundaries at 773 K. Moreover, dislocation loop and cavity-free zones beside the lamellar boundaries are seen after irradiation. The average width of the dislocation loop-free zones in γ lamellas at 623 K was about 50 nm on each side from the boundaries (Fig. 6). The cavity-free zones (about 50 nm wide at 773 K) were clearly observed in γ lamellas along α_2/γ and γ/γ lamellar boundaries (Figs. 1 and 5). These results indicate that radiation-induced point defects, interstitials and vacancies are annihilated to the lamellar boundaries, and clustering of the point defects is retarded in a neighborhood about 50 nm wide. The average cavity density is suppressed in the lamellar regions, compared with the γ grains, even though the high density near the lamellar boundaries is considered. The fine lamellar structure can be beneficial for improvement of radiation behavior in TiAl alloys, because the lamellar boundaries act as sinks for radiation defects.

5. Summary

The effects of α_2/γ and γ/γ lamellar boundaries on radiation damage were studied for the Ti-48at.%Al alloy irradiated with He-ions to about 15 dpa at 623 and 773 K. The main results are summarized as follows.

(1) The helium cavity density formed by the irradiation decreases with decreasing lamella width. A linear relationship is shown between the cavity density and the width of the α_2 or γ lamellas. The density in lamellas, less than 300 nm wide, is much lower than that in large γ grains of the specimen.

(2) Cavities are preferentially nucleated on α_2/γ lamellar boundaries. Although the cavities are also formed on γ/γ lamellar boundaries, the nucleation is limited to misfit dislocations on the boundaries.

(3) Defect-free zones, in which no dislocation loops and cavities are formed by the radiation, are in regions about 50 nm wide immediately adjacent to the α_2/γ and γ/γ lamellar boundaries at 773 K.

(4) The lamellar boundaries act as sinks for radiation defects, and the cavity formation is suppressed in regions at least 150 nm from the lamellar boundaries at 773 K.

References

[1] A. Hishinuma, M. Tabuchi, T. Sawai, K. Nakata, Phys. Stat. Sol. A 167 (1998) 521.
[2] Y.-W. Kim, J. Metals 41 (1989) 24.
[3] A. Hishinuma, K. Nakata, K. Fukai, K. Ameyama, M. Tokizane, J. Nucl. Mater. 199 (1993) 167.
[4] K. Nakata, K. Fukai, A. Hishinuma, K. Ameyama, M. Tokizane, J. Nucl. Mater. 202 (1993) 39.
[5] K. Nakata, K. Fukai, A. Hishinuma, K. Ameyama, J. Nucl. Mater. 240 (1997) 221.
[6] Y.S. Yang, S.K. Wu, Philos. Mag. A 67 (1993) 463.
[7] H. Inui, A. Nakamura, M.H. Oh, M. Yamaguchi, Ultramicroscopy 39 (1991) 268.
[8] H. Inui, M.H. Oh, A. Nakamura, M. Yamaguchi, Philos. Mag. A 66 (1992) 539.
[9] F. Appel, P.A. Beaven, R. Wagner, Acta. Metall. 41 (1993) 1721.
[10] L. Zhao, K. Tangri, Acta. Metall. 39 (1991) 2209.