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Radiation growth of beryllium

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ABSTRACT

Beryllium will be used as a neutron multiplier material in the present European HCPB (Helium Cooled Pebble Bed) blanket concept of the DEMO fusion reactor. Therefore, investigation of neutron irradiation influence on dimension stability of beryllium is very important. In this paper, the radiation damage of the TE-56 beryllium grade manufactured by hot extrusion was investigated. The beryllium samples were irradiated in the SM reactor at the temperatures of 70 °C and 200 °C up to neutron fluence of (1.3–14.2) 10^{22} cm^{-2} (E > 0.1 MeV). The measurements of the sample dimensions and density as well as microstructure examinations by X-rays and TEM were carried out. It was shown that superposition of two processes – radiation growth and anisotropic swelling occurs in beryllium under neutron irradiation.

1. Introduction

In the Helium Cooled Pebble Bed (HCPB) blanket of future European fusion power reactor beryllium is needed as a neutron multiplier to maintain sufficiently high neutron flux for tritium breeding [1,2]. Neutron fluence in beryllium can achieve (6–10) 10^{22} cm^{-2} (E > 0.1 MeV) with a corresponding helium production of 20 000–30 000 appm. The dimension stability of beryllium pebbles under irradiation is important demand of the blanket concept. In this work, the influence of low temperature high dose neutron irradiation on geometrical dimensions change and microstructure evolution of beryllium are presented.

2. Experimental

The TE-56 beryllium grade manufactured by hot extrusion technology was used. The chemical composition and grain size of this beryllium grade, manufactured in Ulba Metallurgical Plant, Ust-Kamenogorsk, Kazakhstan, are presented in [3]. The samples were of two types: in the form of cylinders, 6×9 mm for dimension measurement and discs, 3×0.5 mm for TEM examination. The cylinder samples were cut in two orientations – along and across the extrusion axis. The samples were irradiated in the core position channels of the SM high flux reactor, located in Dimitrovgrad, Russia, at 70 °C in the water coolant and at 200 °C in helium in the fluence range of (1.3–14.2) 10^{22} cm^{-2} (E > 0.1 MeV). The geometrical dimensions of each sample before and after irradiation were measured with the accuracy of 0.1%. The same samples were used for X-rays examination utilizing the DARD-5 diffractometer. The TEM discs were thinned to height of 0.2 mm by mechanical grinding and then polished until formation of a hole in an electrolyte containing of ethylene glycol – 350 ml, H_2SO_4 – 1, 5 ml, HNO_3 – 4 ml, $HClO_4$ – 4–5 ml, NaOH by using of the Tenupol-3. The JEM-2000 FX II transmission electron microscope was used for the microstructure examination.

3. Results

3.1. Changes of sample dimensions

For the irradiation temperature of 70 °C (Fig. 1), the dependence of the comparative increase of diameter $\Delta D/D$ (Fig. 1(a)) and height $\Delta H/H$ (Fig. 1(b)) of the beryllium samples on neutron fluence has the different rates for the samples cut along and across the extrusion axis. For the samples cut along the axis the increase of $\Delta D/D$ occurs with comparatively greater rate to the $\Delta H/H$ increase. And on the contrary for the samples cut across the axis the increase of $\Delta D/D$ occurs with comparatively lesser rate to the $\Delta H/H$ increase. For the irradiation temperature of 200 °C (Fig. 2), this effect is lesser in comparison with lower irradiation temperature. So, for $\Delta D/D$ (Fig. 2(a)), the difference between samples cut along and across axis is practically absent and only the increase of $\Delta H/H$ (Fig. 2(b)) to neutron fluence occurs with comparatively lower rate of samples cut across the axis.

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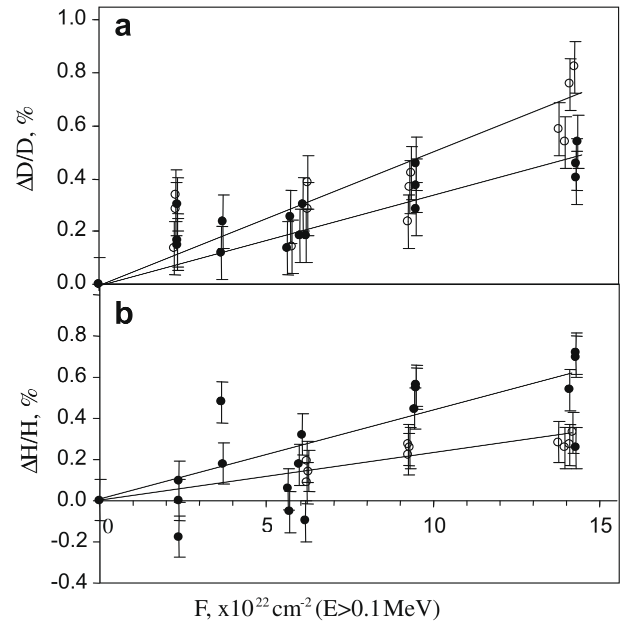

Fig. 1. Dependence of changes of diameter D/D (a) and height H/H (b) of beryllium samples for irradiation temperature of T_{irr} = 70 °C on neutron fluence F: ○ – along the axis; ● – across the axis.

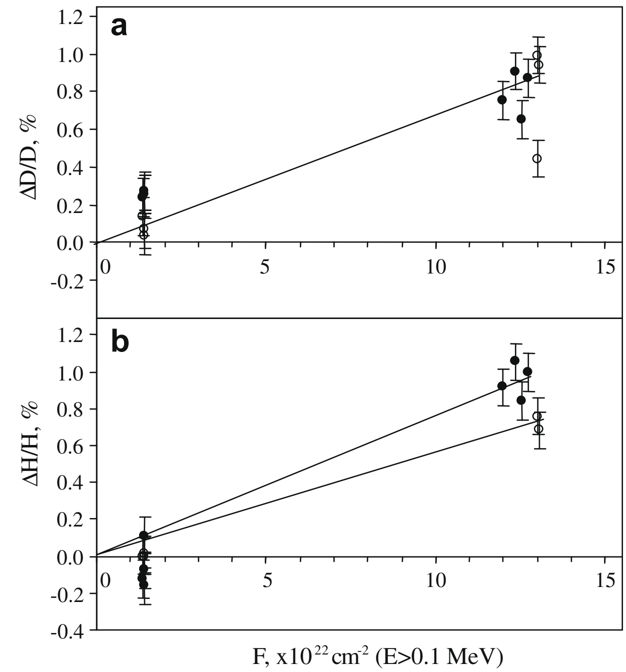

Fig. 2. Dependence of changes of diameter D/D (a) and height H/H (b) of beryllium samples for irradiation temperature of T_{irr} = 200 °C on neutron fluence F: ○ – along the axis; ● – across the axis.

3.2. X-rays investigation

The main parameters for hexagonal close packed lattice of beryllium are the '*a*' and '*c*' parameters [4]. The dependencies of the lattice constants on neutron fluence are presented in Fig. 3. Parameter '*a*' defining the basal plane (0001) is increased with increasing neutron fluence (Fig. 3(a)) but parameter '*c*' which is perpendicular to basal plane is decreased with increasing neutron fluence (Fig. 3(b)). In summary, the total elementary volume '*V*' of beryllium lattice is decreased with increasing neutron fluence (Fig. 3(c)).

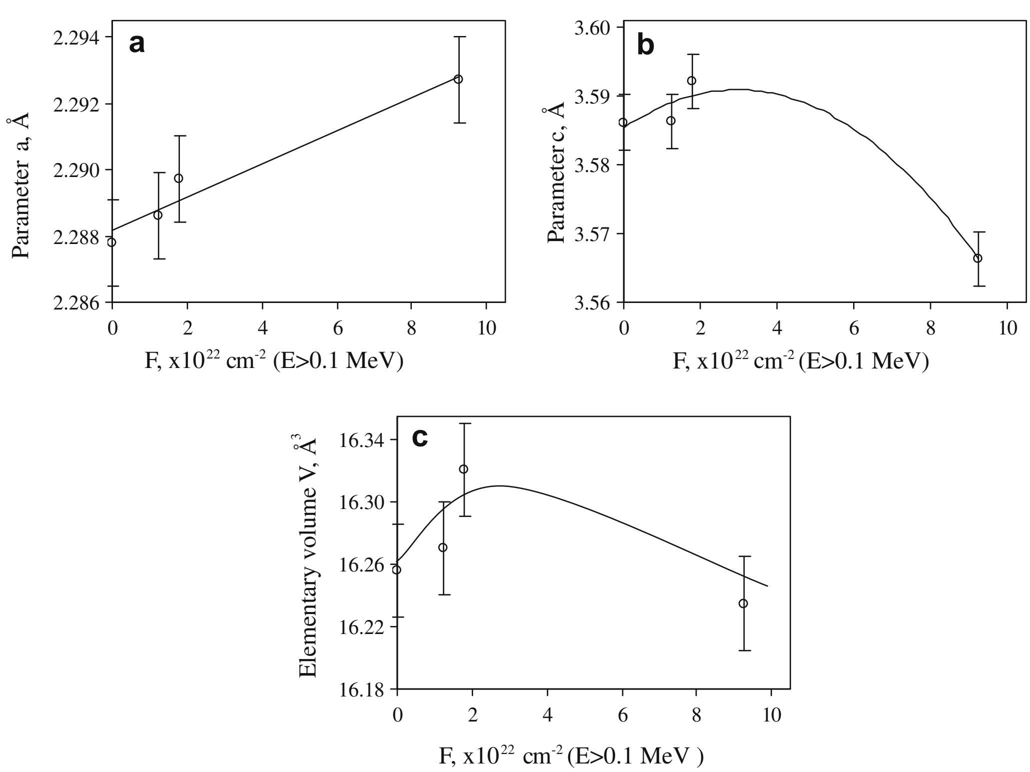

Fig. 3. Dependence of crystal lattice parameters of beryllium for irradiation temperature of T_{irr} = 70 °C on neutron fluence F: (a) parameter '*a*'; (b) parameter '*c*' and (c) elementary volume '*V*'.

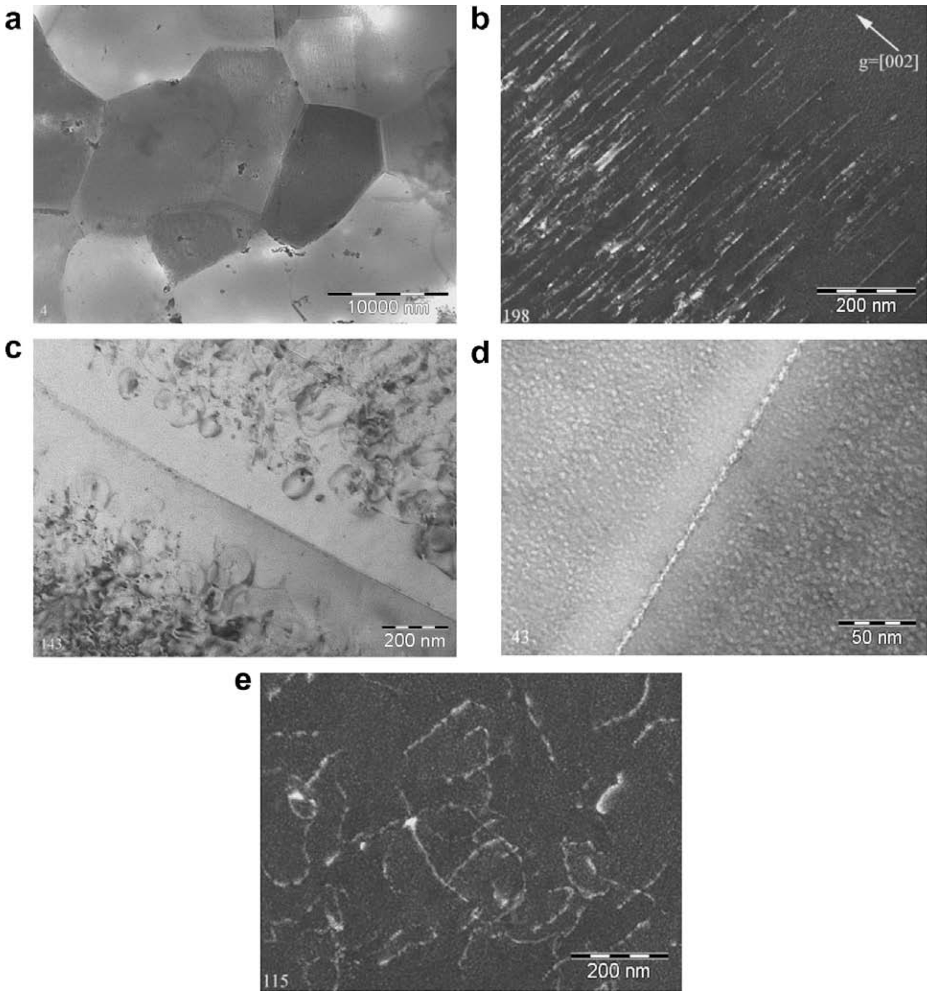

Fig. 4. Microstructure of beryllium after irradiation: (a) general view, T_{irr} = 70 °C, $F = 6 \times 10^{22}$ cm^{-2} (E > 0.1 MeV); (b) dark field image of basal dislocation loops, T_{irr} = 70 °C, $F = 6 \times 10^{22}$ cm^{-2} (E > 0.1 MeV); (c) grain boundary and denuded zone, T_{irr} = 70 °C, $F = 6 \times 10^{22}$ cm^{-2} (E > 0.1 MeV); (d) helium bubbles on grain boundary and into grain bodies, T_{irr} = 200 °C, $F = 13 \times 10^{22}$ cm^{-2} (E > 0.1 MeV) and (e) dark field image of prismatic dislocation loops, T_{irr} = 200 °C, $F = 13 \times 10^{22}$ cm^{-2} (E > 0.1 MeV).

3.3. Microstructure

The general view of beryllium microstructure irradiated at 70 °C is presented in Fig. 4(a). Second phase particles are placed into grain bodies and on grain boundaries. Analysis of micro diffraction shows that they can be identified as beryllium oxide phase. The differences between general microstructure views of beryllium irradiated at 70 °C and 200 °C are absent. Irradiation at 70 °C leads to formation of dislocation loops placed on basal planes (0001) (Fig. 4(b)) and prismatic planes (1010), (1120) (Fig. 4(c)). Determination of dislocation loops nature by method presented in [5] shows that the loops on basal planes are vacancy-type and on prismatic planes are interstitial-type. The size and density of the vacancy-type and interstitial-type loops are very different (Table 1). Irradiation at 200 °C (Fig. 4(e)) also leads to formation of dislocation loops of two types in beryllium but with another parameters as under irradiation at 70 °C. The main feature of beryllium microstructure after irradiation at 200 °C, which is absent at lower temperature, is a presence of large amount of gas bubbles both inside the grains and at the grain boundaries (Fig. 4(d)). The average size of inter granular bubbles (6.8 nm) is larger than the average size of intra granular bubbles (4.3 nm). On the contrary only single gas bubbles are visible in the microstructure of beryllium irradiated at 70 °C. Gas bubbles in neutron irradiated beryllium are filled mainly with helium produced by nuclear transmutation [6]. The denuded zones along grain boundaries are visible at both investigated irradiation temperatures. The width of the dislocation loop denuded zone at 70 °C (110 nm, Fig. 4(c)) is much larger than the bubble denuded zone at 200 °C (15 nm, Fig. 4(d)) but it is impossible to compare between them as these denuded zones were formed by different physical mechanisms. In any case, the presence of denuded zones means that the grain boundaries in beryllium are strong sinks for the point defects (vacancies, interstitials) and gas atoms. The dislocation loops of vacancy-type have the intermittent contrast (Fig. 4(b)). This fact can be the evidence of the helium atom clusters presence on loop borders. The clusters are not visible by electron microscopy, however, their presence leads to creation the deformation fields influencing on the contrast created by the loops in a surrounding matrix.

Table 1
Dislocation loops parameters of irradiated beryllium.

		T_{irr} = 70 °C, $F = 6 \times 10^{22}$ cm^{-2}	T_{irr} = 200 °C, $F = 13 \times 10^{22}$ cm^{-2}
Prismatic loops	Size (nm)	20	80
(interstitial)	Density (m^{-3})	10^{22}	6×10^{20}
Basic loops	Size (nm)	40–500	40–1000
(vacation)	Density (m^{-3})	3×10^{14}	0.5×10^{14}

4. Discussion

Beryllium has the HCP lattice and therefore possesses the anisotropy of physical properties along basal plane (parameter '*a*') and perpendicular to it (in a direction of the axis 'c'). Hot extrusion technology results in crystal texture formation which is manifested in elongation of grains in a direction of extrusion while the basal planes are oriented mainly parallel to the extrusion axis [7]. The neutron irradiation of beryllium leads to formation of self point defects as interstitials and vacancies as well as gaseous products of nuclear reactions as helium and tritium. It is known [8] that helium atoms which are created under irradiation lead to the lattice distortion without bubbles formation but it takes place at low irradiation temperatures only.

The radiation growth of zirconium having the HCP lattice under low temperature neutron irradiation is well known [9,10]. One of the basic attributes of this phenomenon is anisotropic change of geometrical dimensions of the zirconium samples under irradiation with constant volume. The physical model of the phenomenon consists in the directed condensation of the point defects (interstitials and vacancies) on various crystallographic planes [11]. This work shows that the vacancy loops in basal planes and the interstitial loops in prismatic planes are formed in beryllium under irradiation too. However, the basic difference of beryllium from zirconium is radiation-induced formation of a large amount of gas atoms that leads to gas swelling that is to the increase of the material volume. As a result, the total change of geometrical dimensions of irradiated beryllium samples includes the changes caused both by radiation growth and gas swelling which has for beryllium also an anisotropic character [8,12].

5. Conclusion

Low temperature high dose neutron irradiation of the TE-56 beryllium grade produced by the hot extrusion technology leads to anisotropic increase in the geometrical dimensions of the irradiated beryllium samples. The reason of the phenomenon can be superposition of two effects – radiation growth and gas swelling. The presence of dislocation loops of vacancy and interstitial-type preferentially situated in basal and prismatic planes can be considered as possible manifestation of radiation growth in beryllium. On the other hand large amount of gas filled bubbles suggests their contribution to swelling which is more pronounced at elevated irradiation temperatures.

References

[1] A. Moeslang et al., Beryllium for breeder blankets – status of the European R&D, in: Proceedings of the 7th IEA International Workshop on Beryllium Technology, 29th November–2nd December, 2005, Santa Barbara, California, USA, 17th February, 2006.
[2] H. Kawamura et al., Status of beryllium R&D in Japan, in: Proceedings of the 7th IEA International Workshop on Beryllium Technology, 29th November–2nd December, 2005, Santa Barbara, California, USA, 1–7th February, 2006.
[3] V.P. Chakin et al., J. Nucl. Mater. 307–311 (2002) 648.
[4] I.I. Papirov, G.F. Tikhinskij, Modern Investigations of the Beryllium, Garinizdat, Kharkov, 1998. pp. 3–5.
[5] P.B. Hirsch et al., Electron Microscopy of Thin Crystals, London, Butterworths, 1965, Mir, Moskva, 1968, pp. 270–273.
[6] V.P. Chakin et al., Physika Metallov I Metallovedenie 104 (3) (2007) 1.
[7] V.P. Goltsev, G.A. Sernyaev, Z.I. Chechetkina, Radiation Material Science of Beryllium, Science and Engineering, Minsk, 1977, p. 17.
[8] G.A. Sernyaev, Swelling and "spontaneous" cracking of beryllium under low-temperature irradiation, VANT, in: Nuclear Engineering and Technology, vol. 1&2, 1992, p. 35.
[9] B.S. Rodchenkov, Atomnaya technika za rubeghom 3 (1985) 8.
[10] V.Ya. Abramov et al., Radiation growth of zirconium alloys, in: Proceedings of the International Conference on Radiation Material Science, Alushta, USSR, Kharkov, 22–25th May, 1990, vol. 4, p. 35.
[11] G.P. Kobylyansky, V.K. Shamardin, Physika Metallov I Metallovedenie 84 (6) (1997) 121.
[12] G.A. Sernyaev, Radiation Damageability of Beryllium, Yekaterinburg (2001) 134.