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Study of helium bubbles evolution in highly neutron irradiated beryllium by X-ray micro-tomography and metallography methods

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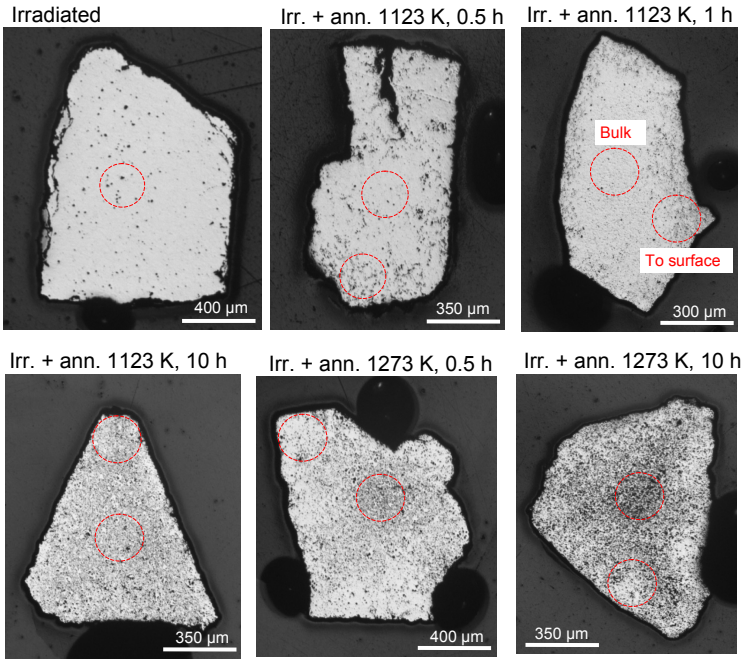
Introduction

Beryllium will be used as a plasma facing material of a first wall and a neutron multiplier of a test blanket module in ITER, and also as a neutron multiplier in the European Helium Cooled Pebble Bed (HCPB) DEMO blanket. Under neutron irradiation beryllium accumulates helium atoms due to nuclear threshold reactions with high energy neutrons. The helium accumulation directly depends on neutron fluence and leads to swelling of Be. At present Be is used as a neutron reflector and moderator in research nuclear reactors. Prominent features of the beryllium use in research reactors are low temperature operation parameters (323-343 K) and a high neutron dose accumulation to the end-of-life of the beryllium blocks. It seems very attractive to use fragments of the irradiated beryllium blocks with following post-irradiation high temperature anneals for reproducing of fusion reactor parameters on temperatures and helium accumulations.

OM images of irradiated Be samples for swelling calculations

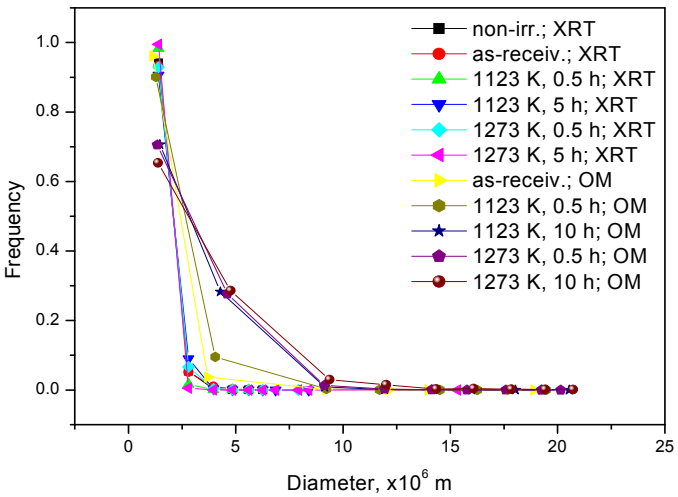


Characterization of Be samples and methods

The samples with character sizes of 1 mm were prepared from fragments of the Be matrix of the BR2 nuclear reactor located at SCK•CEN (Belgium). The original material is the S-200E beryllium grade by Brush Wellman Inc. production which contents in wt. %: < 2.0 BeO, < 0.18 Fe, < 0.15 C, < 0.15 Al, < 0.08 Mg, < 0.08 Si, < 0.04 of each other metallic elements and the average grain size to 10–13 μm. The beryllium matrix has been subjected to a temperature of approximately 323 K during 15 years of the operation resulting a fast neutron fluence with E>1 MeV of 4.67×10^{22} cm^{-2} and He accumulation of 22500 appm. The irradiated beryllium samples were annealed at 1123 K and 1273 K both for 0.5, 1, 5 and 10 h in vacuum.

Optical microscope (OM) Olympus GX51. The OM images were subjected to further image analysis. The Feret diameters of pores and bubbles were measured with their area allowing they had round shapes. But because not all pores are sectioned through their maximum diameter, many of them appear smaller than they actually are. The correction for the truncation effect and further from the corrected 2D area pore distribution to 3D volumetric distribution was performed. The same samples were investigated by X-ray micro-tomography (XRT) at the European Synchrotron Radiation Facility (ESRF). The high-resolution micro-tomography setup at the ID19 beamline with a monochromatic X-ray beam of energy in the range of 7-11 keV and a spatial resolution of 1.4 μm has been used.

Pore distribution in irradiated Be samples by XRT and OM



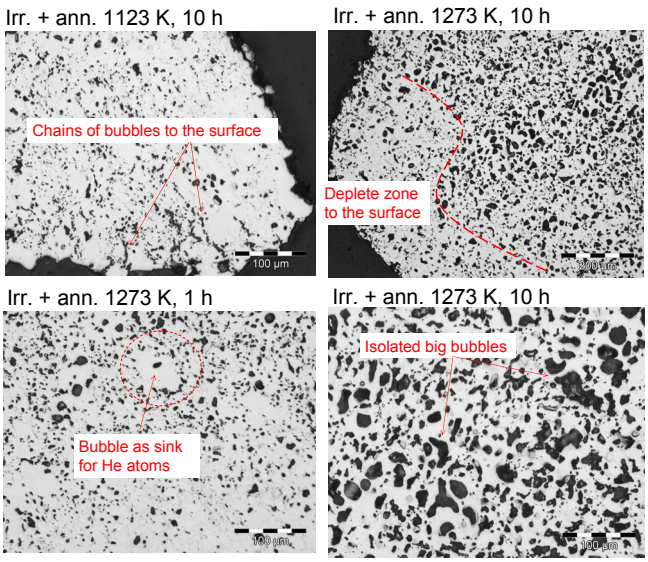
Calculated swelling and diffusion coefficient values for Be

Parameters	Swelling, %	
	Bulk	To surface
Irradiated	2.2	2.2
Irr., ann. 1123 K, 0.5 h	2.8	8.9
Irr., ann. 1123 K, 1 h	2.1	20.0
Irr., ann. 1123 K, 5 h	8.8	11.0
Irr., ann. 1123 K, 10 h	52.0	12.2
Irr., ann. 1273 K, 0.5 h	36.3	4.6
Irr., ann. 1273 K, 1 h	71.2	6.6
Irr., ann. 1273 K, 5 h	77.3	21.2
Irr., ann. 1273 K, 10 h	193.9	23.3

Parameters of anneals	Diffusion coefficient of He D_{He}, x10^8 cm^2/s	Self-diffusion coefficient of Be D_{Be}, x10^8 cm^2/s
1123 K, 0.5 h	15	1.3
1123 K, 1 h	5.3	
1123 K, 5 h	1.1	
1123 K, 10 h	0.18	
1273 K, 0.5 h	4.7	9.9
1273 K, 1 h	4.2	
1273 K, 5 h	2.6	

Extreme high swelling after anneal at 1273 K for 10 h in the bulk comparing to the surface of the Be sample!

He bubble redistribution in Be under anneals



Conclusion

High temperature anneals of low temperature high neutron dose irradiated Be lead to non-uniform formation and redistribution of He bubbles in its microstructure. Diameters, volume density and relative location of bubbles to each other depend on distance from the surface of the sample and parameters of anneals. Surface is both the strongest sink for He atoms and source for vacations. The balance of these opposite fluxes of the defects define a finale microstructure depending on anneal parameters. As a result extreme high swelling can be reached in a bulk of the sample annealed at least at 1273 K comparing to the surface layer swelling value that may cause high internal stresses in irradiated Be.