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Mechanical compression tests of beryllium pebbles after neutron irradiation up to 3000 appm helium production

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HIGHLIGHTS

- Compression tests of highly neutron irradiated beryllium pebbles have been performed.
- Irradiation hardening of beryllium pebbles decreases the steady-state strain-rates.
- The steady-state strain-rates of irradiated beryllium pebbles exceed their swelling rates.

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ABSTRACT

Results: of mechanical compression tests of irradiated and non-irradiated beryllium pebbles with diameters of 1 and 2 mm are presented. The neutron irradiation was performed in the HFR in Petten, The Netherlands at 686–968 K up to 1890–2950 appm helium production. The irradiation at 686 and 753 K cause irradiation hardening due to the gas bubble formation in beryllium. The irradiation-induced hardening leads to decrease of steady-state strain-rates of irradiated beryllium pebbles compared to non-irradiated ones. In contrary, after irradiation at higher temperatures of 861 and 968 K, the steady-state strain-rates of the pebbles increase because annealing of irradiation defects and softening of the material take place. It was shown that the steady-state strain-rates of irradiated beryllium pebbles always exceed their swelling rates.

1. Introduction

Beryllium pebbles with a diameter of 1 mm are planned to be used as neutron multiplier in the helium cooled pebble bed (HCPB) tritium breeding blanket of DEMO [1]. A key issue of DEMO relevant HCPB blankets is mechanical integrity of the beryllium pebbles under high dose neutron irradiation. The neutron irradiation leads to formation of high amounts of helium and tritium in beryllium that causes swelling, i.e. an increase of the pebble volume. The beryllium swelling at temperatures relevant to the blanket conditions (673–923 K) can reach 10–15% and even higher values depending on damage dose [2]. The irradiation-induced swelling of beryllium also in combination with different thermal expansions of the beryllium pebble bed and the structural material (Eurofer steel) can cause high thermal stresses in the pebble bed. In principle, thermal creep of the pebbles should reduce the stresses. But, it is known, that under neutron irradiation degradation of mechanical properties of beryllium occurs which is expressed in hardening and embrittlement [3]. Therefore, only direct mechanical compression tests of beryllium pebbles irradiated at the DEMO blanket relevant conditions can provide the necessary data needed to evaluate a potential compensation of the swelling by the creep deformation.

This paper presents results of compression tests of beryllium pebbles with diameters of 1 and 2 mm irradiated in the High Flux Reactor (HFR), Petten, The Netherlands within the HIDOBE-01 experiment [4].

2. Experimental

The beryllium pebbles with diameters of 1 and 2 mm were fabricated by NGK, Japan using the rotating electrode method (REM) [5]. The HIDOBE-01 irradiation campaign was in the HFR on 2005–2007. The compression tests included mechanical loading of a single pebble at a constant loading value during 80 h. The parameters

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Table 1
Irradiation and mechanical test parameters of beryllium pebbles from HIDOBE-01.

Pebble diameter (mm)	Damage dose (dpa)	^{4}He accumulation (appm)	T_{irr} (K)	T_{test} (K)	Loading (N)
1	11.3	1890	686	698	60
					100
					150
	13.9	2300	753	798	48
					70
					90
	16.3	2680	861	923	40
					55
					70
	18.1	2950	968	1023	10
					15
					20
2	11.3	1890	686	698	240
					400
					600
	13.9	2300	753	798	210
					280
					360
	16.3	2680	861	923	80
					100
					160
	18.1	2950	968	1023	20
					30
					40

of the irradiation and mechanical tests are presented in Table 1. The maximum helium accumulation in beryllium was 2950 appm corresponding to a displacement damage dose of 18.1 dpa. The irradiation temperatures of beryllium pebbles were 686, 753, 861, and 968 K. The compression tests were performed at 698, 798, 923, and 1023 K with three loading values to each testing temperature. It was foreseen to adjust the testing temperatures to the corresponding irradiation temperatures.

Fig. 1 shows the scheme of loading of a beryllium pebble in the mechanical testing machine. Before start of the compression test, the pebble (1) is placed on a supporting bottom (2). Then, the pebble is heated up to testing temperature. After reaching the testing temperature, the loading of the pebble is performed by a loading piston (3). The mechanical tests are carried out in a glove box filled by pure nitrogen. The mechanical testing machine is able to test pebbles up to temperatures of 1273 K with loading values up to 1000 N. The pebble deformation is measured by a strain gauge transducer with accuracy of $\pm 1 \times 10^{-6}$ m. At this study, the testing time was limited to 80 h, hence, the loading values for the tests were selected to obtain clearly visible steady-state strain-rates inside this time.

Optical observations of the beryllium pebbles were performed before and after compression tests. The pebbles after the tests

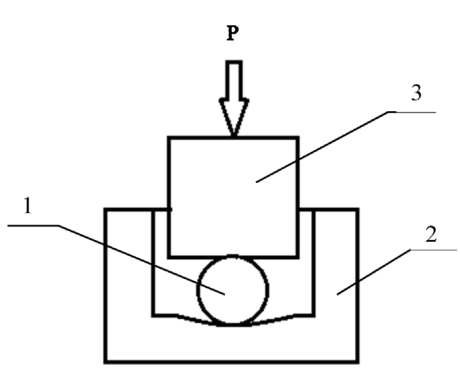

Fig. 1. The scheme of loading of a beryllium pebble during the compression test in the mechanical testing machine: (1) beryllium pebble; (2) supporting bottom; (3) loading moveable piston.

become like barrels. The base diameters were measured to calculate stresses applied to the pebbles under loading. Cross sections of 2 mm non-irradiated beryllium pebbles after mechanical tests were investigated using optical microscope (OM) Olympus GX51.

3. Results

3.1. Mechanical compression tests

As an example, Fig. 2 shows results of a typical deformation measurement of 1 mm beryllium pebbles tested at 1023 K under loading of 15 N before and after irradiation at 968 K. Fig. 2a reveals the deformation curve for testing time of 81 h. It consists of two stages. The first stage is completed after 30 h of the test duration and reflects the primary deformation stage. At this stage, the pebble is deformed by a high strain-rate. The deformation curve for first 3 h of this test (Fig. 2b) shows that immediately after loading (during time up to 1 h) the strong increase in strain of the pebble occurs. The pebble is quickly deformed by the formation of two opposed parallel contact zones resulted from the applied loads (Fig. 1). Figs. 3 and 4 represent this process in details. In particular, an irradiated beryllium pebble has a regular round form before applying of loading (Fig. 3a). Under compression test, two indentations with a diameter of d on opposite sides of the pebble are formed (see Fig. 3b and c). The relation between the pebble diameter D, the indentation diameter d and the distance h between two opposite parallel indentations on the pebble can be easily expressed by the Pythagorean theorem (Fig. 4).

During the primary deformation stage, redistribution of internal stresses and a microstructure evolution (formation of sub-grains [6]) occur in the pebble. Finally, a balance of applied loading to the strength response of the pebble material is achieved to the end of the primary deformation stage. The second deformation stage names the steady-state strain at which the strain-rate has a constant value. In this study, as a rule, the steady-state strain-rate was measured on deformation curves starting from 30–40 h when the slope of the curve became constant.

Fig. 5 shows the steady-state strain-rate versus stress for both non-irradiated and irradiated beryllium pebbles. The neutron