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State of beryllium after irradiation at low temperature up to extremely high neutron doses

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Abstract

A study was made for four beryllium grades manufactured in Russia by hot extrusion (HE) and hot isostatic pressing (HIP) methods. Irradiation of specimens in the SM-3 reactor at a temperature of 70 °C up to a neutron fluence of $(0.6\text{–}11.1)\times10^{22}$ cm^{-2} ($E > 0.1$ eV) was performed and followed by post irradiation examination. The obtained results do not provide evidence of the advantage of one beryllium grade over another in terms of resistance to radiation damage in the fission reactor. In particular, neutron irradiation leads to absolutely brittle failure of all investigated beryllium specimens, according to the results of mechanical tensile and compression tests. Swelling of all grades at the maximum neutron dose does not exceed 1–2%. Some difference among the irradiated beryllium grades becomes apparent only in the brittle strength level.

1. Introduction

At present, beryllium is considered as a blanket material for the DEMO fusion reactor where it will be exposed to the neutron flux of high energy. Towards the end of the irradiation cycle neutron fluence at this reactor can reach $(10\text{–}20)\times10^{22}$ cm^{-2} ($E > 0.1$ eV), resulting in significant damage of material structure and corresponding degradation of physical–mechanical properties [1–3]. Similar neutron fluence can be accumulated in the existing high flux fission reactors. The analysis of beryllium radiation damage under high dose neutron irradiation in the fission reactor enables predicting to a certain extent behaviour of this material under fusion reactor conditions.

In this work, results are presented of neutron irradiation influence, performed in the SM-3 reactor at temperature of 70 °C within a wide fluence range, on swelling and mechanical properties of different Russian beryllium grades. The recently obtained data at the maximum neutron doses are of particular interest.

2. Materials, experimental technique

In this work four grades of beryllium manufactured by hot extrusion (HE) and hot isostatic pressing (HIP) were used. Chemical composition and grain sizes of the investigated beryllium grades are shown in Table 1. The specimens for tensile tests were in the form of cylindrical dumbbells with a guage section diameter of 3 mm and a length of 10 mm, for the compression tests – the cylindrical specimens which had a 6 mm diameter and 8 mm length. The specimens of the E-56 and E-30 anisotropic grades were prepared in two orientations – along and across of the extrusion axis. In swelling calculation the geometrical sizes were measured only on the cylindrical specimens. The measurement error did not exceed 0.1%. Density of the initial and irradiated specimens was measured by a hydrostatic method, the measurement error was 0.2%.

The specimens were irradiated in non-sealed capsules placed in the experimental channels of the SM-3 reactor

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Table 1
Chemical composition and grain sizes of investigated beryllium grades

Grade	Technology	Average grain size (μm)	Chemical composition (% mass)							
			Be	BeO	O	Fe	Al	Si	C	Mg
TE-56	HE	25	98.6	1.48	0.98	0.17	0.026	0.016	0.08	No data
TE-30	HE	15	98.1	2.5	1.66	0.11	0.015	0.013	0.088	0.002
TIP	HIP	12	98.8	1.3	0.89	0.13	0.013	No data	0.07	0.0066
DIP	HIP	13	98.6	2.0	1.3	0.03	0.005	No data	0.067	0.0016

core. During irradiation the specimens were washed by primary circuit water, and so the temperature was close to coolant temperature and was approximately 70 °C. Neutron fluence was in the range of $(0.6\text{–}11.1)\times 10^{22}$ cm^{-2} ($E > 0.1$ eV).

3. Experimental results

3.1. Swelling

It should be noted that swelling of the anisotropic grades of beryllium manufactured by the HE method was averaged according to the total number of the irradiated specimens cut from each orientation (along or across the extrusion axis). Swelling of the TIP and DIP anisotropic grades was also calculated according to the total specimens number of each grade. As a rule, the number of each type of beryllium grade specimen investigated was 8–10 pieces for calculation in terms of geometrical sizes and anisotropical grade density and the number of the anisotropical grades was 4–5 pieces.

Dose dependence of swelling of the TE-56 irradiated beryllium grade is shown in Fig. 1. Swelling was measured in terms of changes of specimen geometrical sizes and density under irradiation. It can be observed that swelling increases with irradiation dose and this growth is, as a whole, monotonic. However the dose dependence cannot be shown by one line due to considerable data dispersion. Therefore, swelling versus the neutron dose is shown in the Fig. 1 as a crosshatched region. The greatest swelling is observed on the specimens irradiated up to the maximum dose and its value exceeds 2%.

Dose dependence of swelling obtained on restricted number of the irradiated beryllium specimens of the TE-30 grade is shown in Fig. 2. Maximum swelling is 1.2% at a fluence of 6×10^{22} cm^{-2} ($E > 0.1$ MeV). It approximately corresponds with swelling of the TE-56 beryllium grade at comparable neutron fluence.

Dose dependence of beryllium swelling of the TIP and DIP grades manufactured by HIP technology is shown in Fig. 3. As a whole, this dependence is similar to dose dependence of the anisotropical beryllium grades shown above. However, it should be noted that the swelling level of the DIP beryllium grade at the maximum neutron dose, determined according to the density measurement results, is considerably lower than the

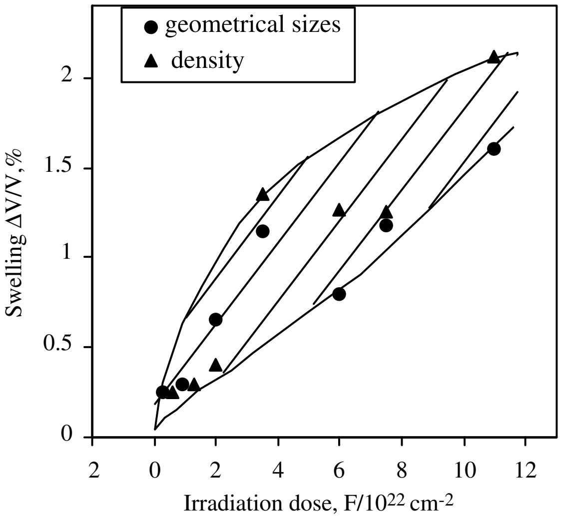

Fig. 1. Dose dependence of swelling of the irradiated TE-56 beryllium grade.

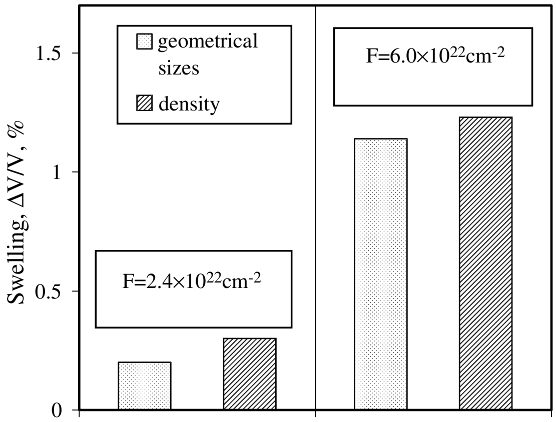

Fig. 2. Dose dependence of swelling of the irradiated TE-30 beryllium grade.

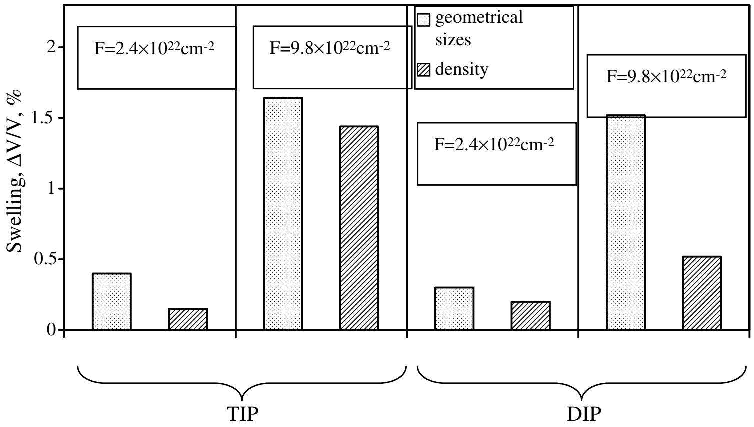

Fig. 3. Dose dependence of swelling of the irradiated TIP and DIP beryllium grades.

swelling level of other beryllium grades at similar doses (0.5% against 1.5–2%). The swelling value obtained from the density measurements is similar to those of other grades. In this connection, additional density measurements are apparently needed of the DIP beryllium grade specimens irradiated at fluence of $\sim 10\times 10^{22}$ cm^{-2} ($E > 0.1$ MeV) and above to confirm the results reported in this paper.

3.2. Mechanical properties

All irradiated specimens of the investigated beryllium grades had absolutely brittle failure during the mechanical tests at room temperature and so, only one parameter obtained by these tests is considered later – the brittle strength. The ultimate strength was measured in initial state.

Dose dependence of the brittle strength of the TE-56 grade specimens cut out along and across the extrusion axis is shown in the Fig. 4 according to the results of the tensile and compression tests. As a whole, the brittle strength level of the irradiated specimens considerably decreases with neutron dose, however, this decrease is mainly monotonic but not always. The most sharp fall occurs within the neutron fluence region from 0 to 1×10^{22} cm^{-2} ($E > 0.1$ MeV), when the strength level falls by a factor of 4 or more. This foot radiation embrittlement indicates that considerable damage of the beryllium microstructure takes place already at the initial phase of low temperature neutron irradiation. A subsequent accumulation of the radiation defects with neutron fluence results in a monotonic decrease of the brittle strength of the irradiated beryllium specimens, except for the range of $(6–8)\times 10^{22}$ cm^{-2} ($E > 0.1$ MeV) according to the results of the tensile tests (Fig. 4(a)). At this point the brittle strength of the specimens cut out along the extrusion axis sharply decreases from 130–200 MPa to ~100 MPa. The brittle strength stabilises at this level with further neutron dose. In fact, within this dose range a difference between the brittle strength levels of the irradiated specimens cut out along and across the extrusion axis (observed at the lesser doses) disappears. Or rather, the brittle strength of the specimens cut out along the axis decreases to the brittle strength level of the specimens cut out across the extrusion axis. During the compression tests (Fig. 4(b)) the dose dependence of the brittle strength of the TE-56 beryllium grade within the indicated dose range is on the contrary smoothly monotonic. However, the brittle strength of the specimens cut out across the axis is somewhat greater than the brittle strength of the specimens cut out along the extrusion axis in the higher dose range. During the compression tests at the maximum doses the brittle strength is apparently stabilised at 500–600 MPa.

Dose dependence of the TE-30 beryllium grade brittle strength is shown in the Fig. 5. A sudden brittle strength reduction is observed according to the tensile tests results (Fig. 5(a)) already at neutron fluence of 6×10^{22} cm^{-2} ($E > 0.1$ eV), when its value is only 30–50 MPa. The compression tests results indicate the retention of more acceptable level of the brittle strength (Fig. 5(b)).

Dose dependence of the brittle strength of the irradiated TIP and DIP beryllium grades is shown in the Fig. 6. According to the tensile tests (Fig. 6(a)) the two grades behave quite differently. The TIP grade has some increase of the brittle strength with increasing dose, where as the DIP grade has its abrupt decrease. Here it is necessary to have in view that absolutely brittle failure allows some instability of the results that can lead to unfounded conclusions due to the limited number of the irradiated specimens. Therefore there is no doubt that it is necessary to specify the results obtained during additional investigations of the TIP and DIP grades irradiated at the maximum neutron doses. The results of the compression tests (Fig. 6(b)) indicate that the decrease

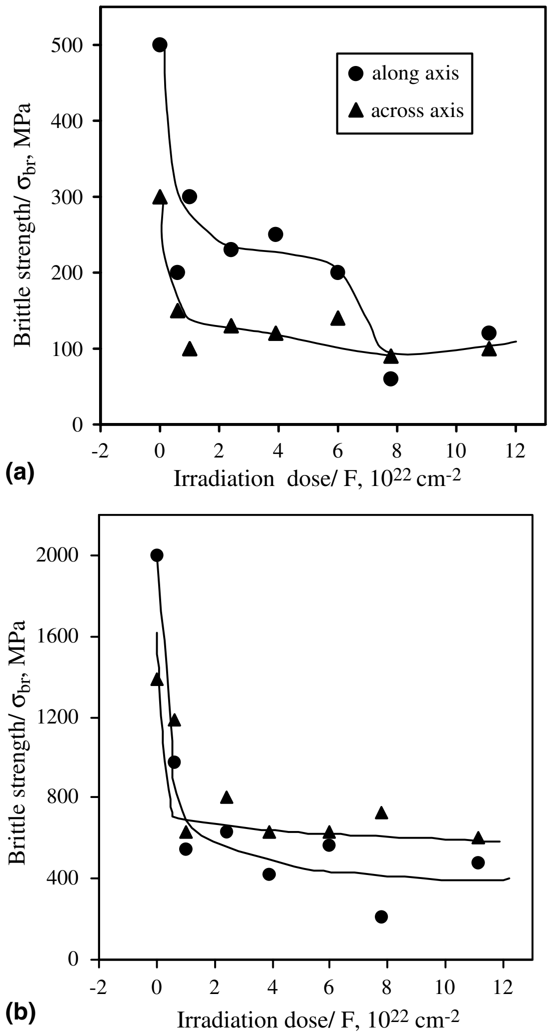

Fig. 4. Dose dependence of brittle strength (σ_{br}) of the irradiated TE-56 beryllium grade ($T_{test} = 20$ °C): (a) tensile mechanical tests; (b) compression mechanical tests.

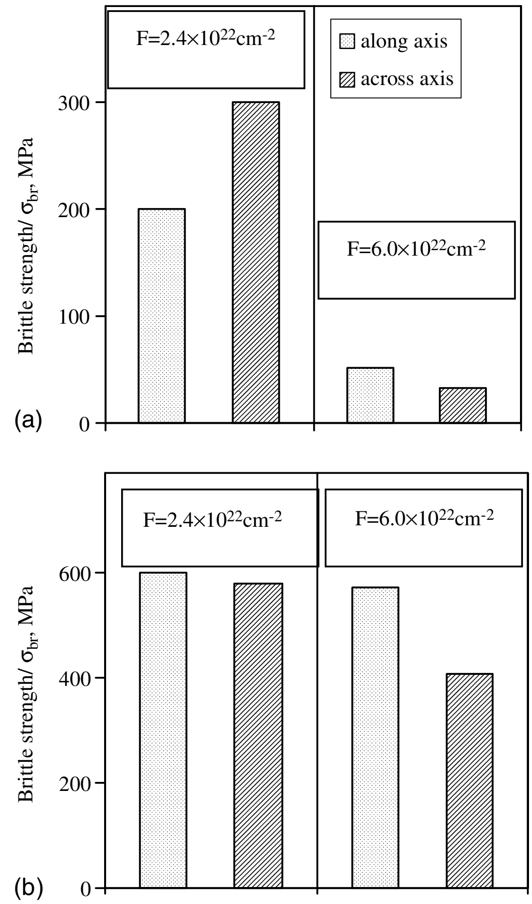

Fig. 5. Dose dependence of the brittle strength (σ_{br}) of the irradiated TE-30 beryllium grade ($T_{test} = 20$ °C): (a) tensile mechanical tests; (b) compression mechanical tests.

of the brittle strength level is monotonic with increasing dose which correlates with behaviour of other investigated beryllium grades under low temperature neutron irradiation.

4. Discussion

In the literature there are practically no data on beryllium properties irradiated up to high neutron doses when the accumulation of radiation defects, transmuted helium and the expected degradation of the physical–mechanical properties are maximum. There properties are determining factors for substantiation of serviceability of beryllium blanket used in the DEMO fusion reactor. From this point of view the investigations performed in the fission reactors within the low temperature irradiation region (70–200 °C) can be considered as an assessment of radiation resistance of beryllium in the lower region of the assumed temperature range of the fusion reactor. A comparison of the swelling values at the maximum achieved doses shows that there is no significant difference between the investigated beryllium grades. In all cases swelling is approximately of 1–2% (except for the DIP grade mentioned above). Such swelling is probably not excessive a critical in terms of dimensional stability of irradiated beryllium products. However, on closer examination of the degradation of the beryllium mechanical properties under low temperature neutron irradiation it is difficult to diminish the role of swelling [4]. Swelling anisotropy of separate beryllium crystallites as a metal with hexagonal close packed lattice results in considerable boundary weakening and provokes brittle grain-boundary failure.

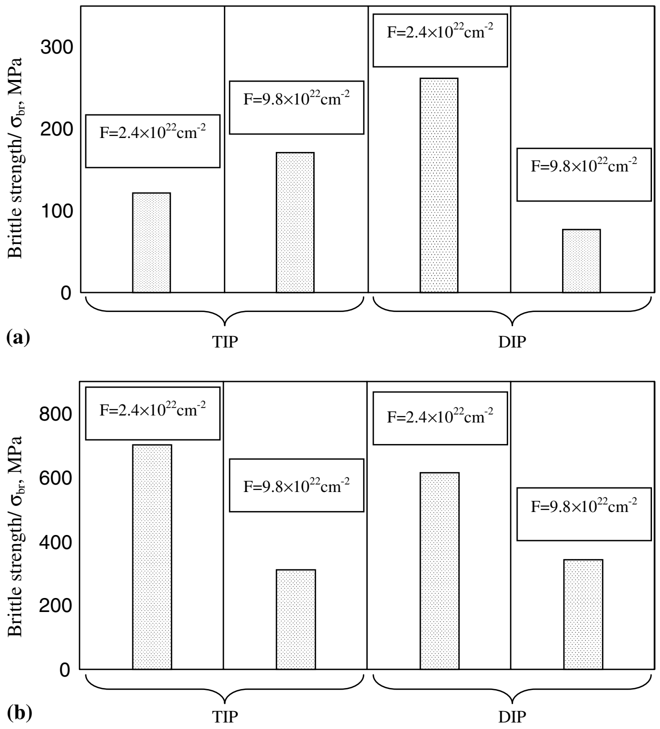

Fig. 6. Dose dependence of the brittle strength (σ_{br}) of the irradiated TIP and DP beryllium grades ($T_{test} = 20$ °C): (a) tensile mechanical tests; (b) compression and mechanical tests.

Accordingly, swelling increase with neutron dose provokes degradation of beryllium mechanical properties manifested in a gradual decrease of the brittle strength level. In a theory a critical dose must exist when the strength of beryllium irradiated at low temperature must fall practically to zero and the compact material must break up into the separate grains. However, the maximum neutron doses of $(10–11) \times 10^{22}$ cm^{-2} ($E > 0.1$ eV) achieved in this work and the mechanical tests testify that the margin of brittle strength of the investigated specimens remained to some degree. The rapid decrease of the brittle strength of the anisotropic TE-30 grade, more fine-grained in comparison with the TE-56 grade, is somewhat unexpected. Apparently, the brittle strength value of the irradiated specimens of this grade determined from the tensile tests results (30–50 MPa) can already considered as unsatisfactory.

5. Summary

1. Irradiation of several Russian beryllium grades manufactured by hot extrusion and hot isostatic pressing was carried out in the SM-3 reactor at a temperature of 70 °C up to a neutron fluence of $(0.6–11.1) \times 10^{22}$ cm^{-2} ($E > 0.1$ eV) and the post-irradiation examinations of swelling and mechanical properties were performed.
2. Swelling of the investigated beryllium grades at the maximum neutron fluence is 1–2%. No significant difference between them was observed terms of volume change accumulation with neutron fluence.
3. Degradation of the beryllium mechanical properties according to the mechanical tensile and compression tests results is expressed in absolutely brittle failure of all tested irradiated specimens and in the successive decrease of the material brittle strength with irradiation increasing dose. The brittle strength level of the investigated beryllium grades from the tensile tests results is 30–170 MPa at the maximum neutron fluence and from the compression tests is 300–600 MPa.

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