Materials Physics and Mechanics 38 (2018) 40-47 Received: March 16, 2018

TECHNIQUE OF DURABILITY ESTIMATION FOR THIN BERYLLIUM FOILS DURING THEIR WORK IN X-RAY DETECTORS

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Abstract The stress-strain state for thin beryllium windows of circular shape under cyclic loading by external pressure was calculated using finite element method. The technique for estimating the beryllium window's fracture probability was proposed. Technique is to compare the accumulated plastic strain in a foil with a certain value of the critical plastic strain, determined experimentally by foil samples bending tests. An experimental study of the durability for beryllium windows with a thickness of 8 μm under cyclic loading with external pressure was performed. Good convergence between the predicted and the fact number of load cycles without fracture was established.

Keywords: thin beryllium foils; beryllium fracture; beryllium cyclic deformation; beryllium X-ray windows.

1. Introduction

Beryllium foils of circular shape (so-called beryllium windows) with a thickness from 5 to 10 μm are widely used in the manufacture of Si-Pin, SDD and other X-ray detectors [1-4]. The characteristics of X-ray detectors directly depend on the thickness of used foil, which pasted or soldered to detector body (Fig. 1).

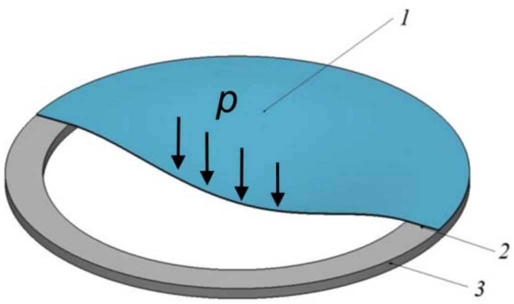

Fig. 1. Scheme of beryllium window fixed on the X-ray detector (1 – beryllium window, 2 – soldering area, 3 – metal frame).

To operate the X-ray detector, it is necessary to provide a high vacuum with a residual pressure of 10^{-5} – 10^{-7} Pa inside its chamber. So the beryllium window is exposed to an external pressure of 1 atmosphere (101325 Pa) during the detector operation. In some cases, the pressure can reach a value of 1.2 atmospheres. External pressure provides a significant mechanical load on the detector window, as result of which the foil experiences deformation.

http://dx.doi.org/10.18720/MPM.3812018_6

Beryllium is a brittle material with low plasticity, so even a slight plastic deformation can cause fracture of the beryllium window, which will lead to vacuum loss and detector failure.

During X-ray detector operation a significant number of exhaust and inflow cycles of atmosphere is performed in its chamber, i.e. loading is cyclical. External pressure does not affect the whole area of beryllium window, but only the part of it that is not fixed in the frame (Fig. 1) called «window aperture» or «active area». Producers of X-ray detectors tend to increase the active area. However, it is important to ensure the absence of foil fracture during detector operation. Thus, it is necessary to have information about plastic deformation in the beryllium window under loading and its fracture probability at a given strain.

The aim of this work is to develop the technique of durability estimation for thin beryllium foils during their work in X-ray detectors under cyclic loading. It will allow selecting the optimal ratio of aperture and thickness for beryllium X-ray window reliable operation.

2. Numerical simulation of window cyclic loading by external pressure

The problem of plastic deformation for thin foil does not have an exact analytical solution, thus it was solved in ABAQUS using an axisymmetric setting.

Mesh consisted of 50 SAX1 elements, which thickness corresponded to the loaded foil thickness. For points of mesh, belonging to the soldering area, any translational and rotational displacements were excluded. For nodes, which corresponding to the aperture region, pressure p equal to 1 or 1.2atm, given by a cyclic law with a duration of one complete loading cycle of 4s, was applied.

The material properties were determined by the stress-strain curve [5], the elasticity modulus E = 290 GPa, and the Poisson's ratio $\nu = 0.02$ [6].

3. Results of modeling and their discussion

As result of the calculations, distribution fields of stresses, displacements, and accumulated strains in beryllium windows were obtained and their change during number of cycles increasing was established.

The maximum values of maximum principal stress σ_1 and strain ε_i appear in a narrow window area directly bordering on the embedding (Fig. 2), in this region beryllium deforms plastically. Thus, it is the critical area where the foil fracture is most probable.

As the number of cycles increases, the values of accumulated plastic strain ε_i in the critical window region first increase sharply, and then stabilize, staying unchanged (Fig. 3). Calculations show that the strain ε_i in the critical region cease to increase when 1000 to 1500 loading cycles are reached (Fig. 3).

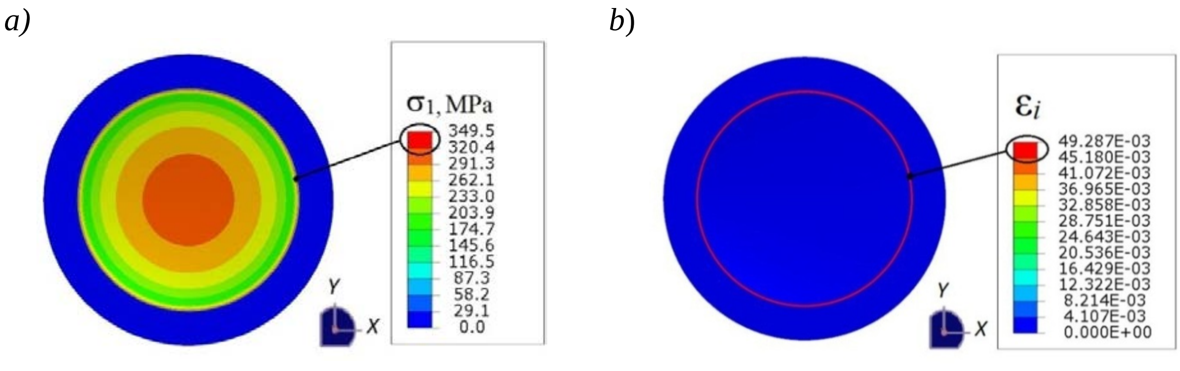

Fig. 2. The distribution field of maximum principal stress σ_i (*a*) and accumulated plastic strain ε_i (*b*) for a window with diameter of 9.2 mm, aperture of 7 mm and thickness of 8 μm after 1500 cycles of loading with external pressure at 1 atm.

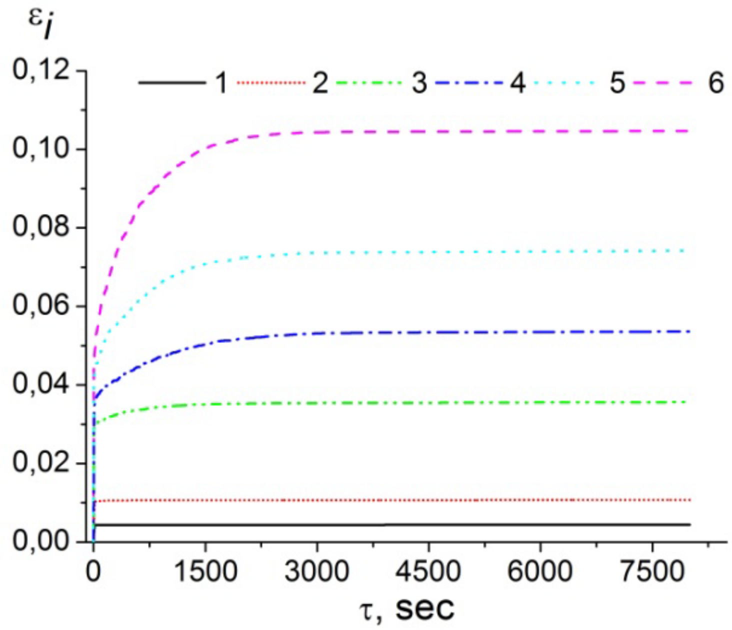

Fig. 3. Dependence of the accumulated plastic strain ε_i values change in the critical region on the loading time for beryllium window with aperture of 10 mm at cyclic load by external pressure p = 1 atm for different foil thicknesses: 1 – 30 μm; 2 – 25 μm; 3 – 15 μm; 4 – 12 μm; 5 – 8 μm; 6 – 5 μm.

As a result of the calculations, values of maximum deflections at center of beryllium window (U_{max}, Fig. 4, *a*) and maximum accumulated strains in the critical region (ε_i, Fig. 4, *b*) for different foil thicknesses and pressure levels were obtained. Deflections and strains are determined by the aperture and the thickness of used foil and can both substantially increase and practically not differ from zero.

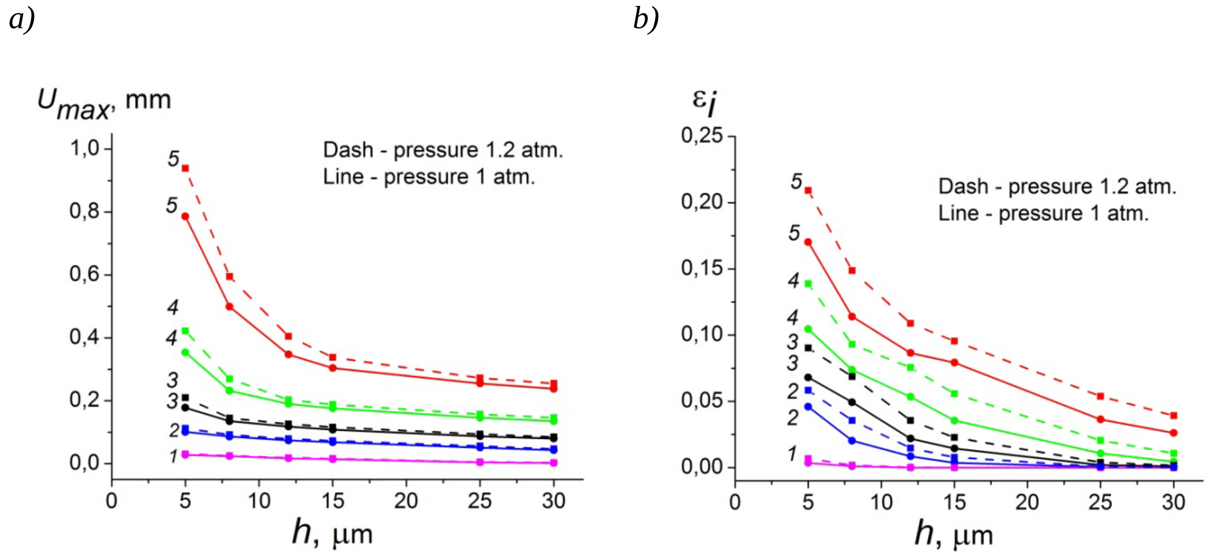

Fig. 4. Dependence of the change in the maximum displacement value $U_{\max}$ (*a*) and dependence of the change in the accumulated plastic strain ε_i value in the critical region of the beryllium window (*b*) after 1500 loading cycles on the window thickness at different pressures and apertures (1 – 2 mm, 2 – 5 mm, 3 – 7 mm, 4 – 10 mm, 5 – 15 mm).

4. Method for determining of ultimate plastic strain values

For foils with a thickness of 5 – 30 μm from brittle materials such as beryllium, it is impossible to perform an evaluation of mechanical characteristics using standard techniques as tensile test, compression test, etc. Proceeding from this, to determine the ultimate values of plastic strain, the most informative and available are the tests for foil samples bending up to fracture. When bending, the plastic deformation is localized in the bending region, in this same part the main tensile stresses act (Fig. 5).

Knowing the bending angle at the fracture moment (i.e., the formation of the first cracks) during experimental testing, it is possible to calculate the accumulated plastic strain for a given bending angle, which will be the limiting (C_{ult}).

Calculation of the accumulated plastic strain values at beryllium foil bending can also be performed using the finite element method (Fig. 5). For comparison, Fig.5 also presents the results of bending modeling for foils with a thickness of 200 and 250 μm. In Fig. 6 shows the calculated dependences of the accumulated strains on the bending angle α for different foil thicknesses. It has seen that the value of deformation achieved during bending decreases with decrease in thickness of curved foil at same bending angle.

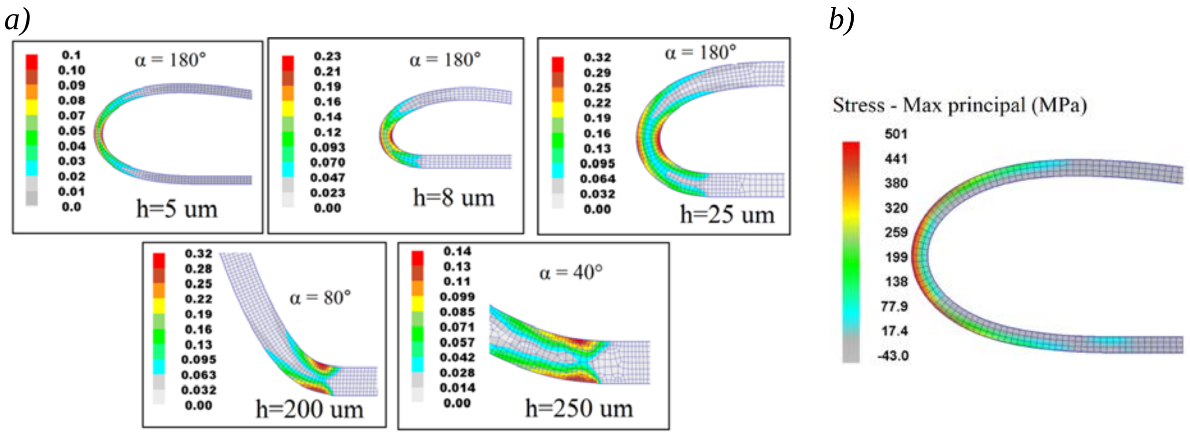

Fig. 5. The distribution of accumulated plastic strain in foils with a thickness of 5-250 μm after bending with angle α (*a*) and distribution of maximum principal stress σ_1 (*b*) at bending of 5 μm thickness foil.

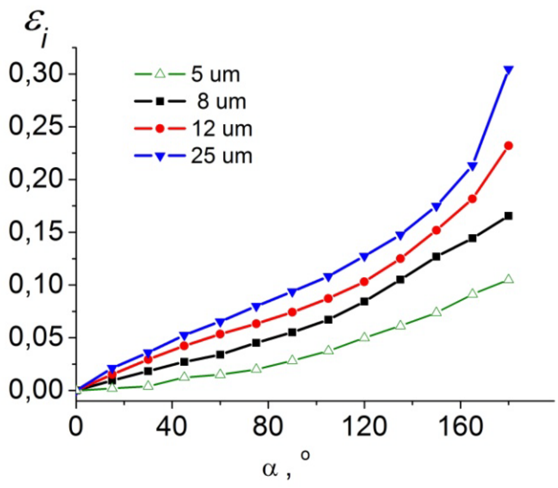

Fig. 6. The calculated dependencies of the accumulated plastic strain values at the bending angle α for different foil thicknesses.

5. Experimental investigation of beryllium windows fracture under cyclic loading by external pressure

To test the adequacy of the developed technique, cyclic tests for beryllium foil samples were performed. Foils with a thickness of 8 μm were chosen to testing, since it is most often used in X-ray detectors, and is also more prone to fracture compared to samples having a large thickness.

The outer diameter of the samples was 15 mm with aperture of 10 mm. The foils were connected to the metal frame using low-melting solder. The tests were carried out either before reaching 2000 loading cycles, or before the beginning of window fracture. Samples with an initial helium leakage rate no more than 10^{-10} mbar l/sec were used for the test. To control the moment of fracture begin the helium leak detector MS-40 from VIC was used.

It should be noted that beryllium X-ray windows have a very high cost, and therefore the scope of experimental investigations was limited. The tested foils were obtained from distilled beryllium grades by hot, warm and cold rolling methods in combination with heat treatments in vacuum. The studies were performed on foil samples with relatively low and high plastic properties. Surface defects (cracks, chains of inclusions, etc.) were on some foils (Fig. 7). The reasons for the various mechanical properties and features of their change during beryllium foils production were not considered in this work. We only note that increase in the beryllium plasticity is possible due to using of severe cold plastic deformation, which contributes to the fine crystalline structure formation in beryllium. It is widely known that this can significantly improve the metal mechanical properties [7-10].

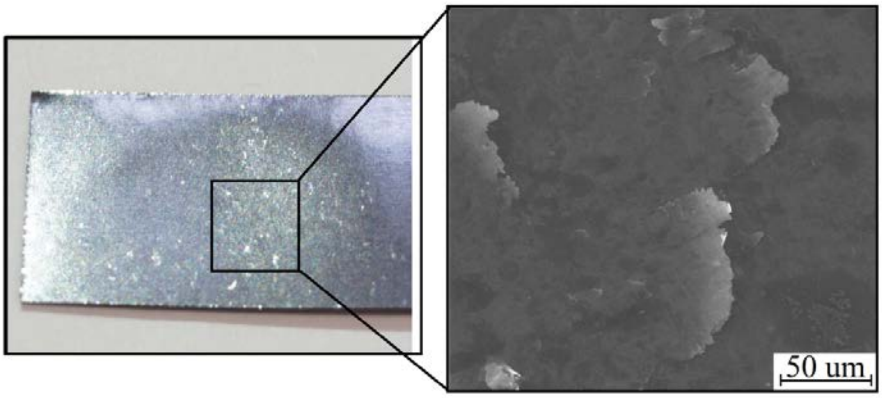

Fig. 7. Photograph and SEM-image of surface defects on beryllium foil.

Before cyclic tests, the ultimate plastic strain values were experimentally established for each group of foils according to the proposed bending test technique.

Results of bending for foil sample with surface defects presents in Fig. 8. It has seen that in the region of tensile stresses fracture and exfoliation of beryllium occur even at small deformations. Bending accompanies by cracks formation and their size can reach 300 – 500 μm. Thus, the presence of defects in the beryllium foil will lead to its instantaneous fracture at first loading. Beryllium windows for X-ray should not have any surface defects.

When bending samples with relatively low plastic properties, but without of surface defects, sample fracture occurred at bending angles 70-80°. Fracture character for this samples type is shown in Fig. 9. When bending samples with relatively high plastic properties at angle 180° no their fracture occurs (Fig. 10, *a*). SEM analyze showed that an insignificant number of microcracks are located along the grain boundaries in this case (Fig. 10, *b*).

Estimated number of loading cycles which beryllium foil is able to sustain without fracture was predicted (Table 1) from the dependence on Fig. 3.

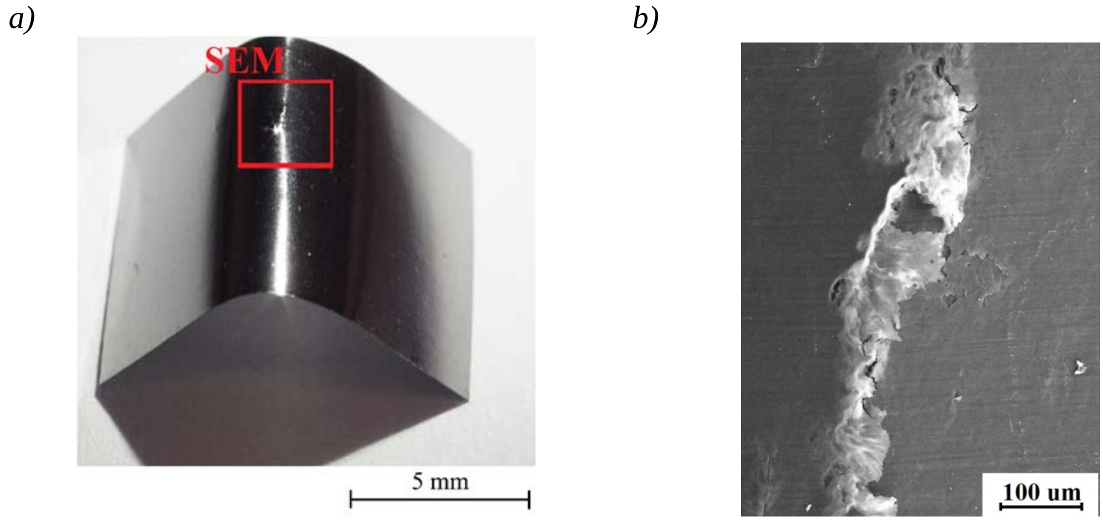

Fig. 8. Photograph (*a*) and SEM-image (*b*) of defect opening after bending at angle 30° (*b*).

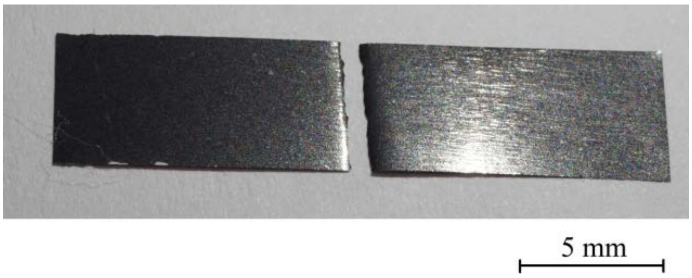

Fig. 9. Photograph of fractured sample with relatively low plastic properties after bending at angle 75°.

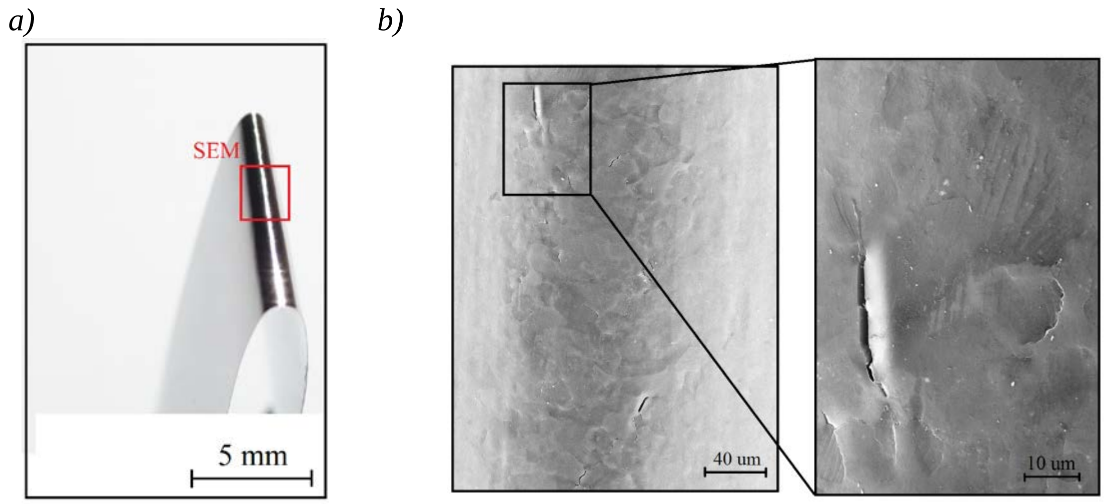

Fig. 10. Photograph of sample with a thickness of 8 μm with relatively high plastic properties after bending with angle 180° (*a*) and SEM- image of bending region (*b*).

The results of cyclic tests showed (Table 1) that foil samples having ultimate values $C_{\text{ult}} > 0.165$ withstand 2000 cycles of loading without fracture signs, while foil samples with values C_{ult} = 0.045 begin to destruct after reaching 44 – 75 cycles. The cracks formation is indicated by an increase of helium leakage rate to 10^{-4} – 10^{-6} mbar l/sec.

Table 1. Results of cyclic testing for foil samples thickness of 8 μm an aperture of 10 mm with difference in plastic properties.

Number of sample	Experimental values of ultimate plastic strain (C_{ult})	Number of cycles without fracture, predicted	Number of cycles without fracture, actual	Leak rate, mbar l/sec
1	<0.02 (with surface defects)	0	0	$>10^{-4}$
2	<0.02 (with surface defects)	0	0	$>10^{-4}$
3	<0.02 (with surface defects)	0	0	$>10^{-4}$
4	0,045	60	44	$>10^{-6}$
5	0,045	60	52	$>10^{-6}$
6	0,045	60	75	$>10^{-6}$
4	>0.165	> 2000	2000	$<10^{-10}$
5	>0.165	> 2000	2000	$<10^{-10}$
6	>0.165	> 2000	2000	$<10^{-10}$

In Fig. 11 shows photos of the foil sample at the stages of vacuum buildup and atmosphere inflow respectively. Level of the maximum vertical displacement in the window center during the vacuum buildup measured using the epoxy resin imprint method applied to the window aperture, was 250 – 270 μm which corresponds to the modeling data (see Fig. 4, *a*).

a) *b*)

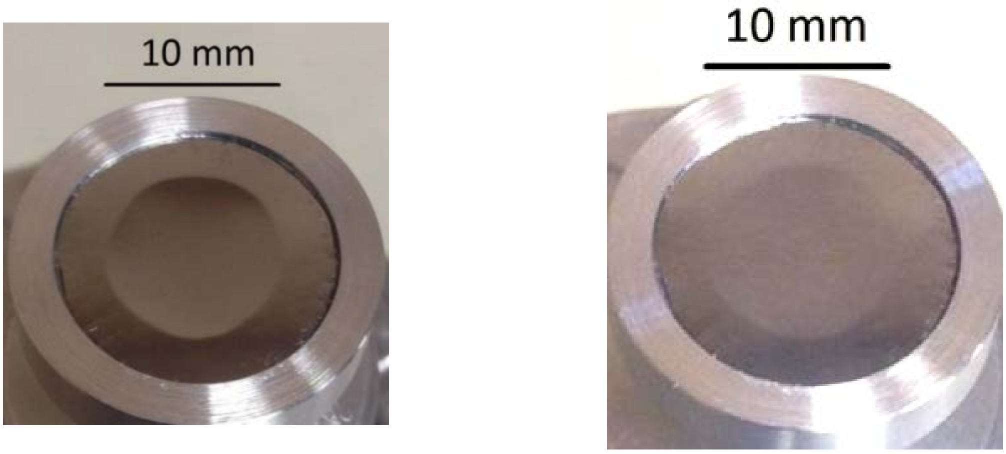

Fig. 11. Deformation of the foil sample at the stages of vacuum buildup (*a*) and atmosphere inflow (*b*).

According to Fig. 11 beryllium window remains concave at the atmosphere inflow stage, which indicates the beryllium plastic deformation in the critical region (Fig. 2).

Since the fracture of beryllium windows without defects under cyclic loading is facilitated by the accumulation of plastic strain combined with low plasticity of the beryllium foil, reduction of fracture probability can be achieved either by increasing the foil thickness (at constant aperture) or by increasing the beryllium foil plastic properties. The second way is more preferable, since increasing the window thickness adversely affects the characteristics of the X-ray detectors.

6. Conclusions

1. It has been established that when a thin beryllium window is operated in an X-ray detector under cyclic loading conditions, emergence and accumulation of plastic deformation in a narrow window area directly bordering on the embedding are possible. The presence or absence of plastic deformation is determined by window aperture and foil thickness.
2. It is shown that the probability of beryllium window fracture can be estimated by comparing the accumulated plastic strain value in a foil with a certain value of the ultimate plastic strain value which determined experimentally by bending test.
3. The low plasticity of the beryllium window has an extremely negative effect on its durability in the X-ray detector. Foils with thickness of 8 μm or less for their reliable use in X-ray detectors should have high plastic properties and not have any surface defects.

Acknowledgement. *This work was financially supported President of the Russian Federation grant (agreement Nr. MK-1402.2017.8).*

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