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INVESTIGATION OF DEFORMATION AND FRACTURE FOR THIN BERYLLIUM FOILS UNDER STATIC LOADING BY EXTERNAL PRESSURE

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Abstract. In this paper numerical and experimental studies of deformation and fracture of thin beryllium disks with a thickness of 5-100 μm are performed. Disks, intended for use as X-ray windows, were obtained by the method of severe cold deformation. It is shown that beryllium foils under loading by external pressure (or bulge test) have higher values of ultimate strains than in tensile tests. It is established that the fracture at bulge test occurs at values of the accumulated plastic strain amounting to 15-20%, what very high for beryllium.
Keywords: thin beryllium foils; mechanical properties of beryllium foil; plasticity of beryllium; bulge test; beryllium fracture.

1. Introduction

Beryllium, due to its small atomic weight and low density, has a unique transmission capacity for X-ray radiation, what makes it widely used in the production of windows for X-ray detectors [1-2]. X-ray window represents thin beryllium foil with 5-30 μm thick, which soldered or pasted to the detector body (Fig. 1).

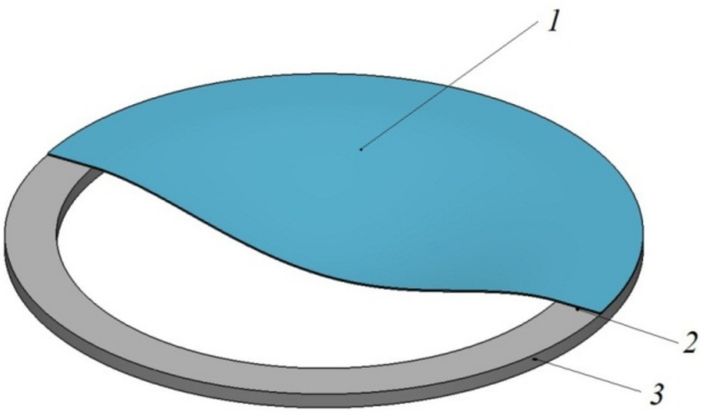

Fig. 1. Scheme of fixing beryllium foil to X-ray detector (1 - beryllium foil, 2 - soldering area, 3 - detector body).

When the detector is operating, a high vacuum must be created in its chamber, so that the beryllium window is subjected to loading by external atmospheric pressure. The loading, depending on the type of detector and character of its operation, can be either static or cyclic.

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Due to small thickness and large area beryllium foil can be significantly deformed under loading, which can cause its fracture and lead to the failure of the detector.

The stress-strain state of the foil and, therefore, the probability of its fracture, are determined by the level of beryllium mechanical properties. It is well known that the methods commonly used to measure mechanical properties on full-size samples are not directly applicable to thin foils [3]. For example, the mechanical properties of thin foils (the thickness of which is 100 or more times smaller than the width of the sample) during tensile tests can significantly differ from the mechanical properties obtained by testing full-size samples from the same material (the so-called "scale factor") [4-5].

Some evaluation of the foil mechanical properties can be obtained by tensile tests, but only very small strains can be achieved by the foil tension [6]. This fact prevents the determination of such quantities as the hardening of the material or the ultimate strain. Beryllium is a brittle material and has a low plasticity, so information about plasticity and ultimate deformation is extremely important for assessing the reliability and durability of the beryllium window operation in the X-ray detector.

To eliminate this drawback, a special method of research - bulge test is widely employed. It is one of the most reliable methods for determining the mechanical characteristics of thin foils and is widely used for studying the mechanical properties of thin foils of aluminum, copper, steel, germanium [7-10] and other materials. The loading by external pressure corresponds to the operation conditions of beryllium window in the X-ray detector.

It is well known that severe cold deformation can significantly improve the complex of metal mechanical properties [11-14]. Cold deformation promotes the formation of a fine crystalline structure in beryllium, which provides higher mechanical properties than have foils produced by traditional methods - by hot and warm rolling, chemical thinning and vacuum deposition [15-19].

The aim of this work is to estimate the level of ultimate strains at the fracture moment for thin beryllium foils, obtained by the severe cold plastic deformation, by bulge test.

2. Materials and methods

Thin beryllium foils with a thickness of 5 - 100 μm were obtained by severe cold plastic deformation in combination with heat treatments in high vacuum. Foils destined for testing had circular shape with aperture (region of pressure action) of 5-10 mm.

Beryllium foil, depending on the technology of its production, can have different rheological properties [15-16], in particular, the yield stress (YS). Since the material properties significantly influence on the parameters of its deformation, deformation of foil in three different states was studied.

To determine the values of the YS and hardening rule, tensile test were carried out according to [15] with the determination of the ultimate strain values (ε_{ult}). The test results are shown in Fig. 2.

Table 1 shows the chemical composition of used foils.

Table 1. Chemical composition of prepared beryllium foils.

Element	Be	Al	P	S	Cl	Ca	Cr	Mn	Fe	Ni	Cu	W
Weight %	99.82	0.02	0.02	0.01	0.02	0.03	0.01	0.01	0.02	0.02	0.01	0.01

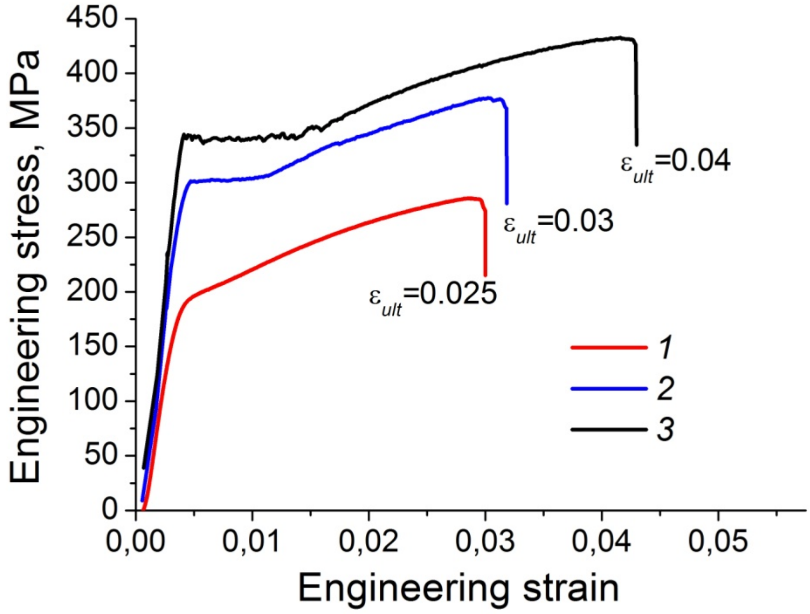


Fig. 2. Stress -strain curves obtained by tensile tests for beryllium foil with a thickness 25 - 50 μm after annealing at different temperatures: 1 - σ_{YS} = 200 MPa; 2 - σ_{YS} = 300 MPa; 3 - σ_{YS} = 350 MPa.

Obtained foils were exposing to loading by external pressure with the help of special equipment. Pressure, for convenience, was measured in atmospheres. Here and hereinafter, the term "atmosphere" (atm) means the physical atmosphere which equals to 101325 Pa. For testing, we used foil samples with an initial helium leakage no more than 10^{-11} Pa·m^3/s.

Analytical dependencies, as well as the finite element method, were used to calculate the parameters of foil stress -strain state.

2. Experimental investigation of deformation and fracture for thin beryllium foils under static loading by external pressure

Experimental studies of thin beryllium foils deformation under static loading by external pressure were carried out using specially developed equipment, the scheme of which is shown in Fig. 3.

Beryllium foils were pasted into metal frames in the form of discs with a hole. Frames with pasted foils were fixed in the tool body with the clamping part. The loading was carried out with compressed helium at rate of pressure increase 0.2 atm/s. The pressure level was measured by EN562 sensor. After reaching the preset pressure, deformed foil was filling with epoxy resin (Fig. 4). After resin curing, the pressure in the system was dropped and then the maximum magnitude of foil deflection was measured. Measurements were performed (Fig. 5) by micrometer (with a measurement accuracy of 1 μm) which was mounted on special stand. Measurements results present in Table 2.

An experimental study of foils fracture was also performed using the equipment shown in Fig. 3. For this analysis thin foils with thickness of 5 - 9 μm were produced and used, since foils having a large thickness (at an aperture of 5-10 mm) could not be brought up to fracture at pressure of up to 6 atm.

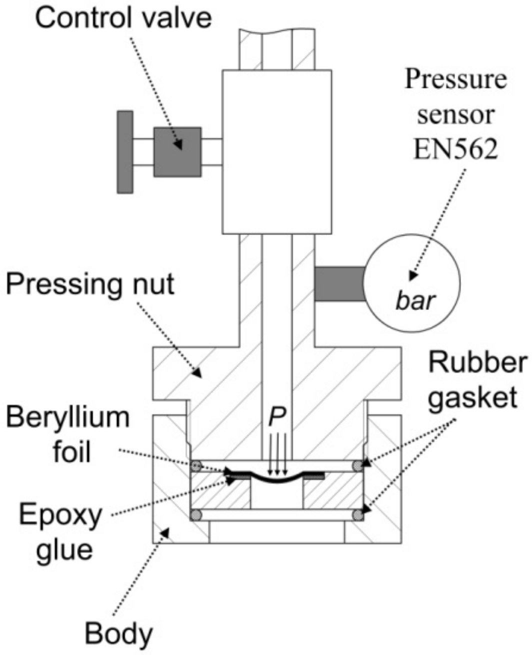


Fig. 3. Equipment for thin beryllium foils bulge tests.

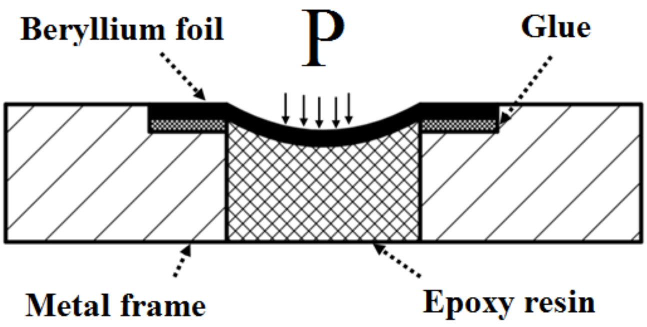


Fig. 4. Fixation of beryllium foil for its deflection measurement.

Table 2. Maximum magnitude of foil deflection under static loading by external pressure.

Foil thickness, μm	Aperture, mm	Pressure, atm	σ_{YS}, MPa	The measured values of foil maximum deflection, μm
15	6.3	4	300	190 – 200
15	6,3	6	300	250 – 270
16	5	6	300	165 – 170
22.5	5	6	300	90 – 100
23	7	6	300	220 – 250
23	10	6	300	335 – 340
100	7	6	200	70 – 90

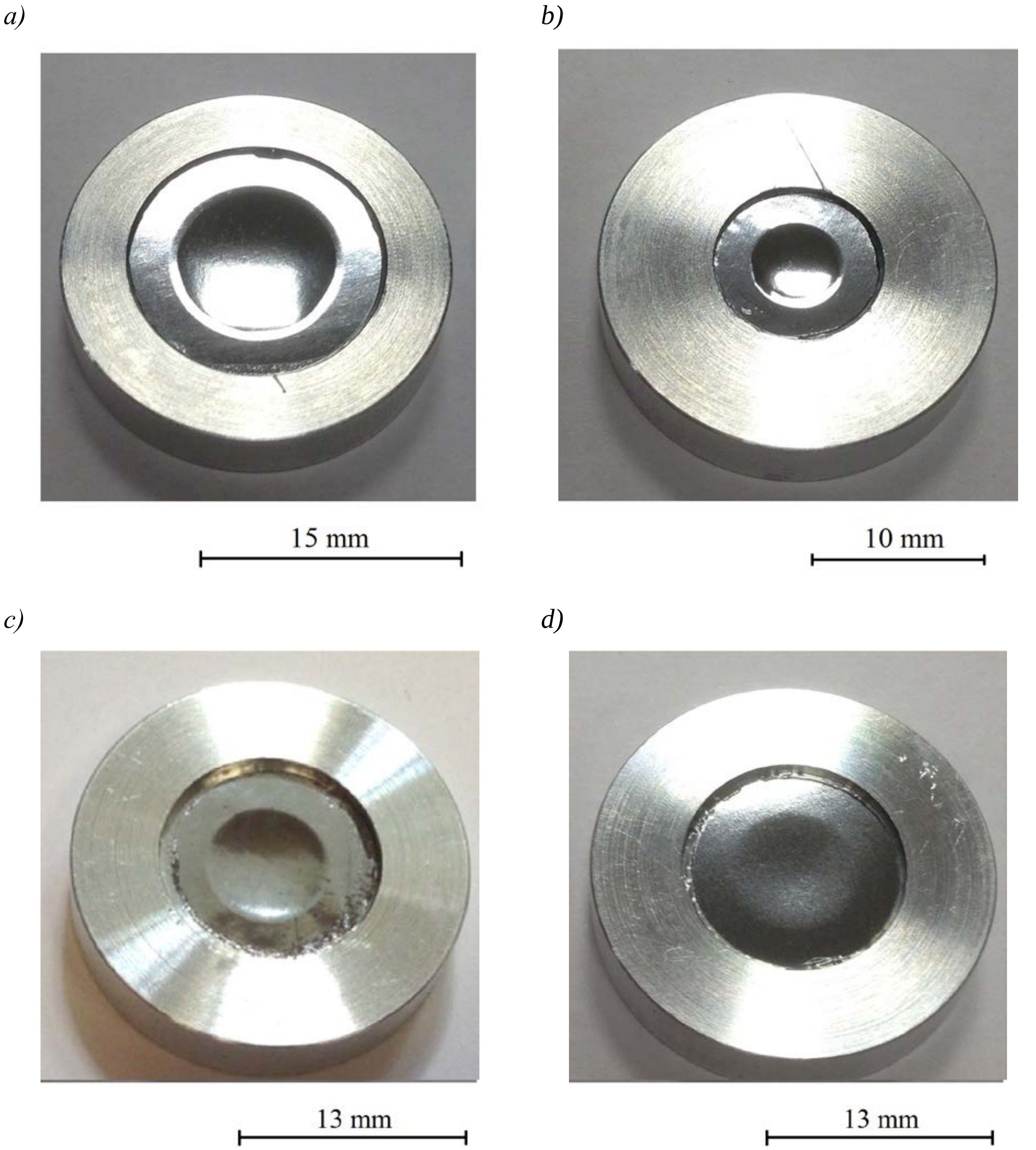


Fig. 5. Samples of fine beryllium foil after loading by external pressure: *a* - foil thickness 23 μm, pressure 6 atm; *b* - foil thickness 16 μm, pressure 6 atm; *c* - foil thickness 5 μm, pressure 3 atm; *d* - foil thickness 100 μm, pressure 6 atm.

3. Numerical study of beryllium foils deformation under static loading by external pressure

The performed experimental studies made it possible to establish the maximum deflections of the foil samples caused by external pressure. Stress -strain state and plastic deformation magnitude accumulated during loading can be estimated using computational methods.

An analytical solution for thin beryllium disks large deflections calculation. An analytical solution for determining the deviation value for large deflections of foils and round-shaped membranes is presented in [17]. The solution is based on the well-known equation for determining the small deflection, w, for a clamped circular plate under a uniform applied pressure P [18]:

$$w(r) = [Pa^4 / 64D] \cdot \left[1 - [r/a]^2\right]^2, \tag{1}$$

where r is the radial coordinate, a – plate radius.

Equation (1) includes the plate flexural rigidity D, which is determined by the formula:

$$D = [Eh^3]/[12[1-\nu^2]], \tag{2}$$

where E and ν are the Young's modulus and the Poisson's ratio of plate material, h - plate thickness.

To determine the large deflections magnitudes of a clamped circular plate, equation (1) is used in the form:

$$w(r) = f\left[1 - [r/a]^2\right]^2, \tag{3}$$

where

$$f = \sqrt[3]{-\beta/2+\gamma} + \sqrt[3]{-\beta/2-\gamma}. \tag{4}$$

$$\gamma = \sqrt{\alpha^3/27 + \beta^2/4}. \tag{5}$$

$$\alpha = 14 \cdot [4h^2 + 3a^2\varepsilon_i[1+\nu]]/[[1+\nu]\cdot[23-9\nu]]. \tag{6}$$

$$\beta = [-7Pa^4h^2]/[8D\cdot[1+\nu]\cdot[23-9\nu]]. \tag{7}$$

Equations (3) - (7) allow to take into account the influence of plate stressed state and build-in residual strain (parameter ε_i in equation (6)) on plate deflection value.

FEM analyze of large deflections for thin beryllium disks. When beryllium foil is loading by external pressure, its deformation can be either elastic or plastic. The problem of foil plastic deformation does not have an exact analytical solution, so it was solved numerically in ABAQUS.

As the boundary conditions, nodes belonging to the window gluing area were fixed. External pressure was applied only to the nodes corresponding to the aperture area.

For the comparative analysis, two models of material - elastic and elastoplastic - were used. For the elastic model, the material properties were set by the elastic modulus E = 290 GPa and Poisson's ratio ν = 0.02. For the elastoplastic model, in addition to the elastic properties, the YS and the experimental flow stress curve for beryllium were additionally specified. Flow stress curve was extrapolated to the region of large deformations in accordance with power law hardening (see Fig. 2).

To analyze the deformation of foils thicker than 50 μm, 3D model with symmetry conditions was created. Two types of elements were used: hexagonal elements C3D8R and tetragonal C3D10M (Fig. 6). The values of deflections using hexagonal and tetragonal elements turned out to be comparable.

The 3D analysis for foils with a thickness of less than 50 μm is associated with considerable computational difficulties at mesh creation. To analyze deformation of foils with a thickness of less than 50 μm two-dimensional axisymmetric model was used. Mesh consisted from 500 SAX1 elements with 15 integration s along the thickness.

Deformations of beryllium windows with a thickness of 5-25 μm with apertures of 5-10 mm, loaded by pressure of 1-7 atm, were calculated with using 2D model.

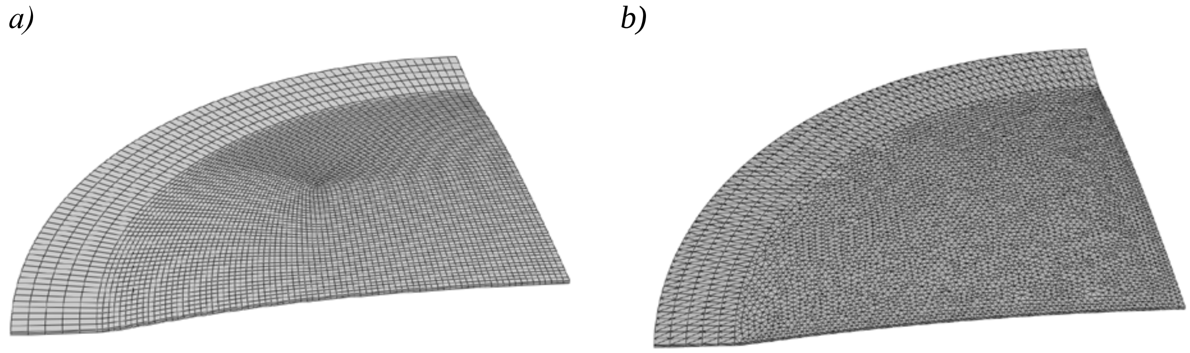


Fig. 6. Form of 200 μm thickness beryllium window with 5 mm aperture after loading by pressure of 2 atm, calculated in ABAQUS using elements C3D8R (a) and C3D10M (b).

Results of calculations and their discussion. Figure 7 shows the calculated foils profiles obtained by using the analytical equations in comparison with the foils profiles calculated in ABAQUS using an elastic model of material. The values of maximum deflections for analytical and FEM solutions are quite close for all thicknesses and apertures sizes. Analytical solution shows somewhat larger values of deflections. The shape of the foil after loading, calculated analytically, differs from that calculated in ABAQUS using an elastic model. It's expressed in a more sharper increase of deflection at radial position. It should be noted that the real form of beryllium foil which loaded by external pressure is closer to the shape calculated in ABAQUS for the elastic model (Fig. 5).

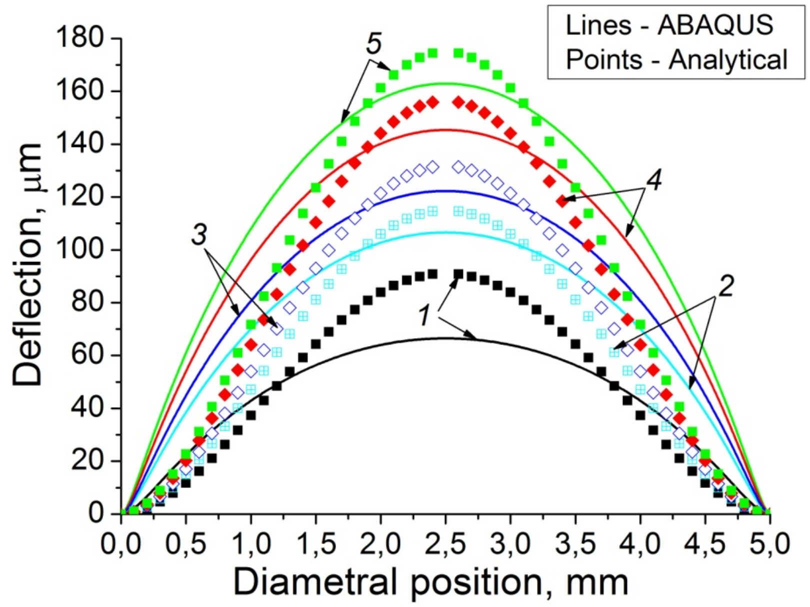
Figure 8 shows a comparison of foil profiles calculated in ABAQUS using an elastic and elastoplastic material models. It can be seen that at low pressure values, the foil profiles practically coincide, but as the pressure increases, the maximum displacements begin to differ significantly. This is due to the appearance and accumulation of plastic strain in narrow window region directly bordering on the embedding (Fig. 9). With increasing pressure, the difference between results of calculations with the elastic and elastoplastic material model increases. The bigger aperture, the more plastic deformation develops (Fig. 10) and a difference is stronger (Fig. 11). Comparison between tests results and calculations is presented in Table 3.

Table 3. Comparison between calculated and experimental values of maximum deflections in beryllium foils under loading by external pressure.

Foil thickness, μm	Aperture, mm	Pressure, atm	σ_{YS}, MPa	MDA, μm	MDE, μm	MDEP, μm	MDM, μm
15	6.3	4	300	164	150	190	190 – 200
15	6,3	6	300	182	169	276	250 – 270
16	5	6	300	131	121	164	165 – 170
22.5	5	6	300	114	106	122	90 – 100
23	7	6	300	182	167	225	220 – 250
23	10	6	300	254	236	369	335 – 340
100	7	6	200	52	40	55	70 – 90

Explanations to the Table 3:
MDA – maximum deflection calculated analytically, μm.
MDE – maximum deflection calculated in ABAQUS with elastic material model, μm.
MDEP – maximum deflection calculated in ABAQUS with elastoplastic material model, μm.
MDM – measured maximum deflection, μm.

a)



b)

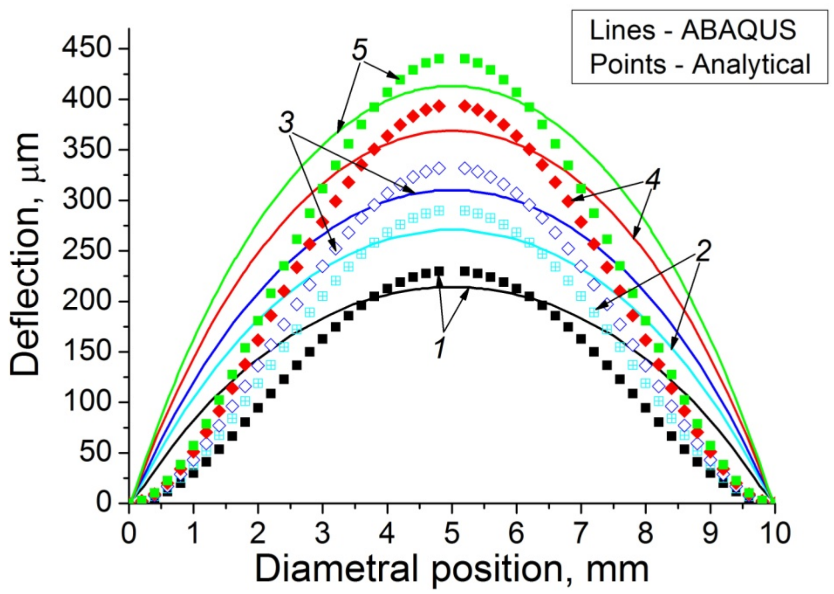
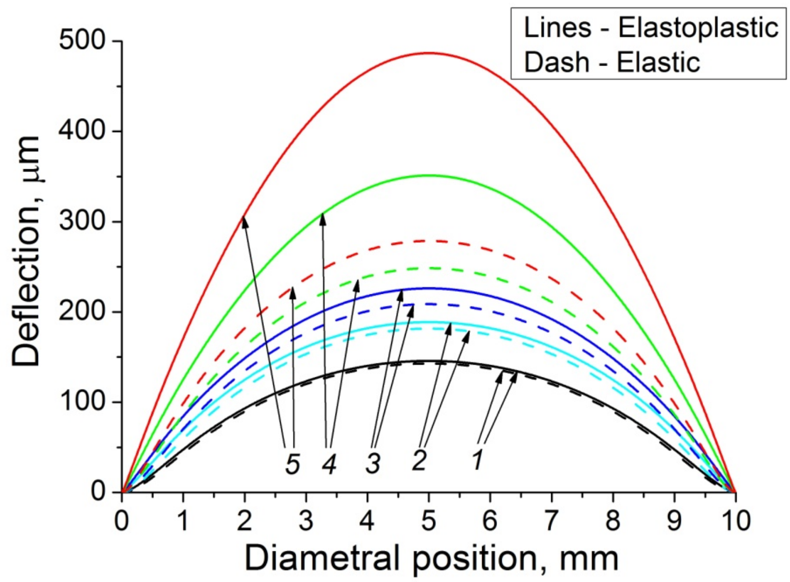


Fig. 7. Profile of 8 μm thick foil under loading by external pressure 1 atm (*1*), 2 atm (*2*), 3 atm (*3*), 5 atm (*4*), 7 atm (*5*), calculated by analytical dependences (3) - (7) in comparison with profile calculated in ABAQUS using elastic material model for the window aperture: *a* - 5 mm; *b* - 10 mm.

Calculations performed in ABAQUS using the elastoplastic material model (see Table 3) show deflections values close to the actual data, which makes it possible to judge the reliability of the calculation results. The deviations of the calculated and experimental results can be explained by the insufficient accuracy of extrapolation of the flow stress curve to the region of large deformations.

a)



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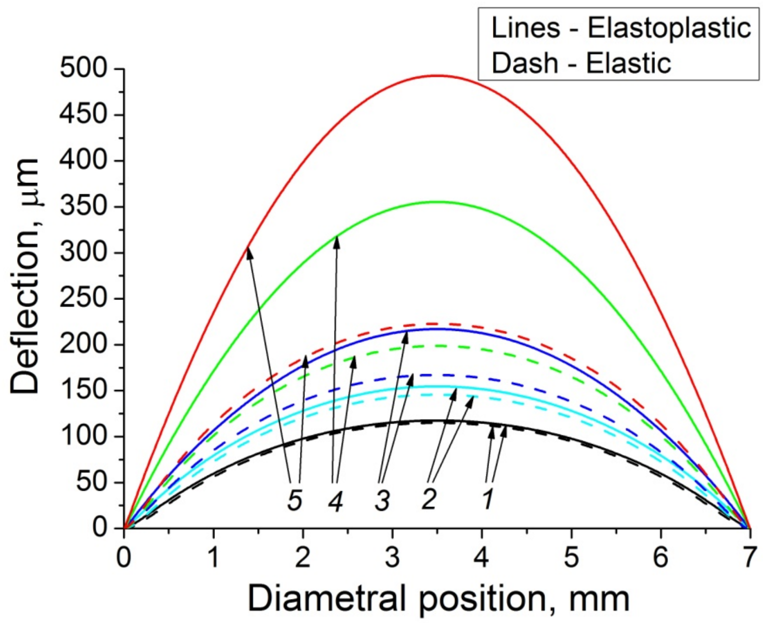

Fig. 8. Foil profile under loading by external pressure 1 atm (*1*), 2 atm (*2*), 3 atm (3), 5 atm (4), 7 atm (5), calculated in ABAQUS for the elastic and elastoplastic material model (σ_{YS} = 300 MPa): *a* - foil thickness 25 μm, aperture 10 mm; *b* - foil thickness 12 μm, aperture 7 mm.

a)
b)
c)

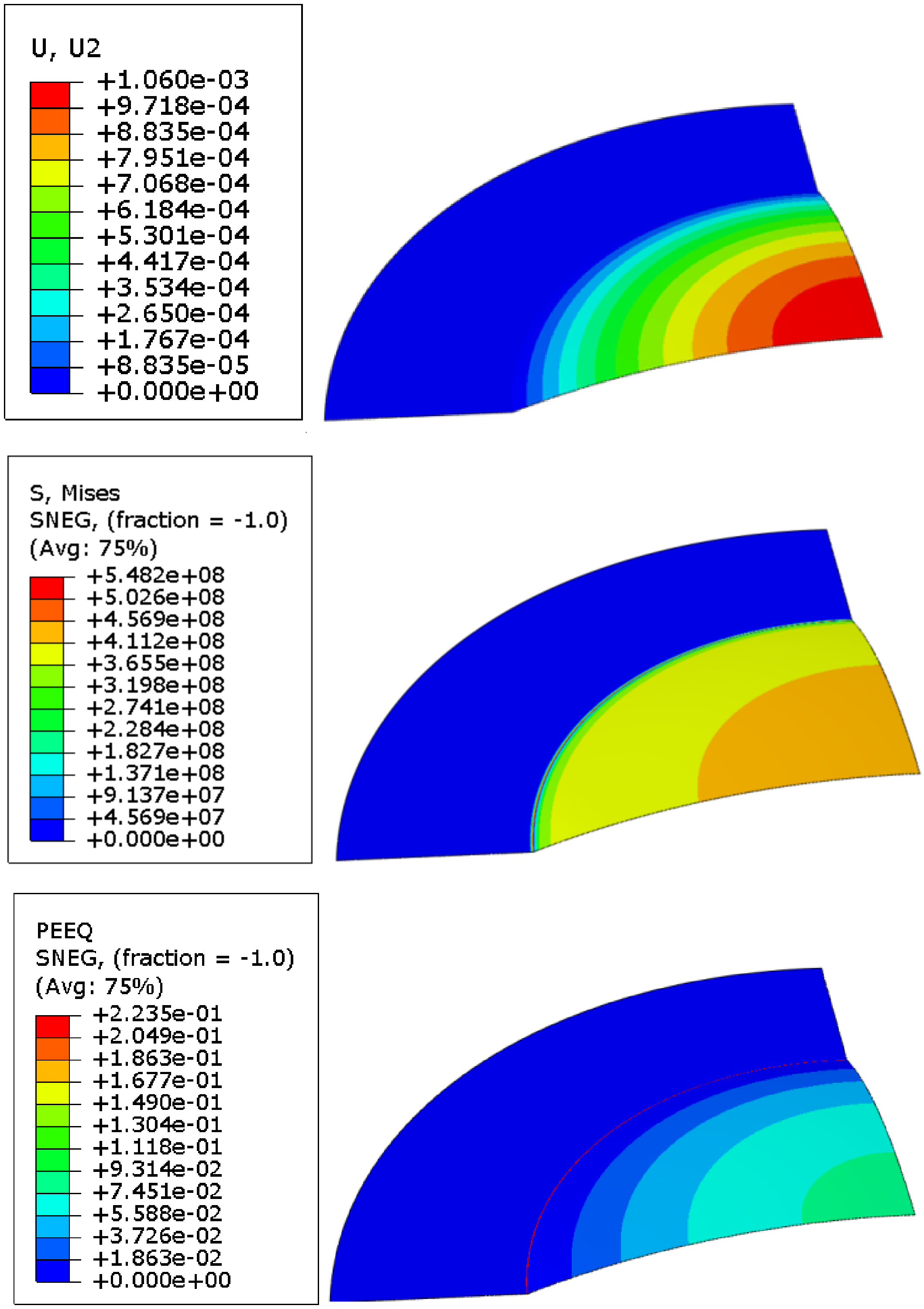

Fig. 9. Calculated in ABAQUS using elastoplastic material model (σ_{YS} = 300 MPa): vertical displacement (*a*), effective stress (*b*), accumulated plastic strain (*c*) for 8 μm thick foil with 10 mm aperture under pressure of 5 atm.

The analytical solution and the solution in ABAQUS using an elastic material model give somewhat underestimated results in terms of the maximum foil deflection. Thus, when calculating the stress -strain state of thin beryllium foils under external loading, the values of accumulated plastic deformation must be taken into account.

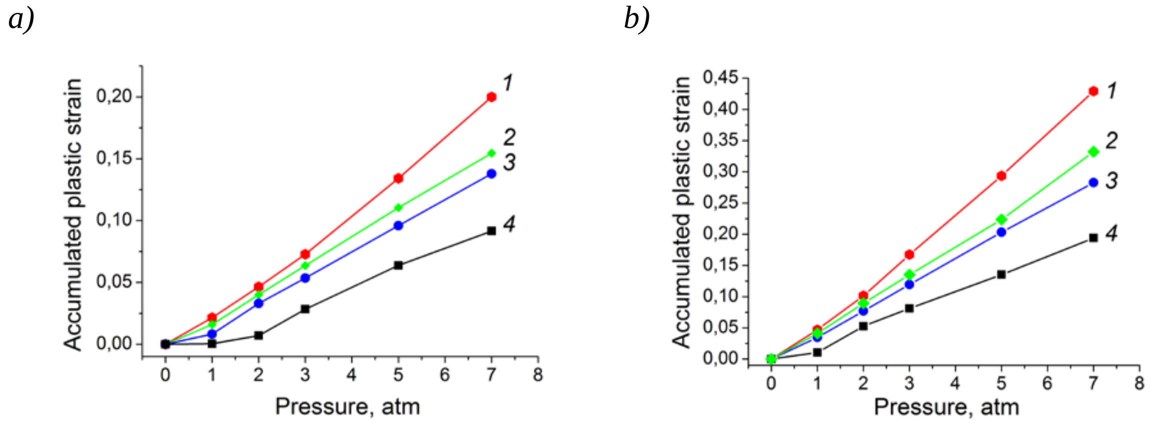

Fig.10. Dependence of maximal accumulated strain on the pressure value for foil with thickness 5 μm (*1*), 8 μm (*2*), 12 μm (*3*), and 25 μm (*4*) for aperture (σ_{YS} = 300 MPa): *a* – 5 mm; *b* - 10 mm.

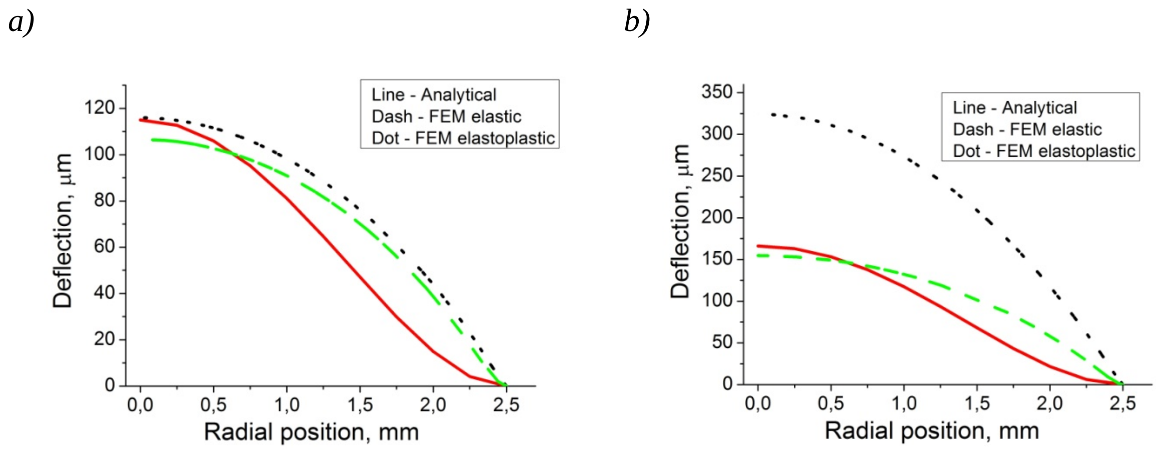

Fig. 11. Comparison between profiles for foil with a thickness of 8 μm and aperture of 5 mm, calculated from analytical dependencies, in ABAQUS with elastic material model, in ABAQUS with elastoplastic material model under external pressure of 2 atm (*a*) and 6 atm (*b*).

The values of the accumulated strain calculated in ABAQUS for the elastoplastic model are presented in Table 4. It can be seen from Table 4 that when loading by external pressure, considerable plastic deformation for beryllium foils can occur up to 15%. Fracture is not observed in these cases.

Table 4. The accumulated plastic strain in thin beryllium foils under external pressure loading.

Foil thickness, μm	Aperture, mm	Pressure, atm	σ_{YS}, MPa	ε
15	6.3	4	300	0.088
15	6.3	6	300	0.154
16	5	6	300	0.101
22.5	5	6	300	0.083
23	7	6	300	0.117
23	10	6	300	0.155
100	7	6	200	0.016

Explanations to the Table 4:
ε – maximal value of accumulated strain calculated in ABAQUS with elastoplastic material model.

Determination of ultimate plastic strain. The measured ultimate pressure, which the beryllium window is capable of withstanding without fracture, makes it possible to estimate the ultimate values of accumulated plastic strain.

When operating detectors, the fracture of window, as a rule, occurs in narrow window region directly bordering on the embedding (Fig. 12), where accumulated plastic strain is maximal. At experimental testing of thin foils by external pressure loading up to fracture, destruction also always occurred in the same place (Fig.13). A photograph of the fracture surface, obtained by scanning electron microscope, is shown in Fig. 12, *d*.

Fig. 12. Typical character of thin beryllium window fracture in the X-ray detector.

Fracture in the presence of plastic deformation can be described with the help of energy fracture criteria, one of which is the phenomenological criterion Ductile Damage Model built into ABAQUS [19-20]. According to this criterion, the fracture occurs when the condition is fulfilled:

$$\omega = \int d\varepsilon^{pl} / \varepsilon_D^{pl} = 1, \tag{8}$$

where ω is the damage parameter: 0 for completely undamaged material, 1 for completely damaged material;
ε_{pl} – accumulated plastic strain;
ε_{plD} – accumulated plastic strain at fracture moment (ultimate strain).

Table 5 presents the ultimate strain values calculated in ABAQUS using results of tests on foils loading by external pressure up to fracture.

Table 5. Calculated values of ultimate strain for thin beryllium foils.

Foil thickness, μm	Aperture, mm	Pressure at fracture, atm	σ_{YS}, MPa	ε_{plD}
9	10	5.1	350	0.18
8.5	5	5.9	200	0.2
5	7	4.1	300	0.154

Explanations to the Table 5:
ε_{plD} - ultimate strain calculated in ABAQUS.

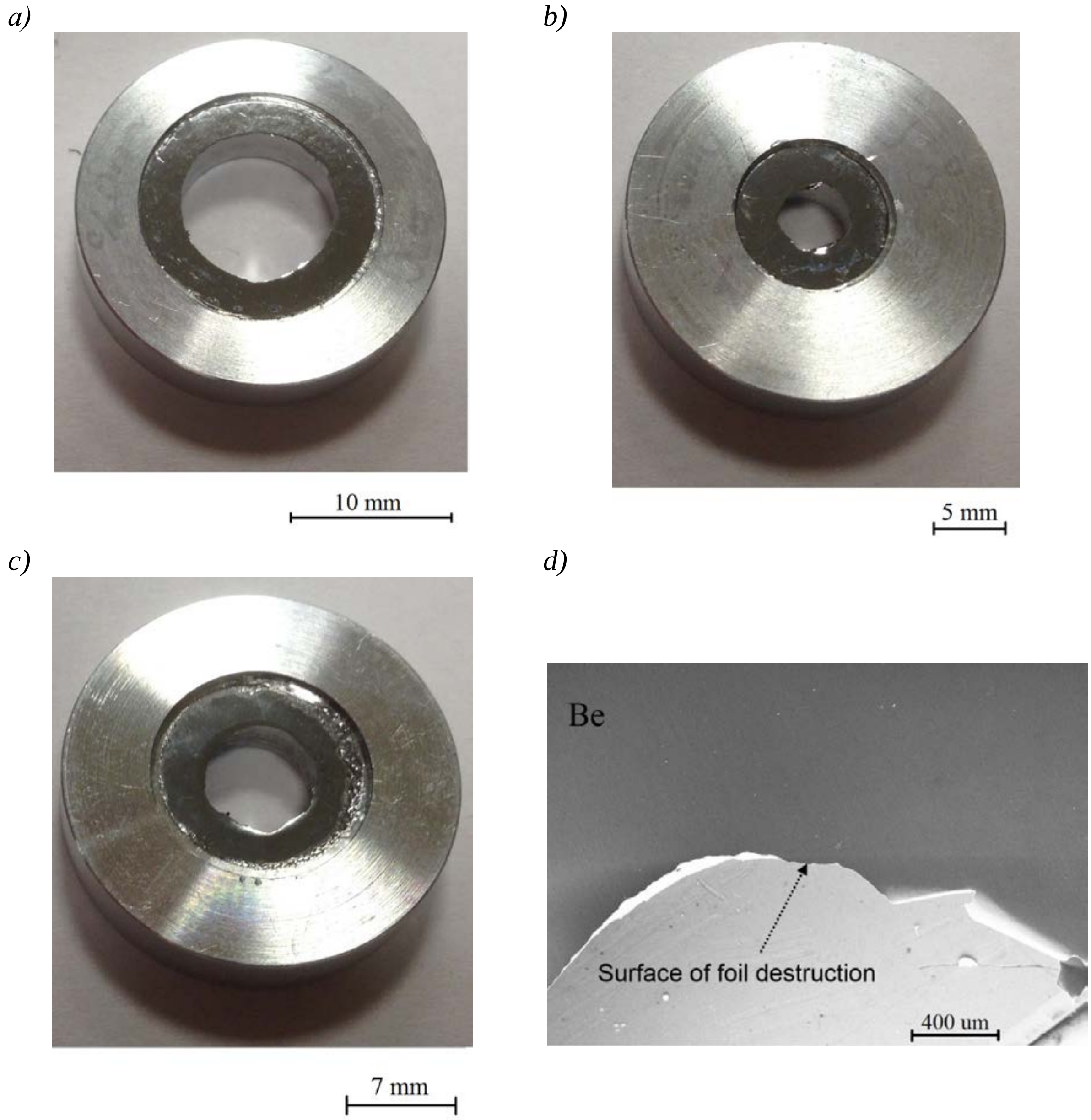

Fig. 13. Results of test for beryllium windows fracture under loading by external pressure: *a* - foil with a thickness of 9 µm, aperture 10 mm, fracture at 5.1 atm; *b* – foil with a thickness of 8.5 µm, aperture 5mm, fracture at 5.9 atm; *c* – foil with a thickness of 5 µm, aperture 7 mm, fracture at 4.1 atm; *d* – photo of the fracture surface obtained by scanning electron microscope.

Thus, performed tests and calculations show that the level of ultimate strain for thin beryllium foils 5 - 10 µm thick, obtained by the severe cold deformation, under loading by external pressure may be up to 15-20%.

4. Conclusions

1. When loading thin beryllium discs by external pressure, plastic deformation may appear in them. The values of the actual and ultimate plastic strain must be taken into account when designing X-ray detectors.
2. Ultimate strain level for beryllium foils under loading by external pressure is an order of magnitude higher than the level established in the tensile tests.

3. Thin beryllium foils with a thickness of 5 - 10 μm, obtained by the severe cold deformation, can withstand without fracture the high for beryllium plastic deformation level of 15-20% under loading by external pressure.
4. Increased plastic properties of beryllium foil allow reduce the thickness and increase the aperture of the X-ray window, which will improve the analytical characteristics of X-ray equipment.

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