Journal of Engineering and Applied Sciences 12 (23): 7242-7249, 2017
ISSN: 1816-949X

Investigation of the Thin Beryllium Windows Fracture Probability under the External Cyclic Load

[1]V.V. Mishin, [1]I.A. Shishov and [2]A. Mincena
[1]Saint-Petersburg Polytechnic University of Peter the Great, St. Petersburg, Russia
[2]BECORP Ltd., Hatfield, United Kingdom

Abstract: The stress-strain state and deformation of thin beryllium round-shaped windows are calculated under cyclic loading by external pressure using the finite element method. The possibility of fracture probability estimating by comparing the accumulated plastic strain in a foil with a certain plastic strain limiting (critical) value was shown for beryllium windows. A technique of plastic strain limiting (critical) intensity experimental determination by testing foil samples for bending up to fracture was proposed. Experimental testing of 0.008 mm thick beryllium windows showed a good match of predicted fracture of beryllium foil with experimental data.

Key words: Thin beryllium foils, beryllium fracture, beryllium deformation, beryllium windows for X-ray detectors, possibility, determination

INTRODUCTION

Beryllium has a unique transmitting capacity for X-rays, both hard and soft which makes it irreplaceable in the process of Si-Pin, SDD and other X-ray detectors manufacturing (Hassan *et al*., 2015; Rollig *et al*., 2015; Imrisek *et al*., 2016; Prost *et al*., 2015; Scharf *et al*., 2011). For now the most spread are detectors which use beryllium foils of round shape (i.e., beryllium windows) with the thickness of 0.008-0.03 mm (sometimes 0.005 mm), soldered or glued into the frame of detector. The transmitting capacity of X-ray window and thus characteristics of X-ray detectors directly depend on the thickness of used foil (Scharf *et al*., 2011; Beckhoff *et al*., 2006).

It is necessary to provide high vacuum with residual pressure 10^{-5}-10^{-7} Pa in order for X-ray detector to function inside of its chamber. Therefore, during detector operational process beryllium window is exposed to external pressure of 1 atm. (in some cases pressure can reach the value of 1.2 atm.). Hereinafter, the term “atmosphere” (atm.) refers to a physical atmosphere equal to 101325 Pa. Such level of pressure causes significant mechanical loading on beryllium window of detector, consequently foil undergoes deformations. In most of the cases deformation type of foil is elastic but under certain conditions it can turn into plastic one. Beryllium is a fragile material with low plastic properties (Walsh, 2009; Papirov *et al*., 2015), therefore, even slight plastic deformation can result in fracture of beryllium window which can lead to the loss of vacuum tightness and breakdown of detector. The premature foil destruction can be determinate by appearance of microcracks which again lead to a loss of vacuum density. Foil macrofracture is often encountered too (Fig. 1). Beryllium ductility depends on production and processing methods (Papirov *et al*., 2014; Papirov and Nikolaenko, 2013) and can differ significantly from batch to batch and even from sample to sample within the batch, therefore, it is difficult to predict beryllium fracture during the plastic deformation.

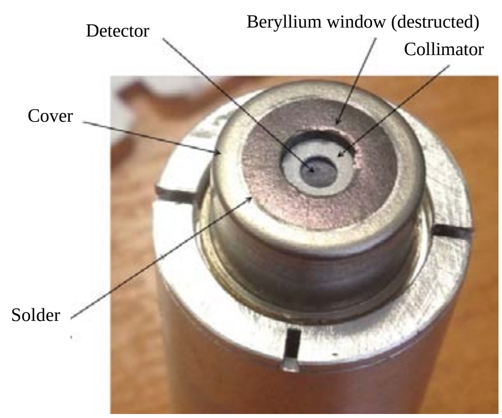

Fig. 1: Fracture of a 0.008 mm thin beryllium foil during operation in SDD X-ray detector

External pressure does not affect the whole area of beryllium window but only the part of it that is not fixed in

Corresponding Author: V.V. Mishin, Saint-Petersburg Polytechnic University of Peter the Great, St. Petersburg, Russia

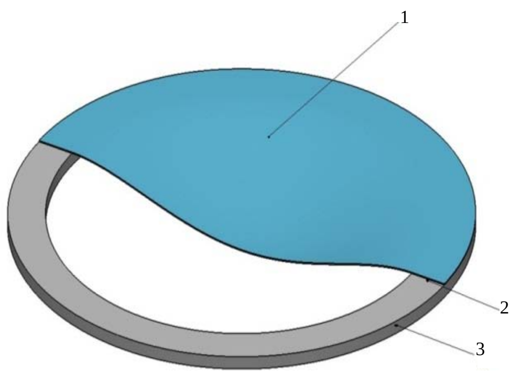

Fig. 2: Scheme of beryllium window fixed on the X-ray detector: 1) Beryllium window; 2) Soldering area and 3) Metal frame

the frame (Fig. 2) called "window aperture" or "active area". Producers of X-ray detectors tend to increase the active area (Amptek Inc., 2017). But process of detector design and beryllium window thickness of must be selected in a way to provide the lack of fracture of beryllium foil with given aperture while operating in order to achieve that it is necessary to have information regarding the absence or presence of plastic deformation of window under the external load.

Generally, to estimate the working capacity of beryllium windows full-scale cycling test are used (Huebner *et al*., 2015a, b) during which the window must withstand a significant number of loading cycles (up to 10000). It is associated with operating nature of X-ray detector, in the process of which a significant number of exhaust and inflow cycles of atmosphere in the detector chamber is performed. Exhaust and inflow of the atmosphere into detector must be enough to avoid jump-in pressure. Generally, one loading cycle within cycling test process should not be <4 sec (Huebner *et al*., 2015a, b).

There are no models in the literature to predict the probability of thin beryllium windows fracture during operation in an X-ray detector, taking into account the main parameters-the aperture (active window area), the thickness and the plastic properties of the foil (Corlett *et al*., 2001; Li *et al*., 2002; Sato *et al*., 1991). Therefore, the main goal of the research is to develop a methodology for estimating the fracture probability of thin beryllium round-shaped windows under the external cyclic load.

MATERIALS AND METHODS

Modeling technique: The problem of a thin foil plastic deformation does not have an exact analytical solution.

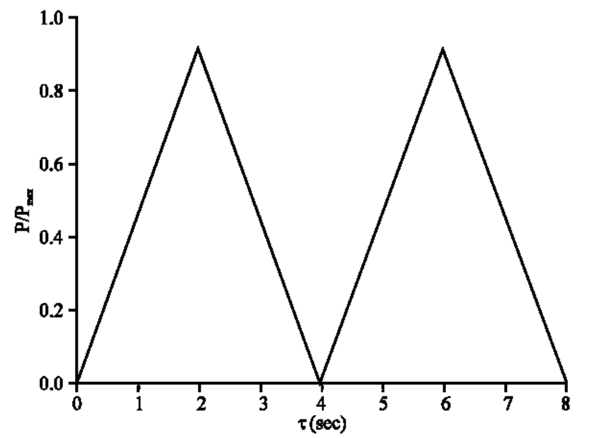

Fig. 3: The cyclic law of the external pressure change, adopted at the simulation

Table 1: Geometric parameters of beryllium windows used in modeling

Window diameter (mm)	Window aperture (mm)	Foil thickness (×10-3 mm)
5	2	5, 8, 12, 15, 25, 30
7.8	5	5, 8, 12, 15, 25, 30
9.2	7	5, 8, 12, 15, 25, 30
12	10	5, 8, 12, 15, 25, 30
20	15	5, 8, 12, 15, 25, 30

Therefore, the finite element method was used to calculate the plastic strain in a beryllium window during cyclic loading.

Software for finite element analysis Abaqus was used for calculation along with axisymmetric formulation. Mesh generation consisted of 50 SAX1 elements. Thickness of the element corresponded to the thickness of the foil for which the loading was modeled. The 15 integration points for thickness were used. For points of mesh belonging to the soldering area any translational and rotational displacements were excluded (Fig. 2, position 2). Pressure p equal to 1 and 1.2 atm. was applied to the nodes corresponding to the aperture region.

The change of pressure p was set according to cyclic rule-lineal increase from 0 atm. to target value p_{max} during 2 sec, then lineal decrease down to 0 atm. for 2 sec (Fig. 3). Therefore, duration of one total loading cycle equaled to 4 sec. The phase of pressure increase while modeling corresponded to the stage of vacuum buildup and the phase of pressure decrease corresponded to the phase of atmosphere inflow into the frame of detector.

Geometric parameters of windows used in modeling are shown in Table 1. The experimental rheological properties of beryllium at room temperature were obtained experimentally (Kolbasnikov *et al*., 2014; Zhigalina *et al*., 2016). The properties of the material were determined by the stress-strain curve (Fig. 4), the elastic modulus E = 290 GPa and the Poisson's ratio, μ = 0.02 (Walsh, 2009).

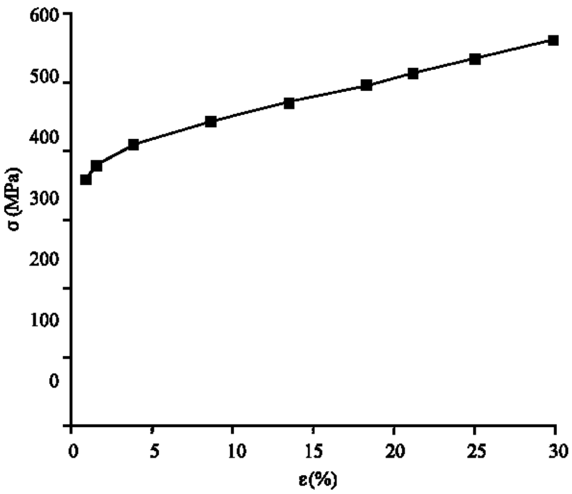

Fig. 4: Beryllium stress-strain curve at room temperature

RESULTS AND DISCUSSION

Results of modeling and their discussion: As a result of modeling the distribution fields of stresses, displacements and strains in beryllium windows were obtained as well as their change character in course of time and at increase of cycle's number.

It was found that the maximum stress and strain effect occur in a narrow window area directly bordering on the embedding (Fig. 5a and b) which is the actual area where beryllium undergoes plastic deformation. Highest values of the maximum principal tensile stresses are also observed in the same area (Fig. 5c). Greatest vertical displacement is observed in the center of the beryllium disk (Fig. 5d).

Therefore, based on strain-stress analysis critical area where failure of beryllium is possible is window area directly on border with embedding.

Figure 6 shows that under cyclic loading the value of the vertical displacement in the center of disk U_z changes according to the rule of applied external pressure, taking maximum value U_{max} at the moment of vacuum build-up and bottom value during the process of atmosphere inflow. In case of pressure decay up to zero values (moment of time, when the difference between of external and internal pressure equals to zero), central area of the disk does not get back to initial position because of plastic deformation of beryllium in critical area. With increase of cycle numbers values of accumulated strain ε_i in critical area of the window first drastically grow but eventually stabilize and remain constant. The calculations show that for all standard sizes of windows under consideration (Table 1) values of strain ε_i in critical area stop growing after 1000-1500 load cycles (Fig. 7). Therefore, using more than 1500 load cycles for vacuum cycling test can be recognized excessive and does not bring any difference.

As the result of calculations dependencies of value of maximum displacement in the center of window U_{max} were obtained (Fig. 8a) and maximum values of accumulated strain ε_i in critical area (Fig. 8b) on foil thickness and pressure level.

The calculations showed that values of maximum displacement U_{max} and accumulated plastic strain ε_i in window critical area are not immediate effected by disk diameter but determining parameter is aperture and foil thickness. Depending on these parameters values U_{max} and ε_i can significantly increase or practically be no different from zero point.

Method for determining of limiting (critical) value of accumulated plastic strain: The limiting (critical, destructive) plastic strain can be determinate experimentally when testing specimens for uniaxial tension. However, it is not possible to perform uniaxial tension tests for specimens of thin beryllium foil. In order to determine limiting values of plastic strain special tests are used when foil samples are bended up to fracture occurs. During the bending process plastic deformation is limited to bend areas as well as main tensile stresses act in this same area (Fig. 9).

Knowing the angle of bending at the moment when initial fracture occur (i.e., the formation of the first cracks) makes it possible to calculate the accumulated plastic strain for a given bending angle which will be the critical plastic strain (C_{lim}).

The issue of calculating the accumulated plastic strain value at the beryllium foil bending was also solved using the finite element method in the Deform Software. The rheological properties of beryllium were set in the same way as in modeling in the Abaqus Software. The problem was solved in a two-dimensional setting using a mesh with rectangular elements. Figure 9a shows the results of calculating the values of the accumulated plastic strain at bending of a 0.008 mm thickness foil by 180° angle. Figure 10 shows the calculated dependences of the accumulated plastic strain values on the angle of bend α for different foil thicknesses.

Photos of samples of beryllium foil that have different plastic properties after experimental testing for bending are shown in Fig. 11.

Experimental investigation of the thin beryllium windows fracture under the external cyclic load: Experimental cyclic tests of beryllium foil samples were performed in order to test created mathematical models adequacy. 0.008 mm thick beryllium foil was chosen for testing which

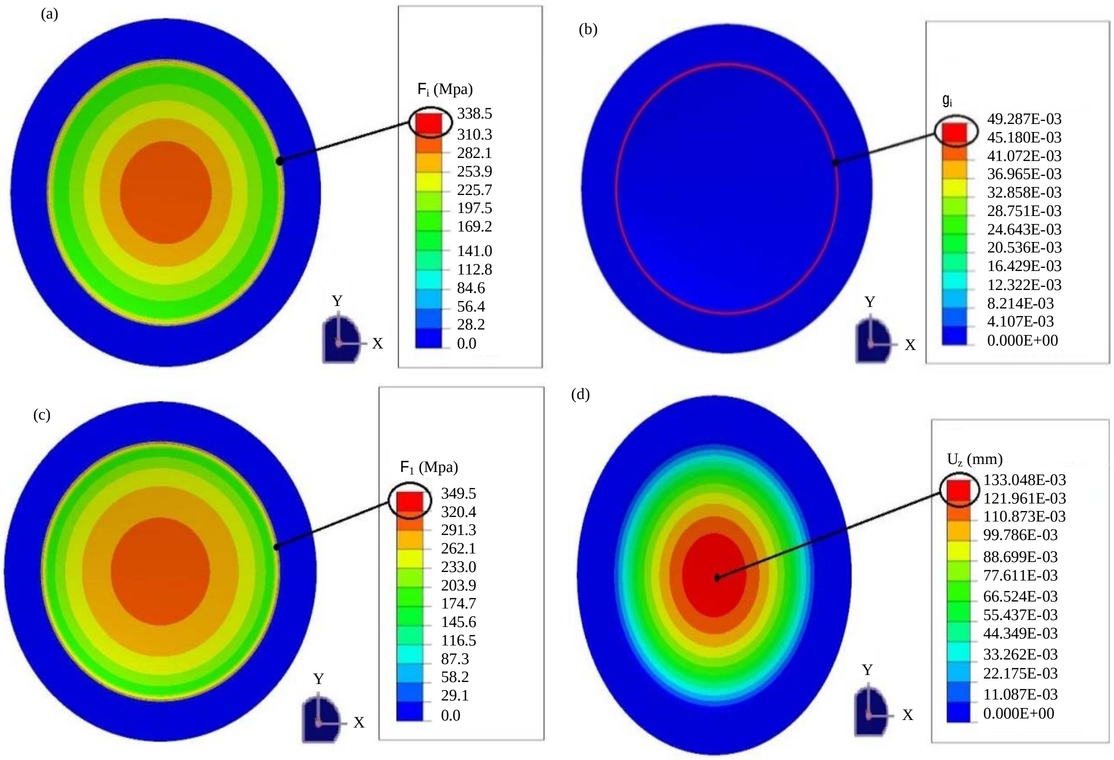

Fig. 5: a) The distribution field of effective stress σ_i; b) Accumulated plastic strain ε_i; c) Maximum principal stress σ_1 and d) Vertical displacements U_z for a window with a diameter of 9.2 mm with aperture of 7 mm and thickness of 0.008 mm after 1500 cycles of loading with external pressure at 1 atm.

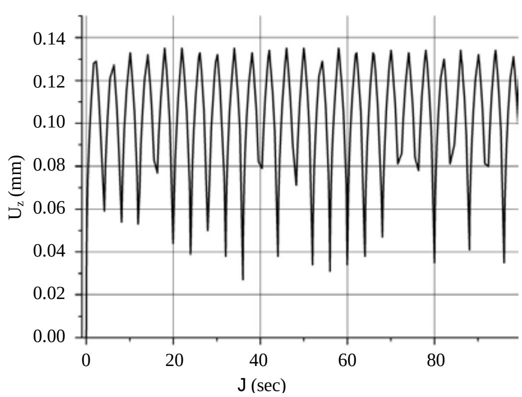

Fig. 6: Dependence of the vertical displacement magnitude for central point of beryllium window with diameter of 9.2 mm, aperture of 7 mm and thickness of 0.008 mm on the loading time at cyclic load by external pressure p = 1 atm.

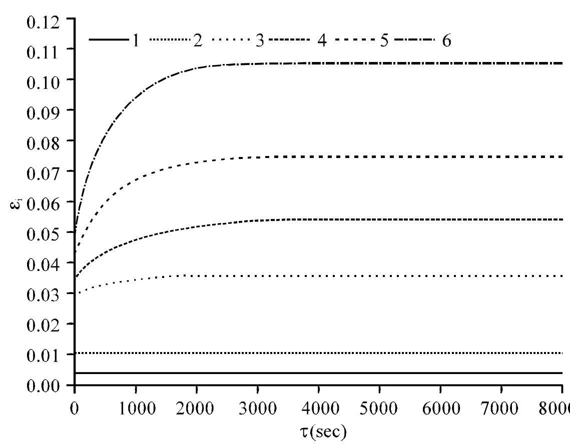

Fig. 7: Dependence of the accumulated plastic strain ε_i values change in the critical region on the loading time for beryllium window with aperture of 10 mm at cyclic load by external pressure p = 1 atm. for different foil thicknesses: 1) 0.03; 2) 0.025; 3) 0.015; 4) 0.012; 5) 0.008 and 6) 0.005 mm

is also often used in X-ray detectors and is also more prone to fracture compared to samples with bigger thickness. Foil was mounted on the metal frame using a low-melting solder. The outer diameter of the sample was 15 mm with an aperture diameter of 10 mm. Tests were carried out either until 2000 cycles of loading or until

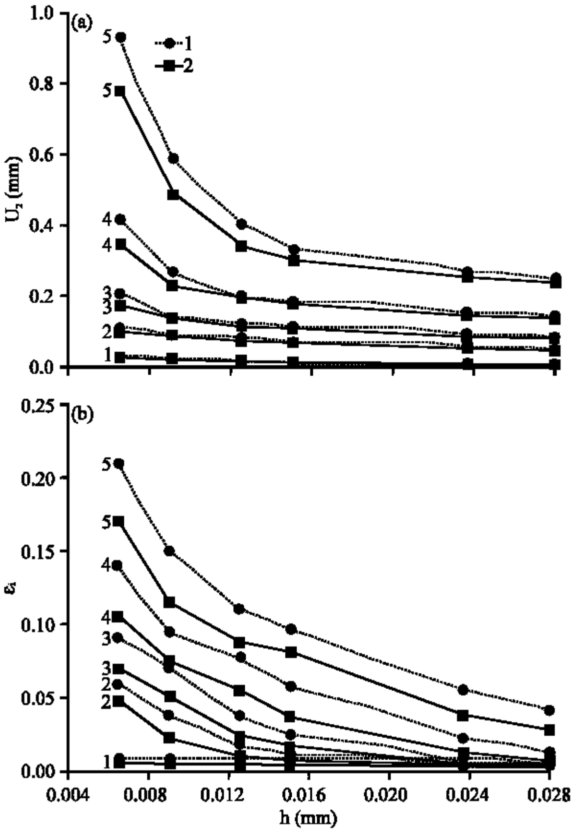

Fig. 8: a) Dependence of the change in the maximum displacement value U_{max} and b) Dependence of the change in the accumulated plastic strain ei value in the critical region of the beryllium window after 1500 loading cycles on the window thickness at different pressures: 1) 1; 2) 1.2 atm. and apertures 1) 2; 2) 5; 3) 7; 4) 10 and 5) 15 mm

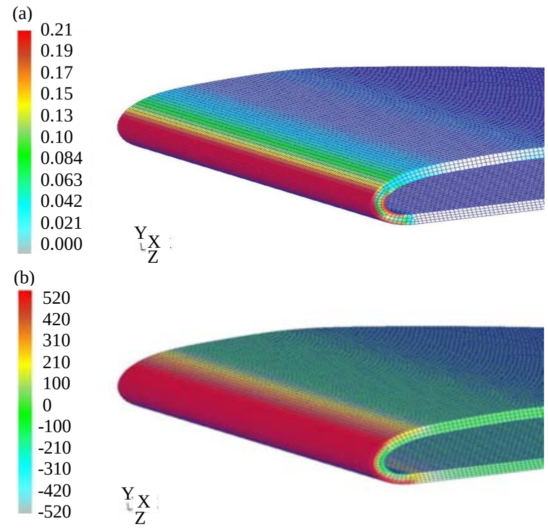

Fig. 9: a) The distribution fields of accumulated plastic strain and b) Maximum principal stress at bending of 0.008 mm thickness foil

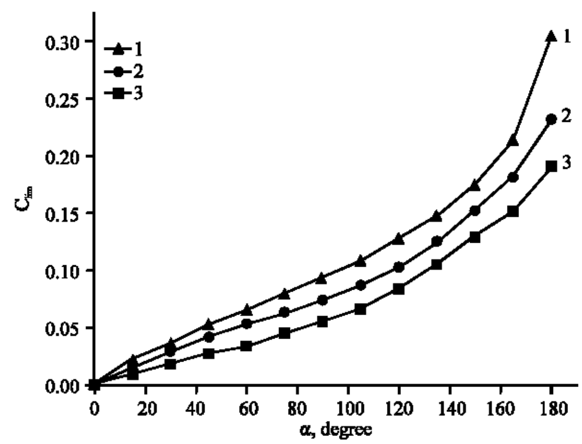

Fig. 10: The calculated dependencies of the accumulated plastic strain values bended at the angle of a for different foil thicknesses: 1) 0.025; 2) 0.012 and 3) 0.008 mm

window fracture begins. Samples with an initial helium leakage rate no more than 10^{-11} Pa×m^3/sec were used for the test. Leak detector MS-40 from VIC and equipment specially manufactured for cyclic tests was used to carry out the research along with scanning electron microscope SUPRA 55 VP WDS/WDX for the analysis of beryllium foils surface cracks.

Amount of experimental studies was limited due to very high price of beryllium windows for X-rays. Foil for tests was obtained from distilled type of beryllium by hot, warm and cold rolling methods in combination with vacuum heat treatments. Foil samples used in this experimental study varied in plastic characteristics due to the difference in temperature-deformation modes of their production. The chemical composition of tested beryllium foils is presented in Table 2 (does not include oxygen/beryllium oxide which maximum content is 0.1-0.3%).

Figure 12b and c show photographs of a foil sample at the stages of vacuum buildup and atmosphere inflow, respectively. According to Fig. 12, beryllium window remains concave at the atmosphere inflow stage which indicates the beryllium plastic deformation in the critical region (Fig. 5). 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 0.25-0.27 mm which corresponds to the modeling data (Fig. 8a).

Before the cyclic tests the limiting (critical) values of accumulated plastic strain were experimentally established

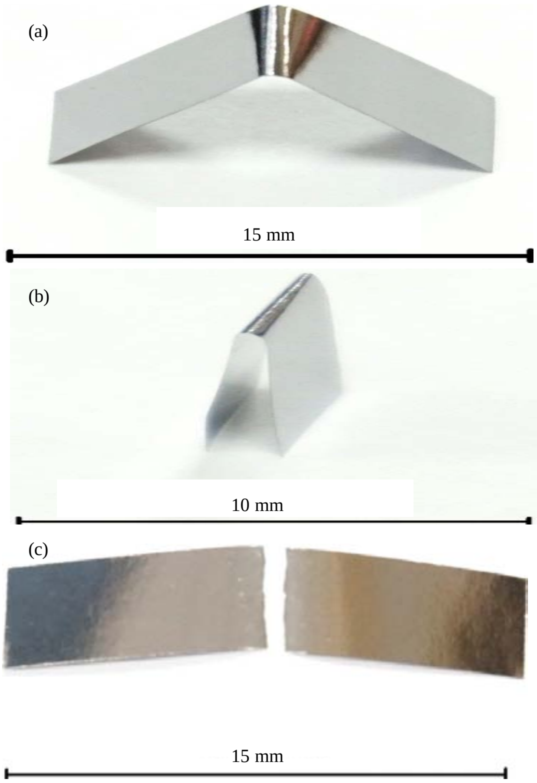

Fig. 11: a, b) The results of experimental bending of 0.008 mm thickness foil with relatively high plastic properties without signs of fracture and c) Fracture of 0.008 mm thickness foil with zero plastic properties at a bending angle of 20°

Table 2: The chemical composition of tested beryllium foils

Elements	Percentage
Be	99.82
Al	0.02
P	0.02
S	0.01
Cl	0.02
Ca	0.03
Cr	0.01
Mn	0.01
Fe	0.02
Ni	0.02
Cu	0.01
W	0.01

for each group of foils according to the technique considered earlier (Table 3). Estimated number of loading cycles which beryllium foil is able to sustain without fracture was obtained (Table 3) from the dependence of the change in the values of the accumulated plastic strain ε_i in the critical region on the loading time of the beryllium window (Fig. 7).

The results of cyclic tests showed (Table 3) that foil samples having a critical v alue of accumulated plastic strain C_{lim}>0.2 withstood 2000 cycles of loading without

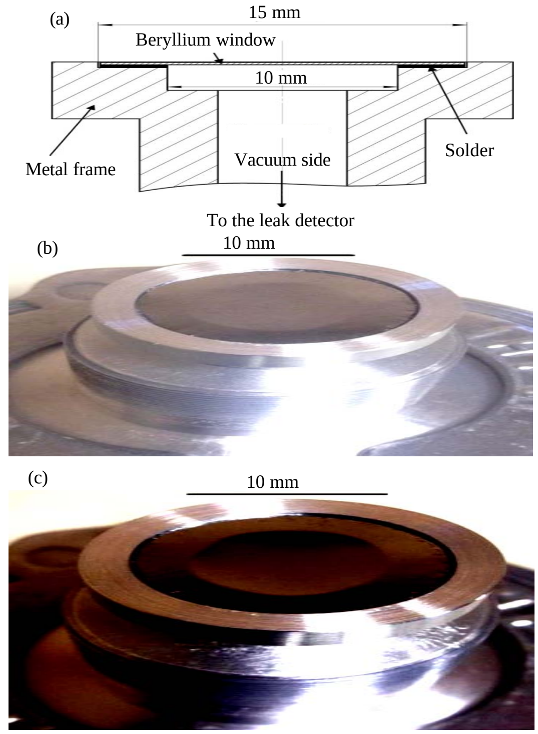

Fig. 12: a) Technical drawing of the frame with aperture of 10 mm for foil cycling tests; b) Deformation of the foil sample at the stages of vacuum buildup and c) Atmosphere inflow

Table 3: Results of cyclic testing for foil samples thickness of 0.008 mm an aperture of 10 mm with difference in plastic properties

Sample No.	Experimental values of critical plastic strain	No. of cycles without fracture, predicted	No. of cycles without fracture, actual
1	0.05	100	90
2	0.05	100	136
3	0.05	100	152
4	0.07	370	422
5	0.07	370	410
6	0.07	370	330
7	>0.2	>2000	2000
8	>0.2	>2000	2000
9	>0.2	>2000	2000

destruction signs while foil samples having a critical value of accumulated plastic strain C_{lim} = 0.05÷0.07 begin to get damaged after 90-420 cycles as evidenced by an increase of helium leakage rate to 10^{-4}-10^{-6} Pa×m^3/sec and formation of cracks. Foil samples with plastic properties value C_{lim} = 0.05 have signs of brittle fracture by the trans-crystalline mechanism (Fig. 13a) while in the samples with C_{lim} = 0.07 the fracture occurs along the grain boundaries (Fig. 13b).

Plastic deformation accumulation combined with the low plasticity of beryllium foil contribute to the fracture of beryllium windows under cyclic loading, however,

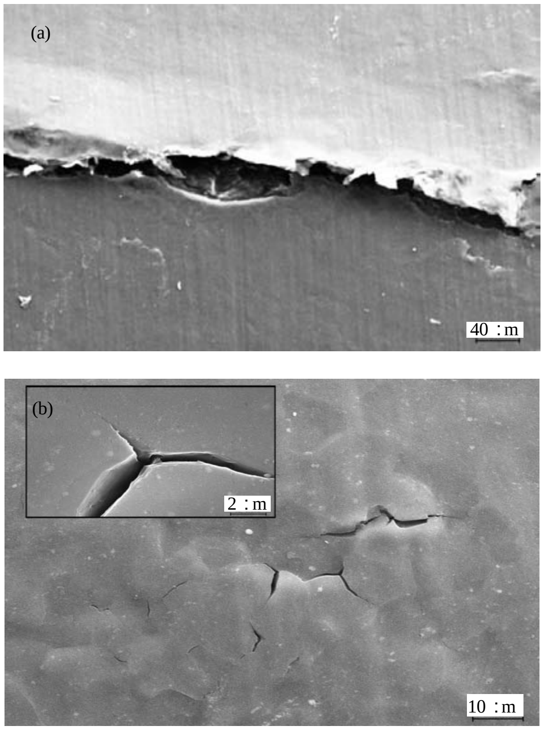

Fig. 13: a) Cracks on the surface of the 0.008 mm thickness beryllium window in the critical region after 120 loading cycles (C_{lim} = 0.05) and b) After 400 loading cycles (C_{lim} = 0.07)

reduction of beryllium window fracture probability can be achieved either by increasing the foil thickness (at constant aperture values) or by increasing of the beryllium foil plastic properties. The second method is more preferable since the increase of window thickness adversely effect on the sensitivity and characteristics of the X-ray detectors.

CONCLUSION

It has been found that it is possible for plastic deformation to appear and accumulate in narrow window region directly bordering on the embedding when a thin beryllium window is operated in an X-ray detector under the external cyclic load. The presence or absence of plastic deformation is determined by the aperture (active area) of the window and the foil thickness.

It was shown that the fracture probability of a beryllium window can be estimated by comparing the accumulated plastic strain in a foil with a certain value of the limiting (critical) plastic strain which can be determined experimentally by testing foil samples using bending method.

The low plasticity properties of the beryllium window have an extremely negative effect on its operability in the X-ray detector. Foil with thickness of 0.008 mm or less used in X-ray detectors must possess high plastic properties.

The obtained data on deflection and plastic deformations of beryllium windows with different aperture and thickness can be used in the X-ray detectors design process.

ACKNOWLEDGEMENT

This research was financially supported President of the Russian Federation grant (Agreement Nr. MK-1402.2017.8).

REFERENCES

Amptek Inc., 2017. This is the true state of the art. Amptek Inc, Bedford, Massachusetts. http://amptek.com/products/70-mm2-fast-sdd.

Beckhoff, B., B. Kanngieber, N. Langhoff, R. Wedell and H. Wolff, 2006. Handbook of Practical X-Ray Fluorescence Analysis. Springer, Berlin, Germany, ISBN:9783540286035, Pages: 863.

Corlett, J.N., N. Hartman and D. Li, 2001. Finite element analysis of thin beryllium windows for a muon cooling channel. Proceedings of the 2001 Conference on Particle Accelerator (PAC'01) Vol. 2, June 18-22, 2001, IEEE, Chicago, Illinois, USA., ISBN: 0-7803-7191-7, pp: 909-911.

Hassan, M.T., M.A. Shariff, A. Hossein, M.J. Abedin and A.F. Hoque *et al*., 2015. Calibration of a new experimental chamber for PIXE analysis at the accelerator facilities division of Atomic Energy Centre Dhaka (AECD). Nucl. Instrum. Methods Phys. Res. Sect. A Accel. Spectrometers Detectors Associated Equipment, 781: 39-43.

Huebner, S., N. Miyakawa, A. Pahlke and F. Kreupl, 2015b. Design and properties of low-energy X-ray transmission windows based on graphenic carbon. Phys. Status Solidi B, 252: 2564-2573.

Huebner, S., N. Miyakawa, S. Kapser, A. Pahlke and F. Kreupl, 2015a. High performance X-ray transmission windows based on graphenic carbon. IEEE. Trans. Nucl. Sci., 62: 588-593.

Imrisek, M., J. Mlynar, V. Loffelmann, V. Weinzettl and T. Odstrcil *et al*., 2016. Optimization of soft X-ray tomography on the COMPASS tokamak. Nukleonika, 61: 403-408.

Kolbasnikov, N.G., V.V. Mishin, I.A. Shishov, I.S. Kistankin and A.V. Zabrodin, 2014. Development of nondestructive warm rolling schedules for nanocrystalline beryllium using mathematical simulation. Russ. Metall., 2014: 785-792.

Li, D., A. Ladran, D. Lozano and R. Rimmer, 2002. Mechanical and thermal analysis of beryllium windows for RF cavities in a muon cooling channel. Proceedings of the 8th European Conference on Particle Accelerator (EPAC'02), June 3-7, 2002, United States Department of Energy, Paris, France, pp: 2163-2165.

Papirov, I.I. and A.A. Nikolaenko, 2013. Beryllium foils for windows in counter of nuclear radiation. Prob. At. Sci. Technol., 88: 235-239.

Papirov, I.I., V.I. Ivantsov, A.A. Nikolaenko, V.S. Shokurov and Y.V. Tuzov, 2015. Study beryllium microplastic deformation. Prob. At. Sci. Technol., 96: 158-165.

Papirov, I.I., V.S. Shokurov, A.I. Pikalov and A.A. Nikolaenko, 2014. Structure and properties of deformated high-purity be. Prob. At. Sci. Technol., 89: 3-9.

Prost, J., P. Wobrauschek and C. Streli, 2015. Comparison of different excitation modes for the analysis of light elements with a TXRF vacuum chamber. Powder Diffr., 30: 93-98.

Rollig, M., S. Ebenhoch, S. Niemes, F. Priester and M. Sturm, 2015. Development of a compact tritium activity monitor and first tritium measurements. Fusion Eng. Des., 100: 177-180.

Sato, T., I. Ochiai, Y. Kato and S. Murayama, 1991. Vibration of beryllium foil window caused by plasma particle bombardment in plasma focus X-ray source. JPN. J. Appl. Phys., 30: 385-391.

Scharf, O., S. Ihle, I. Ordavo, V. Arkadiev and A. Bjeoumikhov *et al*., 2011. Compact pnCCD-based X-ray camera with high spatial and energy resolution: A color X-ray camera. Anal. Chem., 83: 2532-2538.

Walsh, K.A., 2009. Beryllium Chemistry and Processing. ASM International Publishers, New York, USA., ISBN-13:978-0-87170-721-5, Pages: 576.

Zhigalina, O.M., A.A. Semenov, A.V. Zabrodin, D.N. Khmelenin and D.A. Brylev *et al*., 2016. Structure and mechanical properties of foils made of nanocrystalline beryllium. Crystallogr. Rep., 61: 549-557.