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DEFORMED STATE'S SIMULATION OF THE FIRST-GRADE TITANIUM FOIL OF THE ACCELERATOR OUTPUT WINDOW

The output accelerator windows, particularly the used metal foils are studied. The work was carried out to assess the strength of the first-strength grade titanium foil and the choice of variable parameters of the thickness of the foil. Depending on the latter, the simulation was performed by the finite element analysis in the ABAQUS automated software environment. The distributions of displacements, plastic strains of concavity caused by pressure differences, and radial and circumferential stresses have been studied in the foil's static state for 10 metal foils with a thickness of 50…500 *microns*. The basic dimensions of the titanium metal film are introduced: thickness and diameter. Atmospheric pressure was applied as an external force of influence, and the vacuum pressure was assumed to be zero. The metal shells were divided into a large number of nodes, which ensured higher accuracy for simulations. As a result of simulation, curves of the displacements of the selected points of the metal foil in the direction of the Y axis, depending on the values of the radiuses, and the curves of the strains intensities distributions of the metal foil were built, which were also analyzed. The metal foil of the output window was investigated so that simulation results could be applied to both output windows: mechanical connection and diffusion connection.

Keywords: output window, titanium metal foil, vacuum, deformed state.

Introduction. Accelerator output windows play the primary role in accelerator technology, especially in the linear electron accelerator AREAL. Since an ultra-high vacuum is provided in the accelerator, it is necessary to transfer an electron beam from a vacuum to an atmospheric pressure environment, preserving the characteristics of the beam as much as possible.

Modern accelerators are used not only for research purposes but also for solving practical problems. Today particles generated by accelerators can penetrate into any surface, the size of which sometimes reaches several meters. This property of accelerated particles is widely used in a high number of fields. Accelerated particles are no less widely used in radiation technologies, particularly in new materials production (modification), sterilization of medical devices, environmental protection, radiation treatment of food, etc. Obtaining new materials significantly impacts modern mechanical engineering, aircraft engineering, automotive maintenance, the military industry, the production of household items, etc. New materials make it possible to obtain parts with higher physical and mechanical properties in military aircraft, weapons, ammunition productions, and other places. Polymerization makes it possible to obtain new types of modified porous materials, which are also widely used in the production of heat pipes, filters, etc. Electron accelerators make it possible to clean the environment, for example, natural water, running water and its deposits, and emitted gases, as well as recycle solid waste.

Charged particle accelerators are complex equipment and combine various fields of science and technology: radio frequency systems, magnetic systems, vacuum systems, thermoregulation systems, radiation diagnostics technologies, etc. Only an effective combination of all systems and subsystems allows you to control the accelerator and get the desired result. The subsystems include the output windows (Fig. 1), which are an integral part of the accelerator and whose purpose is to extract charged particles from the environment of ultrahigh vacuum ($10^{-8}\ldots10^{-10}$ *mbar*).

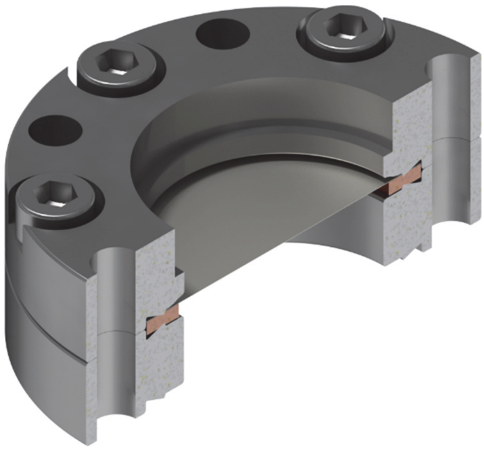


Fig. 1. An accelerator output window model

Since electron accelerators operate in a vacuum environment, a beam of electrons is exited into an atmospheric pressure environment through an output window. The latter has a simple design consisting of one or two flanges, gasket and a metal shell(s). Along with such a simple design, it is difficult to maintain the tightness of the connection, stability, and durability of foil. In literature, examples of patents for output windows with a mechanical connection are given [1-3], from which in [1] it is not determined from what material the sealing ring is made of, and the flange geometry is not shown in the area of its landing, which doesn't comply with international standards of vacuum connections. So, at least, there is a problem with the system's sealing. In [2], a constructive solution is given in terms of the strength of foil, taking two metal foils instead of one, however, in this case, repeated problems arise with inaccuracies in the assembly of the unit and maintaining the stability of the foil. [3] is a solution of a mechanical construction with two foils, between which an intermediate gas (or atmospheric gas with a lower pressure or other inert gas) is poured, which pressure must be controlled by a measuring and signaling unit. Thus, in [3], the problem of stability of two foils was solved (although with the addition of assistive resources), but from the point of view of the beam, it will have a certain scattering in four layers (foil – inert gas – foil – atmosphere) instead of two (foil – atmosphere), which will negatively affect the output parameters of the accelerator. In [4], was designed and calculated a rectangular output window (for specific purposes), in which only the distribution of stress intensity on the foil was studied, and titanium flanges were used. In [5], the structure of the output window with a beryllium metal coating and titanium flanges was studied. It is obvious that in [4, 5] quite expensive and not accessible materials were used, and special-purpose output windows were obtained. In [6], a diagram of the deformation of the first-grade titanium foil with different granule sizes and different heat treatment temperatures was obtained experimentally. The diagrams obtained in [6-8] are applicable for performing virtual calculations of foils as properties characterizing their real elastic-plastic state, which are absent in all calculations in literature, leading to big inaccuracies. Thus, having studied the characteristics of the foils used in the output windows used in accelerator technology, we can say that the later deserves a more thorough study.

The purpose of the work is a computer simulation of the deformed state of the first-grade titanium foils used in accelerator technology.

The initial data of the task. The process was simulated in the SIMULIA 2019 software environment (ABAQUS) with the following initial data: the studied foil thicknesses δ =50...500 *microns*, diameter d =36.83 *mm*. Since the function of the output windows is to conduct an electron beam from a vacuum to an atmospheric pressure environment with minimal losses, the atmospheric pressure of 1 *atm* used as an external influence.

The influence of the vacuum is assumed to be 0 *atm* since an ultra-high vacuum is provided in the accelerators, the pressure of which is $10^{-8}...10^{-10}$ *torr*. The separation range of the foil finite element grid: the number of nodes is 1110...5166, the type of cubic elements is CAX4R, and the number of elements is 920...4422. The simulation was carried out for an axisymmetric foil section (Fig. 1).

Based on the studies carried out in [7], the deformation diagram of a pure first-grade titanium material was used for modeling (Fig. 2) as a plastic property of it. The following physical and mechanical properties of the material were also introduced as initial data: density $\rho = 4510\ kg/m^3$, Young's modulus $E = 1{,}05 \cdot 10^5 MPa$, Poisson's ratio $\mu = 0{,}37$.

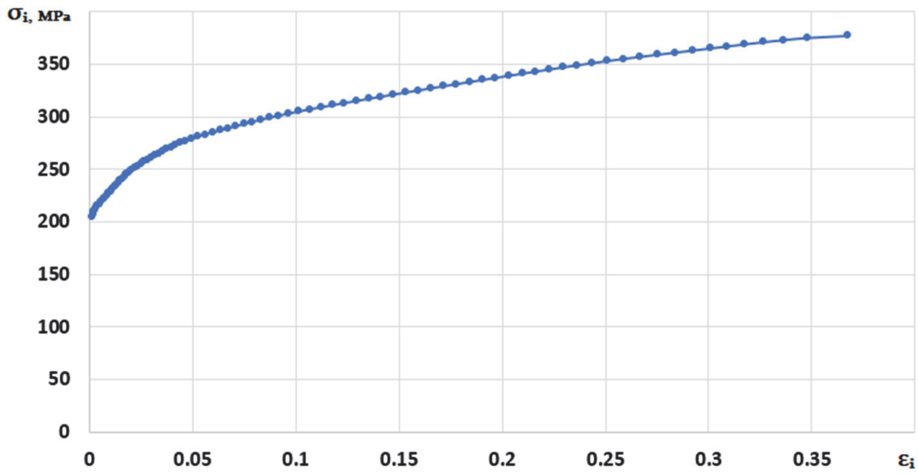
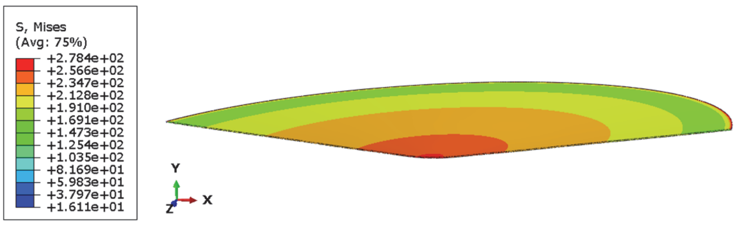


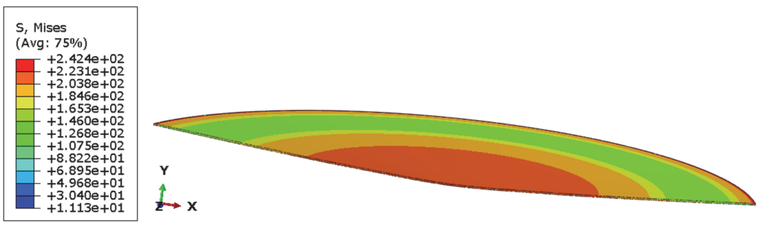
Fig.2. Deformation diagram of the first-grade titanium material

Modeling of the first strength grade titanium foil of accelerator output windows. Due to the influence of the atmospheric pressure, the titanium foil in the accelerator output window unit undergoes plastic deformation up to its plastic destruction. Since there are no studies of the stress-strain states of the foils of the output windows of accelerators in the available literature, the primary task is to study only the foil as the most vulnerable part of the output window.

Fig. 3 shows the zones of stress intensity distribution ($\sigma_i = Mises$) and deformations ($\varepsilon_i = PEEQ$) and displacements in the direction of the y axis ($u_y = U2$).



a)



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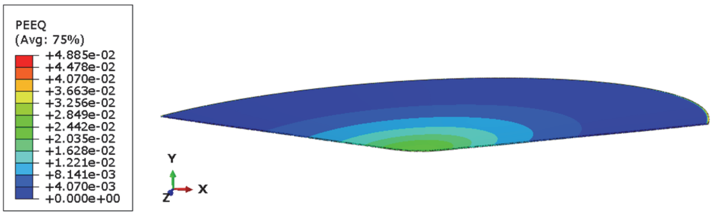

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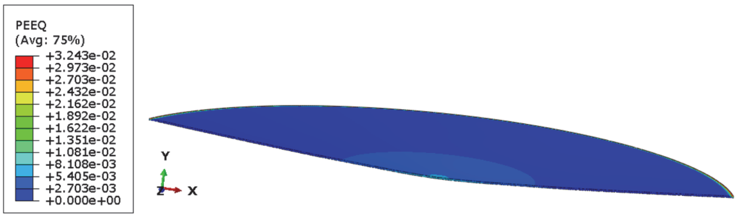

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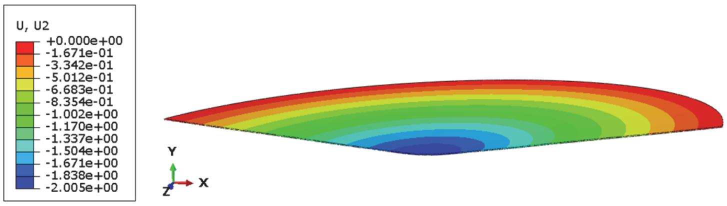

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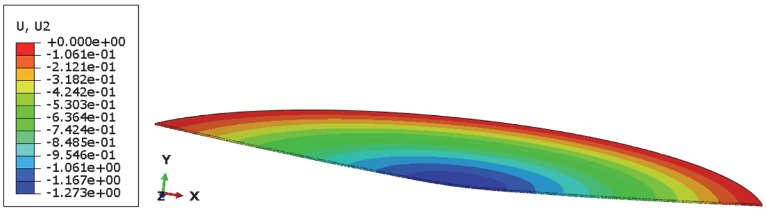

f)

Fig. 3. Zones' distribution of the stress-strain state of the titanium shell: σ_i (a, b), ε_i (c, d), u_y (e, f), where: δ=60 microns (a, c, e) and δ=100 microns (b, d, f)

When the foil is mechanically connected, it is attached at the edges between the flange and the O-ring, i.e. the fastening is carried out along the flange's knife edge. Based on the above, in the ASE, the foil was fixed in diameter with the deprivation of six degrees of freedom. The modeling was carried out in the APS "ABAQUS" for the 10 thicknesses of the foils. A total of 30 distribution zones were obtained, 6 of which are shown in Fig. 2.

The simulation output from the finite element analyses was derived from the fixed section of the foil to the center. Since the foil bends towards the vacuum, and the nodes on this side receive maximum displacements, it is advisable to take the values of the stress-strain state components from this side. The following diagrams were obtained for the above nodes (Fig. 4).

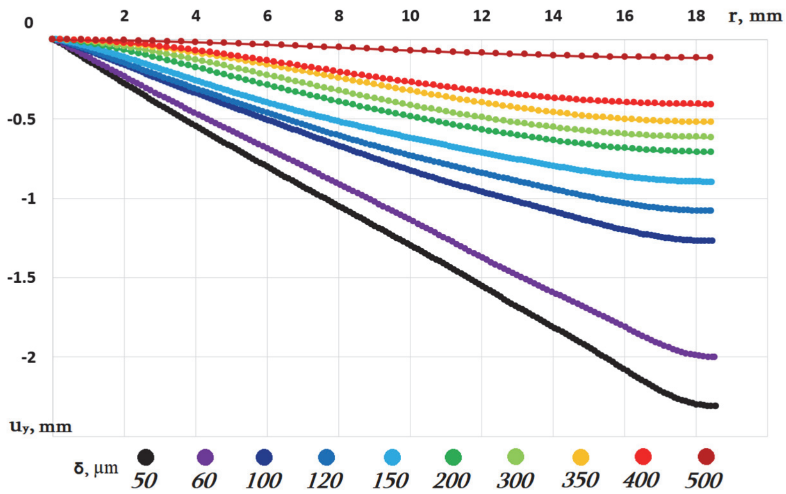

Fig. 4. Displacements of the selected nodes of the foil relative to the Y axis depending on the values of the radius

Fig. 4 shows the displacements of the selected nodes of the foil in the direction of the Y axis for 10 thicknesses of the range δ=50...500 *microns*. The diagrams obtained correspond to the shapes of the sections of foil. The greatest interest are the displacements of the central nodes of the foil, which at a thickness of 50 and 60 *microns* take quite large values. During the study of thicknesses, revealed the phenomenon that at a thickness of 60 *microns*, radial and circumferential stresses $(\sigma_m, \sigma_\theta)$ for all nodes in the fixation zone, they take positive values, whereas at a thickness of 100 *microns*, the stresses in the nodes from the atmospheric pressure side are positive, and in the nodes from the vacuum side are negative (Fig. 5). From the above, it is obvious that in the range from 60 to 100 *microns* there is a value δx of the foil thickness, starting from which, from the vacuum side, the stresses take negative values. Analyzing it, we can say that under the condition δ<δx, the foil in the support nodes undergoes tensile deformations over the entire thickness, and at δx>δ, the foil works like a beam (the upper fibers are stretched, the lower ones: compressed). The phenomenon is more clearly shown in Fig. 5.

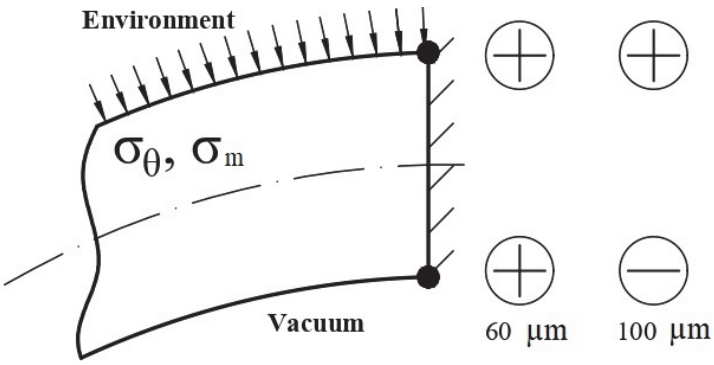

Fig. 5. σ_θ, σ_m stresses' signs in the fixed zone of foil for thicknesses in the range from 60 to 100 microns

To choose the optimal thickness, in addition to the displacements of the nodes, it is necessary to study another important parameter: plastic deformation. Fig. 6 shows the strain intensity curves (εi) of the foil's nodes from the vacuum side at the same 10 thicknesses in the range from 50 to 500 *microns*.

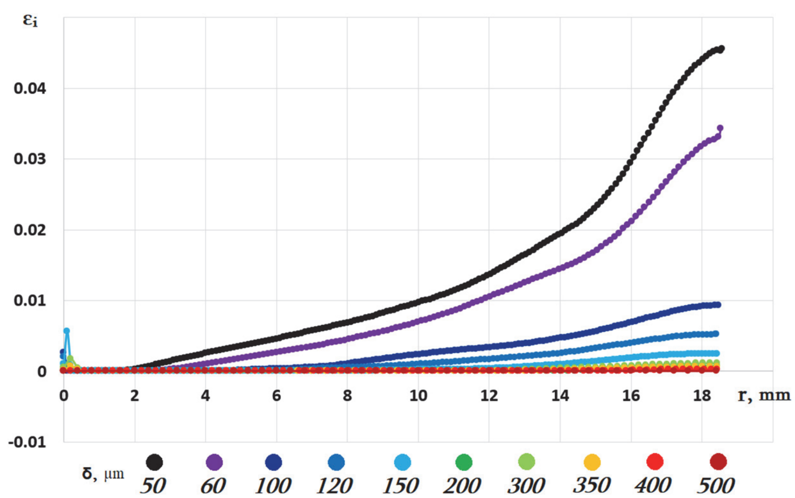

Fig. 6. Strain intensity distribution curves of the metal foil

Comparing the data obtained in Fig. 4-6 it can be assumed that the plastic strains of the central nodes of the foil, which began with the thickness δ_x, sharply decrease. It can be assumed that the sharp decrease in strains is due to the presence of the phenomenon shown in Fig. 5. As for the thicknesses $\delta<\delta_x$, their plastic strains in comparison with the case $\delta>\delta_x$ take on large values. For example, at a thickness of 100 *microns*, plastic strains of the central foil nodes account for ~27% of the strains at a thickness of 60 *microns*. Studying the support nodes for the above thicknesses, it is obvious that there is the following range: 350...δ_y...400, and when $\delta_x \leq \delta \leq \delta_y$, there are insignificant plastic strains in the support nodes (~0.56...0.001%). This phenomenon is explained by elastic strains caused by the tensile stresses of the support nodes at a thicknesses of $\delta < \delta_x$, and at $\delta_x \leq \delta \leq \delta_y$, the support nodes of the foil are subjected to bending deformations crossing the plasticity boundary. As for the case $\delta > \delta_y$, atmospheric pressure doesn't provide sufficient stress state (despite the presence of curvature) to cross the plasticity limit of the support nodes. Nevertheless, it should be noted that at $\delta > \delta_x$, the question arises about the permeability of the titanium foil for the electron beam, that is, deterioration of the initial parameters of the beam is possible. That is, the choice of the thickness of the first-grade titanium foil for the accelerator output windows should be made in the range $\delta_{min} < \delta < \delta_x$, where δ_{min} is the minimum allowable foil thickness. Since the modeling of foils in the ASE was carried out with a dynamic load, in this work only its static state (without vibration processes) is considered, so to accurately determine the thickness of δ_{min}, it is also necessary to study the dynamics of foils, since according to preliminary data, its plastic strains can increased several times, which greatly limits the permissible thickness range.

Conclusion. Studied the stress-strain state of the first-grade titanium foils of accelerator output windows, we obtained:

- with a thickness of 50 to 500 *microns*, the cross-section shapes of metal foils in deformed states as displacement curves of grid nodes;
- in the range from 60 to 100 *microns*, there is a value δ_x of the foil thickness, starting from which, from the vacuum side, the stresses σ_m and σ_θ take negative values, i.e. in the case of $\delta > \delta_x$, the foil is subjected to bending in the support zone;
- plastic strains of the central nodes of the foil, starting from the thickness δ_x, decrease sharply, and plastic strains for the thickness $\delta < \delta_x$ in comparison with the case $\delta > \delta_x$ take large values (for example: $(\varepsilon_i^{100\ mkm}/\varepsilon_i^{60\ mkm}) \cdot 100\% \approx$ $\approx 27\%$);
- at $\delta_x \leq \delta \leq \delta_y$, there are insignificant plastic strains in the support nodes (~0.56...0.001%);
- it became clear that the choice of thicknesses should be made in the range $\delta_{min} < \delta < \delta_x$, to clarify which it is also necessary to study the dynamics of metal foils.

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ԱՐԱԳԱՑՈՒՑՉԻ ԵԼՔԱՅԻՆ ՊԱՏՈՒՀԱՆԻ, ԱՌԱՋԻՆ ԴԱՍԻ ՏԻՏԱՆԵ ՄԵՏԱՂԱԹԱՂԱՆԹԻ ԴԵՖՈՐՄԱՑՎԱԾ ՎԻՃԱԿԻ ՄՈԴԵԼԱՎՈՐՈՒՄԸ

Ուսումնասիրվել են արագացուցչային ելքային պատուհանները, մասնավորապես՝ նրանց մեջ կիրառվող մետաղաթաղանթները։ Աշխատանքներ են կատարվել առաջին ամրության դասի տիտանե մետաղաթաղանթի ամրության գնահատման համար՝ փոփոխական բնութագիր ընտրելով մետաղաթաղանթի հաստությունը։ Վերջինից կախված՝ մոդելավորումներ է կատարվել ABAQUS ավտոմատացված ծրագրային միջավայրում (ԱԾՄ) վերջավոր տարրերի մեթոդով (ՎՏՄ)։ Ստատիկ վիճակում ուսումնասիրվել են 50...500 *մկմ* միջակայքի 10 հաստությունների մետաղաթաղանթների՝ ճնշման տարբերությունից առաջացած գոգավորության պլաստիկ դեֆորմացիաների, շառավղային և շրջանային լարում-

ների բաշխվածությունները, տեղափոխությունները: Ներմուծվել են տիտանի մետաղաթաղանթի հիմնական չափերը՝ հաստությունը, տրամագիծը: Որպես արտաքին ազդող ուժ կիրառվել է մթնոլորտային ճնշումը, իսկ վակուումի միջոցով ճնշումն ընդունվել է զրո: Մետաղաթաղանթները բաժանվել են մեծ թվով հանգույցների, որով ապահովվել են մոդելավորումների մեծ ճշտությունները: Մոդելավորումների արդյունքում կառուցվել են Y առանցքի նկատմամբ մետաղաթաղանթի ընտրված կետերի տեղափոխությունների գրաֆիկները՝ կախված շառավղի մեծություններից, և մետաղաթաղանթի դեֆորմացիաների ինտենսիվության բաշխման կորերը, որոնք ևս վերլուծվել են: Ելքային պատուհանի մետաղաթաղանթն ուսումնասիրվել է այնպես, որ մոդելավորումների արդյունքները կիրառելի լինեն ելքային պատուհանների և՛ մեխանիկական միացման, և՛ դիֆուզիոն միացման դեպքերում:

Առանցքային բառեր. ելքային պատուհան, տիտանե մետաղաթաղանթ, վակուում, դեֆորմացված վիճակ:

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МОДЕЛИРОВАНИЕ ДЕФОРМИРОВАННОГО СОСТОЯНИЯ ТИТАНОВОЙ ФОЛЬГИ ПЕРВОГО КЛАССА ВЫХОДНОГО ОКНА УСКОРИТЕЛЯ

Изучены выходные окна ускорителя, в частности, используемая в них металлическая фольга. Работа проводилась с целью оценки прочности титановой фольги первого класса прочности и выбора переменных характеристик толщины фольги. В зависимости от последнего выполнено моделирование методом конечных элементов в автоматизированной программной среде ABAQUS. В статическом состоянии изучены распределения, смещения 10 металлических пленок толщиной 50…500 *мкм*, пластические деформации вогнутости, вызванные разницей давлений, а также радиальные и окружные напряжения. Проведен сравнительный анализ полученных результатов и определен наиболее оптимальный диапазон толщины металлической фольги с точки зрения прочности для выбранного материала. В качестве внешней силы воздействия применялось атмосферное давление, а давление со стороны вакуума принималось равным нулю. Металлические оболочки были разделены на большое количество узлов, что обеспечивало большую точность в моделированиях. В результате моделирования построены графики смещений выбранных точек металлической фольги относительно оси Y в зависимости от значений радиуса и кривые распределения интенсивности деформаций металлической фольги, проведен их анализ. Металлическая фольга выходного окна была исследована таким образом, что результаты моделирования применимы к выходным окнам, как к механическому соединению, так и к диффузионному.

Ключевые слова: выходное окно, титановая металлическая фольга, вакуум, деформированное состояние.