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STRESS-STRAIN STATE ANALYSIS OF THE FIRST-GRADE TITANIUM FOIL OF THE ACCELERATOR OUTPUT WINDOW IN A STATIC STATE*

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Abstract

The stress-strain state of the titanium foils of the accelerator output windows at various thicknesses was studied with the choice of first-grade titanium foil as a brand. The latter is more affordable and accessible compared to a second-grade titanium foil. The deformation diagram, density, Young's modulus, and Poisson's ratio of the first-grade titanium were selected as initial data. Atmospheric pressure was used as an external pressure, and the pressure from the vacuum side was taken as zero. The latter is acceptable in simulations of ultrahigh vacuum assemblies since it does not affect the overall picture of the stress-strain state. In addition to studying the central nodes of the metal foil, the sealing nodes were also considered as an object of research, with the study of stress intensity, meridional and circumferential stresses, and maximum displacements of the centre. Based on the results, a function was obtained that allows us to accurately calculate the displacements of the centre of the first-grade titanium foil depending on its thickness. The analysis of the received data was carried out.

INTRODUCTION

The AREAL project [1] is considered as the first phase of CANDLE synchrotron light source creation in Armenia. AREAL now has two output windows. The output windows (see Fig. 1) are used to extract the generated beam from the accelerator.

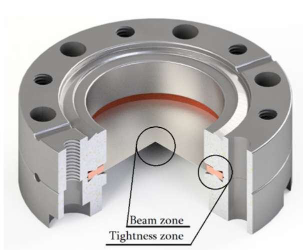

Figure 1: The accelerator output windows and its danger zones.

Beryllium windows are the best choice for X-ray studies [2], but not for accelerators in general. Beryllium in accelerators is a toxic material not only for human health [3], but the damages of the output window made of it pollute the beamline, too.

Another non-metallic material of the output window may be graphite. In particular, DESY [4] window is based on graphite consisting of a 500 μm carbon fiber reinforced graphite carrier material, coated on one side with less than 50 μm layer of pyrolytic graphite to make the porous substrate leak tight. For this type of output window, the beam divergence due to scattering is higher compared with titanium material.

Aluminium output windows also commonly are used in accelerators. Despite the lower values of the permissible temperature of aluminium alloy, foils are preferable for operation with high current densities of the output electron beam in low-energy accelerators [5].

Metal foils are also used, on which another material is deposited [6]. Thus, it is possible to give the foil additional strength and resistance from the thermal effects of the beam passing through it. The thickness of the deposited layer is approximately 1 μm. However, it should be noted that obtaining such a layer is a rather complicated process and requires additional resources.

Nowadays, Titanium and its alloys are considered the most common choice for accelerator output windows. Two grade titanium alloys are mainly used, Gr-2 and Gr-5. Second-grade titanium alloy is popular for medium and high energies. On average, a Gr-5 titanium foil can withstand up to 10^7 cycles [7]. Consequently, durability is provided in the case of titanium. In an accelerator with an energy of 300-350 keV, when applying a 50 μm thick titanium foil of the VT1–0 brand, an analogue of Gr-2, about half of the resulting beam is absorbed [6, 8]. It is noteworthy to say that the energy of 100 keV and below is completely absorbed by the metal foil of this thickness. When studying the output windows, the research was carried out mainly by studying the thermal factor. In the CAE automated software environment, thermal studies by the finite element method are even less [7, 9, 10]. As for the power effects of the output unit, there are no such studies.

The metal foil is deformed by atmospheric pressure, as a result of which the metal foil deflects, acquiring concavity. Two danger zones arise: one is the tightness zone, and the other is the beam zone (see Fig. 1). The latter has also been investigated in this work.

Comparing titanium Gr-1 and Gr-2 alloys, we can say that they have the same price, Ti Gr-2 surpasses Gr-1 in its mechanical properties, but it is noteworthy that the amount of oxygen in Gr-1 is Max 0.18% [11], while Gr-2 has Max 0.25% [12]. It is known that in conditions of ultrahigh vacuum, substances containing less oxygen are preferable.

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Thus, the Titanium Grade 1 brand was chosen as the material of the metal foil. Titanium Gr-1 is the highest purity grade commercially available.

INITIAL DATA OF SIMULATION

The process was simulated in the SIMULIA 2019 software environment (ABAQUS) with the following initial data: the studied foil diameter d=36.83 mm, thicknesses δ=50...500 μm. The following physical and mechanical properties of the material were also introduced as initial data: density ρ=4510 kg/m^3, Young's modulus E=1.05·10^5 MPa, Poisson’s ratio μ=0,37. As the feature of the output windows is to extract an electron beam from UHV to an atmospheric pressure environment with minimal losses, the atmospheric pressure of 1 atm is used as an external influence. The influence from the UHV side is assumed to be 0 atm since 10^{-8}...10^{-10} Torr is provided in accelerators and will not cause any mechanical changes.

Based on the research carried out in [13], the stress-strain diagram of a pure first-grade titanium material was used for simulation (Fig. 2) to define foils' plastic properties.

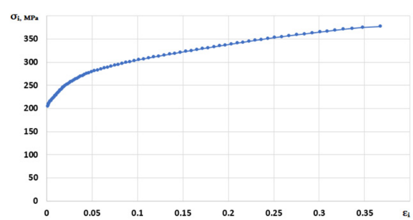
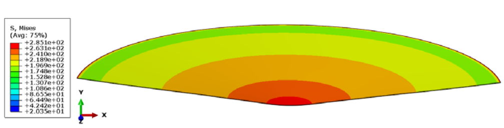


Figure 2: Stress-strain diagram of the first-grade titanium material [13].

SIMULATION

Conducted simulations allowed us to get the zones of stress intensity distribution (Von Mises stress), the components of stress state – circumferential (σ_θ), meridional (σ_m) stresses, and displacement in the direction of the y-axis. Fig. 3 illustrates two edge cases of the foil thickness range – 50 microns (Fig. 3a, c, e, g) and 500 microns (Fig. 3b, d, f, h).



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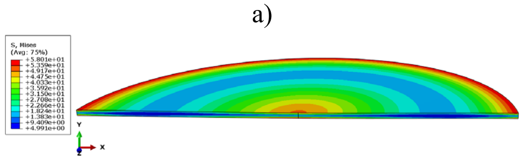
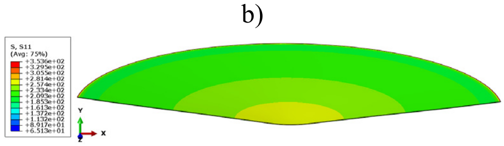
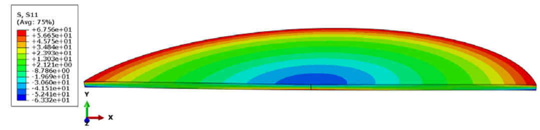


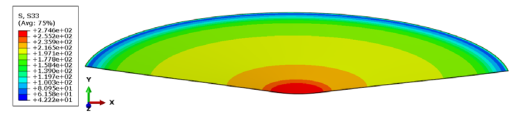
b)



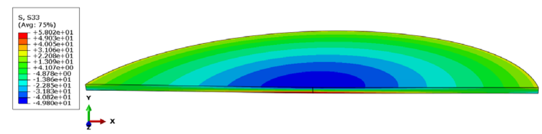
c)



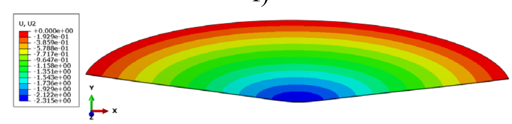
d)



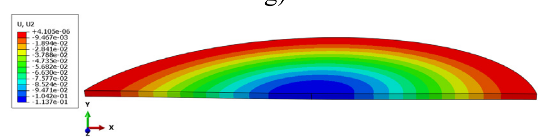
e)



f)



g)



h)

Figure 3: Mises (a, b), meridional (c, d), circumferential (e, f) stresses, and displacement in the direction of the y-axis (g, h), where foils have 50 μm (a, c, e, g) and 500 μm (b, d, f, h) thicknesses.

According to simulation results (Fig. 3) 50 μm and 60 μm foils’ stress intensity values in the center nodes are about 266 MPa, which is higher than the ultimate tensile strength (240 MPa) of the titanium Grade 1 material [11]. From this perspective, it is not recommended to take those values for foil thicknesses. For other ticknesses: 100 μm – ~226.7 MPa, 120 μm – ~217.5 MPa, 150 μm – ~208.7 MPa, 200 μm – ~202.5 MPa, …, 400 μm – ~151.9 MPa, 500 μm – ~58 MPa. From the stress intensity values mentioned above, in the case of 100 μm foil thickness, the margin of safety of the foil will be approximately 1.059. If we take 150 μm foil thickness, then the margin of safety will be about 1.15. On the one hand, if foil should work under a significant thermal influence, then it will be recommended to take 300 μm foil thickness to have about 66 MPa additional gap for thermal stresses. On the other hand, if we don’t have significant thermal changes caused by the beam, then we can take 100 μm foil thickness as the minimum acceptable, or 150 μm as a more reliable option. However, it should also be calculated the transparency of the foil for the beam with specific energy, for instance, 300 μm foil thickness is quite thick, and how appropriate would it be, is still a question, and maybe the use of an additional metal grid for the foil [8, 14, 15] or another grade of titanium material would be more reasonable.

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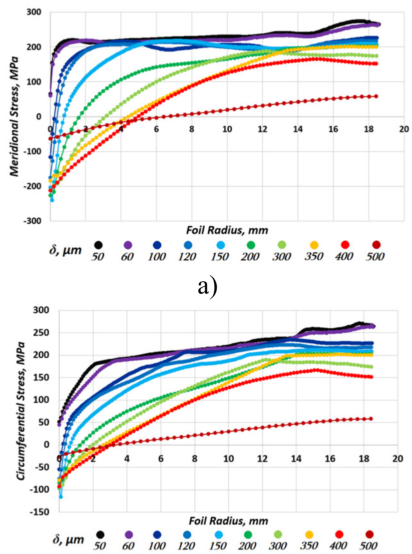
Nevertheless, to investigate the stress state of the foils more clearly, the curves of meridional and circumferential stresses were plotted in Fig. 4 for different thicknesses. All data were taken from the vacuum side, starting from the outer edge nodes of the foil up to the center, therefore 0 mm corresponds to the outer edge node, and 18.415 mm corresponds to the center node of the foil (Fig. 4).



a)

b)

Figure 4: Meridional (a) and circumferential (b) stresses distribution on foil radius for δ=50...500 microns.

From Fig. 4a we can observe that the meridional stresses are distributed approximately uniformly by foil radius for the thicknesses up to 120 μm. Next, in the case of thicknesses from 150 to 500 μm, it is clear that meridional stresses change gradually. This phenomenon can be explained as foils up to 120 μm loaded as much as about all their nodes are under tension because of their deflection (higher than 1 mm). Hence, we can conclude that titanium Grade 1 foils with a deflection higher than 1 mm have approximately uniformly distributed meridional stresses. Meanwhile, in Fig. 4b circumferential stresses are distributed with gradual increase for all foil thicknesses. To compare, meridional and circumferential stresses are approximately equal to each other in the center nodes of the foil, concurrently at the outer edge nodes the meridional stresses are higher in the module than circumferential ones. Around the fixed nodes meridional stresses are higher because of their tension related with to foil deflection. Another important phenomenon noted during simulations is that in the range of 60…100 μm thicknesses, there should be one thickness value, starting from which foil in its outer edge fixed nodes begin to work under bending. Up to this thickness value foil in the fixed nodes works under tension (stresses are positive both from the atmospheric pressure and vacuum side). Next, starting from that thickness point the stresses in the fixed nodes from the vacuum side begin to change their values as negative, simultaneously, from the atmospheric pressure side they remain positive, which means, that foil works under bending.

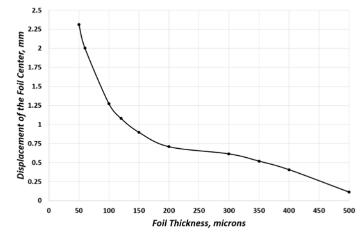


Figure 5: Displacement of the foil center nodes from the vacuum side for each foil thickness.

From Fig. 3 we can note that in the case of titanium grade 1 foil with thicknesses range – δ=50...500 μm, the maximal displacement at the center points ranged from approximately 2.315 mm to 0.114 mm. To introduce the deflection of the foil for all thicknesses, the curve of Fig. 5 was obtained from simulations. With the use of the data from Fig. 5, the approximate function was obtained for fast analytical calculations of titanium grade 1 material circular foil center deflection (h_{max}, mm) for various thicknesses.

$$h_{max}=-10^{-12}\delta^5+2\cdot10^{-9}\delta^4-10^{-6}\delta^3+0.0004\delta^2-0.0575\delta+4.4021$$

The provided h_{max} approximate function above will be useful to avoid time-consuming simulations, and for fast analytical calculations, we only need the thickness value (in μm) of the foil.

CONCLUSION

The finite element analysis of first-grade titanium material foil of the accelerator output window for different thickness values was developed. It is revealed that 150 μm thickness is a good option from the strength point of view, on the other hand, if the output window should be influenced by high thermal processes, then foil with 300 μm is recommended, which will have an additional approximately 66 MPa gap for thermal stresses. Here we shall note that for this kind of thick window, the beam transmission should also be calculated.

It is identified that meridional stresses had higher values in the module around the outer edge nodes of the foil, compared with circumferential ones, in parallel, meridional and circumferential stresses were approximately equal around the centre nodes of the foil. Meanwhile, in the range of 60…100 μm thicknesses foil began to bend at the fixed nodes.

The most vital part of this research is the obtained approximate function of the foil deflection, which will be useful to avoid time-spending simulations. With the help of it, it is quite easy to calculate the foil deflection (in mm) at the centre nodes for titanium grade 1 material for various thicknesses (in μm) with high accuracy.

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REFERENCES

[1] V. M. Tsakanov *et al.*, "AREAL test facility for advanced accelerator and radiation source concepts", *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 829, pp. 284–290, Sep. 2016. doi:10.1016/j.nima.2016.03.062

[2] https://insoptics.com/beryllium-windows-1

[3] Hazardous substance fact sheet, https://nj.gov/health/eoh/rtkweb/documents/fs/0222.pdf

[4] Z. Amirkhanyan *et al.*, "Heating and Beam Impact of High Intensity Exit Windows for FLASHlab@PITZ", in *Proc. IPAC'22*, Bangkok, Thailand, Jun. 2022, pp. 2958-2961. doi:10.18429/JACoW-IPAC2022-THPOMS010

[5] L. V. Bodakin, A. I. Gusakov, O. V. Komarov, S. L. Kosogorov, S. A. Motovilov, and N. A. Uspenskii, "Application of aluminum and titanium foils in low-energy wide-aperture electron accelerators", *Technical Physics*, vol. 61, no. 9, pp. 1404–1410, Sep. 2016. doi:10.1134/s1063784216090036

[6] A. G. Knyazeva, V. I. Kushch, G. E. Remnev, V. V. Ezhov, and E. A. Smolyanskiy, "TiN coating effect on the elastoplastic behaviour of Ti film for electron beam exit window", *Bull. Soc. Vac. Coaters*, vol. 143, pp. 356–362, Sep. 2017. doi:10.1016/j.vacuum.2017.06.044

[7] C. R. Ader, M. W. McGee, L. E. Nobrega, and E. A. Voirin, "Overview of Fabrication Techniques and Lessons Learned with Accelerator Vacuum Windows", in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, pp. 51-54. doi:10.18429/JACoW-IPAC2018-MOZGBE4

[8] I. S. Egorov *et al.,* "The output window of the «ASTRA» high-current electron accelerator", *Mathematics and Mechanics*, pp. 91–94, 2013 (in Russian).

[9] N. Manivannan *et al.*, "Chromium coated silicon nitride electron beam exit window", *Bull. Soc. Vac. Coaters*, vol. 113, pp. 19–23, Mar. 2015. doi:10.1016/j.vacuum.2014.11.024

[10] C. R. Ader, M. L. Alvarez, J. S. Batko, R. Campos, M. W. McGee, and A. C. Watts, "Accelerator Vacuum Windows: A Review of Past Research and a Strategy for the Development of a New Design for Improved Safety and Longevity for Particle Accelerators", in *Proc. IPAC'19*, Melbourne, Australia, May 2019, pp. 2237-2239. doi:10.18429/JACoW-IPAC2019-WEXXPLS2

[11] ASM Material Data Sheet Titanium Grade 1, https://asm.maweb.com/search/SpecificMaterial.asp?bassnum=mtu010

[12] ASM Material Data Sheet Titanium Grade 2, https://asm.matweb.com/search/SpecificMaterial.asp?bassnum=MTU020

[13] B. Lu *et al.,* "Titanium based cranial reconstruction using incremental sheet forming", *International Journal of Material Forming,* vol. 9, pp. 361-370, 2016.

[14] I. Egorov, A. Poloskov, M. Serebrennikov, and G. Remnev, "Self-bearing membrane exit window with the separate anode for sub-microsecond electron accelerator", *Bull. Soc. Vac. Coaters*, vol. 173, p. 109111, Mar. 2020. doi:10.1016/j.vacuum.2019.109111

[15] Yu.A. Kotov *et al.,* "The output window of a charged particle accelerator", *Inventions for the patent RU 2137247 C1,* pp. 1-4, 1999.