NUMERICAL-EXPERIMENTAL COMPARATIVE RESEARCH OF TITANIUM FOIL GRADES FOR ACCELERATOR OUTPUT WINDOWS*

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Abstract

The stress-strain state of titanium foils used for accelerator output windows was investigated with various foil thicknesses and titanium grades. Initial material data included deformation diagrams, densities, Young's moduli, and Poisson's ratios for each grade. Experimental studies were performed to validate the central displacements of Titanium Grade 2 foils. Measurements were conducted using a Hexagon precision measurement machine to determine the effective friction coefficients between titanium and two contacting materials: stainless steel 304L and oxygen-free copper. The latter was obtained via fitting the displacement curves of the initial simulations and experimental measurements conducted. These coefficients were subsequently incorporated into refined numerical simulations to obtain a more accurate representation of the stress–strain state within the sealing region of the output window assembly. Comparative analyses of the simulation results were carried out for all selected titanium grades. The advantages and limitations of each grade were evaluated in terms of mechanical performance, deformation behavior, and suitability for use in accelerator output window applications.

INTRODUCTION

Accelerator output windows serve as transition units for the generated beam when it passes from a vacuum environment to an atmospheric-pressure environment. During this transition, the metal foil absorbs a certain portion of the beam, thereby altering its characteristics.

The AREAL linear electron accelerator at the CANDLE Synchrotron Research Institute [1-6] is equipped with two output windows, each consisting of two flanges, a 50 µm thick Grade 2 titanium foil, and a copper gasket (see Fig. 1). This assembly is sealed using bolts, nuts, and washers, forming a detachable joint.

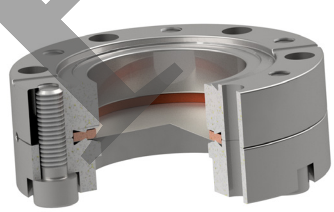

Figure 1: Accelerator output window assembly.

The output window assembly can be realized using detachable and non-detachable joints. In detachable joints, the gasket is plastically deformed to ensure sealing. These joints can be configured in two ways, depending on the foil position: above-gasket and beneath-gasket. In non-detachable joints, vacuum brazing or welding is applied. These can also be classified into two types: brazing using molten filler material and diffusion bonding using specially designed foil-type filler materials. A summary of these approaches is illustrated in Fig. 2.

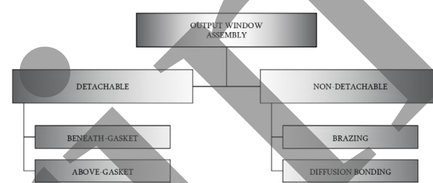

Figure 2: Methods of output window fabrication.

Various foil materials are used in accelerators [7-9], but titanium foils are the most commonly applied. However, selecting the appropriate titanium grade remains a challenge. In accelerator technology, Grade 2 and Grade 5 titanium foils are widely used. Grade 1 titanium (Ti Gr-1) foils are generally not suitable for the AREAL linear electron accelerator, since the required stable thickness is too high, making the foil act as a barrier rather than a window for the beam [10, 11]. Therefore, it is essential to investigate not only Grade 2 but also Grade 5 titanium foils.

The stability of the foil in the assembly depends on its diameter. In the AREAL linear electron accelerator, one side of the output window uses a DN35CF–DN40CF flange [12], while the other side uses an ATLAS flange [13]. In both cases, the foil is fixed along a circular line passing through the tip of the knife edge. This circle defines the effective diameter of the foil.

Table 1: Properties of Ti Gr-2 and Gr-5

Properties	**Gr-2**	**Gr-5**
Density (g/cc)	4.51	4.43
Tensile Strength, Ultimate (MPa)	430	950
Tensile Strength, Yield (MPa)	340	880
Poisson's Ratio	0.34	0.342
Modulus of Elasticity (GPa)	102	113.8

Before thermal effects become significant, the foil in accelerator output windows is primarily subjected to atmospheric pressure. As a result, it experiences deformation during each vacuum pumping cycle. Under identical thickness conditions, Grade 2 and Grade 5 titanium foils exhibit different mechanical behaviors [14-15]. Table 1 a comparison of these materials shows that although Ti Gr-5 has superior mechanical properties, it is less economically advantageous.

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Thus, it is essential to conduct a detailed comparative analysis of Grade 2 and Grade 5 titanium foils to determine their suitability and preferred application in accelerator technology.

INITIAL DATA OF SIMULATION

The process was simulated using the SIMULIA ABAQUS 2019 environment. The initial geometric parameters included a foil diameter of d = 36.83 mm and thicknesses of δ = 30; 40; 50 μm. The material was simulated using the physical and mechanical properties given in the Table 1. These values are consistent with typical properties of titanium-based materials used in finite element simulations. Given that the output window is designed to enable electron beam extraction from an ultra-high vacuum (UHV) environment into atmospheric conditions with minimal losses, an external pressure of 1 atm was applied. The pressure on the UHV side was assumed to be 0 atm, as vacuum levels of 10^{-8}–10^{-10} Torr, commonly achieved in accelerator systems, do not induce significant mechanical effects.

The plastic behavior of the flange and foil materials was defined using the stress–strain curves, adopted from [7, 16] (see Fig. 3), which was incorporated into the model to accurately represent the elastoplastic response of the foil and flanges.

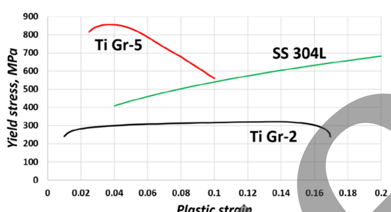

Figure 3: Stress-strain diagram of the stainless steel 304L, titanium Gr-2 and Gr-5 materials [7, 16].

EXPERIMENTS AND SIMULATIONS

The output window with titanium Gr-2 foil was assembled and pumped as the reference experiment. The foil was scanned with the Hexagon precision measurement machine, which is pre-calibrated, and its measurement deviation was 0.2 μm. Meanwhile, the preliminary simulation was conducted with the friction coefficients from the literature [7]: stainless steel (SS) 304L with titanium – 0.48, SS304L with oxygen-free high conductivity (OFHC) copper – 0.15, and titanium with OFHC copper – 0.62. The deflections of the reference experiment and the preliminary simulation are tried to fit to obtain the more or less actual friction coefficients. The resulting actual friction coefficients were: SS304L with titanium – 0.5, SS304L with OFHC copper – 0.15, and titanium with OFHC copper – 0.7. The further simulations were carried out using the obtained friction coefficients, including the assumption that they will not vary as much for the titaniums of different grades.

The simulations were separated into two phases: first phase – tightening phase, and second phase – vacuum pumping phase. This allowed us to investigate the stress state of the output windows more efficiently.

According to simulations conducted the stress intensity distributions (Von Mises stresses), and displacement (deflection) in the direction of the y-axis (normal direction). Figure 4 illustrates the Von Mises stress distribution zones of the output window with titanium Gr-2 foil after the second phase. The δ = 30 μm thickness is not presented in Fig. 4, because during the simulation, it was torn.

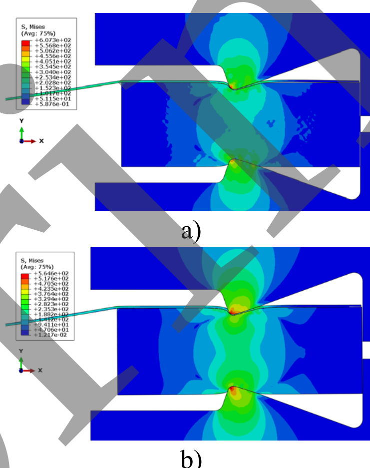

Figure 4: Von Mises stress distribution zones after second phase of the output window sealing zone with the titanium Gr-2 foil, when δ = 40 μm (a), and δ = 50 μm (b).

To evaluate the stress-strain state in the sealing region, two contact interfaces were analyzed: the knife edge–foil interface (upper flange in Fig. 4) and the knife edge–gasket interface (lower flange in Fig. 4). At the initial stage, both interfaces demonstrate similar stress distributions and comparable magnitudes. The maximum stresses – approximately 628–665 MPa and 677.4–700 MPa for foil thicknesses of 40 μm and 50 μm, respectively – are concentrated at the knife-edge tips due to the penetration effect.

In the subsequent stage, noticeable differences arise in both stress distribution and magnitude between the two interfaces. In the knife edge–gasket contact region (lower flange, Figs. 4a, b), the peak stress at the knife-edge tip decreases to about 514.6 MPa and 564.6 MPa for the respective thicknesses, indicating stress relaxation during vacuum pumping. Conversely, in the knife edge–foil interface (upper flange, Figs. 4a, b), the corresponding peak stresses are approximately 607.3 MPa and 544.2 MPa. For the 40 μm foil, the highest stress is observed at the knife edge–foil interface, whereas for the 50 μm foil, it occurs at the knife edge–gasket interface.

Figure 5 illustrates the Von Mises stress distribution zones of the output window with titanium Gr-5 foil after the second phase.

For the titanium Gr-5 output windows, during the initial stage, both interfaces also exhibit comparable stress distributions and magnitudes. The peak stresses – approximately 630.2, 644.3, and 669.9 MPa for foil thicknesses of 30, 40, and 50 μm, respectively – are localized at the knife-edge tips as a result of the penetration process. It is obvious that with the foil thickness growth, the peak stress value at the knife edge tip is higher.

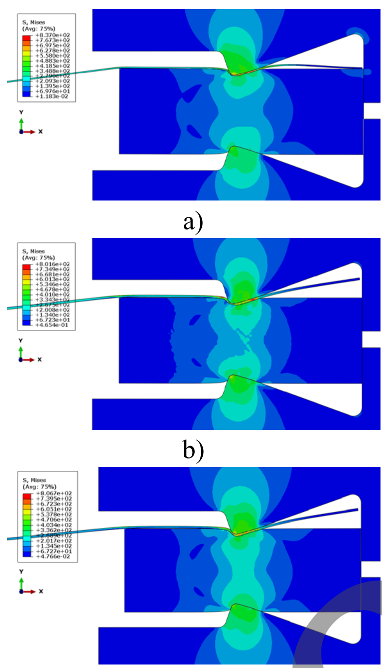

Figure 5: Von Mises stress distribution zones after second phase of the output window sealing zone with the titanium Gr-5 foil, when δ=30 μm (a), δ=40 μm (b), and δ=50 μm (c).

In the subsequent stage, however, both the stress distribution and magnitude differ between the two interfaces. In the knife edge–gasket contact zone (bottom flange, Fig. 5a, b, c), the maximum stress at the knife-edge tip decreases to approximately 535.98, 614.2, and 591.9 MPa for the respective thicknesses, indicating stress relaxation during vacuum pumping. In contrast, in the knife edge–foil interface (top flange, Figs. 5a, b, c), the maximum stresses are approximately 684.3, 482.3, and 665.6 MPa, with the stress localization zone shifting slightly toward the outer side of the flange. It is noteworthy that only in the case of the 40 μm thickness, the maximum stress value at the tip is higher in the knife edge–gasket interaction zone. For other two thicknesses, the higher stress concentration is at the tip in the knife edge–foil interface. The explanation of that phenomenon at this stage is quite hard and requires further research.

The Von Mises stress distribution curves in the center nodes of the foils are demonstrated in the Fig. 6. The 0 mm is the center of the foil (Fig. 6). The stress values are presented for the 20 mm diameter of the foil.

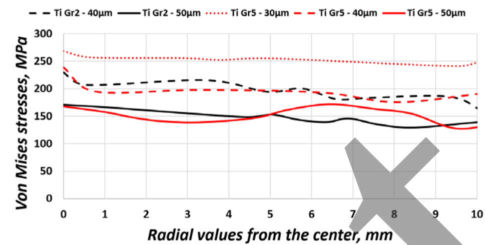

Figure 6: Von Mises stress distribution curves of the center nodes of the foils.

From Fig. 6, it is obvious that the stress state in the foil is approximately the same for the titanium Gr-2 and Gr-5 materials with δ = 40 μm and δ = 50 μm. However, as the titanium Gr-2 foil with δ = 30 μm thickness is torn, the stress state in the foil exceeded 300–320 MPa. Thus, the titanium Gr-5 foil with δ = 30 μm thickness still has a minimum 50 MPa stress gap, and it is more or less stable.

The deflection curves of the foils for the same center region are illustrated in Fig. 7. From Fig. 7, it is noteworthy that the curves for the titanium Gr-5 foils change in the same trend. The titanium Gr-2 foil with δ = 50 μm thickness is still deflected in the same trend. However, the trend has changed for the δ = 40 μm thickness of the same material. The latter phenomenon demonstrates the approach to a thickness that is dangerous in terms of strength, and is the extreme thickness.

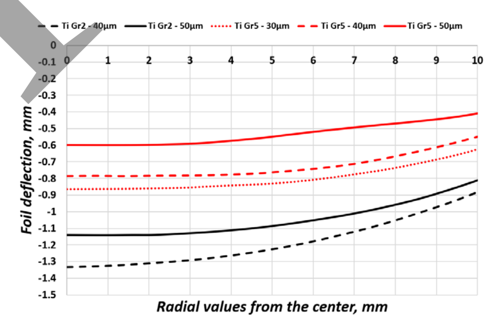

Figure 7: Deflection curves of the titanium Gr-2 and Gr-5 foils' center nodes from the atmospheric pressure side.

CONCLUSION

Investigation of the accelerator output windows with titanium Gr-2 and Gr-5 foils was carried out using the experimental correction of the friction coefficients for the more precise stress state simulations. According to the research conducted, from the mechanical perspective (without the thermal analysis), the titanium Gr-5 is allowable for use, even with the δ = 30 μm thickness. Meanwhile, the titanium Gr-2 is recommended with the δ = 50 μm thickness, because the foils with δ ≤ 40 μm thicknesses require further and deeper evaluation.

REFERENCES

[1] G. Zanyan *et al*., "Low emittance booster design for CANDLE storage ring", in *Proc. IPAC'11*, San Sebastian, Spain, Sep. 2011, paper THPC137, pp. 3209-3211.

[2] 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

[3] B. Grigoryan *et al*., "Advanced research electron accelerator laboratory based on photocathode RF gun", in *Proc. IPAC'11*, San Sebastian, Spain, Sep. 2011, paper TUPC031, pp. 1066-1068.

[4] B. Grigoryan *et al*., "Beam phase-space study for AREAL RF photogun linac", in *Proc. IPAC'11*, San Sebastian, Spain, Sep. 2011, paper TUPC032, pp. 1069-1071.

[5] B. Grigoryan *et al*., "Status of AREAL RF Photogun Test Facility", in *Proc. IPAC'14, Dresden, Germany*, Jun. 2014, pp. 620-623. doi:10.18429/JACoW-IPAC2014-MOPRI017

[6] A. Gevorgyan *et al*., "Design and performance of ultimate vacuum system for the AREAL test facility", in *Proc. IPAC'14, Dresden, Germany*, Jun. 2014, pp. 2311-2313. doi:10.18429/JACoW-IPAC2014-WEPME025

[7] H. Isunts *et al*., "The analysis and experimental research of the output windows with foil above-gasket positioning in accelerator technology", *Vacuum,* vol. 243, p. 114830, Jan. 2026. doi:10.1016/j.vacuum.2025.114830

[8] H. A. Isunts, "Output windows in accelerator technology", *Proceedings of NPUA, Mechanics, Machine Science, Machine building,* no. 1, pp. 9-28, 2024 (in Russian). doi:10.53297/18293387-2024.1-9

[9] H. Isunts *et al.*, "Overview of accelerator output windows, their parts and preferred materials", *J. Instrum.,* vol. 20, no. 9, p. T09002, Sep. 2025. doi: 10.1088/1748-0221/20/09/T09002

[10] H. Isunts *et al.*, "Deformed state's simulation of the first-grade titanium foil of the accelerator output window", in *Proc. the RA NAS and NPUA, 76,* pp. 269-278, 2023. doi:10.53297/0002306X-2023.v76.3-269

[11] H. Isunts *et al.*, "Stress-strain state analysis of the first-grade titanium foil of the accelerator output window in a static state", in *Proc. IPAC'24*, Nashville, TN, USA, May 2024, pp. 1560-1563. doi: 10.18429/JACoW-IPAC2024-TUPR57

[12] https://www.lesker.com/newweb/flanges/flanges_cf_316ss.cfm?pgid=fixedbored

[13] https://www.atlasuhv.com/part/fwfss-0275

[14] https://asm.matweb.com/search/Specific-Material.asp?bassnum=mtu021

[15] https://asm.matweb.com/search/specific-material.asp?bassnum=mtp641

[16] C. N. Elias *et al.*, "Mechanical properties, surface morphology and stability of a modified commercially pure high strength titanium alloy for dental implants", *Dental Materials*, vol. 31, no. 2, Feb. 2015, pp. 1-13. doi:10.1016/j.dental.2014.10.002