Fabrication and Characterization of W-Al Transmission Targets for Micro-CT by Magnetron Sputtering (Postprint)

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Abstract

Based on the theoretical model for end-window transmission Micro-CT targets, the basic structure of a W-Al transmission target was designed. The thicknesses of the W target layer and Al substrate were respectively determined using Geant4 simulation software in conjunction with Müller's target temperature rise calculation model. Using the structural parameters of YXLON's W-Al transmission target as a reference, W thin films with thicknesses of 2, 5, and 8 mm were prepared on Al substrates via magnetron sputtering. Microstructural morphology analysis via SEM yielded W thin film target surfaces with favorable density and uniformity. Employing YXLON's X-ray tube, experimental investigations were conducted on the X-ray output efficiency and corresponding power requirements for the three targets of varying thicknesses. The results demonstrated that the optimal W target layer thickness is 5 mm, at which point the target achieves maximum X-ray output efficiency and minimum power consumption for X-ray generation. Building upon this, comparative experiments on X-ray output efficiency and imaging performance were performed. The findings indicated that the W-Al transmission target with a 5 mm W target layer surpasses YXLON's W-Al transmission target in both X-ray output efficiency and power requirements, as well as X-ray imaging performance, thereby satisfying the application requirements for high-quality targets in Micro-CT.

Full Text

Abstract

Micro-computed tomography (Micro-CT) is an emerging three-dimensional high-resolution imaging technique whose performance depends fundamentally on the brightness of its X-ray source, typically a compact electron-impact X-ray tube. Achieving higher X-ray brightness requires minimizing the X-ray source size, yet

this brightness is ultimately limited by the maximum heat dissipation capacity of the X-ray target. As the electron beam spot size decreases, the power density on the metallic target increases, causing significant temperature elevation at the target surface and consequently reducing X-ray brightness. A practical solution to this challenge is the multi-film target architecture, comprising a thin-film target layer on a thicker substrate. The substrate material should feature low atomic number and high thermal conductivity to minimize signal X-ray absorption while effectively conducting heat away from the target. In designing such multi-film targets, two critical factors must be considered: the maximum sustainable power density without performance degradation or damage, and the X-ray generation efficiency in the target material including self-absorption effects.

This work designs a basic W-Al transmission target structure based on the theoretical model of end-window transmission targets for Micro-CT. The thicknesses of the tungsten target layer and aluminum substrate are determined through Geant4 simulation software and Müller's target temperature rise model, respectively. Following the structural parameters of YXLON's W-Al transmission target, tungsten films with thicknesses of 2, 5, and 8 m were prepared on aluminum substrates via magnetron sputtering. SEM analysis revealed well-densified and uniform tungsten films. Performance testing using YXLON's X-ray tube demonstrated that the optimal tungsten film thickness is 5 m, yielding maximum X-ray emission efficiency with minimum required power. Comparative experiments on X-ray emission efficiency and imaging quality further show that the 5 m W-Al transmission target outperforms YXLON's commercial target in both X-ray output intensity/power requirements and imaging performance, meeting the demanding requirements for high-quality Micro-CT targets.

Keywords: micro-computed tomography, magnetron sputtering, transmission target, tungsten film

Introduction

Micro-computed tomography (Micro-CT), with its ultra-high spatial resolution (1–100 m) and non-destructive imaging capabilities, is internationally recognized as the premier non-destructive testing methodology. By scanning samples with X-rays without causing damage, Micro-CT generates three-dimensional grayscale images that clearly, accurately, and intuitively reveal internal structures, density distributions, and defect characteristics. Consequently, Micro-CT has found widespread applications across life sciences, materials science, and geology, playing increasingly important roles in recent years in non-destructive testing of micro-electro-mechanical systems (MEMS), fusion target spheres, and missile intelligent fuzes.

The spatial resolution of Micro-CT primarily depends on the quality, intensity, and focal spot size of the X-ray source. Micro-CT systems employ two main types of X-ray sources: micro-focus X-ray tubes and synchrotron radiation.

Compared with synchrotron radiation, micro-focus X-ray tubes offer advantages of lower cost, compact size, and larger field of view, making them the most widely used X-ray sources in current Micro-CT systems. These tubes operate by focusing electrons into a micro-beam that bombards a target material to generate micro-focus X-rays.

Conventional micro-focus X-ray tubes utilize reflective thick targets that exhibit extremely low X-ray generation efficiency, failing to meet the requirements of ultra-high resolution Micro-CT. Novel micro-focus X-ray tubes developed internationally employ end-window transmission thin targets with thicknesses of only a few micrometers, allowing X-rays to transmit directly through the thin target with minimal energy loss. Compared with conventional reflective targets, these transmission thin targets achieve higher X-ray generation efficiency and flux density under equivalent power conditions. However, the fabrication process for end-window transmission thin targets is extremely complex, limiting widespread adoption of this new tube technology. These transmission thin targets consist of composite structures comprising a thin film of high atomic number, high melting point, and high thermal conductivity material coated onto a substrate with low atomic number and high X-ray transmittance. When a finely focused electron beam strikes the target surface, substantial heat generation elevates the target temperature, potentially causing target material ablation, cracking, melting, or delamination, which severely degrades or damages X-ray output quality.

As a critical component of Micro-CT systems, target quality and long-term stability directly impact Micro-CT lifespan and represent the primary challenge in developing high-quality micro-focus X-ray tubes. Consequently, research on fabrication processes for end-window transmission thin targets has become increasingly important. While numerous studies have investigated Micro-CT X-ray spectrum measurement, imaging techniques, and image processing, research on target materials remains scarce. International reports on end-window transmission thin targets have been limited to Monte Carlo simulation studies of target structures and theoretical investigations, without detailed fabrication process descriptions. Domestic research has reported on powder metallurgy methods for medical CT targets and high-power irradiation accelerator X-ray conversion targets, but these materials do not satisfy Micro-CT target requirements. Therefore, developing proprietary practical Micro-CT targets holds significant practical value and economic importance for enhancing the domestic production rate of X-ray imaging systems.

This work first designs a basic W-Al transmission target structure based on the theoretical model of end-window transmission Micro-CT targets. Building upon computational simulations to optimize target thickness, magnetron sputtering technology is employed to fabricate Micro-CT W-Al transmission targets, with scanning electron microscopy (SEM) used to characterize and analyze the fabrication process and performance. Finally, using YXLON-225kV X-ray tube's original W-Al transmission target (a new, unused target) as a reference, comparative studies and analyses are conducted on the X-ray emission efficiency and imaging performance of the fabricated targets. Based on comprehensive analysis, this work adopts magnetron sputtering to prepare W-Al transmission targets to meet Micro-CT application requirements.

1.1 Basic Structure

Micro-CT transmission targets typically feature an end-window architecture composed of a target layer and substrate. These targets are characterized by a thin target layer, generally on the order of micrometers, coated onto the substrate surface. The target layer serves as the bombardment surface where the electron beam generates X-rays, while the substrate functions as the X-ray exit window. When a micro-focused electron beam strikes the target surface, the high thermal load may cause target melting, requiring target materials with high melting points and good thermal conductivity—properties satisfied by high atomic number materials such as tungsten (W) and molybdenum (Mo). Tungsten is commonly employed as the target layer material for transmission targets due to its high melting point, low vapor pressure, and high atomic number, ensuring substantial X-ray generation under electron bombardment. Substrate materials typically utilize low atomic number materials with good thermal conductivity and low X-ray absorption, such as beryllium (Be), diamond, and aluminum (Al). In this work, tungsten is selected as the target layer material and aluminum as the substrate material.

The critical design parameter is selecting appropriate thicknesses for both target layer and substrate, as these dramatically affect X-ray emission efficiency. If the target layer is too thin, X-ray yield remains low; if excessively thick, although X-ray generation increases, self-absorption within the target material reduces the transmitted X-ray intensity. The substrate must balance heat conduction requirements with minimal X-ray absorption.

1.2 Basic Theory

X-rays are generated when high-energy electrons bombard the target surface and undergo inelastic collisions with atomic electrons and Coulomb fields, producing both characteristic X-rays from electron excitations and continuous X-rays (bremsstrahlung) from electron-nucleus interactions. During transmission through the target, generated X-rays undergo partial absorption, affecting the output intensity. The absorption depends primarily on target material (atomic number), electron incident energy, and the angle between the target surface and X-ray emission direction. As is well known, X-rays generated by perpendicularly incident electron beams originate not only from the outermost target surface but from a thin subsurface layer. Based on this principle, a theoretical model for W-Al end-window transmission targets has been established [Figure 1: see original paper].

According to this theoretical model, letting x represent the average depth of this thin layer from the surface, the angle between characteristic X-rays and the target surface, h_1 the tungsten target layer thickness, h_2 the aluminum substrate thickness, and S the detector window area, the X-ray intensity I exiting the detector window can be approximated as:

exp(-

where I_0 is the initial X-ray intensity, $_1$ is the linear attenuation coefficient of tungsten, and $_2$ is the linear attenuation coefficient of aluminum. This expression demonstrates that X-ray intensity depends on target attenuation coefficients, target thicknesses, average electron penetration depth, and X-ray emission angle, with non-uniform angular distribution exhibiting maximum intensity in specific directions.

1.3 Target Thickness Design

Based on the theoretical analysis above, Geant4 (Geometry and Tracking) software was employed to simulate the optimal target layer thickness for maximum X-ray yield at various acceleration voltages. Using a tungsten target layer as an example, simulations assumed 10^8 incident electrons. Considering that different voltages produce different X-ray energy spectra (both continuous and characteristic), acceleration voltages of 10, 30, 50, 70, and 90 kV were evaluated, with transmitted photon counts through the tungsten layer representing X-ray yield. The results are presented in [Figure 2: see original paper]a, showing that optimal target thickness increases with voltage.

Since characteristic X-ray spectra require electrons to penetrate a certain depth into the tungsten target layer, and the K-series characteristic X-ray threshold voltage for tungsten is 69.5 kV, the electron acceleration voltage must exceed this value. According to Waddington's formula [10] and combined with Yang et al.'s research [30], at 70 kV acceleration voltage (slightly above tungsten's K-series threshold), electrons can penetrate tungsten layers with average thickness greater than 5 m. Therefore, this work simulated the relationship between X-ray yield and tungsten target thickness at 70 kV using Geant4, with results shown in [Figure 2: see original paper]b. Based on these calculations, the tungsten target layer thickness was optimized to 5 m.

The aluminum substrate thickness was designed using Müller's target temperature rise model [10]. For a target with radius R and electron beam spot radius r (where r R), the maximum input power W is given by:

m = 15.8) = 0 = 2 ln 2 exp(-)tanh(

where T is the melting point of the tungsten target layer, k is the thermal conductivity coefficient, h is the target thickness, and T_0 is the temperature at the target edge. For thin tungsten targets where X-rays can transmit through, W can be calculated as:

1 + 2 ln

Equation (3) indicates that the maximum sustainable input power depends on target material, thickness, and structure, increasing as the electron beam focal spot size decreases. Approximately 1% of the high-energy electron beam's energy converts to X-rays during tungsten target bombardment, with most energy transforming into heat that rapidly elevates target temperature. Without optimization, this can cause target volatilization and melting. For pure tungsten targets, the maximum sustainable heat load is approximately 200 W/mm^2. In this W-Al target system, since aluminum's melting point is relatively low (~660°C), the aluminum substrate's melting point serves as a critical design constraint. Based on Müller's temperature rise model and comprehensive considerations of minimal X-ray absorption, the aluminum substrate thickness was optimized to 250 m for 70 kV acceleration voltage.

2 Preparation Process and Microstructure

With a total thickness of approximately 255 m, the W-Al target qualifies as a thin target, particularly the tungsten target layer at only a few micrometers. Additionally, tungsten and aluminum exhibit significant differences in physical properties (mechanical strength, heat capacity, thermal stress, thermal expansion coefficient, etc.). Traditional powder metallurgy methods prove difficult for fabricating such W-Al thin targets, whereas physical methods such as vacuum evaporation, sputtering, and ion plating may be more suitable. After comprehensive evaluation of thin film preparation methods, this work employed sputtering to deposit tungsten films onto machined aluminum substrates as the target layer material.

Tungsten films were prepared using DC magnetron sputtering equipment under the following conditions: base vacuum of 4$×10^{-4}$ Pa, working pressure of 1.0 Pa. The specific fabrication process involved: (1) pre-sputtering the tungsten target to remove surface contaminants and ensure film purity; (2) setting sputtering power to 100 W with staged heating (initial temperature 400°C, followed by 200°C) for total sputtering duration of 4–12 hours; (3) maintaining argon flow after sputtering for oxidation protection; and (4) furnace cooling to room temperature to obtain the W-Al transmission target.

In this work, three W-Al targets with different tungsten layer thicknesses were fabricated while maintaining a constant aluminum substrate thickness of 250 m. Tungsten film thickness was measured using a step profiler, yielding thicknesses of approximately 2, 5, and 8 m for the three films.

SEM images of the ~5 m tungsten film are shown in [Figure 3: see original paper]a and b, revealing excellent density and uniformity with grain sizes below 1 m and no obvious intergranular gaps. The tungsten film exhibited good adhesion to the aluminum substrate without delamination, confirming the feasibility of magnetron sputtering for Micro-CT thin transmission target fabrication. In contrast, [Figure 3: see original paper]c and d show SEM images of the tungsten target layer from YXLON's original target, which exhibits poor density and noticeable delamination between the tungsten film and aluminum substrate.

3 Target Quality Measurement and Evaluation

High-quality targets should generate maximum X-ray intensity while minimizing self-absorption, producing strong transmitted X-ray beams ideal for nondestructive testing imaging. Therefore, this work evaluates target quality primarily by measuring transmitted X-ray intensity using a radiation detector positioned along the target window axis at a fixed distance.

The measurement methodology employed a YXLON X-ray tube featuring three operational modes: nano-focus, micro-focus, and high-power. The tube's original W-Al transmission target (unused) served as the reference, with identical structure to our design: theoretical thicknesses of 5 m tungsten layer and 250 m aluminum substrate, actual total thickness of 248 m. Initially, the original YXLON W-Al target was used to measure X-ray intensity at approximately 50 cm from the target window. Subsequently, the three fabricated W-Al targets with varying thicknesses were installed and measured under identical conditions. Considering the operating parameters of our independently developed micro-focus X-ray source (acceleration voltage 0–90 kV, tube current 0–1000 A), the YXLON tube current was fixed at 153 mA while the electron acceleration voltage was varied until the radiation detector reached full scale (110 mR/h). The measured X-ray intensities and power consumptions for the four different targets are presented in [Figure 4: see original paper].

As shown in [Figure 4: see original paper]a, c, and e, among the three fabricated targets with 2, 5, and 8 m tungsten layer thicknesses, the 5 m W-Al transmission target consistently produced higher X-ray intensities across nano-focus, micro-focus, and high-power modes. Comparing the other two thicknesses, the 8 m target exhibited higher X-ray emission efficiency than the 2 m target, which showed the lowest efficiency. These experimental results align with Geant4 simulation predictions: the 2 m tungsten layer is too thin for adequate X-ray yield, while the 8 m layer, though generating more X-rays, suffers from excessive self-absorption, resulting in lower transmitted intensity.

Notably, high-quality targets must not only produce intense X-rays but also minimize the power required for X-ray generation. As illustrated in [Figure 4: see original paper]b, d, and f, the 5 m W-Al transmission target consumes relatively lower power compared to the other two targets, which show similar and higher power consumption. Consequently, the optimal tungsten layer thickness is determined to be 5 m, providing both high conversion efficiency from electron beam to X-rays and minimal X-ray absorption.

Furthermore, [Figure 4: see original paper] demonstrates that under identical conditions across all operational modes, the 5 m target exhibits higher X-ray emission efficiency and lower power consumption than YXLON's target, indicating superior performance. To further compare X-ray characteristics, emission efficiency experiments were conducted at a fixed acceleration voltage of 40 kV with varying tube currents, with results shown in [Figure 5: see original paper]. The 5 m W-Al target achieves more than double the X-ray emission efficiency of YXLON's target across nano-focus, micro-focus, and high-power modes while consuming less power. This superiority likely stems from YXLON's target exhibiting poor tungsten film density, weak adhesion to the aluminum substrate causing partial delamination, and insufficient tungsten thickness—factors that severely degrade X-ray yield and output intensity. Further investigation is warranted to confirm these mechanisms.

CCD (charge-coupled device) array detector imaging experiments revealed that target quality affects not only X-ray emission efficiency but also imaging clarity. The CCD detector was positioned on the target window axis at 20 cm from the window (30 cm in front of the radiation detector). Under YXLON's nano-focus mode, imaging experiments were performed using both the 5 m W-Al target and YXLON's original target at two conditions: 50 kV acceleration voltage with 53 mA emission current, and 60 kV with 153 mA emission current. The samples were 50 mm diameter tungsten wire and silicon chips, with 10 s exposure time. The resulting CCD images are shown in [Figure 6: see original paper].

The images demonstrate that under identical conditions, the 5 m W-Al target produces clearer X-ray images, confirming higher X-ray intensity. This occurs because stronger X-ray intensity detected by the radiation detector behind the CCD detector yields better image signal-to-noise ratios, sharper boundaries, and higher edge definition. At 50 kV and 53 mA, the 5 m target produced 0.354 mR/h versus 0.297 mR/h for YXLON's target. At 60 kV and 153 mA, the values were 2.166 mR/h and 1.464 mR/h, respectively. These imaging results further confirm that the 5 m W-Al target outperforms YXLON's target and meets the stringent requirements for high-quality Micro-CT targets.

Conclusion

Based on the theoretical model of end-window transmission X-ray targets, a W-Al transmission target structure was designed. Tungsten films with thicknesses of 2, 5, and 8 m were successfully fabricated on aluminum substrates via magnetron sputtering, yielding dense and uniform tungsten films. Experimental results demonstrate that the 5 m tungsten layer thickness provides maximum X-ray emission efficiency with minimum power consumption, confirming the Geant4 simulation predictions. The 5 m W-Al transmission target exhibits superior performance compared to YXLON's target in terms of X-ray emission efficiency, power requirements, and imaging quality. This superiority arises from YXLON's target suffering from poor tungsten film adhesion, partial delamination, and insufficient thickness, which severely limit X-ray yield and output intensity. The 5 m W-Al transmission target successfully satisfies the demanding requirements for high-quality Micro-CT targets.

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Note: Figure translations are in progress. See original paper for figures.