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AN APPROACH FOR THICKNESS ESTIMATION OF ANODIZED TITANIUM OXIDE USING DIGITAL CAMERA

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ABSTRACT

This paper presents a novel approach for estimating the thickness of anodized titanium oxide layers using digital imaging and thin film interference principles. Traditional methods for thin film thickness measurement, such as ellipsometry and X-ray reflectivity, offer high precision but can be costly and complex. In contrast, the proposed technique leverages the correlation between oxide layer thickness and the interference colors observed in anodized titanium surfaces. Using a digital camera, images of the anodized samples are captured under controlled lighting conditions, followed by color calibration and analysis. Specialized software then interprets the interference patterns to estimate oxide thickness. This method provides a non-destructive, cost-effective, and accessible alternative for thickness measurement, with potential applications in quality control and material characterization across industries such as aerospace and biomedical devices.

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1. INTRODUCTION

Determining thin film thickness is critical in material science and engineering. Techniques range from basic mechanical methods to advanced optical and electrical approaches. Among these, ellipsometry and X-ray reflectivity are key, measuring film thickness, density, and surface roughness. Other methods, like quartz crystal microbalance and atomic force microscopy, also provide valuable insights into film properties [1–4]. These techniques support industries such as semiconductors and nanotechnology, where accurate thin film characterization is vital.

Challenges arise in ensuring the robustness, efficiency, and cost-effectiveness of thickness measurements. Methods lacking reliability and speed can impact productivity, especially in industrial settings [5,6]. Additionally, variations in film thickness or complex structures, combined with the film's optical properties, complicate measurements and demand advanced calibration techniques [7–9]. Practical considerations, including environmental conditions and production timelines, further complicate the process, requiring streamlined, adaptable solutions.

Ongoing innovations, such as simulation tools for titanium oxide layers [10] and artificial neural networks for thickness measurement [11], are addressing these challenges. Colorimetric analysis and imaging techniques also offer new insights into film properties [12,13]. This research introduces a novel, cost-effective method for estimating anodized titanium oxide thickness based on thin film interference and imaging technology. This approach has significant potential in fields like aerospace and biomedical devices, where precise, non-destructive thickness measurements are critical. By refining these techniques, we aim to advance material characterization and thin film analysis.

2. EXPOSITION

The theoretical basis for a script that calculates color based on thin film interference lies in the fundamental principles of optical interference and the unique behavior of light as it interacts with thin films. Thin film interference occurs when light waves reflect off the top and bottom surfaces of a thin film, leading to constructive or destructive interference patterns depending on the thickness of the film and the wavelength of the light. This phenomenon plays a crucial role in determining the optical properties of thin films and is particularly relevant in materials science and surface engineering, including the characterization of oxide layers on anodized titanium.

In the context of anodized titanium, the oxide layer formed on the surface during the anodization process exhibits thin film interference effects due to its nanoscale thickness. As light strikes the oxide layer, a portion of the incident light is reflected from the top surface of the film, while another portion penetrates the film and is reflected from the interface between the oxide layer and the underlying titanium substrate. These reflected waves interfere with each other, leading to variations in the intensity of reflected light at different wavelengths. A graphical schematic of the principle model for thin film

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interference of anodized titanium is depicted in Fig. 1.

The diagram depicts light incident from air onto the surface of the thin film, with components such as the Fresnel reflection coefficient (r_{12}) representing the portion of light that is reflected at the air-film interface, and the Fresnel transmission coefficient (t_{12}) representing the portion of light that is transmitted into the film. Subsequently, within the film layer, further reflections and transmissions occur, with coefficients such as r_{23} and t_{21} accounting for the reflection and transmission of light between the film and the substrate, and r_{21} representing the reflection of light back into air from the film. The film thickness (*d*) plays a crucial role in determining the phase difference between the reflected and transmitted waves, ultimately influencing the interference pattern observed in the reflected light.

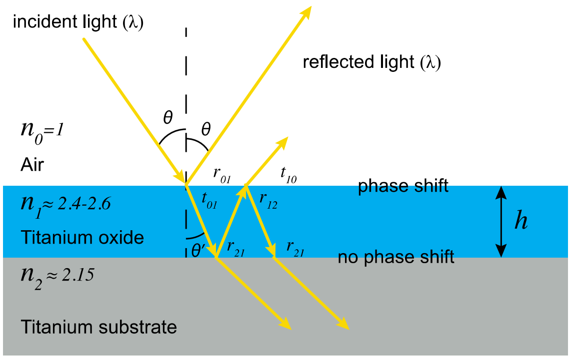

Fig. 1. Principle model of anodized titanium thin film interference with multiple reflections and transmissions (Fresnel reflection coefficients (r_{01}, r_{12}), Fresnel transmission coefficient (t_{01}, t_{10}), (d) oxide thickness

The relationship between thin film interference and the color spectrum observed in anodized titanium arises from the selective reflection and absorption of light by the oxide layer. As the thickness of the oxide layer changes, the interference pattern shifts, resulting in changes in the wavelengths of light that are reinforced or canceled out. This, in turn, influences the perceived color of the oxide layer, which can range from vibrant hues to iridescent effects depending on the thickness and composition of the oxide film.

By understanding the principles of thin film interference and its relationship to the color spectrum, computational scripts can be developed to predict the color of anodized titanium oxide layers based on their thickness. [14, 15] These scripts typically employ mathematical models such as the Fresnel equations or the transfer matrix method to calculate the optical properties of the oxide layer and simulate the interference effects. By simulating the interaction of light with the oxide layer, these scripts provide valuable insights into the optical behavior of anodized titanium and enable precise control over its coloration for a variety of applications, including architectural coatings, decorative finishes, and optoelectronic devices.

3. METHODOLOGY

The methodology encompasses a series of meticulously designed steps aimed at ensuring accuracy, consistency, and reliability in the measurement process. The necessary equipment for the process includes a digital camera capable of RAW image capture and adjustable exposure settings, along with a white box setup featuring diffusion panels for uniform light distribution and a white light source with D65 spectrum. Additionally, a white balance card and color checker palette are essential for accurate color calibration which is necessary for the initial setup. Photo editing software is required for exposure correction and color calibration, while specialized software is needed for thickness estimation and analysis. With these tools and equipment in place, the process of capturing and analyzing images for thickness estimation of anodized titanium oxide layers can be conducted with precision and reliability.

To commence the thickness estimation procedure, anodized titanium oxide samples are meticulously prepared for imaging, ensuring uniformity and consistency across the sample set. Prior to imaging, it is imperative that the anodized titanium samples undergo a thorough cleaning process to remove any oil, dirt, or contaminants that may be present on the surface. A rigorous cleaning process is required as this ensures the integrity of the samples and prevents potential interference with the accuracy of the measurement. Additionally, samples should be thoroughly dried to eliminate any residual moisture, as a contaminated or wet surface can alter the true color of the sample, thereby compromising the accuracy of the color calibration process. Maintaining pristine sample conditions is essential to obtaining reliable and consistent results in the thickness estimation of anodized titanium oxide layers.

Subsequently, images of the samples are acquired using a digital camera within a controlled environment. The camera is positioned at an optimal angle relative to the samples to ensure comprehensive coverage and minimize distortion. Employing a white box setup illuminated by white light with a D65 spectrum, specialized diffusers are strategically placed to ensure uniform light distribution and mitigate glossy reflections from the surface of the samples. This arrangement of lighting elements and camera positioning is essential for capturing the true color and surface characteristics of the anodized samples with maximum fidelity. Images should be captured in RAW camera format to preserve the full range of image data, enabling further precise analysis and interpretation during subsequent processing stages.

In addition to capturing images of the anodized samples within the photographic environment, it is essential to include additional images featuring a white balance card and a color checker palette. These supplementary images serve a crucial role in the calibration process, allowing for the accurate adjustment of color balance and fidelity. The white balance card provides a reference point for neutralizing any color casts or deviations in the captured images, ensuring true color representation. Similarly, the color checker palette offers a standardized set of color patches, enabling precise calibration and alignment of color values across different imaging sessions and devices. By incorporating these calibration elements into the imaging process, the accuracy and reliability of color reproduction are significantly enhanced, facilitating more accurate analysis and interpretation of the anodized samples' surface characteristics.

Upon image acquisition, a comprehensive image processing pipeline is initiated using photo editing software. This includes exposure correction utilizing an 18% grey reference to ensure standardized brightness levels across all images. Furthermore, color calibration is performed employing a color checker to address inherent color variations between different camera sensors, thereby enhancing color accuracy and fidelity.

Following image processing, calibrated images are converted into standard formats such as .png, .jpeg or .tiff for compatibility with subsequent analysis software. The thickness estimation process is facilitated through a specialized software designed specifically for this purpose. Utilizing precalculated scales, the software establishes a reference for thickness measurement, enabling precise and accurate estimation of the anodized layer thickness. While the software primarily relies on precalculated scales for thickness determination, it also offers the capability to generate measurement scales for different thin films based on physical phenomena. This additional feature enhances the versatility and applicability of the software, allowing for the accurate estimation of thickness across a diverse range of materials and surface compositions. By incorporating both precalculated scales and customizable measurement options, the software provides researchers and analysts with a comprehensive toolset for conducting thorough and reliable thickness analysis of thin films in general. Finally, specific areas of interest within the anodized samples are selected for analysis within the software interface. Representative sampling ensures the integrity and reliability of the thickness determination process. The methodology is depicted in Fig. 2, providing a visual representation of the step-by-step process outlined in the study.

The image processing techniques used for thickness estimation of anodized titanium oxide layers begin with the initial calibration of the images, which involves utilizing a color checker and white balance card to ensure accurate color representation.Once the images are calibrated, they are processed using software such as OpenCV.js, a JavaScript implementation of the popular OpenCV library for computer vision tasks. OpenCV.js provides a range of functions and algorithms for image analysis, including color space conversions, histogram equalization, and region-based segmentation. In the context of thickness estimation, OpenCV.js can be used to analyze the colors within selected regions of interest on the anodized titanium oxide samples. [16]. Edge detection algorithms are then applied to the processed images to identify the boundaries of the oxide layer. Edge detection techniques such as the Canny edge detector or the Sobel operator are commonly used to highlight abrupt changes in intensity or color, which often correspond to the edges of objects in the image. By detecting the edges of the oxide layer, the region of interest for thickness estimation can be precisely delineated.

Once the edges are identified, the software matches the colors within the region of interest to precalculated values corresponding to different thicknesses of the oxide layer. These precalculated values are established based on the optical properties of the anodized titanium oxide and the interference patterns observed at various thicknesses. By comparing the colors of the observed oxide layer to the precalculated values, the software can estimate the thickness of the oxide layer with a high degree of accuracy.

In the analysis of limitations or challenges and discussion of potential sources of error in the experimental methodology, several key considerations arise that warrant attention. Firstly, the accuracy of thickness estimation in anodized titanium oxide layers may be influenced by factors such as surface irregularities, variations in sample preparation, and the presence of contaminants. Surface irregularities, including scratches or uneven coatings, can affect the uniformity of the oxide layer and introduce errors in thickness measurement. Variations in sample preparation techniques, such as differences in cleaning procedures or drying methods, may also impact the reliability of the results.

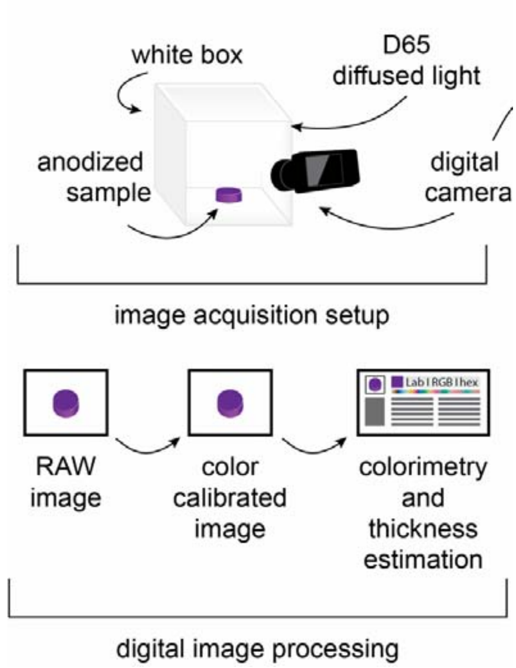

Fig. 2. Schematic representation of the proposed methodology for estimating the thickness of anodized titanium oxide layer

Moreover, the presence of contaminants on the sample surface can interfere with the optical properties of the oxide layer and alter the observed colors, leading to inaccuracies in thickness estimation. Additionally, the sensitivity of digital imaging equipment to changes in lighting conditions and camera settings may introduce variability in the captured images, further complicating the analysis process.

To address these limitations and minimize potential sources of error, several strategies can be employed. Rigorous quality control measures should be implemented during sample preparation to ensure consistency and reproducibility across experiments. This includes thorough cleaning of the sample surface to remove contaminants and meticulous drying to eliminate residual moisture. Standardized imaging protocols, including consistent lighting conditions and camera settings, should be established to enhance the reliability of the captured images.

Furthermore, advanced image processing techniques, such as adaptive thresholding and noise reduction algorithms, can be utilized to enhance the accuracy of edge detection and minimize errors introduced by surface irregularities or image artifacts. Collaborative efforts between material scientists, imaging specialists, and software developers are essential for developing robust analytical tools and methodologies that address the challenges inherent in thickness estimation of anodized titanium oxide layers.

4. CONCLUSION

Accurate measurement of thin film thickness, particularly in anodized titanium oxide layers, plays a crucial role in material characterization across various industries. While established methods such as ellipsometry and X-ray reflectivity offer precision, this paper proposes a novel approach utilizing thin film interference principles and color analysis to estimate thickness via digital imaging. By leveraging advancements in imaging technology, this method provides a non-destructive, cost-effective solution, addressing the complexities posed by film properties. The approach, though promising, requires rigorous sample preparation, standardized imaging protocols, and refined image processing to ensure reliable results, paving the way for future advancements in thin film analysis.

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