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Characterization of Aluminium Reflective Thin Films Deposited by a Modified Thermal Evaporator Designed for Coating Telescope Optics

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ABSTRACT

The primary mirror is the main optical component of reflective telescopes. Typically, it is made by coating a thin reflective film on a concaved glass surface. The thin reflective film is deposited using Physical Vapour Deposition (PVD) methods. However, atypical PVD system should undergo major modifications to match the coating standards used in astronomical optics. Therefore, this research project focused on the aim of assessing the quality of the reflective thin films deposited by a locally assembled PVD system. The uniformity, local thickness variation and reflectivity variation of the coating layers were analyzed using theoretical and experimental methods. Micro-scale water vapour and residuals of the cleaning process were identified as aspects affecting the persistence of the coating and key modifications were made to minimize these effects. It was found that the resultant radial thickness variation is 16.47%for a 254 mm f/2 primary mirror with a hyperbolic surface profile. The uniformity of a 150 nm thick aluminium reflective thin film layer on a 254 mm f/2 primary may radially vary up to 24.7 nm. Therefore, it is confirmed that the PVD process meets the standards of telescope primary optical coating.

Keywords: *Physical Vapor Deposition (PVD), Telescope primary mirrors, Thin reflective layer, Aluminium*

1. INTRODUCTION

The primary mirror consists of a parabolic, spherical or hyperbolic [1] glass surface coated with 100-300nm thin [2] reflective layer to obtain 90-99% reflectivity [3]. The thin reflective layer encompasses a uniformity of less than 10% from edge to centre. A non-uniform thin film can deform the reflected wave front resulting in an aberration and defocusing the optical assembly [4]. Random local thickness variations represent another defective phenomenon and may cause local wave front deviations, wave front roughness and obstruction to wave propagation [5,6,7]. Formation of areas of varying reflectivity [8] is considered the main defect in reflective coatings. The topology of porous metal films [7] and impurities are identified as principal cause of the varying reflectivity [4].Eventually, the impurities can lead to deterioration of the coating [7,17] in a relatively short time. Generally, thin reflective films are made under a vacuum of 10^{-6}Torr[18]by utilizing thermal evaporation, electron beam evaporation, sputtering or plasma arc deposition methods to create atomic level thin layers on a substrate. The method is commonly named Physical Vapor Deposition(PVD)and serves as the main method for coating reflective metals such as Al, Gold(Au), Silver(Ag), Nickle (Ni)[4] or multi-layered metal combinations[19] on telescope primaries. In this research, a PVD machine (modified thermal evaporator) was fabricated locally for coating Aluminium (Al) with 99.99% purity which is specifically designed for coating telescope mirrors in the diameter range 100-260mm.In this system, Al is deposited on a 254mm diameter glass substrate (a telescope primary) using thermal evaporation. A 254 mm diameter telescope primary with a focal length of 508 mm (f/2) was fabricated in a previous research(establishment of a wide-field telescope cluster) and the primary is comprised of a hyperbolic profile. Typical laboratory used PVD systems do not have adequate methods to hold heavy substrates such as telescope mirrors. In addition, substrate-source distance does not ensure a uniform coating for a large surface area(surface area of a 254mm diameter disk).Hence this PVD system was designed to optimize the coating requirements of the particular primary.PVD systems used for large surface coating such as telescope primaries are either specifically built[2]or modified laboratory machines[14] where testing is a paramount requirement to assess the deposited thin films[16,17,19]. In this paper we discuss the quality of the Al thin films coated using the modified thermal evaporator by means of numerical analysis of uniformity, experimental assessment of the varying reflectivity and effects of deterioration of the coat due to impurities.

2. METHODOLOGY

2.1 Fabrication of The Modified Thermal Evaporator

The modified thermal evaporator is composed mainly of a vacuum chamber unit, a multi-stage pumping system, an electrical unit and sensors. Typical PVD systems which function in a high vacuum range (10^{-3}-10^{-6} Torr) [18] are very expensive and complicate instruments. Therefore, a Computer-Aided Design (CAD) was utilized initially and the parts needed for the fabrication of the machine were either purchased or fabricated locally. The chamber unit encompasses a base plate, an electrical feed through, a chamber, a substrate holder and an evaporation source. A Borosilicate glass bell-jar with 350 mm diameter and 500mm height was purchased for the vacuum chamber. The base plate and adjustable substrate holder were fabricated using 316Lgradestainless steel. A two-element high current vacuum feed through was purchased and the source holder was fabricated from 10mm diameter copper rods. The multi-stage pumping system comprises of an oil diffusion pump [18] and a two-stage rotary pump[13,18]. The pumps and vacuum valves were acquired from the Department of Physics, University of Ruhuna and refurbished. A high current switch mode power supply with maximum 300A direct current and 12-30V voltage was selected as the power supply for the source, and Tungsten boats were purchased for Joule heating of Al pellets. A multi-Ionization gauge [9,13]was used for measuring high vacuum(10^{-1}-10^{-8}Torr)while a Pirani gauge [13] and a dial gauge [14]were used for measuring low vacuum (1000-10^{-4}Torr). Some vacuum fittings and valves were fabricated and the parts were duly assembled with vacuum seals and lubricants to complete the system. Materials such as stainless steel, Oxygen-Free Copper (OFC), Fluorocarbon, Silicon rubber and Teflon[13] were used in the locally fabricated instrument to reduce the contamination and out gassing [13,14]. Modifications were done for the source-substrate distance, substrate holding mechanism, orientation of the source-substrate and the power source of the evaporation system.

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2.2 Analysis Methods of the Coating

In thermal evaporation, if a point source is placed concentric with the substrate the vapour will spread with spherical symmetry[10]when the pressure is sufficient to create a mean free

$$\frac{d_{edge}}{d_{center}} = \frac{r_0^2}{r_0^2 + r_W^2} \cos\phi \cos\psi \quad \ldots\ldots\ldots\ldots (01)$$

Where,

ϕ −Angle from the center

ψ −Angle in the edge

r_0 − *direct distance substrate to source*

r_w − *radius of the substrate*

$\frac{d_{edge}}{d_{center}}$ − *thickness ratio of edge and center*

path[12]with minimum collisions[13].Therefore, if a flat substrate is placed the film thickness gradually decreases from the centre to edge. In the case of a spherically-shaped substrate, the thin film deposited is 100% uniform[11].In this case, the substrate denotes a hyperbolic surface, therefore, the film thickness variation across the substrate was studied using the equations for directional dependence of a Knudsen Cell [15,16] and applying a cosine law[15,16]:Equation -01.

Assessment of the varying reflectivity and effects of deterioration of the coat due to impurities were studied using high-resolution photographic evidence of the deposited thin films. Initially, the telescope primaries were coated using the standard pressure conditions and the telescopes were used in the field. Some of the initial coatings were oxidized and degraded relatively within a short period of time. Therefore, attempts were subsequently made to decrease the pressure to a 10^{-6}Torr.However, the results were the same. Hence, further attention was given to the cleaning procedure. The surface conditions of the failed coatings were visually analysed and the level of local oxidization (increase of oxidization activity in particular regions) was determined. The images were obtained using a Digital Single Lens Reflex (DSLR) camera with a 105-200mm full-frame lens placed above the telescope primary whilst the surface was illuminated from the side.

3. RESULTS AND DISCUSSION

Figure1displays the evaluation results of two telescope primaries three months after the coating using the modified thermal evaporator. The images were obtained by illuminating the surface of the thin films sideways in such a way that surface topologies were clearly visible. Image1(a) indicated an image taken of the contamination sites as they appeared in the initially coated telescope primary. Image 1(b) and 2(b) were processed to examine the surface with further clarity. The green arrows in image 1(b) indicate the contamination caused by residual cleaning agents and the encircled area encompasses pin-holes formed in the film due to water vapour adhered to the glass. Images 2(a) and 2(b) indicate the less contaminated surface of the second telescope primary and circular shapes in the surface are oxidized areas stimulated by dust particles settled in the storage phase. Around 14 attempts were made to obtain a persistent coating and the first film was coated in the pressure of $5.6\text{x}10^{-5}$ Torr whilst the second one was coated in the pressure of $1.7\text{x}10^{-5}$ Torr. There is no significant pressure difference between the first and second cases. However, the resultant small differences are suspected to be caused by the cleaning method of the substrates and ambient conditions.

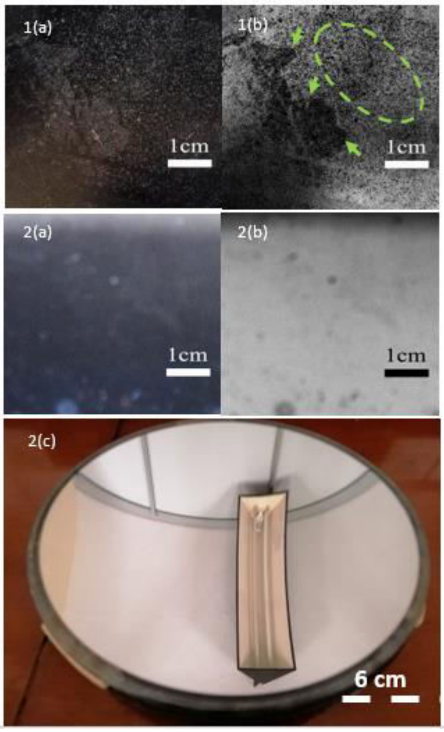

Figure 1: 1(a) and 1(b) indicate contamination of the thin films due to residuals of the cleaning agents(arrows)and pin-holes formed due to water vapour adhered in the glass(inside the circle).2(a) and 2(b) illustrate a coat with minimum contaminants which was coated in a greater vacuum whilst image 2(c) contains the full view of the coated, f/2 254 mm diameter telescope primary.

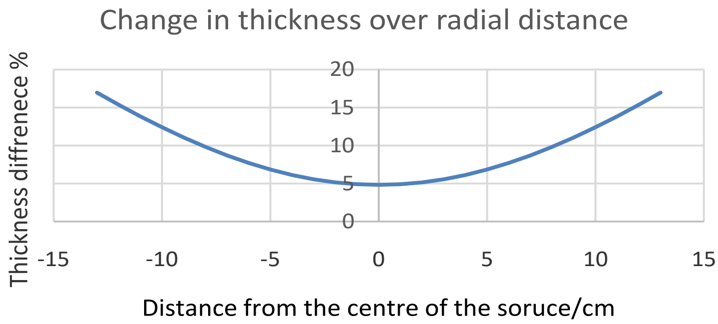

Figure 2: The uniformity change with the radial distance from the centre of the source

Generally, a SiO protective coating is applied on telescope primaries and it will protect the Al coating from rapid degradation. However, this protective coating may introduce new errors to the coating [4] and require further modification in the modified thermal evaporator. Therefore, the effect of the protective coating is not discussed here.

Figure 2 shows uniformity change with the radial distance from the centre of the source to the edge. As indicated, the thickness difference is around 16% at 12 cm radial distance (diameter of the telescope primary is 25.4 cm) from the centre. Radial angle (ψ) change of the surface was assumed a constant. The maximum substrate to source distance permitted in the vacuum chamber is 340mm and the resultant figure-scale wavefront deformation due to non-uniform radial thickness for a flat substrate is 22.98% (maximum at the edge). However, the maximum radial thickness variation is

16.47% for the f/2 254 mm with a hyperbolic surface profile since the substrate used here is concave. Therefore, the expected 150 nm thickness of the reflective thin film on a f/2 254 mm primary may vary radially from 24.7 nm centre to edge. The graph in Figure 2 indicates the thickness difference as a percentage with the radial distance from the centre of the telescope primary. The calculations were done assuming the source as a point. However, the source used here is a boat shape done with a considerable surface area. Therefore, the source is expected to decrease the maximum thickness variation further. We wish to analyse the uniformity change using further experimental methods in future and to compare results with theoretical values.

4. CONCLUSION

In this study, a modified thermal evaporator was fabricated for coating telescope primaries. A reflective Al layer of a thickness range 100-300nm was deposited on the 254mm diameter f/2 telescope primaries in a vacuum of 10^{-5}Torr. The uniformity and persistence of the deposited coatings were analysed using both theoretical and experimental approaches. A theoretical model named Knudsen Cell was used to analyse the uniformity, and direct photographic data was deployed to identify the varying reflectivity and contaminations. According to our initial test a persistent coating was achieved under the pressure range of $1.7\text{x}10^{-5}$Torrto $5.6\text{x}10^{-5}$Torr. A 16.47% radial thickness variation was identified from the theoretical model and the maximum thickness difference was found to be 24nm for a 150nm thick Al layer. The various aspects affecting the persistence of the coatings were identified and modifications were carried out to meet the required quality. It can be concluded that the locally made PVD system is fully adequate for coating telescope primaries to the required standards.

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