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# Investigation and treatment of the aluminizing process for mirrors of astronomical telescopes and optical instruments of space vehicles

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## HIGHLIGHTS

- We model and simulate evaporation rate of Al for thin film deposition by SIMULINK.
- A 45 K/s temperature gradient is necessary to reach the vaporization phase.
- Experimental PI current controller is used to get such temperature gradient.
- Current has to be stepping by 2 A/s until reaching 50 A, then be constant for 20 s.
- The technique is useful in coating telescope and space vehicle mirrors.

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## ABSTRACT

A model is developed to estimate the evaporation rate for aluminum of specific mass used, exploited for thin film deposition process. This model is simulated using MATLAB-SIMULINK program that represented the resistive vaporization source. A feedback temperature sensor is used with Proportional Integral (PI) controller to force the temperature gradient to acquire a trajectory suitable for the evaporation process. The simulation results showed that the temperature gradient of 45 K/s is necessary to reach the vaporization of aluminum in 20 s. Experimental results showed that current gradient of 2 A/s applied to the filament is sufficient to get temperature gradient suitable for Al melting. During the evaporation interval the current has to be constant at 50 A for 20 s in order to evaporate all Al parts. The study demonstrates that this technique will help in automating the vaporization process to avoid irregular coating reflection films on the surface of telescope and space vehicle mirrors.



## 1. Introduction

Optical thin-film coatings have numerous applications in different branches of science and technology and there are many consumer products that use them [1]. Astronomy was in forefront of these branches in which thin-film coating of telescope mirrors started early at the beginning of the last century [2–5]. In astronomical observations, telescope mirrors are considered as the most important components of the optical system [6]. It is considered as the part that receives the weak signals of light coming from celestial objects. Therefore, the quality of the telescope's output data depends mostly on the quality of its mirrors and the coating of their surfaces. As so, the mirrors must be recoated with a reflecting thin film from time to time depending on the telescope surroundings and deterioration of the reflecting coating on their surfaces.

Among various thin film processing techniques, Physical Vapor Deposition (PVD) technique in which thin film deposition in vacuum is widely used in technology and material science. This process involves purely physical processes such as high temperature vacuum evaporation by heating of materials and depositing them on various surfaces [7]. Specifically, in the process of telescope mirrors recoating, the coating material, which is usually aluminum parts, is placed over a few tungsten heating filaments. When the temperature of the filaments exceeds 600 °C, the aluminum melts

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and attaches to the heating coils. When the temperature reaches about 1200 °C, the aluminum evaporates. The evaporating aluminum molecules travel without intermolecular collision from the hot metal source to the cold surface of the mirror and deposit on its surface which becomes a thin layer of deposition [6]. It is a well-known fact that the properties of this thin film are greatly influenced by the deposition conditions and the residual gases present in the deposition system which may affect the optical performance [8]. The vaporization system is highly sensitive to irregularities in temperature distribution. Since the major axis of the vaporization source corresponds to the cross-web direction of the substrate, uniformity along the length of the source is crucial. Gradients of a minor scale produce significant variances in product consistency. Coating thickness and uniformity are directly coupled with source temperature.

The metal coatings for optical applications necessitates excellent performance requirements, some of which are: low optical absorption values, film refractive indices close to bulk values, intensive homogeneous microstructures with smooth surfaces to reduce light scattering and to ensure stable film characteristics under varying conditions of temperature and humidity, high adherence, hardness and abrasion resistance and high environmental stability [9]. Therefore, to ameliorate the performance of the production vaporization source, and enhance the quality of the mirror surfaces, this examination aims to model, predict, and improve the vaporization of aluminum in the subject vaporization source.

The low-voltage, high-current used to heat the tungsten filament is typically supplied by the secondary of a step-down transformer. In the simplest arrangement this is done by adjusting the voltage across the primary of the filament transformer with a Variac [10].

In this paper a physical model is developed for calculating the evaporation rate for aluminum for specific mass used. Our model will consider the transient thermal aluminum of a general tungsten vaporization source utilized in thin film deposition. The model comprises a composite thermal system having time and temperature dependent inputs and properties. The theoretical analysis is followed by experimental work in which resistively heated filaments are used to evaporate aluminum samples in a variety of deposition processes. Finally, in this work we tried to automate the vaporization process in order to overcome the problems arising in the manual control part of the vaporization process which lead to getting irregular coating reflection films on the surface of the telescope mirrors.

## 2. Mathematical model for evaporation source and evaporated aluminum

In what follows we will discuss the mathematical model of evaporated aluminum films condensed on the surface of glass mirrors. The input variable in this model is the electrical voltage of the tungsten filament circuit and the output variable represents the temperature of the tungsten filament. The source of evaporation in this model is the tungsten filament which consists of a set of first order differential equations that represents the storage of thermal energy of the filament alone. These equations are as follows [11]:

$$\frac{dT}{dt} = \frac{1}{C_p\, m}(P_{in} - P_{out}) \tag{1}$$

where $T$ is the absolute temperature, $C_p$ is the temperature-dependent specific heat capacity, $m$ is mass, $P_{in}$ is the input power and $P_{out}$ is the heat transfer losses. Eq. (1) represents the thermal storage of the tungsten only as a heat needed to raise the temperature of the filament from room temperature to another certain temperature. The relation between the input power and temperature is as shown by Eq. (2) where the current in this case depends on the resistance and temperature.

$$P_{in} = VI \tag{2}$$

where: $I$ is the current, $V$ is the voltage.

As the value of $C_p$ depends on the temperature, Eq. (3) below represents the value of $C_p$ as a function of temperature in the range of (300–3500 K) [12].

$$C_p = \sum\nolimits_{n=-1}^{3} A_n \cdot t^n \text{ J/mol} \quad \left(t = T/1000\right) \tag{3}$$

where: 1 mol = 183.85 g, $A_{-1}$ = −0.20869, $A_0$ = 23.70345, $A_1$ = 5.132062, $A_2$ = −1.99922, $A_3$ = 0.734168.

To calculate the resistance of the tungsten filament as a function of its temperature, Eq. (4) below can be used [13]:

$$R_h = R_c \left[\frac{T_h}{T_c}\right]^{1.2285} \tag{4}$$

where $R_c$ is the resistance at cold (or room) temperature $T_c$ and, $R_h$ is the resistance at any other temperature $T_h$.

The heat absorbed due to aluminum contacted parts, which are U-shaped wires clamped to each turn of the helix in the tungsten filament, can be found by calculating the total energy $Q_{Total}$ required to transport the film from solid to gas through vaporization. So, after summing the main elements of energies associated with the phase changes, the total energy $Q_{Total}$ can be obtained as in the following equation; [14].

$$Q_{Total} = Q_{melt} + Q_{fus} + Q_{vap} + Q'_{vap} \tag{5}$$

where $Q_{melt}$ is the energy needed to raise the temperature of metal to the first instant of melting, $Q_{fus}$ is the fusion energy which is the additional energy needed to convert the solid metal into its liquid phase, $Q_{vap}$ is the energy needed to raise the temperature of liquid to its vaporization temperature, and $Q'_{vap}$ is the absorbed energy during the inherent heat of the vaporization. The value of $Q_{melt}$ can be calculated by Eq. (6) as;

$$Q_{melt} = m \int_{T_{amb}}^{T_{melt}} C(T)\,dT \tag{6}$$

where $C$ is the specific heat of aluminum, $T_{melt}$ is the melting temperature, $T_{amb}$ is the ambient temperature.

The factor $C$ is obtained by Eq. (7) using a cubic spline technique developed by Ref. [15] as:

$$\ln C_T = a + b[\ln T - \ln T_i] + c[\ln T - \ln T_i]^2 + d[\ln T - \ln T_i]^3 \tag{7}$$

The Fusion energy $Q_{fus}$ is derived by Eq. (80)

$$Q_{fus} = \Delta H_{fus} \times \frac{m}{M} \tag{8}$$

Here, the heat of fusion for aluminum is $\Delta H_{fus}$, $M$ is the molar mass and $m$ is the filament mass. At this condition, the phase of the aluminum film is totally transformed to be in a liquid. More amount of energy is required to vaporize the film, which is given by the energy for vaporization $Q_{vap}$, calculated by Eq. (9).

$$Q_{vap} = mc[T_{vap} - T_{melt}] \tag{9}$$

where $T_{vap}$ is the vaporisation temperature of aluminum.

The energy absorbed is during the latent heat of vaporization is described by Equation (10) [14].