Temperature estimation using Boltzmann plot method of titanium emission lines produced on electric arc discharge

F F Parada-Becerra¹, V Dugar-Zhabon¹, and P A Tsygankov¹
¹ Universidad Industrial de Santander, Bucaramanga, Colombia

E-mail: freddy.parada@correo.uis.edu.co

Abstract. Temperature is an important characteristic in electric arc discharge processes for physical vapor deposition treatments. In this work, a titanium cathode was used and, by identifying the spectral emission lines in the range 300 nm – 550 nm, it was possible to determine by means of the Boltzmann graphical method the temperature of the plasma generated in specific areas of the cathode surface during the discharge process of Arc. As a result, the estimated temperature has close values for the different emission lines (Ti⁺, Ti⁺⁺, and Ti⁺⁺⁺) with uncertainties lower than 10%.

1. Introduction

Plasmas represent a unique state of matter that allows, under special conditions, to perform surface treatments on materials such as sputtering, implantation, deposition, surface activation, necessary in the development of technological devices with applications in various areas such as microelectronics, metalworking and biomedical among many others. One of the successful industrial applications of plasma materials processing is electric arc discharge. This work presents a diagnosis of the temperature of the plasma generated during the arc discharge using the Boltzmann plot method.

The identification of the active species in the processing of materials assisted by plasma is a fundamental factor to carry out the implantation with ions of multiple energies with respect to the applied potential [1–3]. However, some instability of the source used to feed the electric arc system, together with the unavoidable noise in data acquisition, represent certain difficulties or limitations in the use of electric probes for the identification of multi-charged metal ions [4, 5]. A convenient alternative method is to use optical spectroscopy techniques to identify the degree of ionization and temperature of these species with acceptable precision [6, 7].

The results obtained indicate that the temperature in the arc discharge process for the titanium cathode is in the range of approximately 8800 K, with the presence of multi-charged titanium ions (Ti⁺, Ti⁺⁺, and Ti⁺⁺⁺). The identification of these species allows modifications to be made on the surface of the substrate with different degrees of depth, which is beneficial for the formation of the interface with better adherence.
2. Methodology
The reactor that allows modifying metal surfaces (MOSMET) has an electric arc system to evaporate the cathode material and produce a discharge due to the high current density maintained by a relatively low potential generated by the power supply [6–8]; however, the electrical power dissipated is sufficient for the charging process to be self-sustaining [8–10]. The 178 mm diameter titanium cathode was located in the upper area of the vacuum chamber; the residual pressure in the chamber was less than 1 mPa, which was obtained by means of a turbomolecular pump. The vaporization of the cathode material and its ionization takes place in cathode spots that actually represent volumetric zones of a high-density plasma [11].

The spectrum emitted by the discharge is recorded by means of an optical fiber located in the intermediate zone as indicated in Figure 1(a); during the operation of the arc discharge as such the cathode spot is in totally random movement on the surface producing the titanium vapor and a flow of atomic species of different degrees of ionization [7,10,12].

In addition, due to the fact that the surface where the spot moves is quite small, the energy density that is given off on this surface is very high in the spot together with the atomic species, which is why unwanted microdroplets or macroparticles are produced. To reduce the amount of microdroplets, a coil system was installed that by modulating the magnetic field allows the movement of the spot to be controlled across the cathode surface.

Figure 1 shows the camera with the arc cathode in its upper part and the position of the optical fiber Figure 1(a), the magnetic control scheme of the spot Figure 1(b), the uncontrolled trajectories Figure 1(c) and with control magnetic Figure 1(d). The implementation of the magnetic field modulation system that controls the movement of the spot allows to control the evaporation process of the cathode material (Figure 1(d)) that facilitates producing the formation of both monolayer and multilayer coatings.

![Figure 1](image_url)

**Figure 1.** (a) Discharge chamber, (b) electric arc system with coils for magnetic modulation [12], (c) trajectories with internal radius of cathode points with external magnetic field, and (d) trajectories with external radius of cathode points with external magnetic field. [6].

The emission spectrum is recorded when the path of the cathode spot had a constant radius; for this purpose, the Ocean Optics 4000R spectrometer is used in the optical range as indicated in Figure 2, using a discharge current of 140 A and an applied potential of 26 V in the electric arc.
3. Results
The temperature calculations were determined according to Equation (1) using the Boltzmann method from the relative intensities [13–17].

\[ I_{ki}^{\lambda} = F C_s g_k e^{-\frac{E_k}{K_B T}} U_s(T) A_{ki} , \]  

Where \( I_{ki}^{\lambda} \) is the integrated intensity of a spectral line caused by the transition between the electronic states \( k \), \( e \), \( i \), \( C_s \) is the concentration of the emitting atomic species, \( F \) is an experimental parameter that takes into account the efficiency of the optical radiation collection system, the density of the plasma and the response factor of the detection system, \( g_k \) is the statistical weight of the excited electronic state that has energy \( E_k \), \( K_B \) is the Boltzman constant, \( T \) is the temperature and \( U_s \) is the partition function for the species station \( s \).

Figure 3 shows the linear regression for the temperature of the arc discharge with titanium cathode calculated. In the case of Figure 3(a) for the titanium ions \( Ti^+ \) a temperature of \( T_{Ti^+} = 8888 \pm 490 \, K \), for the case of Figure 3(b) we obtain \( T_{Ti^{++}} = 8766 \pm 570 \, K \), and finally \( T_{Ti^{+++}} = 8758 \pm 525 \, K \) in Figure 3(c). This result is supported on the basis of previous articles [6, 8] and [12] where the research continues by incorporating the detection of ions with a higher degree of ionization and indeed a correlation is found in the results obtained with the published research.

![Figure 3. (a) Experimental Boltzmann plot for \( Ti^+ \), (b) experimental Boltzmann plot for \( Ti^{++} \), and (c) experimental Boltzmann plot for \( Ti^{+++} \).](image-url)
4. Conclusions
The emission lines obtained for titanium ions ($Ti^+$, $Ti^{++}$ y $Ti^{+++}$) indicate that the temperature in this electric arc discharge process is approximately $8804 \pm 528 \, K$. Likewise, the identification of multi-charged ions will improve the implantation profiles in hybrid discharges (electric arc and high voltage) due to the energy they can obtain when accelerated under a negative potential applied to the substrate.

5. Acknowledgement
This work was carried out with the support of the Departamento Administrativo de Ciencia, Tecnología e Innovación, Colombia, and Ministerio de Ciencia Tecnología e Innovación, Colombia, through doctoral scholarship 727, 2015; likewise, to the Universidad Industrial de Santander.

References
[1] Anders A 2007 Brief modern history of cathodic arc coating 50 Years of Vacuum Coating Technology and the Growth of the Society of Vacuum Coaters ed Mattox D M, Harwood Mattox V (Albuquerque: Society of Vacuum Coaters) Chapter 16
[2] Hantzsche E 2003 Mysteries of the arc cathode spot: a retrospective glance IEEE Trans. Plasma Sci. 31 799
[3] Dugar-Zhabon V, Dulce J, Tsygankov P 2002 High voltage pulse discharge for ion treatment of metals Rev. Sci. Instrum. 73 828
[4] Ziegler J F 1992 New Technologies for Ion Implantation (North-Holland: Wiley)
[5] Khvesyuk V I, Tsygankov P A 1997 The use of a highvoltage discharge at low pressure for 3D ion implantation Surf. Coat. Technol. 96 68
[6] Tsygankov P, Plata A, Niño Ely D V, Ochoa C, Parada-Becerra F, Chacón C, Dugar-Zhabon V D 2011 Estudio de características voltio-ampéricas y peculiaridades de funcionamiento de un vaporizador de arco en vacío Revista Colombiana de Física 43 458
[7] Tsygankov P, Parada F, Dugar-Zhabon V, Plata A, Valbuena-Nino E D 2016 Artificially modulated hard coatings produced with a vacuum arc evaporator Journal of Physics: Conference Series 687(1) 012005:1
[8] Parada-Becerra F, Cabanzo R, Dugar-Zhabon V, Tsygankov P, Mejía-Ospino E, V-Niño E D 2012 Plasma temperature measurement in a hybrid discharge by using optical diagnostics Journal of Physics: Conference Series 370(1) 012054:1
[9] Ortiz L L, Parada-Becerra F F, Valbuena-Niño E D, Tsygankov P A, Dugar-Zhabónn V, Plata A 2017 Temperature behaviour on deposition of the titanium nitride thin films on the H13 steel by the electric arc discharge in vacuum Respuestas 22 14
[10] Parada-Becerra F, Dugar-Zhabón V, Garnica H, Tsygankov P 2019 The study of plasma flows generated by a vacuum-arc evaporator with a sectioned titanium-zirconium cathode Journal of Physics: Conference Series 1386(1) 012017:1
[11] Ohring M 1992 Mechanical properties of thin films Materials Science of Thin Films ed Vossen J L (New York: Academic Press) Chapter 12
[12] Parada-Becerra F F, Tsygankov P A, Dugar-Zhabon V, Peña D Y, Coronado J, Gonzalez J, V-Niño E D 2019 Morphologic evaluation of silicon surface modified with titanium and titanium+nitrogen Acta Microscópica 28 39
[13] Griem H R 1974 Spectral line Broadening by Plasma (New York: Academic Press)
[14] Griem H R 1997 Principles of Plasma Spectroscopy (College Park: Cambridge University Press)
[15] Lochte-Hotgreven W 1968 Plasma Diagnostics (Amsterdam: North-Holland Publishing Company)
[16] Bkefi G 1976 Principles of Laser Plasmas (New York: John Wiley & Sons)
[17] Raizer Y, Bazelyan E 1997 Spark Discharge (Broken Sound Parkway: CRC Press)