Turk J Phys
27 (2003) , 69 – 75.

Operation Parameters of The Thermionic Vacuum Arc Discharge

Tamer AKAN
Osmangazi University, Physics Department, Eskisehir-TURKEY

Received 15.07.2002

Abstract

The thermionic vacuum arc (TVA) discharge with evaporating anodes employing directly heated thermionic cathodes is investigated. The TVA discharge generates a pure, gas-free metal vapor plasma containing ions with a directed energy. The TVA is strongly controlled by the cathodic electron beam and there is a quite good stability of important operation parameters like the arc voltage and the arc current.

Key Words: Copper, discharge, plasma processing, vacuum arc

1. Introduction

The development of high-energy plasma devices requires effective organization and interface of the three basic stages of the working process: the generation of an atomic beam of material; the ionization of this beam; and, finally, the acceleration and focusing of the ionized beam. The working media in such devices, however, are usually either gases or easily evaporated materials, for which the generation of a vapor presents no difficulties. In many technological applications, however, it is necessary to produce plasma beams from a variety of solids, including refractory solids. Here it is particularly important to develop simple and effective methods for generating a vapor; the nature of the process involved strongly affects all the subsequent stages and essentially determines the configuration of the plasma device. Until recently, methods for evaporation in vacuum, such as the resistance and electron beam methods, were predominantly used in the vapor generation step. In several cases, however, these methods have proved ineffective (because there was no significant ionization, of isotropic expansion of the vapor, and due to difficulties in controlling the basic properties of the beam). Also, these devices are very often ineffective in energy conversion and technically complicated.

In the plasma methods; the beam is generated by evaporation or sputtering as a result of the erosion of the electrodes which occurs in vacuum electric discharges as these electrodes are bombarded by intense electron or ion beams. Vacuum discharges, in contrast to gas discharges, do not require a special injection of working medium; the medium required to sustain the discharge comes from the consumption of the electrodes (i.e. self-generation). The occurance of different types of vacuum discharges is thus caused primarily by the fundamental differences in the self-consistent processes by which the material is generated and electrons are emitted from the cathode [1].

Cathodic vacuum arcs produce their vapor plasma in cathode spots (microplasmas) at the surface of a consumed cathode. At low currents, the cathodic mechanism of evaporating material is not effective enough to overcome the rapid condensation on the surrounding walls. Thus, this type of electric arc is very unstable and normally extinguishes in fractions of second [2].

Because of this property vacuum arcs have found their main application in the production of high-current circuit breakers [3]. Also, vacuum arcs are used to produce coatings by depositing eroded cathode materials [4]. However, a great disadvantage is the production of macroparticles in the cathode spots. These molten droplets, with a typical size between 0.1 and 10 μm, are incorporated into the coatings and limit this process to applications where a certain content of macroparticles in the film can be tolerated [5].

Recent developments use cathodic vacuum arc systems, including macroparticle filters, and substrate bias for ion energy control [6, 7]. However, due to this, filtering deposition rates are quite low and, from an economic point of view, only applications leading to a high increment value, such as hardcoating of dies, are of practical interest [7].

As the anodic vacuum arc discharge is sustained by the metal vapor evaporated at the anode, a steady arc can be maintained at currents exceeding 20 A [8]. In this case, the discharge takes place between a cold cathode and an anode, which continuously evaporates under vacuum conditions. The arc is ignited by contacting the electrodes; the discharge starts as a cathodic vacuum arc with a non-evaporating anode. Due to the discharge the anode is heated up, anodic material is evaporated, and finally, the discharge operates as an anodic vacuum arc.

The thermionic cathode anodic vacuum arc is a new type of a plasma source, which generates a pure, gasfree metal vapor plasma containing ions with a directed energy. Like the anodic vacuum arc, this source, called the “thermionic vacuum arc (TVA),” produces its plasma via anodic evaporation. In contrast to the anodic vacuum arc, however, the TVA is sustained by means of a hot electron-emitting cathode [9-11].

A new plasma laboratory was founded at our university in 2000. One of our first experimental set-ups was the installation of a TVA system. In this paper the observed volt-ampere characteristics of a pure copper vapor TVA and important operation parameters are presented.

2. Experimental Arrangement

Two different configurations of the electrodes for the thermionic cathode anodic vacuum arc used for the experiments are shown in Figure 1. Both electrodes are placed inside a vacuum vessel employing standard high-vacuum equipment with an end vacuum of 10^{-6} mbarr.

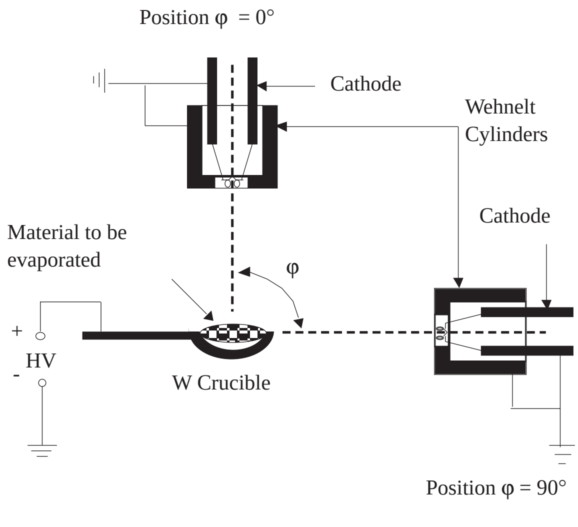

Figure 1. Configuration of the electrodes of thermionic (heated) cathode anodic vacuum arcs. HV indicates the high voltage power supply.

In Figure 1, a directly heated cathode is shown. The heated filament consists of four loops of 0.4 mm diameter tungsten wire wound to a 1 mm inner diameter. The cathode is placed inside a Wehnelt cylinder, which has a front hole of 5 mm diameter. The thermoelectrons emitted by the cathode are focused by the Wehnelt cylinder and are accelerated toward the anode by a high potential. The cathode can be arranged in various relative positions to the anode. This position is defined by an angle φ. Figure 1 shows two extreme positions: $\varphi = 0°$ and $\varphi = 90°$.

The anode consists of a tungsten crucible with a spoonlike shape and a thickness of 0.2 mm. The material to be evaporated is placed inside the crucible. The maximum diameter of its cavity is 10 mm.

The electrodes are connected to a DC high voltage (5kV) power supply. The discharge current is controlled by suitable ballast resistors and adjustment of the DC voltage.

3. Ignition and Operation of the TVA

After increasing the cathode temperature, for a convenient DC voltage applied across the cathode and the anode, the content of the crucible is melted. Due to the accelerated electrons from the heated cathode hitting the anode, a continuous evaporation of the anode material is established. Consequently, under the applied vacuum conditions, a steady state density of metal atoms appears in the interelectrodic gap. With a further increase of the applied voltage, a bright discharge is suddenly established in the interelectrodic space, with simultaneous decrease of the voltage drop over the electrodes and significant increase of the discharge current. This discharge operates in pure metal vapor as could be proven earlier by investigations of the emission spectra [12].

A continuous operation of this discharge requires two basic conditions:

(1) a sufficient high vapor production at the anode to produce a sufficiently high vapor density in the interelectrode space,

(2) a sufficiently high charge carrier production - due to inelastic electron-atom collisions within the interelectrode space - to compensate the continuous loss of charge carriers due to ambipolar diffusion and recombination [5].

Figure 2 shows the voltage-ampere characteristic of the TVA for two different cathode heating currents with copper as the evaporating anode material. The electrode arrangement angle, as defined in Figure 1, is $\varphi = 50°$.

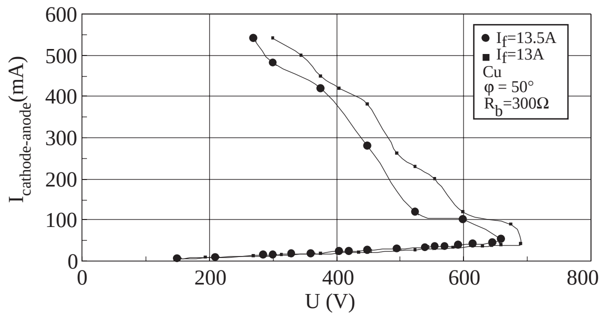

Figure 2. Volt-ampere characteristics of the thermionic vacuum arc in copper vapors for two heating currents.

The branches for low currents with a positive slope represent the characteristics of vacuum diodes, where the characteristic is determined solely by the thermionic emission of the cathode and no significant evaporation of the anode occurs. The maximum voltages correspond to the ignition point, where the above defined conditions allow for ignition of a discharge in the anodic vapor. The ignition (breakdown) voltage of the TVA decreases with increasing cathode heating current I_f. The curves toward higher currents represent the ignited TVA discharges. In these branches of the characteristics the operating voltage decreases toward higher arc currents. The negative slope of the characteristic in this regime requires a ballast resistor for stable operation.

An important parameter of the arc discharge investigated here is the geometry of the electrodes, including the relative position of anode and cathode. This fact can clearly be derived from a comperasition of the results shown in Figures 3 and 4.

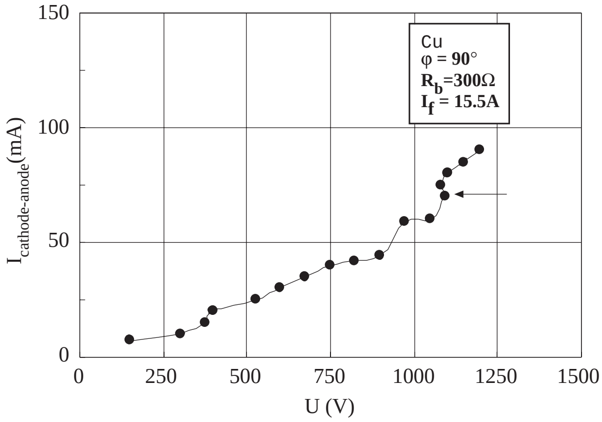

Figure 3. Volt ampere characteristic of the thermionic vacuum arc in copper vapors for $\varphi = 90°$ cathode position displaced downwards for 1 mm.

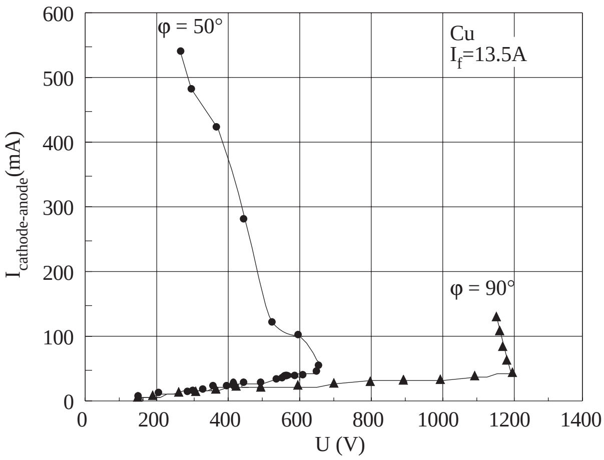

Figure 4. Volt ampere characteristics of the thermionic vacuum arc for two relative positions of the cathode, namely $\varphi = 90°$ and $\varphi = 50°$. In the position $\varphi = 90°$, the cathode is displaced 1mm upwards.

In both experiments, the working parameters are similar. In spite of this fact, the voltage ampere characteristics are quite different in the ignited mode. The appearence of a visible discharge is marked with an arrow in Figure 3. The difference between the results of Figures 3 and 4 is due to a change in the relative position of the anode-cathode system.

The results given in Figure 4 have been obtained using the arrangement of electrodes for $\varphi = 90°$ and $\varphi = 50°$, but for $\varphi = 90°$ with the cathode displaced 1mm upwards. In this case, most of the accelerated electrons from the cathode are incident on the material to be evaporated. The results given in Figure 3 correspond to a situaition where the 1mm displacement has been made downward. In this case, most of the accelerated electrons are incident on the crucible but not on the material to be evaporated. Therefore, the evaporating material is heated indirectly due to its contact with the hot spot on the crucible.

When the electron beam is completely focused onto the evaporating material, breakdown voltage as well as arc voltage drop are at a relatively low level. This behavior is shown in Figure 4. The voltage-ampere characteristics were taken with the same heating current, but different positions of the cathode, i.e., $\varphi = 50°$ and $\varphi = 90°$.

Even after ignition, the thermionic cathode anodic vacuum arc is strongly controlled by the cathodic electron beam. This is proven by the curve in Figure 5, which shows the dependence of the ignited arc current on the cathode heating current I_f. If the heating current is switched off, the arc extinguishes instantaneously.

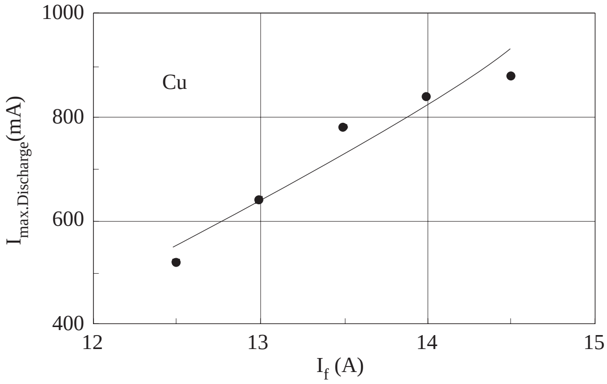

Figure 5. Dependence of the ignited arc current in metal vapors on cathode heating currents.

Figures 6 and 7 show the time dependent signals of the arc voltage and current, respectively. As can be seen, there exists quite a good stability of these important operating parameters.

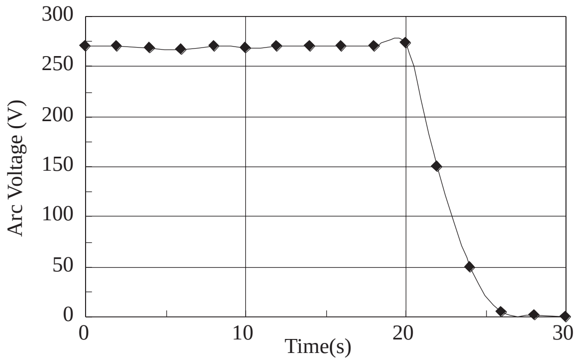

Figure 6. Time resolved record of the arc voltage drop across the copper vapor discharge with heated cathode.

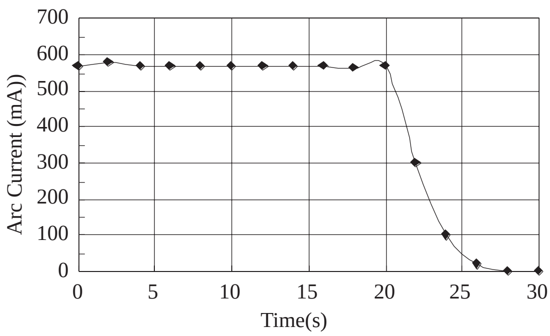

Figure 7. Time resolved record of the thermionic vacuum arc current in copper vapors.

When the time dependence of the arc voltage and current were measured, after 20 seconds the arc was extinguished to observe the time dependence in the same time scale. However, the arc voltage and the arc current are nearly stable untill the copper in the crucible finishes. Figure 8 shows the evaluation of the residual gas pressure in the vacuum vessel.

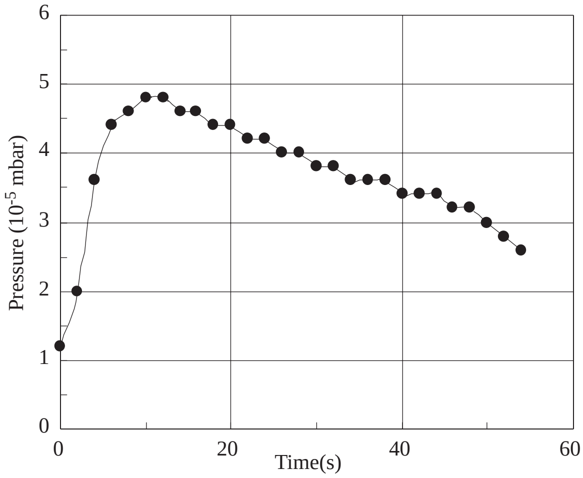

Figure 8. Evaluation of the residual gas pressure in the vacuum vessel during operation of the thermionic vacuum arc.

At arc ignition, a sudden increase in pressure can be observed due to degassing of the evaporating material (copper) and release of gas from the walls bombarded with energetic particles and photons [9]. After arc ignition, the pressure decreases continuously during arc operation. This pressure decrease is probably due to the coverage of the inside wall of the vacuum vessel with a new fresh metal surface which lowers the possible outgasing surfaces or even can adsorb physically or chemically the active molecules of the residual gases.

4. Conclusion

The development of the new type of vacuum arc discharges in the vapor of the anode with cold cathode or heated cathodes opens interesting research possibilities related with numerous basic phenomena. At the same time these discharges offer convincing advantages for emerging technological applications. The TVA has very special properties which derive from the operating conditions and from produced (generated) plasma properties.

Acknowledgement

I am very grateful to Dr. Geavit MUSA, National Institute For Laser, Plasma and Radiation Physics, Bucharest/ROMANIA and Prof. Dr. Naci EKEM, Osmangazi University, Eskisehir/TURKEY, for them guidance in setting up the TVA system in the Osmangazi University, Physics Department.

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