The destruction of pure metal cathodes during the initiation of direct current arc

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Abstract. In this work, the behavior of cathodes made from pure tungsten and pure hafnium in the direct current electric arc at 200 A and in atmospheric pressured argon medium was investigated. The research was focused on the processes happening with the cathodes during the arc initiation phase (first 100 ms after the power input). The processes of rapid cathode destruction were registered, and can be characterized as the destruction of the cathode in liquid phase due to electro-magnetic forces. Characteristic times of the whole process were recorded, as well as the changes in temperature fields on the cathodes surfaces and the rate of mass loss for both types of cathodes. It has been shown that the initial destruction of the cathode plays a major role in the cathodes resource life.

1. Introduction

Now, arc-plasma technologies are used in various fields, such as welding, cutting and smelting of metals, application of coatings, synthesis of graphene materials etc. Understanding of physical-plasma processes creates opportunities for the optimization of existing and creation of new industrial plants. Currently pure metals (such as hafnium [1]) or tungsten [2, 3]) or tungsten with additive materials [4–7] is commonly used as a cathode for plasma arc generators. When pure tungsten is diluted with few percent of additive material (thorium, lanthanum, yttrium etc) its effective work function decreases substantially thus the electrode can achieve the same plasma current at lower temperatures [5, 6]. This generally leads to a higher life time of an electrode and purer plasma created by a plasma generator without the cathode material. Even so, not all applications of plasma generators require the cathode to be indestructible, some applications like arc welding and synthesis of materials can benefit from the electrode material in the plasma stream [8, 9].

Two general types of destruction are well known and documented to this day. The sublimation of the material [10] and particle fragmentation [11]. These types of destructions are not only common in cathodes but can be seen in other destructive processes for example such as the destruction of heat resistant materials [12]. The feature of the investigated destructions in this work is that it can be characterized by a third type that involves the destruction in liquid phase due to electro-magnetic forces.

The destruction of the cathode can generally be divided into three phases. The first phase is the arc binding to the cathode (before it reaches stable operational parameters). The second
Figure 1. The experimental setup: 1—spectrograph DFS-452; 2—Andor 420 Duo video matrix; 3—projection of the image of the arc on the slit of the spectrograph; 4—focusing lens; 5—cathode and electric arc; 6—viewing quartz windows; 7—lens “Helios-40-2”; 8—black and white camera Phantom Miro M110.

phase (destructive) occurs during the stationary mode of operation, and the last one happens when the plasma generator is switched off. In this paper, we investigated the destruction of pure metal cathodes (tungsten and hafnium) during the initial phase of the electric arc burning. In this destruction phase, the arc attaches to the cathode and while it stabilizes, the binding area is increasing, and the cathode loses a big portion of its initial mass while being in liquid phase. This phase lasts for less than a second.

2. Experimental methods

The experiments were conducted on a dc arc plasma torch specifically equipped with two viewing windows opposite the cathode, to monitor its state during the work procedure (as shown in figure 1). The plasma forming gas was argon at atmospheric pressure, distance between an anode and cathode is about 1 cm, the current $I$ was kept at 200 A. All the examined cathodes were cut into conical forms with an apex angle of 60° and fitted into the copper based which was water cooled. Pure hafnium and pure tungsten were used as materials for the cathodes.

The investigated phase lasts for less than a second, $\sim$ 100 ms for pure tungsten and about 0.5 s for pure hafnium. Using a high-speed camera Phantom Miro M110 the arc binding process was recorded from the beginning with a recording speed of 75 000 frames/s. The camera was also previously calibrated against a reference radiation source (tungsten lamp) with a known brightness temperature, which made it possible to transform the camera into a high-speed micropyrometer using an interference filter (with a passband of 590 nm) [13] and retrieve the temperature fields on the surface of the cathodes from the recorded images.
3. Results and discussion

Both materials during all of their operational time starting from the initial arc attachment reside in liquid phase. When a new just cut and polished cathode is used it loses most of its mass during the first 100 ms of the operation, during the first phase. The process by which it loses its mass is presented in figure 2, and can be described as rapid expulsion of the material in the form of stretched fragments followed by an explosion in the thinnest point.

It takes approximately 1 ms from the start of stretching to the moment of explosion, which gives the estimate for the speed of stretching \( v = \frac{L}{\tau} \), where the length of the stretch is \( L \approx 1.5 \text{ mm} \) and \( \tau \approx 1 \text{ ms} \) thus \( v \approx 1.5 \text{ m/s} \). This process continues until the arc binding area sufficiently increases to approximately \( S_W = 0.4 \text{ mm}^2 \) for pure tungsten and \( S_{\text{Hf}} = 8 \text{ mm}^2 \) for pure hafnium, at this point the rapid expulsion of material finishes and stable burning mode is achieved, at which the material loss considerably slows down and starts happening by different mechanism (evaporation). The initial and final state (after the rapid mass expulsion) of pure tungsten cathode are presented in figure 3.

The surface areas, at which the stable operational mode occurs, provide the values for electric current density at \( j_W = \frac{I}{S_W} = 5 \times 10^4 \text{ A/cm}^2 \) and \( j_{\text{Hf}} = \frac{I}{S_{\text{Hf}}} = 2.5 \times 10^3 \text{ A/cm}^2 \). The maximum temperature that the pure tungsten reaches before exploding is \( \approx 4600 \text{ K} \) and for hafnium it is \( \approx 4000 \text{ K} \) (figure 4), and the average temperature they have while in stable mode of operation are 3800 and 3100 K respectively.

The current and final state of operation are presented in figure 3.

We suppose that the stretching of the liquid fragment is the effect of electro-magnetic forces, and the explosion is the result of the constriction due to the magnetic pressure (pinch effect) \( P_B = \frac{B^2}{2\mu_0} \approx \left( \frac{I}{r} \right)^2 \), where \( B \) is the magnetic field strength, \( \mu_0 \) is the vacuum permeability, and \( r \) is the radius of a liquid phase. This pinch effect leads to the decrease of the channels cross section, that increases the current density in the channel (at constant current), and thus increases the heating with the subsequent evaporation and gas formation that leads to an explosion. Volumetric energy release due to joule heating is \( Q \approx \frac{j^2}{\sigma} \), where \( \sigma = \sigma_0 (1 - \alpha DT) \) is electrical conductivity, \( j \) is electric current density, \( \alpha \) is the temperature coefficient of resistivity, \( DT \)
Figure 3. Tungsten cathode before arc initialization (left) and after reaching a stable burning mode (right).

Figure 4. Temperature fields on the surface of the cathodes few microseconds before explosions.

The change of the cathode temperature, $\alpha \Delta T$ increases insignificantly, and $\sigma$ stays in the same order with an increased temperature. Thus, electric current density is $j = I/S \approx I/r^2$ and volumetric energy rapidly increases as $Q \approx j^2/\sigma \approx 1/r^4$. Simple estimation from figure 2 shows that approximately $\Delta m \sim 10^{-3}$ grams of material is blown out per one explosion. Taking into account the time-step of $\tau \approx 10$ ms between two consecutive explosions for pure tungsten and $\tau \approx 2$ ms for hafnium, the estimation for erosion will be $\Delta m/(I\tau) \sim 10^{-4}$ g/C for tungsten and $\sim 10^{-3}$ g/C for hafnium. Which in case of pure tungsten differs by 3 orders from its typical value ($10^{-7}$ g/C) [14] in argon medium and currents of several hundred amperes.
4. Conclusion
In the present experimental research, the behavior of cathodes made from pure tungsten and pure hafnium was investigated during the initial phase of electric arc initiation. The process of cathodes destruction was recorded on high-speed video camera, which showed a cyclical process of material stretching, thinning at a pinch point and then exploding. Characteristic times of these processes and the temperature changes on the cathode surfaces were recorded, and the estimates for mass loss rates were calculated. These processes show that the initial destruction of the cathode plays a major role in its resource life, even if after the initial destruction it continues to work in stable mode. These results may help in design of new plasma equipment especially in cases where the plasma should be kept clear of the cathode material, or in opposite cases where the cathodes material needs to be steadily added into the plasma process (such as arc welding, material deposition and synthesis).

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References
[1] Sargsyan M A, Gadzhiev M Kh, Tereshonok D V and Tyuftyaev A S 2018 Phys. Plasmas 25 073511
[2] Belevtsev A A, Goryachev S V, Isakaev E Kh and Chinnov V F 2013 High Temp. 51 583–93
[3] Gadzhiev M Kh, Sargsyan M A, Tereshonok D V and Tyuftyaev A S 2016 Europhys. Lett. 115 35002
[4] Casado E, Colomer V, Munoz-Serrano E and Sicilia R 2002 J. Phys. D: Appl. Phys. 35 992–7
[5] Sillero J A, Ortega D, Munoz-Serrano E and Casado E 2010 J. Phys. D: Appl. Phys. 43 185204
[6] Alber A Sadek, Masa U and Fukuhisa M 1990 Metall. Mater. Trans. A 21 3221–36
[7] Sargsyan M A, Tereshonok D V, Valyano G E, Scherbakov V V, Konovalov P A and Gadzhiev M Kh 2020 Phys. Plasmas 27 023506
[8] Atsushi A, Keigo T, Takayuki O, Masafumi I, Mineo H, Kenji I, Hiroki K, Makoto S, Tomoko S, Sakae I, Yoshinori A and Masaru H 2017 Jpn. J. Appl. Phys., Part 1 56 035101
[9] Shavelkina M B, Amirov R H, Katarzhis V A and Kiselev V I 2016 J. Phys.: Conf. Ser. 748 012021
[10] Nemchinsky V A and Showalter M S 2003 J. Phys. D: Appl. Phys. D 36 704–12
[11] Manabu T, Taro H, Tomoyuki I, Yushi N and Takayuki W 2016 Jpn. J. Appl. Phys., Part 1 55 07LC01
[12] Chinnov V F, Tyuftyaev A S, Kavyrshin D I, Ageev M A, Sargsyan M A and Gadzhiev M Kh 2018 High Temp. 56 25–32
[13] Goryachev S V, Isakaev E Kh, Myasnikov M I and Chinnov V F 2008 High Temp. 46 752–6
[14] Raizer Yu P 1991 Gas Discharge Physics (Berlin, Heidelberg: Springer-Verlag)