NON-SELF-SUSTAINED ARC DISCHARGE IN VAPORS OF CONSTRUCTIONAL MATERIALS OF NUCLEAR POWER ENGINEERING

A.G. Borisenko, E.G. Kostin, O.A. Rokytskyi, O.A. Fedorovich

Institute for Nuclear Research NAS of Ukraine, Kyiv, Ukraine

E-mail: boris@kinr.kiev.ua

The paper presents the results of experimental studies of the conditions of ignition and burning for non-self-sustained arc discharges in nickel and tantalum vapors. The investigations were carried out with the aim of developing new methods for efficient generation of plasma-free and highly ionized plasma flows of structural materials of nuclear power engineering. In the experiments, the minimum power required to obtaining a sufficient vapor pressure of working material and ignition of vacuum arc discharges was obtained. The values of the minimum discharge power in the conditions of their stable burning were also determined; the current-voltage characteristics of the discharges in vacuum and under conditions of gas input into the vacuum chamber were studied. It is shown that the created plasma streams can be used to deposit the films not only on metallic and semiconductor materials, but also on dielectric substrates.

PACS: 52.50.Dg, 52.80.Vp

INTRODUCTION

At present, the development of corrosion-resistant steels and protective coatings of reactor design elements is one of the main tasks for the further development of nuclear power engineering. The increasing of the material corrosion resistance can increase the use time of existing equipment. As indicated in the publication [1], the modification of surface layers using concentrated energy streams (pulsed electron fluxes, plasma fluxes) can be effective in the development of new corrosion-resistant steels with protective coatings. Flows of the plasma allow to provide not only the alloying of the material, but also to finish processing of the surface layers of components. The most promising process may be the process of surface treatment of components and constructions of nuclear power engineering by streams of plasma without drops, which are obtained from the pure vapors of the relevant materials. All this makes it important and necessary to develop new and improve the existing sources of non-drip plasma flows of materials of construction of the nuclear power engineering and to find new methods for their practical use. It is considered expedient and necessary to develop sources of plasma streams that are generated both in pure vapors of materials and in mixtures of vapor of metals with different gases. The sources of plasma streams based on the non-self-sustained arc discharge in the anode vapors refer specifically to such sources [2-4]. Coatings of such elements as Zr, Mo, Nb, Ti, Ni, Ta, V, Cu and their compounds with different gases are considered promising in solving the problem of anti-corrosion protection.[5]. The thermophysical characteristics of these materials, such as the melting point, the specific heat of melting and evaporation, thermal conductivity, and others, have a fairly large range of values for different metals. Their properties can significantly affect the conditions of ignition of electric discharge in the vapors of these materials, as well as change the conditions for its stable existence. Therefore, the purpose of these studies was to determine the values of the minimum ignition power of discharges and the minimum power of the discharge existence in vapors of different metals. Nickel and tantalum were selected as materials of the initial study.

1. EXPERIMENTAL SETUP

A scheme of the experimental device is shown on Fig. 1. The non-self-sustained arc discharge was ignited between the anode 3, which was water cooled, and grounded cathode 1 in the vapor of the working material 2. The working material in the experiments described was nickel or tantalum.They are placed directly on the upper surface of the anode 3. The cathode of discharge was a 1.8 cm diameter ring and was made of a tungsten wire with a diameter of 1 mm. The distance between the discharge cathode and the working material located on the upper surface of the anode was 5…10 mm.

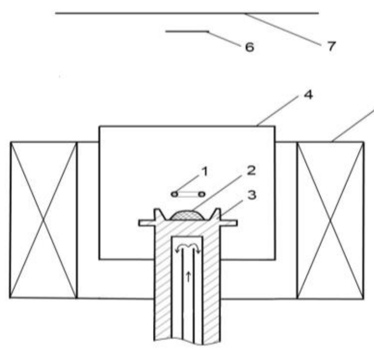

Fig. 1. Scheme of experimental device:
1 – heated cathode; 2 – working material;
3 – cooled anode; 4 – cylindrical electrode;
5 – magnetic coil; 6 – a flat Langmuir probe;
7 – substrate holder-ion collector

The heating current of the cathode was 60 A. This allowed the cathode of the discharge to work in a mode when the current of the thermionic emission from the cathode exceeded the total current of the discharge. The metal electrode 4 eliminates the possibility of direct hit of the plasma stream directly onto the magnetic field coil 5 and had the potential of the grounded cathode in these experiments. With the help of a coil 5, a magnetic field was created in the zone of the discharge gap. It was used to facilitate of the ignition conditions of the discharge and variation of the parameters of the created plasma streams. Flat electrical probe 6 was used to measure the parameters of the plasma streams. It was located on the axis of the system at a distance of 0.17…0.19 m from the anode and was usually located at a negative potential with respect to the discharge cathode, U_6 = -200 V. Electrode 7 allowed to measure the total ion current in the plasma flow, and if necessary, place on it substrates for deposition of films and coatings. In the described experiments, the limiting pressure in the vacuum chamber was $p = (0.5…1) \cdot 10^{-3}$ Pa. In the deposition mode, the pressure in the vacuum chamber was close to the limit pressure and practically did not exceed $(1…2) \cdot 10^{-3}$ Pa.

2. EXPERIMENTAL RESULTS

Fig. 2 shows the current-voltage characteristics of discharge ignition in nickel vapor (curve 1), of stable discharge burning (curve 2) and extinction of discharge (curve 3) at $p = 2 \cdot 10^{-3}$ Pa.

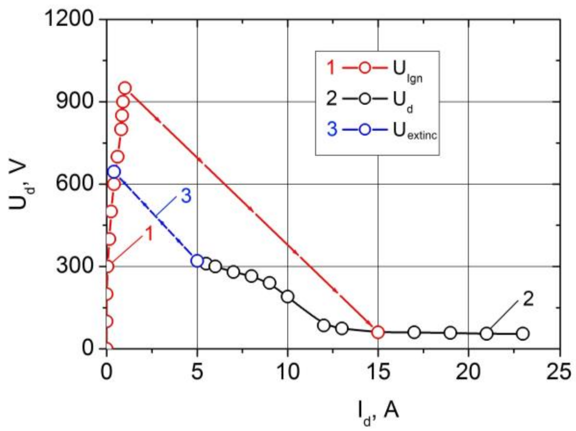

Fig. 2. Characteristics of non-self-sustained arc discharge in nickel vapors

The ignition of a discharge in a vacuum occurred in this way. The appearance of the voltage between the anode 3 and the heated cathode 1 result to the heating of the working material 2 by electrons, which are emitted from the cathode, and the appearance in the gap between the cathode and the discharge anode of the vapor of the working substance. The increase in voltage was accompanied by an increase in the current of thermoelectrons and the growth of vapor pressure of the working substance in the discharge gap. Ignition of arc discharge occurred at ≥1000 W power where the vapor pressure in the discharge gap reaches the necessary value. At a voltage 950…1000 V the discharge current was sharply increased to 15 A. At the same time, significantly, from 1000 to 100 V, the voltage between the anode and the discharge cathode was reduced. Thus there was a transition of discharge from the ignition mode to the regime of its stable burning in a pure vapor of nickel. Thus there was a transition of discharge from the ignition mode to the regime of its stable burning in a pure vapor of nickel. At currents I_d = 7…23 A the voltage of discharge was U_d ≈ 300…100 V. The extinction of discharge took place at a discharge current of less than 5…7 A and is reflected in Fig. 2 of curve 3. With a discharge current of less than 5…6 A discharge does not exist, since the vapor pressure of the working substance in the discharge gap is not sufficient for its existence. Tantalum is a member of the group of high-temperature materials and is promising in relation of the possible creation of coatings of structural elements in nuclear energy engineering with increased corrosion resistance. The thermophysical characteristics of Ta differ substantially from those of Ni. In particular, the melting point and the specific heat of evaporation of Ta are 2 times greater than Ni. That is having the reflection in the characteristics of the discharge in Ta pairs. Typical volt-ampere characteristics of stable existing discharges in nickel vapors (curve 1) and discharge in vapors Ta (curve 2) are shown in Fig. 3. From Fig. 3 it is evident that at identical currents the discharge voltage in vapors of Ta is much higher than for discharge in nickel vapors. In general, the voltage-ampere characteristic of a stable burning non-self- sustained arc discharge in vapors of Ta has the same qualitative dependence as for discharge in Ni vapors.

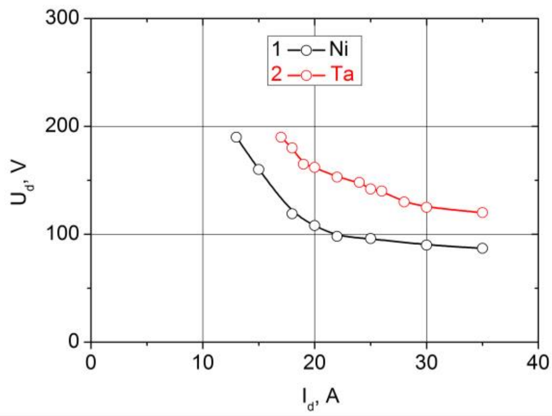

Fig. 3. Volt-ampere characteristics of non-self-sustained arc discharge in vapor of nickel (curve 1) and tantalum (curve 2)

Volt-ampere characteristics of this type of discharge differ significantly from the volt-ampere characteristics of a non-independent arc discharge in gases. In the discharge in gases the discharge voltage increases with increasing discharge current. Fig. 4 shows the electrical power of discharge at various discharge currents. The data show that, with the increase of discharge current, despite the decrease of the discharge voltage, the power which is take in the discharge increases. The given data allow estimating necessary requirements to sources of power supply of discharges. Thus we can say that since for a non-self-sustained arc discharge in nickel vapors, the minimum power of stable burning of the discharge is about 1500…2000 W then to ensure ignition and stable burning of the discharge, it is necessary to use a power source with an output voltage greater than 1000 V and a power of more than 1500 W.

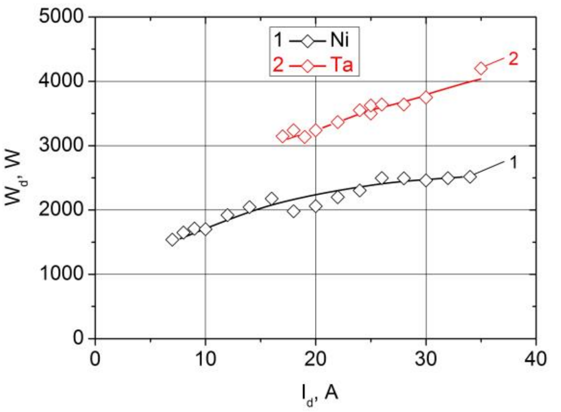

Fig. 4. Dependence of discharge power $W_d = I_d \times U_d$ on the discharge current, I_d, in vapor of nickel (curve 1) and tantalum (curve 2)

For the stable existence of discharge in tantalum vapors with currents of more than 17 A, it is necessary to have a power source of discharge with a power of not less than 3 kW.

The values of ion current, measured by the electrode 7 for various discharge currents, was shown on Fig. 5. In experiments, the electrode 7 had negative potential -200 V, relative to the cathode of discharge. Its size was 0.08 × 0.08 m. The ion current on the electrode 7 for a discharge in a vapor of tantalum was almost 3 times smaller than for nickel.

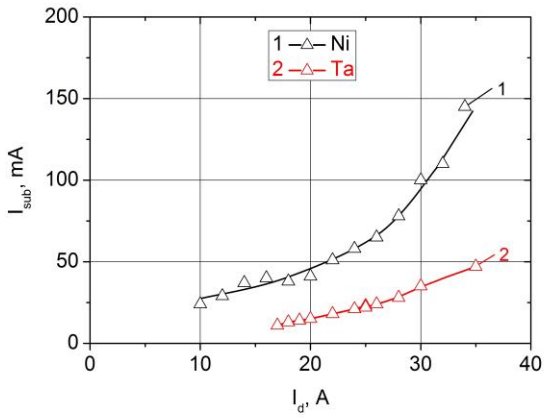

Fig. 5. Dependence of current of ions on electrode 7, I_{sub}, from discharge current, I_d, in vapor of nickel (curve 1) and tantalum (curve 2)

As shown in Fig. 5, with an increase in the discharge current in tantalum vapors there is an increase in the ion current on the electrode 7 from 15 to 40 mA. For discharge in nickel vapor, the current on the electrode 7 increases from 25 to 150 mA. Thus, the average current density of ions on the electrode 7 increases, respectively, in 3 and 6 times. Fig. 6 shows the dependence of the ion currents, which were registered by the electrode 7, on the magnitude of the external magnetic field created by the magnetic coil 5. This data indicate that the maximum current of nickel ions take when the values of the magnetic field induction is

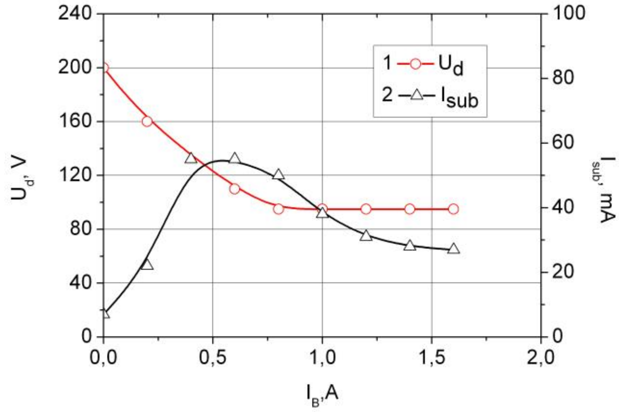

Fig. 6. Dependence of the value of the ion current on the electrode 7, I_{sub}, on the magnitude of the induction of the external magnetic field, B, for discharge in the vapor of nickel

B = 50…140 Gs. It was at these values of B that the following data were obtained.

Fig. 7 shows data of experimental studies of the potential of an isolated electric probe 6, which is located in the center of the created plasma flows. The probe was grounded through a divider with a total resistance of 300 MΩ, or directly connected to a static voltmeter C 50. The obtained data indicate that the potential of an isolated probe located in the center of plasma flows is negative. For discharge in nickel vapor, the floating potential of an isolated probe

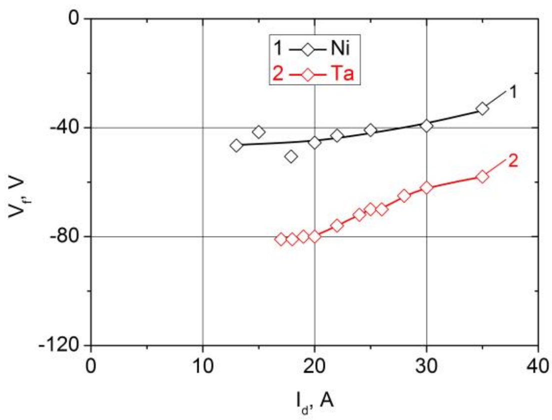

Fig. 7. Dependence of the floating potential of an isolated probe, V_f, on the discharge current, I_d.

is about -40 V across the range of discharge current changes. An isolated electric probe placed at the center of the plasma flow for discharge in tantalum pairs was recorded almost 3 times large the negative potential in the entire range of discharge current.

For discharge in tantalum vapors at discharge currents 6….15)A, the probe fixes a negative potential with the value V_f = - 60…90 V. The experiments have shown that the potential of an isolated probe is almost unchanged throughout the diameter of the plasma flow. These data indicate that the formed plasma streams have a compensated volume charge and can be successfully used to apply films to the substrates of any materials, metallic, semiconductors and dielectric.

CONCLUSIONS

In order to establish new physical principles and methods for efficient generation of droplet and highly ionized plasma streams of structural metals of nuclear power engineering, the main characteristics of non-self-sustained arc discharges in pure vapors of nickel and tantalum were investigated. The conditions of ignition of non-self-sustained vacuum arc and its volt-ampere characteristics were studied and the values of the minimum main power for stable burning of discharges were determined. The obtained data allow us to compare the main characteristics of discharges in the vapors of different materials and to determine the relevant requirements for the power supply of the relevant discharges.

REFERENCES

1. N.A. Azarenkov, V.N. Vojevodin, V.G. Kirichenko, G.P. Kovtun. Nanostructures materials in nuclear energetics // *Vísnyk Kharkívskogo uníversitetu. Seríya "Fízychni Yadra, chastynky, polya"*. 2010, № 887, v. 1/45, p. 4-24 (in Ukrainian).
2. A.G. Borisenko, V.A. Saenko, V.A. Rudnitsky. Non-self-sustained arc discharge in anode material vapors // *IEEE Trans Plasma Science.* 1999, v.27, № 4, p. 877-881.
3. A.G. Borisenko, V.A. Saenko, V.A. Rudnitsky. Semi-self sustained arc discharge in mixtures of metal vapors with gas // *High Temperature*. 1999, v. 37, № l, p.1-8.
4. A.G. Borisenko, Yu.S. Podzirei. Ion energy distribution and basic characteristics of plasma flows of non-self-sustained arc discharge // *Problems of Atomic Science and Technology. Series "Plasma Physics" (21).* 2015, № 1, p. 177-180.
5. I.I. Aksenov, V.A. Belous. Protecting coatings on uranium // *East European Journal of Physics*. 2014, v. 1, № 4, p. 4-25.

Article received 22.10.2018

НЕСАМОСТОЯТЕЛЬНЫЙ ДУГОВОЙ РАЗРЯД В ПАРАХ КОНСТРУКЦИОННЫХ МАТЕРИАЛОВ ЯДЕРНОЙ ЭНЕРГЕТИКИ

А.Г. Борисенко, Е.Г. Костин, О.А. Рокицкий, О.А. Федорович

Представлены результаты экспериментальных исследований условий зажигания и горения несамостоятельных дуговых разрядов в парах никеля и тантала. Исследования были проведены с целью разработки новых методов эффективной генерации бескапельных и высокоионизированных потоков плазмы конструкционных материалов ядерной энергетики. В экспериментах были определены минимальные мощности, необходимые для получения достаточного для развития разрядов давления паров рабочего материала и зажигания вакуумных дуговых разрядов. Были также определены величины минимальной мощности разрядов в условиях их стабильного горения, изучены вольт-амперные характеристики разрядов в вакууме и в условиях напуска газа в разрядную камеру. Показано, что создаваемые плазменные потоки могут быть использованы для осаждения пленок не только на металлические и полупроводниковые, но и на диэлектрические подложки.

НЕСАМОСТІЙНИЙ ДУГОВИЙ РОЗРЯД У ПАРАХ КОНСТРУКЦІЙНИХ МАТЕРІАЛІВ ЯДЕРНОЇ ЕНЕРГЕТИКИ

А.Г. Борисенко, Є.Г. Костін, О.А. Рокицький, О.А. Федорович

Представлено результати експериментальних досліджень умов запалювання і горіння несамостійних дугових розрядів у парах нікелю та танталу. Дослідження були виконані з метою розробки нових методів ефективної генерації безкрапельних і високоіонізованих потоків плазми конструкційних металів ядерної енергетики. В експериментах були визначені мінімальні потужності, необхідні для одержання тиску парів робочого матеріалу, достатнього для запалювання і розвитку вакуумних дугових розрядів у парах металів. Були також визначені величини мінімальної потужності розрядів за умови їх стабільного горіння, вивчені вольт-амперні характеристики розрядів у вакуумі та в умовах напуску газу до розрядної камери. Показано, що утворювані плазмові потоки можуть бути використані для осадження плівок не лише на металеві та напівпровідникові, але й на діелектричні підкладинки.