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INCREASING THE ENERGY EFFICIENCY OF THERMOCATHODES OPERATION

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ABSTRACT The paper presents the results of experimental research on modifying the active area of cathode surfaces applied in the construction of electronic guns and increasing their operating efficiency. The intensity of the thermo-electronic emission current is directly proportional to the area of the active surface of the cathodes used for this purpose. To change the micro-geometry of the metal cathode surface, the method of pulsed electric discharge machining (PEDM) was applied. As a result of the application of the discharge plasma on the surface of the cathodes, Taylor cones with heights ranging from 50 to 100 μm were extracted. The analysis of the obtained current-voltage characteristics allows us to compare the values of the saturation current intensities for unprocessed cathodes and those processed by the proposed technology. The increase of the active area of the cathodes with conical asperities causes the increase of the electronic thermo-emission current by 10^4. A comparing to the cathodes whose active surfaces have not been processed by this method.

KEYWORDS : electric discharge, micro-geometry, meniscus, current-voltage characteristics, cathode, thermo-electronic emission, high vacuum

INTRODUCTION

The physical phenomenon of thermo-electronic emission was discovered in 1881 by the well-known inventor Thomas Alva Edison (1847-1931). This phenomenon has found a vast utility in the construction of devices and is widely applied in the construction and operation of electronic tubes, industrial installations for materials processing by the electron beam [1, 6, 7, 10]. The thermo-electronic emission presents a phenomenon, the essence of which consists in the following: whenever a piece of metal is heated to a certain temperature it begins to emit electrons, consequently, it becomes a source of free charge. The thermal energy absorbed by the metal subjected to heating is transformed into energy of motion of the elementary particles it is composed of (oscillating motion of the ions of the crystal lattice and intensification of the mechanical motion of the electrons that constitute the electronic gas in the metal). The free electrons inside a metallic material, accumulating a considerable kinetic energy, can leave the metal permanently thus becoming free. The free electrons obtained by heating metallic materials are also called thermo-electrons. The material from which the electrode-cathode is made must possess such thermo-physical properties, as work function of the thermo-electrons is minimal. The number of thermo-electrons emitted by the cathode depends on the heating degree of the metal of the cathode. At first it was theoretically assumed, then experimentally confirmed, that the intensity of the thermo-electronic emission current can be expressed with the Richardson-Dushman relation [16]:

$$j_s = AT^2 e^{-\frac{W}{kT}} \qquad (1)$$

where: "js" is the emission current density (mA/mm^2); "A" is the Richardson constant (a proportionality constant, the value of which depends on the properties of the cathode material and the technical conditions of operation of the device), $A = 4\pi mek^2/h^3 \sim 1202$ mA/mm^{2}K^2, "m" is the mass of the electron, "e" is the elementary charge and "h" is the Planck's constant. In practice, "A" can be multiplied by a material-dependent correction factor (see Table 1). A ranges from about 32 to 160 Acm^{-2}K^{-2} for pure (polycrystalline) metals, and has a much larger range for oxidized and composite surfaces. "T" is the temperature (K), "W" is the electron extraction energy (the work function of the cathodic material, expressed in J), "k" is the Boltzmann constant (1.3806488E^{-23} J/K).

TABLE – 1
WORKING FUNCTIONS AND RICHARDSON'S CONSTANTS FOR VARIOUS MATERIALS

Material	W (eV)	A*b (Acm^{-2}K^{-2})
Nickel	4,61	30
Tantalum	4.12	60
Tungsten	4.54	60
Rhenium	4,85	100
Ba deposition on W	1,56	1,5
Cs deposition on W	1,36	3.2
Th deposition on W	2.63	3.0
Thorium	2,54	3,0

Source: simion.com/definition/richardson_dushman.html

From the relation (1) it is observed that the density of the thermo-electronic emission current is an exponential function of the absolute temperature of the cathode. In order to increase the intensity of the thermo-electronic emission current, the method of increasing the heating temperature of the cathode is applied, but this technique is limited (by the physical-mechanical properties of the cathode execution material) because at a limit temperature it softens or even melts, loses its mechanical properties and, as a result, its destruction takes place. Thus, as materials used for the construction of emitters, either pure metals or alloys with a high melting temperature are required, in order to increase their functionality. At present, tungsten or its alloys are widely used as a technical solution for the production of cathodes.

Another method of increasing the intensity of the emission current is to increase the potential difference applied between the cathode and the anode of the electron gun. In this case, the cathode serves as a transmitter and the anode – as an electron receiver. Increasing the value of the electric field strength vector, as if it seems to be aimed at achieving the orientation of the direction of movement of electrons. Nevertheless, in extreme conditions, even at normal temperatures, it can cause "snatching from the cathode" of free electrons, and determine the emitted particles to move towards the anode.

It is also very important to ensure a high degree of vacuum in the working chamber. This is necessary in order to avoid the collision of free electrons with gas molecules or atoms, which could reduce the number of electrons directed to the anode, and, as a result, reduce the intensity of the electron-emitting current.

It is known from the specialty literature [7] that the emission power is directly proportional to the area of the active emission surface ($P_E \sim \Delta A$) and can be expressed with the Boltzmann relation:

$$P_E = k\sigma T^4 \cdot \Delta A \tag{2}$$

where: "PE" is the emission power, "T" is the temperature of the cathode, "k" is the Boltzmann constant, "ΔA" is the active surface area; "σ" is the Stefan-Boltzmann constant. This results in a new method of amplifying the intensity of the thermo-electronic emission current. Therefore, changing the micro-geometry of the cathode surface could influence the output characteristics of the electronic guns. Thus, the research aims to increase the area of the active surface of the thermo-cathode and verify the scientific hypothesis. In accordance with relation (2), we assume that we will obtain a better thermo-electronic emission when keeping the parameter sun changed: temperature, potential difference between electrodes and the degree of vacuum in the working chamber.

There is a number of papers [2-8], in which, using the method of pulsed electric discharge machining (PEDM), on the surface of the cathodes intended for thermo-electronic emission, a prescribed micro-geometry in optimal conditions is created, depending on the properties of the conductive material. Thus, the analysis of the literature allowed to establish that changes in micro-geometry and the area of the active surface by extracting and freezing conical asperities, also called Taylor meniscuses, becomes possible by applying PEDM technology [3].

METHODOLOGY OF EXPERIMENTAL INVESTIGATIONS

Experimental research was performed in air (at ordinary conditions) at solitary discharges. Wires made of W (90%) with Re (10%) alloy, with a diameter (d) of 0.2 mm and 0.25 mm respectively, were applied as material for the execution of the cathodes intended for emission. For the research on the modification of the micro-geometry of the part surfaces by developing capillary waves on the surface of the liquid metal [3] in the conditions of PEDM, an installation was used, which is composed of: current pulse generator, command block, gap ionization block, electrode positioning mechanisms and gap size fixation with micrometric precision [5].

According to the methodology described in [6-7], Taylor cone-shaped asperities were extracted from the cylindrical surfaces of the wires (figure 1). The workpiece was connected in the discharge circuit as an anode, and the tool-electrode as a cathode. Energy parameters of the impulse discharge: Ws = 0.86 J (energy released in the gap), S = 0.3 mm (gap size), n = 1 (number of impulse discharges per unit area).

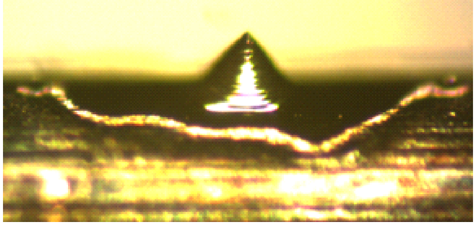

Figure 1: overview of the Taylor cone extracted by applying PEDM (the height and diameter of the base of this meniscus is of the order of 50-60 μm)

In order to build the volt-ampere emission characteristics, several pairs of cathodes were prepared, equal in size and general shape with those applied in industrial installations. For comparison, one set was made of unprocessed cylindrical wire, i.e., exactly like the industrial ones, and the second set was made of cathodes made out of cylindrical wire, but on the work surface of which conical asperities were extracted according to the methodology [5, 6]. Subsequently, the wires were inserted one by one into the working chamber (cathode K in the tube M, figure 2) of the laboratory installation.

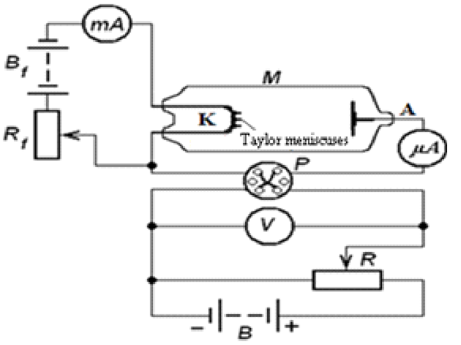

Figure 2: the principal scheme of the installation for measuring the thermo-electronic emission current by the express method

Using the potentiometric scheme, consisting of the battery B and the potentiometer R (fig. 2), the voltage U is applied between the electrodes which is measured by the voltmeter V. The cathode (K) is traversed by electric current (which intensity was measured by a miliammeter mA), which, as a result, heats up (Joule-Lentz effect). The incandescent cathode emits electrons which, under the action of an electric field (created by the potential difference U), acquire an ordered motion. The intensity of the thermo-electronic current I is measured with the help of the micro-ammeter μA. In order to avoid the oxidation of the cathode and the collisions of the electrons emitted by it with the air molecules in the working chamber (tube M, figure 2) preventively a high vacuum is created (the pressure approximately equal to $6 \cdot 10^{-6}$ mbar).

Of course, the express method of measuring the intensity of the electronic thermo-emission current provides us with quantitative information, but in order to talk about certain legitimacies of the phenomenon, much more accurate measurements and obligatory conditions are needed. Thus, a series of measurements of the electronic thermo-emission current were performed in the IFIN-HH research center, using the experimental set-up shown in Fig. 3.

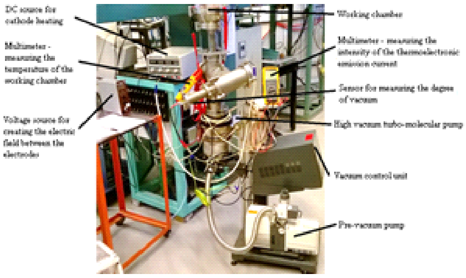

Figure 3: general view of the experimental set-up (IFIN-HH research center)

The emission process was monitored using the installation view window, and the thermal state of the cathode wire was monitored using a thermocouple connected to the temperature measurement multimeter.

RESULTS OF EXPERIMENTAL RESEARCH ON THERMO-ELECTRONIC EMISSION

In general, all phenomena in nature are more or less obvious starting with certain conditions or situations. Thus, at room temperature, the thermo-electronic emission is negligible, since for the release of only an electron from the metal, under the action of an external electric field, theoretically, it would be necessary that its intensity to be of the order of 10^{10} - 10^{11} V/m. Experimentally, it was found that the electronic emission at ambient temperature, also called the cold emission, can also take place for intensities of an external electric field with an intensity of the order of 10^7-10^9 V/m. This fact can be explained only by changing the shape of the potential barrier in the presence of the external electric field, and consequently, the existence of the possibility that some electrons penetrate the threshold through tunnel effect. Next, we will present the experimentally established laws regarding the dependencies of the output factors on those of the research input. According to [7, 10] the intensity of the thermo-electronic current "I" will raise with the increase of the potential difference "U" applied between the anode and the cathode, due to the growth of the electric field intensity between the two electrodes, favoring the emission through electric field, only until a certain value – called the intensity of the saturation current "I_s", which can be determined with the relation:

$$I_s = e \cdot N_{sec} \tag{3}$$

where "e" is the electron charge, and "Nsec" is the maximum number of electrons extracted per second.

The results of the experimental measurements show that the quantities "N_{sec}" and "I_s", respectively, increase very rapidly with the increase of the cathode temperature according to relation (2). On the other hand, according to the same relations, "P_E" is directly proportional to "ΔA".

Experimental measurements of electronic thermo-emission were performed for the active areas of the surfaces, which were considered equal to the diameter of the base of the conical meniscus. Tables 2 and Tables 3 show the experimental values of the diameter of the base and the height of the meniscus depending on the surface processing regime for samples made of tungsten alloys (90% W + 10% Re), and pure tungsten. Based on these results, the area increase of the active surface (ΔA) was also determined, by extracting from it an asperity in the form of Taylor cone. It has been observed that for the tungsten alloy, with the increase of the energy on the condenser battery from 0.18 J to 1.08 J, the height of the meniscuses varies from 49 μm to 126 μm. For pure tungsten, their height varies from 28 μm to 70 μm.

TABLE – 2
DIAMETER OF MENISCUS BASE, ITS HEIGHT AND SURFACE AREA AS A FUNCTION OF CONDENSER BATTERY CAPACITY AND DISCHARGE PULSE DURATION FOR ANODES MADE OF 90% W + 10% Re ALLOY

No.	C, (μF)	Uc, (V)	Wc,(J)	τ, (μs)	hm, (μm)	db.m., (μm)	ΔA, (μm^2)
1.	100	60	0,18	100	49	84	3493,33
2.	200	60	0,36	125	70	84	6049,79
3.	300	60	0,54	160	84	112	9190,21
4.	400	60	0,72	180	98	140	12925,69
5.	500	60	0,90	200	112	168	17259,69
6.	600	60	1,08	220	126	196	22193,96

TABLE – 3
DIAMETER OF MENISCUS BASE, ITS HEIGHT AND SURFACE AREA AS A FUNCTION OF CONDENSER BATTERY CAPACITY AND DISCHARGE PULSE DURATION FOR ANODES MADE OF W

No.	C, (μF)	U_c, (V)	W_c,(J)	τ, (μs)	h_m, (μm)	$d_{b.m.}$, (μm)	ΔA, (μm^2)
1.	100	60	0,18	100	28	56	1206,47
2.	200	60	0,36	125	35	84	1991,94
3.	300	60	0,54	160	42	112	2945,88
4.	400	60	0,72	180	56	140	5154,53
5.	500	60	0,90	200	63	168	6628,23
6.	600	60	1,08	220	70	182	8133,43

As we can see, the height of the meniscuses and the diameter of their base depend largely on the energy accumulated on the condenser battery. In other words, the energy is a very important parameter that influences the formation of meniscuses on metal surfaces, and for energy values 0.36 J; 0.54 J; 0.72 J and 0.9 J the diameters of the base of the meniscuses for these two types of the cathode material are practically identical.

Obtaining, on the surface of the alloy 90%W+10%Re, of the meniscuses with higher height compared to their height on the surface of pure tungsten, can be explained by the "rhenium effect".

Next, we will try to elucidate how the two parameters applied to determine the increase of the active area of the surface (ΔA) summary influence it, the results of the calculations are presented in Tables 2 and 3.

For the wire, with a diameter of 0.2 mm and a length of 66 cm, the electrical resistance was measured, which constituted 3.7 Ω. The resistivity was calculated and the values approximately equal to 17.6·10^(-8) Ω·m were obtained. It turns out that the resistance of the cathode is 0.112 Ω for every 2 cm of its length. For the wire of 0.25 mm in diameter with a length of 134 cm, the resistance was measured and the value of 4.2 Ω was obtained. The determined resistivity for this material has values of approximately 15.38·10^(-8)Ω·m. In this case, the electrical resistance for 2 cm of the length (the real length of the thermo-cathode wire) was equal to 0.063 Ω.

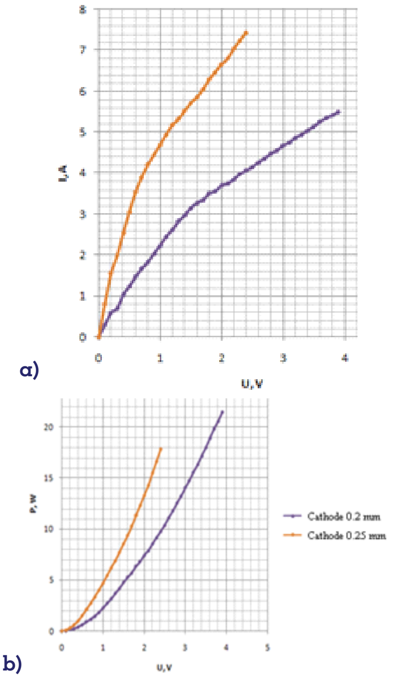

Figure 4: volt-amperic characteristic (a) and the dependence of the power dissipated on the cathode (b) depending on the voltage applied from the power supply for cathodes with diameters of 0.2 and 0.25 mm, respectively, made of tungsten alloy with 10% Re

In the case of the volt-amperic characteristic, the curves in Fig. 5 (a) may be approximated by the relations:

$$I = 2{,}08 \cdot U^{0{,}77} \tag{4}$$

$$I = 4{,}44 \cdot U^{0{,}65} \tag{5}$$

In relation (4), the exponent index is 0.77 (for d = 0.2 mm) and

0.65 (for d = 0.25 mm), which is easily explained by the fact that the cathode with smaller diameter heats up more strongly, and, with it, the intensity of the current increases faster.

Relationships (5) and (6) show the dependence of the power dissipated on the cathode, and, in this case, the same for smaller diameter, the value of the parameter increases faster for the smaller thickness of the wire of the cathode.

$$P = 2{,}08 \cdot U^{1{,}77} \qquad (5)$$

$$P = 4{,}44 \cdot U^{1{,}65} \qquad (6)$$

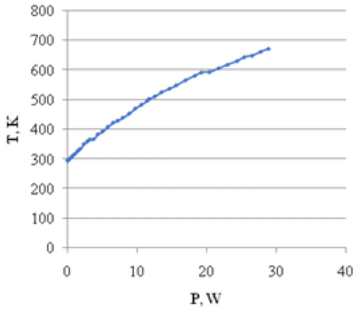

Figure 6: dependence of the cathode temperature on the power dissipated on it by the current source

During the experiment, the "I" and "U" values were measured directly to calculate the power, in order to determine the temperature dependence (see figure 5) on the input parameters. Subsequently, the dependence of the electronic thermal emission current is determined, being possible a comparison of the theoretical data and of the data obtained experimentally, for different cathodes (unprocessed or processed by the PEDM method).

The dependence of the electronic thermo-emission current on the parameters of the power supply (U, I or P) have practically the same shape.

$$T = 293 + 25{,}22 \cdot P^{0{,}84} \qquad (7)$$

The electrical resistivity of the material, respectively the electrical resistance of the thermo-cathodes changes with the change of temperature, which is also confirmed experimentally. Ohm's law cannot be applied for the high temperature range.

Below is the dependence of the intensity of the thermo-electronic emission current on the power of the source (figure 6) for the researched cathodes, in order to determine the maximum values of the saturation current intensity of the thermo-electronic emission.

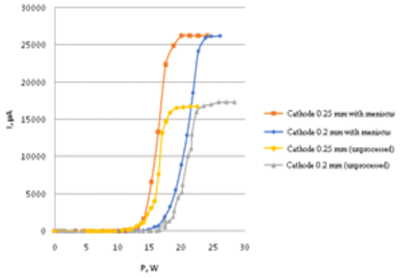

Figure 6: dependence of the intensity of the thermo-electronic emission current on the power of the source

For small values of the applied potential difference U, the current intensity I increases slowly at the beginning. This is explained by the fact that at low values of the potential difference between the electrodes not all the electrons emitted by the cathode reach the anode, being rejected by the electron cloud (negative space charge), located in the space between the anode and the cathode. As the potential difference U continues to increase, the electron cloud disperses and the intensity of the emission current I increases. For U = Us (saturation voltage) the intensity of the emission current no longer increases, because all the electrons emitted by the cathode reach the anode.

For small values of power P dissipated on the cathode, the intensity of the emission current I increases slowly at the beginning for all types of cathodes subjected to measurements. This is also explained by the fact that at low values of the power dissipated on the cathode, the electrons do not receive enough energy to move away from it. If we try to present the experimental dependencies of the intensity of the electronic thermo-emission current as a function of the power dissipated on the cathode from figure 6 by mathematical relations, then they can be written in the form:

$$I = -0{,}007P^6 + 0{,}527P^5 - 12{,}55P^4 + 134{,}2P^3 - 633{,}5P^2 + 1039P - 214{,}0 \qquad (8)$$

$$I = 0{,}019P^6 - 1{,}476P^5 + 41{,}05P^4 - 508{,}0P^3 + 2774{,}P^2 - 5445P + 1326 \qquad (9)$$

$$I = 0{,}000P^6 - 0{,}036P^5 + 2{,}458P^4 - 49{,}18P^3 + 369{,}6P^2 - 910{,}8P + 318{,}2 \qquad (10)$$

$$I = 0{,}021P^6 - 1{,}692P^5 + 49{,}95P^4 - 677{,}9P^3 + 4221P^2 - 9655P + 45{,}19 \qquad (11)$$

Relationships (8) and (9) express respectively the intensity of the electronic thermo-emission current as a function of the power dissipated on it, for the cathode with d = 0.2 mm, d = 0.25 mm and conical asperity on the active surface, and the relations (10) and (11) show the same dependence for cathodes with a smooth (cylindrical) surface.

Comparing the experimental results for all cases, we conclude that the cathodes that were processed by the method of impulse electric discharges with the extraction from the active surface of Taylor-type asperities showed a saturation current intensity for thermoelectronic emission much higher than of cathodes not processed by this method. At the same time, it is observed that the cathode with a larger diameter ensures a faster increase of the electronic current, which can be explained by the fact that it heats up faster. At the same time, it is observed that reaching the value of the saturation current is similar for both smooth cathodes and those with asperities (see figure 6).

Increasing the active area of the cathode by only 0.02 mm ^ 2 considerably influences the increase of the emission current. It would seem that the laws described by the classics of thermo-emission theory are being violated, but this is not the case. As already mentioned in the paper [3, 10] the surface of conical asperity is a complex one, with undulations, and on the surfaces of crystallization grains were observed nano-metric asperities, which in turn can cause increased efficiency of electron emission.

In the research previously performed by the authors [6, 7] it was established that the heating temperature of the cathode satisfies the classical dependencies. The results presented may vary depending on the established regimes and conditions (gap size, cathode heating temperature, dimensions and amount of roughness reported per unit area, Taylor meniscus extraction conditions, degree of oxidation of the processed surface, diameter and material the wire for the execution of the cathode, the degree of vacuum of the working chamber, etc.) for performing the experiment.

CONCLUSIONS:

From the results of the performed research, we conclude that:

- the thermo-electronic emission depends on the properties of the cathode execution material, the area of the emission surface and its heating temperature;

- the results of the experimental researches demonstrate that the increase of the intensity of the thermo-electronic emission current can be achieved by increasing the area of the active surface of the cathodes by extracting the meniscuses, inclusively by applying PEDM;
- the height of the meniscuses and the diameter of their base largely depends on the energy accumulated on the condenser battery which is a very important parameter that influences the formation of meniscuses on metal surfaces;
- in order to obtain truthful results about the value of the intensity of the thermo-electronic emission current, it is necessary to create a high degree vacuum in the working chamber;
- the applied method allows to increase the intensity of the thermo-electronic emission current by about 10^4 A compared to the cathodes whose active surfaces have not been processed by this method.

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