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Conditions of steady arc ignition in vacuum and hollow cathode operational life

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ABSTRACT

Purpose: The aim of this paper is to determine the conditions of steady arc ignition in vacuum and the effect some of the main operating parameters have on the life of tantalum-foil hollow cathodes.

Design/methodology/approach: The experiments presented in this paper have been carried out with equipment for vacuum hollow cathode arc processing similar to what is used in the industry. In order to find out if steady arc ignition is possible, a two-level factorial experiment has been conducted helping to establish the corresponding regression dependency between the factors examined and the starting parameter values. The evaluation of hollow cathode operational life is based on three criteria: indirectly, considering their erosion [μ]; establishing possible damage on their surface which leads to plasma-forming gas leakage and makes the arc unsteady; taking into account the critical change in the cathode shape.

Findings: It has been established that when a multi-stage arc torch is using the necessary minimum amount of the plasma-forming gas for Ø 3.5-mm-diameter hollow cathodes is QAr=0/3 l/h, and, for Ø 6.0-mm-diameter hollow cathodes, it is QAr=2.4 l/h. It has been established that the operational life of tantalum hollow cathodes can be and even exceed 3 hours. Of all the parameters that have been studied, vacuum level has the most negative effect. It has been confirmed that tantalum-foil hollow cathodes are suitable mainly for current intensity values of about 120 A.

Practical implications: The results of the research allow: guaranteed hollow cathode arc ignition regardless of its diameter at the working levels of plasma forming gas; the choice of operating modes ensures the implementation of processes of varying lengths without the need for premature replacement of the hollow cathode.

Originality/value: This paper presents the results showing the conditions necessary for steady arc ignition in vacuum with a hollow cathode of the following diameters: Ø 3.5 mm and Ø 6 mm. The effect of some of the main working parameters on the operational life of hollow cathodes made of tantalum foil is also studied

Keywords: Welding; Vacuum technology; Hollow cathode arc; Erosion

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MANUFACTURING AND PROCESSING

1. Introduction

Hollow cathode arc has been developed in the sixties of last century, as a heat source to operate at low pressures (vacuum). It is suitable for handling chemically active metallic materials such as titanium, copper, aluminium alloys and high-alloyed steels [1-4].

Its typical high density heat flow (5.10^3-10^5 W/sm^2) and high effective coefficient of performance (0.77-0.87) allow it to be assigned to the so-called "highly concentrated sources of energy" which includes also laser and electron beam and plasma arc [5-8].

The hollow cathode arc (HCA) in vacuum is a very prospective source of energy which can be used for carrying out a number of technological processes, such as welding, brazing, soldering, even heat treatment and coating processes, both on Earth and in space [9-11]. This requires its steady ignition, as well as its continuous existence.

In order to ignite and maintain the arc on Earth, multi-stage arc torches are mainly used. They heat the hollow cathode up to a thermal emission temperature by means of a pilot arc, which in turn most often requires a single high-voltage impulse from a capacitor battery [12-14].

Spark discharge and pilot arc take place depending on:

- the distance between the auxiliary electrode of the torch and its base, „L“ (Fig. 1);
- the magnitude of the ignition voltage;
- the pressure of the plasma-forming gas in the torch whose capacity is determined by its consumption, etc.

As a result of the operation of the vacuum pump unit, however, when the hollow cathodes have different diameters but the amount of the plasma-forming gas is the same, the pressure within the torch differs. This in turn is connected in some cases with the need of feeding much greater quantities of plasma-forming gas into the unit than the usual ones in order to create the conditions allowing for arc ignition, after which the amount of gas has to be reduced which is a waste of time and leads to warming up of the workpiece.

Scientific literature provides general information on the necessary distance, „L“, and on the magnitude of the ignition voltage, but there is no information on the connection between these or on the amount of the plasma-forming gas necessary to guarantee steady arc ignition for different diameters of the hollow cathode.

Technological processes carried out with the help of vacuum arc discharge have different duration and working parameters which depend to a great extent on the operational life of the hollow cathodes that have been used. They are made of Tantalum (Ta) or Tungsten (W) foil or rods. Their replacement in case of untimely failure can lengthen the process by more than 0.5-1.0 hour.

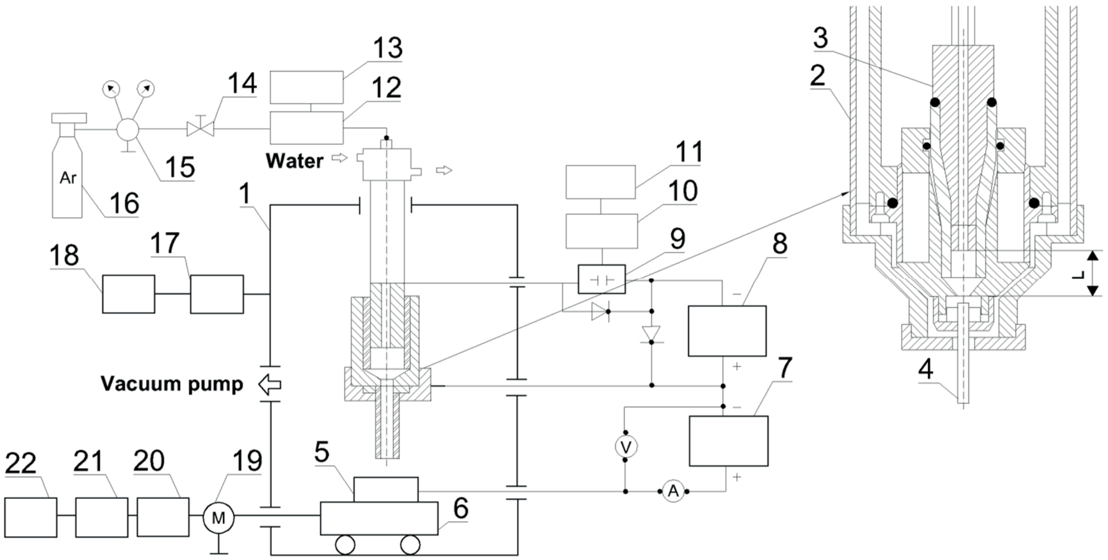

Fig. 1. Scheme of the vacuum installation used: 1 – Vacuum chamber; 2 – Torch; 3 – Auxiliary electrode; 4 – Hollow cathode; 5 – Workpiece; 6 – Auxiliary equipment providing progressive movement; 7 – Main power source; 8 – Auxiliary power source; 9 – Capacitor battery; 10 – Capacitor voltage regulator; 11 – Regulator power supply unit; 12 – Plasma-forming gas flow controller; 13 – Plasma-forming gas monitor (reading gauge); 14 – Micro inlet valve; 15 – Reducing valve; 16 – A cylinder of plasma-forming gas; 17 – Vacuum controller; 18 – Vacuum gauge; 19 – Electric motor setting in motion the welding table; 20 – Amplifier; 21 – Digital-analogue converter operating the electric motor; 22 – Speed setting module

After cathode sputtering speed has been considered, it turns out that its operational life must be tens, even hundreds of hours. However, when using 3-4 mm-diameter cathodes made of tantalum or tungsten foil with current intensity I=100-120 A, it is shorter than 2 hours [12].

According to scientific literature data, the main reason for the destruction of the cathodes is their oxidation during the process as a result of oxygen and water vapor present in the plasma-forming gas that is used [12]. However, there is no information on the way the rest of the parameters affect operation.

The aim of this paper is to determine the conditions of steady arc ignition in vacuum and the effect some of the main operating parameters have on the life of tantalum-foil hollow cathodes.

In order to achieve this aim, the following tasks have had to be carried out:

- determining the main factors influencing steady arc ignition and hollow cathode operational life to be studied;
- choosing the appropriate research and measuring equipment;
- developing a methodology, conducting the experiments and processing the results.

2. Methodology

All the experiments presented in this paper have been carried out with Ruse University equipment for vacuum hollow cathode arc processing similar to what is used in the industry. Figs. 1 and 2 show a scheme and a general layout of the installation. It consists of a 0.5 m^3 vacuum chamber, a vacuum pump unit, gauges for micro gas-collection and for reading the amount of plasma-forming gas, as well as arc welding sources. In the chamber (Position 1) there is a welding torch (Position 2) using multi-level arc ignition, as well as auxiliary welding equipment (Position 6) ensuring the progressive movement of the workpiece along axes X and Y. The pump unit providing the necessary back pressure in the chamber consists of three vacuum pumps having the following characteristics: a pre-vacuum pump whose productivity is 200 m/h, a two-stage rotary pump (Roots) whose productivity is 600 m/h and a steam ejector (diffusion pump) whose productivity is 600 l/s. Pressure reading in the chamber is performed by means of a magnetic electric discharge vacuum gauge PENNINGVAC PM 310 and a resistive vacuum gauge PWN 100 (Position 18).

The plasma-forming gas is Argon (Ar), which is 99.999% pure. It is fed by means of a micro Leybold AG Inlet Valve (Position 14). The respective amount of gas is read by a Hastings Mass Flow Controller (Position 12) and a digital Hastings Flow Monitor (Position 13).

a)

b)

Fig. 2. General layout of the equipment used: a) internal layout of the chamber; b) control panel and pump unit

The arc welding sources (main source – Position 7 and auxiliary source – Position 8) are constant current with drooping characteristics of the welding power source. They allow for the use of maximum welding current of 300 A.

The hollow cathodes used (Position 4) are pipe-shaped which makes gas feed through them easier. They are made of tantalum foil and have the following dimensions: length – l=30 mm, wall thickness – δ=0.2 mm, as well as various diameters.

The anode (Position 5) is made of copper and is water-cooled in order to prevent metal fume emissions during its heating.

2.1. Steady arc ignition

In order to find out if steady arc ignition is possible by means of a hollow cathode, a two-level factorial experiment has been conducted helping to establish the corresponding regression dependency between the factors examined and the starting parameter values.

In this case the following have been used as manageable factors:

- the distance between the auxiliary electrode and the torch base (L);
- the value of the ignition voltage applied between them;
- the starting parameter is the quantity of the plasma-forming gas necessary for arc ignition.

Natural and coded values of the factors are shown in Table 1. The choice of fluctuation levels has been made on the basis of the geometrical dimensions of the torch and on the safety requirements for work on high voltage equipment.

Table 1.
Fluctuation levels of the manageable factors

Fluctuation levels	Natural values		Coded values	
	L, mm	U, V	X1	X2
Upper level	7	600	+1	+1
Middle level	12	500	0	0
Lower level	17	400	-1	-1
Fluctuation range	5	100	-	-

where:

- L, mm is the distance between the auxiliary electrode of the torch and its base;
- U,V is the value of the ignition voltage.

The hollow cathode diameters used are Ø 3.5 mm (used more often when welding) and Ø 6 mm (used more often when brazing). The current intensity is 100 A, and the vacuum level in the chamber is P = 5.100 Pa.

After having established the necessary distance (the auxiliary electrode is compound – Position 3, Fig. 1) and the regulator voltage (Position 10), plasma-forming gas is fed between the electrodes and its amount changes every 0.1 l/h until steady arc ignition has been achieved.

2.2. Hollow cathode operational life

The evaluation of hollow cathode operational life is based on three criteria:

- indirectly, considering their erosion [μ];
- establishing possible damage on their surface which leads to plasma-forming gas leakage and makes the arc unsteady;
- taking into account the critical change in the cathode shape.

It is generally agreed that experiments last for 1 hour.

The following operational life parameters related to both the appropriate technological processes and the operational life of the hollow cathodes used have been studied:

- vacuum level – P = 5.10^0, 5.10^{-1} Pa – connected with the technological process carried out and the chemical composition of the processed materials;
- operation cycle – S = 50% (2-minute operation, 2-minute break) and S=100% (continuous operation);
- current intensity – I= 80, 120, 160 A – determined by the dimensions and the material of the hollow cathode. For tantalum-foil cathodes whose diameter is Ø4 mm, current intensity of 80-160A is used;
- amount of plasma-forming gas - Q_{Ar}= 1.0, 2.0, 3.0 l/h – connected with the diameter of the hollow cathode used and with the density of the heat flow.

The present paper does not study the influence of the purity of the plasma-forming gas.

SARTORIUS RC210D electronic scales, whose accuracy is 0.00001 g, have been used to weigh the hollow cathodes before and after operation in order to establish their corrosion.

3. Results and analysis

3.1. Conditions of steady hollow cathode arc ignition

Table 2 and Fig. 3 show the results proving that steady hollow cathode arc ignition is possible.

Table 2.
Result of the experiments carried out

No.	X_1	X_2	Q_{avg} with d_{hc}= 3.5 mm	Q_{avg} with d_{hc}= 6 mm
1	17	400	0.9	4.1
2	17	500	0.7	3.2
3	17	600	0.3	2.4
4	12	400	1.2	4.4
5	12	500	0.9	3.4
6	12	600	0.5	2.6
7	7	400	1.5	4.6
8	7	500	1.0	3.6
9	7	600	0.7	2.8

where:

- X1(L) is the distance between the auxiliary electrode and the torch base, mm;
- X2 (U) is the value of the ignition voltage, V;
- Q_{avg} is the average amount of plasma-forming gas necessary for steady arc ignition, l/h.

The data of the experiments have been processed using STATISTICA 7, a software product for regression analysis [15]. It has also been used to draw the same response surfaces (Fig. 3) and to obtain the following regression equations:

$$\hat{Y} = 10.29 - 0.05 \cdot X - 0.016 \cdot X_2 - 0.0011 \cdot X^2 + 8 \cdot 10^{-5} \cdot X_1 \cdot X_2 + 5.833 \cdot 10^{-6} \cdot X_2^2$$

with d_{hc}=6 mm (1)

- $\hat{Y}=4.04-0.129\cdot X_1-0.005\cdot X_2+6.67\cdot 10^{-5}\cdot X_1^2+0.0002\cdot X_1\cdot X_2-3.33\cdot 10^{-7}\cdot X_2^2$
  with d_{hc} = 3.5 mm (2)

Figure 3 shows that, generally, shorter distances between the auxiliary electrode and the torch base and lower ignition voltages make steady arc ignition possible when the gas flow rate is higher.

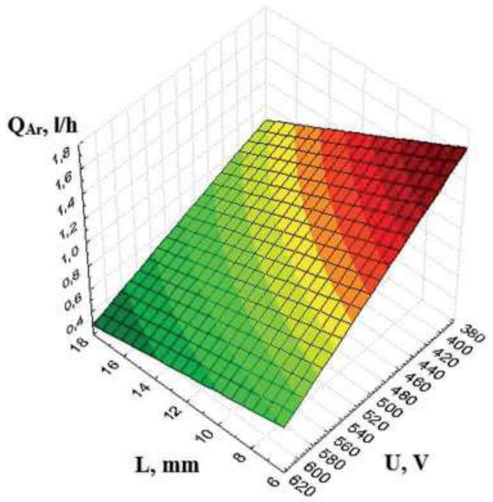

Fig. 3. Relation between the necessary quantity of plasma-forming gas and the values of ignition voltage and the distance between the auxiliary electrode and the torch base

For cathodes with a Ø 3.5 mm diameter, it is possible to use a lower ignition voltage (500 V) regardless of the distance between the electrodes. The quantities of the gas fed are typical for this diameter and for the technological process of welding.

For hollow cathodes with a Ø 6 mm diameter, however, the ignition voltage and, possibly, the distance between the electrodes have to be as great as possible. This could ensure arc ignition using operational quantities of plasma-forming gas and not greater amounts which would require subsequent correction. In case the amount of gas needs to be reduced, ignition and operation start have to be done on starting strips before proceeding to the workpiece.

As it is much easier to change ignition voltage than the distance between the electrodes, an appropriate option is to fit an auxiliary electrode whose length allows for a maximum distance between them and then to increase the voltage until steady cathode hollow arc ignition in vacuum has been obtained.

3.2. Hollow cathode operational life

The results showing the effect of the tested operational parameters on erosion and, hence, on hollow cathode operational life, are presented in Table 3 and Fig. 4.

It can be seen that the operational life of tantalum hollow cathodes that are used, having the operational parameters shown in Table 3, can be and even exceed 3 hours, which is absolutely enough to conduct the different technological processes or a combination of them (e.g. welding and heat treatment processing).

The obtained results presented in Table 3 and Fig. 4 show clearly that the vacuum level in the chamber has the most negative effect on hollow cathode operational life. When the rest of the conditions are the same, reducing the vacuum by a single unit from 5.10^{-1} Pa (Experiment 2, Fig. 4) to 5.10^{0} Pa (Experiment 7, Fig. 4) results in a more than 10-fold erosion increase and 3-fold operational life decrease (Experiments 3 and 7, Fig. 4). The operational life in Experiment 7 varies from 55 to 60 min depending on the rest of the parameters: current intensity and plasma-forming gas quantity.

Table 3.
Results of the experiments carried out

	I, A	Q_{Ar}, l/h	P, Pa	S, %	t, min	Cathode weight, g		μ, g/h	Notes
						before operation	after operation		
1	80	2.0	5.10^{-1}	100	60	1.48490	1.46436	0.02054	No changes
2	120	2.0	5.10^{-1}	100	60	1.46130	1.42826	0.03304	Partial oxidation and destruction
3	120	2.0	5.10^{-1}	100	180	1.53380	-	-	Destroyed during operation
4	160	2.0	5.10^{-1}	100	60	1.46460	1.39339	0.07121	Partial oxidation and destruction
5	120	1.0	5.10^{-1}	100	60	1.48560	1.44685	0.03875	Partial oxidation and destruction
6	120	3.0	5.10^{-1}	100	60	1.47620	1.45741	0.01879	No changes
7	120	2.0	5.10^{0}	100	60	1.59462	1.11358	0,38104	Significantly damaged cathode surface – unsteady arc
8	120	2.0	5.10^{-1}	50	60	1.48930	1.41588	0.07342	Cathode deformation and oxidation

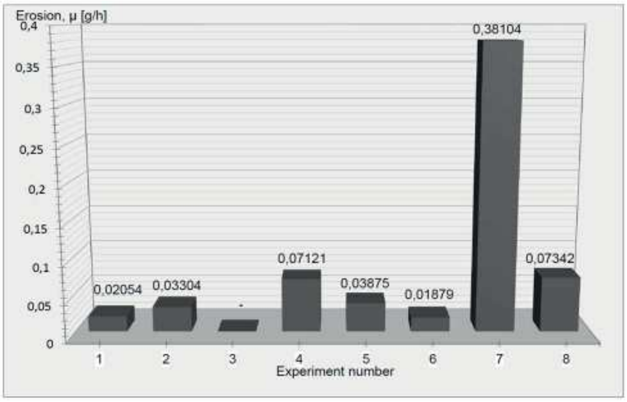

Fig. 4. Erosion values μ (Table 3) of tantalum hollow cathodes obtained for different operational parameters

The presence of cathode surface damages (Fig. 5) is most probably a result of the interaction of the tantalum with the oxygen in the ambient air due to lower vacuum leading to TaO_2 and Ta_2O_5 eutectic structures that have comparably low melting temperatures [1].

The operation cycle also has a significant effect on hollow cathode erosion and operational life. Multiple arc ignition (30-fold in this case) increases erosion more than twice (Experiments 8 and 2) and causes cathode deformation (Fig. 6) as a result of thermal stress during repeated heating and cooling.

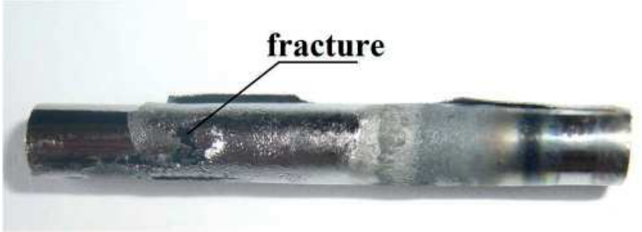

Fig. 5. The way the hollow cathode looks at a vacuum level $P=5.10^0$ Pa (Experiment 7)

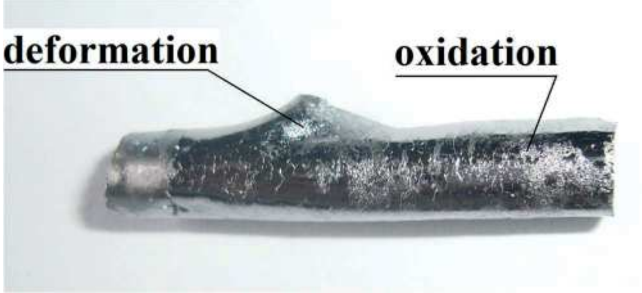

Fig. 6. The way the hollow cathode looks after repeated use S=50% (Experiment 8)

Current intensity also influences significantly hollow cathode erosion and operational life (Experiments 1, 2 and 4). The greatest change is observed when current intensity is 160 A, which confirms scientific data that tantalum-foil hollow cathodes are suitable for currents whose values are approximately up to 120 (150) A. Reducing current intensity decreases erosion and the lowest erosion rate is detected at I=80 A.

Figure 7 shows the way the hollow cathodes used in Experiments look like.

Fig. 7. The way the hollow cathodes look like

Increasing the amount of the plasma-forming gas is related mainly to the decrease of the heat flow density and hence of erosion (Experiments 6, 2 and 5).

The main changes here concern gas quantities of 3.0 l/h. In comparison with the experiment in which 1.0 l/h is used, erosion decreases more than twice and is the lowest erosion rate reported. These results show that the plasma-forming gas used is relatively pure and dry. Otherwise, increasing its amount would have been expected to increase erosion rates.

4. Conclusions

The following more significant conclusions can be drawn from the conducted experiments:

- It has been established that using a multi-stage arc torch the main factors determining the amount of the plasma-forming gas necessary for steady hollow cathode arc ignition in vacuum are the ignition voltage value and the distance between the auxiliary electrode and the torch base.
- It has been established that if the ignition voltage and the distance between the auxiliary electrode and the torch base increase, the amount of the plasma-forming gas that is necessary decreases: the minimum amount for Ø 3.5-mm-diameter hollow cathodes is Q_{Ar}=0.3 l/h, and, for Ø 6.0-mm-diameter hollow cathodes, it is Q_{Ar}=2.4 l/h.
- It has been proved that the quantity of the plasma-forming gas, vacuum level, operation cycle and current

intensity have a significant effect on the operational life of tantalum hollow cathodes.

- Of all the parameters that have been studied, vacuum level has the most negative effect: its decrease by a single unit leads to a 3-fold decrease of the cathode operational life – from 180 min to 55-60 min.
- Operation cycle influences significantly not only erosion, but also the shape of the hollow cathode, which additionally decreases its operational life. Therefore, it is recommended to use operation cycles involving a minimum number of arc ignitions.
- It has been confirmed that tantalum-foil hollow cathodes are suitable mainly for current intensity values of about 120 A. If these values are higher, there is a significant increase in erosion rates and cathode operational life decreases.
- The influence of the amount of the plasma-forming gas is connected mainly with the change in the density of the heat flow: in order to decrease erosion and increase operational life of Ø 4-mm-diameter hollow cathodes, its amount must be more than 2.5 l/h. When the specimens were immersed in Na_2SO_4 solution with lower chloride concentration, steady state potentials, corrosion potentials and corrosion current densities, and hence, corrosion rates, were unaffected by the deformation process. The deformed specimen was less susceptible to pitting corrosion and showed smaller rates of localised (pitting) corrosion than the heat treated one.

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