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DEVELOPMENT OF A METHOD FOR CALCULATING THE VAPOR-GAS ENVELOPE THICKNESS AND STUDYING THE INFLUENCE OF CATHODIC HEATING PROCESS ENERGY CHARACTERISTICS ON THE VAPOR-GAS ENVELOPE THICKNESS

Abstract: *A method for calculating the thickness of the vapor-gas envelope formed around the cathode during electrolytic-plasma heating has been developed, taking into account the energy characteristics of the process. The proposed approach is based on an analysis of the energy balance in the near-cathode region and considers the effects of current density, voltage, thermophysical properties of the electrolyte, and heat-transfer parameters on the conditions of evaporation and vapor-gas mixture formation. Experimental studies were carried out under cathodic heating of steel 20 samples in a Na_2CO_3 solution at 100-300 V with simultaneous recording of temperature and electrical parameters. Numerical modeling of current and energy distribution in the near-cathode region was performed in COMSOL Multiphysics. Relationships between the vapor-gas envelope thickness and the discharge energy parameters were established, and it was shown that its growth is accompanied by the transition from nucleate to film boiling of the electrolyte and by an increase in the cathode heating intensity. The obtained results can be used for selecting electrolytic-plasma processing regimes and for modeling thermal processes in the near-cathode zone.*

Key words: *electrolytic-plasma treatment, steel 20, cathode heating, vapor-gas envelope, envelope thickness, current density, numerical modeling.*

Introduction: One of the key factors determining the efficiency of electrolyte-plasma and cathodic electrolyte-plasma processes is the formation of a stable vapor-gas envelope around the

cathode. The thickness of this envelope directly influences the ionization intensity and, consequently, the surface temperature of the treated sample. However, the precise determination of the envelope parameters is complicated by the complex interaction between thermal, electrical, and hydrodynamic phenomena occurring in the near-cathode zone.

In this regard, the task was set to develop a methodology for calculating the vapor-gas envelope thickness based on the energy characteristics of the cathode heating process-such as current density, voltage drop, specific power, and heat transfer coefficient. The proposed approach allows for linking observable experimental parameters (surface temperature, visual signs of discharge, current load) with the physical characteristics of the envelope, thereby providing a quantitative assessment of the conditions for thermochemical treatment (TCT).

As part of the conducted research, the dependence of the vapor-gas envelope thickness on the main energy parameters of the discharge was determined. The results of the calculations and experimental observations revealed patterns in the variation of the envelope thickness at different levels of cathode heating and allowed for the proposal of criteria ensuring its stable formation. Below are the obtained data and their interpretation, reflecting the relationship between heating modes and the structural-energy characteristics of the near-cathode zone.

Materials and methods

To study the formation and calculate the thickness of the vapor-gas envelope during cathode heating, an electrolyte-plasma treatment unit with a regulated DC power source was utilized. A 20% aqueous solution of sodium carbonate (Na_2CO_3) served as the electrolyte. The cathode voltage was varied within the range of 100-300 V, enabling the realization of various heating modes-from nucleate boiling of the electrolyte to the formation of a stable vapor-gas envelope.

The research subjects were samples of Grade 20 structural steel (AISI 1020 equivalent) with dimensions of $20 \times 20 \times 10$ mm. Prior to the experiments, the sample surfaces were ground using abrasive papers of various grit sizes (from 60 to P2500), subsequently polished with diamond paste (particle size 0.25-0.5 μm), and cleaned with ethyl alcohol.

The surface temperature and heating parameters were recorded using thermocouples and a digital measurement system. To determine the current and energy distribution in the near-cathode zone, numerical modeling was performed in COMSOL Multiphysics 6.2 using the Electric Currents module. The model accounted for the electrophysical properties of both the electrolyte and the steel, as well as the boundary conditions: a negative constant voltage at the cathode and zero potential at the anode surface.

Results and discussion

If we consider the process of electrolytic-plasma treatment from the perspective of the current-voltage dependence, three regions can be distinguished on the volt-ampere characteristic curve (Figure 1). In the first region (phase I), the Faradaic electrolysis process occurs, during which the current reaches a peak value. This is followed by the current interruption region (phase II). When a certain critical voltage V_B is reached, active gas bubble formation begins at the cathode surface, causing the average current to drop. In this phase, bubble boiling of the electrolyte occurs in the near-cathode zone. With a further increase in voltage (phase III), a stable vapor-gas envelope forms around the cathode part as the bubbles merge, resulting in film boiling of the electrolyte. This is the cathodic process region, where the workpiece is heated by the plasma formed. The onset of this process is marked by the achievement of the second critical voltage V_D.

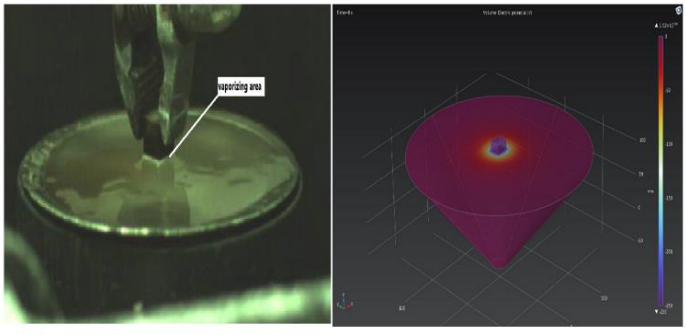

Figure 1 – The region of vapor-gas envelope formation around the cathode workpiece

The formation of bubbles occurs, firstly, due to the electrolysis of the electrolyte solution, which releases gases, and secondly, as a result of the evaporation of the water base of the electrolyte [1]. The mixing of these bubbles forms the basis of the vapor-gas envelope in the near-cathode region. For a vapor-gas envelope to form, the near-cathode layer of the electrolyte solution must be heated to its boiling temperature (Figure 2).

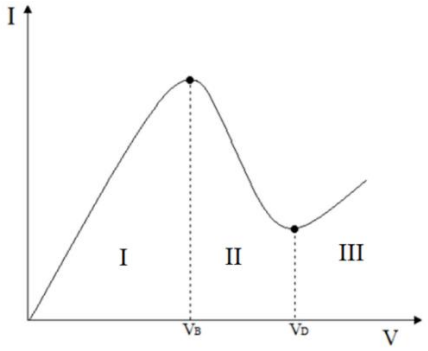

Figure 2 – Volt-ampere characteristic of cathode heating

The vapor-gas envelope (VGE) is a mixture of water vapor, activated OH^- and H^+ particles, and ions present in the electrolyte. The main voltage drop in the electrical circuit occurs precisely in this region, so its properties largely determine the nonlinear nature of the current-voltage dependence of the electrolytic-plasma treatment (EPT) process. The electric field strength in the VGE reaches 10^6-10^7 V/m [2]. At a temperature of around 100 °C, this field causes ionization of the vapors as well as emission of electrons and ions, which sustain a stationary electric discharge and form the so-called electrolyte plasma.

The most common application of electrolytic plasma treatment for steel products is the saturation with light elements – nitriding, carburizing, and boriding. Multicomponent surface modification is also possible, with simultaneous incorporation of several elements (nitrocarburizing, sulfonitrocarburizing) or carbide-forming elements such as tungsten, vanadium, molybdenum, and their combinations. This greatly expands the possibilities for controlling the structure and properties of the surface. Previously, diffusion saturation under electrolytic plasma conditions has been studied for both anodic and cathodic processes, primarily applied to steels and titanium (nitriding, nitrocarburizing). It should be noted that the physico-chemical processes occurring in electrolytic plasma are largely analogous to the processes characteristic of other types of electrochemical-thermal treatment (ECTT).

Passing an electric current through an electrolytic cell containing two metal electrodes – an active and an auxiliary electrode – with a gradual increase of the applied voltage leads to a sequential change of the process regimes [3, 4]. The active electrode, having a significantly smaller surface area, plays a key role in the formation of near-cathode phenomena.

The formation of a stable, continuous vapor-gas envelope (VGE) around the active electrode is a necessary condition for implementing the electrolytic-plasma heating mode of metals. Since in this mode electrochemical processes practically do not affect the establishment of thermal balance, all phenomena occurring at the metal-electrolyte interface are purely thermal in nature. Consequently, the heating of the active electrode can be interpreted as a thermal process analogous to boiling in classical thermophysics.

It is known that as the heat flux density from the heater to the liquid increases, the convective heat transfer regime transitions into the bubble boiling regime. In this case, intensive vaporization of the electrolyte occurs at the heater surface. At a critical heat flux, a continuous vapor layer forms, which results in film boiling.

Based on the analysis of experimental data and literature sources [5-7], the near-electrode region of the active electrode can be represented as a multilayered structure. Layer 6, depending on the composition of the electrolyte, may be either solid and continuous or liquid and porous. In the anodic mode of electrolytic-plasma treatment (EPT), this layer often contains oxide compounds.

The superheated near-electrode region 3 is separated from the bulk of the electrolyte by an isothermal surface. Within this zone, the liquid temperature exceeds the boiling point, while outside the isotherm it remains below boiling. Therefore, region 3 represents a boiling boundary layer in which intensive vaporization occurs. Gas bubbles are also released here due to electrolysis.

According to the proposed model, electric current near the active electrode passes through a multiphase system. In the case of a non-continuous liquid surface layer, possible sequences of transitions include:

metal → electrolyte → gas → electrolyte, or metal → gas → electrolyte.

If the surface layer is continuous and solid (conductive or semiconductive), the transitions may be:

metal → semiconductor → gas → electrolyte, or metal → gas → electrolyte.

In these cases, the nature of conductivity changes from electronic to electron-ion and then to ionic mechanisms.

In the vapor-gas zone, when electric current passes through the electrolytic cell, thermal energy is released in proportion to the resistance of the corresponding segment of the circuit. The resistance of the metallic electrode and the main electrolyte layer is significantly lower than the resistance at the «metal-electrolyte» interface; therefore, the greatest heat release occurs precisely in this region. This leads to intensive bubble boiling of the electrolyte at the electrode surface. The flowing current causes local heating and partial evaporation of the electrolyte.

For the system to transition to a stable heating mode, bubble boiling must shift to film boiling – this occurs when the metal electrode temperature exceeds approximately 125°C. Further increase in energy released at the interface causes dynamic instability of the two-phase boiling layer, resulting in the replacement of bubble boiling by film boiling. In this mode, the surface of the active electrode is covered by a continuous vapor-gas envelope, which stabilizes the discharge process.

It is evident that the resistance of the electrodes and the liquid electrolyte is significantly lower than the resistance of the vapor-gas envelope. Therefore, it can be assumed that the main portion of the electrical energy supplied from the power source is spent on heating and vaporizing the electrolyte.The energy balance of the process can be expressed by the equation:

$$UIt = m(c\Delta T + \psi + c_v \Delta T_v), \quad (1)$$

where I – current intensity (A), m – mass of the evaporated electrolyte (kg), c – specific heat capacity of the electrolyte (J/(kg·K)), ΔT – difference between the initial temperature of the electrolyte and its boiling point (K), ψ – specific latent heat of vaporization (J/kg), $\mathbf{c_v}$ – specific heat capacity of the vapor at constant pressure (J/(kg·K)), $\mathbf{\Delta}T_v$ – difference between the boiling point and the vapor temperature (K).

ΔT_v – the difference between the boiling temperature of the electrolyte solution and the temperature of the vapor.

The mass of the evaporated electrolyte can be expressed as

$$m = \rho S \delta_0, \quad (2)$$

where ρ – density of the liquid electrolyte (kg/m³), S – area of the active electrode surface (m²), and δ_0 – thickness of the liquid layer involved in evaporation (m).

The thickness of the formed vapor-gas envelope is related to $\delta_0$by the following relation:

$$\delta = \delta_0 \frac{\rho}{\rho_v}, \quad (3)$$

where $\rho_v = \frac{\mu P}{RT}$ is the density of water vapor (kg/m³), determined from the ideal gas equation of state; μ\muμ is the average molar mass of the electrolyte (kg/mol); PPP is the pressure (Pa); RRR is the universal gas constant (J/(mol·K)); TTT is the average temperature of the vapor-gas envelope (K), which can be taken as the half-sum of the electrolyte boiling temperature and the cathode surface temperature.

Thus, the expression for calculating the vapor–gas envelope thickness has the form

$$\delta = \delta_0 \frac{\rho RT}{\mu P}. \quad (4)$$

The vapor–gas mixture formed in the envelope region rises upward under the action of the buoyancy (Archimedes) force. Under steady-state conditions, the mass of evaporating liquid must be equal to the mass of vapor rising upward. Analysis of the scheme shows that, in the steady

regime, the vapor velocity is determined by the balance between the buoyancy force and viscous resistance. For the envelope center, this relation can be written as

$$\rho g \delta S = 2 S \eta_v \frac{v}{\delta}, \quad (5)$$

from which the vapor velocity is

$$v = \frac{\rho g \delta^2}{2\eta_v}. \quad (6)$$

The vapor viscosity can be expressed through its molecular characteristics:

$$\eta_v = \frac{\lambda \rho_v}{3}\sqrt{\frac{8RT}{\pi\mu}} = \frac{\lambda P \mu}{3RT}\sqrt{\frac{8RT}{\pi\mu}} = \frac{\lambda P}{3}\sqrt{\frac{8\mu}{\pi RT}}, \quad (7)$$

where λ – is the mean free path of vapor molecules (m).

Since the vapor velocities at both boundaries of the vapor-gas envelope (metal side and electrolyte side) differ, the average vapor flow velocity is taken to be approximately half the maximum value. Thus,

$$v = \frac{\rho g \delta^2}{4\eta_v}. \quad (8)$$

The amount of liquid evaporating from the active electrode surface per unit time must equal the mass of vapor removed upward from the envelope. This condition can be written as

$$\frac{UjS}{c\Delta T + \psi + c_v \Delta T_v} = \rho_v v \delta Z, \quad (9)$$

where jjj is the current density (A/m²), ZZZ is the mean hydraulic size of the surface (m), for a rectangular shape calculated as $Z = \frac{2 \cdot a \cdot b}{(a+b)}$ a,b are the width and length (m), S=ab is the cathode area (m²).

Hence,

$$\frac{Ujab}{c\Delta T + \psi + c_v \Delta T_v} = \delta^3 \frac{2 \cdot a \cdot b}{(a+b)} \frac{P \mu \rho g}{4 \eta_v RT} \quad (10)$$

Finally, the expression for the vapor–gas envelope thickness is obtained as

$$\delta = \sqrt[3]{\frac{2RT\eta_v Uj(a+b)}{(c\Delta T + \psi + c_v \Delta T_v) P \mu \rho g}}$$

Conclusion

In conclusion, the present study proposes a method for calculating the thickness of the vapor-gas envelope formed during cathodic heating in electrolyte-plasma processes. The method is based on an energy approach and accounts for the influence of current density, voltage, thermophysical properties of the electrolyte, and heat transfer parameters. The formation of the vapor-gas envelope is considered as a result of the transition from nucleate to film boiling of the electrolyte with increasing voltage. The main potential drop and heat release occur within the envelope region, which determines the energy distribution in the near-cathode zone. Based on the analysis, relationships between the vapor-gas envelope thickness and the energy parameters of the process were obtained. It was established that an increase in current density and voltage leads to an increase in envelope thickness and to a higher heating intensity of the cathode surface.

The obtained relationships can be used to evaluate cathodic heating regimes and to select parameters of electrolyte-plasma treatment. The presented results make it possible to describe the conditions for stable formation of the vapor-gas envelope and to apply them in further modeling of thermal and electrical processes in the near-cathode region.

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КАТОДТЫҚ ҚЫЗДЫРУ ПРОЦЕСІНІҢ ЭНЕРГЕТИКАЛЫҚ СИПАТТАМАЛАРЫНЫҢ ПАРОГАЗДЫҚ ҚАБЫҚША ҚАЛЫҢДЫҒЫНА ӘСЕРІН ЗЕРТТЕУ ЖӘНЕ ПАРОГАЗДЫҚ ҚАБЫҚША ҚАЛЫҢДЫҒЫН ЕСЕПТЕУ ӘДІСТЕМЕСІН ӘЗІРЛЕУ

Аңдатпа: *Катод маңында электролитті-плазмалық қыздыру кезінде қалыптасатын парогаздық қабықша қалыңдығын есептеу әдістемесі процесстің энергетикалық сипаттамаларын ескере отырып әзірленді. Ұсынылған тәсіл катодтық аймақтағы энергетикалық баланс талдауына негізделген және булану мен парогаздық қоспаның түзілу шарттарына ток тығыздығының, кернеудің, электролиттің жылуфизикалық қасиеттері мен жылуалмасу параметрлерінің әсерін ескереді. Эксперименттік зерттеулер Na_2CO_3 ерітіндісінде 100-300 В кернеуде болат 20 үлгілерін катодтық қыздыру жағдайында жүргізіліп, температуралық және электрлік параметрлер тіркелді. Околокатодтық аймақта ток пен энергияның таралуы COMSOL Multiphysics ортасында сандық модельдеу арқылы зерттелді. Парогаздық қабықша қалыңдығының разрядтың энергетикалық параметрлеріне тәуелділіктері анықталып, оның ұлғаюы электролиттің көпіршікті қайнаудан қабықшалы қайнауға өтуімен және катод бетінің қызу қарқындылығының артуымен қатар жүретіні көрсетілді. Алынған нәтижелер электролитті-плазмалық өңдеу режимдерін таңдауда және прикатодтық аймақтағы жылулық процестерді модельдеуде қолданылуы мүмкін.*

Түйін сөздер: *электролитті-плазмалық өңдеу, болат 20, катодтық қыздыру, парогаздық қабықша, қабықша қалыңдығы, ток тығыздығы, сандық модельдеу.*

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РАЗРАБОТКА МЕТОДИКИ РАСЧЕТА ТОЛЩИНЫ ПАРОГАЗОВОЙ ОБОЛОЧКИ И ИЗУЧЕНИЕ ВЛИЯНИЯ ЭНЕРГЕТИЧЕСКИХ ХАРАКТЕРИСТИК ПРОЦЕССА КАТОДНОГО НАГРЕВА НА ТОЛЩИНЫ ПАРОГАЗОВОЙ ОБОЛОЧКИ

Аннотация: *Разработана методика расчёта толщины парогазовой оболочки, формирующейся вокруг катода при электролитно-плазменном нагреве, с учётом энергетических характеристик процесса. Предложенный подход основан на анализе энергетического баланса в прикатодной зоне и учитывает влияние плотности тока, напряжения, теплофизических свойств электролита и параметров теплообмена на условия испарения и образования парогазовой смеси. Экспериментальные исследования выполнены при катодном нагреве образцов стали 20 в растворе Na_2CO_3 при напряжении 100-300 В с регистрацией температурных и электрических параметров. Численное моделирование распределения тока и энергии в околокатодной области проведено в среде COMSOL Multiphysics. Установлены зависимости толщины парогазовой оболочки от энергетических параметров разряда и показано, что её рост сопровождается переходом от пузырькового к плёночному кипению электролита и повышением интенсивности нагрева катода. Полученные результаты могут быть использованы при выборе режимов электролитно-плазменной обработки и моделировании тепловых процессов в прикатодной зоне.*

Ключевые слова: *электролитно-плазменная обработка, сталь 20, катодный нагрев, парогазовая оболочка, толщина оболочки, плотность тока, численное моделирование.*

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