A study of anode area physical parameters of asymmetric combined gas discharge

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ABSTRACT

The layered structure properties of an asymmetric combined gas discharge have been studied. The main physical parameters of the plasma in the zone of electron acceleration to high energies of tens and hundreds of electron-volts at various values of the supplied microwave power were determined based on the analysis of the discharge current-voltage characteristics. The effect of combined discharge plasma on the surface of products made of various materials and placed in the resonator chamber of a technological unit was experimentally investigated, and it is shown that it can lead to a significant increase in the strength of the processed products in terms of microhardness.

1. Introduction

Durability, as the property of any product to maintain its operability until the transition to the limiting state, is ensured by various methods that allow not only the improvement of the known properties (wear, corrosion and erosion resistance, fatigue strength) when using known materials [1, 2, 3, 4, 5], but also to acquire new, including unique, properties due to the creation of new materials, the structure of which changes at the nanoscale [6, 7, 8, 9]. This makes it possible to increase and maintain the durability indicators for a long time, which is a great advantage for the industrial application of the product.

One of the ways to increase durability is the product working surface modification. There are various modification methods, including plasma techniques: thermohardening [10, 11, 12], ion-plasma diffusion implantation [13, 14], ion-beam hardening treatment [15, 16, 17], which contribute to its hardness increase in varying degrees (by 15–50%).

One of the plasma modification trends involves the exposure of the product surface to a low-pressure gas discharge. A large number of experimental and theoretical works are devoted to the study of this effect, as well as the properties of the discharge itself.

Thus, in [18], the induced changes in the structure and corrosion resistance of martensitic stainless steels nitrided by plasma-immersion ion implantation during various previous heat treatments were investigated. In [19], the results of experimental and analytical studies of ignition modes of a low-pressure discharge in nitrogen with the simultaneous application of constant and high-frequency (HF) electric fields are presented. In [20], a relationship was found between the thicknesses of the cathode and anode regions of a non-self-sustaining high frequency discharge perturbed by dc electric field. An experimental and theoretical study of the ion energy distribution function near electrodes in one- and two-frequency discharges in argon was carried out in [21]. Paper [22] is devoted to the study of the highly ionized plasma dynamics in a pulsed magnetron discharge. It was shown in [23] that low-pressure microwave plasma treatment is an effective method for modifying organic surfaces and leads to the formation of surfaces with very high hydrophilicity. The results of a study of a radio-frequency discharge in hydrogen arising between parallel plates when a positive or negative bias potential is applied to one of them are presented in [24]. It was shown in [25] that high-temperature plasma irradiation of lithium materials leads to a significant modification of the surface structure, the growth of deposited composite films and surface layers with induced self-similar grain size due to strong plasma-surface interaction. Development of surface modification radiation technology: paper [26] is devoted to ion cleaning and high-dose ion implantation.

The effect of a low-temperature plasma of asymmetric combined low-pressure gas discharge on a processed metal surface in a technological unit developed by the authors was previously studied experimentally and theoretically in [27, 28, 29]. It has been shown that it leads to a significant change in surface properties:

– an average 1.5 fold increase in wear resistance;
– an average 2-3-fold increase in microhardness parameter.

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A combined discharge occurs when weakly ionized gas is simultaneously exposed to a microwave field created in the resonator chamber by a magnetron with operating cyclic frequency of $\omega = 1.54 \cdot 10^{10}$ s$^{-1}$, and to a constant electric field arising when a constant positive bias potential is applied to the workpiece (up to 40 mm in diameter and up to 120 mm in length) $\phi_0 \approx 50 \div 250$ V. The resonator chamber is filled with argon or nitrogen at $P = 200 \div 400$ Pa pressure. In this case, a plasma cloud arises immediately near the workpiece surface, which makes it possible to focus the discharge energy on it. The microwave power required for processing the product is $P_0 = 30 \div 150$ W and comes from the magnetron along the ring waveguide through the slots into the resonator chamber. Exposed to the microwave field, the plasma electrons acquire energy up to several hundred eV. The presence of a constant field leads to the emergence of a constant component of the current flowing through the unit and the transportation of electrons to the product surface; the electrons can heat the surface up to the melting temperature. This approach differs significantly from the experiments described in [30], in which the microwave field frequency ($\omega$) was created by an antenna-cathode located inside the resonator chamber filled with Ar with a pressure in the range of $P = 40 \div 130$ Pa, to which a constant negative potential was applied $\phi_0 \approx -100 \div -300$ V. A superdense plasma cloud with a plasma frequency $\omega_p = \sqrt{n_e e^2/\varepsilon_0 m_e} > \omega$ (e – elemental charge, $m_e$ – electron mass) was formed near the antenna; the workpiece was placed inside this cloud. For the microwave field frequency $\omega = 1.54 \cdot 10^{10}$ s$^{-1}$ the electron concentration at which the plasma becomes superdense – opaque to microwave radiation, is $n_e \geq 7.46 \cdot 10^{16}$ m$^{-3}$.

Electromagnetic radiation propagated along the antenna – a titanium rod 300 mm long and 18 mm in diameter, in the ion shell which is the region between the negatively charged rod and the surrounding superdense plasma cloud $n_e \approx 2 \cdot 10^{17}$ m$^{-3}$ in the form of surface plasmon polaritons [31].

The combined gas discharge possesses both the properties of a microwave discharge, considered in [30], and the properties of a non-self-sustained direct current gas discharge. In contrast to the latter, the flow of electrons and ions in the direction of the product surface in a combined discharge is formed under the influence of both constant and alternating fields. Due to the small size of the workpiece and the thickening of the tension lines to its surface when a positive bias potential is applied to it, most of the DC voltage drop between the workpiece (anode) and the resonator chamber walls (cathode) falls on the anode region of the discharge. The combined gas discharge has a layered structure and consists of a near-surface layer, a zone of electron acceleration to high energies, a zone of electron deceleration, a zone of ambipolar diffusion of electrons and ions to the walls of the chamber and the cathode layer. The first three of the above can be attributed to the anode region. The physical processes in the electron deceleration zone have been investigated in detail in [28]. In this regard, the purpose of this work is theoretical and experimental study in order to determine the parameters of the electron acceleration zone and the near-surface layer, as well as to assess their impact on the surface layer physical and mechanical parameter formation. It will be shown that information on the main parameters characterizing the discharge anodic region can be obtained from the analysis of the topological features of the discharge current-voltage characteristic.

2. Materials, methods and approaches

2.1. Brief description of the technological unit

The technological unit includes a control panel (Figure 1, a) placed on a common frame as well as a working chamber, a microwave energy generator, a power source, a vacuum pump, a vacuum line, a computer, a set of measuring equipment (temperature, pressure, flow, current sensors), a control device and free-standing gas cylinders with reducers and connecting hoses.

The workpiece is placed in the vacuum part of the working chamber (Figure 1, b, pos. 1) of 150 mm in diameter and 300 mm in length, through a sluice door (pos. 2). 300 Pa working pressure of process gas (argon, nitrogen or their mixture) admitted through the injection system channel (pos. 3) is created in the chamber with the help of a pump. Then the bias potential (pos. 4) is applied to the workpiece, and the microwave generator is turned on. The energy produced by the microwave generator enters the chamber through a ring waveguide (pos. 5) providing the gas ionization. The interaction of electromagnetic and electrostatic fields allows for the immediate plasma formation around the product surface, which makes it possible to multiply the exposure intensity. During long-term operation of the unit, there is a possibility of cooling the chamber (pos. 7).

The processing time depends on the geometric parameters of the product surface, the chemical, physical and mechanical properties of its material, as well as the parameter values of the technological mode (pressure, bias voltage and anode current of the magnetron), but does not exceed 15 min.

The unit has high energy efficiency (0.9 kW power consumption compared to average 30 kW of analogues) and low cost (10 times less than other plasma units). The characteristics of plasma formation and its interaction with the product surface implemented in the unit make it possible to increase hardness as well as abrasive, corrosion, erosion resistance and improve the surface roughness of the modified product while keeping its original geometric and dimensional accuracy.
unchanged. It is impossible to obtain similar results by other plasma methods.

2.2. Microwave gas discharge structure (layers)

This section is an outline of the spatial structure of an asymmetric low-pressure microwave gas discharge (Figure 2) (for details, see [27, 28, 29]).

Workpiece – 1 to which a positive bias potential \( \phi_0 > 0 \) is applied is located in the center of the resonator chamber – 7 to the surface of which a thin cathode layer – 6 adjoins. Electron generation and acceleration to high energies of up to hundreds eV under the action of a microwave electric field occurs in an intense lilac glow zone – 3 separated from the product – 1 by a thin surface layer – 2. Inside surface layer-2, a negative potential drop between the product and the plasma occurs [32, 33]. On the outside, the electron acceleration zone – 3 borders on the deceleration zone – 4 which, in turn, consists of thinner layers of yellow, orange and red colors, inside which energetic electrons lose their energy as a result of elastic and inelastic collisions with argon atoms [28]. Between the deceleration zone and the cathode layer there is a dark zone of ambipolar diffusion – 5 where electrons together with ions diffuse to the resonator chamber walls. Internal discharge layers: near-surface layer – 2, acceleration zone – 3, and deceleration zone – 4 form a single luminous plasma cloud in the shape of a sphere with a ~1 cm radius, which we will further call the anode area of the discharge. The study of the physical characteristics of the near-surface layer and the acceleration zone included in the anode region is one of the goals of this work. Physical processes in the deceleration zone – 4 were studied in detail earlier in [28].

2.3. Anode area of combined gas discharge

At \( \phi_0 = 0 \) and the microwave field frequency \( \omega = 1.54 \times 10^8 \text{rad s}^{-1} \) the value of the stationary potential of the quasineutral plasma relative to the product for different levels of microwave power, according to estimates based on the ratios given in [34, 35, 36, 37] is \( U_f = -\langle V \rangle \approx 10 \div 150 \text{ V} \). When a constant positive bias potential \( \phi_0 > 0 \) is applied to the workpiece, an asymmetric microwave gas discharge studied earlier in [28] turns into a combined discharge. The product potential \( \phi(t) = V(t) + \phi_0 \) in this case is the sum of the microwave component \( V(t) \), the time average of which \( \langle V \rangle \), and constant potential \( \phi_0 \). It is obvious that due to the small size of the workpiece, most of the DC voltage drop between the workpiece (anode) and the resonator chamber walls (cathode) falls on the anode area.

The number of electrons and ions produced in the acceleration zone under the microwave field is the same. In addition, electrons leave this area of the discharge faster than ions, due to their release to the workpiece surface as an electron current flows. Also, having a significantly higher mobility than ions \( b_e \gg b_i \), electrons move to the walls of the resonator chamber, due to the deceleration process, faster than ions in the same direction during diffusion [38]. For these reasons, the concentration of ions in the acceleration zone exceeds the concentration of electrons \( n_i > n_e \) and it charges positively. In the region of ambipolar diffusion, electrons and ions diffuse together to the resonator chamber walls with a doubled ion diffusion coefficient.

According to Langmuir’s theory, the anode is surrounded by a plasma layer with a positive space charge. A negative potential drop between the product and the plasma occurs in a narrow near-surface layer between them and is determined by the formula

\[
\Delta \phi = k_B T_e \ln \left( \frac{i_e}{i_0} \right),
\]

where \( k_B \) – Boltzmann constant, \( T_e \) – electron temperature, \( i_e \) – electron current strength, \( i_0 \) – electron saturation current, \( e \) – absolute value of the electron charge. In this case, the potential profile is nonmonotonic, and a potential well for slow electrons is formed near the workpiece surface where a significant part of them is trapped [32]. Only electrons with a sufficiently high energy enter the surface of the product. Some of the electrons are reflected back into the plasma by the potential barrier.

Further, in Section 3.1, the values of the main plasma parameters of the anode region were obtained from the analysis of the family of current-voltage characteristics of the gas discharge (Figure 3) based on the Langmuir theory, as well as the modern theoretical research results presented in [32, 33]: electron temperature, ion concentration, average electron energy in the acceleration zone, floating potential and others at different levels of microwave power.

2.4. Experimental research methodology

In order to assess the possibilities of product durability increase through the surface layer hardening when exposed to electrons and ions of the plasma formed under the impact of a microwave field in the combined gas discharge anode region, a study was carried out:

1. On 18 samples of 1.4878 stainless steel with a diameter of 8 mm and a length of 50 mm;
2. On 15 samples of C45E structural steel with a diameter of 10 mm and a length of 50 mm.

The choice of these materials is due to the breadth of their application in various practical fields.

The unique combination of properties and strength characteristics allowed 1.4878 stainless steel to find application in machine building for manufacturing machinery parts and assemblies, in the petrochemical and gas industry in the manufacture of seamless pipes for chemicals and fuels, in medicine for manufacturing surgical instruments. Products made of this type of steel have high characteristics during their long service life.

C45E steel is used for the manufacture of high strength parts, the surface of which is heat treated, normalized or improved. Being characterized by high cutting (turning and milling) machinability, it is used as the main material in machine building. It is used to produce gear shafts, cylinders, camshafts and crankshafts, spindles, chuck jaws, gears, pliers, and a variety of hand tools. It has found application in the manufacture of parts characterized by high material strength with increased exposure to cyclic loads (gear wheels, connecting rod mechanisms). Due to its high strength, C45E steel is often used in the manufacture of fasteners that can withstand lateral loads.
The research methodology included:

- processing at different values of the magnetron anode current (in the range from 25 to 85 mA) that determines the level of the microwave power supplied to the working chamber (from 32 to 140 W):
  - of 1.4878 steel sample pieces at a length of 20 mm for four minutes at a bias potential $\varphi_0 = 175$ V (3 samples at each microwave power value),
  - of C45E steel sample pieces at a length of 20 mm for ten minutes at a bias potential $\varphi_0 = 150$ V (3 samples at each microwave power value);
- temperature recording in the sample holder outside the zone of plasma exposure (lag temperature) using a chromel-copel thermocouple with a 1 s step and an error of 0.1 °C.

Before and after samples processing, their Vickers microhardness was determined using a PMT-3 microhardness tester with an error $\pm 0.33$ mA. In this case, the product is charged to a certain negative, relative to the plasma, equilibrium potential $\Delta \varphi = -U_f$ called floating potential. When applying a bias potential $\varphi_0 = U_f$ to the product, both electronic and ionic currents easily approach the product, and the resulting current flowing through the installation is $i = i_0 + i_e \approx -2.5$ mA $+ 0.33$ mA $= -2.17$ mA.

From the current-voltage characteristic (Figure 3), we find the bias potential $\varphi_0 = U_f \approx 130$ V, corresponding to the current strength value $i = -2.17$ mA.

Let us further use formula (1) to find electron temperature

$$T_e = \frac{-eU_f}{k_B \ln(i_e/i_0)}.$$  

(2)

Substituting $U_f = 130$ V in (2) and at $\varphi_0 = 0$ the value of the electron current $i = i_0 \approx -0.33$ mA, we find for the microwave power level $P_0 = 32$ W the electron temperature $T_e \approx 7.44 \times 10^5$ K.

When applied to the product $\varphi_0 > U_f$ the ionic current decreases compared to the saturation ionic current $i_i = i_0$ with growth $\varphi_0$, and the electron current $i_e = i_e(\varphi_0) \approx -2.5$ mA.

Let us use Bohm’s semiempirical formula for the ion saturation current density

$$j_i = 0.66 n_i(\frac{k_B T_e}{M})^{1/2}.$$  

(3)

Suppose that the workpiece is a ball with a diameter $D = 0.8$ cm; then its surface area is $S \approx 2 \cdot 10^{-4}$ m². Substituting into (2) $j_i = 4i_0/S$ and $S = 1.65 \Lambda/m^2$, $T_e = 7.44 \times 10^5$ K, argon ion mass $M = 6.63 \times 10^{-26}$ kg, we can define $n_i = 1.38 \times 10^{15}$ m⁻³.

Knowledge of the electron temperature makes it possible to estimate the average energy of electrons in the discharge acceleration zone near the product surface, $\tau_e = 3k_B T_e/2 \approx 96$ eV and the mean square speed of their movement $v_{eq} \approx 5.82 \times 10^6$ m/s.

The width of the near-surface layer $l$ can be estimated with the help of the Child-Langmuir law analogue [23, 30]:

$$|\Delta \varphi| = \frac{5}{6} \left( \frac{M}{2e} \right)^{1/3} \left( \frac{3}{2} \right)^{2/3} \left( \frac{l + \lambda_e}{2l + \lambda_i} \right)^{1/3} \frac{1 + \lambda_i}{\lambda_i} l^{1/3}.$$  

(4)
Here $\lambda_i$ – the mean free path of an ion, $e$ – elemental electric charge, $M$ – argon ion mass, $j_i$ – ion current density. Formula (3) can be used when the near-surface layer cannot be considered collisionless, and the ratio $\lambda_i/d = 1/10^2$.

Let us substitute the anode potential drop $\Delta\phi = -U_f = -130$ V and the mean free path of an electron between two successive elastic collisions into (3) $\lambda_i = 1/\sqrt{2n_0}\sigma \approx 48$ $\mu$m. This $\lambda_i$ value is determined for argon atoms concentration $n_0 = P/k_B T_0 = 3.8 \times 10^{22}$ $m^{-3}$ – at pressure $P = 0.00263 \times 10^5$ Pa = $2$ mm Hg. and the temperature of neutral argon atoms $T_0 = 500$ K, $\sigma \approx 3 \times 10^{-19}$ $m^2$ – effective cross-sectional area of collision of argon atoms, where $d_0 = 3.5 \times 10^{-10}$ $m$ – is effective diameter of an argon atom. We find the width of the near-surface layer $l = 2 \times 10^{-8}$ mm $\lambda_i$, which corresponds to the limits of applicability of formula (3) and coincides with its thickness observed in the experiment (Figure 2).

For microwave power level $P_0 = 300$ W Figure 3 shows that the forces of the ionic and electron saturation currents are, respectively, $i_e = 4 \times 10^{-4}$ mA and $i_0 \approx 20.26$ mA. The strength of the current flowing through the unit: $i = i_e + i_i$. At bias potential $\phi_0 = 0$, no current flows through the unit $i = 0$, and electronic current $i_e = -i_0 \approx -10.4$ mA. When applying a bias potential $\phi = U_f$ to the product, both electronic and ionic currents easily approach the product, and the resulting current flowing through the installation is $i = i_e + i_0 \approx -20.26$ mA $+ 10.4$ mA $= -9.86$ mA.

Using the current-voltage characteristic (Figure 3), we find the bias potential $\phi_0 = U_f \approx 35$ V, corresponding to a given current strength value $i$.

Substituting $U_f = 35$ V in (2) and at $\phi_0 = 0$ the value of the electron current $i_e = -i_0 \approx -10.4$ mA, we find the electron temperature $T_e \approx 6.06 \times 10^5$ K, corresponding to the microwave power level $P_0 = 300$ W.

When applied to the product $\phi_0 > U_f$ the ionic current decreases compared to the saturation ionic current $i_i < i_0$ with growth $\phi_0$, and the electron current $i_e = i_0 \approx -20.26$ mA.

Substituting further into (3) $j_0 = i_0/S = 52$ $A/m^2$, $T_e \approx 6.06 \times 10^5$ K, argon ion mass $M \approx 6.63 \times 10^{-26}$ kg, we can define $n_i = 4.82 \times 10^{16}$ $m^{-3}$.

From the value of the electron temperature, we estimate the average energy of electrons in the acceleration zone, $\overline{\epsilon_e} = 3k_B T_e/2 \approx 78$ eV and mean square speed of their movement $v_{ag} \approx 5.25 \times 10^6$ $m/s$.

Using the current-voltage characteristics shown in Figure 3, we estimate the main parameters of the gas discharge plasma. The results are shown in Table 1.

When deriving (1), it is assumed that electrons in a decelerating electric field are distributed according to the Boltzmann law that describes the distribution of particles in a state of chaotic motion in a conservative field of force. This assumption is valid only if the ratio of the ordered motion speed to the chaotic motion speed of electrons $u_i/\gamma_i \rightarrow 0$ and correspondingly $\phi_0 \rightarrow -\infty$. Also, Langmuir model assumes that when crossing the boundary between the plasma and the surface layer, the electron concentration remains unchanged. This is true only if the electron flux entering the anode makes up an insignificant part of the electron flux entering the layer. To eliminate these restrictions, in [32], an implicit, relative to $n_0 = e\Delta\phi/k_B T_e$, equation was obtained:

\[
i_e(i_0) = \exp(-\beta^2) + \operatorname{erf}(\frac{1}{2\sqrt{\beta}}) + \operatorname{sign}(\beta) \exp(\beta^2)
\]

where $\operatorname{erf}(x)$ is a probability integral

\[
\operatorname{erf}(x) = \left(\frac{2}{\sqrt{\pi}}\right) \int_{0}^{x} \exp(-t^2) dt
\]

and the parameter

\[
\beta = \sqrt{-n_i} - \left(\frac{1}{2\sqrt{\pi}}\right) (i_e/i_0).
\]

The plasma parameters calculated on the basis of (5) are given in Table 2.

Note that under certain conditions, the internal structure and parameters of the investigated discharge are close to the internal structure and parameters of the plasma bullet described in [40, 41].

Electrons born in the acceleration zone under the action of the microwave field at microwave power level $P_0 = 32$ W have an average energy $\epsilon_e \approx 96$ eV according to Table 1. If the bias potential $\phi_0 = 0$, most of them are trapped inside a potential pit $eU_f = 130$ eV deep near the product surface. For trapped electrons, the distribution function is close to Maxwell – Boltzmann function with a temperature $T_e \approx 7.44 \times 10^5$ K. Bias potential $\phi_0 > 0$ supply to the product leads to a decrease in the height of the potential barrier that exists near the product surface. Upon reaching $\phi_0 = 130$ V the barrier disappears completely and the electron current becomes equal to the saturation current.

The gas discharge in the unit occurs when the microwave power is applied $P_0 \approx 32$ W. Thus, at a given power value, the amplitude of the microwave field strength near the workpiece surface should be close to the breakdown value $E_0 \approx 10^5$ V/m [42].

Earlier in [28, 43], to estimate the energy acquired by the electron in the microwave field the ratio was used

\[
\epsilon_e = \frac{e^2 \overline{\epsilon_e}^2}{2m_e \alpha_0 (i_0 + \omega^2)}
\]

where $\overline{\epsilon_e}$ – the average relative fraction of energy transferred by an electron to an atom or molecule in the process of elastic and inelastic collisions with them, $\alpha_0$ – the frequency of collisions of an electron with gas atoms, $m_e$ – electron mass.Amplitude of free microwave oscillations of an electron in an electric field

\[
x_0 = \frac{eE_0}{m_e \omega^2}
\]

At $E_0 = 10^5$ V/m, from (9) we find $x_0 \approx 74 \mu$m $= 0.2\lambda_i$. Here $\lambda_i \approx 1/\sqrt{n_i \sigma_{ei}} = 4 \sqrt{2} \lambda_i \approx 272$ $\mu$m – electron mean free path, $\sigma_{ei}$ – effective cross-section area of electrons with argon atoms. During the period of electron oscillations, one collision occurs, thus, $\nu_0 \approx 0.25 \times 10^{15}$ s$^{-1}$ and inequality holds $x_0^2 << \omega^2$. At $\epsilon_e \approx 96$ eV and $E_0 \approx 10^5$ V/m from (5) we define the parameter $\delta_\epsilon \approx 0.04$.

| Microwave power $P_0$ (W) | 32 | 119 | 172 | 225 | 275 | 300 |
|---------------------------|----|-----|-----|-----|-----|-----|
| Floating potential $U_f$ (V) | 130 | 140 | 130 | 118 | 85 | 35 |
| Electronic temperature $T_e$ (K) | 7.44 $\times 10^5$ | 1.52 $\times 10^6$ | 2.69 $\times 10^6$ | 1.91 $\times 10^6$ | 9.30 $\times 10^5$ | 6.06 $\times 10^5$ |
| Ion concentration $n_i$ ($m^{-3}$) | 1.38 $\times 10^{15}$ | 1.10 $\times 10^{16}$ | 1.38 $\times 10^{16}$ | 1.98 $\times 10^{16}$ | 2.36 $\times 10^{16}$ | 4.82 $\times 10^{16}$ |
| Average electron energy in acceleration zone $\overline{\epsilon_e}$ (eV) | 96 | 197 | 348 | 247 | 120 | 78 |
With an increase in the microwave power, the properties of the combined discharge approach the properties of the microwave discharge more and more \[44, 45, 46\].

Considering that \( P_0 \approx E_0^2 \), we find for \( P_0 \approx 172 \) W the amplitude values \( E_0 \approx 2.32 \times 10^8 \) V/m and \( x_0 \approx 172 \) \( \mu \)m \( \approx 0.63 \lambda_e \). Since about 2.5 collisions occur during the period of electron oscillations, the collision frequency is \( \nu_0 \approx 0.63 \times 10^{15} \text{ s}^{-1} \).

For \( E_0 \approx 2.32 \times 10^8 \) V/m and \( \delta_e \approx 0.04 \) from (5) we find \( \delta_e \approx 423 \) eV, which exceeds the value in Table 1 and indicates a depletion of the tail of the electron distribution function in the acceleration zone due to the escape of the most energetic particles to the walls of the resonator chamber and to the product surface. Due to the escape of energetic electrons, the acceleration zone acquires a positive electric charge, and the value indicated in Table 1 \( \tau_e \approx 348 \) eV is the average energy of electrons in the acceleration zone of the combined discharge at \( \phi_0 = 0 \).

Electron mobility \( b_e \), and the conductivity \( \sigma \) of an ionized gas, as is known \[47\], are expressed by the formulas

\[
b_e = \frac{\nu_0}{m_e (\sqrt{\nu_0^2 + \omega^2})}
\]

\[
\sigma = \frac{n_e e^2 \nu_0}{m_e (\sqrt{\nu_0^2 + \omega^2})}
\]

Hence for the microwave power level \( P_0 \approx 172 \) W, using the data in Table 1, we find \( b_e = 2.5 \times 10^{10} \text{ m/s} \cdot \text{N} \) and \( \sigma = 8.83 \times 10^{-3} \text{ Sm/m} \).

### 3.2. Results of an experimental study of the effect of a combined gas discharge plasma on the sample surface

Figure 4 shows the results of experiments as diagrams of the dependence of the average increment of microhardness \( \Delta HV \) of the sample surface on the supplied microwave power. In order to assess the accuracy of \( \Delta HV \) value calculation, their confidence intervals were determined.

Since the measurements were carried out 4 times in accordance with the methodology developed by the authors \[39\] for each load, i.e. sample size \( n \) of obtained values \( \Delta HV \) was small, the Student’s \( t \)-distribution was used to determine the confidence interval, and the accuracy of the interval value \( \Delta HV \) was found by the formula:

\[
\delta = t_{\alpha/2} \frac{s}{\sqrt{n}}
\]

where \( t_{\alpha/2} \) is \( t \)-distribution value (in this case 3.182) for the significance level \( \alpha \) (in this case 0.05) and the number of degrees of freedom \( n - 1 \); \( s \) is the estimate of the standard deviation of the calculated values \( \Delta HV \) from the mean. Then the obtained values \( \delta \) were averaged for each load, then for each sample and then for a group of 3 samples.

Figure 5 shows the results of measuring the dependence of the lag temperature on the bias potential \( \phi_0 \) at microwave power level \( P_0 = 80 \) W.

### 4. Discussion

The optimal conversion of the microwave field energy into the energy of plasma electrons occurs when the conditions \( \omega \sim \nu_0 \) and \( x_0 \sim \lambda_e \) are fulfilled, where \( x_0 \) is the amplitude of free electron oscillations in a microwave field \[24\].

When conditions are met \( \omega \gg \nu_0, x_0 \ll \lambda_e \) electrons move mainly in the phase with a change in the HF electric field. During one half of the period, the accelerating electron gains energy, and during the second half of the period it gives up all the energy to the field while decelerating in it. The power of the HF field consumed by the plasma, in this case, is close to zero. The phase shift between the current and the field is close to \( \pi/2 \). If the inequalities hold \( \omega \ll \nu_0, x_0 \gg \lambda_e \), the efficiency of energy transfer from electrons to heavy plasma particles increases. The gas temperature reaches 1000°F and more. Note that for \( \omega = \nu_0 \) values of mobility \( b_e \) and conductivity \( \sigma \) determined by relations (10), (11), reach a maximum.
For $P_0 = 300$ W average energy of generated electrons $e_0 > 600$ eV. however, due to the escape of fast electrons from the region of acceleration during deceleration and further diffusion to the walls of the resonator chamber, near the surface of the product, as can be seen from Table 2, only electrons with energies $e_0 \leq e_\ast \approx 78$ eV remain.

With an increase in the supplied microwave power, the average energy of electrons generated in the acceleration zone increases, but as follows from the results presented in Tables 1 and 2, the average energy of electrons held in it starts decreasing after reaching the maximum. With an increase in the bias potential applied to the product $\phi_0$ and its approaching $\phi_0 = U_f$ the magnitude of the negative potential difference between the product and the plasma $\phi_0 \to 0$. In such a case, the flow of electrons falling on its surface due to particles held in the potential well increases. The greater the average energy of electrons held in the well, the greater the energy coming from the gas discharge plasma and the more intense its effect on the product surface. It can be seen from Tables 1 and 2 that the supply of microwave power $P_0 > 172$ W to the resonator chamber of the unit is meaningless, since with an increase in $P_0$ it only leads to a decrease in the effect of plasma on the product surface. However, it can be seen from the results of the experiments that the level of microwave power giving a maximum increase in surface layer microhardness, all other things being equal, assuming the constancy of the processing time (4 min for 1.4878 steel and 10 min for 45E steel) applied to the samples of the bias potential (175 V for 1.4878 steel and 150 V for 45E steel), their position coordinates in the resonator chamber is less than 172 W, and depends on the initial physical and mechanical surface layer characteristics. Figure 4 shows that for mild 1.4878 steel the value $P_0 = 32$ W, while for hard 45E steel $P_0 = 93$ W. In this case, the values of the microhardness increments (1.27 and 1.53 times) achieved in both cases are statistically reliable, since the values of the errors $\delta$ in their calculation do not exceed 15% (on average).

With increasing bias potential $\phi_0$, the sample temperature first rises (Figure 5), and then, upon passing through $\phi_0 = U_f \approx 105$ V dependence reaches a plateau, which is due to the fact that the electron current reaches a value equal to the electron saturation current $i_e = i_0$ and further increase $\phi_0$ does not lead to an increase in the number of electrons entering the sample surface.

In general, the results of the studies performed allow for the following conclusion: allowance for the characteristics of the combined gas discharge anode region makes it possible to form such an effect of the combined gas discharge plasma on the surface layer which will ensure a maximum increase in its hardness and, as a consequence, the reliability of products in terms of durability, especially under intensive contact interactions. Hardness increase leads to the fact that the process of gradual abrasion of the modified working part of the surface layer will prevail over the processes of defect formation and development, causing sudden failures (pitting and chipping). This makes it possible to predict a further increase not only in the reliability of the tool in terms of durability, but also in the efficiency of the work processes implemented with the participation of products, since gradual failures have a longer development time than sudden failures which are the result of an abrupt change in state.

5. Conclusion

The results of the research allow for the following conclusions.

1. The main goals have been achieved:
   - the main physical parameter values of the electron acceleration zone and the near-surface layer of the combined gas discharge were determined at various levels of the supplied microwave power;
   - the effect of a combined discharge on the surface of samples made of soft and hard steel has been experimentally studied. It is shown that, other things being equal, assuming the constancy of the processing time, the bias potential applied to the samples, their position coordinates in the resonator chamber, there is a level of microwave power supplied to the chamber from the magnetron that leads to a maximum increase in the surface layer microhardness which depends on its initial physical and mechanical characteristics.

2. Scientific novelty:
   - for the first time, based on current-voltage characteristics analysis, estimates of a number of plasma parameters in the electron acceleration zone were obtained. Thus, at various levels of the supplied microwave power, the corresponding values of the amplitude of the microwave field strength, the value of the equilibrium negative floating potential to which the product is charged relative to plasma, the temperature and average energy of electrons held near the product surface, ion concentration, electron mobility and ionized gas conductivity were determined.
   - for the first time it was shown that electron acceleration to high energies of hundreds of eV occurs under the action of a microwave field in the acceleration zone of electrons, from where they enter the deceleration zone losing energy as a result of elastic and inelastic collisions with argon atoms, and onto the surface of the workpiece. The positive charge of the acceleration zone is determined by the fact that, although electrons and ions are generated in it under the action of a microwave field in equal quantities, electrons having a greater mobility than ions, leave it faster, falling into the deceleration zone and on the product surface. An estimate was obtained for the width of the near-surface layer of the discharge that exists between the product surface and the electron acceleration zone;
   - it was experimentally found that by applying a constant positive bias potential to the product, it is possible to regulate the negative anode voltage drop between the workpiece surface and the positively charged zone of electron acceleration, and thereby the value of the constant component of the ion and electronic currents flowing through the unit. Getting on the product surface, high-energy electrons can heat the surface layer to a high temperature that exceeds the melting point of the material it is made from.

3. Practical value is presented:
   - drawing on the example of samples made of 1.4878 and 45E steels, it is shown that there is a level of microwave power leading to a maximum increase in the surface layer microhardness. This increase was 1.27 times for soft 1.4878 steel and 1.53 times for hard 45E steel;
   - it has been substantiated that the increase in hardness provides a further increase in the reliability of products in terms of durability, as well as the efficiency of work processes with product participation. The increase is associated with a change in the mechanism of wear of the modified surface layer: the process of its gradual abrasion which has a long duration prevails over the defect formation and development processes, resulting in sudden failures due to an abrupt change in state.

Declarations

Author contribution statement

Boris Brzhozovskii: Conceived and designed the experiments; Analyzed and interpreted the data.
Marina Brovkova: Conceived and designed the experiments.
Sergey Gestrin: Analyzed and interpreted the data; Wrote the paper.
Elena Zinina: Performed the experiments.
Vladimir Martynov: Performed the experiments; Wrote the paper.

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