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Research for Application on Plasma Treatment in Mechatronics

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Abstract— **The report provides a historical overview of the topic, examines the physical basis of plasma production, thermal emission and treatment area, types of plasma treatments and the state of technology, types, development and potential of equipment and its application in practice. The advantages and disadvantages are analyzed in Mechatronics.**

Keywords- plasma treatment; technology development; practical applications; potential uses;

I. INTRODUCTION

The Plasma was first identified in a Crook's tube and was described in 1879 during a lecture by the British Association for the Advancement of Science in Sheffield by William Crooks, who called it a "radiating substance." The nature of the substance in Crook's tube was established by Joseph John Thomson, who announced his results at a lecture at the Royal Institute in 1897. The concept of plasma - the fourth state of matter - was introduced in 1928 by the American physicists Langmuir and Tonks (USA). Langmuir is considered to be the founder of plasma jet treatment. Plasma jet processing is a relatively new technology, developed as a more cost-effective alternative to electron and laser beam treatment. The treatment of hazardous household and radioactive waste is a very topical issue for environmental sustainability. That is why solutions based on the application of plasma gasification and incineration in ecology are offered here.

Fig. 1. William Crooks (1832 - 1919), Joseph John Thomson (1856 - 1940) and Irving Langmuir (1881 – 1957)

II. EXPOSITION

A. Physical bases of plasma

Plasma is a state of a gas in which, in addition to neutral atoms and molecules, it also contains excited particles with protons, electrons and positively and negatively charged ions. Plasma is any substance, heated to a temperature at which its vapors are in an ionized state and do not obey the laws of gas dynamics.

The Plasma is divided into two main types according to temperature:

- High temperature (thermonuclear) plasma, which exists at temperatures in the range of $1{\cdot}10^6 – 1{\cdot}10^8$ K;
- Low temperature plasma with temperatures in the range of $1{\cdot}10^3 – 1{\cdot}10^5$ K.

In the universe, over 99% of matter is in the plasma state - stars and interstellar gas. Noteworthy plasmas from the point of view of technology and physics have temperatures between several thousand and a million degrees Kelvin (5000-30000). Within these temperature ranges, the plasma temperature is usually characterized by setting the average thermal energy kT. In practice, an electron volt (eV) is used as a unit of energy, with 1eV equal to $1.6{\cdot}10^{-19}$ J. Fig. 2. shows examples of terrestrial and extraterrestrial plasmas. Time *t* indicates the lifespan of these plasmas.

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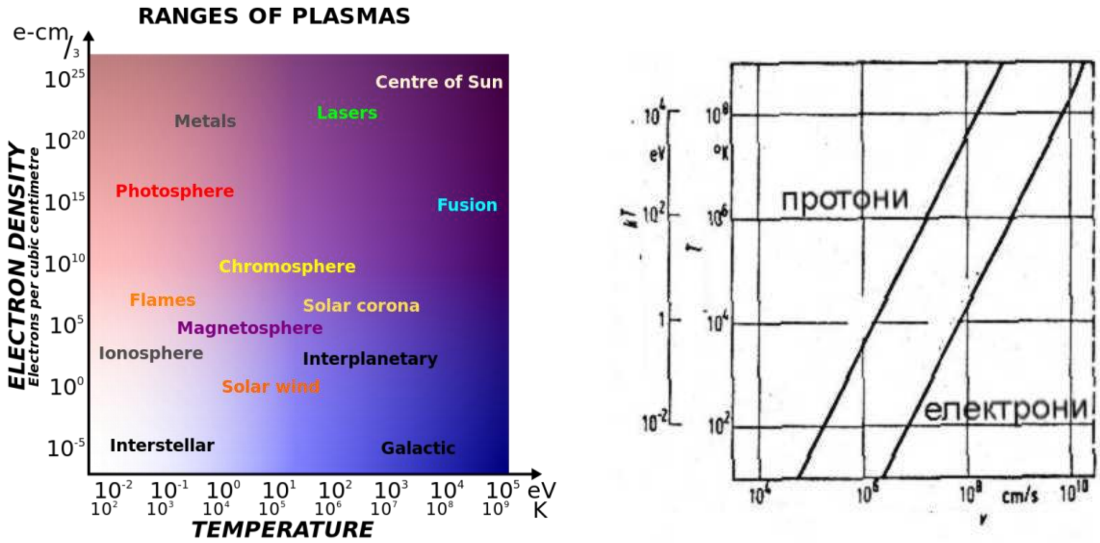

Fig. 2. Examples of terrestrial and extraterrestrial plasmas and dependence of the average velocity V of electrons and ions on temperature T (right)

Temperature T, density n, degree of ionization and electrical conductivity are the most characteristic parameters of plasma. The temperature depends mainly on the type of gas used, in which the dissociation of molecules and ionization of atoms occurs and a mixture of electrically conductive electronic, ionic and neutral gas is formed. The typical temperature distribution in the plasma jet shows that temperatures of 10000 K and above occur only in the fuel nozzle and about 20 mm in front of it. The temperature distribution shown in Fig. 3. refers to a tungsten cathode and a copper nozzle, and Table 1. explains the temperature-used gas-arc voltage relationship [1].

TABLE I. DEPENDENCE BETWEEN TEMPERATURE, GAS AND ARC VOLTAGE (NOTE: AIR CAN ALSO BE USED)

Type of plasma gas	Temperature of plasma, K	Arc voltage, V
argon	14700	40
helium	20300	45
nitrogen	7500	65
hydrogen	5400	120

The plasma temperature T is determined by the kinetic energy of the particles:

$$T = 2/3\ E_k/k = 2/3\ mV^2/2k, \qquad (1)$$

where k is the Boltzmann constant, V^2 is the root mean square velocity, cm^2/s^2 and m is the mass of the particles.

It follows from formula (1) that, the higher the temperature is, the faster the plasma particles are. At relatively low plasma temperatures, the average velocity of the particles assumes observable values. The dependence of the average velocity V of hydrogen ions and electrons on the plasma temperature T shows the graph in Fig. 2. on the right. At the same temperatures, lighter electrons are faster than heavy ions.

The degree of ionization is the ratio of the density of the charged particles ($N_{el.z.}$) to the density of the total number of particles (neutral particles N_0).

$$G = eN_{el.z.}/(eN_0 + eN_{el.z.}) \qquad (2)$$

If this quantity is small, the system is called weakly ionized plasma, in which the average energy of plasma electrons significantly exceeds the average energy of atoms and molecules. Weakly ionized plasma is one in which the electron concentration is $Ne < 7{\cdot}10^{16} cm^{-1}$ (degree of ionization below

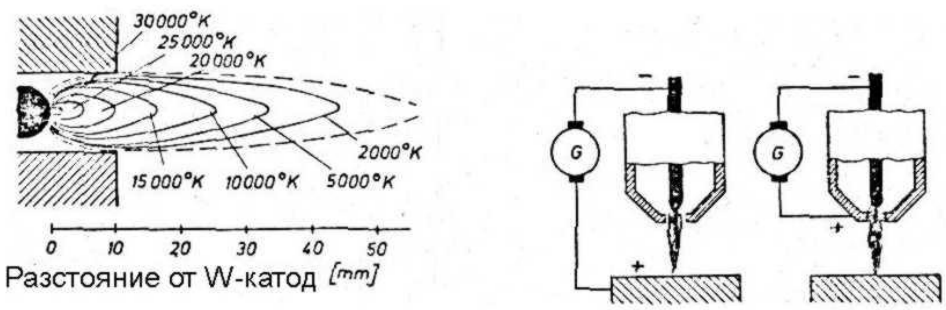

Fig. 3. Temperature distribution in the plasma arc and types of arcs

10%). If the electron concentration $Ne > 7\cdot10^{16}cm^{-1}$ (degree of ionization above 10%), the plasma is highly ionized. Then the relationship between the ionization temperature and the concentration of the components in the plasma is represented by the Egert-Sakha equation:

$$n_e n_i/n_0 = (2Z_i/Z_0)(2\pi m_e kT/h^3)\exp(-E_I/kT), \quad (3)$$

where Z_1 and Z_0 are the statistical sum of ions and neutral particles, respectively; h is the Planck constant; n_0 and n_i - the concentration of neutral particles and ions.

Plasma density is determined by the number of ionized particles in 1 cm^3. The relationship between the ionization temperature and the concentration of the components in the plasma is characterized by the approximate Elvert equation:

$$n_e/n_0 = (3^{3/2} e_n E^2_{I,H} kT/16\alpha^3 n E^3_I g)\exp(-E_I/kT), \quad (4)$$

where α is the Sommerfeld constant; n - the number of valence electrons; e_n - the quantum number of valence electrons; $E_{I,H}$ - hydrogen ionization energy; E_I- gas ionization energy; g - value, accepting values in the range from 1.4 to 4.0 depending on the specific conditions; k is the Boltzmann constant; T – temperature, K.

Due to the minimal ionization energy, the argon guarantees good ignition properties. The large atomic weight of this gas gives the plasma jet a high pulse density, which is necessary for the separation of the molten material. In combination with hydrogen, which in dissociation has an extremely high thermal conductivity, optimal properties are achieved in terms of temperature, speed, for example when cutting and surface quality. Nitrogen application reduces the tendency to form so-called "whiskers" (sharp edges) on the cutting surfaces, but leads to the formation of smoke. Table 2. shows the energy density of different heat sources [2].

Plasma is also characterized by extremely high thermal and electrical conductivity. Its high heat content (enthalpy), which depends not only on its average mass temperature, but also on the type of ionized gas, predetermines its use as a carrier of concentrated heat energy.

TABLE II. ENERGY DENSITY OF DIFFERENT ENERGY SOURCES

Heat source	Flow cross-sectional area, cm^2	Highest density of energy, W/cm^2
Acetylene burner	10^{-2}	10^3-10^4
Light arc	10^{-3}	10^4-10^5
Plasma jet	10^{-3}	10^5-10^6
Electron beam	10^{-7}	10^9

B. Plasma jet production equipment

The plasma jet is obtained by heating various gases with a concentrated electric arc in special generators - plasmotrons. The applied light arc gives part of its heat energy to the used gas, causing instantaneous heating and thus its expansion. The gas exits the nozzle at high speed as an electrically neutral plasma jet, often referred to in practice as a "plasma flame". The jet is fed through burners to the work piece.

The production of the plasma jet is carried out by means of open and closed arcs. If the light arc burns between the negative tungsten electrode through the nozzle and the anode part, the plasma jet method uses the so-called interrupted arc. If the light arc is made from the negative tungsten cathode to the copper nozzle with a positive potential (anode), the method uses the so-called continuous arc. In this case, only hot, glowing plasma gas comes out of the nozzle. The regulation of the main parameters of the plasma jet (temperature and density) is done by using one of the two methods, and the speed - by "shrinking" the jet in the nozzle. Fig. 3. shows the types of plasma jets obtained with open or interrupted and with closed or continuous arc.

The types of plasma burners have direct action and indirect action. In the first type, the arc is obtained between the cathode - tungsten electrode of the burner, and the anode is the workpiece. The plasma temperature is about 6000 K. This type has received a wider application, because from a design point of view it is easier to perform and no discharges are obtained between the nozzle and the electrode. The advantage is that greater potentials can be applied, and hence more power is obtained. The disadvantage is the processing of only electrically conductive materials.

In the second type, the anode is the nozzle of the burner. The efficiency of the arc is increased by using a special water-cooling nozzle that compresses the arc. The temperature is equal to 50000 K, the plasma density reaches $3\cdot10^6 W/cm^2$ at an arc current of 1500 A. Such a burner is used not only for welding and heat treatment as the front, but also for cutting materials (stainless steel, aluminum). Fig. 4 shows burners with direct and indirect action.

The effective heat output q is calculated:

$$q = 0.24\eta UI, \text{ cal/s}; \quad (5)$$

where η is efficiency coefficient (30-50%); U - arc voltage, V; I - current, A.

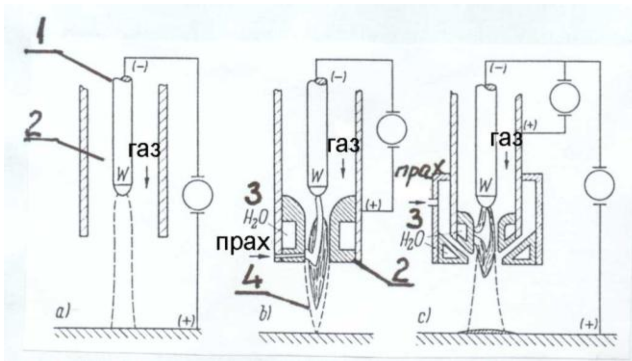

Fig. 4. Plasma burners with direct and indirect action
Legend: 1-tungsten electrode, 2-channel, 3-cooling water, 4-arc column, 5 (2 with indirect burner)-nozzle

The described burners work with direct current and the plasma is obtained by electric resistance heating. Another type of heating, namely induction, is applied to high-frequency burners. Fig. 5 shows a section of an induction plasma burner.

C. Plasma technologies

Plasma technologies, among other things, can be used as a tool for "green chemistry" and waste treatment. Thermal plasma has the potential to play a role in a wide range of chemical processes. Five different categories of technologies are used for waste treatment [3]:

- Plasma pyrolysis;
- Plasma combustion (called plasma burning or plasma oxidation);
- Plasma vitrification;
- Plasma gasification;
- Plasma polishing, which uses plasma to purify gases.

Of these, the plasma gasification is of the greatest importance, detailed in [3, 4].

III. Types of Plasma Cutting Operations

A. Cutting

Plasma cutting is a process that cuts electrically conductive materials using an accelerated jet of hot plasma, which is a jet of ionized gas at temperatures above 20000 K, used to melt and eject the material from the cut. In this cutting method, an inert gas (in some cases compressed air) is fed at very high speed through a nozzle. At the same time, an electric arc is formed through the nozzle to the cutting surface, converting part of this gas into plasma. The plasma is hot enough to melt the metal and moves fast enough to remove the molten material. The main difference between plasma cutting and oxy-fuel cutting is that plasma cutting is performed by melting the material without a chemical reaction, while the latter involves a thermochemical process. That is why plasma cutting is used for all metals and their alloys, for cutting light alloys, stainless steels and non-ferrous metal alloys that are not subject to gas-oxygen cutting. By using torches with sharp electrodes, the energy density is significantly increased and at the same time the gas consumption is reduced. The maximum cutting thickness is up to 40 mm at a given system power of 12 kW, and at lower cutting speeds the quality of the surfaces is improved. A suitable gas for a tungsten electrode is hydrogen with the addition of argon. Another special mixture is the so-called “grison” - helium, neon, nitrogen and hydrogen. It produces cutting almost without slag. Air is used for thorium electrodes. In Fig. 5 on the right the principle of plasma cutting is demonstrated [2], and the technical data of apparatuses and machines for gas-plasma cutting TRUMATIK PLASMAPRES 300 PK and 300 PW from TRUMPF (Germany), as well as AMADA and RASKIN are given in [5]. Since plasma cutting is limited in what it can cut, it is gradually being replaced by laser cutting.

B. Welding and piercing

The plasma jet welding operation can be divided into 3 types:

- microplasma and pulse plasma welding - for a thickness of the welded parts (sheet metal) between 0.05 mm and 1 mm, current from 0.05 A to 20-30 A and a plasma gas quantity below 1 l/min; for a pulse current with a frequency of 10 kHz, magnetic fields are used to regulate the energy density.
- plasma welding - for a thickness of the parts between 1 and 3 mm, current from 20 A to 100 A and a plasma gas quantity from 1 to 2 l/min;
- plasma welding with piercing - for a thickness of the parts between 3 and 8-10 mm, current from 100 A to 350 A and a plasma gas quantity above 2 l/min.

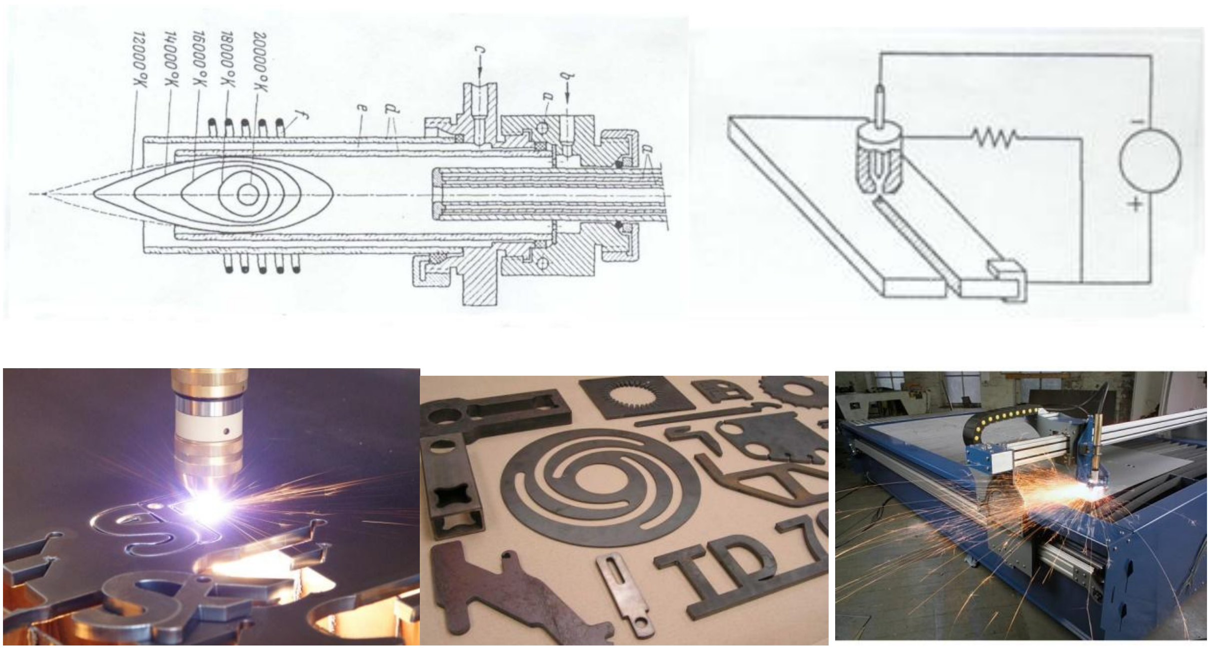

Fig 5. Burner with induction heating. Plasma cutting principle. Plasma cutting and characteristic details made using it [13]
Legend: a-cooling water, b-plasma gas supply, c-cooling gas supply, d-quartz tube, e-cooling, f-inductor

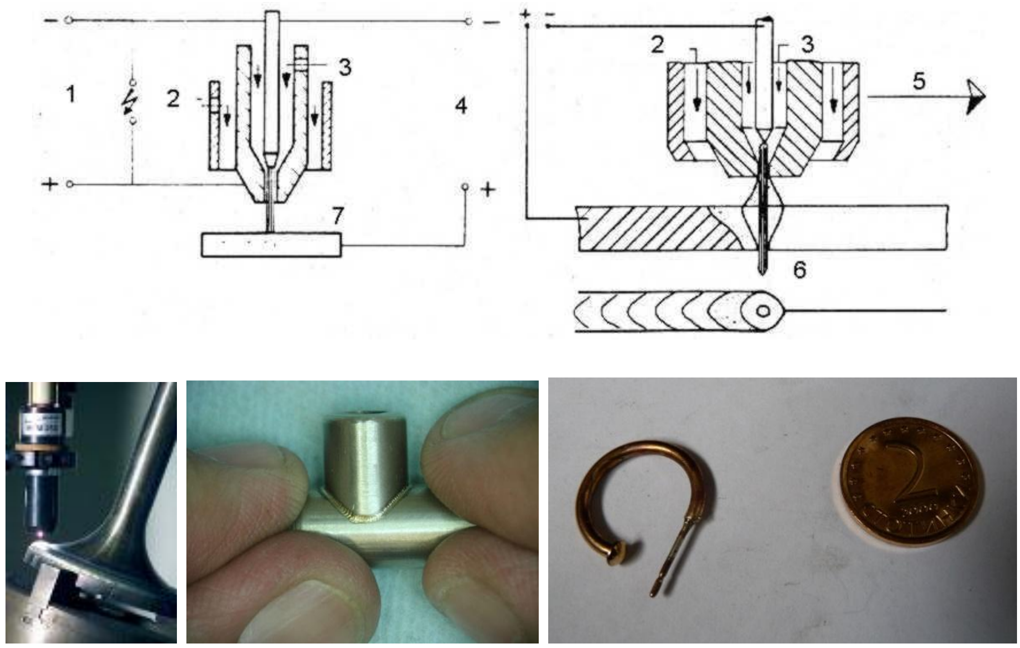

Fig. 6. Principle of operation of plasma welding (piercing) and piercing welding. Details by plasma welding, micro plasma welding and brazing [14]
Legend: 1-auxiliary arc, 2-shielding gas, 3-plasma gas, 4-main arc, 5-feed direction, 6-outgoing plasma jet, 7-detail

The principle of operation in welding according to the second and third types is explained in Fig. 6 [6]. Argon plasma gas is mainly used (due to its relatively low ionization energy, good ignition maintenance is ensured at an open circuit voltage below 100 V). A mixture consisting of 90-95% argon and 5-10% hydrogen is used as a shielding gas when welding high-alloy steels and nickel alloys, since the reduction of hydrogen from the atmosphere has a positive effect on the process. When welding metals such as titanium or copper alloys, as well as glass, a mixture of helium (instead of hydrogen) and argon is used. Controlled (thyristor) rectifiers with two separate power supply sections (for the auxiliary and main arc) are used as current sources in microplasma and plasma welding. Power sources for plasma piercing welding differ from the previous ones only in the current circuit for the auxiliary arc (they have a higher open circuit voltage) and in the provision of plasma gas.

According to the connection scheme, welding is carried out exclusively at a negative potential of the electrode - cathode. The electrode - anode scheme is not used due to its high thermal load. This also applies to the scheme with alternating current power supply, in which difficulties arise in starting the arc. Depending on the type of arc, welding is also divided into spot or seam welding with an interrupted arc and seam welding with a continuous arc. Artificial materials and aluminum are not welded with a plasma jet (due to the negative polarity of the electrode). The welding scheme with a negative electrode is shown in Fig. 6. on the right.

The advantages of plasma jet welding are:

- uses a concentrated light arc with high energy density and minimal deviation in the arc length, which leads to small melting and thermal influence zones with a shape factor of 1 to 2 and good joint quality;
- relatively large processing depth at high speed (in practice 160 cm/min at 1 mm depth, 80 cm/min at 2 mm, 60 cm/min at 3 mm, 50 cm/min at 5 mm and 40 cm/min at 6 cm);
- high arc stability at low currents and lower energy costs;
- reliable ignition and easy positioning through a constantly burning auxiliary arc;
- good possibility of feeding additional material and absence of tungsten inclusions when the electrode touches the workpiece;
- good prerequisites for adjusting the individual parameters in the work process and its automation.

Despite these advantages, for economic reasons, in practice, only microplasma welding of parts with high quality requirements from the electronics industry and aircraft and rocketry is used almost exclusively. The main point is the welding of highly alloyed and silicon steels, nickel, copper, titanium, zirconium and their alloys (especially CrNi+Ne, excluding light metals). At currents up to 100 A, contacts, rheostats and thermocouples, short-circuited windings of stator packages, sensors, etc. are welded.

The plasma jet drilling scheme is identical to the one demonstrated in Figure 5. on the left. The difference lies in the operating mode: current, speed, there is no additional material feed.

C. Dry cleaning by low-pressure plasma

Dry cleaning (etching) is a material removal technique that uses plasma or a chemically reactive gas to selectively remove layers of material from a substrate. Its types are described in [1, 10]. Unlike wet etching, which uses chemical solutions, dry etching is a gas-phase process. The differences are indicated in [9]. The operation is used to ensure the adhesion of joints, varnishing and metallization of parts in the instrument-making, micro-technology and electronics industries for cleaning semiconductors. Dry etching processes usually occur under vacuum conditions, with pressures ranging from a few millitorrs to hundreds of millitorrs. This low-pressure environment helps to maintain a clean etching environment and control the reactivity of the plasma. The pressure is from 50 KPa to 200 KPa, the power - from a few 100 W to more than 1 kW. Oxygen, nitrogen or noble gas is used at a flow rate of 50 ml/min to 500 ml/min. The temperature is from 300 ^{0}C to 10000 ^{0}C, and the duration of treatment is from 1 min to 15 min. The frequency used for ionization of the gas depends on its type.

Dry etching provides better anisotropy (directional etching) and finer control over feature sizes. This makes it more suitable for creating smaller, more precise structures, which is crucial in the production of modern microelectronics. The process sequence is: reaching a vacuum of 100 Pa in a chamber, introducing gas (oxygen, CF_4, SF_6, C_{l2}), ionizing the gas by high frequency (1 MHz) and generating plasma, reacting radicals with the surface layer of the parts and ionizing the molecules, removing particles by electrons with energies of 2 to 5 eV (20000-50000 K), sucking these particles, cleaning the surface of oils and similar inclusions with an inert gas and removing the substrate from the chamber. Plasma cleaning replaces hydrocarbons and water-containing agents, removes oils, greases, as well as waxes, greases and even silicone.

D. Coating application by plasma spraying

In this operation, a high-frequency arc is ignited between a toroidal tungsten cathode and a copper nozzle - anode. The gases nitrogen, hydrogen, argon, helium and their mixtures entering the nozzle are strongly heated and the monatomic gases are partially ionized, and the diatomic gases are dissociated and partially ionized. The sprayed material is fed into the gas mixture in powder form by a so-called carrier gas. The powder particles melt (the temperature is over 20000 ^{0}C) and fall at high speed onto the workpiece for coating. The most common devices for coating are direct current plasma torches that operate with nitrogen or a mixture of nitrogen and hydrogen with a continuous arc at a power of about 1-100 kW. The most commonly used powders are metal, ceramic and metal-ceramic powders made of difficult-to-melt materials that cannot be processed or are difficult to process using conventional flame and arc spraying. The choice of the additional material must be made very carefully. The powders used are usually spherical in shape with a diameter of about 15 μm to 75 μm. The distance from the burner to the workpiece should be in the range of 80-150 mm. The influence of individual process parameters on the quality of the coating is discussed in detail in [7].

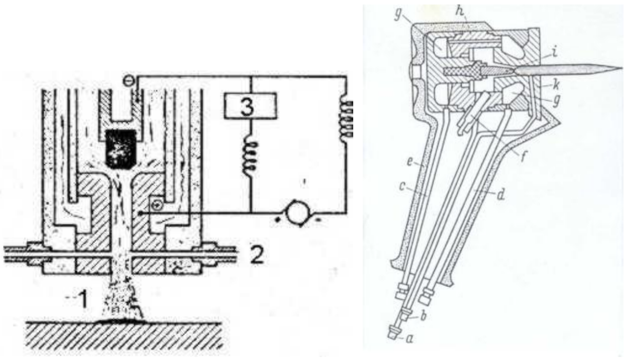

Fig. 8. Application of coatings with a plasma jet and a spray gun
Legend: 1-plasma, 2-powder, 3-HF-generator, a-gas supply, b-powder supply, c-cathode power supply and water outlet, d-anode power supply and water inlet, e-plastic housing, f-ignition electrode, g-water cooling, h-plastic housing, I-tungsten cathode, k-copper anode

To prepare the surface layer of the part in order to retain the coating, sandblasting is most often used, which gives an optimal degree of roughness. After applying the coating, for its mechanical compaction, rolling, pressing or pressing with hammers can be applied. During heat treatment, the resulting coating is alloyed with elements that are also contained in the base material, and during chemical treatment, the pores are filled by changing the surface layer. The principle of applying coatings with a plasma jet is shown in Figure 7., the design of a plasma spraying gun – in Fig. 8 on the right [2], and recommendations for the application of specific powders are given in Table 3.

Fig. 7. Dry etching and gear after cleaning [15]

TABLE III. PLASMA INJECTION MOLDING MATERIALS AND THEIR APPLICATIONS

Aluminum oxides	Electrical insulation of parts operating at high temperatures, T 2030 ^{0}C	Magnesium zirconate	High temperature corrosion resistance and protection against molten metals, T 2130 ^{0}C
Aluminum oxides + titanium oxides	Wear protection, low porosity (pump plungers)	Molybdenum	Good wear resistance and excellent base, T 2620 ^{0}C
Beryllium oxides	Good insulating properties and resistance to thermal shock	Nickel	Suitable corrosion and acid protection under ceramic layers, T 1470 ^{0}C
Kermets	Good wear resistance and corrosion protection at high temperatures	Nickel + aluminum	Good heat resistance and against thermal shock
Chromium carbides	like cermets, but at T 1895 ^{0}C	Nickel + chromium	Good wear resistance and for improving the base
Chromium Carbide And + Cobalt	High wear resistance, excellent protection against ignition	Titanium oxides	Better wear resistance, low porosity and for mixing with other materials, T 1925 ^{0}C
Hafnium oxides	Corrosion protection and thermal barrier up to T 3530 ^{0}C	Tungsten carbides	Wear at particularly high temperatures, T 2850 ^{0}C
Calcium zirconates	Good protection against molten metals T 2350 ^{0}C	Tungsten carbides + cobalt	Good wear resistance at T 1500 ^{0}C
Cobalt	Density in very critical transitions, metal-ceramic	Tungsten carbides + nickel, chromium, silicon, boron	Good wear and corrosion resistance to steam, salt water and weak acid
Cobalt + nickel + chrome + boron	Protection against friction and wear under pressure	Zirconium oxides	Good ignition protection, T 2700 ^{0}C
Cobalt + zirconium	High-hardness, temperature-resistant cermet	Zirconium silicates	For thermal barriers, T 2430 ^{0}C

The production of reinforced canvases with phase-bonded composites is carried out in combination with the plasma spraying operation. The semi-finished product of phase-bonded material is covered with a foil, on which a layer of powder with a certain structure is applied by a plasma jet. Fig. 9. explains the principle of operation in the production of canvases reinforced with phase-bonded material. On the right is a photo of plasma spraying on silicon carbide [8].

E. Plasma restoration of worn parts

In this operation, a layer of up to 4-5 mm is applied, and the welded metal may be different from the base metal. The application rate is 0.9-1 N/h. The main advantage is that the process takes place at relatively low temperatures, which does not cause destruction, deformation or change in the properties of the materials. The economic feasibility of restoring the parts is determined by the possibility of reusing 65-75 percent of them (Fig. 10). Examples:

- application of wear-resistant coatings (silicon carbide, silicon nitride) on metal-cutting tools with a thickness of several micrometers;
- surfacing of worn press and punch tools;

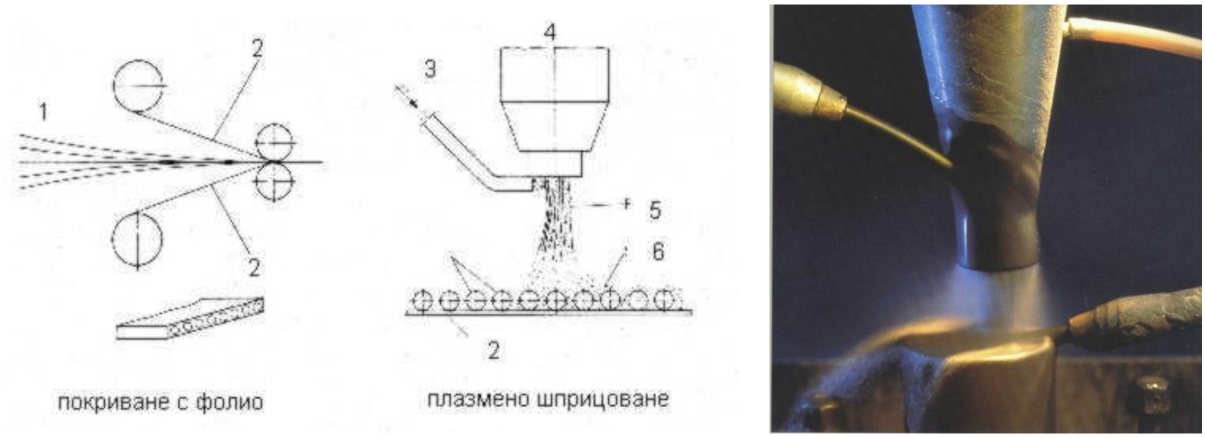

Fig. 9. Production of reinforced canvases by plasma spraying
Legend: 1-fiber, 2-foil, 3-powder, 4-plasma torch, 5-plasma beam, 6-sprayed layer

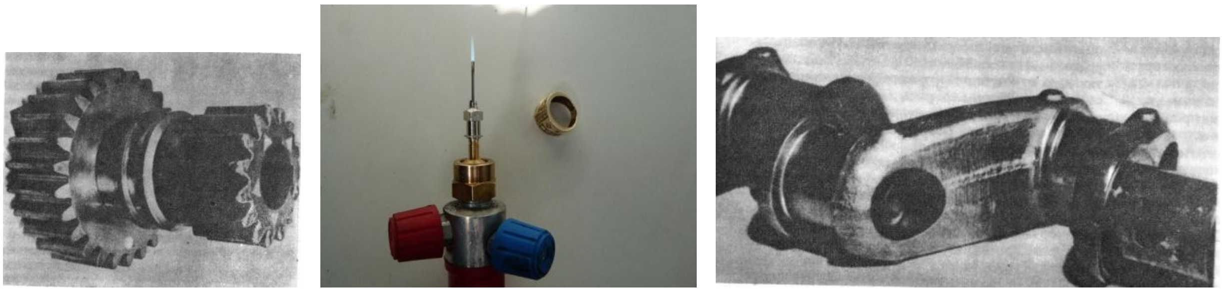

Fig. 10. Details through restoration [16]

- surfacing of parts for the purpose of their reuse (for example, crankshaft journals, gears and other similar expensive parts for the automotive and military industries);
- restoration of rings, tees, splines, cams, connecting rods, etc.

IV. Application of Plasma Jet Processing in Mechatronics

Modern manufacturing processes often require highly specialized techniques to ensure precision, durability, and efficiency in the production of advanced components. Key areas of focus include:

- Cutting and welding of foils, screens, boards, filters and other fine mechanical parts and components of microsystems technology;
- Coating of parts that operate at high temperatures and must be resistant to intense wear;
- Cleaning and activation of the surface layer of metallic and non-metallic materials as preparation for coating;
- Combined processing with other methods (e.g. ion-beam plasma processing).

These advanced processes are critical for meeting the demanding requirements of modern industry, particularly in applications where precision and reliability are paramount. The advantages and disadvantages are analyzed in Mechatronics. Comparing plasma processing with electron beam or laser beam processing can be done using both sources [11, 12].

V. Conclusion

A historical overview is given, the physical foundations of plasma technology, the types of processing and the state of technology, the development and potential of equipment and application in practice are considered.

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Emeritus Prof. Stefan Kartunov was born on May 13, 1956 in Gabrovo, Bulgaria. Graduated TMET “Dr N. Vasiladi”, and from 1977 to 1982 follows a course “Precision Engineering” at Technical University of Gabrovo. From 1982 to 1988 he worked as a technologist at the Institute “Mechatronics” Gabrovo. It PhD successfully defended her thesis on “Aided design of technological processes” in 1992 at the Technical University of Sofia. Currently he is Emeritus Professor at TU Gabrovo. He has published 20 books and more than 150 articles and reports. His research interests are in the field of CAD/CAM systems in micro and nanotechnology and design process for their elements.

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Full Prof. Jelena Purenović and was born on March 9, 1976 in Belgrade. She graduated from elementary school and high school of science and mathematics in Niš with excellent results. Studies at Department of Physics at Faculty of Science and Mathematics of University of Niš, majoring in Applied Physics, were completed in 2002. During 2008 and 2009. year, dr. Jelena Purenović performed volunteer work at Faculty of Electronics in Niš (contract no. 03/02-009/08-001). The contract included professional training provided by mentor’s plan and program by the mentor, as well as regular cooperation in teaching. From 20.10.2011. she was employed as an assistant for narrow scientific field of Physics, and from 11.07.2014. as an assistant professor for narrow scientific field of Physics and Materials Technology at Faculty of Technical Sciences in Čačak. On April 11, 2019. year, she was elected to the position of associate professor for narrow scientific field of Physics and Materials Technology and to the title of full professor for the narrow scientific field of Electrotechnical and technical materials 02.01.2024. year.