Research on the Application of Plasma Treatment in Mechatronics

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***Abstract*— This report provides a historical overview of plasma technology, explores the physical principles of plasma production and thermal emission, and discusses the different types of plasma treatments, current state-of-the-art technology, equipment developments, and their practical applications. It presents specific examples of mechatronics part fabrication.**

Keywords—plasma treatment, technology development, practical applications, potential uses

I. Introduction

A. Historical Overview

Plasma was first identified in a Crookes tube in 1879 by William Crookes, who described it as a 'radiating substance' during a lecture at the British Association for the Advancement of Science in Sheffield. The nature of the substance in the Crookes tube was established by Joseph John Thomson, who presented his findings during a lecture at the Royal Institution in 1897. The concept of plasma, recognized as the fourth state of matter, was introduced in 1928 by American physicists Irving Langmuir and Lewi Tonks. Langmuir is regarded as the pioneer of plasma jet treatment. Plasma jet processing is a relatively new technology developed as a cost-effective alternative to electron and laser beam treatments. The management of hazardous household and radioactive waste is a pressing issue for environmental sustainability. Therefore, solutions based on plasma gasification and incineration are proposed as ecological approaches.

Fig. 1. William Crooks (1832 - 1919), Joseph John Thomson (1856 - 1940) and Irving Langmuir (1881 - 1957) (wikipedia.org/wiki/William_Crookes; */wiki/J._J._Thomson; */wiki/Irving_Langmuir)

II. Exposition

B. Physical bases of plasma

Plasma is a state of matter in which, in addition to neutral atoms and molecules, excited particles such as protons, electrons, and positively and negatively charged ions are present. Plasma refers to any substance heated to a temperature at which its vapors become ionized and no longer follow the laws of gas dynamics.

Plasma is categorized into two main types based on temperature:

- High-temperature (thermonuclear) plasma, existing at temperatures ranging from 1×10^6 to 1×10^8 K;
- Low-temperature plasma, with temperatures ranging from 1×10^3 to 1×10^5 K.

In the universe, over 99% of matter exists in the plasma state, including stars and interstellar gas. Noteworthy plasmas, from the perspective of technology and physics, have temperatures ranging from several thousand to a million degrees Kelvin (5,000–30,000 K). Within these temperature ranges, the plasma temperature is typically characterized by the average thermal energy kT. In practice, the electron volt (eV) is commonly used as a unit of energy, where 1 eV=$1.6.10^{-19}$ J. Fig. 2. illustrates examples of terrestrial and extraterrestrial plasmas. The time *t* represents the lifespan of these plasmas.

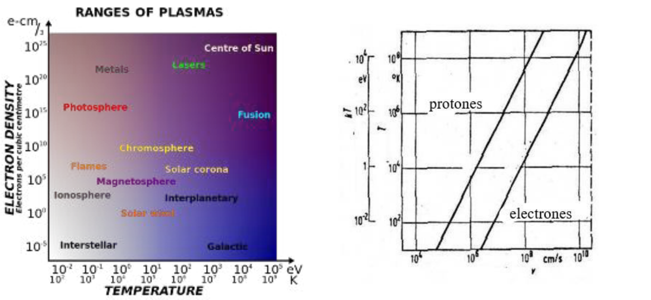
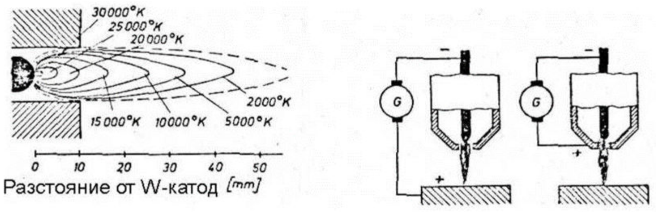


Fig. 2. Examples of terrestrial and extraterrestrial plasmas and dependence of the average velocity V of protones and electrones on temperature T (right) [1, 12]

Temperature (T), density (n), degree of ionization, and electrical conductivity are the most characteristic parameters of plasma. The temperature primarily depends on the type of gas used, where molecular dissociation and atomic ionization occur, forming a mixture of electrically conductive electrons, ions, and neutral gas particles.

A typical temperature distribution in a plasma jet indicates that temperatures of 10,000 K and above are found only within the fuel nozzle and approximately 20 mm in front of it. The temperature distribution shown in Fig. 3 refers to a tungsten cathode and a copper nozzle. Table 1 explains the relationship between temperature, the type of gas used, and arc voltage [1].



Distance from W - cathode

Fig. 3. Examples of terrestrial and extraterrestrial plasmas and dependence of the average velocity V of electrons and ions on temperature T (right) [1]

TABLE I. DEPENDENCE BETWEEN TEMPERATURE, GAS AND ARC VOLTAGE

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:

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

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

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

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

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

If this quantity is small, the system is referred to as weakly ionized plasma, where the average energy of plasma electrons significantly exceeds the average energy of atoms and molecules. Weakly ionized plasma is characterized by an electron concentration $Ne < 7x10^{16}cm^{-1}$ (degree of ionization below 10%).

In contrast, if the electron concentration $Ne > 7x10^{16}cm^{-1}$ (degree of ionization above 10%), the plasma is considered highly ionized. In this case, the relationship between the ionization temperature and the concentration of components in the plasma is described by the Saha-Eggert equation:

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

Here, Z_i and Z_0 represent the statistical sums of ions and neutral particles, respectively. h is the Planck constant, while n_0 and n_i denote the concentrations of neutral particles and ions, respectively.

Plasma density is defined by the number of ionized particles per cubic centimeter (1 cm^3). The relationship between the ionization temperature and the concentration of components in the plasma is characterized by the approximate Elwert equation:

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

Here, α is the Sommerfeld constant, n represents the number of valence electrons, and en is the quantum number of the valence electrons. $E_{I,\ H}$ denotes the ionization energy of hydrogen, while E_I represents the ionization energy of the gas. The parameter g takes values in the range from 1.4 to 4.0, depending on specific conditions. k is the Boltzmann constant, and T is the temperature (measured in Kelvin, K).

Due to its minimal ionization energy, argon ensures excellent ignition properties. The large atomic weight of this gas provides the plasma jet with a high momentum density, which is essential for separating molten material. When combined with hydrogen, which exhibits extremely high thermal conductivity during dissociation, optimal properties are achieved in terms of temperature and velocity, such as during cutting or surface processing.

The use of nitrogen reduces the tendency to form so-called "whiskers" (sharp edges) on cutting surfaces but results in the production of smoke. Table 2 presents the energy density of various heat sources [2].

Plasma is also distinguished by its extremely high thermal and electrical conductivity. Its high heat content (enthalpy), which depends not only on the average mass temperature but also on the type of ionized gas, makes it an ideal 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	1.10^{-2}	1.10^3-1.10^4
Light arc	1.10^{-3}	1.10^4-1.10^5
Plasma jet	1.10^{-3}	1.10^5-1.10^6
Electron beam	1.10^{-7}	1.10^9

C. *Plasma jet production equipment*

The plasma jet is produced by heating various gases with a concentrated electric arc in specialized generators known as plasmotrons. The applied electric arc transfers part of its thermal energy to the gas, resulting in rapid heating and subsequent expansion. The gas exits the nozzle at high speed as an electrically neutral plasma jet, commonly referred to in practice as a "plasma flame." This jet is directed through burners to the workpiece.

The production of a plasma jet is achieved through the use of open and closed arcs. When the electric arc burns between the negative tungsten electrode and the anode, passing through the nozzle, the plasma jet method utilizes the so-called interrupted arc. Conversely, if the arc forms between the negative tungsten cathode and the copper nozzle with a positive potential (anode), the method employs the so-called continuous arc. In this case, only hot, glowing plasma gas exits the nozzle.

The main parameters of the plasma jet, such as temperature and density, are regulated using one of these two methods, while the speed is controlled by "constricting" the jet within the nozzle. Fig. 3. illustrates the types of plasma jets generated with either an open (interrupted) arc or a closed (continuous) arc.

Plasma burners are classified into two types: direct-action and indirect-action burners. In the first type, the arc is formed between the cathode (a tungsten electrode within the burner) and the anode, which is the work piece itself. The plasma temperature reaches approximately 6,000 K. This type of burner has found wider application due to its simpler design, as it avoids discharges between the nozzle and the electrode.

The primary advantage of this type is the ability to apply higher potentials, thereby achieving greater power output. However, its main limitation is that it can only be used to process electrically conductive materials.

In the second type, the anode is the nozzle of the burner. The efficiency of the arc is enhanced by using a specially designed water-cooled nozzle that compresses the arc. The plasma temperature reaches approximately 50,000 K, while the plasma density attains 3.10^6 W/cm^2 at an arc current of 1500 A. This type of burner is utilized not only for welding and heat treatment, as with the direct-action burner, but also for cutting materials such as stainless steel and aluminum.

Fig. 4. illustrates burners with both direct and indirect action. The effective heat output (q) is calculated as follows:

$$q = 0.24\eta UI, \text{ cal/s} \tag{5}$$

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

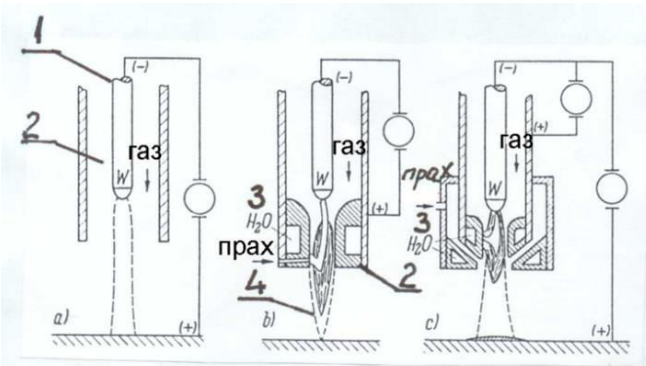


Fig. 4. Examples of terrestrial and extraterrestrial plasmas and dependence of the average velocity V of electrons and ions on temperature T (right) [1]

Legend: 1-tungsten electrode, 2-channel, 3-cooling water, 4-arc column, 5 (2 with indirect burner)-nozzle

The described burners operate with direct current, and plasma is generated through electric resistance heating. Another heating method, induction heating, is used in high-frequency plasma burners. Figure 4 illustrates a cross-section of an induction plasma burner.

D. Plasma technologies

The 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: Decomposition of materials at high temperatures in an oxygen-free environment using plasma.
- Plasma Combustion (also known as plasma burning or plasma oxidation): Combustion processes enhanced by plasma to oxidize waste.
- Plasma Vitrification: Conversion of waste into stable, glass-like materials using plasma.
- Plasma Gasification: Breaking down organic materials into syngas (a mixture of hydrogen and carbon monoxide) using plasma.
- Plasma Polishing: The use of plasma to purify gases by removing impurities

Of these, plasma gasification holds the greatest significance [3, 4].

E. Types of Plasma Cutting Operations

- **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 20,000 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, 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.

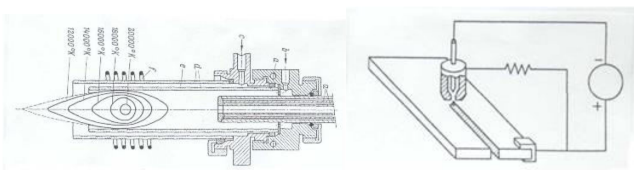


Fig. 5. Burner with induction heating. Plasma cutting principle. Plasma cutting and characteristic details made using it. [2]

Legend: a-cooling water, b-plasma gas supply, c-cooling gas supply, d-quartz tube, e-cooling, f-inductor.

(https://chernevclima.bg/content/plazmeno-ryazane-na-metali.html)

- **Welding and piercing**

Applicable for parts with a thickness between 3 mm and 8–10 mm. This process operates with currents ranging from 100 A to 350 A and a plasma gas flow rate exceeding 2 l/min.

The plasma jet welding operation can be categorized into three types [1, 7, 11]:

- microplasma and pulse plasma welding - suitable for welding parts (sheet metal) with a thickness between 0.05 mm and 1 mm. This process uses a current range from 0.05 A to 20–30 A and a plasma gas flow rate below 1 l/min. For pulse currents with a frequency of 10 kHz, magnetic fields are employed to regulate energy density.
- plasma welding - designed for parts with a thickness between 1 mm and 3 mm, utilizing a current range from 20 A to 100 A and a plasma gas flow rate between 1 and 2 l/min.
- plasma welding with piercing - applicable for parts with a thickness between 3 mm and 8–10 mm. This process operates with currents ranging from 100 A to 350 A and a plasma gas flow rate exceeding 2 l/min.

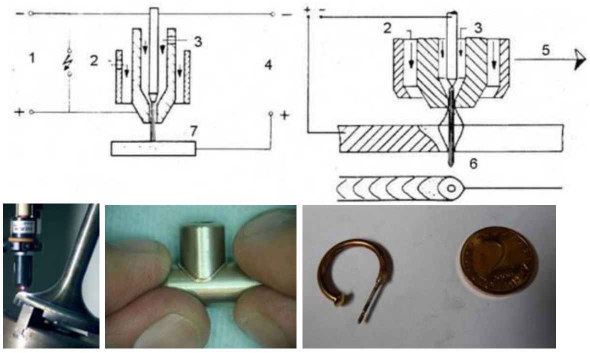


Fig. 6. Principle of operation of plasma welding (piercing) and piercing welding. Details by plasma welding, micro plasma welding and brazing. [6]

Legend: 1-auxiliary arc, 2-shielding gas, 3-plasma gas, 4-main arc, 5-feed direction, 6-outgoing plasma jet, 7-detail.

(https://www.zavariavane.com/микро-спояване/)

The principles of operation for the second and third types of welding are illustrated in Figure 6. Argon is primarily used as the plasma gas because its relatively low ionization energy ensures stable ignition at an open-circuit voltage below 100 V. For welding high-alloy steels and nickel alloys, a shielding gas mixture of 90–95% argon and 5–10% hydrogen is utilized. The presence of hydrogen in this mixture positively influences the process by reducing hydrogen from the atmosphere.

When welding materials such as titanium, copper alloys, or glass, a mixture of helium (substituting hydrogen) and argon is used. Controlled thyristor rectifiers with two separate power supply sections (for the auxiliary and main arcs) serve as current sources in microplasma and plasma welding.

Power sources for plasma piercing welding differ from these only in the current circuit for the auxiliary arc, which operates at a higher open-circuit voltage, and in their plasma gas supply system.

According to the connection scheme, welding is performed exclusively with the electrode at a negative potential (cathode). The electrode-anode configuration is not used due to its high thermal load. This limitation also applies to schemes using alternating current power supplies, where arc initiation becomes challenging.

Based on the type of arc, welding can be categorized into spot or seam welding with an interrupted arc, and seam welding with a continuous arc. Plasma jet welding is not used for artificial materials or aluminum, as the negative polarity of the electrode is incompatible with these materials.

The welding configuration with a negative electrode is illustrated in Fig. 6. (right).

The advantages of plasma jet welding include:

- Utilization of a concentrated light arc with high energy density and minimal deviation in arc length, resulting in small melting and heat-affected zones with a shape factor of 1 to 2 and high joint quality.
- Relatively deep penetration at high processing speeds (e.g., 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 mm depth).
- High arc stability at low currents, leading to lower energy consumption.
- Reliable ignition and precise positioning enabled by a continuously burning auxiliary arc.
- Ease of feeding additional material and prevention of tungsten inclusions, even when the electrode contacts the work piece.
- Excellent potential for fine-tuning individual parameters during the process and facilitating automation.

Despite these advantages, plasma jet welding is primarily limited to micro plasma welding for economic reasons. It is almost exclusively used for parts with high-quality requirements in industries such as electronics, aerospace, and rocketry. The primary applications include welding of highly alloyed and silicon steels, as well as nickel, copper, titanium, zirconium, and their alloys (particularly CrNi+Ne alloys, excluding light metals).

At currents up to 100 A, plasma jet welding is applied for components such as contacts, rheostats, thermocouples, short-circuited windings of stator packages, and sensors.

The plasma jet drilling scheme is identical to the one shown in Fig. 6. (left). The main differences lie in the operating parameters: current, speed, and the absence of additional material feeding.

F. 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 material layers from a substrate. Its various types are detailed in [1, 10]. Unlike wet etching, which involves chemical solutions, dry etching is a gas-phase process, as described in [9].

This technique is widely employed to improve adhesion in joints, varnishing, and metallization of components in the instrument-making, micro-technology, and electronics industries, particularly for cleaning semiconductors. Dry etching processes are typically conducted under vacuum conditions, with pressures ranging from a few millitorrs to hundreds of millitorrs. The low-pressure environment ensures a clean etching process and allows for precise control of plasma reactivity.

The operational parameters are as follows:

- Pressure: 50 to 200 kPa
- Power: From a few hundred watts to over 1 kW
- Gas flow rate: 50 to 500 ml/min, using oxygen, nitrogen, or noble gases
- Temperature: 300 to 1000°C
- Treatment duration: 1 to 15 minutes

The frequency used for gas ionization depends on the specific gas type.

Dry etching offers superior anisotropy (directional etching) and finer control over feature sizes, making it ideal for creating smaller, more precise structures—an essential requirement in the production of modern microelectronics.

The process sequence is as follows:

- Achieving a vacuum of 100 Pa in the etching chamber.
- Introducing a gas (e.g., oxygen, CF_4, SF_6, or Cl_2).
- Ionizing the gas with high-frequency energy (1 MHz) to generate plasma.
- Allowing reactive radicals to interact with the surface layer of the material, ionizing molecules.
- Removing particles using electrons with energies of 2 to 5 eV (equivalent to 20,000–50,000 K).

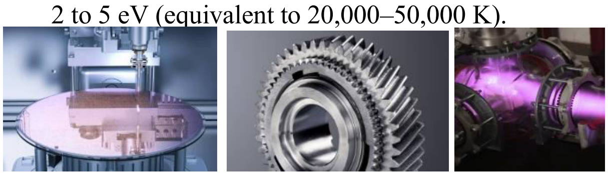


Fig. 7. Principle of operation of plasma welding (piercing) and piercing welding. Details by plasma welding, micro plasma welding and brazing.

(https://www.zintilon.com/bg/blog/wet-etching-vs-dry-etching/)

- Extracting these particles via suction.
- Cleaning the surface of oils and similar contaminants with an inert gas.
- Removing the treated substrate from the chamber.

The production of reinforced canvases with phase-bonded composites is conducted in conjunction with the

Plasma cleaning eliminates hydrocarbons and water-containing agents, effectively removing oils, greases, waxes, and even silicone residues.

G. 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 intensely heated. Monatomic gases become partially ionized, while diatomic gases undergo dissociation and partial ionization.

The sprayed material is introduced into the gas mixture in powder form via a carrier gas. The powder particles melt at temperatures exceeding 20,000°C and are propelled at high speed onto the workpiece to form a coating. The most commonly used equipment for this process are direct current plasma torches, which operate with nitrogen or a nitrogen-hydrogen mixture. These torches feature a continuous arc and operate at power levels ranging from 1 to 100 kW.

The powders used in this process are typically metal, ceramic, or metal-ceramic materials, particularly those that are difficult or impossible to process using conventional flame or arc spraying methods. The selection of additional materials is critical to achieving the desired coating quality. The powders are usually spherical, with diameters ranging from 15 µm to 75 µm.

The distance between the plasma torch and the workpiece should be maintained within 80–150 mm. The influence of individual process parameters on coating quality is discussed in detail in [7].

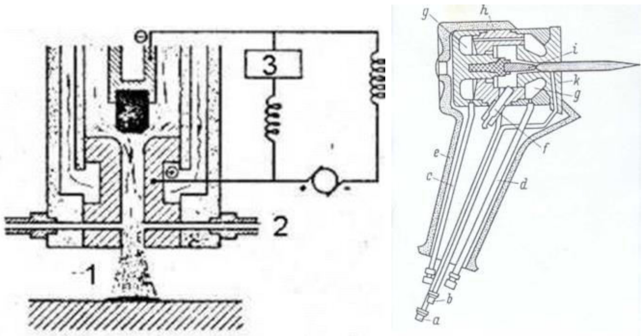


Fig. 8. Application of coatings with a plasma jet and a spray gun. [1]

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 a part for optimal coating adhesion, sandblasting is commonly employed, providing the desired degree of roughness. After the coating is applied, mechanical compaction methods such as rolling, pressing, or hammer pressing can be used to enhance the coating's integrity.

During heat treatment, the applied coating alloys with elements present in the base material, creating a stronger bond. In contrast, chemical treatments fill the pores in the coating by modifying the surface layer.

The principle of applying coatings using a plasma jet is illustrated in Fig. 8. The design of a plasma spraying gun is shown in Fig. 8 (right) [2].

plasma spraying process. A semi-finished phase-bonded material is first covered with a foil, onto which a layer of powder with a specific structure is applied using a plasma jet.

Fig. 9. illustrates the principle of operation in the production of canvases reinforced with phase-bonded material. On the right, a photo of plasma spraying on silicon carbide is shown [8].

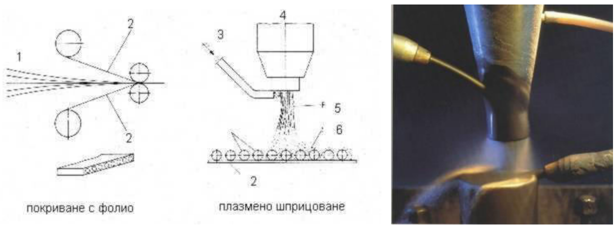


Fig. 9. Application of coatings with a plasma jet and a spray gun. [1]

Legend: 1-fiber, 2-foil, 3-powder, 4-plasma torch, 5-plasma beam, 6-sprayed layer

H. Plasma restoration of worn parts

In this operation, a layer of up to 4–5 mm is applied, and the welded metal can differ from the base metal. The application rate ranges from 0.9 to 1 N/h.

A key advantage of this process is that it occurs at relatively low temperatures, preventing destruction, deformation, or alterations in the material properties. The economic feasibility of restoring parts is demonstrated by the possibility of reusing 65–75% of them (Fig. 9).

Examples:

- Application of wear-resistant coatings (e.g., silicon carbide, silicon nitride) on metal-cutting tools, with a thickness of several micrometers.
- Surfacing of worn press and punch tools.
- Surfacing of parts to enable their reuse, such as crankshaft journals, gears, and other high-value components in the automotive and military industries.
- Restoration of rings, tees, splines, cams, connecting rods, and similar components.

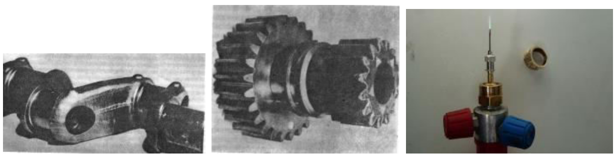


Fig. 10. Details through restoration (https://sandacite.bg/възстановяване-на-авточасти/)

III. 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 delicate materials such as foils, screens, boards, filters, and other fine mechanical parts integral to microsystems technology.
- Coating components designed to operate under extreme conditions, ensuring resistance to high temperatures and intense wear.
- Surface cleaning and activation of both metallic and non-metallic materials to optimize adhesion and performance before coating.
- Integration of these methods with complementary techniques, such as ion-beam plasma processing, to achieve superior results.

These advanced processes are critical for meeting the demanding requirements of modern industry, particularly in applications where precision and reliability are paramount.

IV. Conclusion

A historical overview is given, the physical foundations of plasma technology are considered, the types of processing and the state of the technologies with their main parameters, the designs, development and potential of the equipment and application in practice are considered. The advantages and disadvantages are analyzed in detail in Mechatronics.

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