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THE ISSUE OF POWDER DOSING IN ADVANCED TECHNOLOGICAL APPLICATIONS

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ABSTRACT: The precise dosing of powders represents a critical stage in the realization of advanced technological processes, based on the use of metallic and non-metallic powders. Technologies such as Spark Plasma Sintering (SPS) or Electrical Discharge Machining (EDM) require rigorous control of the quantity and flow rate of powders in order to ensure the quality and repeatability of the process. Through the targeted use of high-quality metallic powders, companies can make their production processes significantly more efficient while also reducing costs. The present study highlights the current types of powder feeders, the main problems encountered in their use, and argues for the necessity of developing a new system adapted to the specific requirements of these advanced technologies.

KEYWORDS: dosing, powders, technologies, precision, automation

1. INTRODUCTION

In the last decade, the use of metallic and non-metallic powders has experienced significant expansion in the field of advanced manufacturing technologies, such as powder metallurgy, additive manufacturing, or special sintering processes [1, 2, 3]. Regarding additive manufacturing, this represents a relatively new technique, which allows the local melting of metallic powders with the aid of a laser beam [4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14], an electron beam [10, 11], a plasma jet [15, 16, 17, 18], or through post-sintering of powders bonded with adhesive [7, 19, 20]. In particular, Spark Plasma Sintering (SPS) and Electrical Discharge Machining (EDM) are processes that impose strict requirements regarding powder dosing: control of mass or volume, ensuring a constant or interrupted flow rate, safe handling of fine powders, as well as integration into closed systems with a high degree of automation [21, 22, 23, 24, 25, 26, 27, 28, 29].

2. CURRENT STATE AND IDENTIFIED ISSUES IN POWDER DOSING

2.1 Additive Manufacturing (AM) by Powder Deposition

Additive manufacturing is a cutting-edge technology that involves building the final part layer by layer. Additive formation with powder deposition represents one of the most advanced directions of development in layer-by-layer manufacturing of functional parts with complex geometries and customized characteristics. This technology allows the production of components through the successive deposition of metallic powders and their controlledfusion. In this section, four relevant technologies are analyzed: deposition with electric arc, plasma jet, electrical discharge in pulses, and laser beam fusion in a powder bed.

2.1.1 Electric Arc Deposition

The method uses an electric arc between an electrode and the substrate to melt metallic powders or additional wire deposited layer by layer. The powders are injected into the arc area through a shielding gas such as argon or helium. It is an adaptation of MIG/MAG welding for additive purposes [17], [30].

The equipment for electric arc metallization (fig. 1) is composed of two wire electrodes, which, with the help of two drive rollers, are introduced into the arc burning zone. The guides ensure the imposed orientation of the additive-wire ends [31].

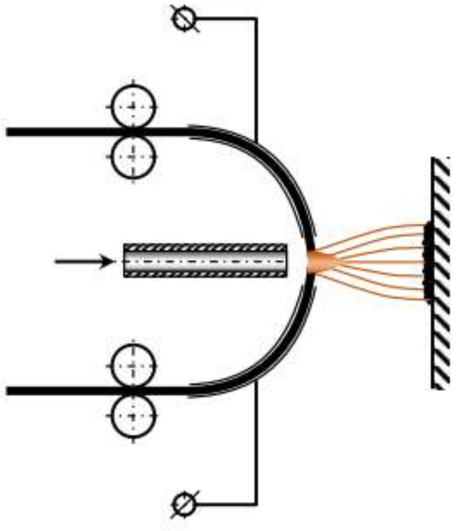

Figure 1. Electric arc metallization [116]

Through the nozzle, gas is supplied at a pressure of 0.6 MPa. The high velocity of the metal particles (120÷200 m/s), the short flight time of 10^{-3} s ensure their plastic deformation, the filling of irregularities with particles, and the adhesion of the particles to each other. Successive layering allows the formation of a deposition with a thickness of up to 10 mm. During processing, the surface of the part is heated by (50÷70) °C, a fact which allows deposition on the surfaces of parts made of metals, plastics, and wood.

- **Advantages:**
  - High deposition efficiency
  - Low equipment costs
  - Flexibility in the use of materials
- **Limitations:**
  - Low geometric precision
  - Increased risk of porosity in the absence of strict parameter control

2.1.2 Plasma Jet Deposition

Plasma jet depositions are intended for the formation on metallic surfaces of films and layers with considerable thicknesses (up to several millimeters), with composition and microstructure different from that of the substrate material.

In this method, the powders are introduced into a plasma jet generated by a high-frequency current, melting rapidly and being deposited on the substrate. The process is known as Plasma Transferred Arc or Plasma Spraying [17], [18].

For heating, partial or complete melting of deposition materials in the form of powder or wire, low-temperature plasma is applied. This represents a partially or completely ionized gas, in which the density of positive and negative charges is approximately equal. Low-temperature plasma is formed during electrical discharge in a gaseous medium and is characterized by high energy concentration in small volumes, by high temperatures and velocities of various physicochemical processes [31].

Physicochemical processes in plasma take place in the temperature range of $10^3÷10^4$ K, pressures of the order of $10^2÷10^8$ Pa, interaction durations within $10^{-5}÷1$ s, at plasma gas movement speeds of about 40÷4000 m/s. In this type of deposition, plasma heats and transports the deposition material, ensuring its transfer to the surface of the target.

Advantages of the method include: the possibility of obtaining surface layers with physical-mechanical properties without deformations of the parts and without changes in the structure of the processed part; the high temperature of the plasma allows the deposition of practically any material, including refractory ones; high productivity of the process (up to 20 kg/h of powders); the possibility of depositing many layers, including composites.

Disadvantages of the method: high porosity of the layers (4÷16) %, relatively high gas consumption (2÷6 thousand l/h), low energy utilization efficiency (up to 10%), high requirements regarding the stability of plasma properties.

In plasma deposition in the atmosphere with the help of plasma accelerators – plasmatrons, the deposition material in the form of powders or wire is introduced into the plasma jet, where it is heated, melted, sprayed, and transported toward the processed surface. Upon impact with it, the particles of the deposition material condense on it, heating the target material. The adhesion of the deposited material with the surface of the part is ensured by mechanical gripping, chemical interaction, diffusion processes, and by micro-welding bridges. The deposition itself can be regarded as a material composed of deformed particles, joined at the contact surface with circular sectors.

Devices for obtaining low-temperature plasma can be classified according to the operating principle into arc plasmatrons, inductive, and high-frequency ones. A wider spread in technology has been obtained by arc plasmatrons. In such plasmatrons, between the non-consumable water-cooled tungsten cathode and the copper anode, made in the form of a nozzle and also water-cooled, the electric arc is ignited, in which the plasma-generating gas in the nozzle (argon, hydrogen, nitrogen) is ionized.

This installation, whose plasmatron is shown in Fig. 2, includes the powder transport device, the special current source, the gas supply system, and the cooled water supply system [31].

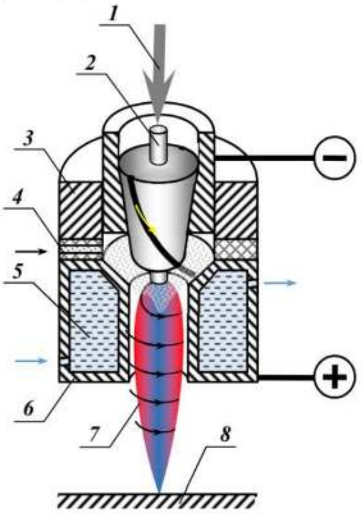

Figure 2. Diagram of the arc plasmatron: 1 – plasma-generating gas; 2 – cathode; 3 – casing; 4 – gas transport; 5 – cooling; 6 – anode; 7 – plasma jet; 8 – processing surface [31]

- **Advantages:**
  - Efficient melting with excellent layer adhesion
  - Adaptability to a variety of materials (oxides, carbides, metals)
  - Precise control over the chemical composition
- **Limitations:**
  - Expensive and complex equipment
  - Requirement of a controlled atmosphere
- **Applications:**
  - Functional layers for wear- and corrosion-protection
  - Fields: aerospace, biomedical, energy [17], [18]

2.1.3 Deposition by Electrical Discharge Pulses / Spark Alloying

The technique involves generating high-voltage pulses that produce electric sparks between an electrode and the surface of the workpiece. This causes localized micro-melting and the deposition of powder on the substrate. It is used both in surface modifications and in micro-layered deposition processes [31], [30], [25]. Surface modification of metals is a cutting-edge technological direction aimed at improving the functional properties of base materials. These techniques harness the energy of electrical discharges to transfer material in the form of powder or electrode onto a metallic surface, generating a consolidated, often alloyed layer with superior physico-chemical characteristics [31], [21], [23].

The process of implementing the method is simple, and the equipment is easily transportable and compact. The schematic electric diagram is shown in Fig. 3. It consists of a direct-current generator (G), which charges the capacitor bank C through a ballast resistor R. The electrode (2), actuated by device (3), is connected as the anode, and the workpiece (2) as the cathode. The operating principle is as follows: the variable capacitor (C) is charged from the DC source (G) through the ballast resistor (R), and when the anode approaches the cathode, a pulsed discharge occurs.

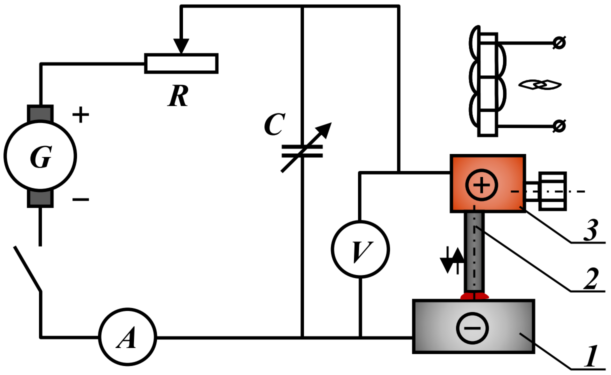

Figure 3. Traditional schematic diagram of the spark alloying installation: 1 – workpiece (cathode); 2 – electrode (anode); 3 – actuation device [31]

Powder deposits formed by applying pulsed electrical discharges are based on the use of high-intensity electrical discharges between an electrode (often made of partially sintered or compacted powders) and the workpiece. The spark generated between the two elements causes local melting of a portion of material from the electrode and even from the substrate, followed by rapid solidification on the surface of the part. By repeating the pulses, an adherent metallic, ceramic, or composite layer is formed [30], [24].

The process is often carried out in a dielectric medium (air, oil, or distilled water), which controls the formation of the electric arc and removes the particles generated by erosion. Parameters such as pulse time, current, frequency, and electrode composition strongly influence the morphology of the resulting layer [22], [25].

A wide variety of metallic, ceramic, and composite materials can be used to form functional layers on metallic surfaces. Among the most frequently used powders are Ti, Nb, Al_2O_3, Cr, graphite, or alloys based on superior metal carbides: WC, TiC, TaC and cobalt (Co) as binder [30], [23].

- **The Practical applications include:**
  - increasing wear resistance (hard layers with carbides or nitrides)
  - corrosion protection (application of Cr or Ni layers on steels)
  - biocompatibilization (Ti implants with hydroxyapatite or functional oxide layers) [26]

Studies have shown that the use of Ti-Nb electrodes in EDC leads to dense, homogeneous, and corrosion-resistant layers on Ti-6Al-4V alloys, being proposed for biomedical applications [30].

In **Fig. 4** the cross-sections of C45 steel samples processed successively with Ti electrodes, then with AlN and SiC powders, are presented [31].

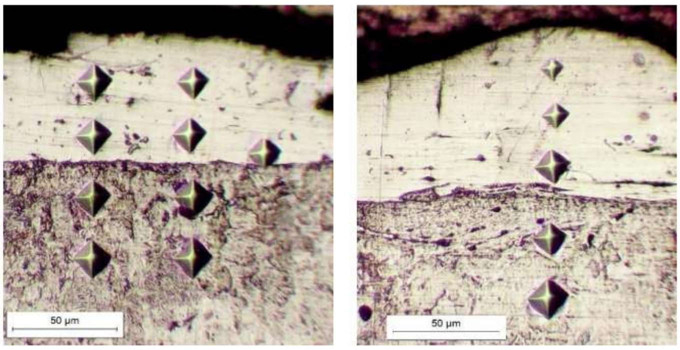

Figure 4. Microstructure of C45 steel samples with layers of ternary compounds: TiAlN (a) and TiSiC (b) [31]

The method of impulse electrical discharge deposition (EDD) fits into a broader context of modern processes for the modification of metallic surfaces, being related to techniques such as Spark Plasma Sintering (SPS) and plasma alloying with double glow discharge. In the case of SPS, powders are sintered between electrodes under pressure and pulsed current; although this method is frequently used for volumetric sintering, it can also be adapted for surface treatments [16], [18]. The technique of plasma alloying with double discharge allows precise control of the thickness and composition of the deposited layer [15].

Current trends in the field aim at the integration of nanostructured powders, intelligent control of electrical discharges, and the use of EDD in extreme environments, such as vacuum or controlled atmospheres [25], [18]. This approach offers an efficient and versatile method for improving the mechanical, chemical, and biological properties of materials, combining the advantages of sintering with those of localized thermal treatment, without compromising the integrity of the base part.

In practice, the major challenges concern ensuring the uniformity of the layer, preventing thermal cracks, and integrating the process into automated production lines [21], [24], [17]. The EDD method is characterized by very high precision, the possibility of deposition in liquid media, and the obtaining of adherent layers with functional texture. The fields of application include biomedical implants, microstructuring, and tribological treatments.

The functional diagram of a spark plasma sintering system, including the associated feeder, is presented in Figure 5, highlighting the way powders are deposited and consolidated through controlled discharges.

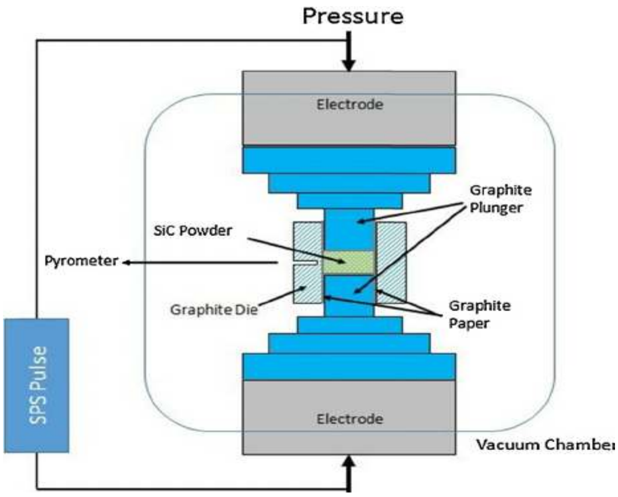

Figure 5. Functional diagram of the spark plasma sintering system [32]

Figure 5 illustrates the functional diagram of a spark plasma sintering (SPS) system [32]. The system is composed of a water-cooled upper electrode, a water-cooled lower electrode, a graphite die, a pulsed current supply system, a uniaxial pressure application mechanism, and a sintering chamber in vacuum or inert atmosphere. The powder is introduced into the cavity of the graphite die, placed between the two cooled electrodes.

After filling the die, the process takes place through the simultaneous application of axial pressure and pulsed current, in a sintering cycle lasting from a few seconds to several minutes. In this configuration, powder dosing is of a static type, the material being introduced into the cavity before the process begins, either manually or through an assisted vibration system. Unlike thermal jet or electron beam technologies, there is no continuous dosing system during operation, which highlights the specific character and limitations of this method in powder application.

- **Disadvantages of this dosing system include:**
  - The need to stop and manually fill the die before each cycle
  - Not adapted for continuous or automated production;
  - Risk of incomplete deaeration of the cavity when using fine powders;
  - Exact dosing is critical but difficult for very small quantities (< 0.1 g);
  - Limited to simple shapes – dosing becomes imprecise for dies with complex geometry [32].

2.1.4 Laser beam fusion in a powder bed is one of the most precise additive manufacturing methods

A high-intensity laser beam selectively scans a layer of metallic powder, melting it locally and thus obtaining a layered structure. The process is repeated successively until the part is completed [17], [18].

Laser deposition of the powder–gas mixture is an advanced technology that ensures high quality of the deposited layer. In this process, a powder flux is injected into the laser heating zone, where its particles are heated and melted together with the material of the part, generating a homogeneous and controlled fusion of the metallic powder into a solidified layer.

Through this method, layers (or bands) with widths of approximately 0.5 to 5 mm and thicknesses between 0.3 and 3 mm are obtained, which allows controlled construction of stratified structures, characteristic of additive manufacturing technologies. As carrier gases for the powder, various options are used — air, carbon dioxide, nitrogen, and inert gases — which contribute to process stability and prevention of material oxidation.

In laser beam fusion in a powder bed, a fine layer of metallic powder is uniformly distributed on the build surface. A focused laser beam follows a programmed path across the layer surface, locally melting the powder and fusing it with the previously solidified layer. Due to the very high heating rate (in the range of 10^4–10^6 K/s) and rapid cooling, the solidified material acquires a fine microcrystalline structure, with improved mechanical properties and non-equilibrium phases that cannot be obtained by conventional methods.

The melted layer solidifies almost instantly, and the process is repeated by depositing a new powder layer and melting it, until the final shape and dimensions of the part are obtained [31].

Physical and technological particularities:

- Energy absorption of the laser is achieved through the interaction of the beam with the powder particles, which, due to their small size and large surface area, enable uniform and controlled melting.
- The high energy density concentrated in a small area ensures rapid melting and metal synthesis without excessive heating of the bulk material of the part, reducing deformations and residual stresses.
- The process takes place in controlled environments (inert gas such as argon or nitrogen), which prevent oxidation and contamination of the material.
- Precise control of the laser parameters (power, scanning speed, focus) and of the powder layer thickness (typically between 20 and 100 µm) is essential for obtaining parts with optimal density and quality.
- **Advantages:**
  - High precision and the possibility of producing complex geometries, impossible or difficult to achieve by traditional methods.
  - Reduced material waste, as the unused powder can be recycled
  - Superior mechanical properties due to the fine microstructure and rapid solidification process
  - Possibility of processing a wide range of metallic alloys, including stainless steels, titanium, aluminum, and special alloys
- **Limitations:**
  - The maximum size of the parts is limited by the size of the powder bed and the equipment used
  - High equipment costs and the need for strict operating conditions
  - Requirement of post-processing for some applications, such as support removal and surface finishing
- **Applications:**
  - The maximum size of the parts is limited by the size of the powder bed and the equipment used
  - Customized implants
  - Aerospace and automotive components
  - Topology-optimized devices

In Figure 6, laser beam fusion in a powder bed is represented, which uses a layer based on powder material.

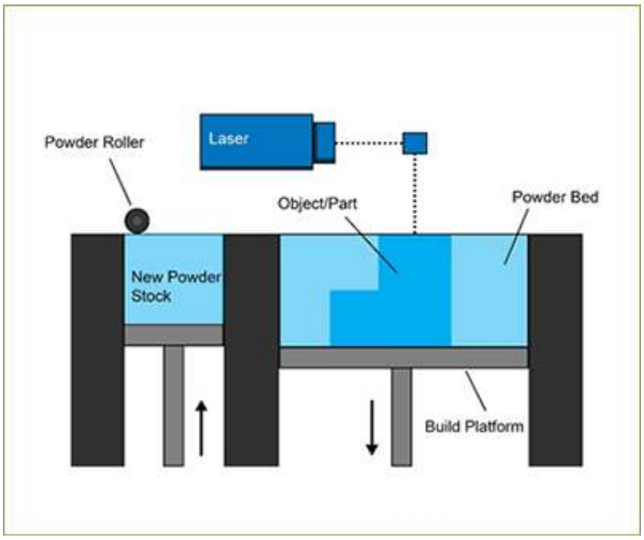

Figure 6. Powder bed fusion with laser beam
Image source: Loughborough University, available on Ecwid Blog – Additive Manufacturing

Powder dosing in the laser deposition process is illustrated in Figure 7.

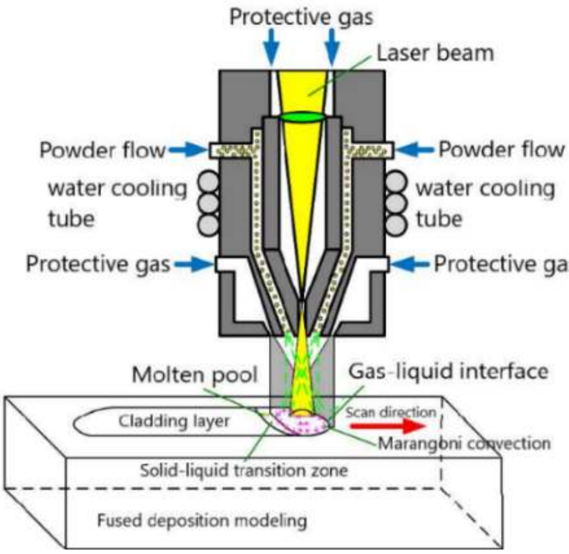

Figure 7. Laser material deposition [33]

The essential elements of the process include:laser beam, coaxial powder nozzle, shielding gas, injected powder, melt pool, and substrate.

Laser beam deposition technology is based on the controlled addition of a layer of material, typically in the form of metallic powder, onto a substrate through local fusion induced by a high-intensity laser beam. In this process, the powder is delivered coaxially, i.e., injected symmetrically around the axis of the laser beam, ensuring uniform distribution and efficient interaction with the processing zone. Under the action of the laser beam, the powder particles melt partially or completely, forming a melt pool that solidifies with the substrate and enables the formation of the deposited layer [33].

The special coaxial nozzle ensures precise powder delivery into the center of the laser beam, while the shielding gas (argon or helium) prevents oxidation of the material and stabilizes the powder jet. This configuration allows for controlled deposition of metallic layers with high density and optimal adhesion, being frequently used for repairs, reinforcements, or the application of functional coatings. However, the deposited layer may exhibit thickness nonuniformities, porosity, or discontinuities caused by insufficiently controlled powder handling conditions.

Consequently, the following disadvantages of coaxial powder feeders in laser cladding can be highlighted:

- High sensitivity to nozzle calibration: minor deviations may result in material losses and reduced layer quality.
- Powder agglomeration in the nozzle, especially for hygroscopic powders or powders with irregular granulation.
- Requirement of a complex synchronization system between the laser head movement and powder feeding.
- High costs associated with coaxial nozzles and their maintenance.

2.1.5 Electron Beam Melting

This method uses an electron beam to melt the powder. The process takes place in a vacuum, making it ideal for reactive alloys such as titanium [34]. It is one of the most precise and efficient methods for producing complex parts from metallic alloys, particularly in the biomedical and aerospace industries.

Fig. 8 illustrates the powder distribution and feeding system in the additive manufacturing process of layer formation by electron beam melting.

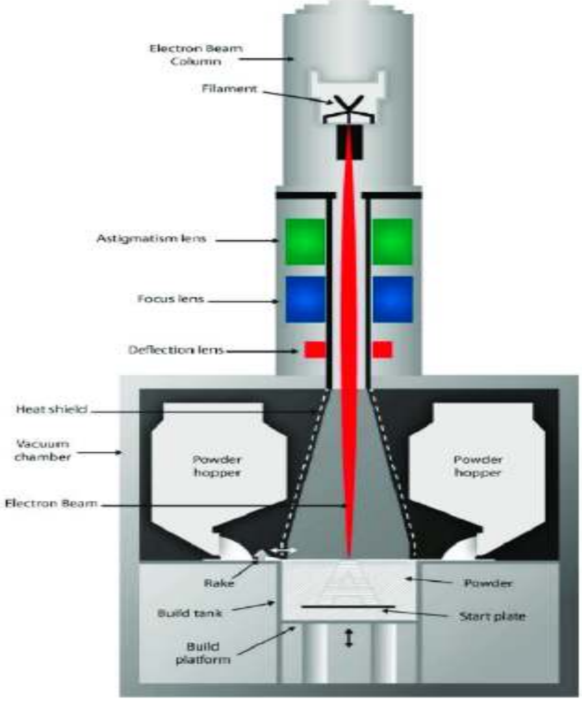

Figure 8. Powder feeder for electron beam melting [35]

The process scheme shown in Fig. 8 includes: vacuum powder hoppers; feeding mechanism (rakes or rollers) for distributing the thin powder layer; layered powder bed; electron beam; lift platform; and powder spraying cartridge.

In practical implementation of this technological process, the powder is dosed from the hoppers during each cycle and distributed on the bed in a uniform layer of the chosen thickness (50–100 μm). The electron beam vaporizes or melts these layers according to the CAD model. In electron beam melting technology, powder dosing is not performed by a typical feeder but rather through a stratified distribution mechanism from sealed hoppers, using a rolling bed or rake [35], [36]. This approach ensures: creation of a uniform powder layer (50–100 µm); continuous feeding and reloading of powder in vacuum after each cycle; and compatibility only with conductive, spherical powders of high flowability.

Advantages of applying this type of powder dosing in the process include: automated feeding integrated into the machine; excellent layer uniformity; suitable for reactive materials in vacuum (e.g., Ti-6Al-4V).

- **Nevertheless, the following disadvantages are noted:**
  - High-vacuum requirements ⇒ complex sealing
  - Irregular powders or those under 15 µm may cause blockages
  - Costly system, difficult to adapt to rapid material changes

Table 1 highlights the main characteristics of deposition and sintering technologies for powders and metallic materials using various energy sources. This analysis allows identifying the advantages and limitations of each method, as well as the most suitable fields of application.

Table 1. Comparison of additive manufacturing technologies and powder-based treatments

Criterion	**Arc Deposition [30]**	**Plasma Jet Deposition [21]**	**Electrical Discharge Deposition [24]**	**Laser Fusion [31]**	**Electron Beam Melting [25]**
Principle	Melting with electric arc	Melting with plasma jet	Controlled electrical sparks	Selective laser melting	Selective melting with electron beam
Process temperature	3,000–4,000 °C	10,000–15,000 °C	>5,000 °C locally	~2,000–3,000 °C	~2,000–3,000 °C (in vacuum)
Energy source	Electric current	Plasma gas and current	High-voltage pulses	High-intensity laser	Accelerated electron beam
Materials	Powders, wires	Metallic/ceramic powders	Conductive powders, electrodes	Fine metallic powders	Conductive metallic powders
Deposition rate	High	Medium–high	Low	Medium	Medium–high [122]
Dimensional accuracy	Low–medium	Medium–high	Very high	Very high	Medium
Layer adhesion	Good	Excellent	Excellent	Excellent	Excellent
Applications	Repairs, large parts	Functional coatings	Implants, microstructuring	Complex functional parts	Implants, critical aerospace parts
Equipment cost	Low	High	Medium–high	High	High
Working atmosphere	Inert	Inert, vacuum	Dielectric, liquid	Inert (Ar, N_2)	Vacuum
Limitations	Porosity, precision	Cost and equipment	Low speed, limited scalability	Cost, residual stresses	Medium precision, limited materials

The comparative analysis shows that the choice of technology depends on the trade-offs between accuracy, deposition rate, costs, and application. Technologies based on electrical discharges (arc, EDP) provide very high temperatures and good adhesion, but may be slower or less precise. Laser and electron beam fusion allow the production of complex parts with high precision, but the equipment is expensive and limited by material type. Plasma jet deposition combines high accuracy and excellent adhesion, making it suitable for functional coatings and complex industrial applications. The table demonstrates that there is no universal method; each technology is differentiated by its balance between accuracy, cost, deposition rate, and material compatibility. The correct choice depends on the final part requirements and process conditions.

Table 2. Comparison between conventional and additive methods in metal powder processing
Adapted from: [10], [37], [2], [38], [39], [8], [30], [23], [25], [17], [18]

Criterion	**Conventional methods (pressing and sintering, casting, machining)**	**Additive methods (layer-by-layer deposition)**
Processing principle	Removal/casting/compression followed by heat treatments	Selective deposition and layered melting
Material used	Pressed powders or bulk materials	Fine metallic powders with controlled properties
Geometric accuracy	Medium – requires post-processing	High – fine details directly from the process
Geometric complexity	Limited – dependent on tools and molds	Very high – optimized, topological geometries

Manufacturing time	Long – multiple sequential stages	Reduced – direct fabrication from digital model
Material utilization rate	Low – significant waste generated	High – efficient use of powder
Equipment cost	Medium – sometimes more affordable	High – advanced equipment
Production flexibility	Low – difficult to adapt for rapid prototyping	High – easy customization, no specific tools
Working atmosphere	Usually in air or controlled atmosphere for sintering	Inert atmosphere or vacuum, depending on method
Typical applications	Standard parts, mass production	Prototypes, implants, unique functional parts

Following the comparisons, we can conclude that conventional methods such as pressing, sintering, or casting provide medium accuracy, generate waste, and have reduced flexibility. Additive methods enable layer-by-layer deposition, with high precision, complex geometries, and efficient material utilization. They offer increased flexibility, rapid adaptability to prototypes, and require a controlled atmosphere (vacuum or inert). Thus, additive methods are ideal for unique functional parts, prototypes, and advanced applications such as implants or aerospace components.

2.1.6 Conclusions on additive manufacturing technologies using powder deposition

The five powder-based additive manufacturing methods provide a broad framework for modern fabrication. The choice of method depends on the type of material, the geometry of the part, the functional requirements, and the available costs. The integration of these technologies into industrial applications reflects the continuous progress toward advanced and customized manufacturing.

Metal powders, through their morphological and chemical characteristics, decisively influence the efficiency of the process and the performance of the final product [2], [39], [8].

2.2 Electrical Discharge Machining with Powders (EDM-P)

2.2.1 Principle of the EDM method and integration of powders into the process

A small table example is presented below. The style of the content of the table is _NTR_Table_Text. You may align the text inside the table left, right, center and justify

The electrical discharge machining (EDM) technology is based on the phenomenon of controlled pulsed discharges between two electrodes immersed in a dielectric (air, oil, or deionized water). The material is thermally eroded by local micro-explosions that generate temperatures exceeding 8000–12000 °C [10].

The integration of conductive or semiconductive powders into the dielectric fluid fundamentally changes the behavior of the electric arc and the quality of the machined surfaces. Powders influence the formation of the plasma channel and the distribution of the electric field, leading to a more uniform distribution of energy and, consequently, to finer and more efficient machining [37], [40].

One of the contemporary methods for forming deposition layers, which enjoys a series of advantages such as: the wide variety of materials used, the possibility of forming sandwich-type layers, ensuring perfect adhesion with the base material of the part, the simplicity of implementation of the method and the equipment applied, is the method of powder deposition.

2.2.2 Mechanism of Action in Powder-Mixed Electrical Discharge Machining (PMEDM)

The powders added to the dielectric liquid reduce the dielectric strength and decrease the critical breakdown distance, which allows for:

- an increase in the volume of material eroded per pulse.
- reduction of electrode wear.
- obtaining a lower surface roughness.
- formation of a modified surface layer with improved properties [10][32].

2.2.3 Types of Powders Used

The diversity of powder materials allows the adaptation of the Powder-Mixed Electrical Discharge Machining (PMEDM) process to a wide range of applications. Among the most commonly used powders are listed in:

Table 3. (Data collected and synthesized from sources [10], [37], [40], [32], [41])

Powder	**Main effect**	**Dominant applications**
Graphite powder	Reduction of electrode wear	Molds, precision machining
Titanium (Ti) powder	Formation of durable functional layers	Biomedical implants, aircraft components
Chromium (Cr) powder	Improvement of the hardened layer durability	Anti-friction coatings
Silicon carbide (SiC) powder	Reduction of surface roughness,	Micromachining, electronics

	increase in hardness	
Copper (Cu) powder	Increase in thermal and electrical conductivity	High-precision electrodes

Table 3 highlights the types of powders used in deposition or sintering processes and their primary roles.

The selected powders directly influence the properties of the resulting layer: graphite reduces electrode wear; titanium enables the formation of durable functional coatings; chromium increases layer durability; SiC enhances hardness and surface finish; and copper improves thermal and electrical conductivity.

The choice of powder is closely correlated with the specific applications — ranging from biomedical implants and aerospace components to micromachining and high-precision electrodes.

2.2.4 Technological parameters and their influence

The performance of the Powder-Mixed Electrical Discharge Machining (PMEDM) process is determined by several factors:

- Particle size – optimal range between 1–10 µm [32].
- Powder concentration in the dielectric – typically between 1–5 g/l; excessive concentration may lead to short circuits.
- Powder material – electrical conductivity and chemical stability influence the discharge channel formation.
- Type of electrical pulses – long pulses are used for rough machining, while short pulses are suited for finishing operations [40].

2.2.5 Advantages over Conventional EDM

The integration of powders provides the following technical advantages:

- Reduced surface roughness (for graphite powder deposition), with average Ra values decreased by up to 30–50% [37].
- Increased machining speed by up to 40% in certain cases.
- Extended electrode lifetime due to reduced wear;
- Possibility of surface functionalization, including particle implantation and micro-alloying.

In biomedical applications, it has been observed that the use of titanium, TiC, or TiN powders in the EDM process can lead to the formation of bioactive surface layers on implants, producing positive effects on osseointegration [32].

2.2.6 Limitations and Challenges

Despite its advantages, the powder-mixed EDM (PMEDM) process involves several challenges:

- Additional costs related to dielectric preparation and filtration.
- Difficult control of powder suspension uniformity.
- Increased risk of short circuits or electrical instability if optimal concentrations are not maintained.
- Lack of widely accepted industrial standards for this technique [41].

2.2.7 Applications and Research Directions of PMEDM

The applicability of powder-mixed EDM is expanding across several domains:

- Manufacturing of injection molds from hard steels;
- Fabrication of miniature components for micro-electromechanical systems (MEMS);
- Machining of Ti-6Al-4V implant components with functionalized surface layers [10];
- Creation of anti-adhesive or superhydrophobic surfaces through morphology control.

Recent research focuses on the use of nanopowders and hybrid dielectric fluids to optimize process parameters in real time [42][43].

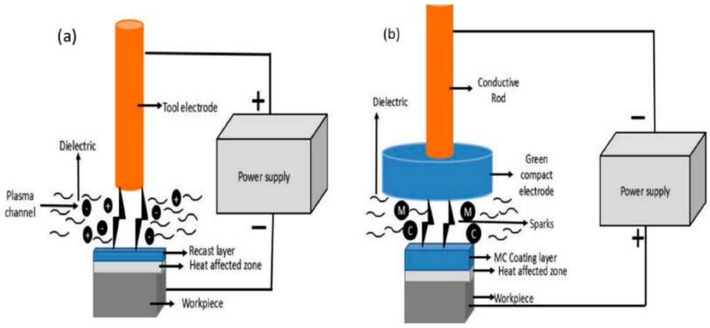

Figure 9. Principle of powder-mixed EDM [31]

2.3 Advantages and limitations of using powders in technological applications

The processing of materials in powder form represents a fundamental technology in modern engineering, offering multiple advantages compared to traditional methods of processing solid materials. However, the application of these methods is not without challenges and limitations.

Table 4. Advantages and limitations of powder-based technologies

Technology	Main advantages	Limitations
Laser fusion	Very high precision, high density, complex design, industrial applications [31]	High cost, residual stresses, long printing time
Electron beam melting	Complete melting, applicable in critical fields (Ti, aerospace), oxide-free [25]	Lower precision, expensive equipment, limited materials
Arc deposition	High deposition rate, low cost, suitable for large parts [30]	Low precision, porosity, mandatory post-processing
Plasma jet deposition	High-quality functional coatings, excellent adhesion [21]	High cost, complex equipment, sensitive to process parameters
Powder-mixed electrical discharge machining (PMEDM)	Fine microstructuring, high-precision coatings, functional surfaces [24]	Low processing speed, limited applicability, difficult process control

3. OWDER FEEDERS USED IN TECHNOLOGICAL APPLICATIONS

In many modern technological processes, the precise control of powder dosing represents a key element in ensuring the quality of the final product, optimizing process efficiency, and guaranteeing operational safety. The fields of application are extremely diverse — from high-precision pharmaceutical processing to 3D metal printing and technologies for space applications — which has led to the development of specialized and varied dosing systems, including volumetric, gravimetric, vibratory, and automated solutions [44], [45].

Powder feeders can be classified according to their operating principle and the implemented control method.

Volumetric feeders provide a constant distribution based on volume, without real-time feedback on the mass of material being dosed. These systems often rely on screws, rotary discs, or calibrated chambers. Although they are known for their robustness and affordability, they are sensitive to variations in the apparent density of the powder, which may affect process uniformity [44], [46].

Gravimetric feeders use integrated weighing systems to continuously measure the mass loss during feeding, allowing compensation for fluctuations caused by changes in material density or cohesion. However, container refilling can induce significant deviations in the feed rate, which requires additional control solutions [47], [48], [49].

Vibratory systems operate by applying controlled vibrations to transport powders toward the processing zone. These solutions are particularly effective for cohesive materials or for achieving very fine layers, a frequent requirement in additive manufacturing [50].

In addition, automated or robotic systems provide a high degree of integration and control, allowing continuous monitoring of the process and adjustment of dosing parameters according to the specific requirements of the application.

Table 5 compares the main types of powder feeders used in various technological applications, highlighting their operating principles, accuracy, compatibility with different types of powders, costs, maintenance requirements, and potential for integration with digital technologies. It can be observed that volumetric feeders are simple and inexpensive, but have medium accuracy and are limited to powders with stable density. Gravimetric feeders offer high accuracy and can adapt to powders with variable characteristics, although they require regular calibration. Vibratory systems are suitable for fine or cohesive powders, with variable precision. Automated or robotic feeders provide the highest accuracy and flexibility, being compatible with most types of powders and integrated with advanced digital systems, although at a higher cost.

The choice of powder feeder type depends on the application requirements: for high-precision processes and digital integration, automated/robotic feeders are optimal; for simpler applications or limited budgets, volumetric or vibratory feeders may be sufficient. Gravimetric feeders represent a compromise between accuracy and cost, being preferred in industries such as pharmaceuticals or chemicals.

Table 5. Comparison of the main types of powder feeders

Criterion	Volumetric	Gravimetric	Vibratory	Automated/Robotic
Operating principle	Fixed volume (screw, wheel)	Real-time weight measurement	Controlled vibrations	Digitally controlled automatic feeding
Accuracy	Medium (±5–10%)	High (±1–2%)	Variable, good for free-flowing powders	Very high (< ±1 mg)

Powder types	Free-flowing, stable density	Variable, hygroscopic, fine	Fine, cohesive	All types, including toxic
Equipment cost	Low	Medium–high	Medium	High
Maintenance	Easy	Requires regular calibration	Easy–medium	Complex
Typical applications	Chemical, food	Pharmaceutical, chemical, continuous	Additive manufacturing, fine metallurgy	Laboratories, R&D, aerospace
Sensitive to refill	Yes	Yes – correctable with algorithms [48]	Slightly	No
Possibility of IT integration	Limited	Partial (with PLC)	Partial	Extensive [54]
Sources	[44], [46]	[47], [48], [49]	[50], [51]	[52], [53], [54]

4. ADVANTAGES AND LIMITATIONS OF SPS AND EDM TECHNOLOGIES (POWDER FEEDING)

In Fig. 10, a method for forming powder deposits using impulse electrical discharges with contact break is proposed [27]. The essence of this method is that the powdered material is introduced between the electrodes in the area of discharge action at the moment when the tool-electrode (anode) moves downward toward the workpiece surface (cathode). This is easily accomplished with industrial installations such as EFI and Elitron, whose tools are equipped with special devices for feeding the inter-electrode gap with powder.

Since the deposition process and the quality of the deposits depend on the precision of powder dosing and the continuous or intermittent introduction of the powder into the gap, several technological schemes for implementing this process are analyzed. In one case, the powder material is introduced into the processing area through tubular electrodes (axial feeding scheme) (Fig. 11). This allows more complete processing of the powder, as the powder exit from the tool-electrode always occurs within the active zone of the plasma channel of the impulse electrical discharge.

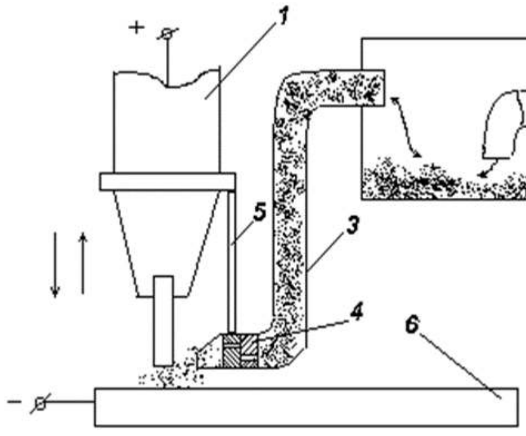

Figure 10. Device for forming contact-break powder deposits with controlled introduction into the interstice during electrode approach periods: vibrator (1); powder feeder (2); connecting tube (3); valve (4); lever (5); workpiece (6).

Experimental research has shown that this scheme for introducing powder into the interstice is more efficient for forming deposits on flat surfaces. Despite the simplicity of implementing this process, it requires the fabrication of tubular tool-electrodes made from the same material as the powder to avoid the influence of the electrode material on the composition and properties of the formed deposits.

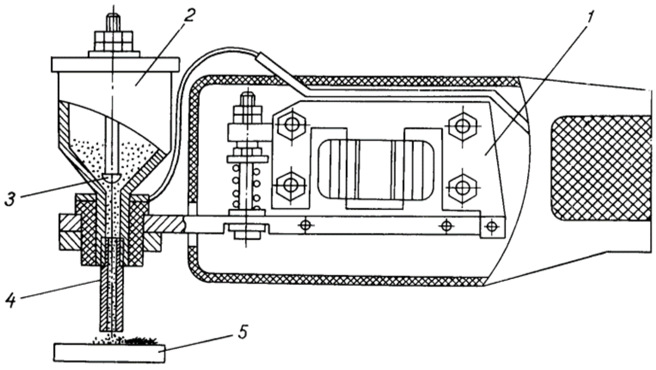

Figure 11. Device for forming powder deposits with controlled introduction of the dispersed material through the tubular electrode: vibrator (1); powder feeder (2); dosing element (3); electrode (4); workpiece (5).

A special case is represented by the scheme for introducing the powder into the interstice through the side or front of the tool electrode (Fig. 12), thus allowing that when the electrodes make contact and the electrical discharge in pulses is initiated, its plasma channel attacks the workpiece surface, which is already covered with powder.

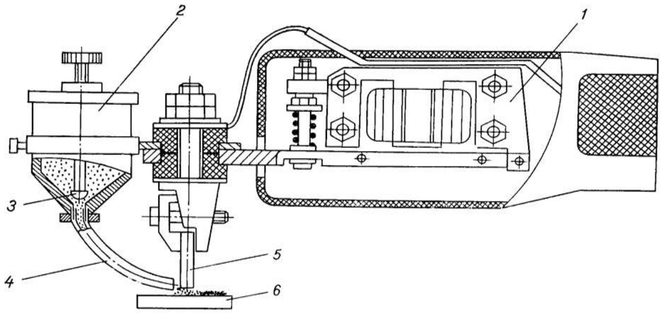

Figure 12. Front feeding scheme of the dispersed material: 1) vibrator; 2) powder feeder; 3) dosing element; 4) nipple; 5) electrode; 6) workpiece

These schemes for feeding powder into the interstice are more technologically advanced and allow the application of coatings even on cylindrical workpiece surfaces (Fig. 13). The latest implementation of the process enables mechanization of the deposition procedure and ensures full continuity and uniformity of the deposited layer in terms of thickness. To achieve this, the powder feeder is installed in such a way that the powder jet enters the interstice tangentially to the workpiece surface. The powder particles, entering the interstice, melt under the combined action of heat exchange with the plasma from the electrical discharge and the Joule-Lenz heat released on their active resistance as the discharge current passes through them. Under the influence of electrodynamic forces, they are transferred onto the workpiece surface and, interacting with the liquid phase of the material, form the deposited layer.

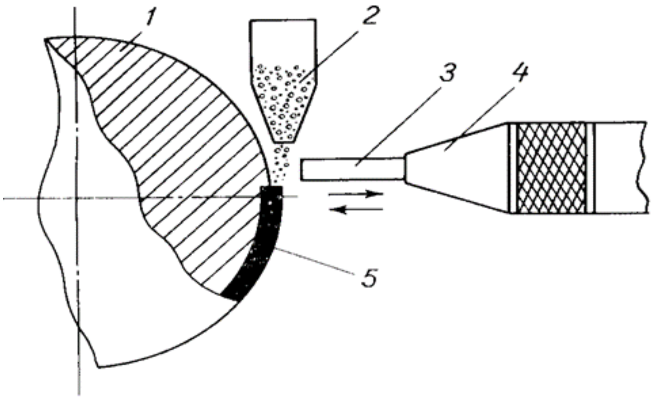

Figure 13. Scheme of deposition formation on the rotational surfaces of cylindrical workpieces: 1) workpiece (cathode); 2) powder feeder; 3) anode; 4) vibrator; 5) alloyed layer

The technological schemes presented above allow for relatively fine dosing and the introduction of powder into the interelectrode gap; however, for each specific case (depending on the deposition regime and the material of the workpiece), the powder feed rate from the dispenser is determined experimentally, based on the processing conditions and the criterion of maximum powder utilization.

By comparing the results obtained in the formation of coatings from compact materials with those achieved using powder-based deposition, several advantages of the latter can be highlighted.

For example, this method enables the formation of coatings on the surfaces of parts made from easily fusible materials such as aluminum and magnesium, due to the redistribution of the energy released in the interelectrode gap between the plasma channel, electrode surfaces, and powder particles. This effect leads to a reduction in the activation energy of the treated surface, resulting in decreased erosion. Furthermore, it considerably facilitates the formation of coatings (with thicknesses of 0.2–0.3 mm) from powders composed of easily fusible materials (tin, lead, cadmium, antimony, etc.) on the surfaces of parts made from structural alloys. Processing with compact electrodes made of such materials is inefficient and, in some cases, practically impossible. During impact with the workpiece surface, the tool electrodes deform. Moreover, due to the low melting point of the anode material, even processing at regimes with minimal discharge energy values (1.0–0.1 J) causes the transfer of a significant amount of liquid-phase material per discharge, resulting in coatings with surface irregularities.

It is necessary to emphasize the possibility of forming multi-phase coatings from mixtures of powders made from different materials. For example, during surface alloying using electrical discharge with contact breaking, when introducing into the interelectrode gap powders composed of easily fusible metals (tin, antimony) together with refractory metals or their compounds (Ti, Zr, TiC, ZrC), composite coatings with heterogeneous structures were obtained (Fig. 14).

Thus, the processes discussed above significantly enhance the applicability of electrical discharge machining with contact breaking for coating formation, due to the possibility of processing parts made from easily fusible materials (such as aluminum and magnesium) and expanding the range of materials used for coating formation.

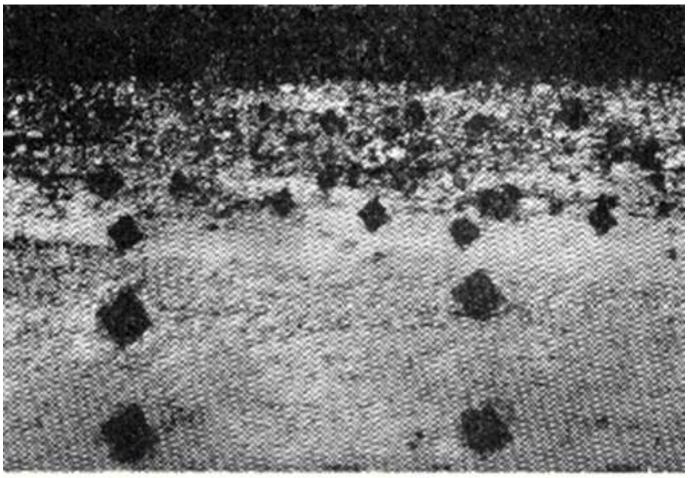

Figure 14. Microstructure of aluminum alloy Al25 after the formation of the coating from **a** powder mixture (TiC + Al + Sn). Discharge energy – 4 J × 200.

To determine the influence of the metallic powder feed rate on the increase of the cathode mass, experimental studies were carried out, based on which a graphical function was constructed (Fig. 15). As the metallic powder feed rate increases during processing, the deposition rate of the layer obtained by electrical discharge machining with contact break also increases [27].

As can be seen in Figure 15, the resulting function exhibits an exponential character. For feed rates within the range of 0...0.4 g/min, the curve can be approximated by a straight line with a relatively small slope. This is explained by the fact that, from the powder stream, the discharge channel captures an increasing number of particles but processes only those in the central zone, thus ensuring the formation of a high-quality coating [39, 4].

With further increases in the powder feed rate, a considerable increase in the cathode mass is observed; however, at the same time, the particles are only superficially processed, and the deposited layer becomes porous and prone to damage. On the processed surface, deposition inhomogeneities can be observed **(Fig. 16).**

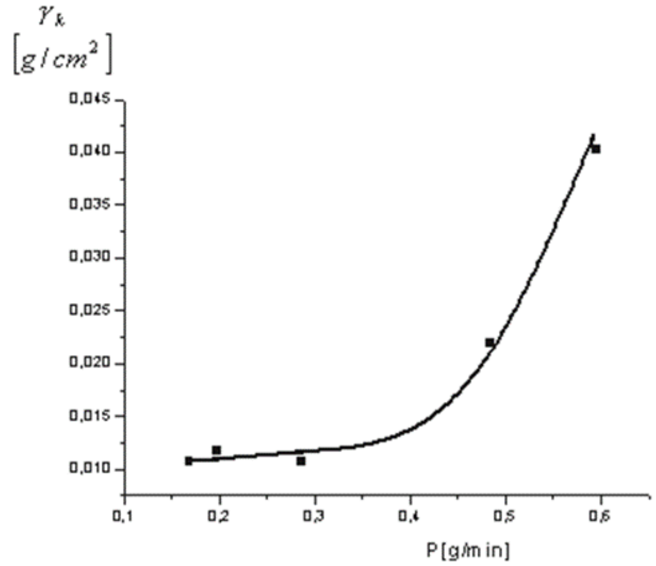

Figure 15. Dependence of the cathode mass variation on the metallic powder feed rate
(Electrode material and processing regime: cathode – Steel 45; anode – copper M-3; I = 0.8 A; powder – BrA-7; τ = 1 min; f = 90 Hz; dg = 120–130 μm.)

In all the machining cases described above, industrial-grade BrA-7 powder with particle diameters of 120–160 μm was used, deposited on Steel 45 samples, while the anode was made of copper grade M-3.

Figure 16 shows the front view of a metallic powder coating made from BrA-7 bronze powder with particle diameters of 120–160 μm, the anode being made of solid bronze BrOȚS-5-5-5, and the workpiece from Steel 45.

Examining the processed surface, it can be seen that it is generally homogeneous; however, some voids are visible, which appear for two reasons [27]: first, due to the uneven movement of the tool-electrode across the machined surface, which depends on the operator's skill level; and second, due to self-destruction of the deposited layer caused by high residual stresses formed within the coating.

Figure 16. General view of the surface layer obtained by the method of metallic powder deposition using pulsed discharges with contact break
(Cathode – Steel 45; Anode – BrOȚS-5-5-5; Metallic powder – BrA-7; Magnification ×20.)

In the context of surface hardening and functionalization of steel or titanium components, the pulsed electrical discharge technology can be effectively utilized for the formation of composite layers by combining the use of a solid electrode with the simultaneous introduction of powders into the interelectrode gap between the anode and cathode. Experimental studies carried out under short-pulse conditions, with energies ranging from 1 to 3 J, have demonstrated a significant increase in the amount of transferred material when the introduced powders are compositionally identical to the electrode material [31].

This approach offers multiple advantages compared to conventional alloying with solid electrodes, enabling the formation of thicker, more uniform coatings enriched in carbides, while also reducing processing time.
The innovative configurations proposed — either by introducing the powder through the interior of a tubular electrode (Fig. 17a) or laterally through an external applicator (Fig. 17b) — enhance the efficiency of mass transfer and allow fine control over the composition of the deposited layer [31].

At the same time, the use of a titanium cathode (BT1 grade), whose thermophysical properties differ significantly from those of C45 steel, confirmed that the general trend of increasing deposited material with higher pulse energy is maintained regardless of the substrate material. This finding demonstrates the broad applicability of the pulsed electrical discharge (PED) technology and its adaptability to various materials.

Therefore, the implementation of this method in industrial or research environments can serve as a viable alternative to conventional alloying technologies, which are often expensive and less accessible, particularly when specialized electrodes are unavailable. Due to the simplicity of the equipment and its versatility of application, the PED technology emerges as a practical and efficient solution for the reconditioning and advanced functionalization of technical surfaces.

A comparison between the results obtained using only a solid anode and those achieved with the additional introduction of powders into the interelectrode gap clearly highlights the advantages of the latter approach. Under identical energy conditions, the resulting coatings are significantly thicker and more uniform.

The two constructive configurations that enable powder feeding — through a tubular anode or via a lateral channel — are shown in Figure 18, emphasizing the flexibility and extended applicability of the PED technology in modern surface alloying processes.

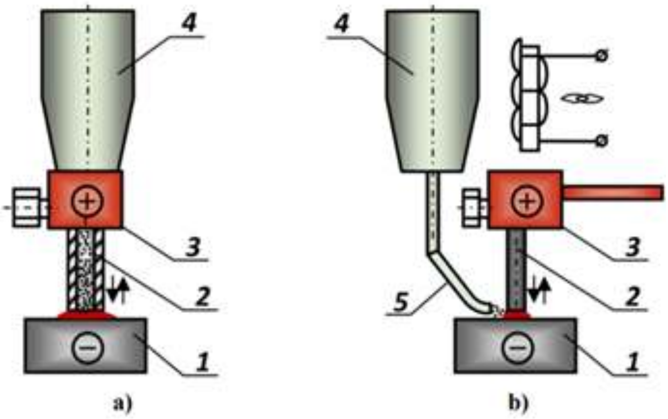

Figure 17. Alloying procedures using powder:
a) powder is introduced into the interelectrode gap through a tubular electrode;
b) powder is introduced from the side. 1 – workpiece (cathode); 2 – electrode (anode); 3 – applicator; 4 – hopper; 5 – powder guide tube [31]

Table 6 highlights the advantages and limitations of powder dosing in two advanced processing technologies: Spark Plasma Sintering (SPS) and Electrical Discharge Machining (EDM) with powders. SPS offers a short sintering time and the production of parts with high density, but it requires strict control over the powder quantity and particle size distribution. EDM enables the creation of functional layers with fine microstructures, yet handling and refilling the powder suspensions present safety issues and challenges in process consistency.

Table 6. Advantages and Limitations of Powder Dosing in SPS and EDM

Technology	Advantages in Powder Dosing	Current Limitations in Dosing
SPS (Spark Plasma Sintering)	Short sintering time, high part density [54]	Requires precise control of powder quantity and particle size distribution [55]
EDM with Powders (Electrical Discharge Machining)	Enables creation of functional layers, fine microstructures [50]	Handling and replenishing powder suspensions, operator safety [48]

Both technologies require precise and well-controlled powder dosing systems to ensure the final quality of the parts. Current limitations emphasize the importance of developing automated and integrated dispensers capable of handling small quantities and sensitive powders, thereby increasing process efficiency and safety.

5. NEED FOR RESEARCH AND PROPOSED DIRECTIONS

A review of the specialized literature shows that, currently, there is no powder dispenser dedicated to applications such as SPS and EDM that can simultaneously provide:

- The high mass/volume dosing precision;
- Continuous or pulsed controlled dosing;
- operation in fully enclosed systems;
- safe handling of fine powders and advanced automation [46–56].

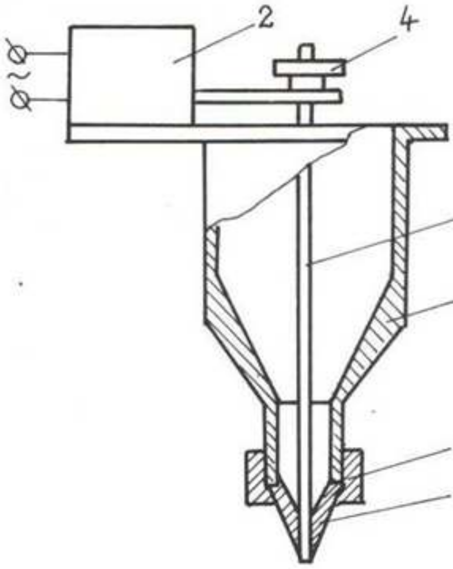

Figure 18. Vibratory hopper of the “Razread” installation: 1 – body; 2 – electromagnetic vibrator; 3 – adjustment pin; 4 – locking nut; 5 – spout; 6 – nut for fixing the spout.

In “Razread”-type installations, designed and built for producing metal powder deposition layers via electrical discharges, conventional vibratory dispensers are used, with powder quantity adjusted by raising or lowering a pin in the conical orifice of a regulator (fig. 18).

The systems used in the “Razread” installation, as well as those mentioned above, have several disadvantages. For example, to adjust the powder flow from the hopper (Fig. 18), it is necessary to stop the operation of the installation and manually raise or lower the adjustment pin. In some designs described in the literature, powder flow is regulated based on the pressure of the transporting gas, a solution that requires the presence of a regulator or pressure amplifier in the system, as highlighted both in recent studies on plasma jet sintering [57] and in the European patent for a high-pressure powder feeding system [58].

Additionally, powder flow can be interrupted due to particle agglomeration, a problem frequently encountered when using non-spherical particles.

Without proper control, the following issues may occur:

- Interruptions in the process or uneven deposits;
- Errors in the temperature and pressure profile;
- Instabilities at the edges of the working area [48].

Most existing powder feeders are not designed for integration into automated systems, which becomes a critical limitation, especially when:

- Dynamic adjustments of flow are required in real-time;
- Each dosing must be monitored and recorded;
- Communication with other components in the production line is needed [51], [49].

Development of a new powder feeder designed to meet these requirements would enable improved process quality, reduced material losses, and increased operator safety.

6. CONCLUSIONS

Following the analysis of over 60 relevant scientific sources, the following general conclusions can be drawn regarding the use of powders in technological applications:

1. Powder dosing is an essential link in the technological chain of advanced processes such as SPS and EDM. The limitations of current feeders justify the need for in-depth research to design and implement an innovative dosing system, specifically adapted to these processes. This article highlights the main identified issues and underpins the general objective of the doctoral research.
2. Metal powders play a crucial role in modern manufacturing technologies, enabling the production of complex parts with controlled properties and minimal material waste [1][58][6].
3. Powder production methods—such as atomization, chemical reduction, and electrochemical techniques—have evolved significantly, leading to improved powder quality and expanded applications [59][60][10].
4. technologies (precision, geometric complexity, material efficiency) and Advances in additive manufacturing and traditional powder metallurgy (pressing and sintering) have resulted in products with refined microstructures, superior mechanical properties, and better adaptability to industrial requirements [9][61][62].
5. The integration of nanopowders and composite powders has enabled the creation of functional materials with applications in medicine, aerospace, microelectronics, and energy [63][11][36].
6. The use of advanced analyses (SEM, XRD, EDS) has significantly contributed to understanding particle behavior during compaction, sintering, and additive manufacturing processes [20][40].
7. Recent research has highlighted both the major advantages of powder-based their limitations (high cost of spherical powders, oxidation, difficult handling) [7][64][65].

Final Conclusion:

- The use of powders in technological applications represents a rapidly expanding field within additive manufacturing, having a significant impact on modern industry. Recent research has shown that by combining advanced processing technologies with innovative materials, unparalleled performance can be achieved compared to traditional manufacturing methods.

"The future belongs to smart materials, precisely manufactured from powders, tailored to the exact needs of each application" [66].

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