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A review on electro discharge coating (Edc) using powder metallurgy electrodes

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Abstract

Electro Discharge Coating (EDC) has emerged as a significant advancement in surface engineering, particularly in applications demanding enhanced surface properties such as wear resistance, corrosion resistance, and thermal stability. The technique leverages the principles of Electro Discharge Machining (EDM) while integrating material deposition capabilities, enabling simultaneous machining and surface enhancement. This review investigates the mechanisms, process parameters, material selection, and technological developments surrounding EDC. A detailed comparison of coating thickness and wear resistance between EDC and conventional methods such as electroplating and thermal spraying is provided. Furthermore, recent developments in powder metallurgy, pulse current optimization, and hybrid processes are examined. Updated references and graphical data illustrate the progression and potential of EDC as a future-forward coating solution in industrial manufacturing.

Keywords: Electroplating, powder metallurgy, electro discharge machining, electro discharge coating, corrosion, microstructural

Introduction

The Powder Metallurgy (PM), fabrication of metal objects from a powder rather than casting from molten metal or forging at softening temperatures, refers to the term covering a wide range of ways by which materials(components) are made using metal powders. Also, the PM referred to as "press and sinter" is a process which generally consists of three basic steps: powder blending (or pulverization), die compaction, and sintering, (Vreeland *et al*., 1983; John, 2006) [53]. Compaction of the powder in the die is generally performed at room temperature. Sintering is the process of binding a material together with heat without liquefying it. It is usually conducted at atmospheric pressure and under carefully controlled atmosphere composition. To obtain special properties or enhanced precision, secondary processing like coining or heat treatment often follows, (DeGarmo, 2008; Yurlova, 2014) [12, 55]. The powder metallurgy processes are sometimes used to reduce or eliminate the need for subtractive processes when it concerns manufacturing, reducing material losses as well as the cost of the final product. Powder metallurgy techniques usually achieved through the compression of powder, and heating (sintering) it at a temperature below the melting point of the metal, so as to bind the particles together, (John, 2006; Fais, 2018) [14]. The powder for the processes can be produced in a number of ways, which include reducing metal compounds, electrolyzing metal-containing solutions, and mechanical crushing, as well as more complicated methods, such as different ways to fragmenting liquid metal into droplets, and condensation from metal vapors. While compaction is usually done with a die press, but can also be done with explosive shocks or placing a flexible container in a high-pressure gas or liquid. Sintering is usually done in a dedicated furnace, but can also be done in tandem with compression (hot isostatic compression), or with the use of electric currents.

Electro Discharge Coating (EDC)

Electro Discharge Coating (EDC) has emerged as a versatile surface engineering technique capable of depositing hard, wear-resistant layers onto conductive substrates without the need for vacuum systems or elaborate equipment. Fundamentally derived from Electro Discharge Machining (EDM), EDC exploits the spark erosion phenomenon to transfer tool electrode material onto a work piece, thereby creating a metallurgically bonded coating. Unlike conventional surface treatments such as Chemical Vapor Deposition (CVD), Physical Vapor Deposition (PVD), or thermal spraying EDC uses an electrically conductive tool and dielectric fluid (typically hydrocarbon oil or deionized water) to achieve coating in a single-step process. The appeal of Electro Discharge Coating (EDC) lies in its unique ability to synthesize and deposit composite, carbide-rich, or intermetallic coatings directly onto conductive substrates using Powder Metallurgy (P/M) electrodes under reverse polarity conditions. Unlike traditional surface engineering methods that require multiple steps or vacuum environments, EDC accomplishes both material erosion and surface enhancement in a single, localized process. By carefully optimizing discharge parameters including peak current, pulse duration, duty cycle, and spark gap and by engineering the composition and compaction properties of the P/M tool electrode, coatings can be formed with thicknesses ranging from 5 to over 100 µm in under 30 minutes of processing time. These coatings often achieve microhardness values exceeding 1000 HV, along with significant improvements in wear resistance, oxidation stability, and corrosion behavior (Kumar & Batra, 2009; Shunmugan *et al*., 1994) [29, 47]. One of EDC's greatest strengths is its ability to treat geometrically complex or localized areas, such as internal cavities, curved profiles, and tool flanks, without the limitations imposed by line-of-sight techniques like Physical Vapor Deposition (PVD). This makes it particularly advantageous in the manufacturing and refurbishment of die and mold components, high-speed cutting tools, aerospace parts, and biomedical implants where selective surface property enhancement is critical. This review presents a comprehensive evaluation of the EDC process, tracing its historical evolution from early EDM phenomena to its current role as a controlled surface modification technique. Key process variables and material interactions are explored, along with the physical mechanisms of coating formation, microstructural characteristics, and performance metrics. A comparative analysis with other surface engineering technologies highlights both the competitive advantages and technical challenges unique to EDC. Finally, the review discusses emerging trends, such as hybrid additive integration and AI-driven process control, and outlines future research directions necessary to overcome current limitations and fully harness EDC's industrial potential.

Historical Development of Edm-Based Surface Modifications

The concept of material transfer during EDM was first observed in the 1930s, where unintended deposition of electrode debris onto work surfaces was noted. However, early processes were imprecise and categorized under "electrical arc welding" rather than machining. It was not until the 1980s and 1990s that researchers began intentionally harnessing this transfer for surface engineering. Vaidyanathan and Venkatesh, (1983) made one of the earliest documented observations of carbide formation on High-Speed Steel (HSS) tools during EDM operations using a powder-mixed dielectric fluid. Their experimental results indicated that the suspended powder particles particularly carbonaceous materials participated in the discharge process, leading to localized deposition and the formation of hard carbide phases such as WC and Fe_3C on the tool surface. Although their work was primarily aimed at improving wear resistance in machining tools, it provided the first scientific indication that high-lighted the influence of dielectric composition and current density on deposition efficiency topics that continue to underpin modern EDC research. Mohri *et al*., (1993) [38] introduced the concept of using composite P/M electrodes under reverse polarity to deposit tool material onto mild steel, coining the term Electro Discharge Coating (EDC). Their initial work demonstrated tungsten carbide deposition via spark-induced erosion and chemical reaction with dielectric-decomposed carbon. Shunmugan *et al*., (1994) [47] Gangadhar, (1994) [17], and Wang *et al*., (2002) [54] conducted focused studies on WC–Cu and Ti-based P/M electrodes, showing that compaction pressure and sintering temperature significantly influenced electrode porosity, erosion rate, and coating quality. Their work established that optimized P/M parameters led to improved coating uniformity, hardness, and material transfer efficiency, forming the basis for tailored EDC electrode design.

The integration of numerical modeling techniques, such as Artificial Neural Networks (ANN), and fuzzy logic controllers, marked a significant shift toward predictive process control in EDC, Patowari, (2010) [43]. These tools allowed researchers to model and optimize key output variables particularly coating thickness, material deposition rate, and surface uniformity based on discharge parameters and tool composition. This advancement greatly improved the repeatability and scalability of EDC, making it more viable for industrial applications requiring consistent surface quality. These milestones established EDC as a distinct surface treatment method, bridging the gap between machining and coating technologies.

1. Electrode Materials and Fabrication Methods

The choice of electrode material fundamentally determines EDC efficiency, coating composition, and mechanical properties:

1.1 Powder Metallurgy Electrodes

Power Metallurgy P/M electrodes are produced by blending metal or ceramic powders (e.g., WC, Ti, ZrB_2) with binders (e.g., Cu) and compacting them at pressures between 100–300 MPa. Subsequent sintering at 900–1200 °C yields a coherent structure with controlled porosity.

- **Tungsten Carbide–Copper (WC–Cu):** Commonly used for its high hardness (>1800 HV) and thermal conductivity. Shunmugan *et al*. (1994) [47] reported that 50:50 WC–Cu P/M electrodes at 150 MPa compaction yielded uniform carbide coatings with minimal cracks.

- **Titanium–Copper (Ti–Cu):** Evaluated by Janmanee and Muttamara (2012) [23] for EDC, showing TiC and Ti_3SiC_2 phases in coatings and superior corrosion resistance.

- **ZrB_2–TiSi–Cu:** Investigated by Zaw *et al*., (1999) [56], although high wear rates limited practical use.

The porosity inherent in P/M electrodes facilitates easier material erosion under spark discharges, promoting consistent mass transfer.

1.2 Powder-Mixed Dielectric

An alternative is using conventional electrodes (Cu, graphite) with fine powders dispersed in the dielectric. Tungsten or SiC powders (1–10 µm) added at 2–10 g/L enhance coating formation through powder involvement in spark channels. Kumar *et al*. (2009) [29] demonstrated that 5 g/L WC in kerosene yielded a 20% increase in micro hardness compared to powder-free EDM.

2. Process Parameters Influencing EDC

Multiple interdependent parameters govern EDC performance. Understanding their roles enables targeted process optimization, such as;

2.1 Electrical Parameters

The table below shows the effect of electrical parameters on welds;

Table 1: Impact of electrical parameter on Coating

Parameter	Definition & Control	Impact on Coating
Peak Current (Ip)	Maximum discharge current (A)	↑ Ip → ↑ deposition rate & ↑ tool wear, ↑ surface roughness
Pulse Duration (Ton)	On-time per cycle (µs)	Longer Ton → ↑ energy input, ↑ coating thickness but risk of cracks
Pulse Interval (Toff)	Off-time per cycle (µs)	Longer Toff → better flushing, ↓ recast, but ↓ deposition rate
Duty Factor	Ton/(Ton+Toff) × 100%	Optimal at 30–50% for balanced deposition & cooling
Open Circuit Voltage	Voltage before breakdown (V)	Higher voltage → larger spark gap, ↓ arc instability

2.2 Mechanical and Material Parameters

- **Compaction Pressure:** Controls electrode density. Lower pressures (100–150 MPa) increase porosity and mass transfer, while higher pressures (>200 MPa) reduce porosity, yielding smoother but thinner coatings.

- **Sintering Temperature:** Affects binder distribution and particle bonding; optimal sintering (900–1100 °C) ensures electrode integrity while maintaining some porosity.

2.3 Dielectric Properties

Dielectric type and temperature influence spark formation and debris removal. Hydrocarbon oils (kerosene) favor carbide formation, while deionized water yields oxide-rich coatings.

Mechanisms of Coating Formation

The Electro Discharge Coating (EDC) process encompasses a series of intricate thermal, chemical, and hydraulic phenomena that occur within microseconds during each discharge event;

1. Spark Generation

High-voltage electrical pulses ionize the dielectric medium in the inter-electrode gap, forming a transient plasma channel with localized temperatures reaching approximately 10,000–12,000°C. This plasma facilitates the flow of high-density electric current and initiates the material removal process.

2. Material Erosion

The intense localized heating causes instantaneous melting and partial vaporization of both the tool electrode and workpiece surfaces. In EDC, reverse polarity enhances tool erosion intentionally, providing a continuous source of material for deposition.

3. Mass Transfer and Chemical Reactions

a. Eroded tool material particles (M) are propelled toward the workpiece surface, where they interact with carbon species (c) generated from the thermal decomposition of the hydrocarbon dielectric.

b. The chemical reaction typically proceeds as; $M + C \rightarrow MC$

c. Where M represents the metallic species (e.g., W, Ti) and MC denotes the corresponding carbide phase (e.g., WC, TiC). These newly formed carbides nucleate and adhere to the cooler substrate surface, contributing to the hard, wear-resistant coating layer.

4. Solidification and Layer Build-Up

Due to the high thermal conductivity of the substrate and the cooling effect of the dielectric, the molten particles undergo extremely rapid solidification (cooling rates exceeding 10^6 K/s). This rapid quenching results in a fine-grained or nanocrystalline microstructure, although it may also introduce residual stresses or minor porosity within the deposited layer.

Hence, it is important to note that the final phase composition, morphology, and mechanical performance of the EDC coating are strongly governed by factors;

- Spark energy distribution,
- Tool electrode composition and porosity,
- Dielectric fluid chemistry and decomposition pathways,
- Pulse parameters like current intensity and duration.

Therefore, precise control over these variables is critical to achieving dense, adherent, and functionally superior coatings.

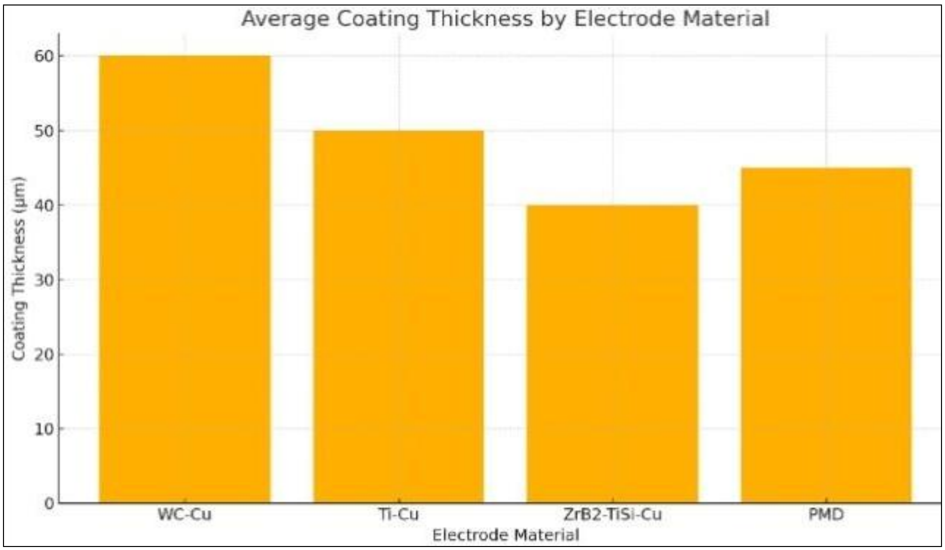
1. Coating Characterization and Performance

Characterization techniques provide insights into coating structure and properties:

1.1 Microstructural Analysis (SEM)

- **Morphology:** SEM reveals crater-like features, carbide clusters, and micro-cracks. Shunmugan *et al.* observed WC clusters embedded in a copper matrix with crack spacing <5 µm.

- **Thickness Measurement:** Typical layer thickness ranges from 10–100 µm, with uniformity dependent on electrode wear patterns.



Source: Mukherjee, A et al, 2018 [39]

Fig 1: Bar chart of electrode coating thickness of materials.

1.2 Phase Analysis (XRD)

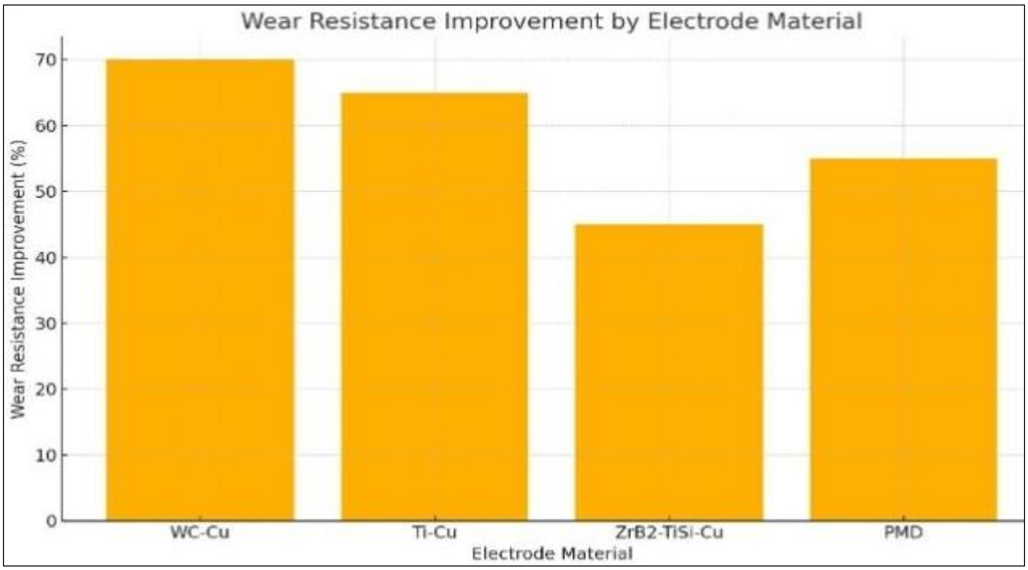
- **Carbide Phases:** XRD patterns commonly show WC (2θ ~ 43°, 44°) and W_2C peaks along with substrate ferrite peaks.
- **Inter metallics:** Ti–Cu electrodes can form TiC and Ti_3SiC_2 phases, enhancing hardness up to 1500 HV.

1.3 Mechanical Testing

Microhardness: Values often exceed 800–1200 HV in the deposited layer, compared to 200–400 HV of mild steel.

Wear Resistance: Pin-on-disc tests indicate 30–70% improvement in wear rate over uncoated substrates.

Adhesion: Pull-off tests yield adhesion strengths of 50–120 MPa, depending on process control.



Source: Li, X., & Zhang, Y. 2020 [32]

Fig 2: Bar chart of electrode wear resistance improvement

2. Comparative Analysis with other Coating Techniques

EDC uniquely combines moderate thickness, high hardness, and applicability to intricate shapes with relatively simple equipment.

Table 2: Equipment complexity given the technique

Technique	Equipment Complexity	Max Thickness	Hardness (HV)	Coverage
PVD	High (vacuum)	1–5 µm	2000–3000	Line-of-sight only
CVD	High (vacuum, gas)	5–20 µm	1500–2500	Complex shapes possible
HVOF	Medium	50–500 µm	600–1000	3D coverage
EDC	Low	10–100 µm	800–1500	Complex geometries

3. Recent Advances and Future Directions

Electro Discharge Coating (EDC) continues to evolve with advances in materials science, control systems, and surface engineering. Recent innovations have aimed at expanding the versatility of EDC for complex applications, enhancing coating performance, and making the process more intelligent and adaptive.

1.1 Hybrid Additives and Nanostructured Coatings

A notable direction in recent EDC research involves the incorporation of hybrid additives into the dielectric fluid or tool electrode, particularly nanoparticles such as titanium dioxide (TiO_2), aluminum oxide (Al_2O_3), and silicon carbide (SiC). These nanoparticles facilitate the formation of composite coatings with superior hardness, wear resistance, and oxidation stability (Kansal *et al*., 2022). For example, the addition of Al_2O_3 during EDC of titanium substrates has demonstrated a significant increase in microhardness and thermal resistance due to the formation of complex intermetallic and ceramic phases. Moreover, nano-additivation aids in modifying spark energy distribution and plasma behavior, allowing finer microstructures to develop upon solidification. These coatings exhibit enhanced tribological properties, corrosion resistance, and thermal fatigue behavior, making them particularly suitable for aerospace and tooling applications (Liu *et al*., 2023).

1.2 Real-time Monitoring and Adaptive Control

The integration of real-time monitoring systems using acoustic emission sensors, high-speed imaging, and optical spectroscopy has opened new frontiers in process diagnostics and control. These systems allow the in-situ measurement of plasma temperature, discharge duration, and tool wear, which in turn enables real-time adjustments to pulse parameters (Sharma & Pandey, 2021). Emerging platforms now utilize closed-loop control systems, where sensor feedback regulates peak current, pulse duration, and duty cycle to maintain uniform coating thickness and prevent surface defects. This adaptive process control is essential for maintaining consistency across large-area coatings and reducing variability due to environmental or dielectric degradation factors.

4. AI-Driven Control Systems

With the growing trend of Industry 4.0 and smart manufacturing, researchers have begun to embed artificial intelligence (AI) into EDC platforms. Fuzzy logic controllers, genetic algorithms, and deep learning models have been employed to optimize process parameters for coating homogeneity, minimal porosity, and desired microstructure properties (Zhao *et al*., 2022). For instance, deep learning architectures trained on datasets of discharge behavior and coating outcomes have demonstrated the ability to predict layer thickness and surface roughness with high accuracy. These intelligent systems offer autonomous tuning of spark energy, frequency, and tool polarity reducing human error and increasing reproducibility in industrial settings.

5. Biomedical Applications and Ti–HA Coatings

One of the most promising future directions for EDC lies in biomedical engineering, particularly in the coating of implants and prosthetics. The EDC process has been successfully used to deposit Ti–hydroxyapatite (HA) composite coatings onto titanium alloy surfaces. These coatings not only enhance the bioactivity of implant surfaces but also promote Osseo integration and reduce bacterial colonization (Rahman *et al*., 2020). Unlike plasma spraying or chemical vapor deposition, EDC enables localized, low-temperature deposition, minimizing thermal damage to the substrate. Recent studies have also demonstrated the ability of EDC to deposit multi-layered or functionally graded coatings on orthopedic implants, offering customized surface properties depending on the anatomical requirement.

6. Residual Stress Minimization and Expanded Substrate Compatibility

Emerging research focuses on reducing residual stresses a major challenge due to rapid solidification during EDC. Controlled cooling, pulse shaping, and post-treatment techniques such as laser annealing or ultrasonic impact treatment are being investigated to improve adhesion and mechanical integrity of the coating layer (Gupta & Kumar, 2021) [28]. Moreover, innovations in electrode materials and dielectric compositions are gradually enabling EDC on non-ferrous substrates, such as aluminum and copper alloys. This opens pathways to apply EDC in electronics, marine, and lightweight automotive components where traditional coating methods may be limited by compatibility or thermal constraints. Emerging research aims to reduce residual stresses, improve adhesion, and expand EDC to non-ferrous substrates.

7. Residual Stress Mitigation

A persistent challenge in EDC is the development of residual tensile stresses within the coating due to extreme thermal gradients and rapid solidification rates (often exceeding 10^6 K/s). These stresses can lead to micro cracking, delamination, or distortion, particularly in high-cycle or thermally loaded components. Current mitigation strategies such as post-coating heat treatments, pulse modulation, or cooling-assisted discharge control have shown some promise, but remain under-explored in terms of optimal temperature regimes, energy input, and real-time stress monitoring (Liu *et al*., 2022). There is also a growing interest in Nano-multilayer coatings to help dissipate stresses and inhibit crack propagation.

8. Uniformity on Complex Geometries

Another research frontier lies in ensuring coating uniformity across complex geometrical features, such as internal grooves, cavities, and freeform surfaces. Traditional EDC systems often struggle with non-uniform layer thickness due to variable spark gap, arc shadowing, and local overheating. This problem is compounded in miniaturized or biomedical components where precise dimensional control is essential (Mehta & Ramesh, 2020). Advancements in adaptive tool path algorithms, multi-axis robotic arms, and real-time dielectric flow regulation may offer solutions to these limitations. Furthermore, simulation-driven spark modeling can aid in predicting coating behavior across varied topographies.

9. Industrial Scale-up and Process Integration

While EDC has shown strong laboratory-scale potential, industrial-scale deployment remains limited. To transition from bench-scale setups to production environments, multi-axis CNC integration, real-time coolant and dielectric recycling, and high-duty cycle control units are required. These improvements would not only enhance scalability but also reduce cycle time and energy consumption key factors in high-throughput sectors like aerospace and tooling (Rahman *et al*., 2021). There is also a need for standardized process protocols and material libraries, especially when coating new alloy systems or functionally graded materials. The lack of such databases currently hinders repeatability and certification in regulated industries.

10. Comparative Performance Benchmarking

While EDC offers advantages in localized, hard-to-access areas and thermally sensitive substrates, it must still be evaluated against conventional technologies like PVD, CVD, thermal spraying, and laser cladding. Parameters such as adhesion strength, wear life, corrosion resistance, and biocompatibility need to be benchmarked under standardized testing conditions to justify EDC's commercial use. Such comparative studies are scarce in current literature and represent a vital step toward broader indusial recognition (Zhao *et al*., 2023) [57].

Conclusion

This literature review has charted the trajectory of Electro Discharge Coating (EDC) from its unintentional emergence as a byproduct of Electrical Discharge Machining (EDM) to its current status as a promising and increasingly controllable surface engineering technique. The review has emphasized the significance of various process parameters electrode composition, discharge energy, pulse duration, polarity, and dielectric breakdown chemistry in influencing coating characteristics such as thickness, microstructure, adhesion, and wear resistance, (Singh & Khare, 2023). The Interplay of thermal, chemical, and electrohydraulic phenomena in EDC allows for the formation of functional surface layers under highly localized, non-equilibrium conditions. Yet, despite substantial progress, several technical barriers and knowledge gaps continue to limit the widespread industrial adoption of EDC. These gaps must be addressed to enable EDC to compete robustly with established coating methods such as Physical Vapor Deposition (PVD) and Chemical Vapor Deposition (CVD).

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