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# Review on Surface Modification and Coating Effects in Wire EDM Machining Performance

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***Abstract*— Wire Electrical Discharge Machining (WEDM) is a widely adopted process for producing intricate and high-precision components where conventional machining methods face limitations. The performance of WEDM is strongly influenced by the properties of the wire electrode, with coated and surface-modified wires offering significant advantages over plain brass wires. This review systematically examines advancements in wire surface modification, from conventional zinc coatings to diffusion-annealed, nano-engineered, and composite structures. Reported improvements include higher material removal rates, reduced surface roughness, superior wear resistance, and greater dimensional stability. Despite these advances, critical gaps remain, particularly in the absence of standardized benchmarking protocols, comprehensive life-cycle and techno-economic evaluations, and scalable fabrication methods. Furthermore, sustainability aspects such as recycling, environmental footprint, and large-scale industrial validation are underexplored. Addressing these limitations will be essential to translate laboratory-level innovations into robust industrial solutions and to ensure the broader adoption of coated wire technologies in advanced manufacturing sectors.**

***Keywords:*** Wire EDM, Coated Electrodes, Surface Modification, Machining Performance, Surface Integrity

## I. INTRODUCTION

The wire electrical discharge machining (WEDM) is an indispensable non-traditional process widely employed for precision machining of hard-to-cut materials such as tool steels, superalloys, and advanced composites. Its unique capability to achieve complex geometries with high dimensional accuracy has made it vital in industries including aerospace, automotive, biomedical, and die Moulding manufacturing. The performance of WEDM, however, is critically governed by the properties of the wire electrode, which influences material removal rate (MRR), surface roughness (SR), tool wear, and overall machining stability.

Conventional uncoated brass wires have long been used due to their good conductivity and availability, but they suffer from limitations such as wire rupture, poor flushing efficiency, and unstable discharge behavior in demanding applications. To address these shortcomings, researchers have focused on surface modification and coatings including zinc-based, diffusion-annealed, nano-structured, composite, and multi-layered systems. These engineered wires enhance spark stability, improve cooling, and minimize adhesion, thereby offering better machining efficiency and surface integrity.

Recent developments also indicate a shift toward advanced functional coatings (e.g., TiC, DLC, $Al_2O_3$, PTFE) and sustainable alternatives such as recycled or nano-textured wires. At the same time, emerging digital approaches like machine learning and multi-objective optimization are being explored to predict coating performance and guide process parameter selection. Despite these advancements, challenges remain in cost-effectiveness, industrial scalability, and standardized benchmarking.

This review aims to provide a comprehensive and structured analysis of coated wire developments in WEDM, categorizing the research into zinc-based, nano-functional, composite, and future-oriented approaches. It highlights the influence of coatings on machining performance parameters, identifies existing limitations, and outlines future research directions toward sustainable and industry-ready coated wires.

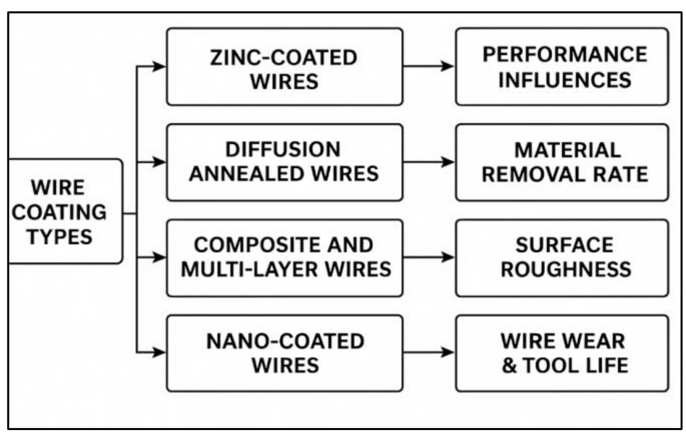


**Figure 1.** **Schematic representation of common wire electrode coating types used in WEDM.**

## II. LITERATURE REVIEW

The literature on coated wires in wire electrical discharge machining (WEDM) spans more than two decades, with research focusing on improving machining efficiency, stability, and surface integrity through various electrode modifications. Studies have investigated zinc-coated, diffusion-annealed, nano-functional, composite, and hybrid wires across different industries and workpiece materials. The following structured table summarizes key contributions, categorized by coating type, highlighting base wire material, modifications, applications, machining performance, and reported limitations.

**Table 1.** Summary of Literature Review on Wire Electrode Surface Modifications and Their Machining Performance in WEDM.

| Sr. No. | Year | Author(s) | Base Wire Material | Coating / Modification | Material to be Cut | Industry / Application | Key Findings | Limitations | Performance Parameters Studied |
|---|---|---|---|---|---|---|---|---|---|
| **A. Zinc-Based Coatings (Conventional & Advanced)** | | | | | | | | | |
| 1 | 2001 | Sánchez et al. | Brass | Galvanized (Zn) | Tool steel (general) | Tool & Die, Automotive | Explosion-effect: zinc vaporization widens plasma channel → improved flushing & higher MRR. | Coating adhesion inconsistent and mainly roughing. | Material removal rate (MRR), cutting stability |
| 2 | 2004 | Liao et al. | Brass | Zinc | SKD11 tool steel (thick workpieces) | Tool & Die | Higher cutting speeds on SKD11, especially for thicker workpieces. | Surface finish may be rougher if not optimized. | Cutting speed, surface roughness (SR) |
| 3 | 2015 | Bobbili et al. | Brass | Galvanized (Zn) | High-strength armor steel | Defense/Automotive | Validated improved MRR on high-strength armor steel using zinc-coated wires. | Unoptimized parameters cause poor finish. | MRR, SR |
| 4 | 2017 | Heshmataloure et al. | Brass | Diffusion-annealed Zn | Tool steel | Tool & Die | Superior speed, finish, and breakage resistance compared to standard galvanized wires on tool steel. | High cost; premium wires. | MRR, SR, breakage |
| 5 | 2018 | Okada et al. | Brass/Steel | Nano-crystalline Zn | Hardened steel | Precision machining | Nano-structure allows more uniform vaporization, stable spark gap and higher feed rates. | High fabrication cost. | Cutting speed, stability |
| 6 | 2021 | Shandley et al. | Brass | Graphene-doped Zn | Alloy steels | Aerospace, Automotive | Graphene doping improved thermal conductivity of coating and reduced wire heating. | Costly and scale-up difficult. | Wire temperature, stability |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 7 | 2021 | Patel et al. | Brass | Micro-porous Zn Coating | Tool steel | Tool & Die | Micro-pores trap dielectric, enhancing cooling/flushing at discharge point. | Durability concerns. | Flushing efficiency, stability |
| 8 | 2021 | Das et al. | Brass | Au-NP augmented Zn | High-strength alloys | Aerospace, Electronics | Improved conductivity, finish. | Very expensive materials. | Conductivity, SR |
| 9 | 2023 | Ikram et al. | Brass | Rare-earth doped Zn | Nickel alloys, superalloys | Aerospace, Energy | Higher spark efficiency and thermal property changes. | Expensive, experimental. | Spark efficiency, MRR |
| 10 | 2023 | Lee & Park | Brass | Hybrid Zn–TiN | Nickel-based alloys | Aerospace | Balanced MRR and SR on nickel-based alloys. | Complex coating process. | MRR, SR |
| 11 | 2023 | Fernandez et al. | Brass | Zn with micro-channels | Alloy steels | Precision machining | Improved Better cooling & lower wire temp. | Intricate manufacturing. | Cooling efficiency, wire temp |
| **B. Nano / Advanced Functional Coatings** | | | | | | | | | |
| 12 | 2019 | Wu et al. | Brass | DLC nano-coating | Hardened steels | Precision, Tool & Die | Reduced wear rate and recast layer. | High cost, complex deposition. | Wire wear, surface integrity |
| 13 | 2020 | Gupta & Singh | Brass | TiC nano-coating | Inconel 625 | Aerospace | Better surface finish, fewer microcracks on Inconel 625. | Lab scale only. | SR, microcracks |
| 14 | 2020 | Akhbarizadeh et al. | Brass | ZnO nano-coating | Tool steels | General machining | Improved dielectric characteristics and spark stability. | Requires specific dielectric mixes. | Stability, dielectric efficiency |
| 15 | 2020 | Sharma et al. | Brass | Nano-composite coatings | Nimonic 80A | Aerospace, Energy | Reduced recast layer and micro-cracks on Nimonic 80A. | Lab scale and industrial viability uncertain. | Surface integrity, SR |
| 16 | 2021 | Huang et al. | Brass | Plasma-sprayed ceramic | Hardened steels | Heavy-duty machining | Enhanced thermal resistance and less breakage | Thick coating affected gap control. | Wire breakage, thermal stability |
| 17 | 2022 | Jain et al. | Brass | $Al_2O_3$ nano-coating | Tool steels | Precision finishing | For finishing cuts and insulating nano-coating reduced stray discharges and overcut | Only Focused on finishing passes. | Accuracy, surface integrity |
| 18 | 2022 | Reddy et al. | Brass | Silver nano- | Alloy steels | Tool & Die, Automotive | Better flushing and Enhanced debris removal. | Scale-up challenges. | Flushing, debris removal |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | textured layer | | | | | |
| 19 | 2022 | Zhao et al. | Brass | PTFE-infused | Tool steels | Precision machining | Reduced friction & vibration (chattering) | Durability at high temperatures uncertain. | Vibration, friction |
| 20 | 2023 | Chen et al. | Brass | Biomimetic textured | Hardened steels | Precision machining | Micro-textures improved dielectric flow and debris removal. | Manufacturing consistency is Hard to reproduce. | Flushing, stability |
| **C. Composite, Alloyed & Alternative Core Wires** | | | | | | | | | |
| 21 | 2008 | Pecas & Henriques | Brass | Multi-layer Zn + barrier | Cemented carbides | Tool & Die, Cutting Tools | Better performance on cemented carbides and controlled vaporization. | High manufacturing cost and sensitive to thickness. | MRR, SR, breakage rate |
| 22 | 2010 | Klocke et al. | Brass | Commercial coated wires | Various steels | Industry benchmarking | Benchmarking: diffusion-annealed wires best overall (speed, finish, breakage resistance). | Industry validation. only. | MRR, SR, breakage resistance |
| 23 | 2011 | Joshi et al. | Brass | Beta-phase brass | Inconel 718 | Aerospace | Higher MRR & SR on Inconel 718. | Costly and Requires thermal control needed. | MRR, SR |
| 24 | 2019 | Martínez et al. | Brass | Ag-doped Zn | Tool steels | Corrosion-critical apps | Slight MRR gains, better corrosion resistance. | Corrosion data limited | Corrosion resistance, MRR |
| 25 | 2020 | Li et al. | Steel core | Brass/Zn thick coating | >500 mm thick steel plates | Heavy industry | High-tensile steel core with thick brass/zinc coating for ultra-thick cutting (>500 mm). | Specialized application. | Thick cutting capability |
| 26 | 2022 | Kumar R. et al. | Brass | Cryogenic treatment | Tool steels | General machining | Improved hardness, wear resistance. | Effects can diminish over time. | Wire Hardness, wire wear |
| 27 | 2022 | Behera et al. | Brass | $MoS_2$ solid lubricant coating | Tool steels | Tool & Die | Reduced friction & vibration in wire guides and potentially improved straightness & reduced breakage. | Mechanical focus only. | Wire breakage, vibration |
| 28 | 2022 | Zhang et al. | Molybdenum | Composite coating | Micro-feature machining | Micro-EDM | For micro-EDM: composite coating improved sparking | Niche micro-EDM application. | Spark stability, wear |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | consistency & wear resistance. | | |
| **D. Reviews, ML-based, & Future-Oriented Studies** | | | | | | | | | |
| 29 | 2011 | Antar et al. | Tungsten | $ZrO_2$ (micro-EDM) | Micro-components | Micro-EDM | Insulated coating minimized stray sparks and improved micro-feature accuracy and reduced overcut. | Brittle wire and micro-EDM niche. | Accuracy, overcut |
| 30 | 2013 | Ho et al. | Brass | — (modeling) | Tool steels | General machining | Modeled wire wear; coated wires lose coating before core erosion. | Key for failure mechanism understanding (Simulation only). | Wire wear, tool life |
| 31 | 2020 | Muthuramalingam et al. | Brass | Generator interaction | Tool steels | EDM system studies | Investigated coated wire interaction perform better on modern generators. | System-level study. | MRR, energy efficiency |
| 32 | 2021 | Pramanik et al. | Brass | (review) | — | General overview | Review Summarized wire electrode coatings development up to 2021. | Review article and synthesis of prior work. | Literature synthesis |
| 33 | 2023 | Singh et al. | Brass | ML optimization for coated wire | Nickel alloys | Predictive modeling | ML used to model and optimize process parameters for a new coated wire and achieved better performance. | Predictive model and needs more experimental validation. | Predicted MRR, SR, life |
| 34 | 2023 | Ojha et al. | Brass | Recycled brass wire with enhanced coating | General steels | Sustainable machining | Focus on sustainability and performance acceptable but not superior. | Performance trade-off. | Sustainability, MRR |

As per the available literature reviewed in Table 1. highlights the progressive evolution of wire coatings in WEDM, ranging from conventional zinc coatings to advanced nano-engineered and composite wires. Coated wires consistently deliver superior machining performance over plain brass, particularly in terms of MRR, SR, WWR, and overall operational stability. However, critical gaps remain in standardized benchmarking protocols, comprehensive lifecycle and techno-economic assessments, scalable fabrication processes, and sustainable deployment at an industrial scale. Addressing these gaps is essential to transform laboratory-level innovations into robust, cost-effective, and widely adopted solutions for diverse manufacturing sectors.

**Table 2.** Comparison of Wire Coating Types and Their Influence on WEDM Performance Parameters

| Wire Type / Coating | Key Advantages | Limitations | Performance Parameters Improved |
|---|---|---|---|
| **Plain Brass Wire** | Low cost, widely available, easy to use | High wear, poor stability, limited to basic applications | Baseline reference |
| **Zinc-Coated Brass Wire** | Improved flushing, higher MRR, reduced rupture | Coating adhesion issues, mainly suitable for roughing cuts | MRR, cutting stability |
| **Diffusion Annealed Wire** | Uniform properties, better conductivity, longer tool life | Higher cost, limited availability, premium product | MRR, SR, wire breakage |
| **Nano-Coated Wire (ZnO, TiC, DLC)** | Reduced friction, improved surface integrity, stable sparks | High fabrication cost, lab-scale research stage | SR, dielectric stability, wire wear |
| **Multi-Layer / Composite Wire** | Higher wear resistance, dimensional accuracy, reduced breakage | Complex manufacturing, costly, sensitive to thickness | MRR, SR, breakage resistance |
| **Hybrid / Doped Wires (Graphene, RE)** | Enhanced thermal conductivity, spark efficiency, balanced MRR & SR | Experimental stage, high cost, scalability challenges | Spark efficiency, wire temperature, surface quality |

Table 2. provides a comparative summary of wire coating types and their influence on WEDM performance parameters. It reinforces the trend that while conventional zinc-coated wires remain effective for general applications, advanced functional coatings such as nano-engineered, composite, and diffusion-treated wires demonstrate significant advantages in precision, stability, and surface integrity. Nevertheless, the lack of uniform evaluation methods across studies makes direct comparison challenging. Future research should emphasize harmonized testing frameworks, integration of predictive modeling, and exploration of sustainable wire designs tailored for high-value industries such as aerospace, biomedical, and micro-manufacturing.

## III. Research Gap

Despite extensive developments, several gaps remain in the current body of literature:

1. **Benchmarking & Standardization** – A lack of standardized experimental protocols makes it difficult to compare coated wires across studies.
2. **Lifecycle & Cost Evaluation** – Very few studies assess long-term tool life, recyclability, and economic feasibility at an industrial scale.
3. **Application-Specific Optimization** – Limited research links wire coating design to specific industry needs (e.g., aerospace alloys, biomedical steels).
4. **Sustainability** – Recycling of brass wires and eco-friendly coating processes are still underexplored.
5. **Digital Integration** – Machine learning and digital twins for predictive modeling of wire performance are only in preliminary stages and need validation.

The author did not find adequate literature establishing standardized experimental protocols for benchmarking coated wire performance across studies. Most existing research does not assess long-term tool life, recyclability, or economic feasibility at an industrial scale. Studies linking wire coating design to application-specific requirements such as aerospace alloys or biomedical steels are also limited. Furthermore, sustainability aspects like brass wire recycling and eco-friendly coating processes remain underexplored, while the integration of digital tools such as machine learning and digital twins for predictive modelling of wire performance is still at a preliminary stage without industrial validation.

## IV. Conclusion

Based on the available literature demonstrates that wire surface modifications have evolved significantly, ranging from conventional zinc coatings to advanced nano-engineered and composite designs. Coated wires consistently outperform plain brass electrodes in terms of material removal rate, surface finish, wire wear resistance, and operational stability. These improvements are particularly relevant to industries requiring precision machining, such as aerospace, defence, automotive, and biomedical manufacturing. Overall, the findings confirm that coated wires are not merely incremental improvements but represent a transformative advancement for WEDM technology. The collective evidence establishes their potential for improving productivity, accuracy, and process reliability across a wide range of applications.

## V. Future direction

The next phase of WEDM wire development is expected to focus on **multi-functional, adaptive, and sustainable coatings**. Hybrid multilayer structures that combine high thermal conductivity, electrical stability, and mechanical durability may enable wires to simultaneously deliver high material removal during roughing and superior surface integrity during finishing. Emerging concepts such as "smart" coatings, capable of adapting their functional properties with changing discharge energy or temperature, hold potential to unify roughing and finishing operations within a single electrode type. From an industrial perspective, addressing scale-up challenges such as coating adhesion during wire drawing, quality control across long wire reels, and cost-effective deposition methods will be critical to commercialization. Application-specific studies tailored to biomedical implants, aerospace superalloys, and advanced composites will further expand the applicability of coated-wire technologies. By combining material science innovations with integrated process optimization and data-driven intelligence, future WEDM systems can achieve new levels of performance, efficiency, and sustainability.

1. Hybrid **& Smart Coatings**: Multi-functional, adaptive coatings that balance MRR (roughing) and SR (finishing) in a single wire.
2. Physics**-Informed ML Models**: Combine plasma simulations with AI for predictive coating performance and process optimization.
3. Sustainable **Manufacturing**: Focus on recycled feedstocks, biodegradable dielectrics, and scalable coating methods for industry adoption.


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