

A Comprehensive Review of Optimization Techniques for Wire Electric Discharge Machining with Material-Specific Focus on AISI D2 Tool Steel

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ABSTRACT

Wire Electric Discharge Machining (WEDM) is widely employed for machining electrically conductive hard-to-machine materials where conventional machining techniques face significant limitations. The machining performance of WEDM is highly dependent on the appropriate selection and optimization of process parameters such as pulse-on time, pulse-off time, peak current, wire feed, and servo voltage. In recent years, a variety of optimization techniques have been applied to enhance key performance characteristics including material removal rate, surface roughness, dimensional accuracy, and surface integrity.

This paper presents a comprehensive review of optimization techniques used for WEDM parameter optimization, with a special emphasis on material-specific studies, particularly AISI D2 tool steel. Classical methods such as Taguchi, Response Surface Methodology, and Grey Relational Analysis are critically analyzed alongside advanced meta-heuristic and artificial intelligence-based techniques including Genetic Algorithm, Particle Swarm Optimization, NSGA-II, Artificial Neural Networks, and hybrid approaches. Recent studies are systematically reviewed and compared through tabular and thematic analysis.

The review highlights that while hybrid and intelligent optimization techniques provide superior predictive accuracy and global optimization capability, limited research has been reported on real-time adaptive optimization, sustainability-oriented objectives, and surface integrity aspects, especially for D2 tool steel. The findings of this review provide valuable insights for researchers and industry professionals in selecting suitable optimization strategies for efficient and reliable WEDM of advanced engineering materials.

Keywords:- Wire Electric Discharge Machining; WEDM Optimization; AISI D2 Tool Steel; Meta-Heuristic Algorithms; Hybrid Optimization Techniques; Surface Integrity; Sustainable Machining.

1. INTRODUCTION

Wire Electrical Discharge Machining (WEDM) is a non-traditional machining process capable of machining electrically conductive materials irrespective of their hardness. Due to the complex and nonlinear nature of WEDM parameters, advanced optimization techniques are required to achieve optimal machining performance.

2. WEDM PROCESS PARAMETERS

Key parameters include electrical parameters such as pulse on time, pulse off time, discharge current, and voltage; mechanical parameters such as wire feed rate and wire tension; and performance characteristics including material removal rate, surface roughness, kerf width, and dimensional accuracy.

3. OPTIMIZATION TECHNIQUES

Recent studies employ classical techniques such as Taguchi and Response Surface Methodology as well as advanced meta-heuristic and hybrid methods including Genetic Algorithm, Particle Swarm Optimization, Artificial Neural Networks, ANFIS-PSO hybrids, NSGA-II, and MOPSO for effective WEDM parameter optimization.

4. DETAILS LITERATURE REVIEW

Table 1 presents a detailed literature review of different optimization techniques used for WEDM parameter optimization (recent Scopus/SCI works).

Author (Year)	Material	Optimization Technique	Key Findings	Research Gap
Zhao et al. (2025)	Alloy Steel	Taguchi	Pulse-on time dominant for MRR & SR	Limited nonlinear handling
Afridi et al. (2025)	AISI D2	RSM	Accurate MRR & SR prediction	Less effective for complex nonlinearity
Sunil et al. (2024)	Inconel 625	RSM + GA	Improved global optimization	High computational cost
Sharma et al. (2023)	Biomedical Alloy	Taguchi–GRA	Balanced multi-response optimization	Weight sensitivity issue
Pasupuleti et al. (2024)	Cupronickel	GRA	Enhanced surface finish	Limited industrial validation
Kumar et al. (2023)	MMCs	GA	Global optimum achieved	Algorithm tuning required
Sharma et al. (2023)	Biomedical Material	PSO	Improved surface quality	Risk of local minima
Kumar et al. (2023)	Composite	ANN	High prediction accuracy	Large dataset requirement
Kumar et al. (2025)	NiTi Alloy	ANFIS–PSO	Significant SR reduction	No real-time control
Nagadeepan et al. (2023)	Ti–6Al–4V	NSGA-II	Pareto-optimal solutions	High computation time

• Literature Review on Materials Used for WEDM – Focus on D2 Tool Steel

Author (Year)	Material	Key Properties	Applications	Research Gap
Afridi et al. (2025)	AISI D2 Tool Steel	High hardness, excellent wear resistance	Punches, dies, molds	Surface integrity not analyzed
Singh et al. (2024)	AISI D2 Tool Steel	Dimensional stability, carbide-rich structure	Cold work tooling	HAZ and micro-crack control not optimized
Zhao et al. (2025)	Tool steels (incl. D2)	High chromium alloy steel	Industrial tooling	Lack of real-time adaptive control
Sunil et al. (2024)	Inconel 625	High temperature & corrosion resistance	Aerospace components	Energy efficiency not considered
Nagadeepan et al. (2023)	Ti–6Al–4V	High strength-to- weight ratio	Biomedical & aerospace parts	Limited comparative machining studies
Kumar et al. (2023)	Metal Matrix Composites	High stiffness and wear resistance	Automotive components	Tool wear modeling missing

• Material-Based Research Gap:

Although AISI D2 tool steel is extensively used in WEDM due to its superior hardness and wear resistance, most reported studies primarily focus on machining performance indicators such as material removal rate and surface roughness. Limited attention has been paid to surface integrity, residual stresses, heat-affected zone

characteristics, and sustainability aspects. Moreover, comparative investigations with other advanced engineering materials under identical WEDM conditions are scarce. This highlights the need for material-oriented, multi-objective, and real-time optimization frameworks for WEDM of D2 tool steel.

- **Applications of D2 Tool Steel in Industry**

Due to its unique combination of hardness, wear resistance, and toughness, D2 steel finds extensive applications in sectors such as automotive, aerospace, machining and tooling industries. Typical applications include:

- Punches and dies for sheet metal forming
- Mandrels and forming rolls
- Shear blades and cut-off tools
- Mold components and die casting dies
- Precision shafts and landing gear components
- Cutting tools requiring abrasion resistance

Industrial tooling environments benefit from D2's ability to maintain dimensional accuracy and resist wear during repetitive processes.

- **Challenges of Machining D2 Steel**

Despite its desirable properties, conventional machining of hardened D2 steel presents significant challenges:

- High hardness causes rapid wear of cutting tools, leading to increased tooling costs.
- High carbon and chromium promote formation of abrasive carbides, making material removal difficult using traditional methods.
- Thermal stress during machining can induce brittleness and microstructural changes when high energy cutting is used.

These factors often result in poor surface finish, higher tool wear, and increased cycle time if conventional machining is attempted without specialized tooling or techniques.

5. RESEARCH GAP IDENTIFIED

Although classical techniques (Taguchi, RSM, GRA) are widely used for WEDM optimization, they show limitations in handling nonlinear and multi-objective problems. Meta-heuristic methods (GA, PSO) improve global search capability but demand high computational effort. Hybrid AI-based techniques (ANN-GA, ANFIS-PSO) offer superior accuracy; however, limited research addresses real-time adaptive optimization and sustainability aspects in WEDM.

Current research focuses on hybrid machine learning models, multi-objective optimization, real-time adaptive control, Industry 4.0 integration, and sustainable machining objectives.

6. CONCLUSION

This paper presented a **comprehensive review of optimization techniques applied to Wire Electric Discharge Machining (WEDM)** with special emphasis on **material-specific studies, particularly AISI D2 tool steel**. Classical optimization methods such as **Taguchi, Response Surface Methodology, and Grey Relational Analysis** have been widely used due to their simplicity and effectiveness in identifying dominant machining parameters. However, these techniques exhibit limitations when dealing with **nonlinear, multi-objective, and complex machining environments**.

Meta-heuristic optimization algorithms including **Genetic Algorithm, Particle Swarm Optimization, and NSGA-II** demonstrate superior global search capability and are effective for multi-response optimization. Nevertheless, they often require significant computational effort and careful tuning of algorithm parameters. Recent studies increasingly adopt **hybrid and artificial intelligence-based techniques** such as **ANN-GA and ANFIS-PSO**, which provide

improved prediction accuracy and optimization efficiency, especially for complex materials like D2 tool steel.

From a material perspective, D2 tool steel is widely preferred for WEDM due to its high hardness, wear resistance, and dimensional stability; however, most studies primarily focus on performance metrics such as **material removal rate and surface roughness**. Limited attention has been given to **surface integrity, heat-affected zone characteristics, residual stresses, and sustainability aspects**, indicating a significant research gap.

Based on the reviewed literature, future research should focus on **real-time adaptive optimization frameworks, material-oriented multi-objective modeling, and sustainable machining strategies**. Integration of intelligent algorithms with process monitoring systems is expected to significantly enhance WEDM performance and component quality. The insights presented in this review will assist researchers and industrial practitioners in selecting appropriate optimization techniques for efficient and reliable WEDM of advanced

engineering materials.

7. REFERENCES

- [1] Zhao, X., Dong, B., Dong, S., & Ming, W. (2025). Research progress on process optimization of metal materials in wire electrical discharge machining. *Metals*, 15(7).
- [2] Afridi, S. A., Younas, M., & Khan, Z. (2025). Multi-objective optimization of WEDM parameters for D2 steel. *International Journal of Precision Engineering and Manufacturing*.
- [3] Sunil, B. D. Y., Goyal, A., Kumar, L., et al. (2024). Optimizing WEDM performance of Inconel 625 using GA and PSO. *Journal of Materials Research and Technology*, 31, 555–569.
- [4] Kumar, L., Goyal, A., Garg, S., et al. (2023). Predictive modeling and optimization of WEDM using hybrid techniques. *International Journal of Interactive Design and Manufacturing*.
- [5] Sharma, V. S., Sharma, N., Singh, G., Gupta, M. K., & Singh, G. (2023). Optimization of WEDM parameters while machining biomedical materials using EDAS-PSO. *Materials*, 16(1), 114.
- [6] Nagadeepan, A., Jayaprakash, G., & Senthilkumar, V. (2023). Multi-objective optimization of WEDM using NSGA-II. *Materials*.
- [7] Jain, S., & Parashar, V. (2023). Hybrid PSO-based optimization of WEDM. *Materials and Manufacturing Processes*.
- [8] Venkatarao, K., et al. (2023). Multi-response optimization of WEDM using TLBO. *International Journal of Advanced Manufacturing Technology*.
- [9] Mahalingam, S. (2024). Performance evaluation and optimization of WEDM. *Processes*, 12(6).
- [10] Pasupuleti, T., Natarajan, M., Kiruthika, J., et al. (2024). Optimization of WEDM parameters using TOPSIS. *SAE Technical Paper*.