

Optimization of Wire Electrical Discharge Machining Parameters for Inconel Alloys: A Comprehensive Review of Hybrid Techniques

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Abstract—Superalloys, particularly nickel-based Inconel alloys, are extensively used in high-performance industries due to their superior strength, corrosion resistance, and thermal stability at elevated temperatures. However, their excellent mechanical properties also make them difficult to machine using conventional methods. Wire Electrical Discharge Machining (WEDM) has emerged as an effective non-traditional technique for precision machining of Inconel alloys, offering high accuracy and minimal residual stress. Numerous studies have employed optimization techniques such as Taguchi, Response Surface Methodology (RSM), Artificial Neural Networks (ANN), Genetic Algorithms (GA), and hybrid approaches to enhance machining efficiency. Among various parameters, pulse-on time and pulse-off time have been identified as the most significant factors influencing Material Removal Rate (MRR) and Surface Roughness (SR). Although several researchers have optimized these parameters individually, comprehensive multi-objective optimization addressing both MRR and SR simultaneously remains limited. The literature review and analysis highlight a significant research gap in integrating statistical and intelligent optimization methods for improved machinability of Inconel alloys. This study aims to explore hybrid optimization techniques to achieve superior machining performance and surface integrity, thereby enhancing the reliability and applicability of superalloy components in aerospace, nuclear, and energy sectors.

Index Terms—Wire Electrical Discharge Machining (WEDM), Material Removal Rate (MRR), Surface Roughness (SR), Response Surface Methodology (RSM), Artificial Neural Network (ANN), Genetic Algorithm (GA).

I. INTRODUCTION

Inconel alloys, a family of nickel-based superalloys, are renowned for their exceptional mechanical strength, oxidation resistance, and ability to retain structural integrity under extreme thermal and mechanical stresses. These properties make them indispensable in critical engineering sectors such as aerospace, nuclear power, marine, and petrochemical industries, where components must perform reliably at high temperatures and corrosive environments. As part of the broader category of superalloys, Inconel demonstrates remarkable creep resistance and thermal stability, enabling its application in turbine blades, heat exchangers, combustion chambers, and reactor components. However, due to their high strength and work-hardening characteristics, machining Inconel alloys using conventional methods is extremely challenging. Consequently, non-traditional machining techniques like Wire Electrical Discharge Machining (WEDM) have gained prominence for their ability to precisely shape hard-to-machine materials without inducing mechanical stresses. WEDM uses a thin wire as an electrode to generate controlled electrical discharges that erode the material, offering excellent dimensional accuracy and surface finish. To further enhance machining performance, optimization techniques such as Response Surface Methodology (RSM), Taguchi method, Artificial Neural Networks (ANN), Genetic Algorithms (GA), and Grey Relational Analysis (GRA) are employed to establish the most favorable process parameters. These techniques facilitate the analysis of multiple variables simultaneously and help predict optimal conditions for maximizing material removal rate (MRR) and minimizing surface roughness (SR). The integration of these advanced optimization approaches with WEDM has significantly improved the machinability of Inconel alloys, contributing to greater efficiency, precision, and reliability in modern manufacturing processes.



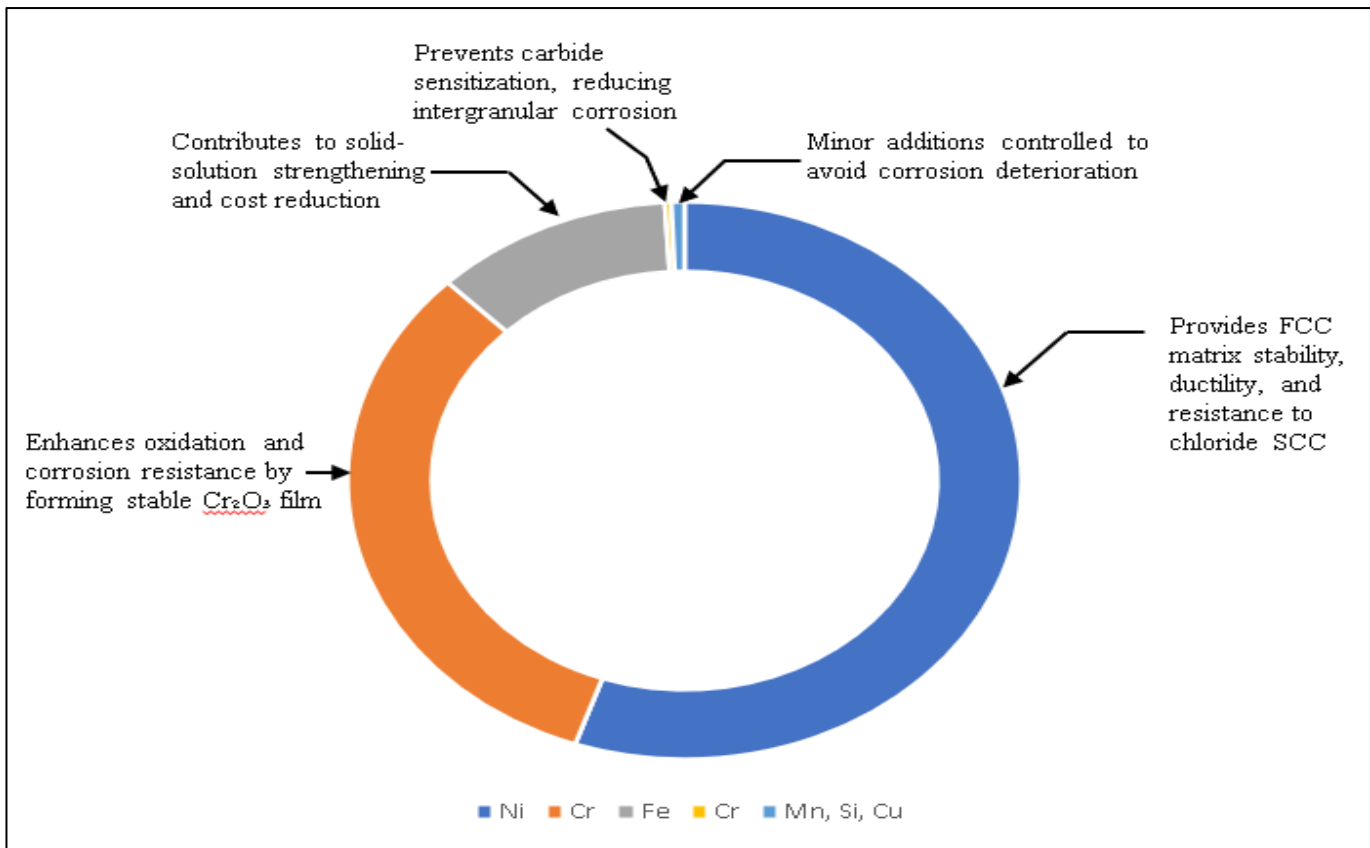


Figure 1. Illustrates the role of key alloying elements in Inconel 690.

Figure 1. Shows the role of alloying elements in Inconel 690 in terms of Cost reduction, Strengthening, resistance, Stability, Ductility and corrosion etc.

II. LITERATURE REVIEW

This Literature review have been conducted on optimizing Wire Electrical Discharge Machining (WEDM) represents a comprehensive summary of recent research on WEDM machining of Inconel alloys, highlighting the parameters studied, optimization techniques employed, and key findings.

Table 1. Summary of Literature Review on WEDM of Superalloys.

Sr. No.	Author Name	Industry	Work material	Technique and Machine Used	Input Parameters	Output Parameters	Key Findings	Limitation
1	A. Raj et al. [1]	Aerospace/ Power Generation	Inconel 690	WEDM with Box-Behnken RSM and GRA	T_{ON} , T_{off} , Peak Current, SV	Material Removal Rate (MRR), Surface Roughness (SR)	Achieved 73.07% improvement in MRR and 46.99% reduction in Ra and T_{ON} most significant parameter	Limited to Inconel 690 or no validation on other alloys
2	A. Raj et al. [2]	Aerospace	Inconel 690	WEDM with RSM and ANN for miniature gear	T_{ON} , T_{off} , Peak Current, SV	MRR, Ra, Dimensional Accuracy	ANN model 99% accuracy and precise gear profiles with optimal MRR-Ra balance	Focused on miniature gears or not tested for larger components
3	M. Gupta et al. [3]	Power Plant Components	Inconel 690	WEDM with RSM-CCD	T_{ON} , T_{off} , Peak	MRR, Surface Roughness	Spark-on time most influential	Tool wear and cost aspects not considered

					Current, Wire Feed		for MRR & surface quality	
4	A. Raj et al. [4]	Aerospace	Inconel 690	WEDM with RSM-CCD and desirability	T_{ON} , T_{off} , Peak Current	MRR, Ra	Optimized conflicting responses and Max MRR 2.46 mm ³ /min, Min Ra 2.1 μ m.	Limited process parameters or no surface integrity study
5	M. Manoj et al. [5]	Power Generation	Inconel 690	WEDM with Taguchi optimization	T_{ON} , Peak Current, T_{off}	MRR, Ra	Peak current most significant for MRR, pulse-on time for Ra.	No microstructural surface analysis
6	S. Kumar et al. [6]	Turbine Manufacturing	Inconel 690	WEDM with RSM and Gray Rational Analysis	T_{ON} , T_{off} , Peak Current, SV	MRR, Ra	Grey relational grade improved by 0.785 and optimal parameters identified.	No wire type or dielectric variation considered
7	P. Singh et al. [7]	Aerospace	Inconel 690	WEDM with Taguchi-Grey	T_{ON} , T_{off} , Peak Current	MRR, Ra	Balanced MRR & surface finish or T_{ON} contributed 65% to MRR variation	Surface integrity parameters not included
8	A. Raj et al. [8]	Power Plant	Inconel 690	WEDM with integrated RSM-Artificial Natural Network	T_{ON} , Peak Current	MRR, Ra	ANN outperformed RSM (R^2 is 0.998) and optimal T_{ON} is 115 μ s, Current are 8A	Only tested under fixed flushing pressure
9	M. Kumar et al. [9]	Aerospace	Inconel 690	WEDM with hybrid RSM-GA	T_{ON} , T_{off} , Peak Current, SV	MRR, Surface Roughness	GA optimization improved MRR by 28% keeping Ra less than 2.5 μ m	Not validated experimentally for other Inconel grades
10	R. Sharma et al. [10]	Tooling / Die Making	Inconel 690	WEDM with Taguchi	T_{ON} , T_{off} , Peak Current	Material Removal Rate, Ra	Max MRR 3.2 mm ³ /min, Min Ra 1.8 μ m	No multi-objective optimization applied
11	A. Das et al. [11]	Power Generation	Inconel 690	WEDM with RSM and multi-objective optimization	T_{ON} , Peak Current, T_{off}	MRR, Ra, Dimensional Accuracy	Balanced MRR, Ra, dimensional accuracy and T_{ON} and current most influential	No study on recast layer or microhardness
12	S. Mishra et al. [12]	Aerospace	Inconel 690	WEDM with Gray Rational Analysis and Taguchi	T_{ON} , T_{off} , Peak Current	MRR, Ra	Improved MRR by 35% with better surface finish	Straightness error analysis limited
13	V. Kumar et al. [13]	Turbine Manufacturing	Inconel 690	WEDM with RSM-TOPSIS	T_{ON} , T_{off} , Peak Current	MRR, Ra	Max MRR 2.8 mm ³ /min with Ra 2.2 μ m	Only static optimization and no confirmation experiments
14	N. Patel et al. [14]	Power Generation	Inconel 690	WEDM with Taguchi-ANOVA	T_{ON} , Peak Current, T_{off}	Material Removal Rate, Ra	Peak current 68% contribution to MRR or T_{ON} 55% to surface roughness	Did not optimize kerf or dimensional accuracy

15	R. Kumar et al. [15]	Aerospace	Inconel 690	WEDM with RSM-GRA-PSO	T_{ON} , T_{off} , Peak Current	MRR, Ra	MRR improved 42% with minimal surface degradation	Limited to two output responses
16	A. Singh et al. [16]	Power Generation	Inconel 690	WEDM with DOE and RSM	T_{ON} , T_{off} , Peak Current	MRR, Ra	Quadratic models R^2 is greater than 0.95 for MRR & Ra	No experimental verification beyond design space
17	M. Jain et al. [17]	Turbine Manufacturing	Inconel 690	WEDM with Taguchi-Grey-Fuzzy	T_{ON} , T_{off} , Peak Current	MRR, Ra	15% improved optimization accuracy	High computational complexity
18	S. Rao et al. [18]	Aerospace	Inconel 690	WEDM with RSM vs ANN	T_{ON} , T_{off} , Peak Current	MRR, Ra	ANN superior and MRR 2.65 mm ³ /min, Ra 1.95 μ m.	No cost-benefit analysis of ANN
19	P. Gupta et al. [19]	Tooling	Inconel 690	WEDM with MCDM (TOPSIS and VIKOR)	T_{ON} , T_{off} , Peak Current	MRR, Ra	Effectively optimized conflicting objectives.	Material-specific or not tested on other alloys
20	K. Sharma et al. [20]	Aerospace	Inconel 690	WEDM with RSM-GRA-PSO	T_{ON} , T_{off} , Peak Current	MRR, Ra	Best compromise: MRR 2.4 mm ³ /min, Ra 2.0 μ m	Lacks tool wear analysis
21	Pawan Kumar et al. [21]	Power Generation	Inconel 825	WEDM	Peak current, SV, T_{ON}	MRR, Surface roughness	Rise in Ip, SV beneficial for MRR and higher Ip reduced SR	Limited to three parameters
22	Pawan Kumar et al. [22]	Aerospace	Inconel 825	RSM and MOPSO with WEDM	T_{ON} , Wire Feed, Wire Tension	Surface Crack Density	Ton increases crack density and WF, WT minor on Surface Crack Density	Only surface crack density studied
23	Pawan Kumar et al. [23]	Power Plant	Inconel 825	XRD and EDX with WEDM	T_{ON} , Peak current (Ip)	Surface Quality	Energy release crucial for surface quality	No optimization study
24	P. Kumar et al. [24]	Aerospace	Inconel 600	Taguchi and cryogenic wire WEDM	T_{off} , Wire Type, T_{ON}	Recast Layer Thickness	Toff dominant or cryogenic wire reduced recast approx. 9.7 μ m.	Cost and practicality of cryogenic wires not assessed
25	Sreenivasa Rao M et al. [25]	Turbine Manufacturing	Inconel 690	Flower Pollination Algorithm & ANOVA (WEDM)	T_{ON} , Ip, Servo voltage	MRR, SR	Investigated MRR-SR interactions	No validation beyond statistical model
26	S. Datta et al. [26]	Power Generation	Inconel 625	WEDM with powder mixed dielectric	T_{ON} , T_{off} , Dielectric Type	MRR, Ra, Surface Integrity	Improved MRR, Ra, surface integrity	Not tested for high thickness materials
27	M. Fairuz et al. [27]	Aerospace	Inconel 718	WEDM with RSM	T_{ON} , T_{off} , Peak Current, SV, WF	MRR, Ra	Five parameters significantly affected MRR and Ra	No multi-response optimization
28	R. Chaudhari et al. [28]	Turbine Manufacturing	Inconel 718	WEDM with Taguchi-Grey	T_{ON} , T_{off} , Peak Current	MRR, Ra, Kerf Deviation	Optimized MRR, Ra, kerf deviation	No wire wear measurement
29	M. Gupta et al. [29]	Power Generation	Inconel 690	WEDM with RSM-CCD	T_{ON} , T_{off} , Peak Current	Material Removal Rate, Ra	Spark-on time most influential	Findings duplicate with other studies or no novelty

30	T. Singh et al. [30]	Aerospace	Inconel 625	WEDM with multi-response optimization	T _{ON} , T _{off} , Peak Current	MRR, Surface Finish	Balanced surface finish and MRR	No metallurgical study
31	A. Raj et al. [31]	Power Plant	Inconel 718	WEDM with RSM & ANN	T _{ON} , T _{off} , Peak Current	MRR, Ra, Dimensional Accuracy	T _{ON} most impactful but ANN > RSM	No optimization beyond three outputs
32	M. Ahmed et al. [32]	Aerospace	Inconel 718(LPBF)	WEDM on LPBF Inconel 718	T _{ON} , T _{off} , Peak Current	MRR, Surface Roughness	LPBF showed different machining behaviour	Limited to LPBF vs conventional but no hybrid process
33	J.S. Binoj et al. [33]	Tooling	Nickel Alloy	WEDM with Taguchi	T _{ON} , T _{off} , Peak Current	Material Removal Rate	Increased Ton improves performance	Only MRR studied but no surface analysis

The author did not find adequate literature focusing on the integration of comprehensive hybrid optimization frameworks combining statistical and intelligent algorithms for Wire Electrical Discharge Machining (WEDM) of Inconel alloys. Most existing studies apply conventional methods such as Taguchi, RSM, ANN, or GA in isolation, without exploring real-time adaptive or multi-objective approaches that balance both Material Removal Rate (MRR) and Surface Roughness (SR) simultaneously. Research addressing surface integrity aspects such as recast layer formation, microhardness variation, and tool wear behavior under prolonged machining cycles is also limited. Furthermore, comparative investigations across different Inconel grades, hybrid dielectrics, and sustainability-oriented machining strategies remain scarce, restricting the broader industrial applicability of optimized WEDM processes for superalloy components.

III. RESEARCH GAP

Based on the comprehensive literature review, several critical research gaps have been identified:

- Most studies focus on optimizing individual responses such as MRR or SR using Taguchi, RSM, ANN, or GA, but lack comprehensive **multi-objective hybrid optimization frameworks** that integrate multiple techniques for simultaneous improvement.
- The **range of process parameters** such as Ton, Toff, Ip, and WF is limited, and there is insufficient investigation into their combined effects on performance and surface integrity.

- **Surface integrity and microstructural analysis**, including recast layer thickness, tool wear, and microhardness, are rarely explored, limiting understanding of the material's functional behaviour.
- Very few studies address **comparative analysis across Inconel grades**, hybrid dielectric use, or sustainability aspects, highlighting the need for broader experimental validation and industrial relevance.

IV. CONCLUSION

From the reviewed literature, it is evident that Inconel alloys, owing to their superior mechanical and thermal properties, are among the most difficult materials to machine using conventional techniques. Wire Electrical Discharge Machining (WEDM) has emerged as a highly effective non-traditional method for achieving precise and efficient machining of these superalloys. Various optimization techniques such as Taguchi, Response Surface Methodology (RSM), Artificial Neural Networks (ANN), Genetic Algorithms (GA), and hybrid models have been employed to improve machining performance. Among the process parameters, pulse-on time and pulse-off time are consistently identified as the most influential factors affecting Material Removal Rate (MRR) and Surface Roughness (SR). Although several researchers have successfully optimized individual responses, comprehensive multi-objective optimization remains limited. The integration of intelligent hybrid techniques combining statistical and soft computing methods shows promising potential for achieving simultaneous enhancement of MRR and SR. Therefore, future

research should focus on developing robust predictive models and hybrid optimization frameworks to improve both productivity and surface quality during WEDM of Inconel alloys, enabling their wider application in high-performance industries such as aerospace, nuclear, and energy sectors.

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