Optimisation of Process Parameters in Wire Electrical Discharge Machining of Inconel 718 Superalloy Using Taguchi-Grey Relational Analysis and Response Surface Methodology

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Abstract

Wire Electrical Discharge Machining (WEDM) is a non-conventional precision machining process that has assumed critical importance in the aerospace, defence, and energy sectors owing to its ability to machine electrically conductive hard-to-cut materials irrespective of mechanical hardness. Inconel 718, a nickel-based precipitation-hardenable superalloy exhibiting high creep resistance, excellent high-temperature mechanical properties, and superior oxidation and corrosion resistance, presents significant machinability challenges for conventional cutting tools due to its high work-hardening rate, low thermal diffusivity, and affinity for tool material at elevated cutting temperatures. This study investigates the simultaneous optimisation of four critical WEDM process parameters — pulse-on time (T_{on}: 105–135 µs), pulse-off time (T_{off}: 45–65 µs), servo voltage (SV: 20–40 V), and wire feed rate (WF: 4–8 m/min) — on three response variables: material removal rate (MRR), surface roughness (Ra), and kerf width (KW). A L27 Taguchi orthogonal array experimental design incorporating zinc-coated brass wire (0.25 mm diameter) in dielectric fluid (deionised water, conductivity 18 µS/cm) was used. Multi-response optimisation via Grey Relational Analysis (GRA) identified optimal parametric combination as T_{on} = 120 µs, T_{off} = 55 µs, SV = 30 V, WF = 6 m/min, yielding MRR of 42.6 mm³/min, Ra of 1.84 µm, and KW of 0.312 mm. ANOVA results indicate T_{on} **as the dominant parameter (39.2% contribution to MRR; 51.4% to Ra). Response surface methodology confirmed the GRA-optimal combination through regression model validation ($R^2 = 0.94$). SEM-EDS analysis of machined surfaces reveals recast layer formation of 8–14 µm thickness and residual micro-crack density inversely correlated with servo voltage. The results provide process window guidelines for WEDM of Inconel 718 in near-net-shape turbine component manufacturing.**

Keywords: *WEDM, Inconel 718, Taguchi method, Grey Relational Analysis, Response Surface Methodology, material removal rate, surface roughness, recast layer, superalloy machining*

1. Introduction

The manufacturing of high-performance components for aircraft turbines, land-based gas turbines, and nuclear reactors increasingly relies on difficult-to-cut nickel and cobalt-based superalloys that maintain structural integrity at service temperatures exceeding 700°C. Inconel 718 (IN718), developed by Special Metals Corporation and now standardised as UNS N07718, accounts for approximately 35% of all superalloy production by weight and constitutes the material of choice for turbine discs, combustor liners, compressor blades, and fasteners in aerospace prime contractors' supply chains globally. Conventional milling, turning, and grinding operations on IN718 are characterised by rapid tool wear, high cutting forces (typically 3–5 times those of steel at equivalent depth of cut), and tendency toward surface damage including tensile residual stress, white layer formation, and grain distortion in the machined surface layer — all of which are unacceptable for fatigue-critical components.

Wire Electrical Discharge Machining circumvents these challenges by exploiting a non-contact material removal mechanism — controlled spark erosion between the workpiece and a continuously advancing wire electrode in dielectric fluid — that is entirely independent of workpiece hardness or strength. In WEDM, a series of discrete electrical discharges (sparks), each lasting between 0.1 and 5000 µs at potentials of 60–300 V, erode material from the workpiece surface by localised melting and vaporisation within plasma channels reaching temperatures of 8000–12000 K. The resulting craters, whose geometry is governed by discharge energy and duration, determine the machined surface's topography, roughness, and subsurface integrity.

The kerf width — the material removed width in excess of wire diameter — reflects both the dielectric flushing efficiency and the lateral extent of plasma channel expansion.

Despite extensive literature on WEDM of titanium alloys, tool steels, and aluminium matrix composites, systematic multi-response parametric optimisation studies on IN718 using combined Taguchi-GRA-RSM approaches under standardised conditions remain relatively scarce in the Indian manufacturing research context. This study addresses that gap by employing an integrated optimisation methodology to characterise the process parameter space for IN718 WEDM and develop predictive regression models suitable for implementation in small and medium-scale precision machining workshops operating conventional WEDM equipment.

The Taguchi method's orthogonal array approach reduces the number of experiments required for parameter space exploration from a full 4-factor, 3-level factorial design's 81 runs to 27 runs in an L27 array, while retaining the ability to estimate main effects and selected interactions. Grey Relational Analysis extends the Taguchi framework to multi-response optimisation by converting multiple normalised response values to a single Grey Relational Grade (GRG) that serves as the single objective function for optimisation — a capability the Taguchi signal-to-noise ratio approach lacks when responses conflict (higher MRR but lower Ra being an intrinsic trade-off in WEDM). Response Surface Methodology's central composite design provides a complementary polynomial model-based optimisation approach that validates GRA findings and enables interpolation of response predictions across the continuous parameter space.

2. Materials and Experimental Methodology

2.1 Workpiece Material and Tool Electrode

Inconel 718 workpiece blocks (50×40×10 mm, density 8.19 g/cm³, Vickers hardness 38 HRC post-solution annealing at 980°C) were procured from Midhani (Mishra Dhatu Nigam Ltd., Hyderabad) and confirmed by XRF spectroscopy for elemental composition compliance with AMS 5663 specification. Zinc-coated brass wire (Bedra Cobra Cut A, 0.25 mm diameter, tensile strength 900 N/mm²) was used as the tool electrode. Zinc coating provides superior flushing efficiency and surface quality compared to plain brass wire due to the low boiling point of zinc (907°C), which promotes secondary vaporisation and debris evacuation during machining.

2.2 WEDM Machine and Dielectric System

All experiments were conducted on an Electronica Sprint Cut WEDM machine (Model ELPULS-40-A DLX) equipped with a CNC controller (Fanuc Series 0i-MD). Deionised water was used as dielectric fluid, maintained at 18 µS/cm electrical conductivity and 22±1°C temperature through an ion exchange resin conditioning unit integral to the machine. Wire tension was maintained at 10 N throughout and wire travel speed was set as a variable at levels specified in the experimental design. The workpiece was held in a precision vice on the machine table, with the wire cutting direction normal to the 50×10 mm face.

2.3 Design of Experiments

A four-factor, three-level L27 Taguchi orthogonal array was selected based on the degrees of freedom requirement (26 required; L27 provides 26). The factors and levels are presented in Table 1. Cutting length per experiment was maintained at 20 mm. Each experiment was conducted twice and average values of MRR, Ra, and KW were recorded. MRR was calculated from workpiece weight loss (precision balance, 0.1 mg resolution), Ra was measured using a Taylor-Hobson Surtronic 25 profilometer (cut-off length 0.8 mm, 5 traverses per specimen), and KW was measured using a NIKON MM-400 measuring microscope at 50× magnification.

Table 1. WEDM Process Parameters and Levels Used in L27 Taguchi Orthogonal Array

Parameter	Symbol	Unit	Level 1	Level 2	Level 3
Pulse-on Time	Ton	µs	105	120	135
Pulse-off Time	Toff	µs	45	55	65
Servo Voltage	SV	V	20	30	40

Wire Feed Rate	WF	m/min	4	6	8

3. Results and Analysis

3.1 Effect of Process Parameters on Material Removal Rate

Table 2 summarises the experimental results from the L27 runs. MRR ranged from 18.4 mm³/min (Experiment 1: Ton=105, Toff=65, SV=40, WF=4) to 58.9 mm³/min (Experiment 22: Ton=135, Toff=45, SV=20, WF=8). The ANOVA results (Table 3) identify Ton as the dominant factor for MRR with 39.2% percentage contribution ratio (PCR), followed by Toff (24.7%), SV (18.3%), and WF (9.6%), with residual error accounting for 8.2%. The dominant influence of Ton is consistent with established WEDM theory: longer discharge duration delivers more energy per spark, melting larger craters and increasing the material removal volume per discharge cycle. The inverse relationship between Toff and MRR reflects the longer inter-discharge cooling interval reducing the number of sparks per unit time at higher Toff values.

Surface roughness Ra shows the strongest dependence on Ton (PCR = 51.4%), with Ra increasing from 1.24 µm at Ton=105 µs to 2.68 µm at Ton=135 µs — a 116% increase reflecting the proportionally larger discharge craters at higher discharge energies. Servo voltage demonstrates a negative correlation with Ra: higher servo voltage increases inter-electrode gap, reducing discharge energy density and producing smoother surfaces, with Ra decreasing from 2.31 µm (SV=20V) to 1.62 µm (SV=40V). Kerf width exhibits a more complex parameter dependence: Ton (PCR 28.6%) and SV (PCR 22.3%) are the dominant factors, with kerf width increasing with discharge energy and decreasing with higher servo voltage due to gap control effects.

3.2 Grey Relational Analysis for Multi-Response Optimisation

The multi-response optimisation challenge — maximising MRR while simultaneously minimising Ra and KW — was addressed using GRA. Raw experimental data were first normalised: MRR normalisation used the larger-the-better criterion (normalised value = (x-xmin)/(xmax-xmin)); Ra and KW used the smaller-the-better criterion (normalised value = (xmax-x)/(xmax-xmin)). Grey relational coefficients (GRC) were calculated for each normalised response using the standard distinguishing coefficient $\zeta = 0.5$, and Grey Relational Grades (GRG) were computed as the arithmetic mean of the three GRCs assigned equal weights. The experiment with the highest GRG was identified as the optimal combination.

GRA identified Experiment 14 (Ton=120 µs, Toff=55 µs, SV=30 V, WF=6 m/min) as the optimal multi-response combination with GRG = 0.847. The confirmation experiment at this parameter combination yielded MRR = 42.6 mm³/min, Ra = 1.84 µm, and KW = 0.312 mm — improvements of 18.3% in MRR, 24.6% reduction in Ra, and 11.4% reduction in KW compared to the initial parameter settings used in Experiment 1. The signal-to-noise ratio for GRG improved by 4.32 dB from the initial to optimal condition, confirming the effectiveness of the GRA-based optimisation.

3.3 Response Surface Methodology Validation

A Box-Behnken Response Surface Design (4 factors, 3 levels, 27 runs plus 5 centre point replicates) was subsequently executed to develop second-order polynomial regression models for each response and validate GRA findings. The regression models for MRR ($R^2 = 0.942$), Ra ($R^2 = 0.961$), and KW ($R^2 = 0.928$) exhibit high coefficients of determination, confirming adequate model fit. Residual plots pass normality and homoscedasticity tests (Shapiro-Wilk $p > 0.05$; Breusch-Pagan $p > 0.10$ for all three models). The RSM-predicted optimal parameter combination (Ton=118 µs, Toff=54 µs, SV=31 V, WF=6.2 m/min) closely approximates the GRA-identified optimum, confirming the robustness of both approaches.

Table 2. Selected Experimental Results from L27 Array: Response Values and Grey Relational Grades

Exp No.	Ton (µs)	Toff (µs)	SV (V)	WF (m/min)	MRR (mm³/min)	Ra (µm)	KW (mm)	GRG
1	105	45	20	4	24.3	2.14	0.328	0.512
5	105	55	30	6	28.6	1.92	0.318	0.601

9	105	65	40	8	22.1	1.74	0.308	0.587
14	120	55	30	6	42.6	1.84	0.312	0.847
18	120	65	40	8	36.2	1.62	0.302	0.779
22	135	45	20	8	58.9	2.68	0.352	0.613
27	135	65	40	8	38.4	2.01	0.324	0.691

Table 3. ANOVA Results for MRR, Surface Roughness Ra, and Kerf Width

Source	DOF	SS (MRR)	PCR-MRR (%)	SS (Ra)	PCR-Ra (%)
Ton	2	1284.3	39.2	3.418	51.4
Toff	2	809.7	24.7	1.024	15.4
SV	2	599.4	18.3	1.186	17.8
WF	2	314.6	9.6	0.448	6.7
Error	18	268.9	8.2	0.574	8.6
Total	26	3276.9	100	6.650	100

4. Microstructural Analysis of Machined Surfaces

SEM examination of machined surfaces was conducted on a JEOL JSM-6490LV scanning electron microscope at 20 kV accelerating voltage. Representative micrographs were obtained from three experiments: the reference condition (Ton=135 µs, SV=20 V — high energy, expected severe damage), the GRA-optimal condition, and the low-energy condition (Ton=105 µs, SV=40 V — minimum expected damage). Cross-sectional specimens for recast layer measurement were prepared by precision sectioning, cold mounting in epoxy, and metallographic polishing to 0.05 µm alumina finish, followed by etching with modified Kalling's reagent to reveal the microstructure.

Recast layer thickness — the re-solidified material layer at the machined surface formed when molten material expelled from the crater partially adheres to the workpiece surface before being flushed away by the dielectric — ranged from 4.2 µm (Ton=105 µs, SV=40 V) to 14.3 µm (Ton=135 µs, SV=20 V). The GRA-optimal condition produced a recast layer of 9.1 µm — within acceptable limits for aerospace component post-machining grinding removal (typically 20–30 µm grinding allowance). EDS mapping of the recast layer at the optimal condition revealed zinc enrichment (3.8 wt%) from the wire coating and slight depletion of niobium (from 4.9 wt% in base IN718 to 3.2 wt% in recast layer), consistent with preferential niobium carbide dissolution during the EDM thermal cycle.

Micro-crack density, quantified as total crack length per unit area in the SEM micrograph at 500× magnification, shows a statistically significant inverse correlation with servo voltage (Pearson $r = -0.78$, $p < 0.01$) and positive correlation with Ton ($r = 0.83$, $p < 0.01$). The inverse relationship with servo voltage reflects the gap control mechanism: higher servo voltage maintains a larger inter-electrode gap, reducing the probability of arc discharge (as opposed to spark discharge), which is the primary cause of macro-crack formation due to its sustained high-energy thermal input. These microstructural findings are consistent with literature on EDM surface integrity of nickel superalloys reported by Rahman et al. (2012) and Hewidy et al. (2005).

5. Discussion

The GRA-identified optimal parameter combination (Ton=120 µs, Toff=55 µs, SV=30 V, WF=6 m/min) represents a balanced operating point on the MRR-Ra-KW trade-off surface that no single-response optimisation could achieve. The 39.2% contribution of Ton to MRR variance is consistent with the fundamental EDM energy equation $E = V \times I \times Ton$, where discharge energy scales linearly with pulse duration at constant voltage and current. The relatively lower contribution of wire feed rate (9.6% for MRR) suggests that within the tested range, fresh wire supply is not the rate-limiting step in the sparking process — an important practical finding for machining shops seeking to reduce wire consumption costs by operating at lower feed rates without significant productivity loss.

The GRG-based optimisation framework's assumption of equal weighting across the three responses may not reflect the priorities of all application contexts. For turbine blade profiles where dimensional accuracy is paramount, kerf width would receive higher weighting; for rotating fatigue-critical discs, Ra and recast layer minimisation (correlated with SV and Ton) would receive priority. The GRG weighting can be adjusted to reflect application-specific requirements using the preference-based approach described by Datta et al. (2008), enabling the experimental database generated in this study to serve as a basis for application-specific optimisation without additional experimentation.

The RSM regression model's high R^2 values (0.928–0.961) and the close agreement between RSM-predicted optimum and GRA-identified optimum provide mutual validation of both methods and suggest that the regression models are suitable for interpolation within the tested parameter space. Extrapolation beyond the tested parameter bounds — particularly at Ton > 135 µs or Toff < 45 µs — is not recommended, as the polynomial model's quadratic terms may not capture the non-linear behaviour at extreme discharge energies where wire breakage probability increases significantly.

6. Conclusion

This study has demonstrated the effective application of integrated Taguchi-GRA-RSM methodology for multi-response optimisation of WEDM of Inconel 718 superalloy. The principal conclusions are: (i) Pulse-on time is the dominant factor for both MRR (PCR 39.2%) and Ra (PCR 51.4%), confirming its primacy in the energy delivery mechanism; (ii) the GRA-optimal parameter combination (Ton=120 µs, Toff=55 µs, SV=30 V, WF=6 m/min) achieves MRR of 42.6 mm^3/min, Ra of 1.84 µm, and KW of 0.312 mm — a balanced multi-response optimum; (iii) recast layer thickness at the optimal condition (9.1 µm) is within post-machining grinding allowance for aerospace components; (iv) RSM regression models with $R^2>0.92$ provide reliable predictive capability across the parameter space. Future work should investigate the effect of dielectric additives (nano-powders, surfactants) on surface integrity and explore higher Ton ranges accessible with thicker wire diameters.

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