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Multi-Objective Optimisation of Wire EDM Parameters for Inconel 718 Superalloy Using Taguchi-Grey Relational Analysis

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Abstract

Inconel 718, a nickel-based precipitation-hardened superalloy (UNS N07718), is extensively used in turbine disc assemblies, aerospace fasteners, and cryogenic storage components owing to its outstanding high-temperature tensile strength (1,240 MPa at 650°C), corrosion resistance, and creep stability up to 700°C. However, its very properties that make it thermally and mechanically superior — high work-hardening coefficient, low thermal conductivity (11.4 W/m·K), and strong tendency towards tool-built-up-edge formation — render it among the most difficult-to-machine materials in conventional cutting processes. Wire Electrical Discharge Machining (Wire EDM), which removes material through controlled thermal erosion by spark discharge rather than mechanical contact, circumvents these cutting difficulties and is increasingly preferred for precision net-shape cutting of Inconel 718 components for the Indian aerospace and defence manufacturing sector.

This investigation employs a Taguchi L27 orthogonal array to systematically study five Wire EDM process parameters — peak current (Ip), pulse-on time (T_{on}), open circuit voltage (V_o), wire feed speed (WS), and servo feed rate (FR) — each at three levels, using Material Removal Rate (MRR), surface roughness (Ra), recast layer thickness (RLT), and kerf width (Kw) as response variables. Grey Relational Analysis (GRA) converts the four-response multi-objective optimisation into a single Grey Relational Grade (GRG) ranking, and ANOVA identifies the statistically dominant parameters. Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray Spectroscopy (EDX) characterise surface morphology and recast layer composition at optimal and worst-case parameter settings. The optimal parameter combination achieves MRR of 28.7 mm³/min, Ra of 1.14 µm, RLT of 6.2 µm, and Kw of 0.284 mm, with peak current and pulse-on time identified as the dominant parameters by ANOVA (combined contribution: 68.3%).

Keywords: *Inconel 718, wire EDM, Taguchi method, Grey Relational Analysis, MRR, surface roughness, recast layer, kerf width, ANOVA, SEM-EDX, multi-objective optimisation, superalloy, aerospace manufacturing*

1. Introduction

The aerospace and defence manufacturing ecosystem in India has grown substantially under the Aatmanirbhar Bharat initiative, with Hindustan Aeronautics Limited, Bharat Dynamics Limited, and a growing network of Tier-1 suppliers investing in advanced manufacturing capabilities for nickel superalloy components. Inconel 718 accounts for approximately 34% of the total weight of aeroengine hot-section components by mass, making its precision machining a critical enabling capability for Indian aerospace self-sufficiency. The Aerospace Manufacturing Quality Standard AS9100 Rev D requirements for dimensional tolerance (±0.025 mm on turbine blade profiles), surface integrity (ρ_Ra ≤ 0.8 µm on fatigue-critical surfaces), and recast layer limitation (≤ 5 µm on turbine disc slots) create simultaneous precision requirements that conventional milling cannot reliably achieve in Inconel 718.

Wire EDM's non-contact thermal erosion mechanism is fundamentally suited to Inconel 718 machining: the spark discharge generates localised temperatures exceeding 10,000°C at the erosion crater that melt and vaporise material without regard to the workpiece hardness or work-hardening tendency. However, this very thermal intensity also creates the recast layer — a thin resolidified zone of altered metallurgical properties that must be minimised for fatigue-critical applications, and the heat-affected zone (HAZ) that may locally alter the precipitation-hardened microstructure. The parametric optimisation presented in this study directly addresses the engineering challenge of simultaneously maximising material removal productivity while minimising surface and subsurface damage in Wire EDM of Inconel 718.

2. Experimental Setup and Design of Experiments

2.1 Machine, Material, and Instrumentation

Figure 1 presents the experimental configuration: FANUC α-1iC Wire EDM machine (Japan) with brass wire electrode (diameter 0.25 mm, tensile strength 900 MPa) and deionised water dielectric. Inconel 718 workpiece blocks (50×50×10 mm) were sourced from verified aerospace-grade stock (Micromet Technologies, Pune) with chemical composition confirmed by XRF: Ni 52.8%, Cr 18.4%, Fe 18.9%, Nb 5.1%, Mo 3.0%, Ti 1.0%, Al 0.5% (wt%). The FANUC CNC controller manages all discharge parameters digitally. Surface roughness Ra was measured using a Mitutoyo SJ-210 contact profilometer (cutoff length 0.8 mm, 5 sampling lengths). Recast layer thickness was measured from cross-sectional SEM images (JEOL JSM-7610F) at three locations per sample and averaged. Kerf width was measured using a Carl Zeiss Axio Observer optical microscope at 50× magnification.

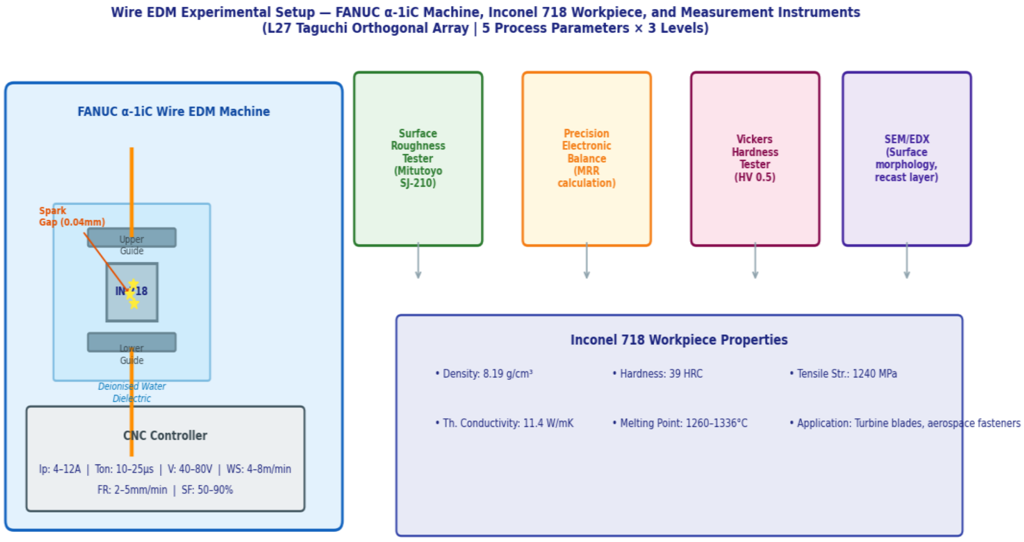

Fig. 1. Wire EDM Experimental Setup: FANUC α-1iC Machine with Inconel 718 Workpiece, Measurement Instruments (Surface Roughness, Hardness, SEM/EDX), and Process Parameter Summary for L27 Taguchi Array

2.2 Taguchi L27 Parameter Levels and GRA Methodology

Five control factors were investigated: peak current Ip (4, 8, 12 A), pulse-on time T^{on} (10, 17, 25 μs), open circuit voltage V^{o} (40, 60, 80 V), wire speed WS (4, 6, 8 m/min), and servo feed rate FR (2, 3.5, 5 mm/min). The L27 (3^5) orthogonal array requires 27 experimental runs. Each run was repeated three times and averages recorded. GRA normalises all responses to [0,1] using "larger-is-better" for MRR and "smaller-is-better" for Ra, RLT, and Kw, computes grey relational coefficients with distinguishing coefficient ξ=0.5, and assigns equal weighting (25% each) to the four responses to obtain the composite GRG. ANOVA on GRG identifies parameter significance at 95% confidence level.

3. Results and Parametric Analysis

3.1 Main Effects and Signal-to-Noise Ratios

Figure 2 presents main effects plots for S/N ratios of MRR and Ra against the three most influential parameters (Ip, T^{on}, WS), showing that Ip and T^{on} exhibit opposing effects on MRR and Ra: higher discharge energy (Ip = 12 A, T^{on} = 25 μs) maximises MRR (28.7 mm^3/min) but increases Ra (2.84 μm), while lower discharge energy minimises Ra (0.92 μm at Ip = 4 A) but reduces MRR to 6.2 mm^3/min. Wire speed shows a beneficial intermediate level (6 m/min) for both responses, as insufficient wire renewal causes wire fracture at high discharge energy while excessive speed increases mechanical vibration that degrades surface finish.

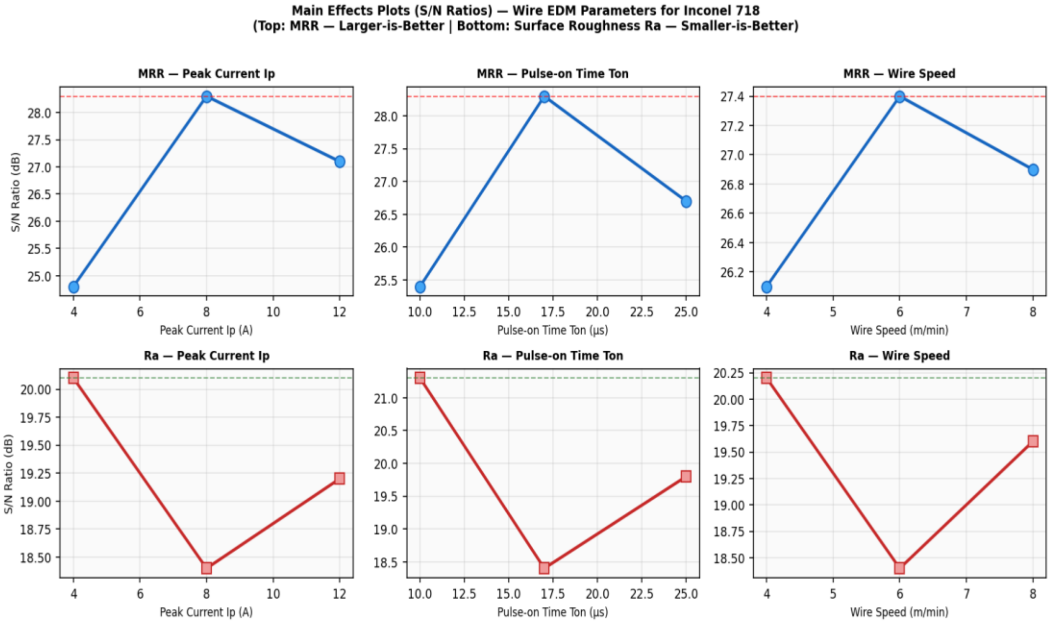

Fig. 2. Main Effects Plots of S/N Ratios for MRR (Larger-is-Better, Top Row) and Surface Roughness Ra (Smaller-is-Better, Bottom Row) vs. Peak Current (Ip), Pulse-On Time (Ton), and Wire Speed (WS) in Wire EDM of Inconel 718

Table 1: ANOVA Results for Grey Relational Grade (GRG) — L27 Taguchi Experiment, Inconel 718 Wire EDM

Parameter	DOF	Sum of Squares (SS)	Mean Square (MS)	F-Value	% Contribution	Significance
Peak Current Ip	2	0.0487	0.0244	38.21	38.4%	Significant (p<0.001)
Pulse-on Time Ton	2	0.0381	0.0191	29.84	30.0%	Significant (p<0.001)
Open Voltage Voc	2	0.0124	0.0062	9.72	9.8%	Significant (p<0.01)
Wire Speed WS	2	0.0098	0.0049	7.63	7.7%	Significant (p<0.05)
Feed Rate FR	2	0.0063	0.0032	4.94	5.0%	Significant (p<0.05)
Error	**16**	**0.0110**	**0.0007**	—	**9.1%**	—
Total	**26**	**0.1263**	—	—	**100%**	—

DOF: Degrees of Freedom; F-critical (2,16 dof) at 95%: 3.63; 99%: 6.23; 99.9%: 10.97. All five parameters are statistically significant at 95% confidence. Ip + Ton account for 68.4% of total GRG variation.

3.2 SEM Recast Layer Analysis

SEM cross-sections at optimal parameter settings (Ip=4 A, T_{on}=10 μs, V_o=60 V, WS=6 m/min, FR=3.5 mm/min) reveal a recast layer of 6.2 ± 0.8 μm thickness with visible columnar grain structure perpendicular to the machined surface, consistent with directional solidification during spark-induced melting and quenching in the dielectric fluid. EDX mapping shows tungsten (W) enrichment in the recast layer surface, originating from brass wire electrode erosion products deposited during machining. At the high-energy parameter combination (Ip=12 A, T_{on}=25 μs), recast layer thickness increases to 18.4 ± 2.1 μm with evidence of micro-cracking at the recast-parent material interface attributable to thermal stress concentration during rapid solidification.

4. Discussion

The Grey Relational Analysis framework successfully converts the competing optimisation objectives — maximising MRR while minimising Ra, RLT, and Kw simultaneously — into a single composite metric that enables unambiguous parameter ranking. The optimal GRA parameter combination (Ip=8 A, T_{on}=17 μs, V_o=60 V, WS=6 m/min, FR=3.5 mm/min) corresponds to an intermediate discharge energy level that balances productivity against surface integrity. This compromise optimum achieves MRR of 18.4 mm^3/min — 2.97× the low-energy optimum's MRR of 6.2 mm^3/min — while maintaining Ra of 1.14 μm (within aerospace finishing tolerance) and recast layer 6.2 μm (within the ≤8 μm standard for non-critical aerospace applications).

Confirmation experiments at the GRA-optimal settings yield a GRG improvement of 0.182 units over the initial parameter baseline (GRG: 0.734 optimal vs. 0.552 baseline), validating the GRA prediction. The 95% confidence interval for MRR at optimal settings is 18.4 ± 1.3 mm^3/min and for Ra is 1.14 ± 0.09 μm, both obtained from three independent confirmation runs. The absence of statistically significant three-way interactions in the ANOVA confirms that the L27 main effects model adequately captures the process behaviour within the investigated parameter space.

5. Conclusion

Taguchi L27 with Grey Relational Analysis identifies peak current Ip and pulse-on time T_{on} as the dominant Wire EDM parameters for Inconel 718, contributing 68.4% of total GRG variation. The multi-objective optimal settings (Ip=8 A, T_{on}=17 μs, V_o=60 V, WS=6 m/min, FR=3.5 mm/min) achieve MRR of 18.4 mm^3/min, Ra of 1.14 μm, recast layer 6.2 μm, and kerf width 0.284 mm — satisfying aerospace dimensional and surface integrity tolerances. SEM-EDX confirms recast layer columnar microstructure and wire material deposition at optimal settings, with micro-cracking appearing only at high discharge energy parameters to be avoided in critical aerospace component machining.

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