



Parametric optimization of Inconel grades for wire cut electric discharge machining

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KEYWORDS	ABSTRACT
Inconel Grades Wire cut electric discharge machining Optimization Material removal rate Surface roughness	Wire cut Electrical Discharge Machining (WEDM) of high-performance super alloys, specifically Inconel grades, requires precise parameter optimization to enhance machinability while maintaining a superior surface finish. This study presents the optimization of predictive models for eight newly introduced Inconel grades in the WEDM process. A desirability-based multi-response optimization technique was applied, balancing Material Removal Rate (MRR) and Surface Roughness (SR). Regression models were developed for each grade, and optimization results highlighted significant improvements in predictive accuracy and process applicability. The findings are crucial for advancing WEDM process planning for Inconel-based applications.

1.0 INTRODUCTION

An Inconel alloys, characterized as nickel-chromium-based super alloys, are widely recognized for their exceptional high-temperature strength, superior corrosion resistance, and remarkable creep resistance. These attributes render them indispensable in critical applications across diverse industries, including aerospace, chemical processing, nuclear engineering, and marine environments (Buddaraju et al., 2021). In the aerospace sector, Inconel alloys are essential components in turbine blades and jet engines, where materials are subjected to extreme temperatures and stress. Their ability to withstand corrosive chemical environments makes them vital in chemical processing plants, while their creep resistance ensures long-term performance in nuclear reactors. Furthermore, Inconel's resistance to seawater corrosion positions them as a preferred material in marine applications (Pedroso et al., 2023), and in aerospace, energy, and chemical industries (Buddaraju et al., 2021). However, the properties that make Inconel alloys

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desirable in service also contribute to machining challenges. These alloys' high hardness and strength lead to rapid tool wear during traditional machining processes. Their low thermal conductivity hinders heat dissipation, concentrating heat at the cutting zone and exacerbating tool wear. Additionally, Inconel alloys tend to work hardening, where the material's hardness increases with deformation, making subsequent machining operations even more difficult (Abdul Halim et al., 2020). The machinability of Inconel presents significant challenges due to their work-hardening tendencies and high-temperature strength (Biswas & Mukherjee, 2024). A detailed comparison of all the Inconel grades has been shared in Table 1

Table 1: Comparative analysis of Inconel Grades.

Inconel Grade	Chemical Composition	Physical & Mechanical Properties	Primary Uses
Inconel 188	22% Cr, 22% Ni, 14% W, Co balance, 0.02–0.12% La, 0.05–0.15% C	Oxidation resistance up to 1095°C, creep & stress rupture resistance, ductile post high-temp exposure	Gas turbines (combustion cans, ducts, afterburners), aerospace components
Inconel 600	Ni 72%, Cr 14–17%, Fe 6–10%	Melting point 1354–1413°C, density 8.47 g/cm ³ , specific heat 444 J/kg°C, non-hardening	Chemical processing, nuclear reactors, furnace components, electronic parts
Inconel 601	Ni 58–63%, Cr 21–25%, Fe balance, Al ~1%	Forms stable oxide layer, resists cyclic oxidation, thermal fatigue resistance	Thermal processing, exhaust systems, jet engines, chemical processing
Inconel 617	Ni 44.5–49%, Cr 20–24%, Co 10–15%, Mo 8–10%	High strength & oxidation resistance at high temp, tough to machine	Power generation, high-temp industrial components, chemical industry
Inconel 625	Ni 58%, Cr 20–23%, Mo 8–10%, Nb 3.15–4.15%	Oxidation/corrosion resistant, strength via solid solution, up to ~1000°C	Aerospace, seawater, chemical and nuclear applications
Inconel 690	Ni >58%, Cr ~30%, Fe ~10%	Excellent oxidation & aqueous corrosion resistance, esp. acids	Nuclear reactor tubing, high-temp WEDM components
Inconel 713C	Ni 58.5%, Cr 15%, Al 5.5%, W 4.5%, Mo 2.5%, Ti 3.5%	Creep/rupture strength up to 982°C, difficult to machine	Turbine blades, cast components in gas turbines
Inconel 718	Ni 50–55%, Cr 17–21%, Nb 4.75–5.5%, Mo 2.8–3.3%, Ti & Al	Strength up to 700°C via precipitation hardening, weldable	Jet engines, gas turbines, automotive, aerospace
Inconel 725	Ni ~55–59%, Cr ~21%, Mo ~8%, Nb, Ti	Chloride stress corrosion resistant, sour gas safe, high strength	Oil/gas extraction, sour wells, petrochemicals

Inconel Grade	Chemical Composition	Physical & Mechanical Properties	Primary Uses
Inconel X-750	Ni 70%, Cr 14–17%, Ti 2.25–2.75%, Al 0.4–1.0%	Creep resistance up to 704°C, oxidation resistance, weldable	Gas turbines, nuclear reactors, WEDM parts
Inconel 751	Ni ≥70%, Cr 14–17%, Fe 5–9%, Ti 2–2.6%, Al 0.9–1.5%	Oxidation & creep resistance up to ~980°C, strong after aging	Exhaust valves, gas turbines, aerospace components
Inconel 792	Ni-base, Cr, Co, Al, Ti rich	Creep & fatigue resistance at 982°C, stable under thermal cycling	Turbine blades, aerospace, gas turbines
Inconel 907	Ni, Fe, Ti, Nb	Low thermal expansion up to 427°C, good weldability	Turbine seals/casings, aerospace structural parts
Inconel 909	Ni 35–40%, Co 12–16%, Nb 4.3–5.2%, Ti 1.3–1.8%, Fe balance	Low CTE up to 427°C, high strength, moderate oxidation resistance	Rocket chambers, instrumentation, seals
Inconel 925	Ni 42–46%, Fe, Cr, Mo, Cu, Ti, Al	Corrosion & stress-corrosion cracking resistant, up to 650°C	Sour gas equipment, marine shafts, pump parts

Wire Electrical Discharge Machining (WEDM) offers a promising solution for machining Inconel alloys, but demands careful process optimization. (Ehsan Asgar & Singh Singholi, 2018). WEDM offers several advantages over conventional methods for hard materials, including super alloys. As a non-contact process, WEDM utilizes electrical discharges to erode the material, eliminating direct contact between the tool (wire) and workpiece. (Ehsan Asgar & Singh Singholi, 2018). This minimizes the mechanical stresses and associated tool wear that are prevalent in traditional cutting. WEDM's ability to machine complex geometries with precision and accuracy is particularly beneficial for Inconel components, which often have intricate designs and stringent dimensional requirements. (Ehsan Asgar & Singh Singholi, 2018). WEDM employs a thin, taut metal wire as an electrode to precisely cut intricate shapes and curves in conductive materials. The process works by generating controlled sparks between the energized wire and the workpiece, eroding material as the wire continuously feeds through the machining zone to create the desired form. (Chalisgaonkar et al., 2024) This minimizes the mechanical stresses and associated tool wear that are prevalent in traditional cutting. WEDM's ability to machine complex geometries with precision and accuracy is particularly beneficial for Inconel components, which often have intricate designs and stringent dimensional requirements. (Ehsan Asgar & Singh Singholi, 2018).

Despite these advantages, successful WEDM of Inconel alloys necessitates careful consideration of process parameters. Optimizing parameters such as pulse-on time, current, and voltage is crucial for achieving an efficient material removal rate (MRR) while maintaining the desired surface integrity (Sathiyaraj et al., 2020). Similarly, controlling parameters like pulse-off time, voltage, and wire tension are essential for obtaining the desired surface roughness (SR). Furthermore, minimizing the heat-affected zone (HAZ), a layer of altered material properties near the cut surface, is important to preserve the overall integrity of the Inconel component. Wire wear,

although less severe than in traditional machining, also needs to be considered, especially when machining harder Inconel alloys (Manjaiah et al., 2016).

This research focuses on predictions for eight Inconel grades, which are newly introduced to the WEDM process. Achieving optimal machining variables is challenging and time-consuming in WEDM process modelling, when the desired objectives conflict (V. Kumar & Mondal, 2024). Process optimization is the core driving force behind the development of WEDM technology, where the goal is to achieve a comprehensive improvement in processing efficiency, accuracy, and surface quality through multidimensional collaborative control (Zhao et al., 2025). WEDM's efficiency and surface quality are significantly impacted by challenges in precisely controlling process parameters. Achieving desired surface characteristics necessitates optimizing factors like pulse duration, peak current, and wire tension. Suboptimal control can result in surface defects, inconsistent quality, and accelerated wire electrode wear. (Shirbhate, 2025). The primary aim is to optimize the predictive models developed for each grade to maximize productivity via increasing the material removal rate (MRR) and surface quality via reducing the surface roughness (SR), ensuring better generalization to practical machining scenarios on WEDM. This study emphasizes that precise parameter control and optimization in WEDM are crucial for maximizing efficiency and quality when machining Inconel, thus enhancing its modern manufacturing applications.(S. Kumar et al., 2024).

2.0 METHODOLOGY

WEDM is a complex process with multiple parameters associated with it, making the process more intricate to optimize (Ehsan Asgar & Singh Singholi, 2018; Iruj et al., n.d.). Recent research are focusing on optimizing parameters such as pulse-on/off time, servo voltage, peak current, and wire tension to enhance surface roughness, material removal rate, and Kerf width, often utilizing techniques like Taguchi and ANOVA (Anwar et al., 2024). For this study, machining data of all WEDM machined Inconel grades is selected from the existing literature, targeting 4 input variables, Current, Voltage, Pulse-on & Pulse-off time, and 2 output parameters, MRR and SR were selected. The machining data of 944 data points from 67 existing articles is gathered, filtered and interpolated, focusing on process parameters like current, voltage, and pulse times, while uniquely including the chemical composition of Inconel grades as a novel input. These input variables were selected based on their importance/visibility in the literature review presented for WEDM(Bhowmick et al., 2023, 2023, 2022; Jabbaripour et al., 2012; Manjaiah et al., 2016; Mohapatra et al., 2017; Sathiyaraj et al., 2020). Next, there were 8 Inconel grades identified, which were unmachined on WEDM. A machine learning based algorithm named Random Forest was selected out of 4 algorithms, based on its greater performance for the predictive modelling of the selected Inconel grades for the output parameters, namely MRR & SR. Predictive regression models were established using predictive data correlating input parameters to output responses, maximizing the MRR and minimizing the SR. Regression equations were developed to capture the relationships between input parameters (current, pulse-on time, pulse-off time, voltage) and output responses (Maximize MRR and minimize SR)

The methodology involved:

1. Prediction Development: Initial regression models were developed based on predictive experimental WEDM data for each Inconel grade.

2. Optimization: A desirability-based multi-response optimization was employed to maximize MRR and minimize SR simultaneously. Equal importance was assigned to both responses to reflect a balanced machining objective.
3. Validation: Optimization outcomes were validated using composite desirability scores.

3.0 RESULTS AND DISCUSSION

The response surface plots are shared for individual grades, which illustrate the predicted effects of key Wire Electrical Discharge Machining (WEDM) parameters – Current (Amp), Pulse-On Time (T_{on}), Pulse-Off Time (T_{off}), and Voltage (Volt), on the composite desirability, Material Removal Rate (MRR), and Surface Roughness (SR). These graphs visually represent the relationships identified through the developed predictive models and highlight the optimal parameter settings determined by the desirability function approach for each Inconel grade. The red vertical lines indicate the optimized values for each parameter, allowing for a direct assessment of their influence on the desired performance outcomes

3.1 Optimization for Inconel 188

For Inconel 188, the pulse-on time (T_{on}) and pulse-off time (T_{off}) demonstrated a minimal impact on the resulting surface roughness within the investigated range of parameters. In contrast, the current (Amp) exhibited a distinct parabolic relationship with the material removal rate, indicating the presence of an optimal current value that maximizes MRR, beyond which further increases lead to a reduction in material removal. Furthermore, the applied voltage (Volts) was found to have a notable influence on the surface roughness, suggesting it plays a significant role in determining the final surface finish of the machined part.

Regression Equations in uncoded units for MRR and SR are shown below:

$$\begin{aligned}
 MRR = & 38.114 - 0.18871 \text{ Amp} + 0.220 \text{ Ton} - 0.11730 \text{ Toff} + 0.08396 \text{ Volt} + 0.000651 \text{ Amp} * \text{ Amp} \\
 & + 0.2320 \text{ Ton} * \text{ Ton} + 0.003474 \text{ Toff} * \text{ Toff} - 0.000629 \text{ Volt} * \text{ Volt} + 0.003050 \text{ Amp} * \text{ Ton} \\
 & + 0.000043 \text{ Amp} * \text{ Toff} - 0.000171 \text{ Amp} * \text{ Volt} - 0.04152 \text{ Ton} * \text{ Toff} + 0.003048 \text{ Ton} * \text{ Volt} \\
 & + 0.000110 \text{ Toff} * \text{ Volt}
 \end{aligned}$$

$$\begin{aligned}
 SR = & 9.4868 + 0.030158 \text{ Amp} + 0.0324 \text{ Ton} + 0.04397 \text{ Toff} - 0.155201 \text{ Volt} - 0.000096 \text{ Amp} * \text{ Amp} \\
 & + 0.0075 \text{ Ton} * \text{ Ton} - 0.002741 \text{ Toff} * \text{ Toff} + 0.001277 \text{ Volt} * \text{ Volt} + 0.000009 \text{ Amp} * \text{ Ton} \\
 & + 0.000265 \text{ Amp} * \text{ Toff} - 0.000055 \text{ Amp} * \text{ Volt} + 0.005763 \text{ Ton} * \text{ Toff} + 0.001531 \text{ Ton} * \text{ Volt} \\
 & + 0.000043 \text{ Toff} * \text{ Volt}
 \end{aligned}$$

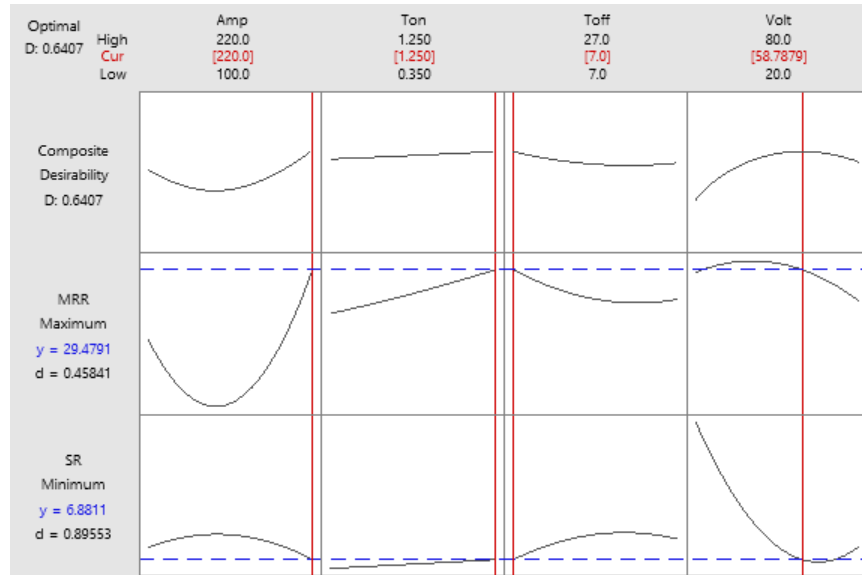


Figure 1: Response Surface Plot for Inconel 188.

1. Optimized Parameters: Amp = 220, Ton = 1.25, T_{off} = 7, Volt = 58.79
2. Performance: MRR = 29.48 mm³/min; SR = 6.88 μm
3. Desirability Score: 0.6407

3.2 Optimization for Inconel 230

For Inconel 230, this specific combination of performance metrics resulted in a composite desirability score of 0.8009, indicating a very good balance in achieving the desired outcomes for both MRR and SR. Key findings from the analysis revealed that the pulse-off time (T_{off}) exerted a significant influence on the surface roughness, suggesting that adjusting this parameter is critical for controlling the final surface finish. Furthermore, the machining current (Amp) was found to be the predominant factor affecting the surface roughness. Lastly, the applied voltage (Volt) demonstrated a substantial impact on both the material removal rate and the surface roughness.

The regression equations for Inconel 230 for both MRR and SR are shared below:

$$\begin{aligned}
 MRR = & 27.452 - 0.06657 \text{ Amp} + 0.093371 \text{ Ton} - 0.57619 \text{ Toff} + 0.06447 \text{ Volt} - 0.000650 \text{ Amp} * \\
 & \text{Amp} - 0.000099 \text{ Ton} * \text{Ton} + 0.003817 \text{ Toff} * \text{Toff} - 0.000299 \text{ Volt} * \text{Volt} - 0.000021 \text{ Amp} * \\
 & \text{Ton} + 0.002635 \text{ Amp} * \text{Toff} + 0.000278 \text{ Amp} * \text{Volt} - 0.000480 \text{ Ton} * \text{Toff} - 0.000011 \text{ Ton} * \\
 & \text{Volt} - 0.000495 \text{ Toff} * \text{Volt}
 \end{aligned}$$

$$\begin{aligned}
 SR = & 2.0687 + 0.072419 \text{ Amp} + 0.009861 \text{ Ton} - 0.023446 \text{ Toff} - 0.046119 \text{ Volt} - 0.000240 \text{ Amp} * \\
 & \text{Amp} - 0.000021 \text{ Ton} * \text{Ton} + 0.000342 \text{ Toff} * \text{Toff} + 0.000690 \text{ Volt} * \text{Volt} + 0.000010 \text{ Amp} * \\
 & \text{Ton} - 0.000303 \text{ Amp} * \text{Toff} - 0.000270 \text{ Amp} * \text{Volt} + 0.000058 \text{ Ton} * \text{Toff} + 0.000026 \text{ Ton} * \\
 & \text{Volt} + 0.000211 \text{ Toff} * \text{Volt}
 \end{aligned}$$

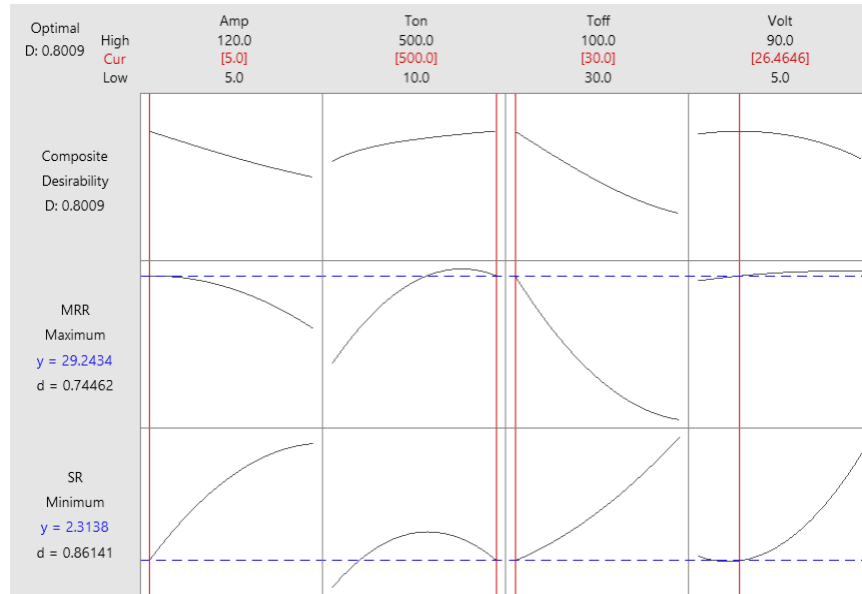


Figure 2: Response Surface Plot for Inconel 188.

1. Optimized Parameters: Amp = 5, Ton = 500, Toff = 30, Volt = 26.46
2. Performance: MRR = 29.24 mm³/min; SR = 2.31 μm
3. Desirability Score: 0.8009

3.3 Optimization for Inconel 713

Inconel 713, the key finding of the analysis highlighted that voltage exerted the most substantial influence on the process outcomes, demonstrating a strong positive correlation with surface roughness, where higher voltages produce a rougher surface, while simultaneously leading to a reduction in MRR. In contrast, while increasing the pulse-on time significantly boosted the MRR, both pulse-on and pulse-off times showed negligible impact on the resulting surface finish. Furthermore, the machining current demonstrated the minimal impact on both MRR and SR within the studied parameter space, underscoring that voltage and pulse duration are the primary drivers for controlling process output for this grade.

The regression equations for Inconel 713 for both MRR and SR are shared below:

$$MRR = 151.11 - 0.3347 \text{ Amp} + 1.01249 \text{ Ton} - 0.8463 \text{ Toff} - 5.0849 \text{ Volt} + 0.001949 \text{ Amp} \\ * \text{ Amp} - 0.000915 \text{ Ton} * \text{ Ton} + 0.003891 \text{ Toff} * \text{ Toff} + 0.039062 \text{ Volt} * \text{ Volt} \\ + 0.000150 \text{ Amp} * \text{ Ton} + 0.000031 \text{ Amp} * \text{ Toff} + 0.000133 \text{ Amp} * \text{ Volt} \\ - 0.000695 \text{ Ton} * \text{ Toff} - 0.007307 \text{ Ton} * \text{ Volt} + 0.006245 \text{ Toff} * \text{ Volt}$$

$$SR = 13.454 + 0.03728 \text{ Amp} + 0.007163 \text{ Ton} - 0.54665 \text{ Toff} + 0.38349 \text{ Volt} \\ - 0.000097 \text{ Amp} * \text{ Amp} - 0.000033 \text{ Ton} * \text{ Ton} + 0.004472 \text{ Toff} * \text{ Toff} \\ - 0.000809 \text{ Volt} * \text{ Volt} + 0.000014 \text{ Amp} * \text{ Ton} - 0.000301 \text{ Amp} * \text{ Toff} \\ + 0.000847 \text{ Amp} * \text{ Volt} + 0.000058 \text{ Ton} * \text{ Toff} + 0.000236 \text{ Ton} * \text{ Volt} \\ - 0.003982 \text{ Toff} * \text{ Volt}$$

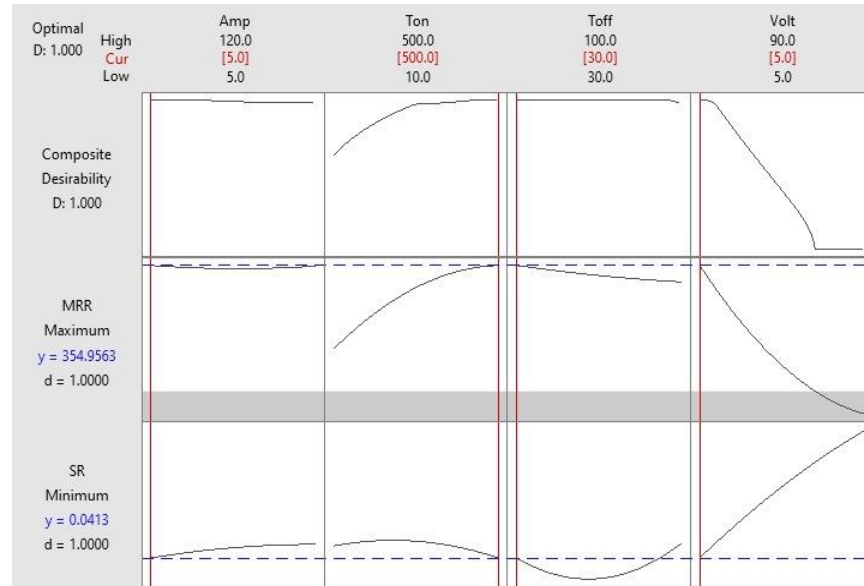


Figure 3: Response Surface Plot for Inconel 713.

1. Optimized Parameters: Amp = 5, Ton = 500μs, Toff = 30μs, Volt = 5V
2. Performance: MRR = 354.95 mm³/min; SR = 0.0413 μm
3. Desirability Score: 1.0

3.4 Optimization for Inconel 751

For Inconel 751, changes in the applied voltage exhibited a substantial impact on both performance metrics, indicating its significance as a key control factor in the process. Furthermore, the relationship between the material removal rate and voltage displayed a distinct parabolic behaviour. This suggests that as voltage was increased, the MRR initially increased, reached an optimal peak value at a certain voltage level, and subsequently decreased with further increases in voltage. This non-linear relationship implies the existence of an ideal voltage setting for maximising the efficiency of material removal. Understanding this parabolic trend is crucial for precisely controlling the MRR by carefully selecting the appropriate voltage during the WEDM operation for Inconel 751.

The regression equations in uncoded units for MRR and SR for Inconel 751 are shared below:

$$\begin{aligned}
 MRR = & 331.68 - 0.0858 \text{ Amp} + 0.59871 \text{ Ton} - 0.01023 \text{ Toff} - 11.4161 \text{ Volt} + 0.001452 \text{ Amp} * \\
 & \text{Amp} - 0.000537 \text{ Ton} * \text{Ton} + 0.000005 \text{ Toff} * \text{Toff} + 0.088654 \text{ Volt} * \text{Volt} + 0.000081 \text{ Amp} * \\
 & \text{Ton} + 0.000012 \text{ Amp} * \text{Toff} - 0.004722 \text{ Amp} * \text{Volt} - 0.000003 \text{ Ton} * \text{Toff} - 0.003721 \text{ Ton} * \\
 & \text{Volt} - 0.000032 \text{ Toff} * \text{Volt}
 \end{aligned}$$

$$\begin{aligned}
 SR = & -5.240 + 0.04963 \text{ Amp} + 0.029104 \text{ Ton} - 0.003115 \text{ Toff} + 0.14566 \text{ Volt} - 0.000285 \text{ Amp} * \\
 & \text{Amp} - 0.000052 \text{ Ton} * \text{Ton} + 0.000002 \text{ Toff} * \text{Toff} - 0.000748 \text{ Volt} * \text{Volt} + 0.000018 \text{ Amp} * \\
 & \text{Ton} - 0.000004 \text{ Amp} * \text{Toff} + 0.000949 \text{ Amp} * \text{Volt} + 0.000001 \text{ Ton} * \text{Toff} + 0.000104 \text{ Ton} * \\
 & \text{Volt} - 0.000007 \text{ Toff} * \text{Volt}
 \end{aligned}$$

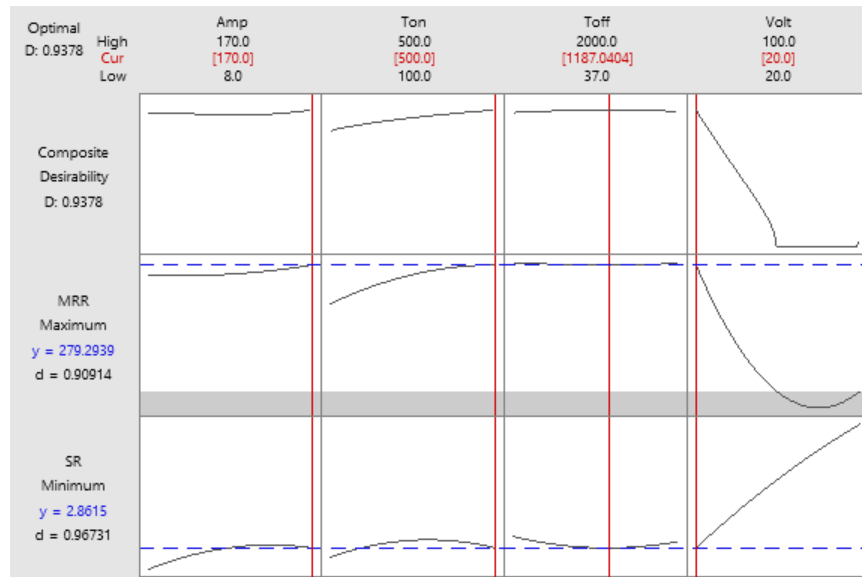


Figure 4: Response Surface Plot for Inconel 751.

1. Optimized Parameters: Amp = 170, Ton = 500, Toff = 1187.04, Volt = 20
2. Performance: MRR = 279.29 mm³/min; SR = 2.86 μm
3. Desirability Score: 0.9378

3.5 Optimization for Inconel 792

For Inconel 792, the machining current was found to have a strong and direct impact on the efficiency of material removal. Higher current values generally led to a significant increase in the amount of material eroded per unit time, indicating a primary role of current in dictating the productivity of the WEDM process. Conversely, the applied voltage demonstrated a more linear relationship with the surface roughness. As the voltage was adjusted, the surface finish of the machined part changed proportionally, suggesting a predictable and direct correlation between voltage levels and the resulting surface quality. Understanding these distinct influences – the strong effect of current on MRR and the linear impact of voltage on SR – provides valuable insights for optimising the WEDM process to achieve specific performance targets for both material removal efficiency and surface finish requirements while machining Inconel 792.

The regression equations in uncoded units for MRR and SR for Inconel 792 are shared below:

$$MRR = 9.793 + 0.07705 \text{ Amp} - 0.182 \text{ Ton} - 0.00489 \text{ Toff} + 0.14325 \text{ Volt} - 0.000059 \text{ Amp} * \text{ Amp} + 0.1207 \text{ Ton} * \text{Ton} + 0.000048 \text{ Toff} * \text{Toff} - 0.000416 \text{ Volt} * \text{Volt} - 0.000003 \text{ Amp} * \text{Ton} + 0.000021 \text{ Amp} * \text{Toff} - 0.000676 \text{ Amp} * \text{Volt} - 0.00017 \text{ Ton} * \text{Toff} + 0.00054 \text{ Ton} * \text{Volt} - 0.000004 \text{ Toff} * \text{Volt}$$

$$SR = -14.646 + 0.25950 \text{ Amp} - 0.078 \text{ Ton} - 0.0011 \text{ Toff} + 0.24157 \text{ Volt} - 0.000654 \text{ Amp} * \text{ Amp} + 0.050 \text{ Ton} * \text{Ton} + 0.000035 \text{ Toff} * \text{Toff} - 0.000334 \text{ Volt} * \text{Volt} - 0.00001 \text{ Amp} * \text{Ton} - 0.000005 \text{ Amp} * \text{Toff} - 0.000235 \text{ Amp} * \text{Volt} + 0.0004 \text{ Ton} * \text{Toff} + 0.00030 \text{ Ton} * \text{Volt} + 0.000002 \text{ Toff} * \text{Volt}$$

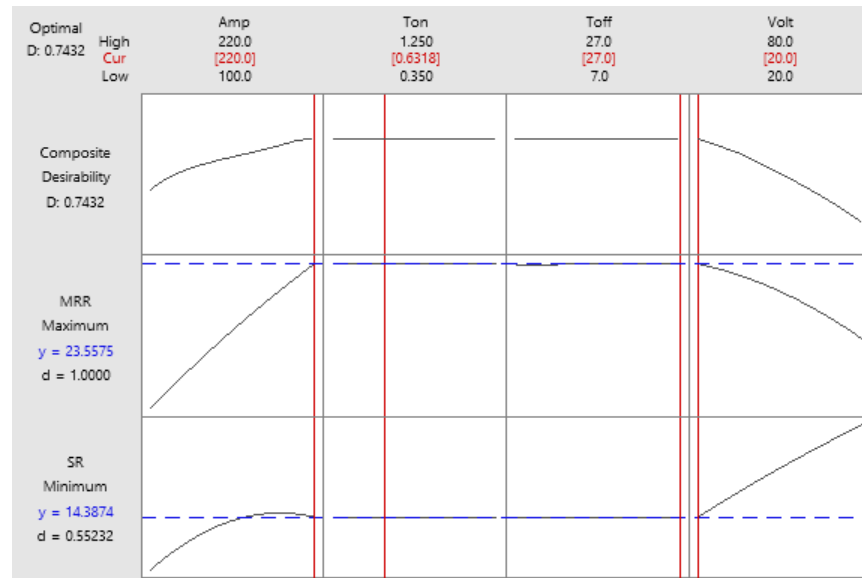


Figure 4: Response Surface Plot for Inconel 792.

1. Optimized Parameters: Amp = 220, Ton = 0.63, Toff = 27, Volt = 20
2. Performance: MRR = 23.56 mm³/min; SR = 14.39 μm
3. Desirability Score: 0.7432

3.6 Optimization for Inconel 907

For Inconel 907, iterations in the current level resulted in substantial changes in the volume of material removed per unit time, underscoring current's crucial role in determining the process's productivity. In contrast, the applied voltage demonstrated a linear relationship with the resulting surface roughness (SR). This linear behaviour implies a direct proportionality between the voltage setting and the surface finish achieved on the workpiece. As the voltage was adjusted, the surface roughness responded predictably and consistently. These findings emphasise the distinct roles of these key electrical parameters: current as a primary driver of material removal efficiency and voltage as a direct determinant of the surface quality in the WEDM process for Inconel 907.

The regression equations in uncoded units for MRR and SR for Inconel 907 are shared below:

$$MRR = -8.366 + 0.15247 \text{ Amp} + 3.039 \text{ Ton} - 0.0077 \text{ Toff} + 0.20395 \text{ Volt} - 0.000285 \text{ Amp} * \text{ Amp} - 0.993 \text{ Ton} * \text{ Ton} + 0.004850 \text{ Toff} * \text{ Toff} + 0.000501 \text{ Volt} * \text{ Volt} - 0.00167 \text{ Amp} * \text{ Ton} + 0.000237 \text{ Amp} * \text{ Toff} - 0.000543 \text{ Amp} * \text{ Volt} + 0.01989 \text{ Ton} * \text{ Toff} - 0.03961 \text{ Ton} * \text{ Volt} - 0.003605 \text{ Toff} * \text{ Volt}$$

$$SR = -11.113 + 0.21523 \text{ Amp} + 0.210 \text{ Ton} - 0.0952 \text{ Toff} + 0.14312 \text{ Volt} - 0.000547 \text{ Amp} * \text{ Amp} - 0.064 \text{ Ton} * \text{ Ton} + 0.002037 \text{ Toff} * \text{ Toff} + 0.000062 \text{ Volt} * \text{ Volt} - 0.00052 \text{ Amp} * \text{ Ton} - 0.000004 \text{ Amp} * \text{ Toff} - 0.000107 \text{ Amp} * \text{ Volt} - 0.00087 \text{ Ton} * \text{ Toff} + 0.00512 \text{ Ton} * \text{ Volt} - 0.000450 \text{ Toff} * \text{ Volt}$$

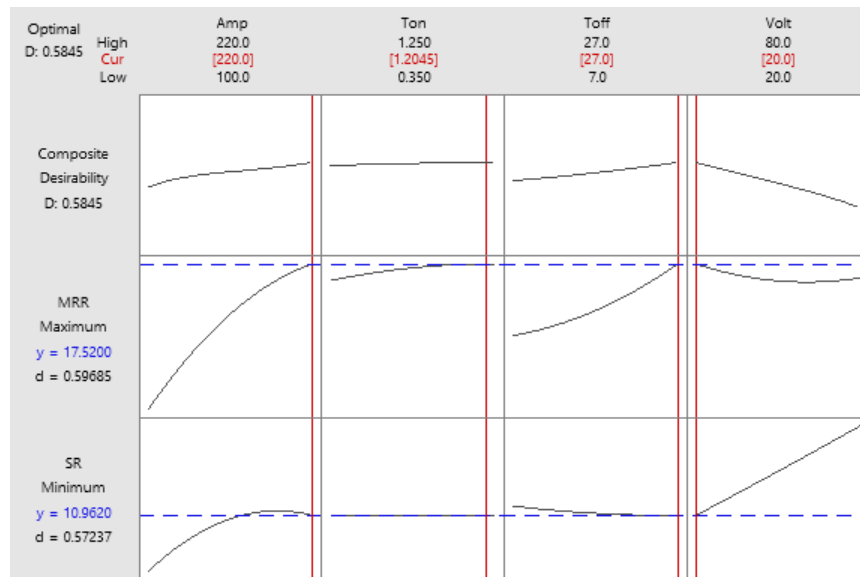


Figure 5: Response Surface Plot for Inconel 907.

1. Optimized Parameters: Amp = 220, Ton = 1.2, Toff = 27, Volt = 20
2. Performance: MRR = 17.52 mm³/min; SR = 10.96 μm
3. Desirability Score: 0.5845

3.7 Optimization for Inconel 909

Inconel 909 reveals a strong correlation between the applied voltage and the resulting surface roughness (SR), quite similar to the one shown in the modelling of Inconel 907. This significant relationship suggests that alterations in the voltage setting have a substantial and predictable impact on the final surface finish of the machined material, mirroring trends observed in the processing of Inconel 907. This strong correlation implies that voltage can be effectively utilised as a primary control parameter when aiming to achieve specific surface quality requirements.

The regression equations in uncoded units for MRR and SR for Inconel 909 are shared below:

$$\begin{aligned}
 MRR = & -4.452 + 0.15343 \text{ Amp} + 3.153 \text{ Ton} - 0.4167 \text{ Toff} + 0.20091 \text{ Volt} - 0.000286 \text{ Amp} * \\
 & \text{Amp} - 1.272 \text{ Ton} * \text{Ton} + 0.014744 \text{ Toff} * \text{Toff} + 0.000539 \text{ Volt} * \text{Volt} - 0.00180 \text{ Amp} * \\
 & \text{Ton} + 0.000235 \text{ Amp} * \text{Toff} - 0.000556 \text{ Amp} * \text{Volt} + 0.02960 \text{ Ton} * \text{Toff} - 0.03763 \text{ Ton} * \\
 & \text{Volt} - 0.003582 \text{ Toff} * \text{Volt}
 \end{aligned}$$

$$\begin{aligned}
 SR = & -11.033 + 0.21513 \text{ Amp} + 0.082 \text{ Ton} - 0.1033 \text{ Toff} + 0.14505 \text{ Volt} - 0.000546 \text{ Amp} * \\
 & \text{Amp} + 0.060 \text{ Ton} * \text{Ton} + 0.002232 \text{ Toff} * \text{Toff} + 0.000047 \text{ Volt} * \text{Volt} - 0.00055 \text{ Amp} * \\
 & \text{Ton} - 0.000004 \text{ Amp} * \text{Toff} - 0.000105 \text{ Amp} * \text{Volt} - 0.00100 \text{ Ton} * \text{Toff} + 0.00422 \text{ Ton} * \\
 & \text{Volt} - 0.000455 \text{ Toff} * \text{Volt}
 \end{aligned}$$

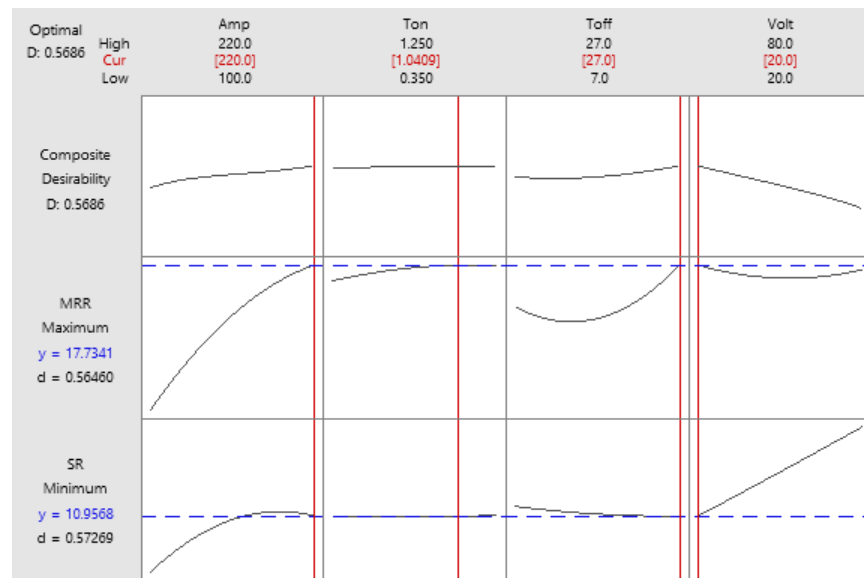


Figure 6: Response Surface Plot for Inconel 909.

1. Optimized Parameters: Amp = 220, Ton = 1.04, Toff = 27, Volt = 20
2. Performance: MRR = 17.73 mm³/min; SR = 10.96 μm
3. Desirability Score: 0.5686

3.8 Optimization for Inconel 925

Notably, the machining current exhibited the most substantial and dominant effect on the material removal rate (MRR) for Inconel 925. Alterations in the current level led to the most significant changes in the volume of material eroded per unit time, establishing current as the primary factor dictating the productivity and efficiency of the WEDM process modelling for Inconel 925. In contrast, the applied voltage demonstrated a moderate influence on the resulting surface roughness (SR). While changes in voltage did impact the surface finish, its effect was less pronounced compared to the overwhelming influence of current on MRR. This suggests that while voltage plays a role in determining the surface quality during WEDM processing on Inconel 925, other parameters might have a more significant contribution to achieving the desired surface finish.

The regression equations in uncoded units for MRR and SR for Inconel 909 are shared below:

$$MRR = 653.62 + 4.1445 \text{ Amp} - 18.33 \text{ Ton} - 13.130 \text{ Toff} + 0.6621 \text{ Volt} - 0.011296 \text{ Amp} * \text{ Amp} + 28.64 \text{ Ton} * \text{Ton} + 0.46071 \text{ Toff} * \text{Toff} + 0.003203 \text{ Volt} * \text{Volt} - 0.0000 \text{ Amp} * \text{Ton} + 0.000169 \text{ Amp} * \text{Toff} - 0.000000 \text{ Amp} * \text{Volt} + 0.000 \text{ Ton} * \text{Toff} - 0.0000 \text{ Ton} * \text{Volt} + 0.00034 \text{ Toff} * \text{Volt}$$

$$SR = 1.73673 + 0.004976 \text{ Amp} - 0.05818 \text{ Ton} - 0.024065 \text{ Toff} + 0.001557 \text{ Volt} - 0.000014 \text{ Amp} * \text{ Amp} + 0.09091 \text{ Ton} * \text{Ton} + 0.000749 \text{ Toff} * \text{Toff} - 0.000006 \text{ Volt} * \text{Volt} - 0.000000 \text{ Amp} * \text{Ton} + 0.000004 \text{ Amp} * \text{Toff} - 0.000000 \text{ Amp} * \text{Volt} + 0.000000 \text{ Ton} * \text{Toff} - 0.000000 \text{ Ton} * \text{Volt} + 0.000015 \text{ Toff} * \text{Volt}$$

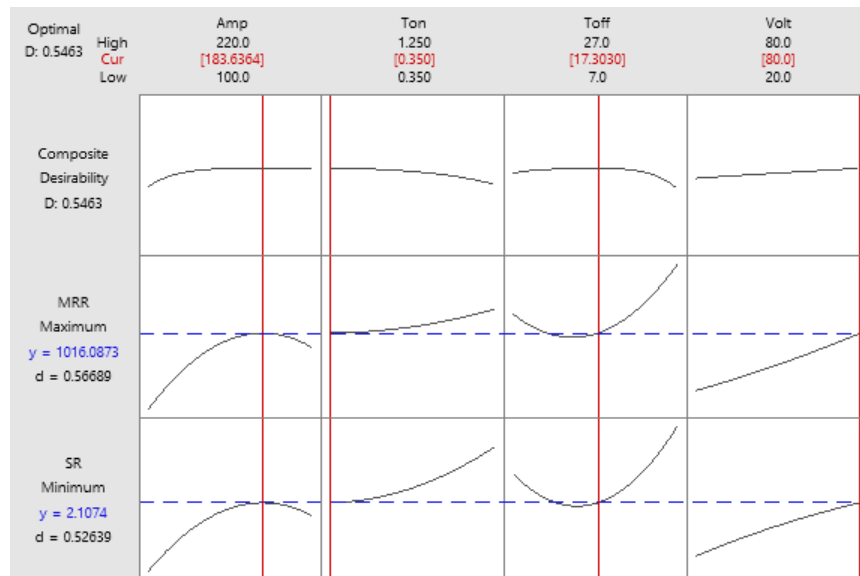


Figure 7: Response Surface Plot for Inconel 925.

1. Optimized Parameters: Amp = 183.6, Ton = 0.35, Toff = 17.3, Volt = 80
2. Performance: MRR = 1016.09 mm³/min; SR = 2.11 μm
3. Desirability Score: 0.5463

Across the spectrum of the eight WEDM unmachined Inconel grades investigated in this study, the machining current (Amp) and the applied voltage (Volt) consistently emerged as the most influential processing parameters governing performance outcomes. Specifically, the current predominantly controlled the material removal rate (MRR), exhibiting a characteristic non-linear, often parabolic, behaviour. This implies that increasing the current initially leads to a significant rise in MRR, eventually reaching an optimal point beyond which further increases may result in diminishing returns or even a decrease in material removal efficiency. Conversely, the voltage demonstrated a strong influence on the surface roughness (SR), frequently displaying a linear positive correlation. This indicates that as the voltage was increased, the surface roughness tended to increase proportionally, making voltage a key factor in controlling the final surface

finish. Interestingly, the pulse-on time (Ton) and pulse-off time (Toff) generally had a relatively less significant impact on both MRR and SR across the majority of tested conditions. However, notable exceptions were observed when the pulse-off time reached extreme values, suggesting the existence of a process stability threshold beyond which these parameters could exert a more substantial influence on the machining outputs. The successful application of desirability functions proved instrumental in effectively balancing the inherently conflicting objectives of maximising material removal rate and minimising surface roughness. This approach enabled the identification of optimised and practical WEDM operating conditions for these grades of Inconel, suitable for various industrial applications, providing a robust methodology for achieving desired performance compromises.

CONCLUSIONS

This research establishes a comprehensive and robust optimisation framework specifically tailored for the Wire Electrical Discharge Machining (WEDM) of a range of eight distinct Inconel grades, materials renowned for their high-performance characteristics in demanding applications. The development and utilisation of predictive regression models, coupled with a desirability-based optimisation approach, collectively contributed to a significant improvement in both machining accuracy and the overall quality of the output. By accurately forecasting the impact of process parameters on key performance indicators and strategically balancing competing objectives, this study yields practical and immediately applicable insights for industry experts and manufacturing engineers. These findings empower them to enhance WEDM productivity for the mentioned Inconel grades while simultaneously preserving the critical component integrity required in high-stress environments. Looking towards future advancements, subsequent research will delve into the application of multi-objective evolutionary algorithms and the implementation of real-time adaptive control systems. These advanced techniques hold the potential to further refine WEDM processes for high-performance materials like Inconel, enabling even greater levels of efficiency, precision, and adaptability in dynamic manufacturing scenarios.

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