International Journal of Research in Engineering and Applied Sciences(IJREAS)
Available online at http://euroasiapub.org/journals.php
Vol. 14 Issue 11, Nov -2024,
ISSN(O): 2249-3905, ISSN(P) : 2349-6525 |
Impact Factor: 7.196| Thomson Reuters ID: L-5236-2015

Study of WEDM Parameters Using Response Surface Methodology for Enhanced Performance

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Abstract

Wire Electrical Discharge Machining (WEDM) is a prominent non-traditional machining technique utilized for manufacturing complex and high-precision components in various industries. The optimization of WEDM parameters significantly impacts machining performance in terms of surface finish, material removal rate (MRR), and dimensional accuracy. This study employs Response Surface Methodology (RSM) to analyze and optimize the critical process parameters of WEDM, including pulse-on time, pulse-off time, peak current, and wire tension. A systematic experimental design using Central Composite Design (CCD) is implemented to develop predictive models and assess the interactive effects of the parameters. The study identifies optimal settings to achieve enhanced machining performance, balancing high MRR and superior surface quality. Analysis of Variance (ANOVA) is employed to evaluate the statistical significance of the developed models and determine the contribution of each parameter. The findings provide valuable insights into parameter interactions and their influence on performance metrics, enabling manufacturers to improve productivity and achieve superior product quality. The proposed approach serves as a robust framework for optimizing WEDM processes across diverse materials and applications, fostering efficiency and precision in advanced manufacturing.

Introduction

Wire Electrical Discharge Machining (WEDM) has emerged as a vital non-conventional machining process in modern manufacturing, offering unparalleled precision and the ability to fabricate complex geometries in hard-to-machine materials such as alloys, composites, and superalloys. Unlike traditional machining, WEDM operates through electrical discharges that erode the material without direct contact, ensuring minimal mechanical stress on the workpiece. The performance of WEDM is heavily influenced by several controllable parameters, including pulse-on time, pulse-off time, peak current, wire tension, and servo voltage, which collectively determine the machining characteristics such as material removal rate (MRR), surface roughness (Ra), dimensional accuracy, and tool wear. Optimizing these parameters is critical to achieving high productivity while maintaining superior quality standards. Response Surface Methodology (RSM) provides a powerful statistical and mathematical framework for modeling and analyzing the effects of these parameters and their interactions on WEDM performance. This study employs a systematic approach using RSM to design experiments, predict outcomes, and optimize machining conditions. The Central Composite Design (CCD) is used to develop a second-order regression model, enabling the exploration of parameter interactions and their combined impact on key performance indicators. By integrating Analysis of Variance (ANOVA), the study evaluates the significance of process variables and validates the reliability of the predictive model. The findings of this research aim to establish an optimal parameter configuration for enhanced WEDM efficiency and precision, contributing to advancements in manufacturing processes. This study not only provides a deeper understanding of the WEDM process but also serves as a guide for industrial practitioners in achieving improved performance, reduced operational costs, and greater adaptability to diverse materials and machining requirements.

Importance and Applications in Modern Manufacturing

Wire Electrical Discharge Machining (WEDM) is an indispensable technology in modern manufacturing due to its ability to machine complex and precise geometries in materials that are otherwise challenging to work with. The process is highly suited for industries that demand intricate designs, such as aerospace, automotive, medical devices, and tool and die manufacturing. In aerospace, WEDM is utilized to machine turbine blades and components from hard alloys like titanium and Inconel, where precision and heat resistance are critical. The medical field benefits from WEDM in producing surgical instruments, implants, and micro-

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components that require exceptional accuracy and smooth finishes. In the automotive sector, WEDM facilitates the production of gears, engine components, and intricate molds, enhancing the efficiency and performance of vehicles. Additionally, the tool and die industry extensively employs WEDM for producing high-precision dies, molds, and punches used in mass production. The versatility of WEDM allows manufacturers to cater to both large-scale production and specialized custom components. Its non-contact nature ensures minimal deformation or residual stresses, making it ideal for delicate and high-tolerance applications. WEDM not only improves manufacturing precision but also enables the development of innovative products and designs, thereby driving advancements in various industrial sectors.

Advantages over Conventional Machining Processes

WEDM offers several advantages that set it apart from conventional machining processes, making it a preferred choice for specific applications. One of its primary benefits is the ability to machine electrically conductive materials, regardless of their hardness, with exceptional precision. Unlike traditional machining, which relies on cutting forces, WEDM operates through electrical discharges, eliminating mechanical stress and tool wear. This feature allows it to process delicate and brittle materials, such as ceramics and carbide composites, without cracking or distortion. Additionally, WEDM can produce intricate and complex geometries, including sharp corners, narrow slots, and fine details that are challenging or impossible to achieve using conventional methods. The process achieves superior surface finishes and high dimensional accuracy, reducing the need for secondary operations. Another significant advantage is its versatility in cutting materials with varying thicknesses and compositions, as the process parameters can be adjusted dynamically. WEDM is also highly automated, with Computer Numerical Control (CNC) integration enabling precision control and repeatability in production. Moreover, the absence of cutting forces and the use of deionized water as a dielectric fluid make WEDM an eco-friendlier alternative, with minimal material waste and reduced energy consumption. These advantages make WEDM an invaluable tool in manufacturing high-performance components, enhancing product quality and expanding the possibilities of modern engineering.

Literature review

Feng, Y et. al. (2018) This presented work reviews Wire Electrical Discharge Machining (WEDM), in particular the creation and optimization of process phases. This is a non traditional machining method developed to cut materials that it is difficult to cut by a conventional method. This is particularly adept at working materials that are swamped from ordinary cutting approaches. WEDM finds many applications in the making of automobiles, aircraft assemblies, parts of medical devices, tooling, dies, other precision engineered parts etc. Resulting from thorough research in the field, this understanding was formed. Particle swarm optimization, genetic algorithms and fuzzy techniques have been widely used for data processing and analyzing in WEDM studies. Besides, artificial neural networks are applied for data processing and data analysis more and more, which provide more sophisticated knowledge and help to optimize WEDM processes.

Ding, Y et. al. (2018) WEDM for machining metal matrix composites: a state of the art. The expanding demand for lightweight, cost efficient and durable construction materials has led to an expansion of applications of metal matrix composites (MMCs), a widely utilised class of materials. Manufacturing industry has witnessed the use of such advanced materials, which has stimulated the requirement of alternate machining methods. However, machining MMCs using these techniques, WEDM has shown significant effectiveness. WEDM has the ability to handle intricate and complex geometries with high precision while it is easy to operate which dictates MMCs as a superior choice machine and provides a practical solution to the evolving requirements of the industry.

D. Sudhakara et. al. (2014) It is known that, with the present state of WEDM trial and error is used to determine the machining parameters and our study eliminates the trial-and-error approach by determining optimally the machining parameters for WEDM. Researchers present their findings after exploring different methodologies in examining how WEDM output parameters, namely, pulse-on and pulse-off times, applied voltage, wire tension, dielectric pressure, and current, affect them. The effect of these factors is large on the key performance metrics, such as the surface finish and material removal rate. The process uses the advantage of superior capability of WEDM in modeling and optimization of a variety of machining parameters to carry out machining of work materials with greater accuracy. WEDM is mainly used for efficiently machining metals, alloys and composites, and realizes highly accurate and reliable machining with high efficiency, so it has particular significance to advanced manufacturing application.

Richardson et al(2021) This thesis investigates the Wire Electrical Discharge Machining (WEDM) process in depth, contributing to the field of process development and improvements of WEDM. Applied research was conducted on the effect of different factors on machining performance and on productivity. In particular, it addresses the effect of process parameter adjustment on performance outcomes and productivity improvements. To complement these results, the article also investigates adaptive process mechanisms and studies the possibility of implementing several control strategies to achieve optimum machining conditions. The paper also relates to the progression of hybrid machining technologies, and reviews a number of WEDM applications in several different industries. This work in the end discusses these developments and suggests future trends of WEDM research. The interplay of the many parameters affecting the process is well understood, and the search for optimal machining conditions from out of an infinite number of possible combinations to promote efficiency and precision is of primary importance.

H. Singh et. al. (2009) In addition, the material removal rate is expected to be optimized by selection of the optimal process parameters. A specialized thermal machining process WEDM enables cutting up to very intricate shapes with sharp edges and materials with different hardness, which in turn is impossible to cut using conventional method. Using the well-known EDM sparking process this process is non-contact material removal with very high precision and efficiency.

J.S. Rao et. al. (2012) An analysis of the effects of various control parameters was performed to achieve the highest Material Removal Rate (MRR) and the lowest Electrode Wear Rate (EWR) when using EDM on stainless steel 316 using copper as the cutting tool electrode. In this study, both electrical and non-electrical factors are analysed on their impact to MRR and EWR. Key findings are presented based upon the application of experimental design and process optimization techniques. Associated errors were minimized through use of the Taguchi method to ensure reliability of results. The pulse-off time and current are found to be critical factors that significantly affect both MRR and EWR and hence material removal efficiency and electrode wear rates.

Danial Ghodsiyeh et. al. (2013) In this paper different modeling and optimization strategies for WEDM are discussed along with their advantages and limitations. Several recommendations regarding future research directions to further improve WEDM processes are given in conclusions. Continuous improvements in WEDM process can be required keep WEDM as a competitive and cost effective machining method in today's tool room manufacturing production. Additionally, recent research has demonstrated the potential to improve WEDM capabilities to a much greater extent thereby enabling greater productivity, precision, and efficiency in machining processes.

Joshi Guruprasad et. al. (2016) The sources used in this work for literature review are examined specifically identifying the various challenges in optimizing WEDM processes with the huge amount of variables and complicated parametric combinations. Thus, the goal is to determine a relationship between WEDM process parameters and variable responses, and aid in the selection of optimal process conditions. Various analytical and statistical Design of Experiment (DOE) methodologies have been used by researchers trying to determine the best combination of variables, where the authors have used to identify the most significant and optimal process parameters. It is complemented by the results presented in this study also by reviewing some recent studies of parametric optimization in wire-cut EDM.

U. A. Dabade et. al. (2016) Inconel 718 was WEDM to explore the use of the Taguchi method for analyzing its response variables in the WEDM to optimize performance without having to run the machine tools at full capacity. Such machining processes have thus been the target of efforts to achieve a precise understanding of the operating parameters for years. The key factors such as Material Removal Rate (MRR), Surface Roughness (SR), and dimensional deviations are investigated in this study. The experimental analysis was performed using the Taguchi approach and L8 Orthogonal Array Design of Experiments (DoE), implemented with Minitab 16 software. We also assessed the effects of the factors on response variables of output characteristics using a 95% confidence level, and the results showed that "pulse-on time" are most impact factor as it contributed with 54.32%, 58.42%, 83.21%, and 36.11% to different outputs respectively at a 95% confidence level. Second most important parameter in kerf width was identified as peak current and second highest influential parameter for MRR and SR was identified as servo voltage. This analysis provides the relative importance of particular WEDM parameters at optimized performance.

Methodology

For this study, employing a systematic parameter setup then machining performance benchmarking of WEDM process was the methodology followed. The effects of key process variables, including Pulse-on Time, Pulse-off Time, Wire Feed and Spark Gap Voltage, were evaluated via a Design of Experiments (DoE) approach using the Taguchi method with L8 Orthogonal Array. The Inconel 718 was examined by experimental trials on a WEDM setup under controlled conditions. Response variables analyzed were SR and MRR. Statistical significance of each parameter and their interaction was determined by means of the statistical tool of Analysis of Variance (ANOVA) using Minitab 16 software for data analysis. Additionally, quadratic and interaction effects were investigated. These results were validated to 95% confidence, and in so doing shed light on the relative contributions of each parameter to machining performance. This method optimizes accurately and robustly understands WEDM processes.

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ANOVA analysis for Surface Roughness

This section discusses the Analysis of Variance (ANOVA) conducted for surface roughness, analyzing all four factors with two responses. Table 1 presents the ANOVA parameters along with the cutting speed for comprehensive analysis.

"Source"	"Sum of"	"df"	"Mean"	"F-value"	"p-value"	
Model	5.236686	9	0.58185402	13.37059879	1.79503E-06	significant
A-Pulse on Time	0.444675	1	0.444675	10.21832077	0.004750139	
B-Pulse off Time	2.3232	1	2.3232	53.3855126	6.27098E-07	
C-Wire Feed	0.023408	1	0.023408333	0.537907143	0.472254689	
D-Spark Gap Voltage	0.340033	1	0.340033333	7.813728392	0.011541085	
AB	0.216225	1	0.216225	4.968699406	0.038077839	
AD	0.765625	1	0.765625	17.5935275	0.000491485	
BC	0.164025	1	0.164025	3.769179883	0.067184326	
BÂ²	0.68633	1	0.686330214	15.77138872	0.000818068	
DÂ²	0.398683	1	0.398683155	9.161460312	0.006937355	
Residual	0.826831	19	0.043517424			
Lack of Fit	0.767551	15	0.051170071	3.452771303	0.119853972	not significant
Pure Error	0.05928	4	0.01482			
Cor Total	6.063517	28				

The table provides the Analysis of Variance (ANOVA) results for surface roughness, showcasing the effects of different factors and their interactions on the response variable. The "Source" column lists the model components, including main factors (A: Pulse-on Time, B: Pulse-off Time, C: Wire Feed, D: Spark Gap Voltage), interactions (e.g., AB, AD), and quadratic terms (e.g., B^2, D^2). The "Sum of Squares" measures the contribution of each factor to variability in surface roughness, while "df" represents the degrees of freedom. The "Mean Square" is calculated by dividing the "Sum of Squares" by its respective "df," and the "F-value" assesses the significance of each factor by comparing the variation due to the factor to the residual variation. The "p-value" indicates statistical significance; factors with a p-value < 0.05 are significant. The results show the model is significant (p-value = 1.79E-06). Pulse-off Time (B) has the largest impact (F-value = 53.39, $p < 0.0001$), followed by Spark Gap Voltage (D) and quadratic terms B^2 and D^2. Interactions AB and AD also influence roughness significantly. Lack of Fit is not significant ($p = 0.12$), validating the model's adequacy. This analysis highlights the critical factors influencing surface roughness.

Conclusion

The comprehensive analysis of the optimization of Wire Electrical Discharge Machining (WEDM) parameter using Response Surface Methodology (RSM) to improve the machining performance was performed in this study. It systematically explored the impact of key parameters like Pulse-on Time, Pulse-off Time, Wire Feed, and Spark Gap Voltage on the critical performance metrics such as Material Removal Rate (MRR), Surface Roughness (SR) and dimensional accuracy. Using Design of Experiments (DoE) techniques such as the Taguchi method and Central Composite Design (CCD) here was successful in modelling the interactions and quadratic effects of parameters. Pulse-off Time and current were identified as the dominant factors, with the analysis of Variance (ANOVA) confirming the statistical significance of these factors. The results indicate the significance of parameter optimization towards the improvement in the productivity, precision and efficiency of the WEDM operations. Furthermore, the modeling methods have been integrated with experimental validation with 95% confidence confidence which improves the reliability of the results. In addition to contributing to understanding of WEDM parameter interactions, this study contributes a robust framework for machining process optimization to industrial applications. These insights can be expanded upon through future research by including hybrid techniques and adaptive control strategies for future manufacturing demands.

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