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Research Article

Experimental study and analysis on generating contour feature on Inconel 625 using Micro-EDM

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ABSTRACT

An experimental investigation into the generation of contour features on Inconel 625 utilizing Micro Electrical Discharge Machining (Micro EDM). The primary focus is optimizing crucial process parameters, namely pulse off time, pulse on time, and current, to enhance machining efficiency and quality. The study employs a systematic approach to explore the impact of varying gap voltage and current on the Micro EDM process. The optimization seeks to reduce surface roughness, one of the main variables affecting the overall performance of the machining process, through a series of carefully designed experiments. The experimental results will be systematically analyzed to establish correlations between process parameters and machining outcomes. The optimum values obtained from the RSM technique for current, pulse off, and pulse on time are 3 amp, 7.23µ sec, and 6.83µ sec, respectively.

Keywords: Micro EDM, EDM, Contour, Microchannel, Electro discharge

1. Introduction

Micro-EDM is a non-contact thermal process for fabricating micro-parts in the 50-100 µm range, utilizing thermoelectric energy between the workpiece and electrode (Mahendran, 2010). It offers high precision and good surface quality for micro-tools, components, and features (Tiwary et al., 2013). However, challenges include low material removal rate, tool wear, and surface roughness (Mukhopadhyay & Sarkar, 2019). Recent advancements focus on enhancing machining efficiency and surface quality through ultrasonic vibration and magnetic field assistance (Mukhopadhyay & Sarkar, 2019). Research trends involve optimizing process parameters and investigating dielectric fluids, pulse characteristics, and ultrasonic vibration effects (Kadirvel et al., 2012). Optimization methods like Taguchi, ANN, grey relational analysis, and fuzzy logic control systems have improved micro-EDM performance (Kadirvel et al., 2012). Ongoing research aims to fabricate high aspect ratio micro-structures and expand industrial applications of micro-EDM (Mukhopadhyay & Sarkar, 2019; Kadirvel et al., 2012).

2. Material and methodology

For the present study, Inconel 625 is a nickel-based superalloy known for its exceptional resistance to corrosion oxidation, high strength, and excellent weldability. Inconel 625 is available in various forms, such as sheets, plates, bars, wires, pipes, and tubing. Inconel 625 is relatively expensive compared to other alloys due to its unique properties and composition. The chemical composition of the alloy is shown in the table.1 below, along with the sample image in Fig.1

Element	Ni	Cr	Fe	Mo	Nb	Co	Si	P	S
Percentage	58	20-30	5	8-10	3.15-4.15	1	0.5	0.15	0.15

Table.1 Chemical Composition of Inconel 625

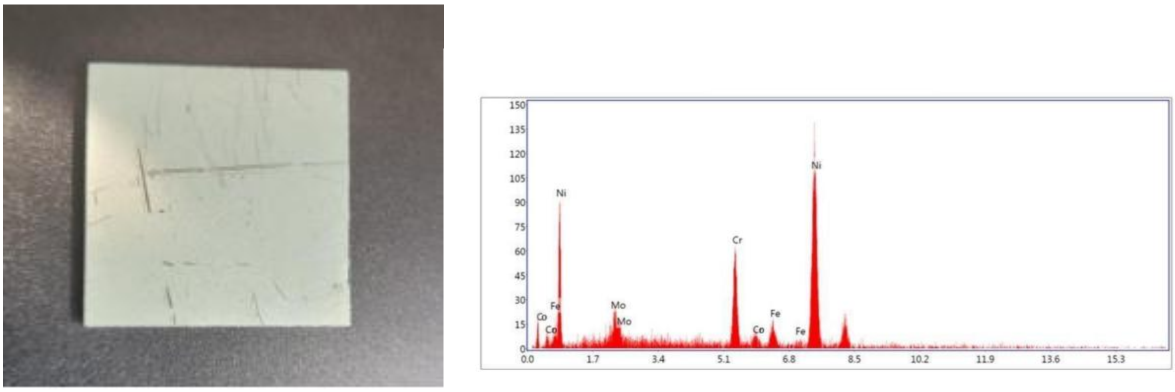

Fig.1 a) Workpiece before machining. b) EDAX of the Inconel 625

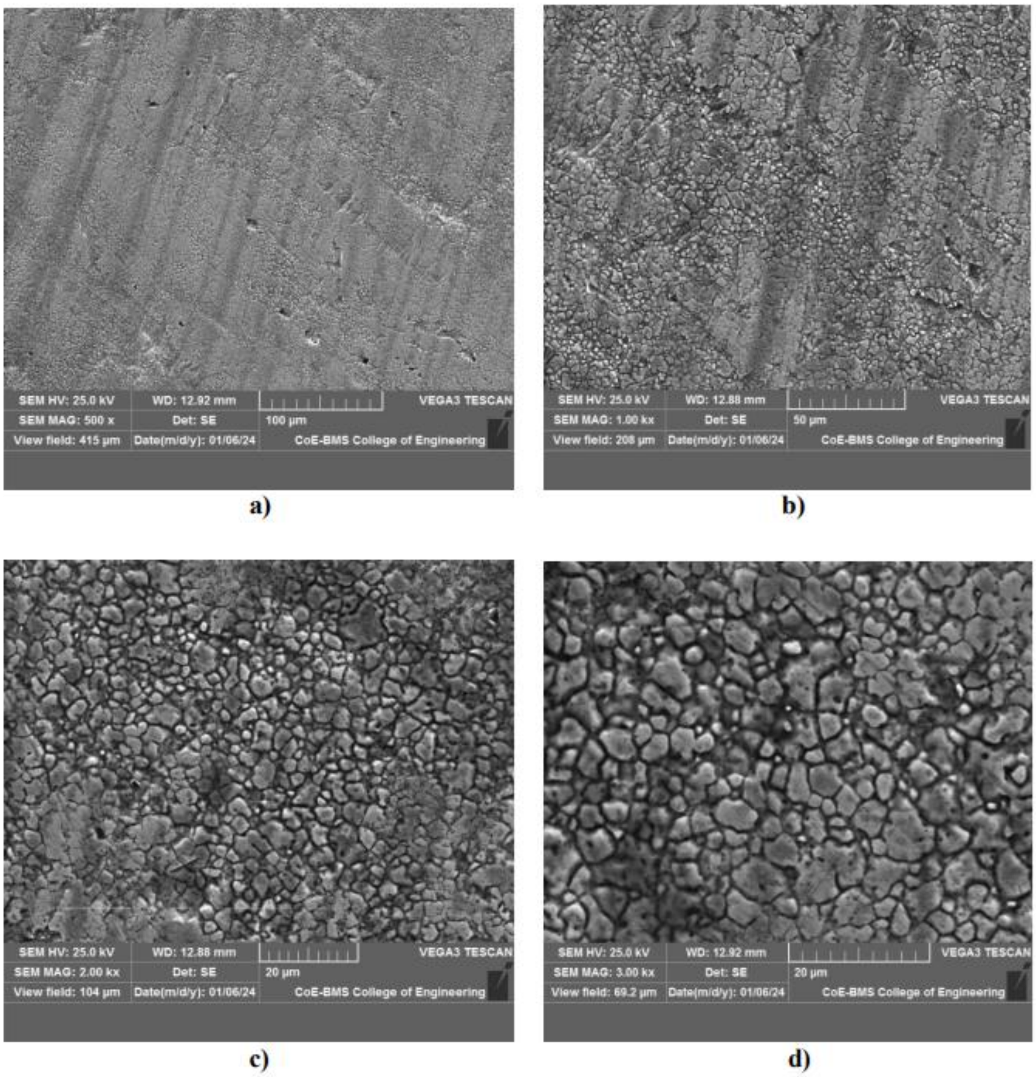

Fig.2 a),b),c)&d) are the magnified images of Inconel 625 before machining

3. Experimentation

The experimentation of the present materials is performed by die-sinking CNC-operated EDM machine by designing and manufacturing a unique tool in the shape of a contour shape also, the process parameters are varied and optimized by the Response surface methodology and in the process of electrical discharge machining (EDM), several critical parameters influence machining efficiency, accuracy, and material removal rate. Discharge current represents the current passing through the spark gap during each pulse, significantly determining the material removal rate. Closely related to this is the pulse on/off time, which dictates the duration of active and inactive periods in each electrical discharge cycle. This parameter not only affects the rate of material removal but also influences surface finish and electrode wear. Another key factor is the gap voltage, which refers to the electrical potential difference between the tool electrode and the workpiece across the spark gap, ensuring consistent spark generation. The discharge energy, which is the total energy transferred to the workpiece during machining, directly impacts the efficiency and overall material removal rate. To maintain precision and stability, the dielectric medium plays a crucial role in preventing arcing, flushing away debris, and facilitating controlled electrical discharges, mainly in micromachining applications where accuracy is paramount. Additionally, machining parameters such as feed rate and depth determine how aggressively material is removed, affecting machining time and surface quality. Lastly, the tool electrode lift time, or the duration for which the electrode is retracted between discharges, influences spark stability, debris removal, and machining consistency. Together, these factors govern the overall performance of Micro EDM, making their careful optimization essential for achieving precise and efficient machining results.

Several factors influence machining efficiency, cost, and final product quality in the Micro EDM process. One of the key aspects is surface finish, which determines the quality of the machined surface, often measured in terms of roughness. A smoother surface enhances both the appearance and functionality of the final product. Another critical factor is the material removal rate (MRR), which indicates how efficiently material is removed from the workpiece. MRR is directly influenced by the discharge pulse energy, with higher energy levels generally leading to faster machining. However, this comes with a trade-off, as electrode wear rate also plays a crucial role—higher wear can occur due to abnormal discharges, leading to frequent tool replacements and affecting process stability. This directly impacts tooling costs, which include expenses related to electrode material, reconditioning, and replacements. Additionally, energy consumption is a significant consideration, as the amount of electrical energy used during the micro EDM process affects overall operational costs. Another vital aspect is debris removal efficiency, which depends on how effectively the dielectric fluid flushes away debris. Efficient debris removal enhances machining stability, minimizes electrode wear, and ensures consistent performance. Optimizing these factors is essential to balance machining speed, cost-effectiveness, and precision in micro EDM applications. Response Surface Methodology (RSM) is a powerful mathematical and statistical approach to developing empirical models and optimizing processes by analyzing the relationships between multiple input factors and a response variable. In RSM, experiments are carefully designed to optimize an output variable influenced by several input parameters. Researchers can identify the best conditions to achieve the desired outcome efficiently by conducting multiple trials with different variable combinations. However, the process is not without challenges, as several sources of error can affect the accuracy of the results. Numerical noise in computer simulations may arise due to insufficient convergence in iterative methods, rounding errors, or the discrete representation of a continuous physical phenomenon. Similarly, in physical experiments, measurement inaccuracies can lead to flawed conclusions, ultimately affecting the reliability of the findings. To address these uncertainties, RSM assumes that errors occur randomly, allowing for a more practical approach to handling variations in experimental data. One of the significant advantages of RSM is that it reduces reliance on expensive analytical techniques like Computational Fluid Dynamics (CFD) analysis, making it a cost-effective tool for design optimization. By systematically analyzing input-output relationships, RSM provides a structured and efficient way to enhance process performance while minimizing errors and resource consumption. The steps are shown in Fig. 3

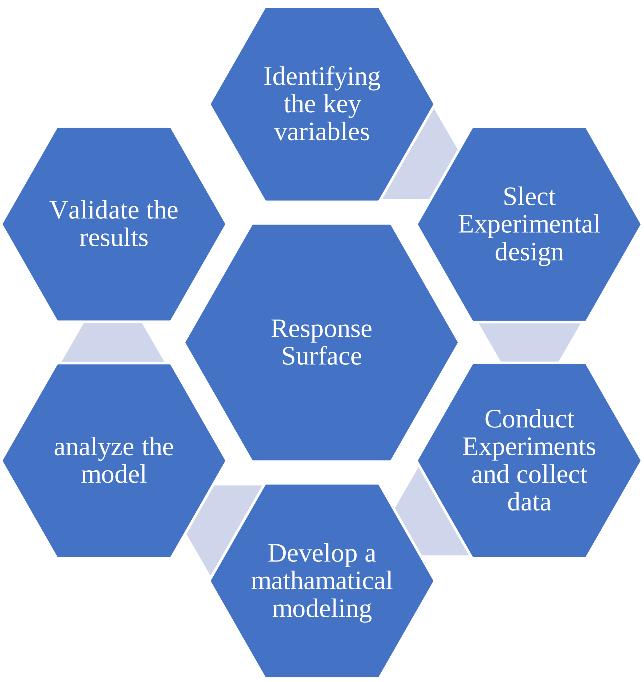

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Fig 3 Steps in Response Surface Method

Design of Experiments (DOE) involves planning and executing experiments to efficiently gather data and analyze the impact of various factors on a response. Several design methods exist, each with its advantages and applications. RSM relies mainly on the design of experiments, abbreviated as DoE. This method was developed primarily to fit the models for the physical experiment data. It is also used for numerical experiment data. Complete Factorial Design: All possible combinations of factor levels are tested in a full factorial design. This method provides a complete and systematic exploration of the factor space but may require many experimental runs, especially with multiple factors in the present study. Box-Behnken Design: This type of response surface design uses a set of three-level combinations for each factor. Box-Behnken designs are efficient in exploring quadratic response surfaces and require fewer experimental runs compared to full factorial designs. The DoE are shown below

	C1	C2	C3	C4	C5	C6
	StdOrder	RunOrder	Current (amp)	Pulse OFF (μ sec)	Pulse ON (μ sec)	Sa (μm)
1	3	1	3	8	6	2.454
2	7	2	3	6	7	3.973
3	13	3	5	6	6	5.609
4	1	4	3	4	6	5.280
5	4	5	7	8	6	7.439
6	14	6	5	6	6	6.715
7	6	7	7	6	5	7.286
8	11	8	5	4	7	8.804
9	8	9	7	6	7	12.115
10	2	10	7	4	6	14.519
11	10	11	5	8	5	4.685
12	15	12	5	6	6	4.229
13	9	13	5	4	5	5.289
14	12	14	5	8	7	7.215
15	5	15	3	6	5	5.925

Fig.4 DOE generated using Box Behnken method and Responses

Fig.5 Experimented contour feature

4. Results and discussion

The surface profile is analyzed using a confocal microscope. Confocal microscopy stands at the forefront of modern scientific imaging techniques, offering researchers unparalleled capabilities in capturing detailed three-dimensional representations of objects. Its versatility extends beyond mere visualization, as it provides a sophisticated means of studying surface characteristics by generating topographic maps. This innovative approach enables scientists and engineers to delve deep into the intricate details of surfaces, facilitating comprehensive analyses with implications spanning numerous fields of research and industry. Once the three-dimensional representation is created, the next step is analysis, where researchers use various quantitative metrics to extract valuable insights from the data. One key metric in this process is surface roughness, which plays a vital role in defining the texture of a specimen's surface. Surface roughness is commonly measured using parameters like Ra (average roughness), Rq (root mean square roughness), and Rz (maximum peak-to-valley height). Each provides a unique perspective on different aspects of the surface's morphology. These parameters help quantify the deviations of the surface profile from an ideal reference plane, offering a detailed view of surface irregularities. The images are shown in Fig.6

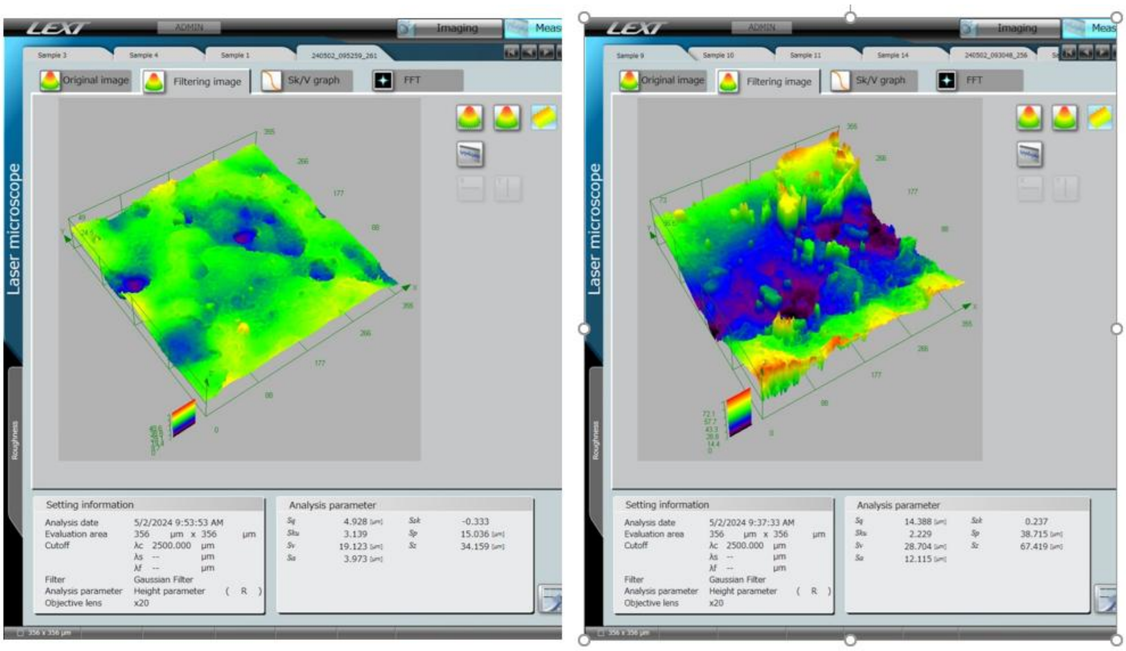

Fig.6 Confocal images of machined surface

The response surface method has shown that the model fits best by achieving the R-value of 0.96. The corresponding graphs are shown below in Fig.7

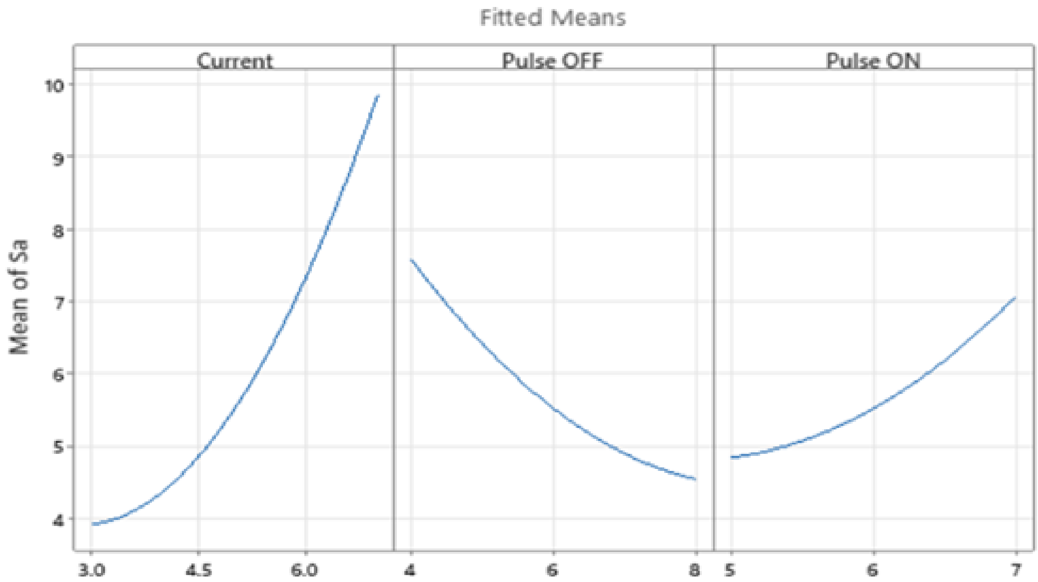

Fig.7 Mean effect Plot for surface roughness

5. Conclusion:

The following conclusions are drawn from the present work

- The surface roughness values in µm increase when there is an increase in peak current from 3 amp. to 7 amp. So, the peak current must be kept at an optimum for a minimum Sa value.
- When the pulse on time increases, the surface roughness values also increase. So, for better surface finish, the pulse on time must be optimum.
- The roughness (Sa) value decreases with an increase in pulse-off time.
- The optimum values obtained from the RSM technique for current, pulse off, and pulse on time are 3 amp, 7.23µ sec, and 6.83µ sec respectively. The corresponding optimum surface roughness value obtained is 3.54µ meters.
- In summary, the application of RSM optimization in surface roughness analysis facilitates the identification of optimal process parameters that minimize surface roughness and enhance surface quality. By systematically analyzing the effects of individual parameters and their interactions, RSM empowers manufacturers to optimize machining processes for superior surface finish and overall product quality.
- Percentage of error obtained between measured and predicted values is 15.43758 which lies within the accepted range

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