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Experimental investigation & optimization of Wire Electrical Discharge Machining (WEDM) Parameter for Material Removal Rate (MRR) in Machining of AISI D3 Tool Steel

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Abstract - *This study investigates the effects of key process parameters in Wire Electrical Discharge Machining (WEDM) on the Material Removal Rate (MRR) during the machining of AISI D3 tool steel. Using a one-variable-at-a-time (OVAT) approach and Taguchi-based L9 orthogonal array for experimental design, the influence of pulse on time (TON), pulse off time (TOFF), peak current (IP), and wire feed rate (WF) was evaluated. Experimental trials were conducted on an ELECTRONICA SPRINTCUT machine using 0.18 mm zinc-coated brass wire and deionized water as the dielectric medium. Analysis of Variance (ANOVA) identified pulse on time and wire feed rate as the most significant contributors to MRR variation. A regression model was developed to predict MRR with high accuracy (R^2 = 94.17%). Results reveal that increasing TON and TOFF enhances MRR, while higher WF and IP tend to reduce it. These findings provide a basis for optimizing WEDM parameters to improve machining efficiency of hard tool steels like AISI D3.*

Key Words: Wire EDM, Material Removal Rate, AISI D3 Tool Steel, Pulse On Time, Taguchi Method, ANOVA

1.INTRODUCTION

Wire Electrical Discharge Machining (Wire EDM) is a non-traditional machining process that utilizes a series of rapid, controlled electrical discharges (sparks) to erode electrically conductive materials. This process occurs between a thin, continuously moving wire electrode and the work piece, separated by a minute spark gap filled with an insulated dielectric fluid, typically de-ionized water.

During the machining operation, high-frequency pulses of alternating or direct current are discharged from the wire to the work piece. These discharges, occurring at rates exceeding one hundred thousand times per second and lasting less than a microsecond, generate intense heat, estimated between 15,000° to 21,000° Fahrenheit. This extreme heat causes localized melting and vaporization of a tiny volume of material from both the workpiece and a small portion of the wire electrode. The wire electrode, usually made of brass, copper, or a brass-zinc alloy, ranges in thickness from 0.001 to 0.014 inches and is fed from a spool. As the wire moves along a programmed path, the sparks progressively erode the workpiece, creating the desired shape or cut.

The dielectric fluid plays a crucial role in the Wire EDM process. It acts as an insulator between the wire and the workpiece until sufficient voltage is applied to ionize it, allowing a controlled spark to occur. Furthermore, the pressurized flow of the dielectric fluid through top and bottom flushing nozzles effectively removes the eroded particles (chips) from the cutting zone, preventing short circuits and ensuring efficient machining. The continuous flow of the dielectric also dissipates the heat generated by the sparks, preventing thermal expansion of the work piece, which could compromise dimensional and positional accuracy. To maintain consistent machining conditions and accuracy, the dielectric fluid is continuously filtered to remove suspended solids and passed through a chiller to maintain a constant temperature.

In essence, Wire EDM removes material through spark erosion, making it essential for the workpiece to be electrically conductive. The process allows for the creation of intricate and complex shapes with high precision and surface finish, with the volume of material removed being directly related to the desired cutting speed and surface quality.

2. LITERATURE SURVEY

This compilation summarizes several studies exploring the influence of Wire Electrical Discharge Machining (WEDM) parameters on performance. Researchers have investigated how varying pulse-on time, pulse-off time, voltage, current, wire feed, wire tension, and flushing pressure affect Material Removal Rate (MRR), surface roughness, and kerf width.

M Siva Kumar et al. [2]utilized Taguchi's L18 array to study AISI D3 steel, finding that increased pulse-on time, current, and voltage enhanced MRR, while pulse-off time had a minimal impact. Vaghela et al., also using AISI D3, employed Taguchi's L9 array, measuring MRR, surface roughness, and kerf width, and varying similar parameters.

Deepa Singh et al.[4]using a ZNC-250 machine and SK2MCr4 steel, employed Taguchi's L9 to study pulse times, current, and servo voltage, again measuring MRR, surface roughness, and kerf width. Singh and Sharma[7], employing Taguchi's L18, examined H13 tool steel, demonstrating that higher pulse-on time and current increased MRR, while servo voltage and pulse-off time decreased it. They also found that surface roughness increased with wire tension, pulse-off time, and servo voltage, but decreased with wire feed, pulse-on time, and current.

[7]Sharma et al. utilized Response Surface Methodology (RSM) and Central Composite Rotatable Design (CCRD) to model WEDM of D2 steel, showing that increased pulse-on time and voltage increased surface roughness, while increased peak current decreased it. Singh and Pradhan[8], using Taguchi's L27, examined AISI D2 steel, finding that pulse times significantly impacted MRR and cutting rate, and pulse-on time and servo voltage affected surface roughness.

Kanlayasiri and Boonmung [10] studied DC53 steel, finding that increased pulse-on time and peak current significantly increased surface roughness. Parashar et al.[11], using Taguchi's L32, investigated steel and found that gap voltage, pulse times, wire feed, and flushing pressure influenced kerf width.

These studies consistently highlight the significant influence of pulse-on time and current on MRR. They also demonstrate the complex interactions between various parameters and their effects on surface roughness and kerf width, emphasizing the need for careful parameter selection to optimize WEDM processes.

3.METHODOLOGY

This study was designed to experimentally analyze and optimize the influence of selected WEDM process parameters on the Material Removal Rate (MRR) during the machining of AISI D3 tool steel. The methodology followed a systematic approach encompassing material selection, parameter identification, experimental design, execution, and data analysis.

A. Work Material and Electrode

AISI D3 cold work tool steel was selected as the work piece material due to its high hardness and wear resistance, commonly used in dies and cutting tools. The work piece dimensions were 100 mm × 100 mm × 10 mm. The electrode used for machining was a 0.25 mm diameter zinc-coated brass wire, chosen for its good conductivity and mechanical strength. Deionized water served as the dielectric fluid to ensure proper flushing and spark generation.

B. Experimental Setup

Machining operations were conducted on an ELECTRONICA SPRINTCUT Wire EDM machine. The setup provided consistent and controlled machining conditions. The dielectric system maintained a constant temperature and filtered debris to ensure accuracy and surface quality.

Fig -1: ELPULS-40 A

Fig. 2: Tested Specimens

C. Selection of Input Parameters

Four critical WEDM parameters were selected based on literature and machine capability:

A. Wire Feed Rate (WF): 2, 3, 4 m/min
B. Pulse On Time (Ton): 112, 114, 116 µs
C. Pulse Off Time (Toff): 46, 47, 48 µs
D. Peak Current (Ip): 210, 220, 230 A

Other machining conditions were kept constant, including:

a) Wire Tension: 8 kg
b) Servo Voltage: 20 V
c) Servo Feed: 2120 mm/min
d) Dielectric Flushing Pressure: 1 kg/cm^2
e) Peak Voltage: 2 V

D. Design of Experiments

A Taguchi-based L9 orthogonal array was employed for efficient experimental design, minimizing the number of trials while maximizing the information gained. This approach allowed the analysis of individual parameter effects on MRR with statistical reliability.

E. Measurement of Response

The primary response variable was Material Removal Rate (MRR), calculated from the volume of material removed over time. The formula used was:

$$MRR = \frac{\text{Cutting length} \times \text{Width} \times \text{Thickness}}{\text{Machining Time}}$$

Additionally, the Signal-to-Noise (S/N) ratio was computed for MRR using the "larger-is-better" criterion to assess process stability and optimize parameter levels.

F. Statistical Analysis

Analysis of Variance (ANOVA) was conducted to determine the contribution and significance of each parameter. A multiple linear regression model was developed to predict MRR based on the selected input variables. Statistical tools, including Minitab 17, were used for analysis and model development.

4. EXPERIMENTAL RESULTS AND MODELLING RESPONSE VARIABLES

The experimental trials were conducted in accordance with the L9 orthogonal array design derived from Taguchi methodology. The aim was to analyze the influence of Wire EDM parameters—Wire Feed Rate (WF), Pulse On Time (Ton), Pulse Off Time (Toff), and Peak Current (Ip)—on the Material Removal Rate (MRR) during the machining of AISI D3 tool steel.

A. Experimental Observations

A total of nine experiments were performed, varying the four selected process parameters at three levels each. The measured values of MRR and their corresponding Signal-to-Noise (S/N) ratios are presented in Table 1

Exp. No	WF (m/min)	Ton (µs)	Toff (µs)	Ip (A)	MRR (mm^3/min)	S/N Ratio (dB)
1	2	112	46	210	19.7759	25.9227
2	2	114	47	230	21.2615	26.5519
3	2	116	48	220	23.0415	27.2502
4	3	112	47	220	19.6980	25.8884
5	3	114	48	210	20.6186	26.2852
6	3	116	46	230	21.3068	26.5704
7	4	112	48	230	19.3673	25.7414
8	4	114	46	220	20.0000	26.0206
9	4	116	47	210	19.9071	25.9802

Table -1: L9 Orthogonal Array – Experimental Results

B. Analysis of Variance (ANOVA)

ANOVA was used to identify the statistical significance and contribution of each parameter toward the variation in MRR. The results are shown in Table 2.

The results show that Pulse on Time is the most influential parameter on MRR, followed by Wire Feed Rate, Peak Current, and Pulse off Time.

Source	DOF	Adj SS	Adj MS	% Contribution
Wire Feed Rate	2	0.461593	0.230797	36.05%
Pulse On Time	2	0.860415	0.430208	46.76%
Pulse Off Time	2	0.128044	0.064022	8.10%
Peak Current	2	0.165220	0.082610	9.09%
Total	8	1.81723		100%

Table -2: ANOVA for MRR

C. Regression Modeling

A multiple linear regression model was developed to predict MRR as a function of the input parameters:

$$\mathbf{MRR=-53.6-0.857WF+0.4512Ton+0.380Toff+0.0336Ip}$$

This model yielded a coefficient of determination (R^2) of 94.17%, indicating a high degree of fit between the predicted and observed values. The adjusted R^2 was 88.34%, and the predicted R^2 was 66.99%, reflecting good model predictability within the tested parameter range.

D. Signal-to-Noise Ratio and Optimization

The S/N ratio analysis for MRR was conducted using the "larger-is-better" criterion. The response table (Table 8) revealed that the optimal levels for maximizing MRR were:

a)Wire Feed Rate: Level 1 (2 m/min)
b)Pulse On Time: Level 3 (116 µs)
c)Pulse Off Time: Level 3 (48 µs)
d)Peak Current: Level 2 (220 A)

The main effects plots confirmed these findings, highlighting Ton as the most sensitive parameter for enhancing MRR.

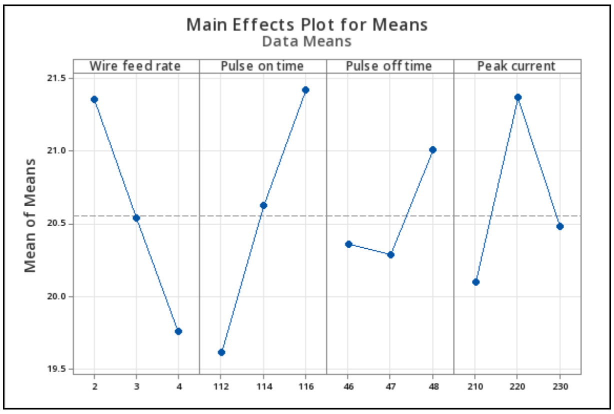

Chart -1: Main Effects Plot For Means

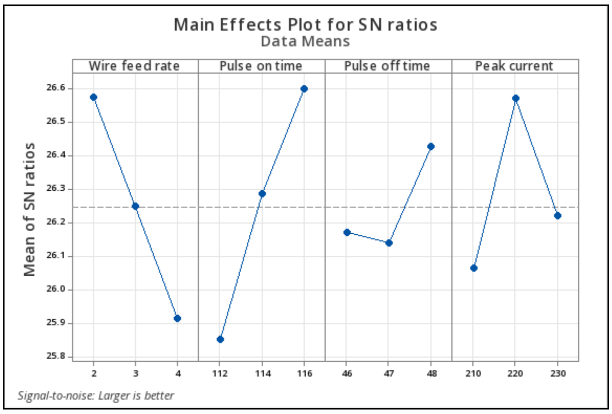

Chart -2: Main Effects Plot For S/N Ratios

Level	Wire feed rate	Pulse on time	Pulse off time	Peak current
1	26.57	25.85	26.17	26.06
2	26.25	26.29	26.14	26.57
3	25.91	26.60	26.43	26.22
Delta	0.66	0.75	0.29	0.51
Rank	2	1	4	3

Table -3: Response Table for S/N Ratios

5. CONCLUSIONS

This study optimized WEDM parameters to improve MRR while machining AISI D3 tool steel. Experimental results revealed that increasing pulse on time and pulse off time enhances MRR, while higher wire feed rate and peak current reduce it. Among all parameters, pulse on time had the most significant impact. The developed regression model predicted MRR with high accuracy. These findings provide valuable insights for selecting optimal WEDM settings to improve machining efficiency of hard tool steels.

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