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Exploring MRR in Wire EDM of Titanium Grade 5: A Statistical Analysis

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Abstract

The present study delves into exploring how various parameters of the WEDM process influence the material removal rate (MRR) behavior of Titanium grade 5 alloy, employing Taguchi methodology. Four key process parameters, namely pulse on time (Ton), pulse off time (Toff), wire feed (WF), and gap voltage (V), each with three levels, are chosen to effective MRR. Utilizing the L9 orthogonal array (OA), the study examines the impact of these input parameters and their interactions. S/N ratio analysis is employed to pinpoint the optimal conditions for maximizing MRR within the experimental range. Analysis of variance (ANOVA) is conducted to assess the significance of the process parameters. Subsequently, a confirmation test is carried out to validate the efficacy of the chosen design. Results indicate that at the optimal condition, the S/N ratio of MRR has improved by 13.5% compared to the initial condition.

Keywords: *WEDM, Titanium alloy, Taguchi methodology, Orthogonal array, ANOVA*

1. Introduction

In today's globalized world, the transportation industry faces heightened pressure to prioritize product processes and quality to remain competitive. The demand for weight reduction in automotive components necessitates the development of high-quality materials capable of withstanding fatigue, offering higher strength-to-weight ratios even at elevated temperatures, and providing excellent corrosion resistance [1]. Titanium alloy (grade 5) emerges as a prime candidate for such requirements, as it encompasses these desired properties. Notably, titanium alloys find widespread use in biomedical implants such as dental and knee implants, as well as in aerospace, nuclear, chemical, automotive, food, electronic, and military industries etc [2]. However, conventional machining of titanium and its alloys poses challenges due to excessive tool wear and high cutting temperatures [3]. Consequently, non-traditional machining methods become essential.

The manufacturing industry is undergoing a significant transformation, marked by the integration of "intelligent" systems and machines capable of automatic control and responsive behaviour [4]. Traditional machining methods often struggle with the mechanical properties and chemical reactivity of materials, prompting a shift towards non-traditional machining processes. These methods offer the advantage of producing high-quality surfaces and intricate shapes. Within

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this context, Wire Electrical Discharge Machining (WEDM) emerges as a promising solution. WEDM is particularly adept at high-precision machining regardless of material properties [5]. This energy-based process allows for complex part production and involves the removal of material through a series of electrical discharges between a wire electrode and the workpiece [6-8]. Wire Electrical Discharge Machining (WEDM) has become a prevalent method for crafting delicate components with high aspect ratios in various aerospace and aeronautical applications [9]. In this process, a slender wire serves as the electrode, transforming electrical energy into thermal energy to induce spark erosion and cut materials. Material removal occurs through a sequence of discrete electrical discharges between the wire electrode and the workpiece [10]. Notably, the absence of direct contact between the workpiece and the wire electrode eliminates vibration issues and mechanical stress during machining. In WEDM, the wire descends vertically while the table's movement remains horizontal, controlled by a CNC controller. Additionally, the wire is wound between two spools, ensuring constant alternation of active wire segments to prevent material erosion [4].

The research community has tried to various approaches to assess the machining characteristics of different titanium alloys. For instance, Kuriakose and Shunmugam [11] introduced a novel methodology to explore the impact of different process parameters on the machining characteristics of Ti-6Al-4V alloy using WEDM. They utilized Artificial Neural Network (ANN) to optimize machining parameters. Similarly, Sarkar et al. [12] investigated the machining characteristics of titanium aluminide, employing ANN to optimize WEDM machining parameters. Poro et al. [13] developed a semi-empirical model to demonstrate the effect of material characteristics and WEDM parameters on machining efficiency. Pasam et al. [14] employed the Taguchi method to optimize WEDM parameters for surface roughness of titanium alloys. Kumar et al. [15] focused on the machinability of commercially pure titanium using CNC-based WEDM. Garg et al. [16] explored the role of different process parameters of WEDM on surface roughness of titanium alloy. Despite extensive research, optimization of WEDM machining parameters for MRR behavior in titanium grade 5 remains unexplored. This study aims to fill this gap in the literature by conducting the aforementioned investigation. In this study titanium grade 5 is taken as work piece material and Taguchi based L9 orthogonal array is employed to optimize the MRR. Pulse on time (Ton), pulse off time (Toff), wire feed (WF) and gap voltage (V) are chosen as process parameters. Three levels of each parameter are also chosen to fulfil the objective. Analysis of variance is performed to establish significant parameters and finally validation test is carried out to confirm experimental results.

2. Experimental Details

2.1 Experimental setup

In this study, we have opted for titanium alloy (Grade 5) as our workpieces material. Table 1 presents the typical composition of this material. To ensure a high-quality design for well-organized systems, we've employed the Taguchi method, a widely recognized statistical technique. Taguchi introduced the concept of robust design, aimed at minimizing variations in both product and process design. This approach typically encompasses system design, tolerance, and parameter design. Here, we've focused on optimizing the machining parameters of titanium Grade 5 through parametric design. To streamline our experiments, we've utilized the orthogonal array (OA) concept, reducing the number of trials required. In Taguchi methodology, a loss function gauges the deviation between experimental and desired values, subsequently converted into a signal-to-noise (S/N) ratio. This ratio aids in assessing the effect of response output. Our objective in this study is to maximize the MRR, thus adopting a "higher the better" criterion. We utilize ANOVA and S/N ratio analyses to identify significant parameters and achieve optimality. The Taguchi method, owing to its efficiency in resource utilization, allows for systematic application with minimal resource expenditure. For our study, we've chosen four input factors, each with 3 levels, employing the L9 orthogonal array based on a degree of freedom (DOF) approach, as outlined in Table 2.

Table 1. Chemical composition of Titanium grade 5

Titanium (Ti)	**Carbon (C)**	**Nitrogen (N)**	**Aluminium (Al)**	**Iron (Fe)**	**Oxygen (O)**	**Hydrogen (H)**	**Vanadium (V)**
Balance	0.08	0.03	5.5-6.75	0.35	0.20	0.015	3.5-4.5

Table 2. Design factors and their level

Design factors	**Unit**	**Levels**		
		1	**2**	**3**
Pulse on (T_{on})	μs	4	6	8
Pulse off (T_{off})	μs	8	10	12
Wire feed (WF)	m/min	6	8	10
Gap voltage (V)	V	50	55	60

A CNC wire-EDM (WT 355, JOEMARS) was applied for machining of titanium grade 5 bar. In the course of machining, pulse-on time (Ton), pulse-off time (Toff), wire feed (WF), and gap voltages (V) are fluctuated while all other parameters are kept in fixed condition. Continual parameters and values are shown in Table 3. MRR is the output variable of present study. It is measured with the help of a digital vernier (MITUTOYO, PRC).

Table 3. Continual parameters during machining

Parameter	**Value**
Wire	Copper wire (ϕ 0.25mm)
Shape cut	10×7 mm^2
Thickness and height of the work piece	13 mm
Angle of cut	Vertical
Driving system	AC Servo Motor
Dielectric	De-ionized water

3. Result and discussion

S/N ratio can analyse the fluctuation of trial results. Taguchi proposed the use of S/N ratio than simple moving average method of preliminary experimental outcomes. S/N ratio statistically transforms the experimental outcomes to system data. Accordingly, S/N ratio analysis of MRR is executed by succeeding higher the better principle. Signal to noise ratio is assessed as:

$$\frac{S}{N} = -10\log\left(\frac{1}{n}\sum\frac{1}{y^2}\right) \qquad (1)$$

Where, n = number of experiments, y = observed data.

Table 4 shows the preliminary experimental results of MRR with their corresponding S/N ratio outputs. Mean S/N ratio value for every level of four parameters and their delta values are conferred in Table 5. Depending on delta values, ranks are presented to every input factor. Total mean value is exhibited in Table 5. Table 5 yields that pulse on time (Ton) is ranked as 1. Hence pulse on time has highest influence on MRR.

Table 4. Preliminary experimental results of MRR with their corresponding S/N ratio.

Sl. No.	**Ton**	**T_{off}**	**WF**	**V**	**MRR (mm^3/min)**	**S/N ratio**
1	4	8	6	50	5.917	15.4420
2	4	10	8	60	4.296	12.6613
3	4	12	10	70	4.536	13.1335
4	6	8	8	70	8.011	18.0737
5	6	10	10	50	7.867	17.9162
6	6	12	6	60	6.656	16.4643
7	8	8	10	60	7.235	17.1888
8	8	10	6	70	7.455	17.4489
9	8	12	8	50	7.118	17.0472

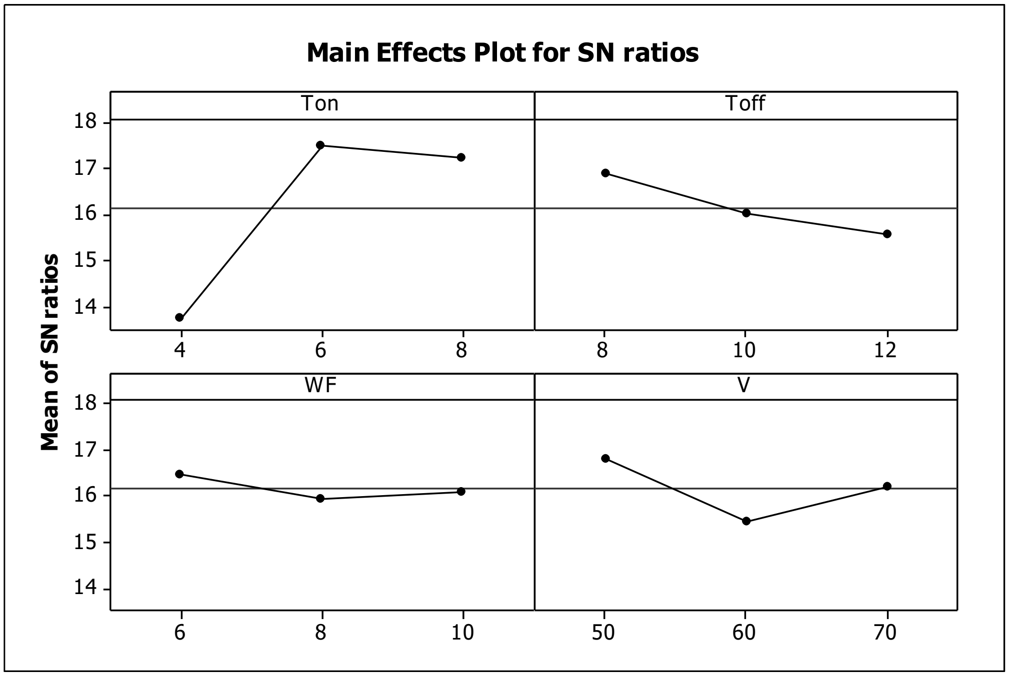

Fig. 1 Main effect plot for S/N ratio of Kerf width

Table 5. Response table for MRR

Level	T_{on}	T_{off}	WF	V
1	13.75	16.9	16.45	16.8
2	17.48	16.01	15.93	15.44
3	17.23	15.55	16.08	16.22
Rank	1	3	4	2
Delta	3.74	1.35	0.52	1.36

Total mean S/N ratio = 16.15 dB

Figure 1 shows the main effect plot of the current study. Main effect plot assists to achieve the optimal condition of machining parameters to maximum MRR. Combination of parametric levels which present highest S/N ratio is considered to be the optimal condition. Thus it can be said from Figure 1 that Ton2Toff1WF1V1 is the optimal condition. ANOVA is a typical statistical method to investigate the significance of input factors within the experimental range. ANOVA table consists of source variables and their corresponding degree of freedom, sum of square, mean square and percentage contribution. ANOVA table for MRR of Ti Grade 5 machined by WEDM is shown in Table 6. ANOVA table shows that the pulse on time (Ton) is most significant parameter while pulse off time (Toff) and gap voltage (V) are of moderate significance due to their contributions.

The predicted optimality is established by conducting confirmation test. For confirmation test, optimal condition is correlated with initial condition. For current study, $T_{on}2T_{off}2WF2V2$ is taken as initial condition and predicted value of S/N ratio is computed by following equation,

$$\hat{\gamma} = \gamma_m + \sum_{i=1}^{o} (\overline{\gamma_i} - \gamma_m) \tag{2}$$

Where, γ_m = total mean S/N ratio, $\overline{\gamma_i}$ = mean S/N ratio at optimum level, o = number of significantly affected process parameter. Result of confirmation test is presented in Table 7. Table 7 shows that S/N ratio of optimal condition is increased by 13.5% from the initial condition. Hence it can be said that the considered design is successfully employed for maximum MRR.

Table 6. Results of ANOVA for MRR

Source	DOF	Sum of square	Mean square	% Contribution
T_{on}	2	26.1761	13.0881	81.14
T_{off}	2	2.8402	1.4201	8.80
WF	2	0.4367	0.2183	1.35
V	2	2.8090	1.4045	8.71
Total	8	32.2619		

Table 7. Results of confirmation test

Initial condition		Optimal condition	
		Prediction	Experimentation
Level	$T_{on}2T_{off}2WF2V2$	$T_{on}2T_{off}1WF1V1$	$T_{on}2T_{off}1WF1V1$
MRR(mm3/min)	5.926		7.525
S/N ratio (dB)	15.4552	17.48	17.5301

4. Conclusions

In current study, the approach of Taguchi robust design is employed for optimising WEDM process parameters to maximize MRR behavior of Titanium grade 5 alloy. Experimental outcomes have been transformed into Signal-to-Noise (S/N) ratio values, and a main effect plot has been constructed. Analysis of variance (ANOVA) has been conducted to identify the key process parameters, and the results have been validated through confirmation testing. The main effect plot indicates that the optimal condition for this study is achieved with specific settings: Ton2Toff1WF1V1. ANOVA reveals that pulse on time exerts the most significant influence, followed by pulse off time and gap voltage, which have a moderate impact. The confirmation test demonstrates a noteworthy 13.5% improvement in the S/N ratio at the optimal condition compared to the initial condition.

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