Parametric Study of MRR and Surface Integrity for 304 Stainless Steel in EDM

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Abstract. 304 stainless steel is a promising material that is extensively used in manufacturing industries. Herein, the influence of the machining parameters electrical discharge machining (EDM) on the material removal rate (MRR) and surface integrity of 304 stainless steel are investigated. The improvement in the MRR with the optimum experimental conditions compared to the initial condition is 64% by the Taguchi methodology. The topography of the section surface produced by EDM with different pulse durations is studied. We founded that the section surface integrity becomes poorer with the increase in the pulse duration.

1. Introduction
Electrical discharge machining (EDM) is critical in modern manufacturing and is developing rapidly in the fabrication of various parts and components used in aerospace, energy, transportation, and medical care [1]. In the EDM process, a material is vaporized and melted by a local high temperature during each electric discharge [2]. Thus, the machining force exerted on the electrode and workpiece is almost 0 N [3]. Hence, the research on the machining characteristics of EDM to generate precise machining is therefore essential.

304 stainless steel is widely used owing to its good corrosion resistance, heat resistance, and outstanding mechanical properties. The primary 304 stainless steel processing methods are laser cutting, water jet cutting, plasma machining and EDM [4]. Additionally, EDM is the most common mean for stainless steel machining. Many studies pertaining to the optimization of EDM parameters have been reported. Chiang and Chang elucidated the surface roughness and MRR of the WEDM (wire electrical discharge machining) process for an AI2O3 particle-reinforced material based on the Grey relational analysis method [5]. The MRR and surface integrity are two important measure indicators for EDM. The MRR study for the EN47 spring steel in WEDM was investigated by S. Banerjee [6]. The improvement in MRR of the EN47 spring steel machining at the optimal condition compared to the initial condition is 26% by the Taguchi methodology. Hence, the machining products are evaluated by the MRR and surface integrity. Optimizing the machining parameters for obtaining a stable surface modification based on the Taguchi method has proven to be more efficient. Moreover, Rahul et al.
applied the Taguchi philosophy to optimize the electro-discharge machining responses of the super alloy Inconel 718 and addressed that the open-circuit voltage is the most significant parameter that influences the machining performances of the super alloy Inconel 718 [7].

The aforementioned studies pertained to WEDM or the influence of a single factor on EDM. Based on the electrical discharge that forms machining, we propose the study of the influence of machining parameters on the MRR and surface integrity of 304 stainless steel in EDM.

2. Experiments

2.1. Experimental setup
In our experiment, an 800-µm-thick 304 stainless steel was used as a workpiece of which the chemical composition is shown in Table 1.

| Chemical Composition (wt. %) | Cr  | Mn  | Si  | Ni  | Mo  | C   | p   | S   | Fe   |
|-----------------------------|-----|-----|-----|-----|-----|-----|-----|-----|------|
| Desired obtained            | 18.50 | 0.88 | 0.59 | 8.12 | 0.30 | 0.05 | 0.015 | 0.028 | Balance |

The electrode material was brass, which was fabricated by the medium-speed wire cutting machine (model: H-CUT32F), see figure 1. 304 stainless steel was machined by a square brass electrode with a manual electrical discharge machine. As shown in figure 1, the EDM machine was manufactured by the Shenzhen Du Feng Engineering Co., Ltd with the reciprocating feed.

Figure 1. (a) Medium-speed wire cutting machine (model: H-CUT32F) (b) EDM machine reciprocating feed.

The laser scanning confocal microscope (model: VK-X250) manufactured by KEYENCE, Japan was used to measure the workpiece size after processing. A FIB-SEM double-beam electron microscope (model 2016) was used to observe the surface morphology of the workpiece section after machining. Figure 2 provides a profile of the electrode and workpiece. The tip section of the electrode is a square with a side length of 2.45 mm. The workpiece is a 304 stainless steel of thickness 800 µm.
2.2. Design of experiments
Considering the time-consuming and huge economic expenditure of the full factorial design, the Taguchi design was applied to the experiment instead. The list of all parameters (fixed and variable) and levels are provided in Table 2-3. Four controllable factors exist in the work, each with three levels. Regardless of the factor interaction, the $L_9^{(3^4)}$ form is designed using Minitab 2017. The response factor is the MRR, which is calculated by the following formula [6]:

$$M = \frac{a \times h}{T}$$  \hspace{1cm} (1)

Where $M$ is material removal rate ($\text{mm}^3/\text{min}$), $a$ is total machining area ($\text{mm}^2$), $h$ is the thickness of the workpiece plate (mm) and $T$ (min) is total time taken. Each experimental machining time is recorded by the EDM machine.

3. Results and discussions
3.1. Taguchi analysis
The Taguchi method uses the robust design into the design process of the product in advance. By considering the uncontrollable noise factor, the product quality is deteriorated owing to the deviation from the established target value because of characteristic errors. This work aims to maximize the MMR by the Taguchi method. Hence, “the larger the better” is chosen. The estimated S/N ratio is calculated as [9]:

$$S/N \text{ ratio for HB}=-10 \log \left(\frac{1}{n} \sum \frac{1}{y^2}\right)$$  \hspace{1cm} (2)

Where $y$ is the observed date and $n$ is the number of observations.

The experimental values of the MRR is shown in Table 2. Table 3 and Table 4 show the response table for the S/N ratio and the response table for the means. According to the rank order, the significant correlation between factors and the response data as well as the relative importance of each factor in the model can be determined. From the rank order presented in Table 3, it appears that pulse duration is the most critical factor for the MRR in EDM, followed by the open voltage, pulse off time, and continuous processing time. Fig. 3 and Fig. 4 show the primary effects plot for the S/N ratio and main effects plot for means. Based on the information contained in Fig. 3, $T_{on}$ (70μs), $T_{off}$ (50μs), $T$ (8s), and $U$ (250V) are the optimal parameters.
Table 2. The experiment parameters and corresponding MRR

| Number | $T_{on}$ ($\mu s$) | $T_{off}$ ($\mu s$) | $T$ (s) | $U$ (V) | WRR (mm³/min) |
|--------|-------------------|-------------------|--------|--------|---------------|
| 1      | 6                 | 50                | 5      | 90     | 0.742         |
| 2      | 6                 | 90                | 8      | 190    | 1.279         |
| 3      | 6                 | 210               | 12     | 250    | 0.752         |
| 4      | 31                | 50                | 8      | 250    | 2.297         |
| 5      | 31                | 90                | 12     | 90     | 1.033         |
| 6      | 31                | 210               | 5      | 190    | 1.329         |
| 7      | 70                | 50                | 12     | 190    | 2.266         |
| 8      | 70                | 90                | 5      | 250    | 2.333         |
| 9      | 70                | 210               | 8      | 90     | 1.425         |

Table 3. Response table for the S/N ratio

| Level | $T_{on}$ ($\mu s$) | $T_{off}$ ($\mu s$) | $T$ (s) | $U$ (V) |
|-------|-------------------|-------------------|--------|--------|
| 1     | -0.9763           | 3.9120            | 2.4120 | 0.2567 |
| 2     | 3.3253            | 3.2591            | 4.1463 | 3.9037 |
| 3     | 5.8469            | 1.0248            | 1.6376 | 4.0355 |
| Delta | 6.8231            | 2.8872            | 2.5087 | 3.7788 |
| Rank  | 1                 | 3                 | 4      | 2      |

Table 4. Response table for the means

| Level | $T_{on}$ ($\mu s$) | $T_{off}$ ($\mu s$) | $T$ (s) | $U$ (V) |
|-------|-------------------|-------------------|--------|--------|
| 1     | 0.9244            | 1.7683            | 1.4679 | 1.0668 |
| 2     | 1.5530            | 1.5483            | 1.6671 | 1.6245 |
| 3     | 2.0080            | 1.1688            | 1.3503 | 1.7940 |
| Delta | 1.0836            | 0.5995            | 0.3168 | 0.7271 |
| Rank  | 1                 | 3                 | 4      | 2      |

Figure 3. Main effects plot for SN ratio.
3.2. Verification
The S/N ratio and the mean prediction value obtained from the Taguchi prediction by Minitab are 9.74476 and 2.75199 respectively. The experiment was conducted to validate the results acquired from optimization. The MRR is 2.339 (mm\(^3\)/min) using the optimized machining parameters, which improved 64% compared to the initial condition.

3.3. Effects of pulse duration on surface integrity
Owing to the Taguchi analysis results, the pulse duration is a decisive factor for the machining. Accordingly, the sectional morphology of samples machined at different pulse durations were observed using FIB-SEM double-beam electron microscopy. As shown in Fig. 5, it appears that the craters generated in the sparking are smaller with a pulse duration of 6µs. Therefore, the section surface is smoother than other simples machined with Ton (31µs) and Ton (70µs). This is because the size of the discharge crater depends on the single pulse energy which is calculated by the formula [10]:

\[ W_o = \int_0^{t_i} u(t) i(t) dt \]  

(3)

Where \( W_o \) is the energy of a single pulse, \( u \) is gap discharge voltage, \( i \), \( t_i \) are discharge current and pulse duration respectively.

Figure 5. a b c sectional morphology after EDM with pulse duration of 6µs, 31µs and 70µs.
From the result depicted in Fig. 6, it appears that micro-cracks and small holes generated in the sparking with discharge process. Virtually, the generation of micro-cracks is caused by the local stress exceeding the limit of the material strength. The material expands non-uniformly, resulting in a large thermal stress during EDM processing. Once the thermal stress exceeds the strength limit, the local destruction of the material occurs and micro-cracks are generated. Furthermore, small holes appeared in the path of the crack. The number of micro-cracks and small holes increases as the pulse energy increases. Therefore, a better surface integrity of the workpiece can be obtained by machining at a shorter pulse duration.

4. Conclusion
We have presented the parametric study of the MRR and the surface integrity of 304 stainless steel in EDM. The Taguchi orthogonal array was successfully applied to optimize the machining parameters for maximizing the MRR. The following results were obtained:
(1) The maximum MMR of 304 stainless steel was obtained when the machining parameters were $T_{on}$ (70μs), $T_{off}$ (50μs), $T$ (8s) and $U$ (250V).

(2) The primary effects plot for the S/N ratio demonstrated that the pulse duration ($T_{on}$) is the most significant factor that influences the MRR of 304 stainless steel in EDM.

(3) The MRR of 304 stainless steel increased 64% compared to the initial experimental condition using the Taguchi method.

(4) The morphological observation of the sample section shows that a better surface integrity of the workpiece can be achieved by machining at a shorter pulse duration.

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