Effect of Micro Wire-EDM Process Parameters on Recast Layer in the Molybdenum Micromachining

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Abstract: The Micro wire electrical discharge machining (Micro wire-EDM) process is a modern machining process with various applications in manufacturing micro-parts. The recast layer remaining on the machined surfaces is an inevitable complication of this process. This layer can subsequently affect the machined parts performance. To optimize the recast layer in the micro wire-EDM of the molybdenum microparts, effect of the process parameters on the distribution amplitude of the recast layer was investigated using the Taguchi method. The obtained results showed that the optimal levels of the micro wire-EDM process parameters for achieving the optimal distribution amplitude of the recast layer are as follows: spark pulse-on time of 0.2 μs, cutting speed of 7 mm/min, process voltage of 17 V, and wire tension of 0.45 kg. Also the importance order of the effect of the process parameters on the distribution amplitude of recast layer is as follows: spark pulse-on time, process voltage, cutting speed, and wire tension.

Keywords: Molybdenum, Micromanufacturing, Micromachining, Micro wire electrical discharge machining, Micro-WEDM, Recast layer

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1 INTRODUCTION

The micro wire-EDM process is an electrical discharge micro-machining (EDM) process for removing material from the surface of the conductive or semi-conductive workpiece through melting and evaporation. During this machining process, molten materials are left as solidified residues (called “recast layer”) on the machined surface as well as the side surfaces of the workpiece. The recast layer makes the surface lumpy, creates residual stress and may causes cracking the cutting surface, leading to the failure of the machined part. The smaller the recast layer, the higher the quality of the machined surfaces. Thus, by reducing the recast area, the quality of both the micro-machining process and the machined molybdenum microparts can be improved.

So far, little research has been conducted on the recast layer of the wire-EDM process. P. Rupajati et al., reported optimization of the recast layer thickness in the wire-EDM process of AISI H13 tool steel using the Taguchi method and fuzzy logic [1]. An empirical research was conducted by T. R. Newtona et al., to determine the essential wire-EDM parameters which contribute to the recast layer formation in the Inconel 718 machining [2]. It was indicated that thickness of the recast layer is increased with energy per discharge, peak discharge current, and discharge pulse duration. H. Shahali et al., indicated that the discharge current and number of finish passes have significant effect on the surface roughness and thickness of the recast layer in the wire-EDM machining of the DIN 1.4542 alloy [3]. Influence of pulse on time during rough cutting, pulse on time, wire tool offset, and constant cutting speed during trim cutting on the recast layer depth through response surface method in the Wire-EDM process was investigated by the A. B. Puri and B. Bhattacharyya [4].

S. Rajesha et al., investigated effect of the EDM process parameters such as gap current, pulse on-time and pulse off-time on the surface roughness of the recast layer using the Taguchi method [5]. Y. Zhang et al., had found that type of the dielectric has a great influence on the characteristics of recast layer [6]. They used water-in-oil (W/O) emulsion as dielectric in the EDM process. Larger surface roughness, thickness and micro hardness of the recast layer is created in W/O emulsion dielectric compared to kerosene and de-ionized water dielectric. Effect of the dielectric liquid and electrode type on the recast layer in the EDM process was studied by the B. Ekmekci [7]. It was seen that the residual stresses of the machined surface increases with non-homogeneities in the recast layer structure. K. T. Chiang et al., presented a model for the recast layer of the spherical graphite (SG) cast iron in the EDM process using the response surface method (RSM). This mathematical model reveals that the quantity and the area fraction of the graphite particle are the most dominant factors on the recast layer thickness. The greater is the graphite particle, the less is the recast layer thickness [8]. Muhammad Azam et al., conducted an empirical research on the influence of pulse-on time, pulse ratio, discharge current, pulse (spark gap), and wire speed parameters on the recast layer in wire-EDM of the high-strength low-alloy (HSLA) steel [9]. R. Mohamed et al. investigated the effect of rotational speed and gap voltage parameters on the recast layer hardness in the micro-EDM process [10].

According to the author's knowledge, no research has been conducted on the recast layer in the micro wire-EDM process. In this study, to optimize the recast layer distribution amplitude in micro wire-EDM of molybdenum microparts, effect of the following parameters on the distribution amplitude of the recast layer was investigated using the Taguchi method: spark pulse on-time, cutting speed, process voltage, and wire tension. The optimal level of the process parameters and the order of importance of the parameters’ effect on distribution amplitude of the recast layer were determined via conducting the S/N ratio analysis and the ANOVA respectively.

2 MATERIALS AND METHODS

A micro-positioning system was applied to perform the Micro-WEDM process. Molybdenum sheets with 100 µm thickness and 10×10 mm dimensions were used as workpiece, deionized water as dielectric, and tungsten wire with 100 µm diameter as the electrode. At first, to determine the parameters ranges, a number of molybdenum micro-features were machined, as shown in Fig. 1. It can be observed that the machined surfaces of the molybdenum micro-features have large recast layer. This factor severely and adversely affects the surface quality and performance of the molybdenum microparts. In the present study, the Taguchi method was used to investigate the effect of process parameters on the recast layer distribution amplitude and to determine the optimal conditions of this process to minimize the amplitude of the recast layer.

2.1. DOE based on the Taguchi Method

According to the Taguchi method, the main function of the process must be initially determined. In this study, the distribution amplitude of the recast layer was defined as the main function of the micro wire-EDM process. The parameters governing the process were determined in the next step of the Taguchi method.

The studied parameters included spark pulse on-time T_{on}, cutting speed S, process voltage V_P, and wire tension W_b. According to the preliminary experiments conducted in this research, four levels were defined for the four process parameters, as shown in table 1.

At this stage of the Taguchi method implementation, an orthogonal array must be selected for conducting the experiments. As shown in table 2 an orthogonal array $L_{16}(4^5)$ was selected for this study.

According to the selected orthogonal array, the required experiments were carried out and image of the recast layers were taken using the Scanning Electron Microscopy (SEM) at a magnification of 300x to 400x. At this stage of the Taguchi method implementation, an orthogonal array must be selected for conducting the experiments. As shown in table 2 an orthogonal array $L_{16}(4^5)$ was selected for this study. According to the selected orthogonal array, the required experiments were carried out and image of the recast layers were taken using the Scanning Electron Microscopy (SEM) at a magnification of 300x to 400x.

Table 1 Parameters of the micro wire-EDM process and their levels

Parameter		Level				Unit
		1	2	3	4	
T_{on}	spark pulse on-time	0.2	0.4	0.6	0.8	µs
S	Cutting Speed	7	8.4	9.8	11.2	mm/min
V_p	Process Voltage	17	19	21	23	V
w_b	Wire Tension	0.45	0.5	0.55	0.6	Kg

Table 2 Layout of the experiments using an L_{16} orthogonal array

Expt. No.	parameters and their levels				L_R (µm)	S/N (dB)
	T_{on}	S	V_p	W_b		
1	1	1	1	1	6.25	-15.917
2	1	2	2	2	7.65	-17.616
3	1	3	3	3	7.7	-17.729
4	1	4	4	4	7.6	-17.616
5	2	1	2	4	8.15	-18.223
6	2	2	1	4	7.6	-17.616
7	2	3	4	2	7.95	-18.007
8	2	4	3	1	7.07	-16.988
9	4	1	3	2	8.25	-18.329
10	4	2	4	1	8.7	-18.79
11	4	3	1	4	7.5	-17.5
12	4	4	2	3	7.5	-17.5
13	4	1	4	3	8.0	-18.062
14	4	2	3	4	8.5	-18.588
15	4	3	2	1	7.5	-17.5
16	4	4	1	2	8.4	-18.486

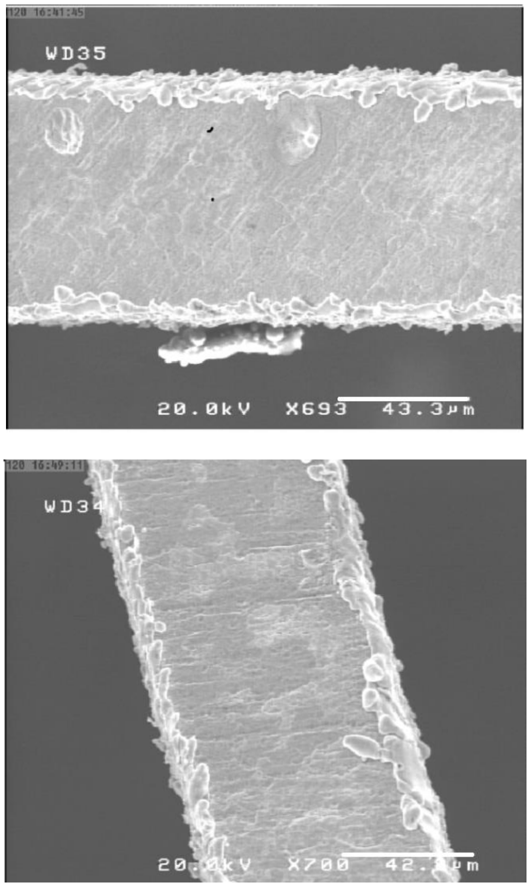

Fig. 1 Recast layer remained on the machined surfaces of micro-features

3 RESULTS AND DISCUSSION

Based on the Taguchi method, there are several types of the S/N ratio depending on the characteristics of the studied function: Lower is Better (LB), Nominal is Best (NB), and Higher is Better (HB). In this study, lower value of distribution amplitude of the recast layer (LB) is selected for better performance of the process. For the LB state, S/N ratio (η) for each test is calculated using Eq. (1).

$$\eta = -10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} L_{\mathrm{Ri}}^{2}\right) \tag{1}$$

Where, L_{Ri} is the distribution amplitude of the recast layer at the i-th iteration of each test. Regardless of the classifications of the S/N ratio (LB, NB, and HB), a higher value for the S/N ratio indicates better performance of the process. Therefore, the optimal level for each parameter is the level that creates the highest S/N ratio. The S/N ratios corresponding to the L_{16} experiments are shown in table 2.

Using this table, the mean value of the S/N ratios for different levels of the process parameters is calculated as follows:

$$\bar{\eta}_{ij} = \frac{1}{m}\sum_{k=1}^{m} \eta_{ijk} \tag{2}$$

Where, $\overline{\eta_{ij}}$ is the average value of the S/N ratios for the i-th parameter at the j-th level, m is the number of iterations of the j-th level for the i-th parameter in table 2. The average values of the S/N ratios at different levels of the process parameters are shown in table 3. Effect of the different levels of process parameters on the S/N ratio is depicted in Fig. 3.

Table 3 Average values of the S/N ratios for different levels of process parameters

Parameter	S/N (dB): Level			
	1	2	3	4
T_{on}	-17.22	-17.71	-18.03	-18.16
S	-17.63	-18.15	-17.68	-17.65
V_p	-17.38	-17.71	-17.91	-18.12
w_b	-17.50	-17.54	-18.31	-17.77

According to the Fig. 3, the following conclusions are obtained:

1. Spark pulse on-time (T_{on}): This parameter indicates pulse on-time of the electric sparks generated between the wire and the workpiece. By reducing the spark pulse on-time, energy of the electric spark is decreased. The shorter the pulse on-time, the less the molten material, and consequently the distribution amplitude of the recast layer is reduced. The S/N ratio is maximized in spark pulse on-time of 0.2 μs (level 1). Therefore, the distribution amplitude of the recast layer at this level is minimized.
2. Cutting speed (S): It can be seen that at level 1 of the cutting speed (7 mm/min) the S/N ratio is maximized. Therefore, the distribution amplitude of the recast layer at this level is the lowest. Cutting speed is especially limited in order to perform accurate cuttings. In cases where high accuracy is required or there is little material to be cut (low-thick sheets), it is better to limit the cutting speed in order to provide more stable machining. High cutting speed causes wire vibration and spark voltage instability, leading to fluctuation in the recast layer distribution amplitude.

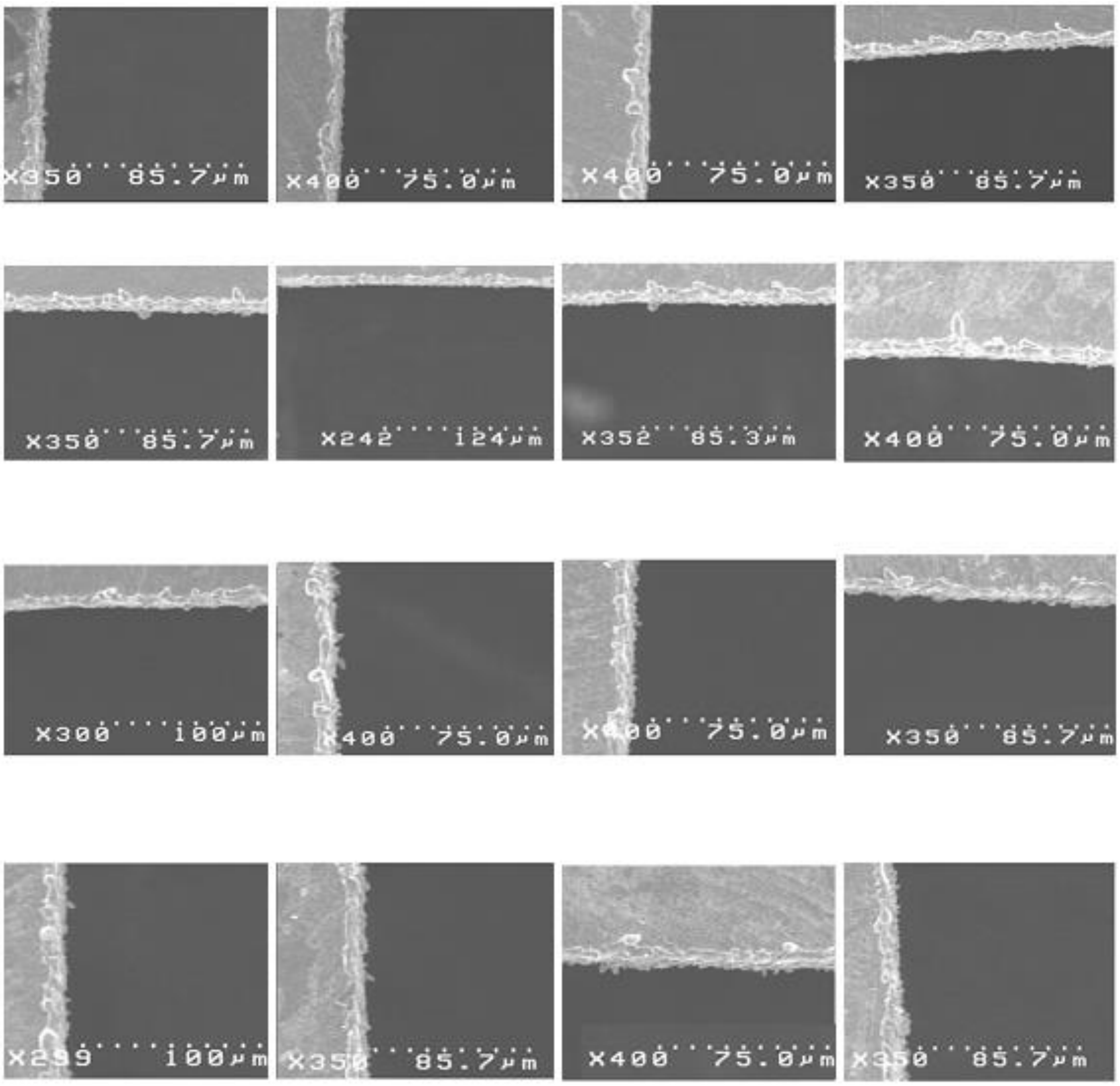

Fig. 2 SEM images of the recast layer on the micro-machined edges (from left to right and top to bottom, shown in the same order as the test numbers listed in table 2).

Table 4 Results of the ANOVA of the S/N ratios

Source	Degree of freedom (f)	Sum of squares (S)	Variance (V=S/f)	F-ratio (V/V_e)	P_p (%)=(S/S_{total}) * 100
T_{on}	3	2.101	0.7	4.861	40.3
S	3	0.749	0.25	4.53	14.4
V_P	3	1.284	0.43	2.99	24.6
W_b	3	0.645	0.215	1.49	12.4
Error	3	0.433	0.144		8.3
total	15	5.212			100

3. Process voltage (V_p): This parameter represents the electrical potential difference between the wire and the workpiece. At higher process voltages, electrical discharge power and thereby amount of the molten material at each spark are further. Therefore, the lowest level of the process voltage (17 V), which is level 1, causes the distribution amplitude of the recast layer to drop to its minimum value.
4. Wire tension (w_b): Wire tension must be adjusted to improve straightness and smoothness of the machined edges and achieve high dimensional accuracy. The S/N ratio in wire tension of 0.45 kg (level 1) is maximized. As a result, the distribution amplitude of the recast layer has the lowest value at this level.

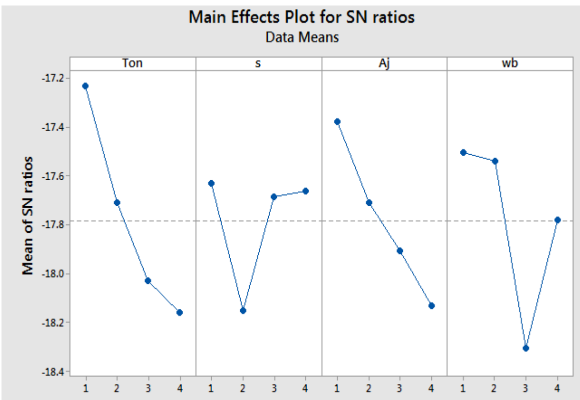

Fig. 3 Effect of the different levels of process parameters on the S/N ratio

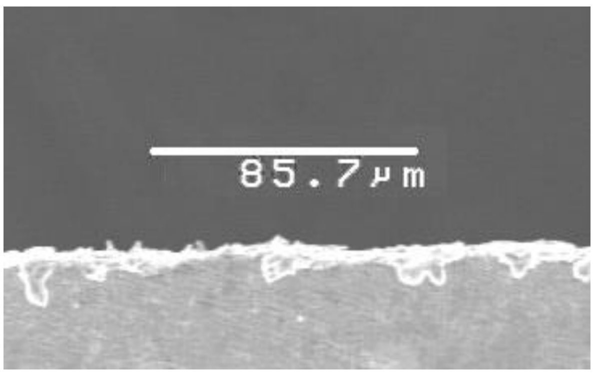

Fig. 4 SEM Image of the recast layer created in confirmation experiment with magnification of 350 times

By summarizing the above results, it can be concluded that the optimal levels of micro wire-EDM process parameters for achieving lowest distribution amplitude of the recast layer are as follows: the spark pulse-on time of 0.2 µs (level 1), the cutting speed of 7 mm/min (level 1), the process voltage of 17 V (level 1), and the wire tension of 0.45 kg (level 1).

3.1. ANOVA of S/N ratios

Relative importance of the effect of micro Wire-EDM process parameters on the distribution amplitude of the recast layer is investigated through analysis of variance (ANOVA) of the S/N ratios. Results of the ANOVA are shown in table 4. According to the mentioned results, the importance order of the effect of the process parameters on the distribution amplitude of the recast layer is as follows: spark pulse-on time, process voltage, cutting speed, and wire tension.

3.2. Confirmation experiment

The final step in the Taguchi method is to evaluate the improvement of the process performance using the optimal level of the process parameters. To perform the confirmation experiment, process parameters were regulated on the optimal level. Fig. 4 shows SEM image of the optimal distribution amplitude of the recast layer generated in the confirmation experiment with a magnification of 350 times. The result of this test shows that the distribution amplitude of the recast layer has been decreased up to 5 µm. This result confirms efficiency of the Taguchi method in optimizing the distribution amplitude of the recast layer.

4 CONCLUSION

In this research, to optimize the distribution amplitude of recast layer in the micro wire-EDM process, effect of the process parameters including spark pulse-on time, cutting speed, process voltage, and wire tension were studied using the Taguchi method. The obtained results showed that the optimal levels of the micro wire-EDM process parameters for achieving the optimal distribution amplitude of the recast layer are as follows: spark pulse-on time of 0.2 µs, cutting speed of 7 mm/min, process voltage of 17 V, and wire tension of 0.45 kg. According to the results of analysis of variance of the S/N ratios, the importance order of the effect of the process parameters on the distribution amplitude of recast layer is as follows: spark pulse-on time, process voltage, cutting speed, and wire tension. In this study, distribution amplitude of the recast layer was decreased up to 5 µm via using the optimal levels of the micro wire-EDM process parameter.

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