Micro Wire Electrical Discharge Machining of MEMS Structures with Optimized Dimensional Deviation

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Abstract: Metal-based microelectromechanical systems are widely used in applications such as micro-energy harvesters, micro-heat exchangers and micro-electromagnetic that require high strength and flexibility. In the fabrication of such systems, micro wire electrical discharge machining (MicroWEDM) is majorly used. This paper studies the effect of the MicroWEDM process parameters on the dimensional deviation of machined MEMS structures including microcantilevers and micro-beams using the Taguchi method. Using optimal levels of the parameters including pulse duration (0.8 µs), cutting speed (8.4 mm/min), voltage (17 V) and wire tension (0.5 kg), the dimensional deviation is reduced about 8.65 times compared with the average of experiments results. The order of effect importance of the process parameters on the dimensional deviation of microstructures obtained by the ANOVA analysis of S/N ratios is as follows: pulse duration, wire tension, process voltage and cutting speed. Dimensional deviation of the micro-features was reduced to 1 µm using the optimal levels of the process parameters.

Keywords: MEMS, Microbeam, Microcantilever, Micromachining, Micro Wire Electrical Discharge Machining, Micro-WEDM

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1 INTRODUCTION

Although in recent decades the use of silicon-based microelectromechanical systems (MEMS) has made significant progress in various industries, metal-based MEMS has always been of interest to researchers because of their unique characteristics. Micro-heat exchangers and micro-electromagnetic relays are among the unique applications of metal-based MEMS. In addition, researches about silicon- and metal-based piezoelectric energy harvesters show that metal energy harvesters not only generate a higher amount of electrical energy but also have higher strength against imposed acceleration [1]. Metal MEMS are also used in some medical applications such as microsurgery equipment because of their higher strength [2]. Due to the wide application of metal-based MEMS, development of metal micro-fabrication technologies is very important.

One of the most important of these processes is the micro-wire electrical discharge machining (MicroWEDM) which is less costly and faster than other micro-fabrication processes such as LIGA and FIB. Since no mechanical force is applied in this method, microstructures with high aspect ratio and high dimensional accuracy can be machined. Therefore, this technology is widely used in micro-mold fabrication for the replication of different microstructures [3-5].

M. Y. Ali et al. [6] compared MicroEDM and MicroWEDM processes in manufacturing micro-gears, which are the key elements in micro-drivers of micro-motors, in terms of surface quality and dimensional accuracy and observed that the MicroWEDM process provides significantly better roughness and accuracy. Y. S. Liao et al. [7] used a technique called reverse MicroWEDM to produce arrays with a high aspect ratio that are widely used in the medical industry and biotechnology. Practical research on the right amount of tension in the brass wire was also conducted in this study, and an anti-vibration system was implemented in order to achieve the highest accuracy. Song Mancang et al. [8] used the WEDM process for manufacturing micro-cantilevers that are basic and useful MEMS elements and achieved high surface finish by adjusting the electrical discharge parameters. Namsun Chou et al. [9] examined the use of metal microarrays made with high aspect ratio using the micro-WEDM process which is used as nerve tissue penetrating electrodes for sampling. B. Khuriachen et al. [10] presented a fuzzy-based model using the particle swarm optimization algorithm for optimizing the micro-WEDM process on titanium alloys.

K.P. Somashekhar et al. [11-12] studied the optimization of micro-WEDM parameters for machining aluminium parts and presented a model based on the Design of Experiments (DOE) technique and the genetic algorithm. D. Rakwal et al. [13] used micro-WEDM to machine silicon microelectrodes and removed the recast layers using chemical etching. A. Schoth et al. [14] presented a micro-WEDM process for fabrication of metallic and ceramic microstructures with high aspect ratio. They used this process to cut complex micro-parts such as gear. S. Di et al. [15] analyzed the cutting kerf in the micro-WEDM process. To study cutting kerf variations in the micro-WEDM process, they proposed a mathematical model for the lateral vibration of the wire. P. Sivaprakasam et al. [16] conducted a study on multi-objective optimization of the micro-WEDM process parameters in titanium alloy machining using the response surface methodology and the genetic algorithm. P. Allen and X. Chen [17] simulated the EDM process on a molybdenum workpiece and analyzed the material removed during a single spark through a thermal model. They then studied the effect of important parameters such as spark pulse duration on the cavities formed on the workpiece and percentage of tool erosion using single-spark experiments.

Zhenlong W. et al. [18] presented analysis of the recast layer characteristics and surface integrity of SiC/Al particulate MMC in the micro-WEDM process. Gupta K. et al. [19] fabricated miniature spur gears with microscale geometry of fine pitch by the WEDM process and investigated effects of the process parameters on the total profile and accumulated pitch errors. Optimization of the conventional wire electrical discharge machining (WEDM) process parameters to perform microfabrication on the copper substrate was conducted by Ali M.Y. and Mohammad A.S. [20]. Analysis of kerf width and its influencing parameters in dry micro-WEDM and a control method to improve the process accuracy was reported by Hoang K.T. and Yang S.H. [21]. Balasubramanian K.R. et al. [22] investigated the combination of optimum process parameter to achieve the desired surface quality and material removal rate in the Micro-WEDM process. However, in the case of fabrication of micro-cantilevers and micro-beams, the precision of fabrication methods is not sufficient enough to fabricate micrometer devices.

This paper presents a method to improve the precision of MicroWEDM fabrication process by which a micrometer accuracy has achieved. The effect of process parameters on the dimensional deviation of microstructures are studied and these parameters are optimized using the Taguchi method in a way that minimizes dimensional deviation. Using optimized process parameters, the dimensional deviation is reduced 8.65 times. Analysis of variance (ANOVA) on the S/N ratios is used to obtain the order of the importance of the process parameters influence on the dimensional deviation of microstructures. Dimensional deviation of the micro-features is reduced to 1 μm using the optimal levels of the process parameters.

2 MAREIALS AND METHODS

Figure 1 shows a high-g steel accelerometer fabricated using MicroWEDM method. An advantage of this method in manufacturing microaccelerometers is achieving the large scale of proof mass that reduces the effects of damping and thermal noises. Therefore, this metal microaccelerometer does not need a high vacuum in packaging. In addition, due to the high fracture toughness of steel, this accelerometer has a wide frequency bandwidth and broad measurement dynamic range, which is suitable for high-g accelerometer applications. This study uses a micro-positioning system for precise positioning of the micro-machining process, a 10×10 mm plate with a thickness of 1 mm as the workpiece, DI water as the dielectric, and a 100-micrometer diameter tungsten wire as the cutting tool. The Taguchi method is used to determine the optimum conditions for micromachining, and the effects of process parameters on the dimensional deviation of microstructures are studied.

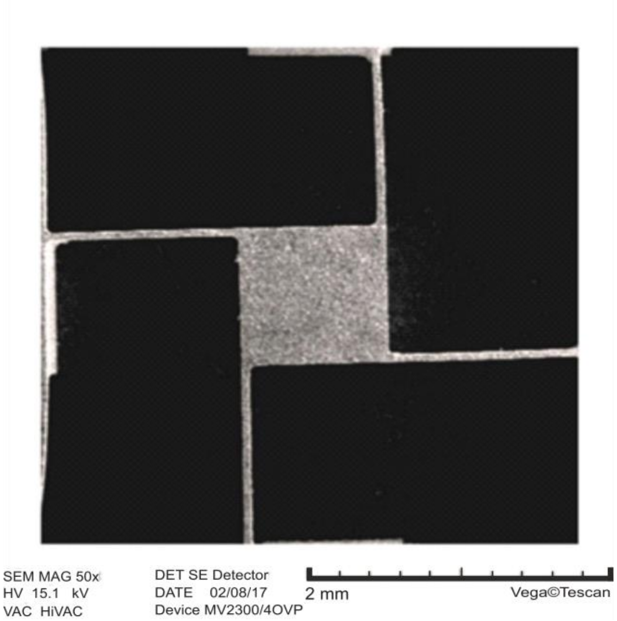

Fig. 1 A spring-mass structure of a high-g microaccelerometer fabricated using the MicroWEDM process.

3 APPLICATION OF TAGUCHI METHOD

Step 1: In accordance with the Taguchi method, the difference between the machined micro-features width and the desired value (dimensional deviation) was defined as the main function of the micro-WEDM process.

Step 2: The parameters studied in Micro-WEDM were: spark pulse on-time, cutting speed, process voltage, and wire tension. The parameters range was determined based on the preliminary studies and experiments as follows:

a) Spark Pulse On-time (T_{on}): This parameter shows the duration of the spark pulses created between the wire and the workpiece. The longer the spark pulse on-time, the more the electrical spark energy. Therefore, with increasing the spark pulse on-time, the wire erosion rate and the material removal rate (MRR) are increased. As a result, the dimensional accuracy of the micro-features is decreased. On the other hand, reducing the spark pulse on-time decreases the electrical spark energy, leading to the reduction of the machining rate. This improves machining accuracy. Therefore, based on the preliminary experiments, the range of spark pulse on-time was considered as 0.2-0.8 µs.

b) Cutting Speed (S): The cutting speed is limited to increase the machining accuracy. If a high accuracy is required or in case there is not sufficient material for cutting (low-thickness sheets), it is better to limit cutting speed to stabilize the machining process. Since, at high speeds, dimensional accuracy of the machined micro-features is reduced due to wire vibration, leading to burr forming on the cut edges. Based on the preliminary experiments, the cutting speed range was taken as 7-11.2 mm/min.

c) Process Voltage (V_p): The potential difference between the wire and the workpiece, can be adjusted between 1 V to 220 V. Process voltage has a great influence on the material removal rate and the surface roughness. Raised process voltage causes an increase in the electrical discharge power and material removal rate. This may lead to fracture of wire or micro-features. Based on the conducted preliminary experiments, the range of process voltage was considered to be between 17 and 23 volts. The process voltage less than 17 volts reduces dramatically the micromachining speed.

d) Wire Tension (W_b): It is of importance to adjust wire tension to improve straightness and smoothness of the cut edges of micro-features and to achieve close dimensional tolerances. Increased wire tension reduces wire vibration, which leads to less dimensional deviation and enhances the smoothness of the machined surfaces. However, increasing wire tension beyond a certain limit would lead to rupturing of the wire. The experiments conducted in this study showed that a wire tension higher than 0.7 kg would rupture the wire and that the lower wire tension limit for this type of wire for cutting workpiece with a thickness of 100-µm was 0.45 kg. Consequently, the wire tension range was considered to be 0.45-0.6 kg. As shown in "Table 1", four levels were defined for the four parameters from among the selected ranges.

Table 1 Parameters of micro-WEDM process and the defined levels

Parameter		level 1	2	3	4	unit
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

Step 3: In this step of the Taguchi method implementation, an orthogonal array was selected for conducting the experiments. To select an appropriate array, we must calculate the sum of the degrees of freedom in the process. This sum equals the total number of comparisons that need to be conducted between different parameter-levels to determine the optimum level. Based on the Taguchi method, the degree of freedom of a parameter with n levels is n-1. In case the process has m parameters, the total degree of freedom of the process is $m(n-1)$. Here, four parameters at 4 levels are defined for the micro-machining process. Therefore, the process has 12 degrees of freedom. The degree of freedom of the selected orthogonal array should be greater than or equal to those for the process parameters. Here, an L_{16} (45) orthogonal array is used with 15 degrees of freedom. This array has 5 columns and 16 rows and it can be used to optimize a process with a maximum number of 5 parameters at 4 levels. Each column of the orthogonal array belongs to one of the process parameters. Sixteen experiments are required to study the effect of all parameters and their levels on the dimensional deviation of the machined micro-features (L_t). “Table 2” shows the experiments layout as an L_{16} orthogonal array. Based on the selected orthogonal array, the required experiments were carried out and images of the resulted micro-features were taken at 300x and 400x magnifications using a scanning electron microscope (SEM). These images are shown in “Fig. 2”. Width of the micro-features shown in “Fig. 2” was measured and their corresponding deviations from the desired value (90 µm) were calculated. The results and their S/N ratios are given in “Table 2”.

4 RESULTS AND DISCUSSION

A. *Analysis of the S/N Ratios*

Based on the Taguchi method, there are several types of S/N ratios including *Lower is Better (LB)*, *Nominal is Best (NB)* and *Higher is Better (HB)*, depending on the process specifications. Here, the lower level of dimensional deviation (LB) was defined as the better performance for the process. For the LB case, the S/N ratio (η) is calculated for each experiment using Eq. (1).

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

Where, L_{ti} is the dimensional deviation in the i^{th} iteration of each test. Regardless of the S/N ratio categorizations (LB, NB, and HB), the higher value of this ratio indicates better performance of the process. Therefore, the optimal level of each parameter is the value that produces the highest value of the S/N ratio.

Table 2 Experiments layout using the L_{16} orthogonal array

Expt. No.	Parameters and their levels T_{on}	S	V_p	W_b	L_t (µm)	S/N (dB)
1	1	1	1	1	3.0	-9.5424
2	1	2	2	2	2.5	-7.9588
3	1	3	3	3	10.5	-20.4238
4	1	4	4	4	19.6	-25.8451
5	2	1	2	3	8.5	-18.5884
6	2	2	1	4	14.5	-23.2274
7	2	3	4	1	13.2	-22.4115
8	2	4	3	2	13.5	-22.6067
9	3	1	3	4	14.6	-23.2871
10	3	2	4	3	7.8	-17.8419
11	3	3	1	2	4.7	-13.4420
12	3	4	2	1	12.8	-22.1442
13	4	1	4	2	2.0	-6.0206
14	4	2	3	1	2.5	-7.9588
15	4	3	2	4	7.2	-17.1466
16	4	4	1	3	1.5	-3.5218

“Table 2” shows the S/N ratios obtained from L_{16} experiments. Using these S/N ratios, the mean value of the S/N ratios for different levels of each process parameter is calculated as:

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

Where, η_{ij} is the mean value of the S/N ratio for the ith parameter at the jth level, m is the number of iterations of level j for parameter i, and η_{ijk} is the S/N ratio corresponding to the k_{th} appearance of level j for parameter i in “Table 2”.

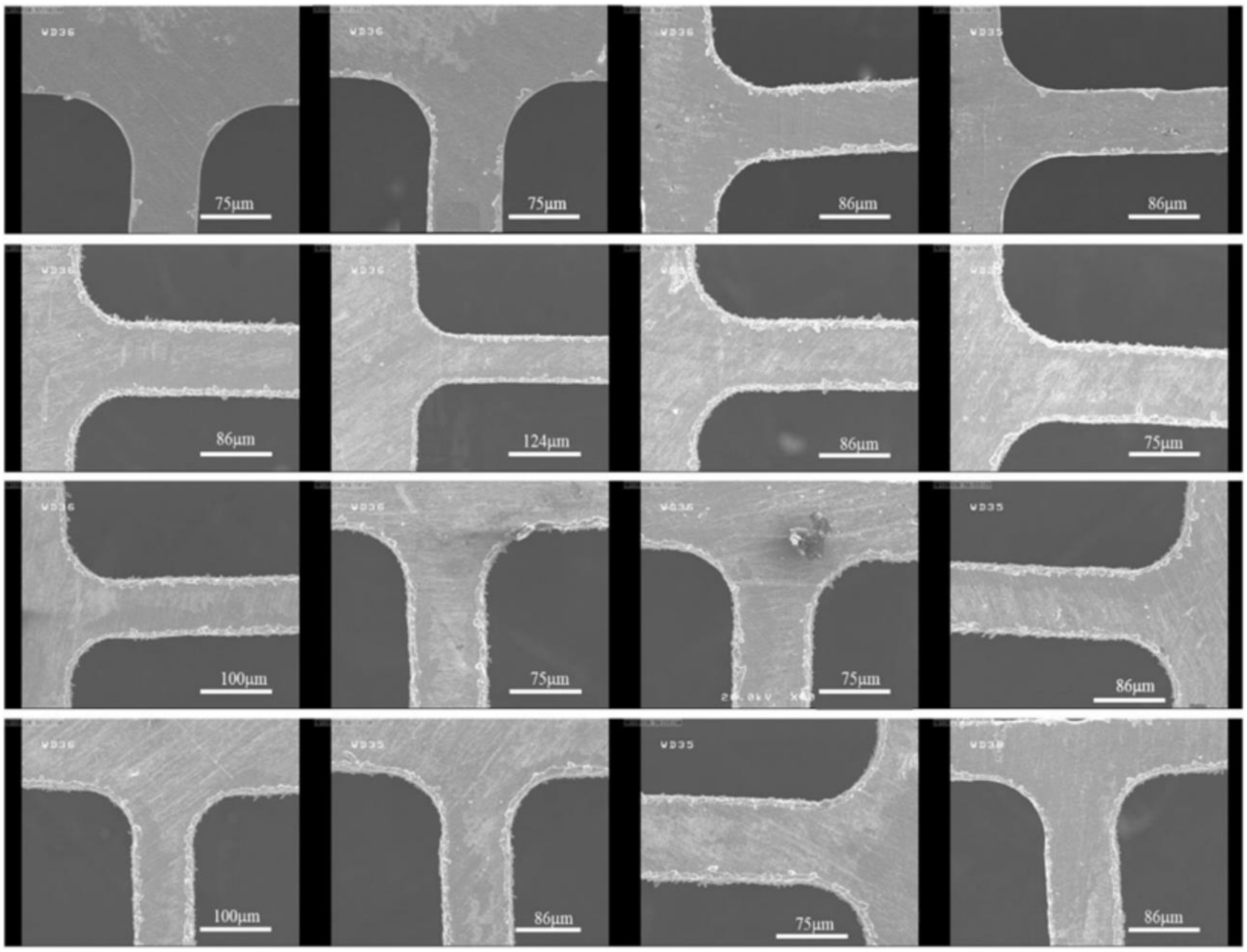

Fig. 2 SEM images of the micro-features based on the experiments layout shown in table 2 (From left to right and top to bottom, corresponding to the number of the experiments).

Table 3 shows the mean value of the S/N ratios at the different levels of the process parameters. Figure 3 shows the effect of different levels of the process parameters on the S/N ratio.The results in "Table 3" and "Fig. 3" lead us to the following conclusions:

a) Spark Pulse On-time (T_{on}): Spark pulse on-time at the level 4 is 0.8μs and the S/N ratio is maximized at this level. Therefore, dimensional deviation of the machined micro-features is less at this level of spark pulse on-time.

Table 3 The mean value of the S/N ratios at different levels of the process parameters.

S/N (dB) / Level	T_{on}	S	V_p	W_b
1	-15.943	-14.360	**-12.433**	-15.514
2	-21.708	**-14.247**	-16.460	**-12.507**
3	-19.179	-18.356	-18.569	-15.094
4	**-8.662**	-18.529	-18.030	-22.377

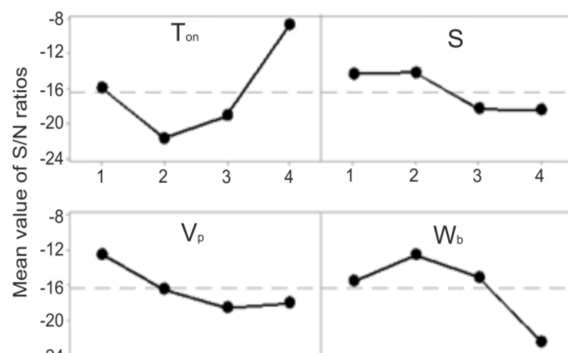

Fig. 3 Effect of different levels of the process parameters on the S/N ratio.

b) Cutting Speed (S): Low cutting speed reduces wire vibration and improves dimensional accuracy of the machined micro-features. At level 2, the cutting speed is 8.4 mm/min and the S/N ratio is maximized. Consequently, the minimum dimensional deviation is obtained at this level of cutting speed.

c) Process Voltage (V_p): Increase of the process voltage raises the electrical discharge power and consequently the material removal rate. As a result, using the lowest voltage level, i.e. level 1 (17 V), minimizes the material removal rate, which in turn improves machining accuracy. Therefore, lower dimensional deviation occurs at this level of the process voltage.

d) Wire Tension (W_b): The S/N ratio is maximized at wire tension level 2 (0.5 kg). Therefore, the dimensional deviation is lower at this level of wire tension.

Consequently, it can be concluded that the optimal levels of micro-WEDM process parameters to achieve the minimum dimensional deviation are as follows: spark pulse on-time of 0.8 µs (level 4), cutting speed of 8.4 mm/min (level 2), process voltage of 17 V (level 1), and wire tension of 0.5 kg (level 2).

B. ANOVA of the S/N Ratios

The relative importance of the effect of different process parameters on the dimensional deviation of machined micro-features is determined via conducting Analysis of Variance (ANOVA) on the S/N ratios. “Table 4” shows the ANOVA results for the S/N ratios. The higher the F-ratio (or the contribution percentage) of a parameter, the more effect of the parameter on the dimensional deviation. Therefore, based on the ANOVA results, the following order of importance was obtained for the effect of Micro-WEDM process parameters on the dimensional deviation of machined micro-features: spark pulse on-time, wire tension, process voltage, and cutting speed.

Table 4 Results of the ANOVA of S/N ratios

Source	f	S	V(S/f)	F(V/V$_e$)	P$_p$(%)
T_{on}	3	383.94	127.98	13.72	48.82
S	3	68.63	22.88	2.45	8.73
V_p	3	92.38	30.79	3.30	11.75
w_b	3	213.45	71.15	7.63	27.14
error	3	27.98	9.33	____	3.56
Total	15	786.38			100

f: Degree of freedom, S: Sum of Squares, V: Variance, Ve: Variance of error, F: F-ratio, Pp(%):(S/S$_{total}$)“*100, Contribution Percentage

C. Confirmation Experiment

Confirmation test is the final step in optimizing dimensional deviation of the machined micro-features based on the Taguchi method. Results of this test prove the correct application of the Taguchi method in the design of experiments. After determining optimal levels of the Micro-WEDM process parameters, a new test was carried out by adjusting the parameters at their optimal level. Figure 4 shows the SEM image of the micro-feature with the optimal dimensional deviation. The dimensional deviation as compared to the desired value is 1 µm. The dimensional deviation has been reduced about 8.65 times as compared with the mean value of the 16 experiments.

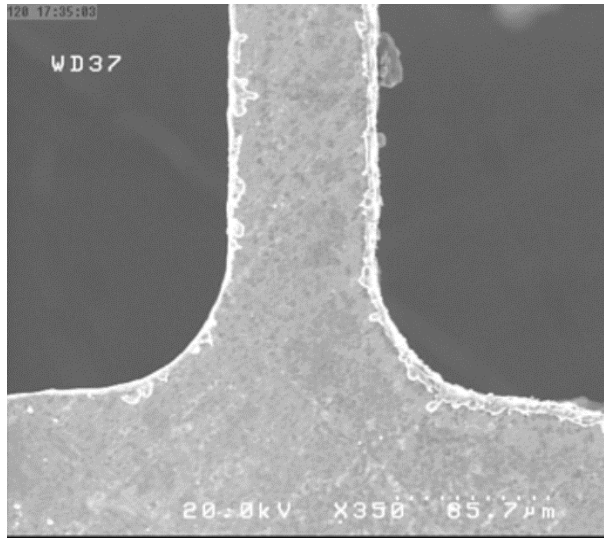

Fig. 4 SEM image of the micro-feature with optimal dimensional deviation.

5 CONCLUSION

In this research, the Micro-WEDM process was implemented for machining some critical micro parts that are extensively used in MEMS. The micro beam-mass and micro-cantilever structures that were fabricated in this study are the basic elements in the microelectromechanical sensors and actuators. Effect of the spark pulse on-time, cutting speed, process voltage, and wire tension parameters on the dimensional deviation of machined micro-features were studied using the Taguchi method to optimize the Micro-WEDM process.

The optimal levels of the Micro-WEDM parameters to achieve minimum dimensional deviation were obtained as follows: spark pulse on-time of 0.8 µs, cutting speed of 8.4 mm/min, process voltage of 17 V, and wire tension of 0.5 kg. Based on the ANOVA of the S/N ratios, the following order of importance was obtained for the effect of the Micro-WEDM process parameters on the dimensional deviation of the machined micro-features:

spark pulse on-time, wire tension, process voltage, and cutting speed. Dimensional deviation of the micro-features was reduced to 1 µm using the optimal levels of the process parameters. The dimensional deviation was reduced to about 8.65 times as compared with the mean value of the dimensional deviation of the experiments.

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