An Ultrasonic Vibration Assisted Electrical Discharge Machining Device with Workpiece Vibration

Hongbing Wang[1,*], Chunhua Sun[2], and Yifei Yang[2]

[1] *Department of Mechanical Electrical EngineeringSuzhou Vocational UniversitySuzhou215104China*
[2] *3C-Product Intelligent Manufacturing Engineering Technology Research and Development CenterSuzhou215104China*
[*] *Corresponding author. E-mail: whb45@163.com*

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For solving the problem of machining micro deep hole in hard material, an ultrasonic vibration assisted electrical discharge machining (UV-EDM) device with workpiece vibration was designed and fabricated. The piezoelectric vibrator which had appropriate longitudinal mode and frequency was designed and tested. The first-order longitudinal vibration frequency of the piezoelectric vibrator was 21450Hz, and the vibration velocity of the piezoelectric vibrator head was about 24 mm/s.Then the influence of ultrasonic vibration on the EDM machining of micro deep hole in die steel was studied. Experiments showed that the efficiency of ultrasonic EDM based on workpiece vibration was higher than that of traditional EDM. The orthogonal experimental design was used to optimize the process parameters. The machining depth was set as the experiment index. Four process parameters, including excitation voltage , pulse current, pulse width and pulse gap, were selected as the experimental factors. The influence degree of the four process parameters on the machining depth was obtained by optimization. And the best level combination of process parameters were obtained. Through the analysis of variance, the interval estimation of the optimal combination was carried out, and the confidence degree of the interval estimation was given. The test result indicated the micro deep hole with diameter Φ0.5mm and high aspect ratio 67 could be drilled effectively with optimized process parameters. The theoretical and experimental results showed that the proposed UV-EDM was valuable in machining micro deep holes with high aspect ratio in hard materials.

Keywords: Ultrasonic EDM; Piezoelectric vibrator; Workpiece vibration; Process parameters; Orthogonal experiment

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1. Introduction

With the progress of the technology and the development of micro mechanics, micro holes with diameter less than 1 mm have been widely used in various fields including aerospace, electronics, photonics, biomedical and medical industries [1]. Electrical Discharge Machining (EDM) is an effective method used to machine micro deep holes. EDM is a process of metal removal by a series of rapidly reoccurring electrical discharge through a small gap filled with dielectric fluid between an electrode and a workpiece [2–4]. Basically, spark flows from the electrode through a dielectric fluid when the gap distance from tool to work piece is reduced to a very small clearance approximately 10 to 100 microns. Electrical energy from the spark is converted into heat energy which improves the work- piece temperature and melts the area on its surface [5]. Debris are created and accumulated in the sparkling gap between an electrode and a workpiece in a diesinking EDM process. If the debris density becomes too great in certain points in the gap, there is a reduction in the resistance, which encourages the formation of abnormal discharges, results in a significant electrode wear or damage and slows down the machining efficiency. For micro deep holes the removal of debris can not be done by the periodical flushing operation with a through hole electrode. As a result, new flushing technologies for micro deep holes, particularly with high aspect ratios, are greatly needed [6, 7]. To improve the machining performance of EDM, a combined method of ultrasonic and electrical discharge machining has been developed in recent decades. The introduction of ultrasonic vibration technology in traditional EDM can exert strong disturbance on the flow of working fluid, thus promoting the elimination of erosion products and improving the machining efficiency and stability [8].

Kremer et al. applied ultrasonic vibrations (20 kHz) to the tool to achieve process improvements. The influence of ultrasonic vibration on spark discharge was further studied through an experimental investigation. They reported that the EDM efficiency was increased and the machined surface, as well as the thermal affected layer, was improved with the aid of ultrasonic vibration [9]. Shervani-Tabar and Abdullah numerically and experimentally studied the effect of vibration of the tool in ultrasonic assisted EDM. The results showed that the material removal rate increased in the ultrasonic assisted EDM [10]. Abdullah A and Shabgard MR designed and analyzed effect of electrode vibration on EDM. The results showed that EDM with electrode vibration had higher material removal rate under low discharge currents and low pulse times [11]. Takashi Endo et al. proposed vibration-assisted machining to micro-EDM using PZT.The results indicated that vibration assistance improved the machining stability and results in an extreme reduction of the machining time [12].

Liu et al. proposed a three-dimensional (3D) model of debris movement in the gap flow field of EDM small hole machining assisted with side flushing and ultrasonic vibration.The results showed that periodic ultrasonic vibration can promote the movement of debris, which was beneficial to the removal of debris in the machining gap [13]. Ni et al. presented an analytical model for calculating the tool-workpiece contact rate (TWCR) in ultrasonic vibration assisted milling (UVAM). The results showed that UVAM method had obvious technical advantages in reducing cutting force, improving finished surface quality, suppressing burrs and optimizing chip formation [14]. Boonsong Chongkolnee and Chaiya Praneetpongrung studied the effect of frequency and amplitude of ultrasonic vibration on EDM efficiency.The results showed that the MRR, TWR and surface roughness of the ultrasonic low frequency(29Khz) system with the large vibration amplitude were better than the high frequency system (59Khz) with the small amplitude [15]. The above studies were mainly focused on the ultrasonic vibration of tool electrode. Another additional way of ultrasonic vibration was workpiece vibration.

Gao and Liu reported that the workpiece vibration induced by ultrasonic vibration had a significant effect on the performance of the EDM process. The results showed that the efficiency of the ultrasonically aided micro-EDM was eight times greater than that of micro-EDM [16]. Gunawan Setia Prihandana1 et al. proposed a low-frequency vibration on workpiece in EDM process. The results showed that low-frequency vibration in EDM process could increase the material removal rate, and decreased the surface roughness and tool wear rate [17]. Jiangtao Chen et al. proposed a horizontal ultrasonic EDM. The ultrasonic vibration unit was installed on the workpiece to make it vibrate horizontally.The results showed the material removal rate (MRR) was increased by nearly 3 times [18].

These papers reported that the flushing effect was significantly enhanced by stirring of dielectric in the sparking gap with the compound of vibration or ultrasonic vibration to the EDM processes. This was particularly significant for machining micro deep holes, where conventional flushing methods became inefficient.

The advantages of ultrasonic EDM were widely concerned, among which there were more researches on the compound ultrasonic vibration of tool electrode and less researches on the compound ultrasonic vibration of workpiece. When ultrasonic vibration was added to the tool electrode it was necessary and difficult to change greatly control system and electrode connection in EDM machine. In addition, ultrasonic vibration could also make the tool electrode swing violently, which had a negative impact on machining efficiency and accuracy.In order to solve this problem, more and more attention had been paid to ultrasonic vibration of workpiece. When ultrasonic vibration of workpiece was used, the change of structure of EDM was relatively small. Most of the existing research focused on the experimental method to explain the effect of ultrasonic vibration. At present, in the EDM of ultrasonic vibration of workpiece, the research of piezoelectric vibrator was very few, and the optimization of process parameters was also lacking.

Hence, an ultrasonic vibration assisted electrical discharge machining (UV-EDM) system with workpiece vibration was proposed and studied in the paper. The piezoelectric vibrator was analyzed and tested, and the process parameters were optimized by orthogonal experiment. Firstly, a piezoelectric vibrator which induced workpiece vibration in UV-EDM was proposed and studied. The piezoelectric vibrator should have appropriate longitudinal mode and frequency. Secondly, UV-EDM system was formed by mounting the piezoelectric vibrator on the worktable of a EDM machine. Then we carried out an experimental study on the effect of ultrasonic vibration on the EDM machining of micro deep hole in die steel. The orthogonal experimental design was used to optimize the process parameters. The machining depth was set as the experiment index of the orthogonal experiment. Four process parameters, including excitation voltage , pulse current, pulse width and pulse gap, were selected as the orthogonal experimental factors. The influence degree of the four process parameters on the experiment index was obtained by optimization. And the best level combination of process parameters were obtained.

2. Design and test of the piezoelectric vibrator

The construction of the UV-EDM device was shown in Fig. 1. In the UV-EDM device, the ultrasonic vibration was added to the workpiece. The proposed UV-EDM device included a EDM machine with a servo actuator, a pulse actuator and a electrode, as well as a excitation power source and the piezoelectric vibrator.

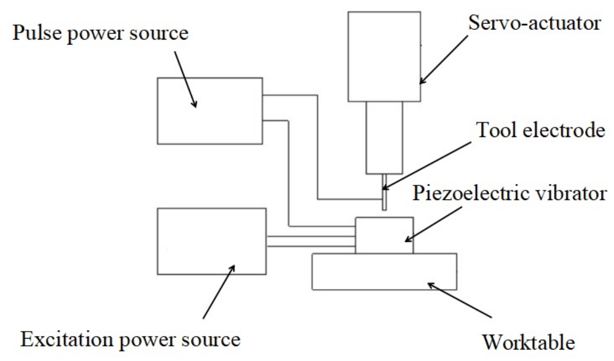

Fig. 1. Schematic of the UV-EDM device.

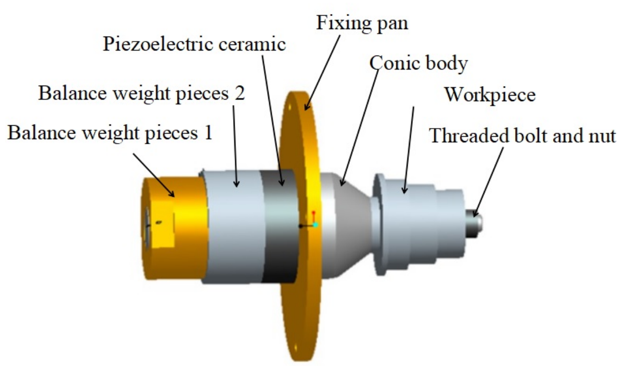

Fig. 2. Geometric model of the piezoelectric vibrator.

When the alternating electric field was applied to the piezoelectric body, various modes of elastic vibration could be excited in the piezoelectric body through the electromechanical coupling effect. When the frequency of the external electric field was consistent with the natural frequency of the elastic vibration in the piezoelectric body, the piezoelectric body entered the mechanical resonance state, which became the piezoelectric vibrator. In the construction of the UV-EDM device the piezoelectric vibrator was a key part. The piezoelectric vibrator should have appropriate longitudinal mode and frequency. The piezoelectric vibrator was composed of an ultrasonic transducer and a workpiece. The ultrasonic transducer was composed of a balance weight pieces 1, a balance weight pieces 2, several piezoelectric ceramics, a fixing pan, a conic body, a nut, a threaded bolt. The piezoelectric vibrator was added on the worktable of the EDM machine. The workpiece was adjoined to the ultrasonic transducer rigidly and vibrates correspondingly. The construction of the piezoelectric vibrator was shown in Fig. 2.

The finite element model of the piezoelectric vibrator was showed in Fig. 3. The element SOLID 5 type of elements was adopted for piezoelectric ceramics and SOLID 5 for the rest of the piezoelectric vibrator.

Modal analysis was conducted using Power dynamic mode extraction method that internally used the subspace iterations. Modal shapes and natural frequencies were calculated. The first longitudinal mode and natural frequency of the piezoelectric vibrator were found by modal analysis. According to the results of modal analysis, the first longitudinal natural frequency was about 21682Hz and the first longitudinal stretch and shrink modes were showed respectively in Fig. 4 and Fig. 5.

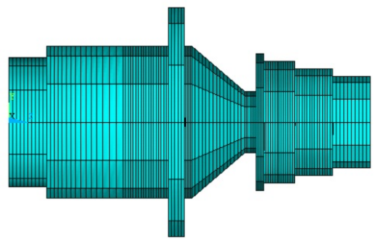

Fig. 3. Finite element model of the piezoelectric vibrator.

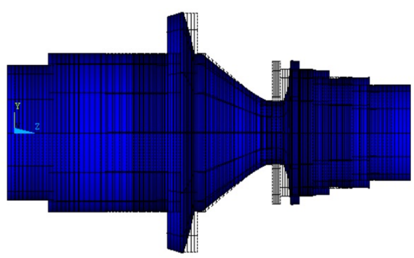

Fig. 4. The first longitudinal stretch mode.

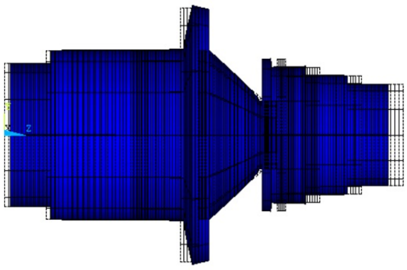

Fig. 5. The first longitudinal shrink mode.

According to the finite element calculation results, the piezoelectric vibrator was manufactured, as shown in Fig. 6. PSV-300F laser Doppler vibrometer was used to make frequency scanning on the piezoelectric vibrator, and the test result of the piezoelectric vibrator was shown in Fig. 7. In the case of excitation voltage of 100V (peak-peak value), the first-order longitudinal vibration frequency (working frequency) of the piezoelectric vibrator was 21450Hz, and the velocity of the piezoelectric vibrator tip was about 24 mm/s. The test result was accord with the calculation of the model analysis.

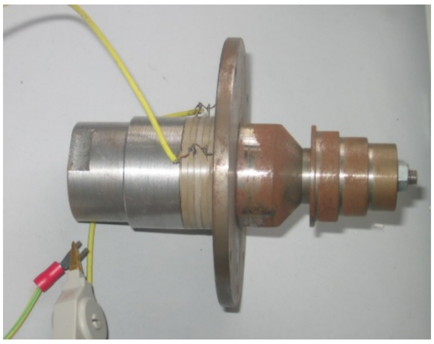

Fig. 6. The piezoelectric vibrator.

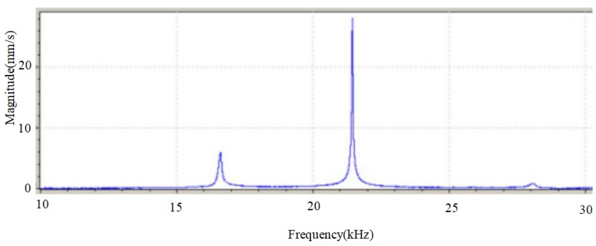

Fig. 7. Frequency scanning result of the vibrator.

3. The design and assembly of the UV-EDM device

An electrical discharge machine (Type BMW DB703) with servo-control generator (Iso-pulse) was used to conduct the experiment. The piezoelectric vibrator was installed on the worktable of the electrical discharge machine. The workpiece was a cylindrical rod screwed with the piezoelectric vibrator tip. The piezoelectric vibrator was driven at certain excitation voltage and work frequency by using a function generator (Type TFG2015G DDS) and it was magnified by a power amplifier (ML3860B). The input excitation voltage from the power amplifier was monitored by a digital oscilloscope (GOS-652G). The experimental device of the UV-EDM was shown schematically in Fig. 8. In order to prevent the piezoelectric vibrator from being affected by water, a cylindrical sleeve was arranged outside the piezoelectric vibrator which was shown in Fig. 9. The piezoelectric vibrator was sealed in the sleeve, and the wire on the piezoelectric vibrator was led out through the round hole on the sleeve. Die steel was selected as the experimental workpiece material. The die steel was a kind of low-alloy carbon tool steel, its grade was CrWMn, its density was 7890 kg/m^3, elastic modulus was 209000 GPa, Poisson's ratio was 0.269, and the hardness after quenching was greater than 62HRC. Other conductive metal materials could also be used to make workpiece. Red copper was used as the tool electrode material with a diameter of 0.5 mm.

Fig. 8. The experimental setup of the UV-EDM.

4. The comparative analysis of EDM with and without UV

The influences of ultrasonic and electrical discharge parameters on the machining efficiency in EDM and UV-EDM were studied. The machining depth of the micro hole in the workpiece expressed the material removal rate.

The machining depth for a micro hole of 0.5mm in

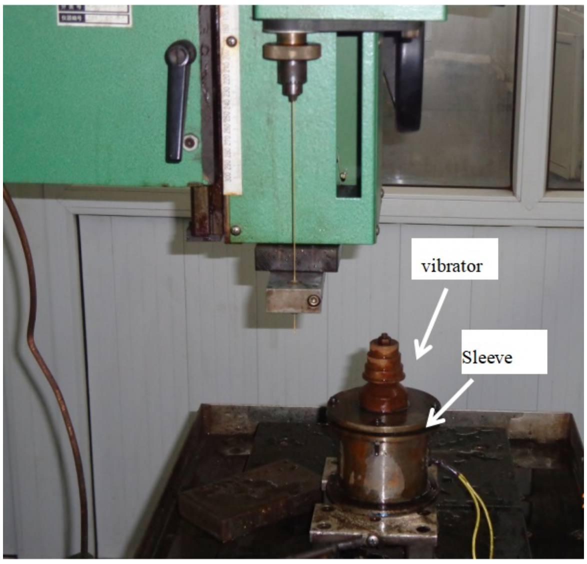

Fig. 9. The piezoelectric vibrator with a cylindrical sleeve.

die steel with and without UV was shown respectively in Fig.10. The process parameters were set as excitation voltage 90V,pulse current 12 A, work frequency 21450Hz, pulse width 12 μs, and pulse gap 18 μs. The machining efficiency was expressed by the material removal rate (MRR) of the workpiece, and formula 1 was the calculation formula of MRR.

$$MRR = \frac{\Delta V}{T} = \frac{HS}{T} = \frac{HR^2\pi}{T}\left(mm^3/s\right) \quad (1)$$

In the formula, ΔV represented the volume of the micro hole, T represented the processing time, H represented the depth of the micro hole, S represented the cross-sectional area of the micro hole, R represented the radius of the micro hole. The tool electrode remained unchanged in machining, only the machining depth changed, so the machining efficiency was measured by the machining depth of the micro hole after machining for a period of time. The higher the machining depth was, the higher the material removal rate of the workpiece was, and the higher the machining efficiency was.

When the machining depth of the micro deep hole was about 6 mm, the machining time with and without UV was about equal. As the machining depth of the micro deep hole became deeper, the machining time with UV advances more obviously. The result showed that the effect of UV was more obvious with the increase of the depth of micro hole. In the UV-EDM device the longitudinal vibration mode of the piezoelectric vibrator created longitudinal compressive and rarefaction wave front which induced very violent and accelerative debris transfer across the spark gap, causing better debris suspension and evacuation from the gap and better dielectric fluid renewal. In UV-EDM process the micro deep hole with aspect ratio 60 and depth 30 mm was successfully machined with an average diameter of 0.5 mm in die steel as shown in Fig. 10.

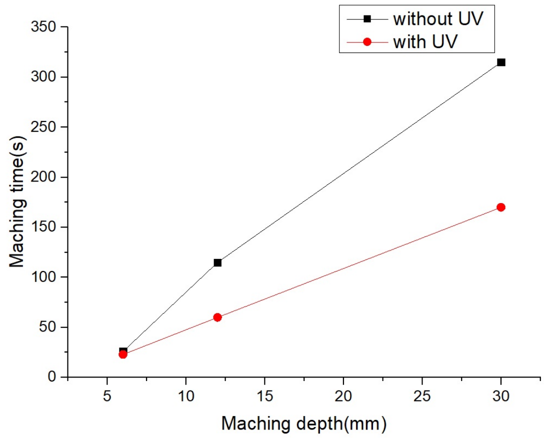

Fig. 10. The piezoelectric vibrator with a cylindrical sleeve.

It can be seen from Fig. 10 that the machining efficiency with UV was significantly improved. The cavitation produced by UV in water intensified the energy accumulation, which was conducive to the generation of electric spark discharge. The water jet produced by the breakdown of cavitation bubble could remove the material on the workpiece surface. At the same time, ultrasonic pumping and eddy current could improve the EDM environment. Therefore, the machining efficiency was improved obviously after the workpiece was added with UV.

In order to further understand the influence of process parameters on the machining efficiency in UV-EDM, the orthogonal experiment was established and the range analysis was carried out. Through the range analysis and variance analysis of orthogonal experimental design to study the experimental data, we could get the most influential factors and the optimal combination of factors. Variance analysis could further estimate the test error and analyze its influence, and judge the primary and secondary and significance of test factors.

5. The orthogonal experimental design of UV-EDM

5.1. The principle of orthogonal experiment design

In the experimental study, when three or more experimental factors need to be examined, it is often difficult to complete if a comprehensive experiment is to be carried out. Orthogonal experiment is a kind of high efficiency experiment

Table 1. Factors and levels of the orthogonal experiment

Levels	Excit-ation voltage (A)/V	Pulse current (B)/A	Pulse width (C)/μs	pulse gap (D)/μs
1	60	9	20	15
2	80	12	30	35
3	100	15	40	55
4	120	18	50	75

design method which arranges multi factor test and finds the optimal level combination. Orthogonal experiment design is a method used to design multi factor experiment scientifically. It uses a set of standardized orthogonal table to arrange the experiment, and the experiment results are processed by mathematical statistics method, so as to get scientific conclusions. Orthogonal table is the basic tool of experimental design. It is a kind of mathematical table based on the idea of balanced distribution and the theory of combinatorial mathematics. Balanced distribution is the core of orthogonal table [19]. An orthogonal table should have three characteristics: orthogonality, representativeness and comprehensive comparability.

5.2. The orthogonal experiment design process of UV-EDM

5.2.1. Design of the orthogonal experiment scheme

The orthogonal experimental design was used to optimize the process parameters. There were many factors that affected the machining efficiency of micro hole in UV- EDM process. It was impossible to study all the factors in a single experiment. Only according to the actual experience, we could choose the factors that had great influence on the experiment indexes and were not clear enough. At the same time, it was necessary to determine the appropriate level of each factor according to professional experience. The experiment index was a characteristic quantity used to measure the experiment effect in an experiment. It was similar to the objective function in mathematics. The experiment index was determined by the purpose of the experiment. A experiment purpose needed at least one experiment index. The reasonable determination of the experiment index needed to analyze the actual experiment according to the professional knowledge and test requirements. For this experiment, the purpose of the experiment was to find the optimal process parameters to maximize the machining depth(H) of UV-EDM. The machining depth of UV-EDM depended on the process parameters. Therefore, the machining depth could be used as the experiment index of this experiment, and it was a quantitative index. The factors that might affect the experiment index in the test were called factors. So four process parameters were set as orthogonal experimental factors: excitation voltage (A), pulse current (B), pulse width (C) and pulse gap (D). All four factors are controllable. The various states or different values of factors in the experiment were called factor levels. With reference to practical experience, the range of values for each factor were set as excitation voltage (A) 60 $\sim$ 90V, pulse current (B) 6 $\sim$ 14A, pulse width (C) 20 $\sim$ 50 μs and pulse gap (D) 15 $\sim$ 75 μs. The level of each factor was designed as shown in Table 1. The processing time was 60s in every experiment.

The orthogonal experiment of four factors and four levels was arranged. The orthogonal table could be recorded as $L_{16}\left(4^4\right)$, Where L stood for the orthogonal table, the number 16 in the lower right corner of L stood for the number of tests, the base number 4 in brackets stood for the horizontal number of factors, and the index 4 stood for four factors. The orthogonal table could arrange four horizontal factors. If the experiment of 4 factors and 4 levels were carried out comprehensively, the number of comprehensive tests was 4^4, that was 256, and only 16 times would be needed to adopt the orthogonal experiment. The minimum implementation part was 16/256. The effect of saving test times was obvious.

5.2.2. Treatment of experiment results-range method

The scheme and results of orthogonal experiment were shown in Table 2. K1, K2, K3 and K4 was respectively the sum of the experiment index (Machining depth H) at the same level of each factor. The calculation process was as follows.

Level 1 of factor A: $K_1 = H_1 + H_2 + H_3 + H_4 = 10.66 + 11.36 + 11.76 + 9.91 = 43.75$;

Level 2 of factor A: $K_2 = H_5 + H_6 + H_7 + H_8 = 11.06 + 11.22 + 13.08 + 12.09 = 47.45$;

Level 3 of factor A: $K_3 = H_9 + H_{10} + H_{11} + H_{12} = 10.43 + 10.92 + 12.79 + 13.61 = 47.75$;

Level 4 of factor A: $K_4 = H_{13} + H_{14} + H_{15} + H_{16} = 9.59 + 12.35 + 12.5 + 11.31 = 45.75$;

In the same way, the sum of the experiment index of B factor, C factor and D factor could be obtained.

$\overline{K_1}, \overline{K_2}, \overline{K_3}, \overline{K_4}$ was respectively the average value of the experiment index at the same level of each factor. The calculation process was as follows.

Level 1 of factor A : $\overline{K_1} = K_1/4 = 43.75/4 = 10.93$;

Level 1 of factor A : $\overrightarrow{K_2} = K_2/4 = 47.45/4 = 11.86$; $\overline{K_3} = K_3/4 = 47.75/4 = 11.94$; $\overline{K_4} = K_4/4 = 45.75/4 = 11.44$; In the same way, the average value of the experiment index of B factor, C factor and D factor could be obtained. The optimal level of each factor was judged by the value of $\overline{K_1}, \overline{K_2}, \overline{K_3}$ and $\overline{K_4}$. The combination of the optimal level of each factor was the optimal combination.

Range R was the change range of the experiment index when the level of each factor changed. The greater the R of the factor, the greater the influence on the experiment index, so it was more important. So we could judge the primary and secondary factors according to the range. The calculation formula of the range R of factor A was:

$R = \max[\overline{K_1}, \overline{K_2}, \overline{K_3}, \overline{K_4}] - \min[\overline{K_1}, \overline{K_2}, \overline{K_3}, \overline{K_4}] = 11.94 - 10.93 = 1.01$. In the same way, the range R of B factor, C factor and D factor could be obtained.

In Table 2, according to the range R of each factor we can see that the influence degree of the four process parameters on the machining depth was: B (pulse current) > D(pulse gap) > C (pulse width) > A (excitation voltage), which meant that pulse current had the greatest influence on the machining depth, and pulse gap, pulse width and excitation voltage decrease in turn. According to the value of $\overline{K_1}, \overrightarrow{K_2}, \overline{K_3}$ and $\overline{K_4}$, the best level combination of process parameters were A3-B3-C2-D1, then excitation voltage was 100V, pulse current was 15A, pulse width was 30 μs, and pulse gap was 15 μs.

5.2.3. *Treatment of experiment results-variance analysis*

The range analysis method was simple and convenient to use, and the optimized results could be obtained through simple calculation, but the range analysis method could not estimate the experiment error, and the analysis of variance method could further estimate the experiment error and analyze its influence. When variance analysis was used, it was required to leave a blank column in the orthogonal experiment table as the error estimation value, as shown in Table 2.

1. Decomposition of degree of freedom and sum of squares

The total variation of the 16 observed values in the orthogonal experiment consisted of five parts: factor A, factor B, factor C, factor D and error variation. For a group of experimental data, $H_1, H_2, \cdots, H_{16}$, the average value of these data was $\bar{H}$, then the difference $H_t - \bar{H}(i = 1, 2, \cdots, 16)$ was the deviation of the group of data, the value of the deviation was expressed by the sample variance $\hat{\sigma}^2$, and the calculation formula was $\hat{\sigma}^2 = S/f$, where $S = \sum_{i=1}^{16} (H_i - \bar{H})^2$ was the sum of squares of deviation of this group of data, and f was the degree of freedom. Therefore, the formula of the sum of squares and the degree of freedom was as follows:

$S = S_A + S_B + S_C + S_D + S_e, \quad f = f_A + f_B + f_C + f_D + f_e$. The application of variance analysis in orthogonal design could estimate the experimental error and analyze its influence, and judge the primary and secondary and significance of experimental factors.

2. Calculation of sum of square and degree of freedom

The total sum of square could be calculated as follows:

$S = \sum_{i=1}^{16} (H_i - \bar{H})^2 = \sum_{i=1}^{16} H_i - \frac{1}{16} \left(\sum_{i=1}^{16} H_i \right)^2 = 10.66^2 + 11.36^2 + \cdots + 11.31^2 - 2132.13 = 19.23$

Then the sum of square of factor A was:

$S_A = \frac{1}{4} \sum_{i=1}^{4} K_i^2 - \frac{1}{16} \left(\sum_{i=1}^{16} H_i \right)^2 = \frac{1}{4} \left(43.75^2 + 47.45^2 + 47.75^2 + 45.75^2 \right) - 2132.13 = 2.54$

Using the same method, the sum of squares of the other three factors could be obtained: $S_B = 8.78, S_C = 2.68, S_D = 4.25$

The sum of square of error was:

$S_e = S - S_A - S_B - S_C - S_D = 19.23 - 2.54 - 8.78 - 2.68 - 4.25 = 0.98$

The degree of freedom f of the sum of square of total deviations was equal to the number of the experiment minus 1 in the orthogonal table, and the degree of freedom of the sum of square of deviation of various factors was equal to the number of levels minus 1.Therefore, it could be concluded that: The total degree of freedom was $f = n - 1 = 15$, the other four factors were all 3, and the error degree of freedom was equal to 3.

3. Significance test

According to the data calculated above, the variance analysis data results could be listed, as shown in Table 3.

F test was used to test the significance of factors. For example, if F value of factor A was $F = \frac{S_A/f_e}{S_e/f_e}$, then significance level α was selected and critical value $F_\alpha(f_A, f_e)$ was found from F distribution table. If $F_A > F_\alpha(f_A, f_e)$ occurred, it indicated that under significance level α, the level change of factor A had significant influence on the experiment index, and the confidence degree of this conclusion was $100(1 - \alpha)\%$.

It could be seen from Table 3 that according to the results of F test, the significance level of factor B was 0.1 and that of the other three factors was 0.25. It could be seen that the most significant factor affecting the machining depth was B factor, followed by D factor, C factor and a factor. Combined with the analysis results in Table 2, the optimal combination A3-B3-C2-D1 could be determined.

4.Confidence analysis

After the optimal combination was selected, the interval

Table 2. The orthogonal experimental table $L_{16}(4^4)$ and results.

Experiment number	A(Excitation voltage/V)	B (Pulse current/A)	C (Pulse width / μs)	D (Pulse gap / μs)	Empty column	Maching depth(H) (mm)
1	1(60)	1(9)	1(20)	1(15)	1	10.66
2	1(60)	2(12)	2(30)	2(35)	2	11.36
3	1(60)	3(15)	3(40)	3(55)	3	11.76
4	1(60)	4(18)	4(50)	4(75)	4	9.97
5	2(80)	1(9)	2(30)	3(55)	4	11.06
6	2(80)	2(12)	1(20)	4(75)	3	11.22
7	2(80)	3(15)	4(50)	1(15)	2	13.08
8	2(80)	4(16)	3(40)	2(35)	1	12.09
9	3(100)	1(9)	3(40)	4(75)	2	10.43
10	3(100)	2(12)	4(50)	3(55)	1	10.92
11	3(100)	3(15)	1(20)	2(35)	4	12.79
12	3(100)	4(18)	2(30)	1(15)	3	13.61
13	4(120)	1(9)	4(50)	2(35)	3	9.59
14	4(120)	2(12)	3(40)	1(15)	4	12.35
15	4(120)	3(15)	2(30)	4(75)	1	12.5
16	4(120)	4(18)	1(20)	3(55)	2	11.31
K_1	43.75	41.74	45.98	49.69	46.17	
K_2	47.45	45.85	48.52	45.82	46.18	
K_3	47.75	50.13	46.62	45.05	46.18	
K_4	45.75	46.97	43.56	44.13	46.17	
$\overline{K_1}$	10.93	10.44	11.49	**12.42**	11.54	
$\overline{K_2}$	11.86	11.46	**12.13**	11.45	11.55	
$\overline{K_3}$	**11.94**	**12.53**	11.66	11.26	11.55	
$\overline{K_4}$	11.44	11.74	10.89	11.03	11.54	
R	1.01	2.09	1.24	1.4	0.01	
Importance of factors	BPulse current	>D(Pulse gap)>	CPulse width	> AExcitation voltage		
Best level combination			A3-B3-C2-D1			

estimation of the experiment index of the optimal combination was needed, and the confidence degree of the interval estimation was given at the same time. In the interval estimation, the estimation value $\hat{H}_0$ was calculated first, and then the error ε_a was calculated. α was the maximum significant level of significant factor. The significance level of significant factor B in this experiment was 0.1, so the maximum significance level was 0.1. If the interval of the test index was estimated to be $\hat{H}_a \pm \varepsilon_a$, there was a probability of $1-\alpha$ to determine the true value of the experiment index of the optimal combination would be between $\hat{H}_a - \varepsilon_a$ and $\hat{H}_a + \varepsilon_a$. The following was the specific calculation.

$\hat{H}_a = \hat{\mu} + \hat{a}_3 + \hat{b}_3 + \hat{c}_2 + \hat{d}_1$, Through calculation, we could get the following results: $\hat{\mu} = \bar{H} = 11.544, \hat{a}_3 = 0.394, \hat{b}_9 = 0.989, \hat{c}_2 = 0.586, \hat{d}_1 = 0.876$. Finally, we could get the following result: $\hat{H}_a = 14.389$.

Error limit $\varepsilon_a = \sqrt{F_a\left(1, f_c + f_0\right)\left(S_e + S_e'\right) / \left[\left(f_c + f_e\right)\frac{N}{1+f^*}\right]}$.

Where, f' was the sum of the degrees of freedom of the insignificant factors; S " was the sum of the squares of the deviations of the insignificant factors; N was the total number of the experiment; f^* was the sum of the degrees of freedom of significant factors. It could be obtained from calculation that $f_e' = 9, S_e' = 9.47, N = 16, S_e = 0.98, f_c = 3, f^* = 3$. According to the table in reference [19] , it could be concluded that $F_{0.1}(1, 3+9) = 3.17$ So we could get the following result:

Error limit $\varepsilon_a = \sqrt{3.17 \times (0.98 + 9.47) / \left[(3+9)\frac{16}{1+3}\right]} = 0.83$

Therefore, if the combination A3-B3-C2-D1 was the optimal combination, the true value of the index would be between $14.389 - 0.83$ and $14.389 + 0.83$, that was, between $13.559 - 15.219$, and the confidence level was $100(1-\alpha)\% = 100(1-0.1)\% = 90\%$ The optimized process parameters were selected and the machining time was set as 150s, the machining depth could reach 33.5mm, and the depth diameter ratio was about 67 .The machining depth obtained by using the optimized process parameters had been significantly improved.

Table 3. The variance analysis data results.

Source of variance	Sum of squares of deviations S	Freedom F	Mean square sum MS	f	Significance level α
Factor A	2.54	3	0.847	2.589	0.25
Factor B	8.78	3	2.927	8.950	0.1
Factor C	2.68	3	0.893	2.732	0.25
Factor D	4.25	3	1.417	4.332	0.25
Error	0.98	3	0.327		
The sum	19.23	15	The critical value F_α $F_{0.25}(3,3) = 2.36, F_{0.1}(3,3) = 5.39, F_{0.05}(3,3) = 9.28$		

5.2.4. Influences of process parameters on the machining depth

Fig. 11 showed the influence of excitation voltage on the machining depth for a micro hole of 0.5mm in die steel. It was seen that the machining depth increased rapidly when excitation voltage started to increase from A1(60V), then when excitation voltage changed from A2(80V) to A3(100V) the machining depth changed slowly. At last when excitation voltage exceeded A3(100V), the machining depth started to decrease. The result indicated excitation voltage had an optimum value. The results showed that the increase of excitation voltage was beneficial to the improvement of machining depth, but to a certain extent, the machining speed began to decline, so it was necessary to find the best value of excitation voltage. Thus, the circulation of dielectric and the removal of machining debris are improved.

The magnitude of the excitation voltage was directly proportional to the amplitude of the piezoelectric vibrator. The larger amplitude of piezoelectric vibrator would produce a larger pressure between tool electrode and workpiece. Therefore, the dielectric circulation and the removal of machining debris were enhanced. The machining depth increased with the increase of excitation voltage. At this time, the pressure between the tool electrode and the workpiece was not large enough to destroy the stability of the tool electrode. When the excitation voltage increased to a certain extent, the excessive pressure between the tool electrode and the workpiece made the dielectric vibrate violently, which caused the tool electrode to skew, and then affected the machining efficiency.The excitation voltage and the amplitude of the piezoelectric vibrator should be appropriate to achieve the best processing efficiency. The energy of a single pulse current depended on charge voltage and current between the electrode and the workpiece and charge time. So the energy of the single pulse was expressed by equation 2.

$$W_{st} = \int_0^t u(t)i(t)dt \qquad (2)$$

where t_c was charge time of the single pulse (μs) which was also named pulse width, $u(t)$(V) was charge voltage which changed with time between the electrode and the workpiece, $At)$ (A) was pulse current which changed with time between the electrode and the work-piece.

Fig. 12 showed the influence of pulse current on the ma-

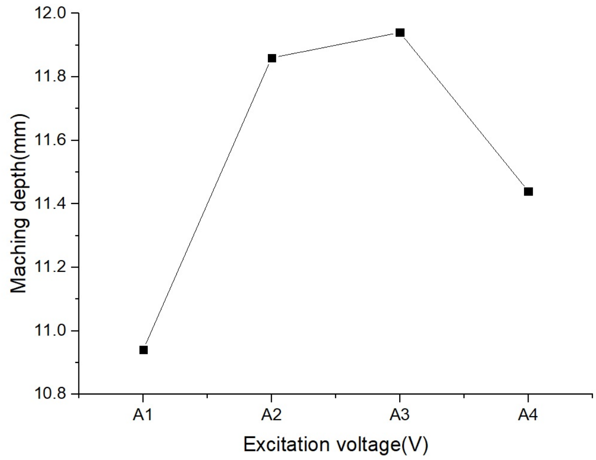

Fig. 11. Machining depth against excitation voltage with UV.

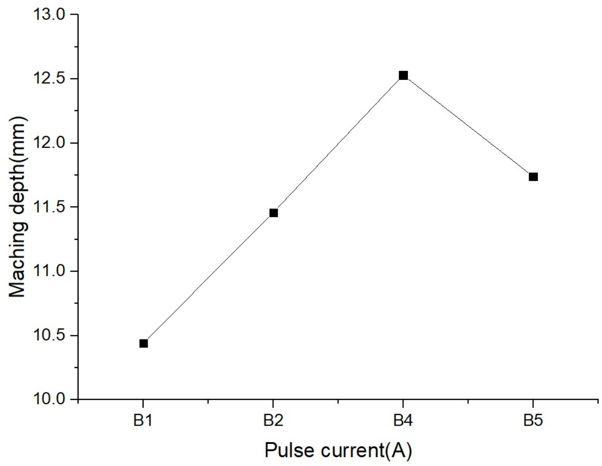

Fig. 12. Machining depth against pulse current with UV.

chining depth for a micro deep hole of 0.5mm in die steel with UV. The result dictated the machining depth increased when pulse current changed from B1(9A) to $B_3(M,5A)$. However, when pulse current exceeded B 3(15A), the machine depth decreased greatly.

It is dictated that increasing pulse current was useful to improving the machine depth with UV when pulse current was in a definite range, but the machine depth dropped as discharge current became too high. According to equation 1, the charge energy of a single pulse increased with a large increasing current. Accordingly the intensive explosion force was induced and the dielectric fluid flowed acutely. With the increase of pulse current, the explosive force would be strong, and the working fluid would vibrate violently, which would affect the stability of the tool electrode and weaken the machining efficiency. So the optimum value of pulse current should be found.

Fig. 13 showed the machining depth against pulse width on the machining depth for a micro hole of 0.5mm in die steel with UV. The result dictated the machining depth increased when pulse width changed from C1(20μs) to C2(30 μs). However, when pulse width exceeded C2(30μs), the machining depth dropped greatly. Pulse width had an optimized value. According to equation 1, the charge energy of a single pulse increased with a large increasing (pulse width). With the increase of pulse width, the energy carried by the single pulse increased correspondingly, which was beneficial to the workpiece processing. The increase of pulse with improved the circulation and discharge environment of working fluid, intensified the movement of particles in the working medium, made it easier to form discharge channels, and improved the processing of workpieces with high pulse energy more obviously. With the increase of pulse width, the explosive force would also become strong, and the working fluid would vibrate violently at the same time, which would weaken the efficiency of machining. So the optimum value of pulse width should also be found.

Fig. 14 showed the machining depth against pulse gap on the machining depth for a micro hole of 0.5mm in die steel with UV.The result dictated the machining depth decreased when discharge current changed from D1(15μs) to D4(75μs).With the increase of pulse with, the energy carried by the single pulse decreased correspondingly, which was not beneficial to the workpiece processing. From the result of the machining experiment of micro holesit could be seen that the proposed UV-EDM device could drill micro deep holes with high aspect ratio in hard materials such as die steel.

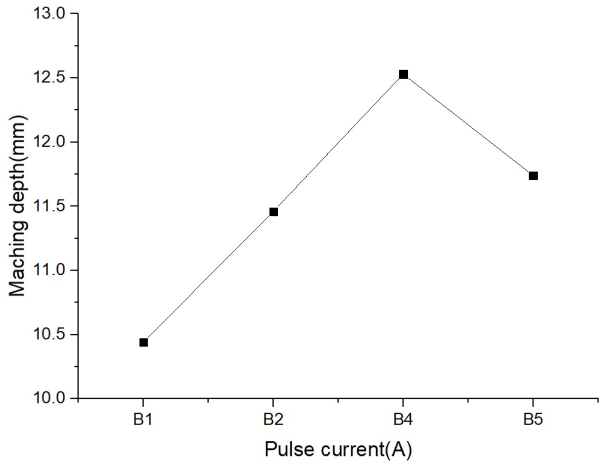

Fig. 13. Machining depth against excitation voltage with UV.

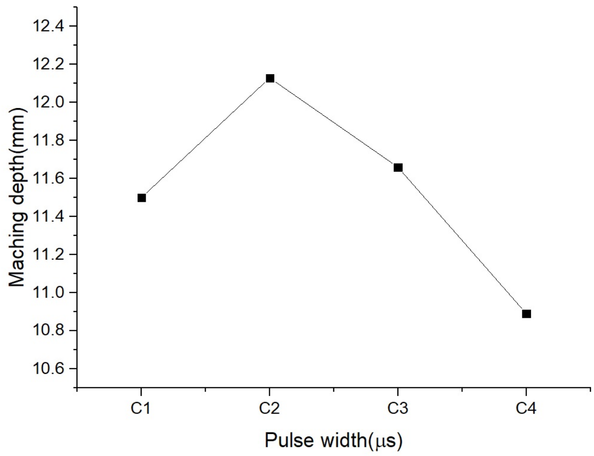

Fig. 14. Machining depth against pulse current with UV.

6. Conclusion

1) The ultrasonic vibration assisted EDM device with workpiece vibration was constructed. The device consisted of a EDM machine including a servo actuator and pulse actuator and electrode, excitation power source, a piezoelectric vibrator which induced ultrasonic vibration of the workpiece. The piezoelectric vibrator was designed, fabricated and tested. The first longitudinal natural frequency was about 21682 Hz by modal analysis, The test result showed the first-order longitudinal vibration frequency (working frequency) of the piezoelectric vibrator was 21450 Hz and the velocity of the piezoelectric vibrator tip was about 24 mm/s. The test result was accord with the calculation of the model analysis.

2) A machining experiment was studied on the effect of ultrasonic vibration on the EDM machining of micro deep

hole in die steel. The orthogonal experimental design was used to optimize the process parameters. The best level combination and the influence degree of the four process parameters on the machining depth index were gotten by the orthogonal experimental design Through the analysis of variance,the interval estimation of the experiment index machining depth of the optimal combination was carried out, and the confidence degree of the interval estimation was given.

3) The machining depth with diameter Φ0.5 mm could reach 33.5 mm, and the depth diameter ratio was about 67 with the optimized process parameters and machining time 150 s. The proposed UV-EDM device could effectively drill micro deep holes with high aspect ratio in hard materials such as die steel.

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