Thermodynamic simulation modeling analysis and experimental research of vertical ultrasonic vibration assisted EDM

Yinghuai Dong1,2 · Jiajun Liu1 · Guangyan Li3 · Yan Wang1,2

Received: 21 June 2021 / Accepted: 19 December 2021 / Published online: 15 January 2022
© The Author(s), under exclusive licence to Springer-Verlag London Ltd., part of Springer Nature 2022

Abstract
Compared with traditional EDM, ultrasonic vibration assisted EDM (UEDM) shows better performance in machining efficiency and surface quality. However, the material removal process of UEDM is complex, and there are many influencing factors. It is difficult to describe the material removal process accurately. In this study, based on the voltage variation during UEDM processing and combined with the heat transfer theory, the material removal model of TC4 titanium alloy under the condition of single pulse vertical UEDM is established. The material removal process of UEDM under different amplitudes is analyzed. The machining efficiency and surface quality of UEDM with different amplitude of ultrasonic vibration under the condition of vertical ultrasonic vibration are verified by UEDM experiments. The best material removal rate (MRR) can be obtained by adjusting the current and ultrasonic amplitude, which can improve the efficiency of UEDM.

Keywords UEDM · Temperature field model · MRR · Surface topography

1 Introduction

EDM is in a certain discharge medium; through the instantaneous pulse discharge at both ends of the electrode, the instantaneous local high temperature is produced in the ion channel, which makes the surface of the workpiece melt or even vaporize, as to achieve the purpose of material removal on the workpiece surface [1]. Due to the high energy density of the discharge, EDM has a very important position in the field of processing metal materials with high hardness, high melting point, high toughness, and brittleness, especially in aerospace, medical devices, and other industries. However, during the EDM process, the processing debris is gathered in the machining gap, which is prone to some undesirable phenomena, such as secondary discharge, arc discharge, and short circuit [2]. With the increase of machining depth, this phenomenon is more obvious, resulting in the gradual decrease of EDM efficiency with the machining depth. The cavitation of ultrasonic waves can impact and crush debris, and accelerate the circulation of working fluid and improve the stability of discharge. Therefore, researchers are committed to UEDM.

The MRR of EDM can be improved by applying high-frequency ultrasonic vibration to the electrode or workpiece, using the cavitation and pumping effect of ultrasonic vibration to accelerate the flow of working fluid in the discharge gap and the discharge residue discharge. Kremer et al. investigated the effects of ultrasonic vibration on the processing and surface modification of EDM. The results showed a significant increase in MRR and a more stable machining process after the application of ultrasonic vibration. Subsequently, it was found that ultrasonic vibration-assisted EDM processing resulted in a reduction in the surface heat affected layer, a reduction in thermal residual stresses, and a reduction in micro-cracking [3, 4]. Lin et al. used a combination of ultrasonic machining (USM) and electrical discharge machining (EDM) process used to study the machining characteristics of Ti-6Al-4V. The results showed that this combination process could increase the MRR and reduce the thickness of the recast
In addition, from the voltage waveform analysis, this combination could reduce abnormal discharge and improve discharge efficiency [5]. Abdullah et al. studied the effect of ultrasonic vibration-assisted EDM processing of carbon-water tungsten carbide (WC-CO) on the surface integrity of tool electrodes. Surface integrity was improved by ultrasonic-assisted EDM as shown by SEM micro-hardness tests with indicated morphological analysis [6, 7]. Shabgard and Alenabi studied the effects of electrode vibration, current and pulse width on MRR, electrode loss, stability of the machining process, and machined surface quality by machining titanium alloys with UEDM. The results showed that high-frequency vibration of the electrode reduced micro-crack density and electrode loss in finishing, but increased recast layer thickness, micro-crack density, and electrode loss in rough machining [8]. Li et al. proposed a method which micro-EDM and micro-ultrasonic machining (micro-USM) combined milling of ZrB2-SiC-carbon composite 3D micro-cavities and the method had been verified by experiment. The results shown more recast layer have been removed with higher ultrasonic amplitude processing. The proper machining parameters were obtained and applied to the fabrication of micro-cavities [9]. Liu et al. modeled the three-dimensional (3D) gap flow field based on kinetic simulation and quantitatively analyzed the motion law of gap debris at different amplitudes and frequencies as well as different aspect ratios. The results showed that periodic ultrasonic vibration facilitated chip removal in the machining gap, in the machining gap, ensuring the stability of the machining process and improving the machining efficiency [10]. Wang et al. studied the horizontal UEDM material removal mechanism based on heat transfer theory, analyzed the surface formation process and the influence law of ultrasonic vibration by establishing a UEDM single-pulse removal volume model, and verified the correctness of their theoretical derivation by simulation and experiment [1]. Choubey et al. [11] used two-dimensional axisymmetric FEM to predict the crater shape with and without vibration micro-EDM and obtained the surface temperature distribution and MRR of the workpiece [11]. Li and Bai showed that under the same discharge energy condition, the discharge voltage of EDM increases with the increase of gap width, and the diameter and depth of the discharge crater decrease with the increase of the gap width [12].

Researchers have conducted more thorough experimental investigations on UEDM, but there are relatively few studies on the material removal process and surface formation process of UEDM. In this study, based on the voltage change during UEDM, the mathematical model of UEDM material removal process is established by using EDM heat transfer theory, and the single-pulse UEDM removal volume model is analyzed by ANSYS thermodynamic simulation. The correctness of the theoretical model is verified by experiments, and the best matching ratio between ultrasonic amplitude and EDM process is revealed, which provides a reference for UEDM parameters setting.

### 2 UEDM mathematical model

In EDM, the machine tool servo system controls the tool electrode to approach the workpiece electrode. When the gap between the electrodes is certain distance, the charged particles penetrate the discharge gap and form a discharge channel in the medium. Due to the high-speed collision of charged particles in the discharge channel, the energy density of the discharge channel is very high. In addition, the medium has a compression effect on the discharge channel, resulting in a sharp rise in temperature, and the high temperature makes the electrode surface material melt or even vaporize. Part of the metal on the surface of the tool and workpiece is removed, and craters are formed on the surface of the workpiece [2]. Figure 1 is a schematic diagram of EDM craters.

The thermal physical process of UEDM is comparable to that of EDM, which is very short and complex. However, different from EDM, the high-frequency vibration of ultrasound will constantly change the discharge gap, which can reduce short circuit and arc discharge. The cavitation, pumping, and vortex effects of ultrasound have a significantly improved effect on the pulsed discharge state. When the binding force between molten metal and liquid molecules is insufficient to withstand the interaction pressure caused by ultrasonic high-frequency vibration, the molten metal material will be discharged from the discharge gap, which improves the removal rate of processed materials.

**Fig. 1** Schematic diagram of craters in EDM
2.1 Mathematical model of UEDM discharge energy

In the process of EDM, when the inter-electrode medium is broken down, the power supply rapidly releases energy in the discharge channel and converts the electric energy into thermal energy, magnetic energy, light energy, sound energy and electromagnetic wave radiation, etc. Assuming that the entire energy generated by the pulsed power supply in the discharge gap is $W$, the energy consists of three main components: the energy released from the discharge channel plasma $W_c$, the energy released from the positive surface $W_a$, and the energy released from the negative surface $W_k$:

$$ W = W_r + W_a + W_k $$

(1)

The energy released by the plasma in the discharge channel can be expressed as follows:

$$ W_r = \int_0^{t_k} U_r(t)I(t)dt $$

(2)

where,

- $U_r(t) =$ Discharge voltage (V)
- $I(t) =$ Discharge current (A)
- $t_k =$ Discharge duration in the discharge channel (s)

When the dielectric properties between the electrodes are not yet destroyed, it is considered that the applied voltage $U$ is uniformly distributed in the discharge medium, and when the distance between the electrodes is $H_0$, the electric field strength in the discharge medium is elastic $U/H_0$. When the inter-electrode dielectric is broken down and discharged, the intrapolar potential distribution and point field intensity change abruptly [2]:

$$ W_r = \int_0^{t_h} E_r(t)H_0i(t)dt $$

(3)

where,

- $E =$ Electric field strength
- $H_0 =$ Polar distance

The discharge gap during the machining process changes with the amplitude of the ultrasonic vibration when the ultrasonic vibration acts on the electrode or the workpiece. In the UEDM processing, due to the high-frequency vibration of the ultrasound, the actual discharge gap varies with the amplitude and frequency of the ultrasound. The actual machining gap of the UEDM is

$$ H = H_0 + A \sin(2\pi ft + \varphi) $$

(4)

where,

- $A =$ Ultrasonic amplitude
- $F =$ Ultrasonic vibration frequency
- $\varphi =$ Initial phase

During the UEDM processing, the ultrasound high-frequency vibration constantly changes the discharge distance, causing the continuous change of the intrapolar discharge gap results in the variation in the plasma channel (as shown in a later study). The formula of ultrasonic vibration-assisted plasma voltage equation is

$$ U_t = E_t(H_0 + A\sin(2\pi ft + \varphi)) $$

(5)

The energy of the ultrasonic vibration auxiliary electric spark plasma channel discharge is

$$ W_t = \int_0^{t_h} E_t(t)(H_0 + A\sin(2\pi wt + \varphi))i(t)dt $$

(6)

2.2 UEDM heat source model

Most of the energy released by EDM discharge is in the form of thermal energy, which is finally distributed on the positive and negative electrodes to form an instantaneous high-temperature heat source. The heat source on the electrode is normally divided into a body heat source and a surface heat source, while the body heat source accounts for only 1% or 2% of the surface heat source. Therefore, the heat source generated by the electric spark discharge will be dominated by the surface heat source [2]. The diameter of the heat source area is usually related to the pulse width, open-circuit voltage, and peak current. The heat flux density of single pulse spark discharge is Gaussian distribution, and the heat flux equation for a single spark is as in the equation below [13]:

$$ q_{(t)} = \frac{4.57}{\pi R(t)^2}(\beta U_r(t)I(t) + 0.5) \exp \left(-\frac{4.5}{R(t)^2} \right) $$

(7)

where,

- $\beta =$ The energy distribution coefficient
- $U =$ The voltage in discharge channel (V)
- $I =$ The current in discharge channel (A)
- $R(t) =$ The radius of t discharge channel at time (µm)

During the UEDM processing, the Gaussian heat source is changed due to the change of the discharge voltage with the constant change of the amplitude. The heat flux equation for single-pulse UEDM is as shown in the equation below:

$$ q_{(t)} = \frac{4.57}{\pi R(t)^2}(h_0 + A\sin(2\pi ft + \varphi)) \times I(t) \exp \left(-\frac{4.5}{R(t)^2} \right) $$

(8)
2.3 Energy distribution

In the study of the energy distribution coefficient of bipolar discharge, Dibitoto et al. reported that the heat absorption on the cathode and anode is 18.3% and 8%, respectively, and the rest of the heat is lost to the interstitial fluid [14]. Shabgard et al. proved that the proportion of heat flux entering the electrode is not constant, but a function related to the input parameters of the process. The correlation between the pulse current and the pulse conduction time obtained by power regression modeling, such as the formula [15]:

\[ f_c = 5.5998 \times I^{-0.3401} \times T_i^{0.2989} \] (9)

\[ f_a = -19.2521 + 38.8627 \times I^{-0.2008} \times T_i^{0.1889} \] (10)

where,

- \( f_c \) = Cathode energy coefficient
- \( f_a \) = Anode energy coefficient

2.4 Spark discharge radius

The discharge radius of the spark is also an important factor in the process of simulation modeling. In this study, the radius of the discharge channel (spark) is chosen from the work of Ikai and Hashiguchi, and the radius is called the equivalent heat input radius, and the size depends on the function of pulse current and pulse on-time [16], as shown in the following equation:

\[ R(t) = 2.04 \times T_i^{0.43} \times T_i^{0.44} \] (11)

where,

- \( I \) = The pulse current (A)
- \( T_i \) = The pulse turn-on time (μs)

2.5 Heat transfer model

Heat transfer in the EDM process is a transient nonlinear heat conduction problem. The Gaussian heat source distribution is applied to the electrode surface heat source for material removal. It is assumed that the volume heat source \( q_v = 0 \), of the workpiece, satisfies the Fourier conduction theory, and the differential equation of heat conduction in the cylindrical coordinate system is obtained [17]:

\[
\frac{1}{r} \frac{\partial}{\partial r} \left( K_r \frac{\partial T}{\partial r} \right) + \frac{\partial}{\partial z} \left( K_z \frac{\partial T}{\partial z} \right) = \rho C_p \frac{\partial T}{\partial t}
\] (12)

where,

- \( T \) = Temperature (K)
- \( t \) = Time (s)
- \( \rho \) = Density (kg/m³)
- \( K_r, K_z \) = Thermal conductivity (W·m⁻¹K⁻¹)
- \( C_p \) = Material heat capacity (J·kg⁻¹K⁻¹)
- \( r, z \) = The position of the point in the cylindrical coordinate system

2.6 Setting of boundary conditions

The boundary conditions are set as shown in the Fig. 2. During the EDM, the top surface of the workpiece is subjected to heat flux within the spark radius “R.” The surface of the workpiece is melted or even vaporized and contact with the discharge medium beyond the radius R. Boundaries B₂, B₃ and B₄ consider that there is no heat transfer between the spark discharge area and infinitely far away from the spark discharge area. The loss heat flux is assumed to be zero. When the discharge time \( t > 0 \), the boundary condition is set as follows [15]:

\[ K(\partial T/\partial z) = \begin{cases} h_c(T - T_0) & r > R \\ q(r) & r \leq R \\ 0 & \end{cases} \] (13)

On boundaries B₂, B₃, and B₄:

\[ \partial T/\partial n = 0 \] (14)

As shown in Fig. 2, \( q_m \) is the heat flux into the workpiece, and \( H_c \) is the convective heat transfer coefficient. The discharge medium is kerosene, and the convective heat transfer coefficient is 500–1000 W/m²·K; \( T_0 \) is room temperature, and the direction n is perpendicular to the boundary. The initial temperature \( T_0 \) is taken as the ambient temperature of the dielectrics immersed in it (the initial temperature is 25 °C).
3 Simulation analysis of single-pulse UEDM

According to the theoretical derivation of UEDM mentioned above, the transient thermodynamic finite element analysis of single-pulse discharge is carried out, and the parameters are simulated numerically.

The processed material is TC4 titanium alloy. The sample physical properties and related parameters are shown in Table 1. The simulation parameters are set as shown in Table 2.

In addition, due to the large number of factors influencing UEDM processing, the model needs to be appropriately simplified, the following assumptions are put forward for the model:

1. The model is only for a single pulse UEDM, and the model is central axisymmetric.
2. The electrode in single-pulse EDM is regarded as a semi-infinite body due to the volume of the removed material is much smaller than that of the electrode.
3. Ignore the effect of material phase change on the MRR in the process of analysis.
4. Neglect the effect of thermal radiation and heat conduction on temperature, due to thermal radiation and heat conduction are relatively small relative to heat flux.
5. The heat flux incident on the electrode has nothing to do with the affected surface profile.

### Table 1 Physical property parameters of TC4 titanium alloy

| Temperature T/℃ | Thermal conductivity λ/(W·m⁻¹·℃⁻¹) | Specific heat capacity c/(J·kg⁻¹·℃⁻¹) |
|------------------|----------------------------------|----------------------------------|
| 25               | 5.42                             | 678.13                           |
| 100              | 6.68                             | 690.69                           |
| 200              | 8.76                             | 703.25                           |
| 300              | 10.43                            | 740.92                           |
| 400              | 12.52                            | 753.48                           |
| 500              | 14.18                            | 879.06                           |
| 600              | 15.86                            | 920.92                           |
| 700              | 15.86                            | 926.78                           |
| 800              | 15.86                            | 1000.64                          |
| 1000             | 15.86                            | 1046.50                          |
| 1660             | 15.86                            | 1088.36                          |

### Table 2 Simulation parameter setting

| EDM parameter setting | Ultrasonic parameter setting |
|----------------------|-----------------------------|
| Current (A) Voltage (V) Discharge time (μs) | Frequency (Hz) Amplitude (μm) |
| 2 25 50 | 20000 0, 5, 10, 15 |

3.1 Simulation results of single-pulse EDM

The simulation results of EDM machining temperature field are shown in Fig. 3.

The results of the transient thermodynamic analysis of the EDM temperature field are shown in Fig. 3. It is assumed that all the melting materials are removed and the simulation results are processed to obtain the results shown in Fig. 3a, where the central temperature is 5773.3 °C and gradually decreases with increasing radius and depth. The material removal part that reaches the melting temperature will be excluded from the discharge gap in the form of debris, and the depth of material removed is 13.8 μm, as shown in Fig. 3b.

3.2 Simulation results of single-pulse UEDM

UEDM simulation is based on EDM simulation with the addition of ultrasonic vibration parameters, which affects the heat flux of the discharge gap by changing the discharge gap of EDM and then affects the MRR of the workpiece surface. UEDM simulation results are shown in Figs. 4 to 6.

By comparing the temperature field distribution clouds and removal material profile views of EDM and UEDM, it can be observed that there was a substantial increase in the surface temperature and material removal volume of the workpiece after applying ultrasonic vibration. The center temperature and material removal volume gradually increased with the increase of amplitude. When 5-μm amplitude was applied, the center temperature was 7254.8 °C, and the material removal depth was 18.6 μm, as shown in Fig. 4. The center temperature was 7978.7 °C, and the material removal depth was 19.7 μm when the amplitude was increased to 10 μm, as shown in Fig. 5. When the amplitude reached 15 μm, the center temperature is 8702.6 °C, and the material removal depth is 20.4 μm, as shown in Fig. 6.

Analyzing the reasons, we believe that the high-frequency vibration of ultrasound constantly changes the discharge gap of UEDM, which makes the discharge voltage increase and then decrease with the amplitude, and the transient increase of voltage makes the transient heat flux of UEDM increase, which makes the central temperature increase.

4 Experimental verification

4.1 Test equipment and parameter setting

In this experiment, UEDM is realized by CHMER-EDM machine tool and self-made ultrasonic vibration table. The oscilloscope (Siglent SDS 1072CFL) is used to detect and collect the voltage waveform between the electrodes, and
the microstructure is observed by scanning electron microscope (SEM). The UEDM experimental device is shown in Fig. 7.

In order to prove the voltage change of EDM assisted by different ultrasonic amplitudes, experiments are designed to verify the variation characteristics of EDM efficiency with ultrasonic amplitudes under different current and pulse width conditions. UEDM parameters are set as shown in Table 3.

In this study, the copper electrode of φ3mm is used, and the workpiece is made of 2 mm × 20 mm × 30 mm TC4 titanium alloy with a processing depth of 0.2 mm. During the UEDM, carbon deposition occurs on the end face of the electrode after each machining, which affects the next processing. It is necessary to flatten the end face of the electrode. Thereby, the electrode surface is finely machined with a micro electric grinding hammer to ensure that the end face of the electrode is smooth and uniform before each machining.
In the discharge process, the discharge voltage waveform during EDM and UEDM are collected respectively, as shown in Fig. 8.

During the EDM processing, the discharge frequency is about 5 kHz. When the open circuit voltage breaks through the discharge medium, the electrodes start to discharge. The discharge voltage is relatively stable, as shown in Fig. 8a.

When the ultrasonic vibration with a frequency of 20 kHz and an amplitude of 5 μm is applied, the regular sinusoidal variation of the voltage waveform on the basis of the EDM voltage waveform can be observed, as shown in Fig. 8b. With the increase of ultrasonic amplitude, the inter-electrode voltage change increases, accompanied by unstable voltage mutation, as shown in Fig. 8c. When the ultrasonic amplitude increases to 15 μm, the voltage amplitude increases as the unstable voltage increases, and even the discharge channel collapses resulting in re-breakdown discharge [18].

According to the analysis of the reason, the high-frequency ultrasonic vibration constantly changes the discharge gap. The high-frequency change of the gap leads to the change of...
discharge voltage, which makes the discharge voltage change with the change of ultrasonic amplitude. The period of the change of discharge voltage is consistent with the frequency of ultrasonic vibration. In addition, the increasing amplitude of ultrasonic vibration causes an instantaneous increase in the discharge gap, which results in the collapse of the discharge channel followed by an instantaneous re-establishment of the discharge channel. It can conclude that the lower amplitude ultrasonic vibration will cause the continuous change of voltage. When the ultrasonic amplitude reaches a certain value, it will lead to the instantaneous collapse and reconstruction of the discharge channel.

4.3 Analysis of material removal surface mechanism

4.3.1 Analysis of MRR

During the processing of UEDM, the MRR is expressed in terms of the time taken to remove the same volume. This paper intends to compare the MRR at different amplitudes under different current conditions. The results are shown in Fig. 9.

As can be seen from Fig. 9, the MRR of the workpiece increases at first and then decreases with the increase of ultrasonic amplitude, and in low current machining (I ≤ 2A), the MRR is the highest when the ultrasonic amplitude is 5μm. When the current is greater than 4A, the workpiece MRR is highest at the ultrasonic amplitude of 10μm. Compared with the MRR of ultrasonic amplitude applied by different current, it can be concluded that applying ultrasonic amplitude at low currents is more effective for EDM.

In the actual machining, with the increase of the discharge current, the maximum discharge gap increases during the discharge period. The discharge gap was small for low current processing. When ultrasonic vibration with an amplitude of 5μm was applied, the discharge voltage was vibrated within the maximum discharge gap, changing the discharge voltage magnitude, and the discharge channel was not collapse. The discharge channel is collapsed and re-established when the ultrasonic amplitude increases above 5μm, which means the ultrasonic amplitude increases exceeds the maximum discharge gap of EDM. The single discharge energy is reduced, resulting in lower processing efficiency. So the highest MRR was achieved when ultrasonic vibration of 5μm amplitude was applied. When the current was increased to more than 4A, the maximum discharge gap increased, and the discharge voltage still vibrated within the maximum discharge gap when ultrasonic vibration of 10μm amplitude was applied, corresponding to the best MRR.

4.3.2 Surface topography analysis

By observing the surface morphology of the workpiece treated by scanning electron microscope (SEM) under different ultrasonic amplitudes, the micro-morphology of the workpiece surface is analyzed as shown in Fig. 10.
As shown in Fig. 10a, it showed that the crater size obtained by EDM discharge were generally between 20 and 30 μm. After applying ultrasonic vibration with an amplitude of 5 μm, the number of discharge craters increased significantly, although the discharge craters was still between 20 and 30 μm, as shown in Fig. 10b. When the ultrasonic amplitude was increased by 10 μm or more, it could be seen that most of the discharge craters were generally less than 10 μm. With the amplitude increasing, the depth of the craters gradually decreases, and the surface flattens out, as shown in Fig. 10c, d.

The results show that the introduction of ultrasonic vibration can improve the discharge probability. In addition, the recast area is reduced, and the machined surface is more polished under the influence of the cavitation effect of ultrasonic vibration. The diameter and depth of the discharge craters decreased with the decrease of the pulse width. With the increase of amplitude, the discharge channel is collapsed and

![Fig. 8 Voltage waveforms with different ultrasonic amplitudes.](image)

(a) EDM Voltage waveform  (b) UEDM voltage waveform with 5μm amplitude

(c) UEDM voltage waveform with 10μm amplitude  (d) UEDM voltage waveform with 15μm amplitude

![Fig. 9 MRR with different ultrasound amplitude parameters](image)
(a) EDM surface

(b) UEDM surface with 5µm amplitude

(c) UEDM surface with 10µm amplitude

(d) UEDM surface with 15µm amplitude
The first draft of the manuscript was written by Jiajun Liu, and all performed by Yinghuai Dong, Jiajun Liu, Guangyan Li, and Yan Wang. All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Yinghuai Dong, Jiajun Liu, Guangyan Li, and Yan Wang. The first draft of the manuscript was written by Jiajun Liu, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

**Funding** This work supported by Natural Science Foundation of Tianjin City (18JCYBJC88900, 18JQJNC05200, 18JQJNC75300) and National Natural Science Foundation of China (51505334).

**Availability of data and materials** All data generated or analyzed during this study are included in this published article.

**Declarations**

**Ethics approval** Not applicable.

**Consent to participate** Not applicable.

**Consent for publication** Not applicable.

**Competing interest** The authors declare no competing interests.

**References**

1. Wang Y, Liu ZQ, Shi J, Dong YH, Yang S, Zhang XF, Lin B (2020) Analysis of material removal and surface generation mechanism of ultrasonic Vibration-assisted EDM. Int J Adv Manuf Technol 110(1–2):177–189. https://doi.org/10.1007/s00170-020-05769-x
2. Yang XX (2015) Principle and process application of EDM. National Defense Industry Press, Beijing
3. Kremer D, Lebrun JL, Hosari B (1989) Effects of ultrasonic vibrations on the performances in EDM. Annals of the CIRP 38(1):199–202
4. Kremer D, Lhaubt C, Moisan A (1991) A study of the effect of synchronizing ultrasonic vibrations with pulses in EDM. Annals of the CIRP 40(1):211–214
5. Lin YC, Yan BH, Chang YS (2000) Machining characteristics of titanium alloy (Ti–6Al–4V) using a combination process of EDM with USM. J Mater Process Technol 104(3):171–177. https://doi.org/10.1016/S0924–0136(00)00539–2
6. Abdullah A, Shabgard MR (2008) Effect of ultrasonic vibration of tool on electrical discharge machining of cemented tungsten carbide (WC-Co). Int J Adv Manuf Technol 38(11–12):1137–1147. https://doi.org/10.1007/s00170-007-1168-8
7. Abdullah A, Shabgard MR, Ivanov A (2009) Effect of ultrasonic assisted EDM on the surface integrity of cemented tungsten carbide (WC-Co). Int J Adv Manuf Technol 41(3–4):268–280. https://doi.org/10.1007/s00170-008-1476-7
8. Shabgard MR, Alenabi H (2015) Ultrasonic assisted electrical discharge machining of Ti–6Al–4V alloy. Mater Manuf Process 30(8):991–1000. https://doi.org/10.1080/10426914.2015.1004686
9. Li HC, Wang ZL, Wang YK, Liu HZ, Zhao ZX (2018) Micro-EDM and micro-USM combined milling of ZrB2–SiC-graphite composite for 3D micro-cavities. Int J Adv Manuf Technol 99:2635–2645. https://doi.org/10.1007/s00170-018-2568-7
10. Liu Y, Chang H, Zhang WC (2018) A simulation study of debris removal process in ultrasonic vibration assisted electrical discharge machining (EDM) of deep holes. Micromachines 9(8):378. https://doi.org/10.3390/mi9080378
11. Choubey M, Maity KP, Sharma A (2020) Finite element modeling of material removal rate in micro-EDM process with and
without ultrasonic vibration. Grey Systems: Theory and Application 10(3):311–319. https://doi.org/10.1108/GS-11-2019-0047
12. Li ZK, Bai J (2017) Impulse discharge method to investigate the influence of gap width on discharge characteristics in micro-EDM. Int J Adv Manuf Technol 90(5–8):1769–1777. https://doi.org/10.1007/s00170-016-9508-1
13. Giridharan A, Samuel GL (2015) Modeling and analysis of crater formation during wire electrical discharge turning (WEDT) process. Int J Adv Manuf Technol 77(5–8):1229–1247. https://doi.org/10.1007/s00170-014-6540-x
14. Dibito DD, Eubank PT, Patel MR, Barrufet MA (1989) Theoretical models of the electrical discharge machining process. I. A simple cathode erosion model. J Appl Phys 66(9):4095–4103
15. Shahgard M, Ahmadi R, Seyedzavvar M, Oliaei SNB (2013) Mathematical and numerical modeling of the effect of input parameters on the flushing efficiency of plasma channel in EDM process. Int J Mach Tool Manuf 65:79–87. https://doi.org/10.1016/j.ijmachtods.2012.10.004
16. Ikai T, Fujita I, Hashiguchi K (1995) Heat input for crater formation in EDM. Proceedings of International Symposium for Electro Machining-ISEMXI. EPFL, Lausanne, Switzerland, pp 163–170
17. Joshi SN, Pande SS (2009) Development of an intelligent process model for EDM. Int J Adv Manuf Technol 45(3–4):300–317. https://doi.org/10.1007/s00170-009-1972-4
18. Dong YH, Li GY, Wang Y, Song JB, Yang S, Yu HY (2021) Study on the effective discharge energy mechanism of vertical ultrasonic vibration assisted EDM. Proc IMechE Part B: J Eng Manuf 1–9. https://doi.org/10.1177/09544054211028527

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.