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A Study of Fabricating Nano-W Colloid by Discharge Energy Enhancement of the micro-EDM System

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Abstract
This study enhanced the discharge energy of an existing micro-electric discharge machining (EDM) system to provide the system with the ability to prepare nano-tungsten (nano-W) colloid. The energy-enhanced EDM system, referred to as the upgraded-micro-EDM system, enables spark discharge using tungsten wires immersed in deionized water to produce nano-W colloids. Compared with the chemical preparation method, the processing environment for preparing colloids will not have nanoparticle escape in this study. Among the nano-W colloids prepared using the upgraded-micro-EDM system and an industrial EDM system, the colloid prepared by the upgraded-micro-EDM system exhibited more favorable absorbance, suspensibility, and particle size. The colloid prepared by the upgraded-micro-EDM system with the pulse on time and off time of 10–10μs had an absorbance of 0.277 at the wavelength of 315 nm, ζ potential of –64.9 mV, and an average particle size of 164.9 nm. Transmission electron microscope imaging revealed the minimum particle size of approximately 11 nm, and the X-ray diffractometer spectrum verified that the colloid contained only W₂O₆ and W nanoparticles. Relative to industrial EDM applications for nano-W colloid preparation, the upgraded system boasts lower costs and smaller size, and produces nano-W colloid with superior performance. These advantages contribute to the competitiveness of electrical spark discharge method in the preparation of high-quality nano-W colloids.

Keywords: electrical spark discharge method; nano-W colloid; electrical discharge machining; interelectrode gap

1. Introduction
Tungsten (W) is a transition metal with high hardness, a high melting point, and high heat conductivity. The metal has high stability and exists in various compounds in nature, with tungsten carbide (WC) and tungsten trioxide (WO₃) the more common forms. Research has been performed on WC applications in mechanical processing [1, 2] and catalysts [3, 4] and on its material properties [5, 6]. Studies have also been conducted on the material properties of WO₃ [7, 8] and its applications in thin films [9, 10] and sensors [11, 12]. Research topics explored regarding the development of tungsten nanocomposite materials include the mechanical alloying of copper-tungsten (C-W) composite alloys [13], friction stir alloying of aluminum-tungsten (Al-W) composite [14], and discharge plasma sintering of copper-tungsten nanocomposite materials [15]. Given the widespread application of nano-tungsten (nano-W) materials, their production is crucial for nanomaterial research. Currently, chemical methods are generally employed for the preparation of nano-W materials. However, such methods risk contamination and is plagued with nanoparticle dissipation problems. Literature indicates that exposure to nanoparticles can have adverse health effects. For example, the inhalation of nanoparticles may result in lung tissue lesions [16]. Therefore, resolving the problem of flying dust in the preparation environment is crucial [17]. The use of Electrical Discharge Machining (EDM) to obtain nanomaterials from melting the surface of electrode materials is called the Electric Spark Discharge Method (ESDM) [18-20]. A recent study employed an ESDM for the preparation of WO₃ · H₂O nanoparticles [21]. The study adopted pulse generators, vibrators, deionized water, and two W electrodes to prepare nanoparticles in deionized water, thereby avoiding problems encountered in the chemical method. The proposed nano-W colloid
preparation method has a simple equipment framework, but it lacks the server-based interelectrode gap (IEG) control mechanism of industrial EDM. Therefore, the IEG cannot be dynamically adjusted in accordance with the IEG resistance and often exhibits poor discharge performance [22]. This reduces the nanoparticle yield per units of time and electrode material. The ESDM in industrial nano-W colloid preparation entails large, costly equipment. To avoid the aforementioned disadvantages, this study upgraded the existing micro-EDM system used for nano-W colloid preparation. In this paper, the existing and upgraded micro-electrical discharge machining systems are referred as the existing-micro-EDM and upgraded-micro-EDM system, respectively [23]. This study evaluated the advantages of the micro-EDM system in nano-W colloid preparation by assessing the properties of nano-W colloids prepared using the upgraded-micro-EDM system and an industrial ESDM system.

2. Materials and Methods

2.1. ESDM principle

The principle of the ESDM is to activate periodic spark discharges in the dielectric fluid (DF) in the electrode gap by using pulse voltage. This subject the surface material of the electrodes to high-temperature vaporization and rapid condensation in the DF, thus producing nanoparticles. The preparation efficiency is associated with the IEG discharge rate. Factors influencing the IEG discharge rate include pulse voltage, time variables, slag residue between the IEG, and the dielectric strength of the DF. Figure 1 presents the discharging process of a single cycle and the discharged voltage and current. The anode and cathode of the pulse voltages are separately connected to the two electrodes. \(V_{\text{IEG}}\) and \(I_{\text{IEG}}\) represent the IEG voltage and current, respectively [24]. Figure 1(a) displays the sparking process of the ESDM, with \(T_1\), \(T_2\), \(T_3\), and \(T_4\) sequentially representing the discharge, ionization, slag generation and expulsion, and insulation recovery of the DF stages, respectively. \(T_1\)–\(T_4\) occur during the \(T_{\text{on}}\) stage of the pulse period; \(T_4\) occurs during the \(T_{\text{off}}\) stage of the period. Figure 1(b) indicates \(V_{\text{IEG}}\) and \(I_{\text{IEG}}\) during \(T_1\)–\(T_4\). During the \(T_1\) stage, few DF molecules in the IEG are ionized in the electric field. A discharge channel is formed in the IEG, and trace amounts of electrons are emitted from the cathode surface to the anode surface [25], [26]. During the subsequent \(T_2\) stage, large numbers of DF molecules in the IEG are subjected to high-speed impact by electrons and are ionized. The aforementioned process of ionization by collision rapidly increases the number of positive ions and free electrons in the IEG, both of which rapidly shoot toward the opposite electrode, forming a narrow plasma column in the IEG. The resistance of the DF (\(R_{\text{df}}\)) rapidly drops due to insulation breakdown, which results in a decrease in \(V_{\text{IEG}}\) and a rapid increase of \(I_{\text{IEG}}\) to the maximum value. During the \(T_3\) stage, numerous free electrons and positive ions in the IEG rapidly impact the opposite electrode under the effect of the electric field. At impact, kinetic energy is converted to heat, which melts and vaporizes the surface material of the electrodes and causes the DF in the IEG to vaporize and expand [27]. The impact caused by the vaporization and expansion of DF pushes the metallic vapor away from the IEG, where it makes direct contact with the surrounding low-temperature DF and rapidly condenses into nanoparticles or submicron particles. At this stage, \(I_{\text{IEG}}\) is maintained at the maximum value due to the insulation breakdown of the DF. Contrarily, \(V_{\text{IEG}}\) is maintained at a fixed value as sparking continues in the IEG. During the \(T_4\) stage, the pulse source is in the off state, and the melted material residues in the IEG are expelled from it. The \(R_{\text{df}}\) returns to the insulation state and \(I_{\text{IEG}}\) and \(V_{\text{IEG}}\) rapidly drop to zero. Through the aforementioned periodic discharging process, metallic particles can be suspended in the DF.
Figure 1. Discharge cycle of the ESDM: (a) discharge process; (b) \( V_{IEG} \) and \( I_{IEG} \).

2.2. Existing-micro-EDM system

The existing-micro-EDM system is comprised of a production mechanism, a servo circuit, and a computer interface control unit (CICU). Figure 2 depicts the architecture of the existing-micro-EDM system, and Figure 3 is a photograph of the system. In the production mechanism, a movable electrode is fixated to a slider set on a slide rail. The position of the slider on the rail is controlled using a direct current motor. Therefore, the IEG is modified by controlling the motor speed. The main function of the CICU, which consists of a personal computer, VisSim software, and an RT-DAC4/PCI card [28, 29], is to process the input/output signals of the servo circuit. The main screen of the CICU is presented in Figure 4. Users may control the motor speed by setting the variables of the proportional, integral, and derivative (PID) controller (marked by red dotted rectangle A). Additionally, users may set the production time by using the variable \( T_{on} - T_{off} \) (in red dotted rectangle B). The servo circuit is composed of a discharge circuit, a motor control feedback circuit, and a discharge state identification circuit. The function of the discharge circuit is to provide the required IEG pulse voltage by controlling the ON/OFF state of the transistor [30, 31]; the motor control feedback circuit to control the IEG and measure the IEG disposition [32]; and the discharge state identification circuit to determine the IEG discharge state.

2.3 Upgrade of discharge circuit and motor control feedback circuit

This study used the existing-micro-EDM system for nano-W colloid preparation. However, instrument analysis revealed that the produced colloid did not possess the properties of nano-W colloid. This study inferred the reason that the system was unable to produce nano-W colloids because of insufficient discharge energy in the IEG. To equip the system with superior nano-W colloid preparation capability, this study upgraded the discharge circuit and the motor control feedback unit to enhance the system discharge...
2.3.1. Discharge circuit modification

The discharge circuit of the existing-micro-EDM system is depicted in Figure 5. The circuit is composed of a 96V DC power source, an IRF740 transistor, a TLP250 optical coupled isolator, and 5 cement resistors. The rated voltage ($V_{DS}$) and current ($I_D$) of the IRF740 transistor are 400 V and 10 A, respectively. This circuit is used to provide the high-frequency IEG pulse voltage. The voltage is generated by first using the CICU to output a PWM signal to the input end of (CON1) of the TLP250 optimal coupled insulator of the discharge circuit for the set production time ($T_{on}$–$T_{off}$). The TLP250 insulator subsequently outputs the signal to the IRF740 transistor gate, which results in its alteration between the ON/OFF state in accordance with the gate signal. This rapid alteration in the ON/OFF state of the IRF740 transistor gate converts DC power source to the high-frequency pulse voltage required for IEG discharge. When the transistor is in a conducting state, the pulse source emits a discharging current through the IEG. This circuit path is composed of serially connected resistors $R_3$, $R_{4A}$, and $R_{4B}$ and the electrodes. $R_{4A}$ and $R_{4B}$ serve as the current-limiting resistor of the IEG. The circuit path has an open circuit voltage of 96 V and a combined series resistance between $R_3$, $R_{4A}$, and $R_{4B}$ of 21 $\Omega$. Therefore, the maximum IEG discharge current is 4.6 A. When the transistor is in the cut-off state, the energy stored in the IEG may be discharged through the circuit formed by the serial connection of $R_{2A}$, $R_{2B}$, $R_3$, and $R_{4A}$ with $R_{4B}$. The release of this stored energy provides the IEG with a favorable insulation property before the next discharge cycle. An LED serves as a discharge indicator; if the LED is conducted, the system is in the colloid preparation process.

To provide the upgraded-micro-EDM system with the function to prepare nano-W, this study increased the power source voltage of the circuit from 96 V to 192 V to enhance the energy discharged in the IEG. Additionally, this study upgraded the scale of specific components, particularly the three sections (i.e., A, B, and C) marked in the red dotted rectangles in Figure 5, in the existing-micro-EDM system to enable the discharging process to be conducted at a suitable range. In section A, this study replaced the 96 V direct power source with a 192 V direct power source. In section B, the resistance of $R_{4A}$ and $R_{4B}$ were increased proportionally with the increase in voltage; specifically, the two resistors were strengthened to 20 $\Omega$. The upgraded design has a maximum discharge current of 4.68 A. This enables the upgraded-micro-EDM system to achieve the same current as the existing-micro-EDM system and ensures that the discharge circuit is maintained within a suitable working range. When the system voltage is increased to 192 V, the ringing effect in the discharging process would generate a surge voltage greater than 500 V. This voltage exceeds the tolerance of the IRF740 transistor; therefore, a more suitable transistor is required to ensure the operation stability of the discharge circuit. This study substituted the IRF740 transistor with the IPP60R060P7 transistor, which can withstand a voltage of 600 V. This upgrade is indicated in section C of Figure 5.

2.3.2 Motor control feedback circuit modification

Figure 6 presents the motor control feedback circuit of the existing-micro-EDM system. The circuit is composed of a differential amplifier, a resistor-capacitor (RC) low-pass filter, an ISO122P isolation amplifier, a motor driver, a 74LS07 buffer, and a 6N137 optocoupler. The functions of the circuit include monitoring the IEG displacement and controlling the IEG distance. IEG displacement is monitored by first using the optical encoder mounted on the motor to output pulse signals
containing data on the motor rotation speed. The CICU then converts the pulse signals into the displacement variables of the IEG. The IEG distance control function of the circuit is used to adjust the IEG distance to ensure suitable sparking discharge. Additionally, the circuit controls the IEG distance through the CICU, which ensures a closed-circuit IEG distance based on the feedback signals on IEG voltage. Because \( V_{IEG} \) is a high-voltage pulse signal, the signal voltage must first be lowered and the signal converted into analog before input into the CICU. In the motor control feedback circuit, \( V_{IEG} \) feedback signals must first be processed using \( R_{f1} \) and \( R_{f2} \) to divide the voltage. Because the resistance of \( R_{f2} \) is 18 times that of \( R_{f1} \), \( V_{Rf1} \) is subjected to \( \frac{1}{19} \)th that of \( V_{IEG} \). The differential amplifier is subsequently employed to extract the voltage signal (\( V_{Rf1} \)) in \( R_{f1} \). The signal output from the differential amplifier first passes the RC low-pass filter for conversion into analog and then is transmitted into the isolation amplifier for input into the CICU. In accordance with the analog signal on IEG voltage, the CICU activates its PID controller to output the motor rotation speed control signal (\( V_{speed\, command} \)) to the motor control feedback circuit [33-35]. In this circuit, \( V_{speed\, command} \) is first processed using the isolation amplifier for input into the motor driver. Next, the motor driver controls the rotation speed of the DC servo motor based on the signal input, thereby controlling the motor rotation speed to ensure a favorable IEG distance for sparking discharge.

The motor control feedback circuit of the upgraded system is marked by the red dotted rectangle in Figure 6. The design was intended to prevent the input voltage for the differential amplifier (\( V_{RF1} \)) from increasing due to system voltage changes. This design ensures that the properties of the motor control feedback circuit of the upgraded system are similar to those of the existing system. In the motor control feedback circuits of the existing system, the resistance of \( V_{RF1} \) is \( \frac{1}{19} \)th that of \( V_{IEG} \). The system voltage of the upgraded system is 192 V, which is two times that of the existing-micro-EDM. If \( V_{RF1} \) in the motor control feedback circuit is \( \frac{1}{38} \) \( V_{IEG} \), \( V_{RF1} \) in the motor control feedback circuit of both the upgraded and existing systems will be identical. This study increased the resistance of \( R_{f2} \) (red dotted section in Figure 6) to 37 k\Ohm, thus enabling the resistance of \( R_{f2} \) to be 37 times that of \( R_{f1} \) and ensuring that \( V_{RF1} \) is \( \frac{1}{38} \) \( V_{IEG} \).

![Figure 6. Motor control feedback circuit of the existing-micro-EDM system.](image)

3. Results and Discussion

The industrial EDM and upgraded-micro-EDM systems were used to prepare nano-W colloids under 25 °C, 1 atm. The electrode materials used were tungsten alloy wires 1 mm in diameter with 99.97% purity. The DF used was 200 mL of deionized water. To evaluate the properties of the prepared colloids, this study adopted ultraviolet-visible spectrometry (UV-Vis, Thermo-Helios Omega, Thermo Fisher Scientific Inc, Waltham, MA, USA) and a Zetasizer nano system (Zetasizer, Nano-ZS90, Malvern Zetasizer, Worcestershire, UK) to analyze the absorbance spectrum, intensity, suspension stability, and particle distribution of the colloids. Additionally, transmission electron microscopy (TEM, JEM-2100F, JEOL Ltd, Japan) was employed to observe particle size, shape, and components.

3.1 Property analysis of the nano-W colloids prepared using industrial EDM
Figure 7 presents the industrial EDM system used for nano-W colloid preparation. During preparation, the open circuit voltage and the peak current were 240 V and 6 A, respectively. The preparation time variables ($T_{on}$–$T_{off}$) were set as 10–10, 30–30, 50–50, 70–70, and 90–90 μs; the nano-W colloids prepared using these variables were labelled C-I-EDM 10-10-30 min colloid, C-I-EDM 30-30-30 min colloid, C-I-EDM 50-50-30 min colloid, C-I-EDM 70-70-30 min colloid, and C-I-EDM 90-90-30 min colloid, respectively. The preparation duration of each colloid was 30 min.

Figure 8 presents the UV-Vis analysis results for the colloids. The C-I-EDM 10-10-30 min colloid demonstrated an absorbance peak of 0.242 at a wavelength of 316 nm, and the C-I-EDM 30-30-30 min colloid had an absorbance peak of 0.158 at a wavelength of 315 nm. The C-I-EDM 50-50-30 min colloid, C-I-EDM 70-70-30 min colloid, and C-I-EDM 90-90-30 min colloid did not exhibit a notable wavelength. As Figure 8 indicates, both the C-I-EDM 10-10-30 min colloid and the C-I-EDM 30-30-30 min colloid contained nano-W particles. The $\zeta$ potential and particle size distribution by number of the two colloids are presented in Figs. 9 and 10. The C-I-EDM 10-10-30 min colloid had a $\zeta$ potential of $-61.3$ mV, an average particle size of 216.3 nm, and 100% particle size distribution of 80.51 nm at peak 1. The C-I-EDM 30-30-30 min colloid had a $\zeta$ potential of $-32.6$ mV, an average particle size of 252.2 nm, and a 99.3% particle size distribution of 68.27 nm at peak 1.
Figure 10. Analysis of C-I-EDM 30-30-30 min colloid: (a) ζ potential; (b) particle size distribution report by number.

Table 1 compares the properties of the C-I-EDM 10-10-30 min and C-I-EDM 30-30-30 min colloids. Analysis of the particle size distribution by number revealed that the particle sizes of both colloids met the requirement for nanometer scale. Additionally, the absolute ζ potential of both colloids exceeded 30 mV, indicating that both exhibited favorable suspension stability. The absorbance peak and absolute ζ potential of the C-I-EDM 10-10-30 min colloid was much greater than that of the C-I-EDM 30-30-30 min colloid, thereby indicating that the C-I-EDM 10-10-30 min colloid possessed a greater nanoparticle concentration and more favorable suspension stability. Further analysis revealed that the C-I-EDM 10-10-30 min colloid exhibited a smaller average particle size than that of the C-I-EDM 30-30-30 min colloid. In sum, the analysis indicated that the properties of the C-I-EDM 10-10-30 min colloid were more favorable than those of the C-I-EDM 30-30-30 min colloid.

Figure 11 displays TEM images of the C-I-EDM 10-10-30 min colloid. Figure 11(a) presents the image recorded under ×20,000 magnification. In the magnified image, numerous black and grey spots of nano-W particles can be observed. Figure 11(b) depicts part of Figure 11(a) (indicated by the square) at ×400,000 magnification. The nano-W particles are observed as quadrangles and have a particle size of 80 nm. This finding is consistent with the measured average particle size of 80.51 nm at peak 1 (Figure 9(b)). Figure 11(c) presents a magnification of the image in Figure 9(b) (indicated by the square) at ×800,000 at a scale of 5 nm. The width of the lattice line of the nano-W particles was revealed to be 0.223 nm.

Table 1. Property comparison between the C-I-EDM 10-10-30 min colloid and C-I-EDM 30-30-30 min colloid

| Colloid          | C-I-EDM 10-10-30 min colloids | C-I-EDM 30-30-30 min colloids |
|------------------|-------------------------------|-------------------------------|
| Wavelength       | 316 nm                        | 315 nm                        |
| Absorbance peak  | 0.242                         | 0.158                         |
| ζ potential      | -61.3 mV                      | -32.6 mV                      |
| Average particle size | 216.3 nm                  | 252.2 nm                      |
| Particle size distribution at peak 1 | 80.51 nm                  | 68.27 nm                      |

Figure 11. TEM images of the C-I-EDM 10-10-30 min colloid (a) ×20,000; (b) ×400,000; and (c) ×800,000.

3.2 Property analysis of nano-W colloids prepared using the upgraded-micro-EDM system

In the preparation of nano-W colloids using the upgraded-micro-EDM system, the
open circuit voltage and the peak current were set as 192 V and 4.7 A, respectively. This study labelled the colloid prepared using a preparation time variable (T\text{on}–T\text{off}) of 10–10 μs and preparation duration of 16 min as C-M-EDM 10-10-16 min colloid. UV-Vis analysis of the colloid is presented in Figure 12. The colloid exhibited an absorbance peak of 0.277 at a wavelength of 315 nm, thereby suggesting that the prepared colloid contained nano-W particles. The ζ potential and particle size distribution by number analysis of the colloid are displayed in Figure 13; the colloid had a ζ potential of −64.9 mV and an average particle size of 164.9 nm. The colloid had a 100% particle size distribution of 83.41 nm at peak 1. The absolute ζ potential of the colloid is greater than 30 mV, indicating that the colloid exhibits favorable suspension stability.

Figure 12. Absorption spectrum of C-M-EDM 10-10-16 min colloid.

3.3 Component analysis of nano-W colloids

This study employed an X-ray diffractometer (XRD; Panalytical, Empyrean...
model, Netherlands, CuKα radiation at 45 kV) to analyze the crystal structures of the nano-W particles in the colloids prepared using the industrial EDM and the upgraded-micro-EDM system, namely the C-I-EDM 10-10-30 min colloid and the C-M-EDM 10-10-16 min colloid. Figure 15 depicts the XRD spectrums of the colloids. Both spectrums contained $W_{2.00}$ and $W$ diffraction peaks. The International Centre for Diffraction Data labelled $W_{2.00}$ as 96-900-8559 and W as 00-047-1319. This result indicates that both colloids contained two tungsten products with different crystal structures, namely $W_{2.00}$ and W. Figure 15 indicates that the position of the diffraction peak at the 20 degree angle of both colloids corresponded to the same crystal orientation. Therefore, this study inferred that the colloids contained the same crystallized materials. Table 2 lists the position of the diffraction peak at the 20 degree angle and the Miller indices of the $W_{2.00}$ and W components in the two colloids.

| Compound name | Chem. formula | The positions 20° and Miller indices (h k l) |
|---------------|---------------|------------------------------------------|
| Tungsten      | $W_{2.00}$    | 40.2°(0 1 1)                             |
|               |               | 58.2°(0 2 0)                             |
|               |               | 73.1°(1 2 1)                             |
|               |               | 87.0°(0 2 2)                             |
| Tungsten      | W             | 35.5°(2 0 0)                             |
|               |               | 39.8°(2 1 0)                             |
|               |               | 43.8°(2 1 1)                             |
|               |               | 63.7°(2 2 2)                             |
|               |               | 66.7°(3 2 0)                             |
|               |               | 69.6°(3 2 1)                             |
|               |               | 75.1°(4 0 0)                             |
|               |               | 86.0°(4 2 0)                             |
|               |               | 88.6°(4 2 1)                             |

3.4 Property comparison of nano-W colloids prepared using industrial EDM and the upgraded-micro-EDM system

This study compared the properties of the C-I-EDM 10-10-30 min colloid and the C-M-EDM 10-10-16 min colloid to evaluate the advantages of using the micro-EDM system to prepare nano-W colloids. The items compared were absorbance spectrum intensity, suspension stability, particle size distribution by number, and surface properties (Table 3). First, in the particle size distribution by number, the sizes of the particles in both samples indicated they were nanoparticles. The absolute ζ potential of both colloids exceeded 30 mV, indicating favorable suspension stability. However, the absorbance peak and absolute ζ potential of the C-M-EDM 10-10-16 min colloid were greater than those of the C-I-EDM 10-10-30 min colloid, thereby suggesting that the C-M-EDM 10-10-16 min colloid had a higher nanoparticle concentration and more favorable suspension stability. The comparison also revealed that the C-M-EDM 10-10-16 min colloid had a smaller average particle size. According to the analysis of nanoparticle concentration, suspension stability, and average particle size, the properties of the C-M-EDM 10-10-16 min colloid surpassed those of the C-I-EDM 10-10-30 min colloid. TEM analysis revealed the particle size of the C-M-

![XRD pattern of C-I-EDM 10-10-30 min colloid and C-M-EDM 10-10-16 min colloid.](image)
EDM 10-10-16 min colloid to be 11 nm, much smaller than that of the C-I-EDM 10-10-30 min colloid. Additionally, both colloids had the same lattice line width. This indicates that the nanoparticles observed in the TEM image were of the same crystal structure material. In sum, the micro-EDM system produced colloids with higher suspension stability, nanoparticle concentration, and smaller particle size in less time. The results indicate that the micro-EDM system has superior performance in nano-W colloid preparation.

Table 3. Property comparison of the C-I-EDM 10-10-30 min colloid and C-M-EDM 10-10-16 min colloid

| Property                       | C-I-EDM 10-10-30 min colloids | C-M-EDM 10-10-16 min colloids |
|--------------------------------|--------------------------------|--------------------------------|
| Wavelength                     | 316 nm                         | 315 nm                         |
| Absorbance peak                | 0.242                          | 0.277                          |
| ζ potential                    | -61.3 mV                       | -64.9 mV                       |
| Average particle size          | 216.3 nm                       | 164.9 nm                       |
| Particle size distribution at peak 1 | 80.51 nm                     | 83.41 nm                       |
| Lattice line width             | 0.223 nm                       | 0.223 nm                       |
| Particle appearance and morphology | 80 nm, quadrangle particle shape | 11–12 nm, irregular particle shape |

4. Conclusions

The upgraded-micro-EDM system proposed in this study increased the voltage of the existing-micro-EDM system from 96 V to 192 V. The discharge energy provided by this voltage enabled the system to prepare nano-W colloids at room temperature and pressure. When the preparation time $T_{on}-T_{off}$ was 10-10 μs, the upgraded-micro-EDM system and the industrial EDM system prepared the nano-W colloid with the preparation durations of 16 minutes and 30 minutes, respectively. Analysis of instruments revealed that both colloids had Nano-scale tungsten particles with good suspension. Analysis of the colloidal performance revealed that the colloid prepared by the upgraded-micro-EDM system exhibited better performances in terms of absorbance, suspensibility, and particle size. These results indicated that the upgraded-micro-EDM system prepared nano-W colloids with better performances in a shorter time than the industrial EDM system. The conclusions are as follows:

1. Analysis of UV-Vis and Zetasizer showed that the colloid prepared by the upgraded-micro-EDM system with the pulse on time and off time of 10–10 μs and a preparation time of 16 minutes had an absorbance of 0.277 at the wavelength of 315 nm, ζ potential of −64.9 mV, and an average particle size of 164.9 nm. TEM analysis showed that the particle size of this colloid is about 11–12 nm.

2. Compared with the industrial EDM system applications for nano-W colloid preparation, the upgraded-micro-EDM system had the advantages of low costs, smaller size, and produced nano-W colloid with superior performance. Compared with the chemical preparation method for nano-W colloids, the upgraded-Micro-EDM system for preparing colloids would not have nanoparticles dissipate in the process environment. In sum, the upgraded-micro-EDM system can be an advanced technology for preparing high-quality nano-W colloids.

Availability of data and materials
Not applicable

Competing interests
The authors declare that there is no conflict of interest regarding the publication of this paper.

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Authors’ Contributions
Project administration, Kuo-Hsiung Tseng; Resources, Kuo-Hsiung Tseng and Chaur-Yang Chang; Supervision, Chaur-Yang Chang and Kuo-Hsiung Tseng; Funding acquisition, Chaur-Yang Chang; Data curation, Zih-Yuan Lin and Meng-Yun Chung; Formal analysis, Zih-Yuan Lin; Methodology, Jui-Tsun Chang and Zih-
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