UDC 621.9.048

# RESEARCH ON METHODS OF IMPROVING THE QUALITY OF THE COATING OF LOW-MELTING ALLOY B83 FORMED BY ELECTROSPARK PROCESSING METHODS

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*The electro-spark deposition (ESD) process uses electric spark discharge to coat and melt conductive materials onto the surface of the substrate to form an alloyed coating. It can realize the function of strengthening or repairing the surface of parts. Because of the low cost and simple processing, this process is often used to generate anti-wear coatings and anti-friction coatings on the surface of parts to extend its service life. The improvement of surface quality of electro-spark deposition has always been the focus of research in the scientific and industrial circles. Soft metals can be used as antifriction materials to reduce metal surface friction and improve service life. Low-temperature soft metals are prone to melting and bending when electrodes are working, and with which the improvement of surface quality has become a processing difficulty. The Babbitt B83 is one of the characteristic materials of low-temperature soft metals. It has good ability to reduce surface friction and improve corrosion resistance. As the outermost layer of the composite coating, it can meet the special requirements of parts surface remanufacturing. In this article, the use of vibration, control energy, reasonable control of the discharge gap can be obtained better surface quality of low temperature soft metal by new vibration method. In the case of the same discharge energy, the surface roughness of the new ESD process was 43% less than the surface roughness of the traditional vibration deposition process, and the standard deviation was 73% less. With the discharge gap was controlled at 0.377~0.6mm, continuous ESD sputtering can be achieved. The major vibration frequency was 337 Hz, the vibration impact was small, which can achieve the continuous deposition of low-temperature soft metal. And 3mm electrode did not appear bending. Reasonable selection of argon protection process can reduce the generation of oxide film and improve the surface quality of B83 material. The process can reduce the coating thickness of soft metals and the cost of ESD coatings, thus it will make some precious friction-reducing metal materials widely available. It provided a new solution for continuous processing of ESD on robots and multi-axis machine.*

***Key words:*** *electro-spark deposition, quality, coating, surface layer, alloy, babbitt, vibration, roughness, technology, processing, equipment.*

DOI https://doi.org/10.32782/msnau.2023.3.1

## Introduction

The ESD coating had a certain roughness on the deposited surface due to the discharge energy and processing factors (Vizureanu P., 2018; Rukanskis M., 2019). As the thickness of deposition increased, the surface quality of the coating decreased. When the deposition thickness increased in the ESD process, surface unevenness increased, defects such as internal bubbles and surface cracks appeared, and the surface quality deteriorated (Jiao Z., 2016; Shao-hua H., 2012; Katinas E. et al., 2019). It has been a hot research issue for scientists to study how to improve the surface quality of ESD coatings (Tang S.K., 2009; J.L. Reynolds et al., 2003). The surface quality of the coating can be improved by changing deposition parameters or new technologies (Renna G. et al., 2019). However, low-temperature soft metal coatings were different from hard high-temperature metal materials by ESD (Z. Zhengchuan et al., 2023; Z. Zhang, 2021). Compared with other metal coatings, the surface quality of soft metal was poor. Because the electrode temperature rose too quickly, continuous processing cannot be performed. Low-temperature soft metal coatings have become a processing problem for the ESD process. In recent years, with the deepening of research, certain new solutions have emerged for traditional ESD. Norbert Radek et al. used WC–Co-$Al_2O_3$ electrodes made of nanostructured powders to deposit on the surface of 45 steel (Radek N. & Bartkowiak K., 2010), and then performed laser surface melting. Mykhailo Dovzhyk and V.B. Tarelnyk used grinding technology to improve the accuracy of high-strength stainless steel BHC-2 (Tarelnyk V. et al., 2016). Frangini et al. proposed that dynamic control of spring force can improve the stability of the ESD process and reduce roughness (Frangini S. & Masci A., 2010). Liu proposed a composite method of ultrasonic impact rolling and electric spark deposition to reduce the surface roughness of ESD coatings (Y. Liu et al., 2015). Han et al. studied the single-point gap discharge, single-point contact discharge and rotating electrode continuous discharge mechanisms of rotating electrode spark deposition (H. Hongbiao et al., 2019). Chen et al. proposed that the electrode end integrated with ultrasound and used mold steel 718 as an electrode on the surface of the H13 substrate to study the influence of processing parameters on the surface deposition thickness (C. Chunmu et al., 2011). Zhan used ultrasonic surface rolling (USR) to strengthen the QAl9–4 aluminum bronze forming layer. As the pressure increased, the surface accuracy improved (Z. Yong, 2021). Wood used a multi-axis additive robot manufacturing system (ARMS) on 4340 steel to improve the quality of coatings by ESD (Wood W. et al., 2017). Stephen Peterkin proposed the use of electro-spark deposition of parameter and movement pattern to improve the quality of TiC/Ni coatings (Peterkin S., 2017). Dong strengthened the surface of 65Mn to improve the surface deposition quality with ultrasonic vibration assisted electrodes (C.J. Dong et al., 2011). D.M. Tabatabai et al. used diamond smoothing technology to improve the deposition surface of gas turbine engines (D.M. Tabatabai et al., 2020). These methods used ultrasonic vibration, changing the discharge gap, electro-spark deposition process, and composite process processing. Deposition of soft metals required separate equipment for processing, and the process was complicated by increased surface accuracy. These increased the processing cost. The use of vibration, control energy, reasonable discharge gap can be obtained better coating quality of low temperature soft metal. Typical low temperature soft metals include Sn, Zn, Al, Pb, Ag and their alloys. They can be used as antifriction materials to reduce metal surface friction during electro-spark deposition. Due to their low melting temperature, the electrodes were easily melted by heat resulting in non-uniformity of the melt droplets and large surface roughness with the traditional vibrating electrode or rotating electrode deposition process. At the same time, the overheated electrode rod was easily bent by heat. It caused to stop for a period of time to cool down in the processing. The problem of bending the heated electrode was reduced by increasing the vibration frequency and reducing the shock amplitude. The quality of deposition of soft metals was improved by lowering the temperature of the electrode droplets by means of energy control. This process made it easy to automate the production of CNC and robotic processes, and improved the efficiency and quality of coating deposition.

## Materials and Methods

### Material Analysis

The deposition substrate was 45 steel. The block B83 (YUNNAN TIN CO.) was cut into rod-shaped electrodes with a diameter of 3mm and a length of 35mm with a wire EDM cutting machine. Babbitt B83 is a tin-based alloy, and its composition is as shown in Table 1.

Table 1

**Composition of Babbitt B83**

| Material | Sn | Sb | Cu | Orther |
|---|---|---|---|---|
| $SnSb_{11}Cu_6$ | 83.10% | 11.02% | 5.83% | 0.05% |

### Deposition process

A 45 steel plate that had 2 mm thick was cut into 25*30 mm size. The surface of the specimen was abraded with sandpaper grinding 240#, 400#, 800#, 1000#. The specimens were cleaned by ultrasonic cleaning machine (JP-010T, JIEMENG CO.) for 10 minutes, and then the surface was blown dry by hairdryer. The specimens were wiped with anhydrous ethanol to remove the grease stains on the surface of the specimens. The ESD equipment (XKS-250, Jingcheng Measurement Equipment Co.) was used, as shown in Figure 1. Argon was used as a protective gas. A new type of vibration handle was used. The maximum working distance of the vibration handle was 0.6mm. When the electrode head of the vibration handle was too short from the specimen, the electrode could not vibrate. B83 rod with a diameter of 3 mm and a length of 20 mm was selected as the electrode.

**Fig. 1. Electro-spark deposition equipment**

Materials Testing methods

The vibration handle was fixed on the bracket. The piezoelectric acceleration sensor SA-AV-D100 was selected, and its parameters were shown in Table 2, and its signal was transmitted into the data collector (YE6232B) to select the IEPE mode, and the vibration parameters were measured through the software YE7600 (Wuxi SHIAO Co., China). The sensor was fixed on a vise and the distance between the electrode head and the sensor was set with a thin sheet of the same kind of equal thickness metal. The vibration distance experimental program was shown in Table 3. Two sets of deposition experiments with different vibration handles were carried out on the low temperature soft tin alloy B83.The specimens were weighed by a balance (AR1140, OHAUS, 0.0001g analytical accuracy). The surface 2D and 3D morphology was observed with a super depth of field microscope (DM6, LEICA).Then, the surface roughness tests were measured with a roughness meter (JB-IC, Taiming Optical Co. Ltd.).

Table 2

**Sensor Parameter List**

| Model | Value | Unit |
|---|---|---|
| Frequency range | 1-10000 | Hz |
| Maximum Allowable Acceleration | $5\times10^2$ | $m\cdot s^{-2}$ |
| Maximum lateral sensitivity | <5% | % |
| Reference sensitivity | 10.03 | $mV/m\cdot s^{-2}$ |
| Weight | 9 | g |

Table 3

**Vibration distance test**

| No. | Vibrating distance |
|---|---|
| 1 | 0.092 mm |
| 2 | 0.187 mm |
| 3 | 0.377 mm |

## Results and Discussion

Vibration characteristics

A piezoelectric accelerometer was used to perform a vibration test on the head of the electrode. Test time was 9 seconds. During the vibration stabilization stage of 4~5 seconds, the corresponding vibration parameters were analyzed. Firstly, the time average of 20 vibration waveforms of three consecutive time periods was taken during the stabilization process. Then the average vibration time was calculated, the average vibration frequency was calculated and its corresponding impact force was taken, as shown in Table 4. As shown in Figure 2, when the distance was 0.092 mm, the impact frequency was simultaneously closer to the vibration distance due to the influence of the soft metal, which caused the electrodes to fail to leave the surface of the sensor. The vibration generated by the vibration handle was limited. The electrode was not able to leave the sensor, the amplitude was reduced, and the vibration frequency was lowered. When the distance was increased to 0.187 mm, the vibration electrode trip increased but produced a larger shock. Due to the short stroke, the electrode was rebounded by the sensor, and before it rebounded to the maximum length, it was subjected to the continuous impact of the handle. The handle produced a larger impact. When the distance increased to 0.377 mm, at this time the vibration electrode vibration can achieve repeated movement of the electrode. The vibration handle vibration was completely released and the vibration handle vibration was not affected by the sensor vibration. Through calculations, it was found that the larger the gap, the frequency gradually increased, and the amplitude reached stability in Figure 3. When a certain distance was reached, the frequency no longer increased. At this time, compared with the traditional vibration handle, the new vibration handle had increased in frequency, decreased in amplitude, and reduced in impact force.

Table 4

**Electrode vibration parameters in the 4~5 s stable phase**

| No | Frequency (Hz) | 20 vibration waveform peak times (s) | Average individual vibration waveform time (s) | Maximum amplitude (g) | Maximum impact (N) |
|---|---|---|---|---|---|
| 1 | 259 | 0.077147 | 0.003857 | 1.320983 | 0.12 |
| 2 | 262 | 0.076423 | 0.003821 | 105.95 | 9.34 |
| 3 | 337 | 0.05927 | 0.002964 | 4.1051 | 0.36 |

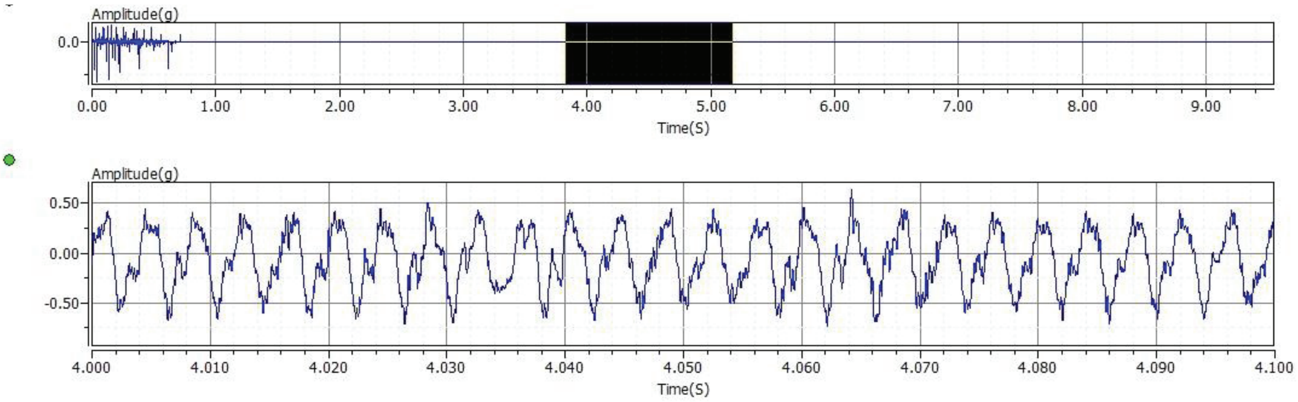
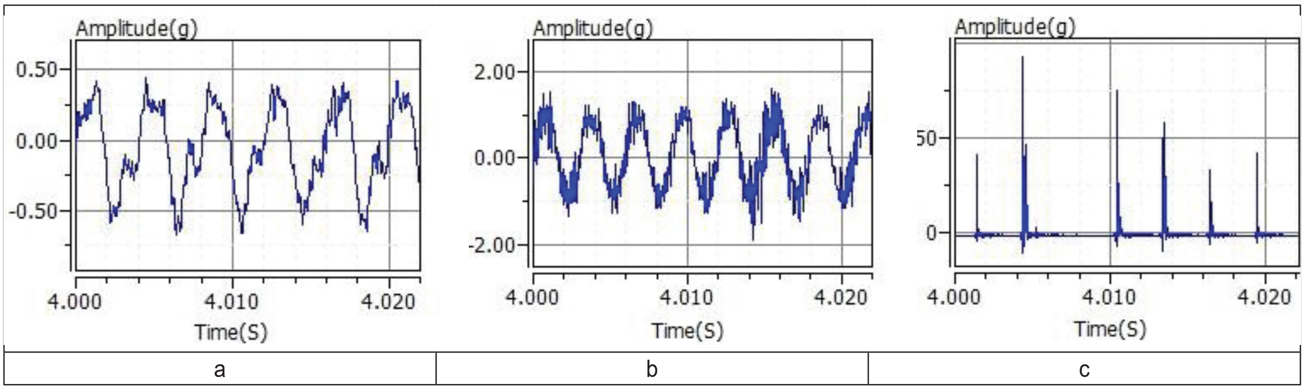


**Fig. 2. Vibration characteristics in time domain**



a b c

**Fig. 3. 4~5 s electrode vibration waveforms**

FFT statistics were performed for the 4 to 5 second interval through YE7600 software with FFT analysis module in Figure 4. As shown in Table 5, through the comparison of the experimental results of samples 1, 2, and 3, sample 3 has a 33.7 % increase in vibration frequency, a 97.2 % increase in amplitude, and an increase in impact force compared to sample 1. When the electrode gap reaches a certain range, the handle will produce a greater impact force and the vibration cycle will change, such as specimen 2. Therefore, it can be seen from experiments that by reducing the pressure between the electrode and the deposition substrate and appropriately increasing the distance between the electrode and the substrate surface, a stable vibration frequency and stable impact force can be obtained. 1) The vibration gap wasn't less than 0.377 mm; 2) select the appropriate impact force and frequency, to ensure that the soft, low melting point metal surface deposition quality. Appropriate impact force and frequency ensure the deposited quality of soft cryogenic soft metal surfaces.

Table 5

**FFT parameters of the frequency domain signal**

| No | FFT amplitude (g) | Frequency (Hz) |
|---|---|---|
| 1 | 0.37 | 252 |
| 2 | 1.54 | 331 |
| 3 | 0.73 | 337 |

Energy calculation

In order to control the softening of the electrode by heat and the melting point of the deposits during continuous deposition of low-temperature soft metals, the RC (push-pull) pulsed ESD equipment was used. The device can deliver very small individual pulse energy, as shown in Equation 1. It met the requirements of continuous machining of cryogenic alloys, as shown in Table 6. The circuit efficiency is minimum 30–40 %. This ensures that the molten droplets can be thermally melted and deposited. If the deposition energy was too small, the deposition efficiency will be too low. The size of the molten droplets can be used to calculate the minimum operating frequency of the vibrating electrode melting during the electro-spark deposition.

$$W_i = \frac{1}{2}\eta C U^2 \qquad (1)$$

In Equation 1: $W_i$ – the electro-spark deposition of energy; η – the electro-spark deposition of efficiency; $C$ – discharge capacitor; $U$ – voltage.

Table 6

**RC power supply**

| No. | Circuit Type | Capacitance | Voltage | Efficiency | $W_i$(J) |
|---|---|---|---|---|---|
| Level 1 | RC | 2.2μF | 35 v | 40% | $5.39\times10^{-4}$ |
| Level 2 | RC | 4μF | 35 v | 40% | $9.8\times10^{-4}$ |
| Level 3 | RC | 10μF | 35 v | 40% | $2.45\times10^{-3}$ |

Deposition quality

According to the experimental results in Table 3, it should be ensured that the B83 electrode has sufficient

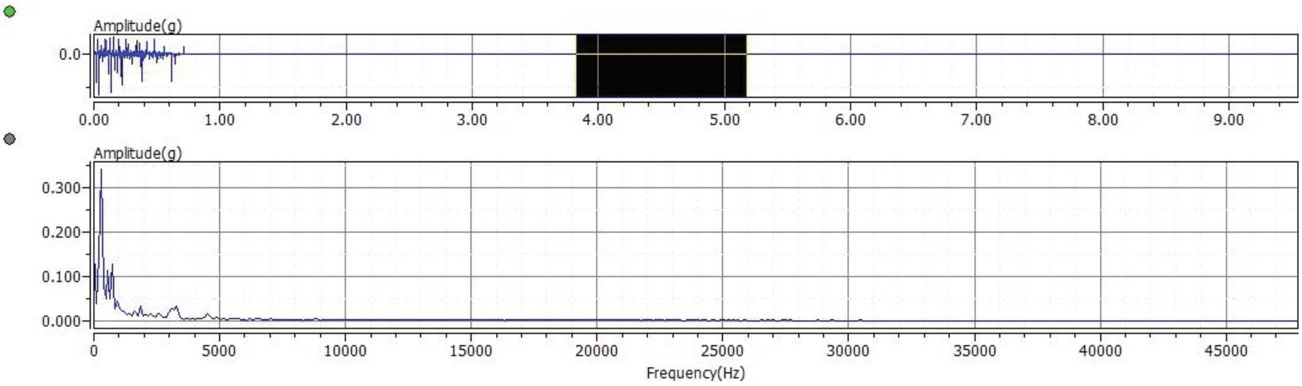


**Fig. 4. Vibration characteristic parameters in the frequency domain**

discharge gap with the specimen. If the gap was small, the electrode was in continuous contact on the surface of the specimen, there was no discharge space for the electrode, and the capacitor was not fully charged. At the head of the electrode, no sputtering electric sparks appeared. There was a short circuit of the current, and the overall temperature of the electrode rose quickly, but it did not reach the melting point. The electrode was subjected to repeated friction on the surface of the specimen, and there was very little change in the quality of the specimen. A small amount of B83 metal particles adhered to the surface. If the gap is too large, the electrode cannot contact the specimen and ESD coating cannot be achieved. Therefore, two sets of tests were conducted for comparison while ensuring a sufficient discharge gap for the electrode (>0.377 mm). One group chose the traditional vibration handle (TVH), the electrical parameters were selected as level-2 in Table 6, referred to as (TVH-2). Three deposition experiments of B83 were performed to take the average value. In the other group, a new type of vibration handle (NTVH) was selected. According to Table 6, the electrical parameters were selected as level-1, level-2 and level-3, referred to as NTVH-1, NTVH-2 and NTVH-3. The deposition time was recorded. With the use of a balance, three measurements of the sample mass were averaged according to the before and after experiments. The two average values were subtracted to obtain the coating mass. In Figure 5, it was found that the B83 coating deposited by traditional vibration ESD had the largest deposition quality.

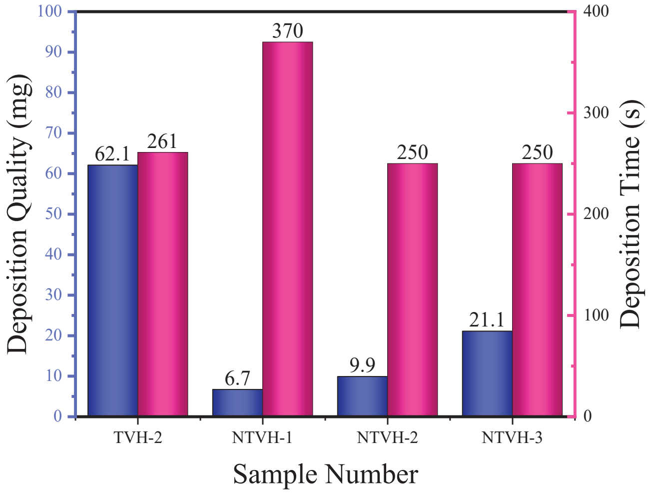


**Fig. 5. Deposition quality and deposition time**

During the deposition process, with the accumulation of time, the electrode temperature on the electrode surface increased and large molten droplets appeared. The large molten droplets have poor bonding with the coating and cannot be processed. The electrode had to be cooled and deposition needed to be paused. After the electrode had cooled, further deposition was performed. However, in the new vibration handle process, the B83 deposition quality was smaller than that of the traditional vibration handle method. When the discharge energy was 9.8×10–4J (level 2), the deposited mass of the new vibration method (NTVH-2) was 16 % of that of the traditional vibration method (TVH-2). This was due to the increase in frequency, the decrease in deposition time, the decrease in impact and the smaller melt droplets, which controlled the increase in electrode temperature. As shown in Figure 5, as the deposition energy increases, the mass of the coating deposited by the new vibration mode increased and the thickness of the coating increased accordingly. In terms of deposition time, NTVH-1 had the longest time in order to ensure that the coating would cover the entire surface. This was because its smaller droplets caused an increase in the number of vibration impacts, which resulted in a longer deposition time. The other three vibration times were close to each other. In all of the new vibration modes, the deposition process can be carried out continuously without electrode cooling, and no larger molten droplets appeared.

### Surface morphology

The sample surface was observed with a Leica ultra-depth-of-field microscope (LEICA DM6). It can be seen in Figure 6 that the surface coating droplets deposited on the traditional vibrating handle have the largest drop. In Figures 7, 8 and 9, the surface of the sample with the new vibration mode was relatively flat. In the new vibration deposition method, as the discharge energy increased, the surface unevenness increased. As shown in Figure 7b, the surface of NTVH-1 was the most homogeneous, the surface color was basically the same, and smaller deposited melt droplets appeared. The coating uniformity of NTVH-2 was slightly reduced, and the color of the droplet in the super depth of field image was close to that of the surrounding area, which indicated that the height of the droplet was not large in Figure 8b. The coating uniformity of NTVH-3 was further reduced. It appeared that craters and raised molten droplets, and the color changed greatly, but the large areas of the same color coatings were connected together in Figure 9b. In the traditional vibration mode, the height of the molten drop was larger, there were obvious bulges around it, and the surface uniformity was the worst, as shown in Figure 6b. From the 2D morphology and 3D super-field morphology, it can be seen that TVH-2 has the largest melt droplet and the new vibration mode has the smallest melt droplet. The droplets of the new vibration mode were smaller than the droplets of the traditional vibration, which was the reason for the enhanced surface quality of the new vibration mode. From Fig. 6a and Fig. 7a, it can be seen that non-white metal oxide film appeared on the surface of TVH-2 and NTVH-1 coatings. The impact contact time was long in the traditional vibration mode, the surface temperature increased, and the molten droplets were prone to oxidation. Because of the long deposition time on the NTVH-1 surface, when the argon gas failed to fully protect the deposited film, the deposited film was thinner and more susceptible to oxidation. In the new vibration mode, with the increase of energy, the thickness of the deposited layer increased, and the black oxide layer on the surface decreased instead. In order to improve the surface quality, argon protection process should be reasonably designed to prevent the appearance of surface oxide film.

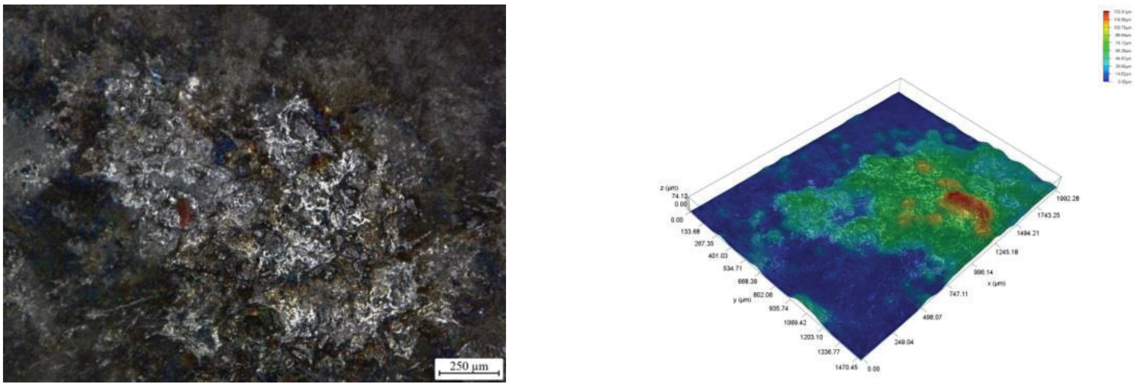


Fig. 6. Surface of TVH-2: a-2D morphology, b-super depth of field 3D morphology

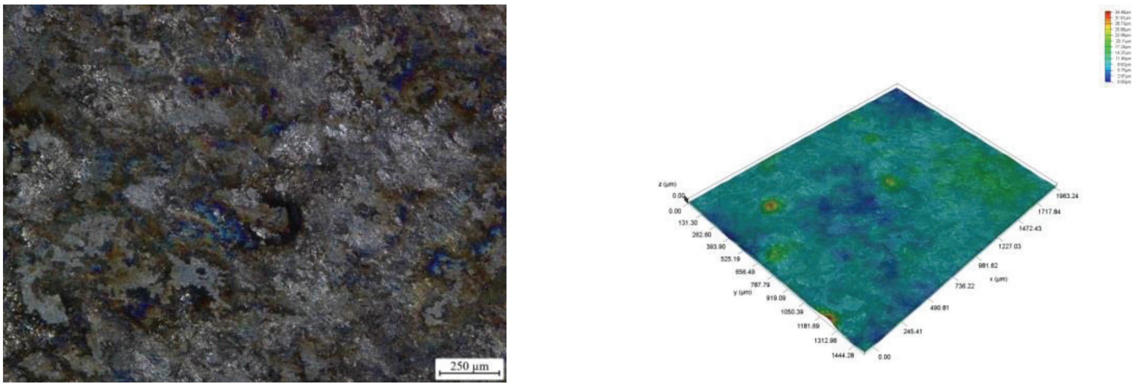


Fig. 7. Surface of NTVH-1: a-2D morphology, b- super depth of field 3D morphology

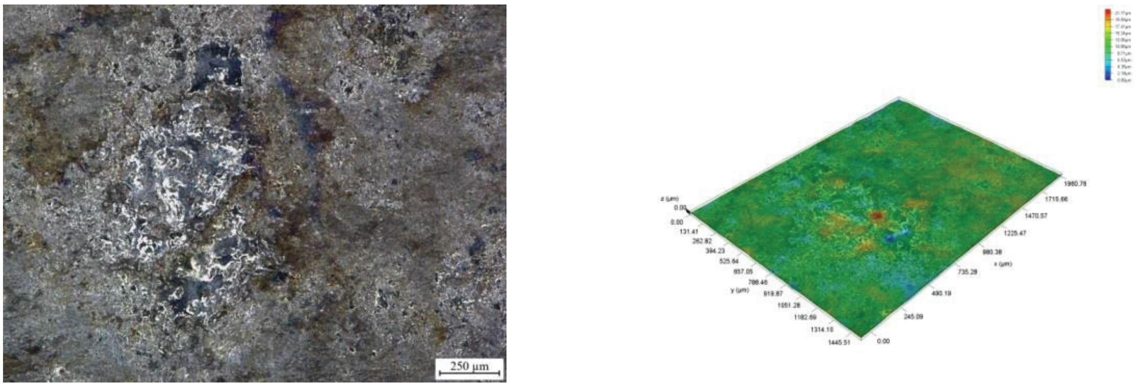


Fig. 8. Surface of NTVH-2: a-2D morphology, b-super depth of field 3D morphology

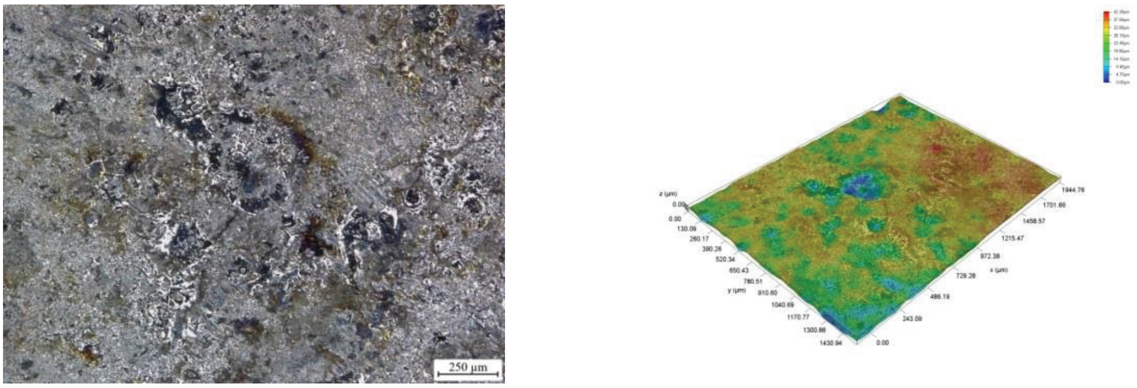


Fig. 9. Surface of NTVH-3: a-2D morphology, b-super depth of field 3D morphology

### Surface roughness

The surface roughness of the specimen was measured by using a roughness meter. Each specimen surface was measured three times. The standard $\lambda_s$ = 0.8 was selected and the surface was measured in 4.8 mm length. In Figure 10, it can be seen that the value of roughness of TVH-2 was the largest, which was 1.264 μm, and the value of NTVH-1 was the smallest, which was 0.664 μm. The smaller value of roughness means better surface quality. The standard deviation of TVH-2 was the largest, but the standard deviation of sample NTVH-1 was the smallest. It indicated that the uniformity of NTVH-1 was the best. With the same energy, the roughness of specimen NTVH-2 was reduced by 43% than specimen TVH-2, and the standard deviation of specimen NTVH-2 was reduced by 73% than specimen TVH-2. It showed that specimen NTVH-2 had better surface uniformity than specimen TVH-2. It indicated that the new vibration handle can effectively improve the surface accuracy. Even specimen NTVH-3 with greater discharge energy still had smaller surface roughness than sample TVH-2, which had a 25% reduction in roughness value. As the energy of the new vibration mode increased, the roughness value became larger and larger, and the standard deviation gradually increased.

## Conclusions

Increasing the vibration frequency, reducing the impact force, and the appropriate discharge gap can effectively improve the deposition quality and achieve continuous deposition of low-temperature soft metals. Reducing the coating thickness of soft metals will lower the cost of ESD coatings, thus which will make some expensive friction-reducing metal materials for a wide range of applications. This method can make use of robots and multi-axis machine for continuous deposition. It provides a new solution for automated ESD processing. It is also possible to obtain a more homogeneous intermetallic compound coating. In the future, surface quality and deposition time can be further improved by mechanized processing.

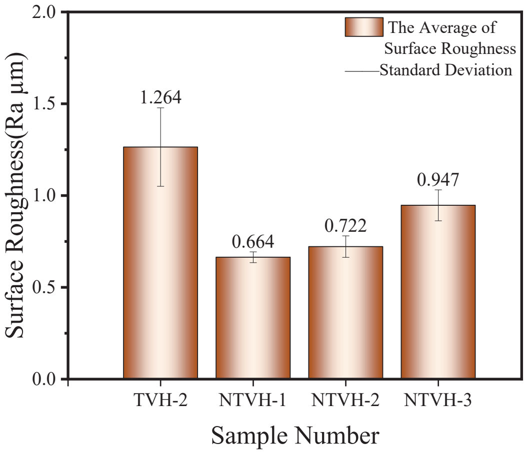


**Fig. 10. Surface roughness of B83 coating**

1) With the reasonable discharge gap and the same discharge energy, the surface roughness of the new ESD deposition process was 43% lower than that of the traditional vibration deposition process, and the standard deviation was reduced by 73%. The surface roughness and uniformity of the B83 coatings are further improved by the new vibration deposition process.

2) The discharge gap is controlled at 0.377~0.6 mm, which can achieve continuous sputtering of electro-sparks. The main vibration frequency is 337Hz, the vibration impact is small, and the continuous deposition of low-temperature soft metals can be achieved. The electrode of B83 material with a diameter of 3 mm did not appear to be bent, and the deposited coating had good surface quality.

3) When the discharge energy increases, the new ESD vibration deposition process increases the quality of the coating,. And the thickness of the coating also increases accordingly. Reasonable selection of the argon protection process can reduce the formation of oxide films and improve surface quality.

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## ***Дослідження методів підвищення якості покриття легкоплавкого сплаву Б83, що сформовані методами електроіскрової обробки***

*Процес електроіскрового легування (ЕІЛ) використовує електричний іскровий розряд для нанесення і розплавлення струмопровідних матеріалів на поверхню підкладки з утворенням легованого шару покриття. Метод може використовуватися для зміцнення або відновлення поверхонь деталей. Через низьку вартість і просту обробку цей процес часто використовується для створення зносостійких та антифрикційних покриттів на поверхні деталей для збільшення терміну їх служби. Покращення якості поверхні електроіскрового легування завжди було в центрі уваги досліджень науковців та фахівців-практиків. М'які метали можуть бути використані як антифрикційні матеріали для зменшення тертя металевих поверхонь і збільшення терміну служби. Електроди з легкоплавких м'яких металевих сплавів схильні до розплавлення і згинання під час обробки, що значно ускладнює формування якісного поверхневого шару деталі. Одним з характерних легкоплавких м'яких сплавів є бабіт Б83. Він має хорошу здатність зменшувати поверхневе тертя і покращувати корозійну стійкість. В якості зовнішнього шару комбінованого покриття, він здатен забезпечувати особливі вимоги до відновлених поверхонь деталей. В представленій роботі досліджується вплив параметрів вібрації, енергії розряду, розрядного зазору на якість поверхні легкоплавкого м'якого сплаву за допомогою нового вібраційного методу. При збережені величини енергії розряду, шорсткість обробленої запропонованою технологією поверхні була на 43% меншою в порівнянні з традиційною технологією, а стандартне відхилення було на 73% меншим. При регулюванні розрядного зазору в діапазоні 0,377 ~ 0,6 мм, отримано безперервне електростатичне розпилення наплавлюваного матеріалу. Обробка виконувалася при частоті вібрації 337 Гц, що забезпечує мінімізацію вібраційного впливу, безперервне осадження легкоплавкого м'якого сплаву на оброблювану поверхню та дозволяє уникнути деформації електрода діаметром 3 мм. Використання аргону для захисту зони обробки дозволяє зменшити утворення оксидної плівки та покращити якість обробленої поверхні. Запропонований процес ЕІЛ забезпечує зменшення товщини покриття м'якими металами та сплавами та їх собівартість порівняно з традиційними методами, що зробить більш доступними деякі дорогоцінні антифрикційні металеві матеріали. Запропоноване рішення для безперервної обробки ЕІЛ покриттів може бути адаптовано для використання на роботизованих та автоматизованих верстатних комплексах.*

***Ключові слова:** електроіскрове легування, якість, покриття, поверхневий шар, сплав, бабіт, вібрація, шорсткість, технологія, обробка, обладнання.*