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Process Localization at the Electrolyte Jet Machining for Additive Manufacturing

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Rapid prototyping manufacturing (RPM) has received high interest in the field of engineering. However, the current processing methods are complex and expensive, and it is difficult to prepare nanostructure materials, which limits further applications. Electrolyte jet machining is an emerging precision manufacturing technology that uses an electrolyte jet to generate a metallic deposit with a high deposition rate and a nanocrystalline material structure. This paper is devoted to developing a new type of prototyping technology that employs electrolyte jet machining to form a micro-metallic part with a nanocrystalline material. The new manufacturing method is expected to cover the shortcomings of the current RPM technology. The concept of incorporating electrolyte jet machining and rapid prototyping technology as well as an experimental practice are introduced. It is believed that the forming precision of electrolyte jet machining is determined by process localization, which is mainly influenced by the technical parameters, including the nozzle diameter, jet distance, current density, and nozzle scan speed. The technical parameters are studied regarding their effects on the process localization. It is proven that the application of a small nozzle diameter, low current density and fast scan speed is highly favourable for reducing the size of the electroformed spot and for improving process localization. A group of nanocrystalline copper parts with a good shape have been produced using optimized parameters.

Keywords: Rapid prototyping manufacturing (RPM), electrolyte jet machining, nanocrystalline material, copper parts, process localization,

1. INTRODUCTION

Rapid prototyping manufacturing (RPM) is currently receiving high interest in the field of engineering. This technology adopts an additive manufacturing concept to transform the complex manufacturing of three-dimensional (3D) parts into simple two-dimensional (2D) laminated manufacturing [1-4]. Commonly used RPM technologies include SLA, FDM, LOM and SLS, which have been intensively employed in the industry. However, these processes are often complex and costly and must be followed by bonding and sintering to obtain solid parts, resulting in forming accuracy problems caused by shrinkage and residual stress [5, 6]. Moreover, it is very difficult to obtain materials with nanostructures using these methods, so the mechanical performance of the finished parts has certain limitations, affecting further applications. Therefore, a simple and economical manufacturing method that combines rapid prototyping and nanomaterial fabrication is urgently needed to meet engineering requirements.

Electroforming is a kind of electrodeposition technology that makes use of the principle of metal ion electrodeposition in the cathode to produce products and has a high manufacturing accuracy [7]. Among the various electrodeposition methods, electrolyte jet machining, also known as jet electrodeposition, shows special advantages [8-10]. Because the nozzle sprays the electrolyte onto a cathode plate in the jet state (see Fig. 1 for the principle), it has the following advantages to become an effective manufacturing method: (1) A high current density. Based on a proven practice, the current density can be increased by up to one hundred times, which highly increases the electrodeposition rate. The general electrodeposition rate is approximately 1.5 μm/min, while the electrolyte jet machining rate can reach up to 50 μm/min. (2) A dense deposit material structure with fine grains. The high current density contributes to increasing grain nucleation and growth, so it effectively consolidates the deposit microstructure with fine grains and brings about good mechanical properties. (3) Excellent process localization. Since the metal ions are consequently electrodeposited on the cathode surface exclusively in the impingement zone, electrodeposition only occurs in the nozzle jet direction on the cathode. Therefore, there is no residual stress, and no sintering process is needed. [11-14].

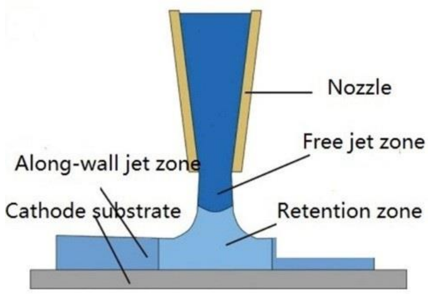

Figure 1. Schematic diagram for a typical electrolyte jet machining process

In recent years, electrolyte jet machining (also called jet electrodeposition) as an advanced manufacturing process method has been widely used in micro/nano manufacturing [12-15]. Rajput et al. [16, 17] used the jet electrodeposition method to form a micro three-dimensional column and frame structure with a certain thickness. A mathematical model of the deposition rate was established to simulate the potential distribution and electric field process in the jet region. Alkire and Chen et al. [18] proposed an electrochemical 3D printing method based on the jet electrodeposition principle to form a local metal microstructure at room temperature. Since the selected processing object has a small forming scale, it effectively overcomes the disadvantage of a slow forming speed. Kim et al. [19] developed a selective copper microstructure processing method using the jet electrodeposition process. A 430 μm wide copper microstructure was prepared by using a 290 μm nozzle diameter.

From the above literature review, it can be determined that the wide usage of electrolyte jet machining technology has been proven effective in the micro/nano manufacturing industry because of its unique advantages, including good localization and a dense nanocrystalline structure of the deposit material. Therefore, it has potential and is applicable for incorporation with RPM to become a new type of micro-metallic parts manufacturing technology. Based on these findings, this paper describes the concept of incorporating electrolyte jet machining and rapid prototyping technology with experimental practice. Moreover, the effects of the technical parameters on process localization are investigated in a fundamental experiment. The experimental conditions are optimized to generate a group of copper micro-metallic parts.

2. EXPERIMENTAL

2.1 The principle of the manufacturing process

Electrolyte jet machining rapid prototyping is based on the principle of discrete stacking. As shown in Fig. 2, the forming process path is obtained from a computer-aided design (CAD) 3D model of discrete parts. Under the control of a computer, the electrolyte containing the deposited metal ions is selectively sprayed onto the cathode by a high-speed jet to form an electrodeposition layer according to the forming process trace. In this way, a direct metallic solid is formed quickly by stacking layer by layer. In the process of electrolyte jet machining, the CAD system generates the 3D model of the part and outputs the STL file that contains the section shape of each layer of the part model using slicing software. The planar scanning trace of the nozzle is obtained and transferred to the servo system, which responds by driving the nozzle to perform two-dimensional scanning movement and switches the electrodeposition power supply on and off according to the generated trace or NC code. Thus, the electrolyte flowing through the anode cavity nozzle at a high speed can be electroformed on the cathode plate quickly, forming a layer of the part. Once one layer is completed, the nozzle is lifted by a one-layer-thick distance to generate a new deposit layer, and a three-dimensional part can be achieved after all the path instructions are executed.

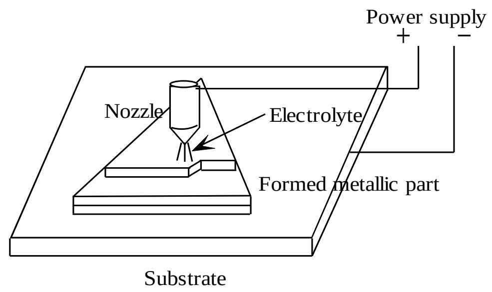

Figure 2. Schematic diagram of electrolyte jet machining based on rapid prototyping

2.2 Experimental setup configuration

Fig. 3a shows the experimental facility employed in this study. The system comprises a computer control system, an electrolyte circulation system, a nozzle, a nozzle-lifting mechanism, and an electroforming power supply. The computer control system includes the control system, servo drive and other parts. The special self-developed control software can slice the part model according to the geometry information provided by the part CAD model, generate the two-dimensional scanning trace of the nozzle, and coordinate the auxiliary movement of each part, as shown in Fig. 3b. The nozzle lifting mechanism is responsible for lifting of the nozzle. When a certain deposit thickness has been made by a nozzle, the lifting mechanism will raise the nozzle to a certain height and then electroform the next layer. The electrolyte circulation system mainly supplies the electrolyte with a certain pressure and flow to the anode cavity through the magnetic pump.

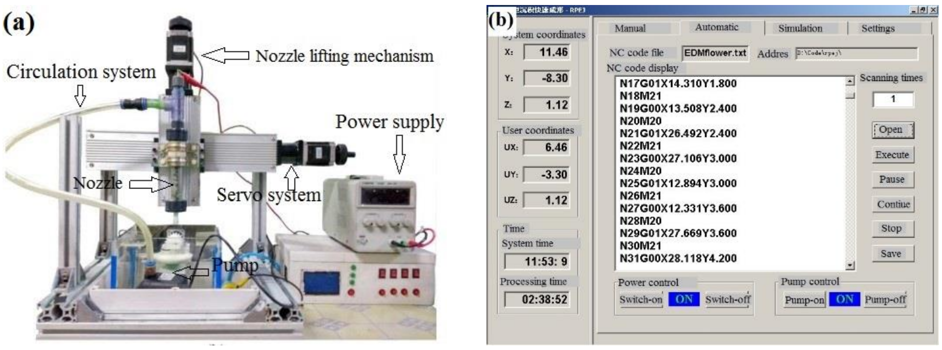

Figure 3. Electrolyte jet machining rapid prototyping system: (a) experimental setup and (b) control software interface

A copper rod was installed inside the nozzle cavity as an anode, and 304 stainless steel with dimensions of 80 mm×20 mm×2 mm acts as the cathode substrate. The electrolyte contained 250 g/l $CuSO_4 \bullet 5H_2O$ (Nanjing regent; 99% purities) and 50 g/l H_2SO_4 (Nanjing regent; 98% purities). The pH value of the electrolyte was maintained at 4 by adding dilute sulfuric acid or NaOH. Table 1 shows the other experimental conditions.

Table 1. Electrolyte jet machining experimental parameters

Electrolyte jet machining parameters	Values
Nozzle diameter	1-3 mm
Current density	150-450 A/dm^2
Jet distance	0-10 mm
The ratio of the jet distance to nozzle diameter (H/D)	1/4, 1/2, 1, 2, 3
Jet speed	2-10 m/s
Nozzle scan speed	1-15 mm/s

2.3 Process localization of electrolyte jet machining

The process localization of electrolyte jet machining refers to the consistency between the electroformed spot size (the area impinged by the electrolyte jet where electrodeposition occurs on the cathode) and the nozzle diameter. According to the voltage distribution of electrolyte jet machining, as shown in Fig. 4, in the jet between the nozzle and the impact zone, the voltage will only change in the Z direction. In the wall jet region, because the liquid layer is very thin (typical value is 0.05 cm), there is a significant voltage gradient in the R direction. When the radial distance increases from r to 3r, the voltage decreases from $0.1V_0$ to $0.0001V_0$. Consequently, when electrolyte jet machining is carried out under a certain voltage, throughout the whole jet action area, only the cathode surface close to the nozzle can have a metal deposition, while the cathode surface far away from the centre of the nozzle will have no metal deposition due to the weak electric field, as seen in Fig. 4. Therefore, the size of the electroformed spot is consistent with the nozzle diameter. When a small nozzle is used, a small deposit spot can be obtained, which plays a key role in the combination of electrolyte jet machining and rapid prototyping technology to realize selective electrodeposition on the cathode surface. The quality of localization has a direct impact on the contour shape and dimensional accuracy of rapid prototyping of a metal mould. In electrolyte jet machining, the main factors affecting the spot size include the nozzle diameter, electroforming current density, distance from nozzle to cathode (jet distance), jet speed, nozzle scan speed, and so on. In the following studies, the influences of various factors on the electroformed size and process localization will be studied and optimized based on the specific process conditions.

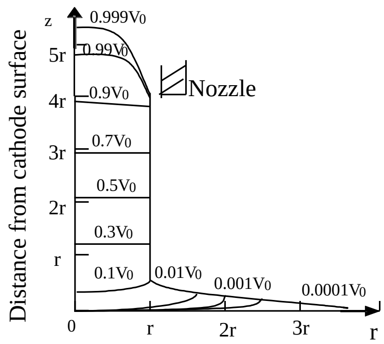

Figure 4. Calculated potential distribution in the impinging jet-affected zone

3. RESULTS AND DISCUSSION

3.1 Influence of the nozzle diameter on the electroformed spot size

Fig. 5 shows the relationship between the electroformed spot size and the nozzle diameter measured with an electrodeposition voltage of 100 V applied and an H/D ratio of 1:1. It can be seen from the figure that the size of the electroformed spot increases proportionally with the increase in the nozzle diameter. The size of the electroformed spot is approximately twice that of the nozzle diameter, which is consistent with the experimental conclusion in the literature [14, 20]. As the nozzle diameter reaches 4 mm, the size of the electroformed spot is approximately 4 times that when the nozzle diameter is 1 mm. It can be concluded that if the other process parameters are fixed, if a relatively small nozzle diameter is applied, the electroformed spot size will decrease correspondingly, providing a better dimensional accuracy for the rapid electrolyte jet machining of metal parts.

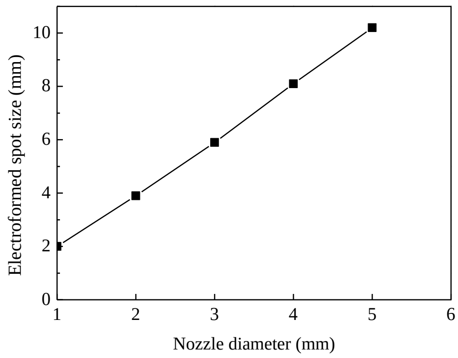

Figure 5. Effect of the nozzle diameter on the electroformed spot size

Fig. 6 shows the thickness distribution of the deposit coating prepared with different nozzle diameters and electroforming voltages. It can be seen that the thickness distribution of the deposit layer in the electroformed spot is uneven, and the deposit layer at the centre of the electroformed spot has the largest thickness. With an increase in the distance from the spot centre, the coating thickness becomes thinner. It can also be seen from the figure that the radial distance from the centre of the spot is approximately equal to the nozzle radius, that is, the thickness of the deposit layer becomes obviously thinner, and then the thickness of the deposit layer increases with the radial distance. Then, the rate of change begins to slow down. The variation trend of the thickness of the deposit layer in the electroformed spot is similar to the results in the literature [21], and the thickness of the deposit layer displays an exponential function distribution. In the process of electrodeposition, the current density at the centre of the deposition layer has a larger distribution, while the current density along the edge area has a weaker distribution. The difference in the current distribution directly affects the corresponding deposition speed, as the current efficiency is fixed. According to the theory of electrodeposition, when the current efficiency is 100%, the current density is directly proportional to the electrodeposition speed. At the spot centre, the current density obviously becomes large with increasing electrodeposition speed. Conversely, at the edge of the spot, the electrodeposition speed slows, as a much weaker current density is distributed. Under the experimental conditions, there is no obvious observed hydrogen precipitation, and the current efficiency can be regarded as approximately 100%. The thickness of the casting layer reflects the distribution characteristics of the electric field strength.

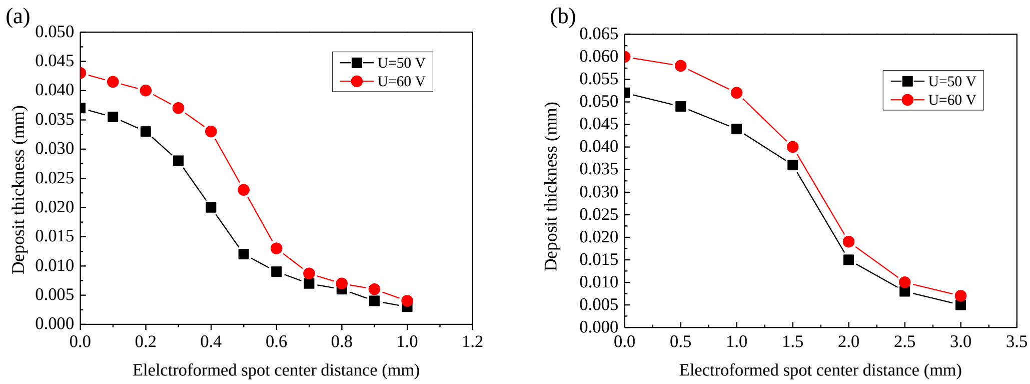

Figure 6. Thickness distribution of the deposit thickness with different nozzle diameters: (a) 1 mm; (b) 3 mm

Fig. 7 shows the surface morphology of the deposit layer at the centre and edge of the electroformed spot with a current density of 400 A/dm^2. The surface morphologies of the two places appear to be quite different. It can be seen that the electroforming spot centre in Fig. 7a seems very coarse, and there are a number of nodules larger than 10 μm, while at the electroforming spot edge, the surface appears comparatively smooth, and there are hardly large nodules. According to the analysis above, the current density distributes differently between the centre and edge. The high current is concentrated at the centre, which promotes grain growth and produces bulky nodules. Conversely, less current is distributed at the edge of the spot, which correspondingly leads to the deposition of a refined-grain coating.

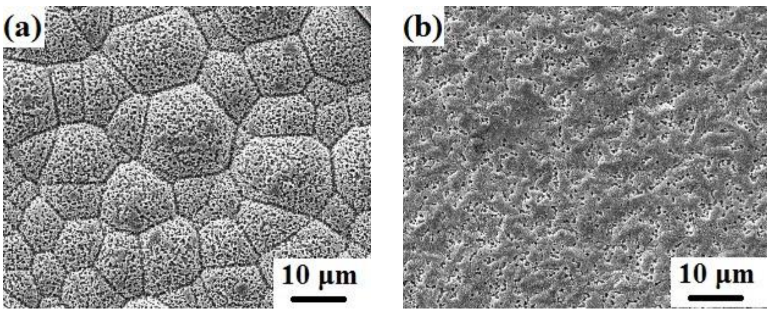

Figure 7. SEM appearance of the surface at different positions of casting spots with (a) the electroforming spot centre and (b) the electroforming spot edge

3.2 Influence of the jet distance on the process localization

In the experiment, under the conditions of 1, 2, and 3 mm nozzle diameters and H/D ratios of 1/4, 1/2, 1, 2, and 3, the influence of the jet distance on the localization using different nozzle diameters was studied. Fig. 8 shows the effect of the jet distance on the spot size with different nozzle diameters applied. It can be seen that when the H/D ratio ≥ 1, the jet distance has less of an influence on the size of the electroformed spot, and the electroformed spot size shows a limited increase with increasing jet distance. Furthermore, when the H/D ratio <1, the jet distance begins to exert a greater effect on the electroformed spot size, which obviously decreases with a decrease in the jet distance. When a very small jet distance is applied, the electroformed spot will tend to be the same as the nozzle diameter. Fig. 9 displays the actual image of electroformed spots obtained with different jet distances and with the same nozzle diameters applied. It shows that with an increase in the jet distance, the spot size also increases as well.

The phenomenon of the electroformed spot size varying with the jet distance can be explained with the distribution of the flow and electric field between the nozzle and cathode. When a large jet distance is applied, because the pressure of the electrolyte is not very high in the range of the experimental flow rate, the change in the jet distance has little influence on the flow field and electric field distribution between the nozzle and the cathode. However, when the jet distance between the nozzle and the cathode is small, the flow field distribution between the nozzle and the cathode plate is changed. Therefore, the shape of the original impinging area and the flow area along the wall changes as well. As a result, the two areas' thicknesses become thinner, and the electric field strength along the wall jet area becomes weaker. Thus, the size of the electroformed spots decreases [22-24]. When the electroforming voltage is constant, the size of the spot depends on the distribution of the flow field and the electric field. Therefore, when the other parameters are fixed, the closer the distance between the nozzle and the cathode is, the smaller the size of the electroformed spot, which will improve the process localization during manufacturing.

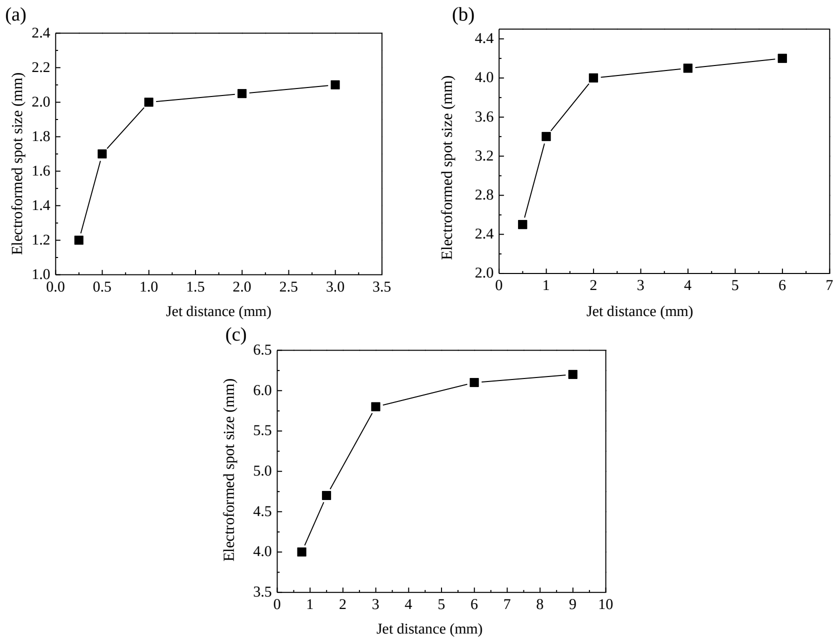

Figure 8. Effect of the spray distance on the size of the electroformed spot with different nozzle diameters: (a) 1 mm; (b) 2 mm; (c) 3 mm

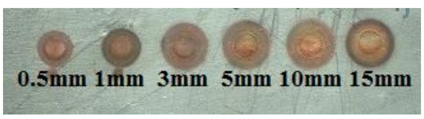

Figure 9. Electroformed spot size comparison with various jet distances

3.3 Influence of the current density on the process localization

The effect of the current density on the electroformed spot size is shown in Fig. 10 with an H/D ratio of 1:1. In the figure, there are three curves that represent nozzle diameters ranging from 1 to 3 mm. At first, it can clearly be seen that the spot size increases with increasing current density in the range of 50 A/dm^2-300 A/dm^2. Additionally, as observed on all three curves, the current density exerts the same promotion effect on the electroformed spot size. In the range of 50 A/dm2-300 A/dm^2, the spot sizes increase by 47%, 36% and 25% as nozzle diameters of 1 mm, 2 mm, and 3 mm are applied, respectively.

The phenomena of the electroformed spot increasing with an increase in the current density can be attributed to the strengthened electric field. With the increase in the current density, the overall electric field strength and the range of the electric field-affected zones on the cathode are also enlarged and strengthened. Therefore, the area of metal deposition is increased, and the electroformed spot is enlarged as well. Obviously, the enlarged electroformed spot affects the process localization, which will largely reduce the forming accuracy. According to the analysis, it can be concluded that a proper increased current density can improve the deposit efficiency, increase the overpotential to promote grain refinement and produce better material microstructure. However, an excessively high current density will affect the process localization and reduce the forming accuracy. Therefore, a reasonable and moderate current density and nozzle diameter should be adopted in the forming process.

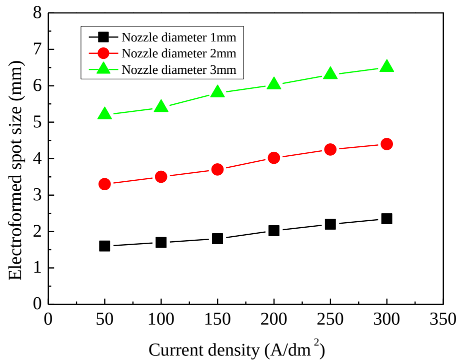

Figure 10. Effect of the current density on the electroformed spot size

3.4 Influence of the nozzle scan speed on the process localization

The effect of the nozzle scan speed on the electroformed spot size is shown in Fig. 11. In the figure, there are three curves that represent nozzle diameters ranging from 1 mm to 3 mm. It can be seen from the figure that when the other parameters are fixed, the electroformed spot size decreases with an increase in the nozzle scan speed. In fact, the decreasing process is divided into two stages. First, when the scan speed increases from 1 mm/s to 5 mm/s, the spot size decreases greatly. Next, if the scan speed exceeds 5 mm/s, the spot size decreases slowly. From Fig. 11, it can be concluded that the nozzle scan speed has an obvious effect on the metal deposition process in the area of the jet electric field on the cathode. Under a certain electroforming voltage, if the nozzle moves at a slow speed, the electric field in the jet action area will correspondingly act for a long duration, which will provide the metal ions enough time to reduce on the cathode. In contrast, if the nozzle scan speed is moving faster, the area where the electric field remains weak has a short action time due to the electric field, and the metal ions in the electrolyte jet will leave before the reduction reaction occurs. Therefore, the electroformed spot size is relatively small. The experimental results reveal that appropriately increasing the nozzle scan speed will reduce the electroformed spot to a certain extent and improve the localization and the forming accuracy.

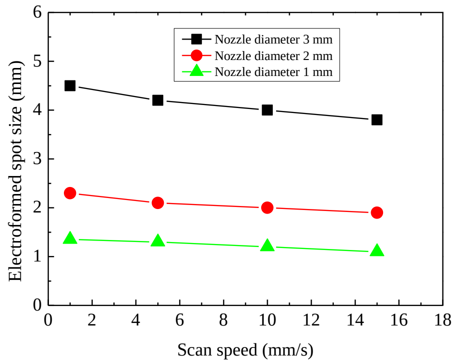

Figure 11. Effect of the nozzle scan speed on the electroformed spot size

3.5 Influence of the jet speed on the process localization

To investigate the effect of the jet speed on the electroformed spot size, an experimental result is conducted, the results of which are shown in Fig. 12, with a 3 mm nozzle diameter. It can be seen that when the electroforming voltage is fixed, the spot size increases with an increase in the jet speed of the electrolyte. How the jet speed influences the spot size can be attributed to the fact that if the jet speed is increased, the amount of metal ions participating in the cathode reduction is also increased, which is equal to the increase in the current density in the deposition area. Obviously, under the strengthening of the current density, the electroformed spot size increases. Therefore, appropriately decreasing the jet speed will reduce the electroformed spot to a certain extent and improve the localization and the forming accuracy.

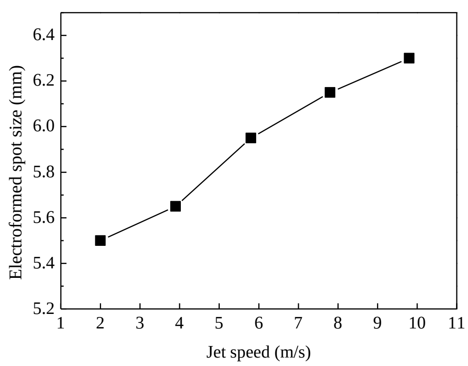

Figure 12. Influence of the jet speed on the electroformed spot size

3.6 Effect of the current density on the deposit material microstructure

The material properties of the formed parts are important criteria for evaluating the forming process. In the electrolyte jet machining process, when the other process parameters are fixed, the surface morphology and structure of the electroforming materials depend on the current density of electroforming. Fig. 13 shows the surface morphology of the deposit coating under different current densities. It can be seen that when a low current density is used, the deposit surface appears flat with refined grains. With an increase in the current density, the deposit surface shows obvious cellular growth with a rough surface. If the current density continues increasing, the deposit surface quality quickly deteriorates and eventually develops dendritic growth, which will reduce the quality of the deposit surface. Therefore, the current density used in electrolyte jet machining should not be too high to obtain a good quality deposit surface. The critical value for the current density is 300 A/dm^2 under this experimental condition. When the current density is less than this value, the deposition surface appears smooth and flat, the particles are refined, and the polymerization is integrated. When the current is greater than this value, the deposition surface gradually deteriorates into cell-like particles [25].

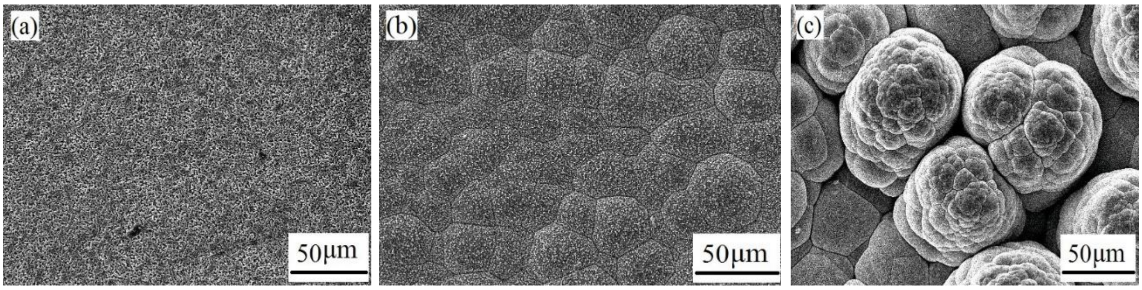

Figure 13. Morphological changes in the deposit surface under the influence of the current density: (a) 150 A/dm^2; (b) 300 A/dm^2; (c) 450 A/dm^2

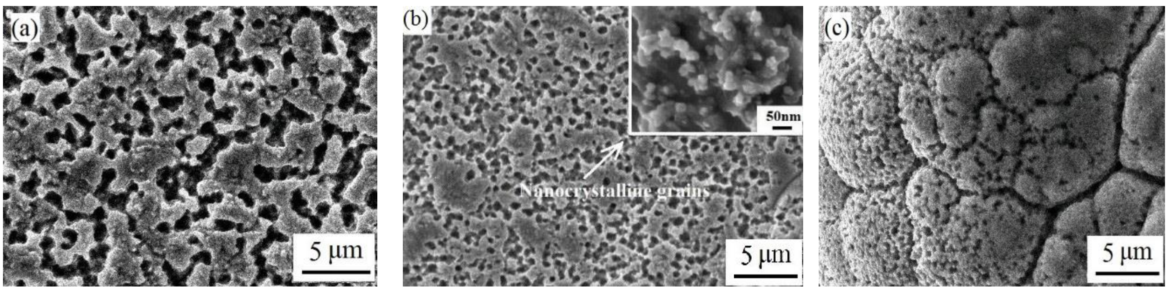

Figure 14. Microstructural changes in the deposit layer under the influence of the current density: (a) 150 A/dm^2; (b) 300 A/dm^2; (c) 450 A/dm^2

In addition, in Fig. 14, the deposit material microstructure varies within the current density range of 150-300 A/dm^2. When the current density exceeds 300 A/dm^2, the cell-like particles gradually expand into cauliflower-like particles, and the pores obviously increase with the deteriorated compactness. Magnified views of the coating microstructure are displayed in the upper right in Fig. 13b with a current density of 300 A/dm^2. It can be observed that a number of extreme nanocrystalline grains are arranged in a close and orderly manner, most of which are between 30 and 50 nm.

From the perspective of deposition efficiency, the electrodeposition speed is related to the current density, which has been verified in literatures [8, 12, 13], and the current parameters with a faster deposition rate should be selected to the greatest extent possible. Therefore, 300 A/dm^2 can be taken as the optimized parameter for the current density.

3.7 Rapid prototyping of copper parts

A group of metal copper parts with a 0.5 mm thickness were formed by the electrolyte jet machining rapid prototyping equipment. The optimized experimental conditions were as follows: current density 300 A/dm^2, jet speed 8 m/s, nozzle scan speed 10 mm/s, nozzle diameter 1 mm, jet distance 0.5 mm, H/D ratio 0.5 and electrolyte temperature 30 ℃. The copper parts have a clear outline with the dimensional accuracy along the X and Y directions up to 10 mm ± 0.2 mm and the fillet radius r < 1.5 mm. It can be seen from the above experimental results that the self-developed electrolyte jet machining rapid prototyping method can directly shape a variety of metal parts with different complex shapes and has a better shape and size accuracy. It can also be concluded that the smaller the nozzle diameter is, the higher the dimensional accuracy of the formed parts is and the smaller the fillet radius that can be achieved. At the same time, by this rapid prototyping method, the copper parts have nanocrystalline structures, which can be expected to have strengthened mechanical properties, including high strength and hardness.

4. CONCLUSION

The concept and application of electrolyte jet machining incorporated with rapid prototyping technology were introduced in this paper. As the forming accuracy of this composite technique is mainly determined by the process localization, the effect of the technical parameters on the process localization was investigated in detail. It was proven that the usage of a small nozzle dimeter, a low current density, and a fast nozzle scan speed helps to generate a small electroforming spot, which favourably enhances the process localization and improves the forming accuracy. Additionally, because a non-uniform electric field is employed in the jet acting area, the deposit coating thickness displays a typical exponential function distribution. A group of copper parts with different shapes and thicknesses were formed by the electrolyte jet machining rapid prototyping method. The dimensional accuracy in the X and Y directions was 10 ± 0.2 mm, and the radius of the fillet reached less than 1.5 mm. The formed parts had a nanocrystalline structure with an average grain size of 40 nm. It can be expected that this method will have good development and application prospects in the manufacturing of micro metal parts with complex shapes.

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