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ELECTROCHEMICAL MICROMACHINING USING VIBRATILE TUNGSTEN WIRE FOR HIGH-ASPECT-RATIO MICROSTRUCTURES

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Introduce

Metallic micro devices have advantages over silicon-based microdevices when subjected to high stresses, high temperatures, and other harsh conditions. Metallic microstructures with high-aspect-ratio serves as basic blocks for metallic microdevices, such as micro gears, micro electromagnetic relays and microchannel heat exchangers.

There are a few technologies and processes for high-aspect-ratio microstructures in metallic materials: (1) in LIGA or LIGA-Like, metallic microstructures are usually fabricated based on the metallic ion electrochemical deposition on a cathode. For example, a nickel-based microchannel cooling plate, with aspect ratio up to 3.6:1, has been successfully fabricated using a modified UV-LIGA process [1]. Line-and-space structures with an aspect ratio up to 5 were successfully transferred from the mother PMMA patterns to the nickel microstructures [2]. Typical high-aspect-ratio copper micro parts in the scale of several hundred microns have been produced by micro electrochemical deposition using a movable mask [3]. X-ray lithography fabrication for polymer structures and metal replica with submicron feature size were determined [4]. However, practical materials made by electrochemical deposition are limited to a few metals such as nickel, copper and their alloys (2). Microcasting technology was investigated to product metallic micro parts with high aspect ratio [5–6]. Three-dimensional precision microcasting requires complex shape mold, however, limit its availability (3). In micro EDM, electrical discharges generated at the gap between the tool (electrode) and workpiece, while both are immersed in a liquid dielectric, remove workpiece material. Various high aspect ratio miniature structures including a microstructure array by micro wire-EDM using a micro wire with diameter of 20 μm [7]. Because of the tool wear, however, micro EDM has great limitations for its applications in micromachining in the future.

Electrochemical micromachining is an electrochemical dissolution process that can remove electrically conductive materials regardless of their hardness and toughness. It has been reported that material removal is strongly localized when ultra short voltage pulses current is used instead of low frequency pulse current [8–9].

This paper is focused on developing a novel technology of electrochemical machining, in which microscale tungsten wire instead of complex shape electrodes is employed to fabricate high-aspect-ratio metallic microstructures. Moreover, a slight vibration of the tungsten wire for effectively refreshing the electrolyte in micro high-aspect-ratio gap is also investigated to improve the stability of the proposed machining process. The technology offers some unique advantages over competing technologies such as no tool wear, better stability, low cost and higher aspect ratio of microstructures. Metallic microstructures with aspect ratio of 10 and with groove width of 15 μm have been obtained electrochemically.

Principle of micromachining

Fig.1 illustrates the principle of the electrochemical micromachining process using a tungsten wire. In the machining process ultra short voltage pulses are applied between workpiece and wire electrode. Electrolyte flows through the micro wire electrode accompanying bubbles up, which is byproduct of electrochemical dissolution process, such as hydrogen. Workpiece is electrochemically removed and narrow groove is produced as the cathode wire moves towards the anode workpiece. The motion track of the micro wire electrode is controlled by computerized numerical control system, and complex shape parts can be fabricated.

Fig. 2 illustrates the sketch of gap in machining process where d is the diameter of the micro tungsten wire, Δb is the inter-electrode frontal gap, and Δs is the inter-electrode side gap. The machining gap between the workpiece (anode) and the wire electrode (cathode) is reduced to microscale. Machining region where the electrodes are in close proximity is strongly charged by the voltage pulses, whereas the charging of the non-machining region is comparatively weaker.

As potential is applied between the two electrodes, the potential profile in the double layers becomes

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similar to that of an equivalent circuit that consists of capacitors and resistors. The equivalent circuit of double layer is shown in Fig. 2. C_d is the capacity of double layer, R_r is the resistivity of double layers, R_e is the resistivity of electrolyte in processing area, R_e' is the resistivity of electrolyte outside processing area. During the harging process of double layers, over potential η is always in the transient and varying state.

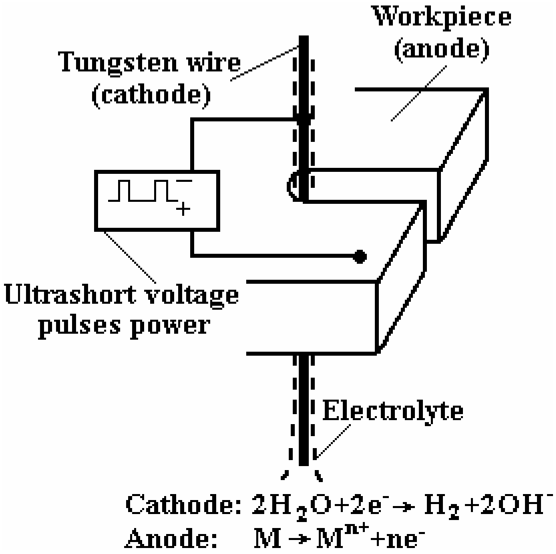

Fig. 1. Schematic of machining process

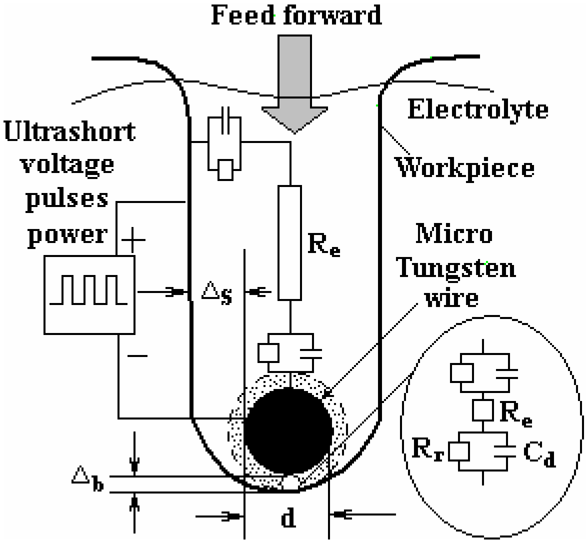

Fig. 2. Sketch of gap in machining process

$$\eta = \eta_\infty \left(1 - \exp\left(-\frac{t}{\tau}\right)\right) \tag{1}$$

Where η_∞ is the stationary value of over-potential, t is polarization time, and τ is time constants of the equivalent circuit. While $t>5\tau$, η would reach 99% of $\eta\infty$. The exponent item of Eq. 1 is evolved with Thaler series, and a pre-digest equation is gotten.

$$\eta = \eta_\infty \frac{t}{\tau} \tag{2}$$

The time constant of the equivalent circuit is

$$\tau = R \cdot C \tag{3}$$

where R is the equivalent circuit resistance of double layers, C is capacity of double layers. R is determined by the component, concentration of electrolyte and inter-electrodes gap. At machining region, both electrodes are in close proximity and resistance R is the lowest due to the shortest current path. The time constant τ_1 is relatively small. In contrast, in the non-machining region, the time constant τ_2 is larger than τ_1 due to the farther distance between the electrodes and the greater electrolyte resistance. Therefore, at the different area of workpiece, the over potential η of the double layers will reach different values.

The smaller gap distance between the wire electrode and workpiece is, the less time constant for double layers charging is. So the charged potential in processing area is higher than that outside processing area. From the Butler-Volmer equation, during the chemical reaction, current is

$$i = i_0 \exp\left(\frac{\beta n F}{HM} \eta\right) \tag{4}$$

Where i_0 is the exchange current density, β is the transfer coefficient, F is the Faraday constant, H is the gas constant and M is the temperature.

The potential of electrochemical double layers at the processing area is in comparison with that outside processing area. From Eq. 4, the current in processing area is far more than that outside the processing area. Ultra short pulse current is employed to improve the machining accuracy, and the machining gap is reduced to the microscale. The machining rate can be controlled by the feed rate of wire electrode, pulse conditions and the concentration of electrolyte because that the current is proportional to the dissolution rate. In addition, the diameter of the wire electrode is decisive for the reduction of both the machining gap and the groove width.

Machining system

The developed wire electrochemical micromachining system is schematically shown in Fig. 3. It consists of electrodes, electrolyte cell, servo control feed unit and unit of online fabrication of wire electrode. The ultrashort pulse voltage was applied to the electrodes. 0.1Mol/l HCl was preferred because the acid electrolyte usually produces much less byproduct than common salt electrolytes, which is important for a steady machining process in so tiny machining gap. The machining control system consisted of a precise XYZ stage and servo-control feed unit. The motion parts of X, Y and Z axes were driven by servo motors with the resolution of 0.1μm. A hall current sensor was used to detect the machining current signal, so status of the micro gap can be detected in real-time. When machining current jumps up, short circuit occurs between the micro wire electrode and workpiece.

Fig. 3. Photo of machining system

Before the process of fabricating microstructures, the position of the wire electrode must be located in order to set the initial inter-electrode gap. The wire electrode with low voltage (about 0.1 V) was controlled automatically to feed forward. When it touch the workpiece, the current would rise suddenly, while the wire electrode was held in position, where the gap was zero. Then the wire electrode retracted 5μm from the initial machining gap.

Experiments and discussion

The stability is most important for this micromachining process with the gap of several micrometers. Micro gap in wire electrochemical machining process is often clogged by the bubbles, especially in fabrication of high aspect ration micro structure. The clogging will lead to short circuit in machining process. The times of short-circuit in machining process per unit time was considered as the evaluating indicator of machining stability. The slight vibration of micro tungsten wire took place along the direction of the wire electrode length can eliminate the clogging effectively, as shown in Fig. 4. Because of back-and-forth movement of wire electrode forms mechanical agitation in micro gap, the slight vibration of the wire effectively can refresh electrolyte in the machining area. Experiments of the wire electrochemical micromachining were carried out to demonstrate the effects of the vibration of wire on the machining stability by fabricating a series of grooves in length of 100µm. Machining feed rate of the wire was 0.125µm/s. The ultra short voltage pulses with pulse amplitude of 5V and pulse period of 1µs was used in machining process. The frequency of slight vibration of the wire was 5HZ. Fig. 5 shows that micro wire electrode with the slight vibration leads to the decrement of times of short-circuit, i.e. the improvement of machining stability.

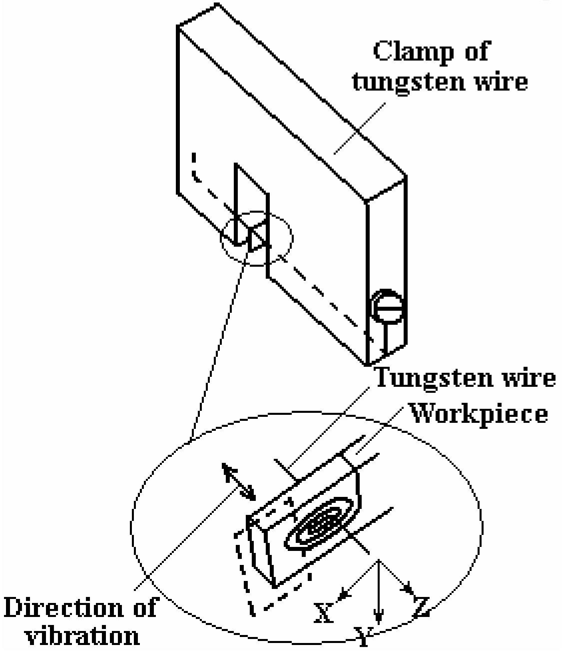

Fig. 4. Sketch of vibratile tungsten wire

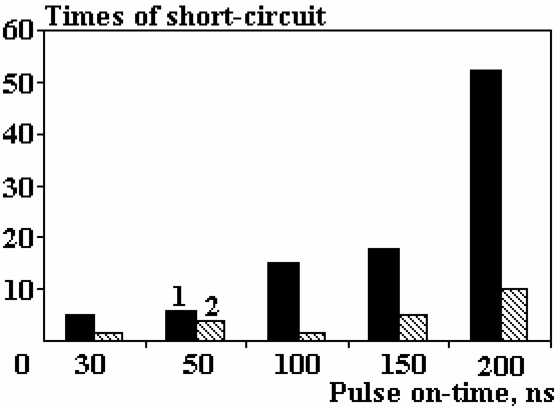

Fig. 5. Effect on machining stability with vibration of tungsten wire

The machining gap, which was estimated as the half of the difference between the slit width and the tool diameter, was considered as the evaluating indicator of machining accuracy. Experiments of the wire electrochemical micromachining were carried out to demonstrate the effects of machining parameters on the machining gap.

The diameter of the wire electrode is decisive for the reduction of both the machining gap and the slit width. To investigate the effects of diameter of wire electrode on the machining gap, a series of 100µm length slits of a nickel plate with the thickness of 80µm were machined with various diameter of wire electrode in 0.1 Mol/l HCl electrolytes. Fig. 6 shows that the thinner wire electrode leads to the decrement of machining gap, i.e. the improvement of machining accuracy. So the wire electrode as thin as possible is suggested for the improvement of the machining accuracy. At the same time, it has been observed that the machining gap width increased with the increase in pulse on-time. The trend was the consequence of more increment of machining gap width at long pulse on-time.

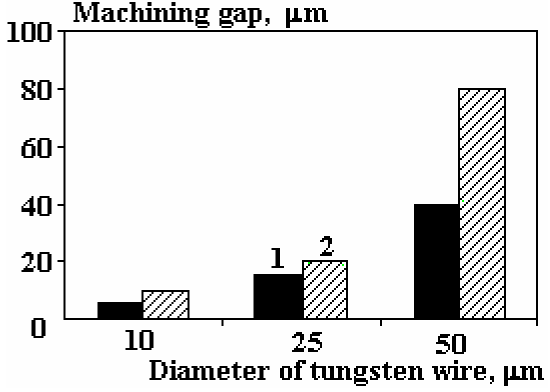

Fig. 6. Variation in machining gap with the diameter of tungsten wire

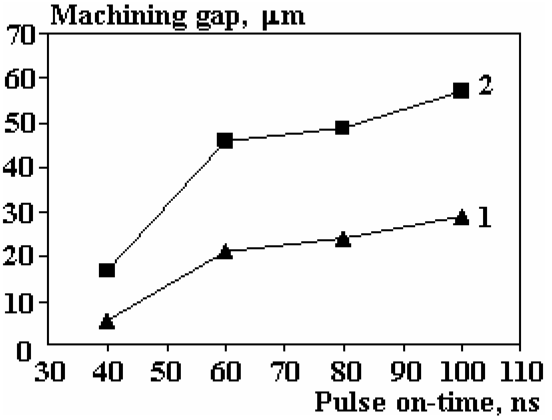

Fig. 7. Variation in machining gap with pulse on-time

Experiments were performed by changing the pulse on-time and the voltage with the identical pulse period of 1µs and wire electrode with diameter of 10µm. Fig. 7 shows that the machining accuracy becomes poor as the pulse on-time increase. However, decreasing the pulse on-time excessively will reduce the energy supply for the dissolution per unit time, and thus more short circuit will occurs with the identical feed rate of wire electrode. Therefore, the pulse on-time as short as possible under a steady machining process is suggested for the improvement of the machining accuracy.

Fig. 8 shows that microstructure with the width of 15µm was machined. Profile of slits was divided into micro line segments, the wire electrode fed forward at constant speed. Machining feed rate of the wire was 0.125µm/s. The ultra short voltage pulses with pulse amplitude of 4V, pulse on-time of 40ns and pulse period of 1µs was used in machining process, and the slight vibration of wire with the frequency of 5HZ was employed for improving machining stability.

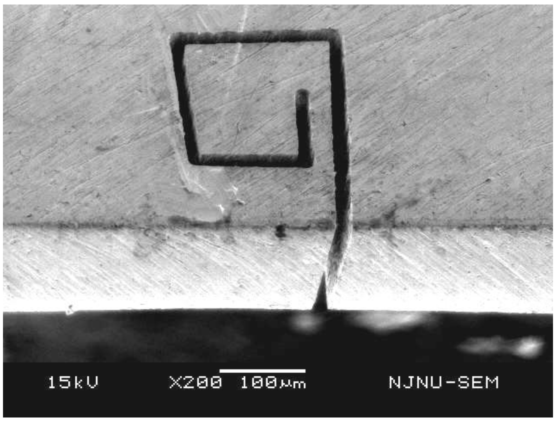

Fig. 8. Micro grooves with high aspect ratio by electrochemical micromachining

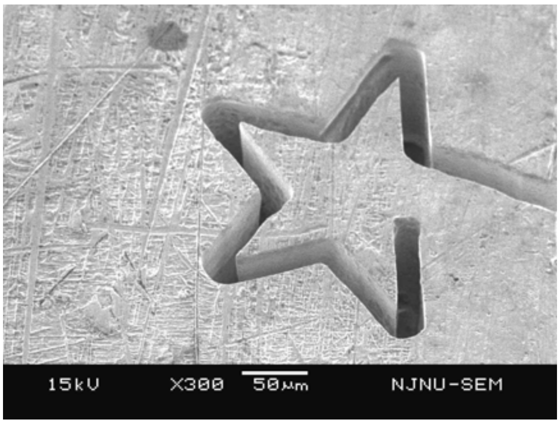

Fig. 9. Micro sharp tips with high aspect ratio by electrochemical micromachining

The motion track of the micro tungsten wire is controlled to move with constant speed following an envelope track, which was offset from the profile of the micro structure. Because the speed of micro wire is constant, the duration of dissolution in per length with dissimilar curvature radius is different. Therefore greater dissolution rates normally occur at the sharp tip than that one elsewhere. There is an approach to solve the problem obviously: accelerating the speed of wire electrode when etching the material with tiny curvature radius. Fig. 9 shows that micro sharp tips with the width of 20µm were etched electrochemically in Nickel board with thickness of 200µm using the proposed method. The aspect ratio of the micro structure is 10, and the curvature radius of the sharp tips is less than 1µm. Machining feed rate of the wire was 0.125µm/s. The ultra short voltage pulses with pulse amplitude of 4.2V, pulse on-time of 50ns and pulse period of 1µs was used in machining process, and the slight vibration of wire with the frequency of 5HZ was employed for improving machining stability.

Conclusion

A novel method for fabricating high-aspect-ratio metallic microstructures by electrochemical micromachining using vibratile tungsten wire was proposed in this paper. According to the principle of electrochemical reactions, the theoretic model of machining process has been developed. The slight vibration of micro tungsten wire took place along the direction of the wire electrode length can improve the machining stability. The wire electrode as thin as possible and the pulse on-time as short as possible under a steady machining process are suggested for the improvement of the machining accuracy. Micro groove with the width of 15µm was machined, and micro sharp-angles structure with aspect ratio of 10 was obtained experimentally.

Acknowledgments

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Summary

Electrochemical micromachining can remove electrically conductive materials with the transferring of ions, so that high precision is achievable. A novel method for fabricating high-aspect-ratio microstructures by electrochemical micromachining using vibratile tungsten wire was proposed in this paper. The slight vibration of tungsten wire can improve the machining stability. The relations between the machining accuracy and machining parameters were experimentally studied. Micro groove with the width of 15μm was machined, and micro sharp-angles structure with aspect ratio of 10 was obtained experimentally.