Experimental Study on Fabricating Micro Monolithic Tungsten Probing Ball for Micro-CMM

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ABSTRACT

Three-dimensional measurement of microstructures requires a 3-D microprobe with small probing ball as well as appropriate nanopositioning and nanomeasuring machines. An electric arc melting method is presented in this paper, which could fabricate the monolithic micro-spherical tip on the tungsten wire. Based on the principles of electrode discharging energy absorption and the surface tension phenomenon, a micro sphere is formed at the needle-shape tip of the tungsten wire. The model of dynamic arc discharging is established to analyze the process of sphere forming. Experiment results reveal that a spherical tip about 60 μm in diameter having less than 1 μm roundness error could be achieved on a 100 μm diameter tungsten wire with the selection of proper process parameters, such as the discharging voltage, discharging time and discharging gap. Quality of the probe is mainly determined by the electro-discharge conditions which affect the solidification force and thermal conductivity. The monolithic microprobe can be used in the micro coordinate measurement machines (Micro-CMMs) to allow the measurement of micro grooves possible.

Keywords: Micro-spherical tip, Monolithic tungsten probe, Discharge parameters, Micro coordinate measurement machine

1. INTRODUCTION

Higher demands on accuracy and precision for the measurement and analysis of micro- and nano-structures over large ranges do arise from the microelectronics, the optics, and the precision engineering industries. As the accuracy of miniature products increases, so does the need for highly accurate micro-3D measurements. The most reliable way to measure the sizes, forms, and space positions of 3D components is by the use of a ball-ended, contact type probe measurement system, such as the micro/nano coordinate measurement machine (CMM). A good ball tip is the basic element for the construction of a contact probe. The contact type probe is capable of measuring high aspect ratio micro-holes, grooves, and side edges that are difficult to be measured by non-contact probes [1].

Styli with micro ruby probing spheres in diameters between 120 μm and 300 μm are the current state-of-the-art. Traditional probe tip is normally fabricated by screwing or gluing a spherical ruby ball to a metal stem, as shown in Figure 1. The accuracy of the diameter and the sphercity of the ball and its center offset to the stem are highly demanded as the probe radius compensation is needed to determine the contact point. As the ball becomes even smaller, the sphericity and center offset of the ball to the stem are difficult to be proportionally downscaled by gluing process. The fabrication of a good monolithic probe stylus is necessary to satisfy the aforementioned requirements.

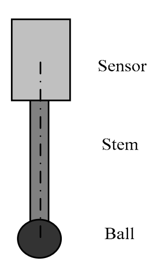

Figure 1: Schematic diagram of a traditional probe.

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Fusing the stem end to form a spherical probing tip can minimize the errors introduced by the traditional assembly process. Ji et al. fabricated an integrated optical fiber tip based on the method of fusion by EDM [2]. The author's group used the commercially available fiber fusion splicer to successfully fabricate micro-spherical fiber probes with good geometrical quality [3, 4]. However, considering the wear of the micro-sphere surface due to the contact or scanning force [5], a harder material of the sphere is necessary. Sheu developed a WEDG technology to fabricate the tip sphere on a tungsten stem, however, the quality could not be controlled well [6, 7]. In this paper, a new EDM technique is proposed to fabricate the good tip-ball on the tungsten wire. The wire is treated as one of the electrodes. With proper control of the process parameters, including the discharging voltage, discharging time and discharging gap, a spherical tip about 60 μm in diameter having less than 1 μm roundness error could be made on a 100 μm diameter tungsten wire.

2. EXPERIMENTS

2.1 Principle of electrode discharging (electric arc)

An electric arc is the electrical breakdown of gas which produces an ongoing plasma discharge, resulting from a current through normally nonconductive media, such as air. The discharging arc is a charged fluid involved in the research processes of heat, electric, magnetic, fluid, and many other fields. Thus, the theory of fluid dynamics can be used to analyze the magnetic properties of arc.

According to the physical properties, the electric arc is divided into three parts (Figure 2): close to the cathode surface of the part is called the cathode area, close to the anode surface of the part called the anode, while the middle part is called the arc column. Some assumptions are to be made: (1) the arc is in the local thermal dynamic equilibrium (LTE) state; (2) the arc is stable, continuous and symmetrical, and is optically thin and laminar flow in the state; and (3) the heat loss due to viscous effect is negligible. Arc behavior model is controlled by the following equations:

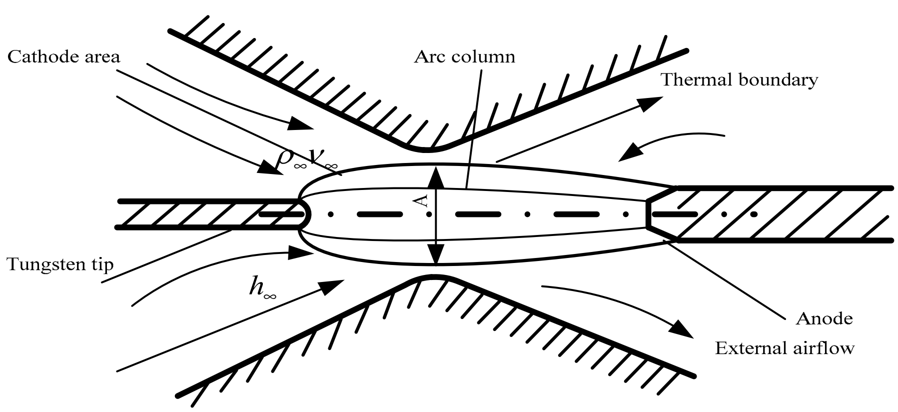


Figure 2: Schematic diagram of arc discharging model.

(a) Energy conservation equation

$$\frac{d}{dz}(\rho_\infty v_\infty h_\circ \Lambda_h \theta_b) = EI(1-f) \tag{1}$$

where, f is the radiation loss share of input power ratio, h is the total enthalpy (stagnation enthalpy of the only gas), Λ_h is the enthalpy shape factor, and θ_b is heat area.

(b) The continuity equation

$$\frac{d(\rho_\infty v_\infty)}{\rho_\infty v_\infty} = (1-M_\infty^2)\frac{dv_\infty}{v_\infty} = -\frac{d(A-\theta_d)}{A-\theta_d} \tag{2}$$

where, M_∞ is the external flow Mach number and θ_d is the displacement area.

Through qualitative analysis of the arc model, power distribution between two electrodes along the electrodes axis is increasing from the center point to the electrodes, the center point between the electrodes has a relatively lower power than that of the neighboring area [11]. The melting point of tungsten is around 3410 ℃. Using the high temperature zone to melt the wire could save the energy.

2.2 Experimental set-up and method

This study adopted a fine tungsten wire in diameter of 100 μm to fabricate a micro ball-ended stylus tip. The tungsten wire was treated as the cathode and a high-voltage pulse generator was supplied, as shown in Fig. 3. The oxidation phenomenon is server when melt tungsten is exposed in the air, causing heavy smokes. The experimental set-up was, therefore, placed in a glass shelter, as indicated by the dotted lines, and filled up with inert gas of argon, in order to protect from atmospheric contamination and avoid the sparkling smoke. A CCD camera is installed outside the shelter to real-time observe the arc discharging condition. The specifications of the high voltage pulse generator are listed in Table 1.

Table 1: The parameters of high voltage pulse generator

Items	parameters
The range of the output voltage	0 - +6 KV
The output circuit	20 mA
Pulse frequency	5 HZ - 500 HZ
Pulse breadth	Adjustable
Pulse mode	single pulse or sequential pulse

The whole setup is economical and flexible to configure. Treating the tungsten wire as an electrode ensures the generated heat high enough to melt the tip while absorbing the arc discharging power. The control unit together with an adjustable power supply was used to control the discharging intensity. The discharging voltage and frequency were controlled by the voltage pulse generator for adjusting the arc temperature to melt the tungsten tip. A timer was employed to control the fabrication time. Two high precision translational stages with 0.5 μm resolution were used to adjust the distance between the electrode and the tungsten tip. A tungsten chuck rotator with strain relief was used as the tungsten holder during the fabrication. The image of discharging process could be observed in real-time, as shown in Fig. 4.

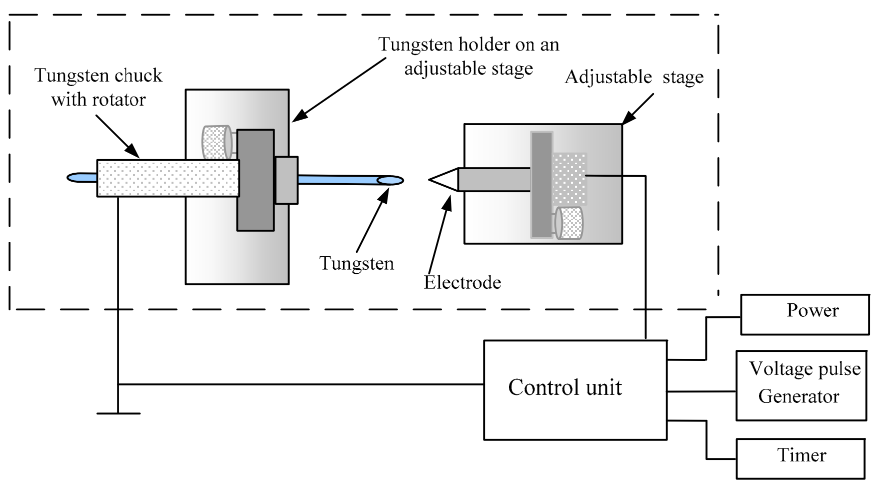


Figure 3: Experimental configuration for fabricating tungsten probe.

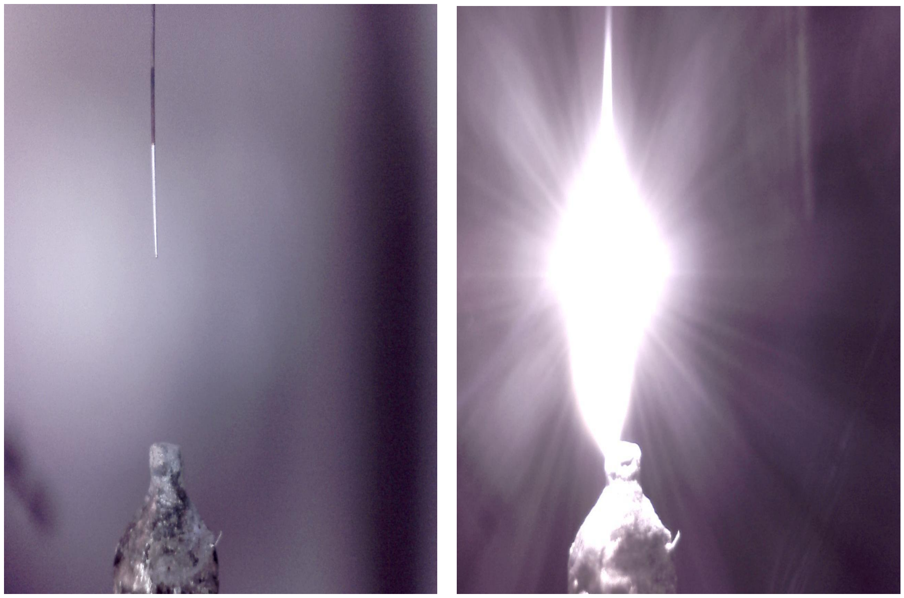
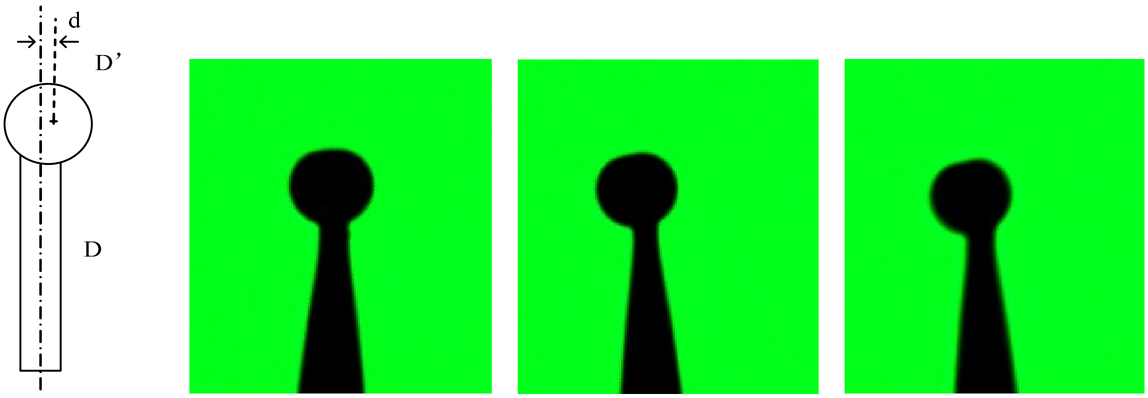


Figure 4: Image of fabrication of tungsten tip, (left) before sparkling, (right) in process.

During solidification the drift of the ball due to gravity effect will cause the offset *d* of the ball from central line DD' of the tungsten stem (Figure 5a). In the previous research of ball tip fabrication on optical fiber by the author's group [3, 4], the fiber was placed at the center of two electrodes. The fiber could be rotated during processing to compensate for the gravity drift. In this study, the tungsten wire is treated as the cathode, which is difficult to be rotated by a proper mechanism that must isolate high voltage. Therefore, proper adjustment of the electrodes' center line and gap, together with the selection of process parameters, determines the offset dimension. If the process is not well controlled, there will be an offset in the tungsten tip and the ball head is flat resulting from vaporization or inadequate surface tension, as shown in Figures 5b to 5d. The high temperature and instantaneous energy caused by electric arc will result in the melting at the front tip of the tungsten electrode, even becomes vaporizing if improper controlled. Unbalanced thermal conductivity and solidification force would lead to a high variation of the sphericity and roundness of the ball-ended tip. Figures 5b to 5d show images of the probe (57 μm in diameter) viewed at different angles in an optical measurement system. The flat ball head becomes a new problem to be resolved. Besides, the offset can never be eliminated completely as the formation is very fast because its damping coefficient is very low. However, it could still be minimized by adjusting the discharging distance between the electrodes and the supplied voltage. An interesting phenomenon was found that the wire tip became tapered shape during the growing of the ball. It is assumed that the heat zone covers a certain length of the wire and thereby causes deformation. The higher the temperature is, the more the deformation will occur. This is the explanation of the formation of needle-shaped tip. Such a tapered geometry is beneficial to this experiment for obtaining smaller ball tip.

The ball tip image is off-line measured by an optical image system, model MUMA made by 3DFamily Co., which consists of a CMOS sensor of 1.3 million pixels (1280 × 1024), a zoom lens of 0.7 to 4.5X, and image magnification of 40X. The smallest field of view (FOV) is about 800 μm × 600 μm, which is clear enough to view the tip ball. A subpixel algorithm is used to detect the image to 0.1 pixels and analyze the geometrical errors [10]. Theoretical resolution can reach 0.1 μm.



(a) (b) 0° (c) 45° (d) 90°

Figure 5: Images of the bad tungsten tip.

The dimension and the quality of the tungsten tip are affected by several process parameters and different combinations of these parameters yield to different fabrication results. The parameters include discharging voltage, discharging time, electrode gap, and the rotational speed.

With the proper selection of discharging voltage and discharging time, the electric arc between the electrodes provides an extremely high temperature field. In such a temperature zone, the tungsten wire tip is melted and formed a spherical surface due to the surface tension phenomenon in solidification. Experimental found that the ball diameter and the straightness of the stem are determined by the surface tension and the gravity force of the spherical ball during its liquid to solid phase transformation.

Table 2. Ball-tip results attributed to a range of fabrication conditions.

No.	Voltage (KV)	Gap (mm)	Time (s)	Average Diameter (μm)	Center Offset (μm)	Roundness Error (μm)
1	2.5	2	10	58.2	4.5	0.7
2	2.5	2	12	60.8	1.5	0.5
3	2.5	3	15	63.5	1.7	1.2
4	3.0	2	10	56.3	3.4	0.6
5	3.0	2	20	59.5	1.0	0.8
6	3.0	3	15	61.7	2.3	0.6

3. RESULTS AND DISCUSSION

The good spherical probe for precision measurement requires three critical characteristics: uniform ball diameter, good roundness, and small center offset of the ball from the stem [8]. The first two dimensions can be controlled by the arc discharging parameters, while the offset distance is mainly attributed to the influence of gravity effect during the ball formation. The effect of gravity can be minimized by rotating the tungsten wire during fabrication. The experimental results of parameter selections are listed in Table 2. At the current stage, three parameters are selected, namely the supplied voltage, electrode gap, and fusion time. The ball tip could be obtained in average diameter of 60 μm. The smaller center offset and roundness error represents the better ball quality. The experiment No. 5 is regarded as the best result. Figure 6 shows its images viewed from different angles and Table 3 lists analyzed data.

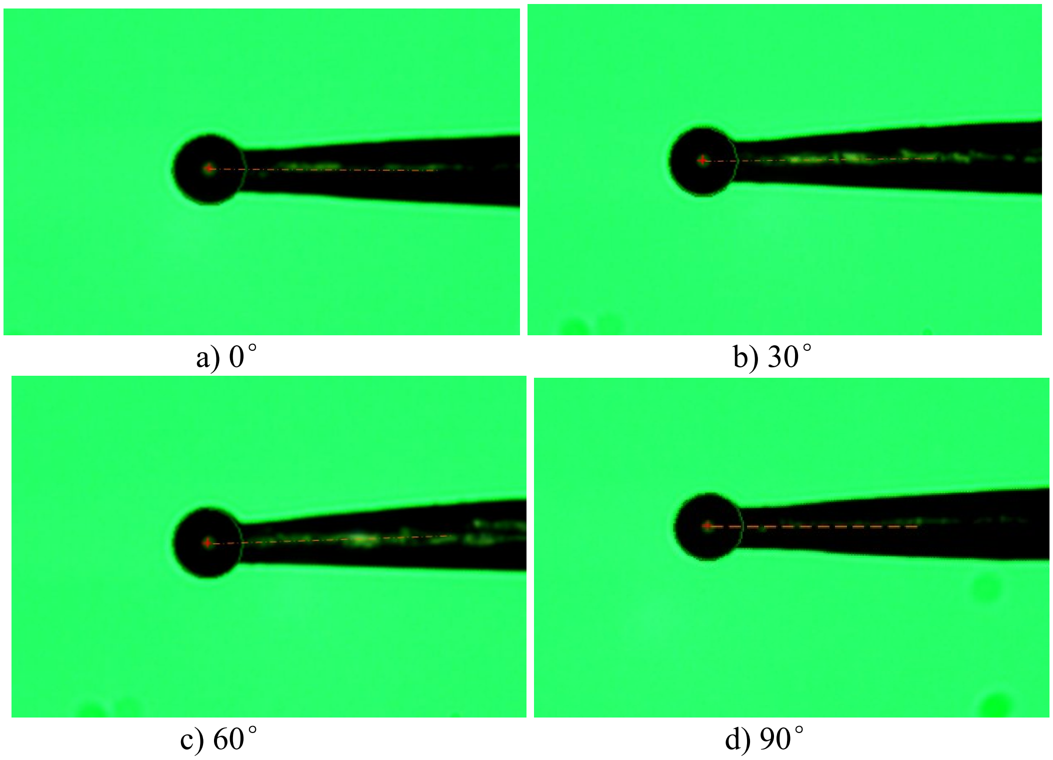


Figure 6: Images of a tungsten tip viewed from different aspect angle.

Table 3. Measurement results of the tungsten ball-tip at four viewed angles (unit in μm).

Angle of view	0°	30°	60°	90°
Diameter	60.1	59.8	58.9	59.5
Roundness	0.80	0.74	0.85	1.04
Center Offset	0.3	0.9	1.6	0.8

It is obvious that under the selected conditions the monolithic probe is approximately 60 μm at the needle-shape tip of the tungsten wire. The average roundness deviation of the ball profile is less than 1 μm. The whole process may not be repeated sometimes, and the result may also be different. The current research reveals the feasibility of fabricating monolithic tungsten probe on the extremely conditions. As there are other fabrication conditions, such as the rotational speed and tip end lateral position adjustment, that have not been studied, further studies will be required to examine their influences.

4. CONCLUSIONS

This paper has demonstrated an economical and flexible system to fabricate the monolithic micro-spherical tip on the tungsten wire. The tungsten tip is treated as an electrode so that the heat generated is high enough to melt the tip while absorbing the arc discharging power. The high temperature and instantaneous energy caused by electric arc will melt the front tip of the tungsten wire. Unbalanced thermal conductivity and solidification force lead to a significant variation of the sphericity and roundness of the ball-ended tip. Experimental results reveal that a spherical tip about 60 μm in diameter having less than 1 μm roundness error and center offset could be achieved on a 100 μm diameter tungsten wire with the selection of proper process parameters, such as the discharging voltage, discharging time and discharging gap. Further studies will focus on the improvement of the ball-tip quality by investigating more parameters. It is known that the tungsten ball is more wearable than the glass fiber ball. It is suitable for the contact type probe in Micro-CMM

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