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Experimental study of fabricating a microball tip on an optical fibre

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Abstract
Many side walls of microholes and grooves are not easily measured by current optical or non-contact measuring instruments. Microcontact probes are increasingly demanded in the market. A good ball tip is the basic element for the construction of a contact probe. This paper proposes a low-cost and in-process system to fabricate a microspherical tip on an optical fibre using a commercial fibre fusion splicer. Based on the principles of arc discharging energy absorption and the surface tension phenomenon, a microsphere is formed at the tip of the optical fibre. Experimental results showed that with the selection of proper process parameters, such as the arc power, cleaning arc power offset, and cleaning time, a spherical tip about 300 μm in diameter and with 6 μm roundness error could be produced using a 125 μm diameter single-mode optical fibre. The offset distance between the ball centre and the fibre stylus central line due to the gravity effect could be suppressed to less than 3 μm by rotating the fibre between the discharging cycles. By forming the sphere probe tip directly on an optical fibre, this approach demonstrates an easy and in-process dimensional controlled method to shorten the manufacturing lead-time for making a 3D microprobe. The microprobe can be used for microscale/nanoscale coordinate measuring machines (CMMs) to enhance the measurement resolution and extend the capability for meso- to micro-objects.

Keywords: microsphere probe, optical fibre, fibre fusion, in-process measurement

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Although many 1D nanoscale measurement systems have been developed and commercialized successfully, ultrahigh precision 3D surface measurement technologies have been paid much attention in research during the last ten years. There are quite a few optical profilers capable of 3D non-contact measurement to the resolution of a nanometer, such as the well known white light interferometer and the holographic digital microscope [1]. These devices cannot cope with the side wall geometry measurement of high aspect ratio microholes, grooves, and edges. The system design and integration of a contact type microscale/nanoscale three-dimensional coordinate measuring machine (3D CMM) has become increasingly important, and the development

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has thus emerged as a new research area due to the need for measuring microparts [2]. This kind of CMM requires higher measurement accuracy and resolution than conventional macroscale 3D CMMs. The design and manufacturing of the microtouch trigger probe becomes one of the critical factors in achieving the measurement capability.

While the MEMS process can fabricate various microstructures, they can never make a complete microsphere with the current technology. One feasible way is to use a layer by layer micro-electro discharge machining (EDM) method to manufacture complex 3D parts and microprobes [3, 4], but this is quite time consuming, and the surface finish is rough due to the electro discharge craters. A new approach with micro-EDM, based on the surface tension principle to fabricate microspherical probes, has been proposed recently [5, 6], but the geometrical accuracy has not met the measurement requirement. Direct fabrication on the fibre tip to form a monolithic microstructure as a particular sensor is another possible approach [7]. This fibre probe can be made to a very small size that allows the measurement into microholes using its deflection effect detected by the CCD [8, 9] or fibre Bragg gratings (FBGs) [10]. The fabrication process for a good fibre probe is not clear. Normally this is company-confidential information.

In this paper a new approach utilizing the cleaning feature of a commercial fibre fusion splicer to fabricate the microball tip directly on an optical fibre and directly monitoring the forming geometry of the sphere with respect to the fibre stem will be described in detail. The optimal processing strategy has also been identified that involves the selection of arc power, cleaning arc power offset, and cleaning time to control the diameter and roundness of the ball. The compensation of the offset distance of the spherical tip centre from the fibre central line is also achieved by rotating the fibre between the discharging cycles. The related experimental set-up is proposed.

2. Experiments

2.1. Experiment method

This study adopts the single mode glass fibre, made by Corning Co., USA, model SMF-28e, for fabricating the ball tip. The material of the fibre core is a purified glass containing 99.999% of SiO_2. The core is surrounded by the cladding, which is covered with PVC coating. The dimensions are illustrated in figure 1. The cladding layer and the core adhere tightly during the roll-forming process of the optical fibre so that they are not separable. The bare fibre stem, therefore, has diameter of 125 μm.

Most fibre fusion splicers provide a cleaning feature to clean the fibre end faces before the fusion joining operation, and an arc check feature to optimize the splicing conditions [11]. In this study the cleaning feature of a commercial fibre fusion splicer is utilized to fabricate microprobes. The geometric profile and dimensions of the probe are measured using an image vision type coordinate measuring machine.

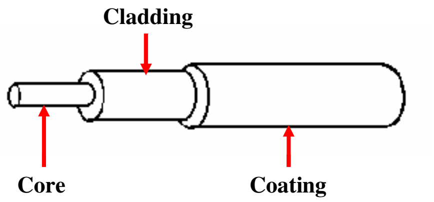

Figure 1. The composition and dimensions of a single mode optical fibre.

2.2. Experiment set-up and procedure

The fibre fusion splicer used in this study is the FITEL S199S model single fibre fusion splicer made by Furukawa Electric Co. Ltd, Japan. Parameters involved in the fusion process are: (1) discharge voltage, current, and frequency; (2) electrode parameters, such as material, shape and gap length; and (3) external conditions, such as kind of gases, pressure, temperature, moisture, and gas flow [12]. In addition, the location of the fibre tip with respect to the electrodes is also critical to the energy absorbed by the optical fibre [13]. Since this splicer has been set up in such a way that the splicing result is optimized, only limited parameters such as the discharge time, the discharge strength, and the distance between the fibre and the discharge electrodes can be varied during the experiment. The electrodes used are made of tungsten with a diameter of 2 mm, apex angle of 30° and electrode gap of 4 mm. The discharging environmental temperature is the normal room temperature. The optimal results can be achieved by adjusting most of those parameters mentioned above. In this study a single mode optical fibre is used.

In order to conduct the experiments effectively and efficiently, the original system configuration, as shown in figure 2(a), has been modified by adding an XY position stage and a rotary stage into the experimental system configuration, as shown in figure 2(b).

The standard operation for ball tip formation on an optical fibre consists of three steps. First, in the fibre preparation process, strip off a portion of fibre coating using a fibre stripper; wipe the bare fibre with cotton soaked with denatured alcohol to remove coating chips adhering to the fibre; and then cleave the fibre end face with a fibre cleaver. Second, in the fibre loading process, open the windshield of the splicer and both the fibre holders and the fibre clamps; load the prepared fibre into the left side of the holder (seen in figure 2(b)) with the stripped portion in the V-groove and make sure that the fibre is properly aligned in the V-groove before closing the fibre holder. This can be done by adjusting the XY stage. The fibre clamp is closed afterwards to hold the fibre on the V-groove. Once the fibre is loaded correctly, the windshield is closed and the splicer is ready to conduct experiments. Lastly, in the formation process, by setting the arc power, the cleaning arc power offset and the cleaning time, the microball tip can be fabricated.

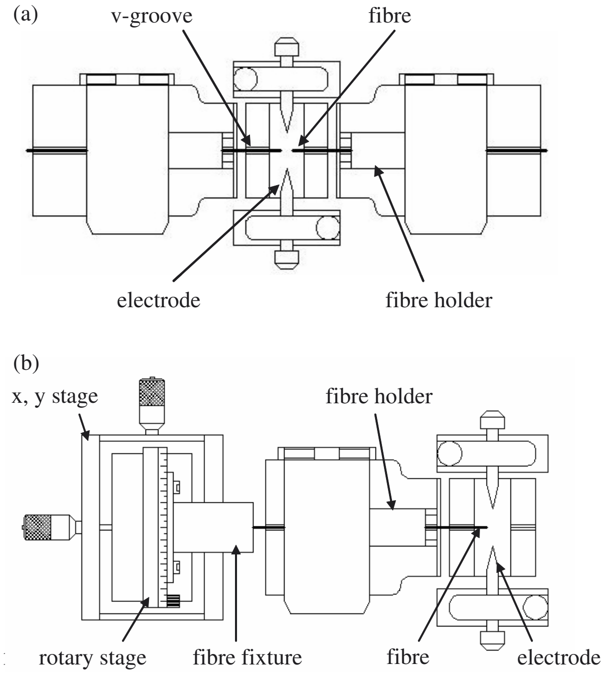

Figure 2. Experimental set-up. (a) Original fibre splicer configuration. (b) Modified experimental configuration.

A good spherical probe for precision measurement requires three critical characteristics: uniform ball diameter, good roundness, and small centre offset of the ball from the stylus. 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. Therefore, the fibre is rotated 180° alternately with respect to the fibre axis to compensate for the bending of the probe tip.

2.3. The in-process measurement system

Micro 3D profiles normally can be measured by a profile interferometer, such as a white light interferometer or a holographic interferometer. Owing to the resolution limit of the interferogram, this technique can only measure the top part of a sphere, such as the microlens or the fibre-tip surface profile [14, 15]. In order to monitor the progressive growth and control the quality of a whole microball, this experiment adopts a 2D image system. A CCD camera, made by PULNIX Inc., model TM-7CN, with 768 × 494 pixels, is mounted above the splicer kit. A zoom lens up to 5.25× magnification from OPTEM Co. is applied to extend the working distance to 80 mm and reduce the field of view to 0.9 mm × 1.2 mm so that each pixel corresponds to about 1.87 μm. The point data are processed by the Laplacian of Gaussian (LoG) smoothing technique with a 1 × 15 mask, and the edge detection is calculated by the zero-crossing point with the second order differentiation of grey levels across the boundary. This image processing technique can yield fast computation time and one tenth subpixel resolution (0.19 μm) to determine the coordinates of each measured boundary point.

After each arc cleaning cycle, the diameter and the roundness of the spherical tip, and the centre offset between the ball and the fibre stylus, are measured at every 90° with respect to the fibre axis so that the shape of the microprobe can be recorded during the fabrication process. This in-process dimensional control system is configured in figure 3.

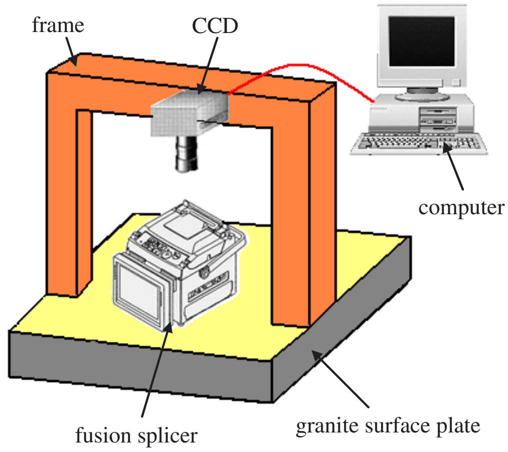

Figure 3. The in-process spherical probe forming system.

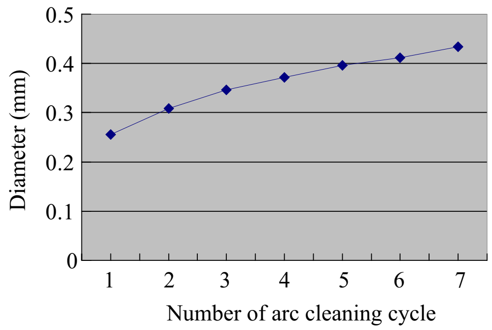

Figure 4. The relationship between the spherical tip diameter and the number of arc cleaning cycles; arc power: 230, cleaning arc power offset: 230, cleaning time: 6000 μs.

3. Results

3.1. Experiment results

The fibre tip absorbs the arc discharging power and melts instantaneously. Due to the surface tension, the melting part of the fibre starts to form a spherical shaped tip gradually during solidification. As the spherical tip grows bigger, the gravity force becomes larger, pulling the tip towards the gravity field. This will cause a droop of the spherical tip and thus yield an increase of offset distance between the centre of the sphere and the central line of the fibre stylus. Figure 4 shows the relationship between the diameter of the spherical tip and the number of arc cleaning cycles when all the other parameters are fixed. It is seen that the diameter increases as the number of cleaning cycles increases.

The effect of gravity can be minimized by rotating the fibre around the axis of the fibre by 180° with respect to the previous offset direction of the spherical tip. However, because the energy will be still too large, causing the spherical tip to

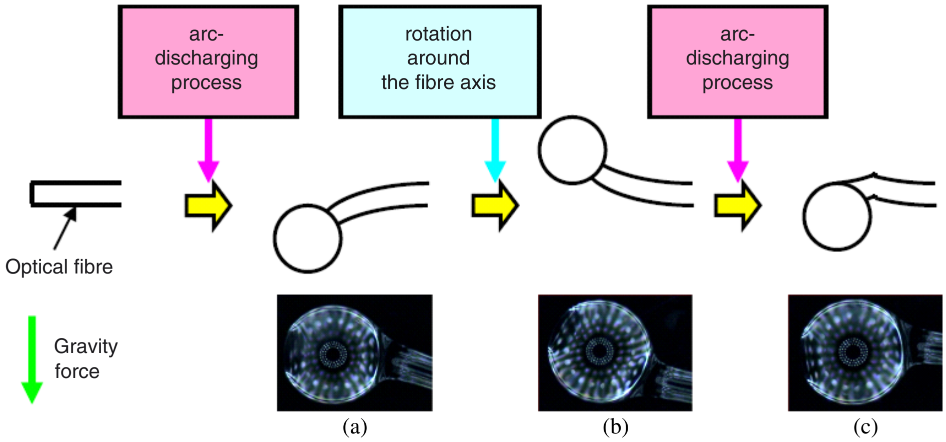

Figure 5. Overcompensation phenomenon (side-view images).

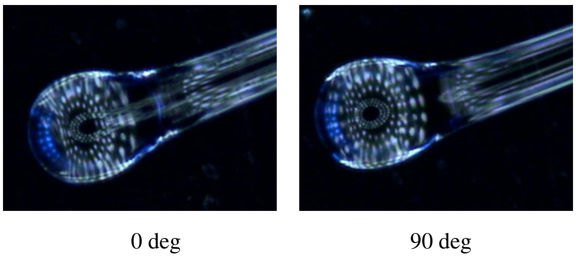

Figure 6. Unacceptable 'droplet' tip shape.

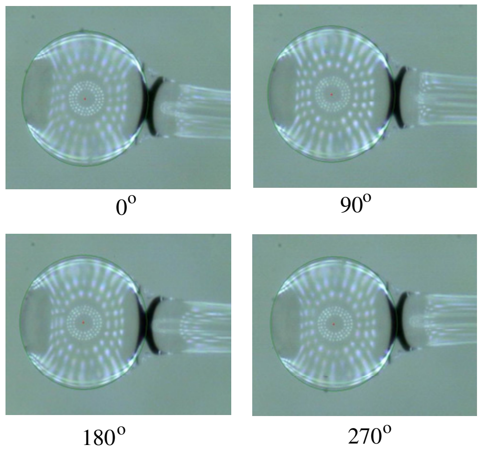

Figure 7. Images of the fibre tip.

Table 1. Values of experiment parameters.

	Step 1	Step 2
Arc power (units)	230	100
Cleaning arc power offset (units)	230	230
Cleaning time (μs)	30 000	500

shift toward the gravity field again due to the increasing weight of the tip, the offset will never be eliminated completely by only rotating the fibre if the power of the arc cleaning cycle remains unchanged. This overcompensation phenomenon is shown in figure 5, where (a) illustrates the tip bending after one cycle of the arc-discharging process, (b) shows the tip after 180° rotation of the original bending and (c) shows the overcompensated tip after the arc-discharging process at position (b). All the figures are side-view images captured by rotating the fibre by 90° after each arc-discharging process.

In other words, if a lower discharge power is set in order to control the mass of the melting tip, the tip does not bend significantly. This can certainly reduce the offset distance between the centre of the sphere and the fibre central line. This will, however, still result in an unacceptable probe tip even though the fibre has been rotated 180° after each discharge cycle, as shown in figure 6. This is due to the fact that there is a gradually solidified segment generated in between the tip and the stem, and thus the tip shape is similar to a droplet instead of a sphere.

In order to compensate the bending of the previous cycle, the parameters have to be adjusted accordingly so that the offset can be eliminated completely. After analysing the experiment results and investigating the phenomenon closely, numerous experiments have been carried out to adjust the process parameters. An optimal processing strategy has thus been derived accordingly. The clue is to first make a spherical tip with required diameter and roundness by applying higher arc power, larger cleaning arc power offset and longer cleaning time, and then to compensate the offset by applying lower arc power, smaller cleaning arc power offset, and shorter cleaning time. Table 1 shows the details of the optimal processing strategy.

3.2. Measurement results

The strategy has been applied to fabricate a number of microprobes. Figure 7 shows an image of one of the probes viewed at four angular positions with respect to the fibre, and the corresponding measurement results are summarized in table 2. The term of roundness is commonly used in metrology. Its numerical method is to find the least-squares circle from sampled circumferential data. The peak-to-valley distance of the sampled data with respect to the fitted circle is defined as the roundness error of the measured circular object.

Table 2. Measurement results of the tip at various rotational angles (in μm).

Dimension	0°	90°	180°	270°
Diameter	344.31	345.09	344.77	343.21
Roundness	6.13	5.30	5.98	5.60
Centre offset	2.50	0.41	0.93	1.54

It is obvious that the droop of the probe tip and the bending of the fibre have been significantly reduced and the overcompensation phenomenon does not appear again. This implies that the strategy does work to the extent that the existing experimental apparatus can handle. Although the measurement results indicate that the bending has not been eliminated completely due to the inaccurate manual control of the fibre rotation, and the roundness due to residual stress induced by the uneven temperature of the fibre tip is significant, improvement of the experimental apparatus and a better control scheme will be further implemented to improve the offset and the roundness of the spherical tip.

4. Discussion

The probe size will be required in different diameters for different holes or grooves. According to the accuracy requirements of microparts, geometrical errors of the probe will also be required to different degrees. Typical target values of roundness and offset errors for practical probe requirement will be less than 1 μm, or even better. As indicated in section 1, the fabrication process of a good fibre probe is confidential to the manufacturers. The market price of a microfibre ball-probe is very high, of the order of around 800 euro per piece (for example, the WFP fibre probe from the Werth Co., Germany). Current work reveals only the feasibility of fabricating a similar probe in a very low cost way, but the accuracy has not been met. Further investigations will focus on the refinement of the splicer set-up for better process control, the derivation of the optimal combination of control parameters with the Taguchi method, the optimization of the discharge environment, and the characterization of the probe tip. In addition, similar to the concept of 'quasi-microgravity effect' that applies a magnetic field to compensate the gravity drop of a horizontally rotating conductive material in the chemical vapour deposition (CVD) or physical vapour deposition (PVD) processes [17], the fibre ball drop could be possibly compensated by ejecting an air flow from bottom. It is expecting that a reliable and cost-effective microprobe can be achieved for micro/nano CMM applications.

5. Conclusions

This research shows the feasibility of utilizing a commercially available fibre fusion splicer to fabricate a microspherical tip on an optical fibre. With the proper selection of working parameters, an optimum processing strategy has been derived to produce a good microball tip. The strategy first focuses on making a tip with required diameter and roundness by applying higher arc power, larger cleaning arc power offset, and longer cleaning time. It then concentrates on compensating the offset due to the gravity force by applying lower arc power, smaller cleaning arc power offset, and shorter cleaning time. The study also reveals the importance of controlling the rotation of the fibre and the temperature distribution of the fibre tip. Different settings of the parameters will produce different shapes of the microprobe. With the combination of the parameters specified in table 1, an optimal shape of microprobe has been achieved after five cleaning cycles. An in-process dimensional control system has also been designed to make the on-line measurement of the probe geometry possible, with resolution to 0.19 μm, so that the fabrication and measurement processes remain in the same coordinate system. Measurement results show that a diameter close to 340 μm, a roundness about 6 μm, and an offset distance of less than 3 μm of an optical fibre ball tip can be achieved.

As many mesoscale to microscale parts have been fabricated by MEMS, energy beam lithography, and microtool machining processes in recent years, the side wall dimension of those components are not easily measured by optical or other non-contact instruments [16]. The microcontact probe technique could provide a possible solution to this problem. The fabrication of a suitable microball tip to allow the probe to engage into a high aspect ratio hole or groove is a basic requirement to produce a good contact probe. This research has developed a low cost and in-process system to make ball tip fabrication possible in a normal laboratory.

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References

[1] Cuche E, Marquet P and Depeursinge C 2000 Spatial filtering for zero-order and twin-image elimination in digital off-axis holography *Appl. Opt.* **39** 4070–5

[2] Liang S 2004 Machining and metrology at micro/nano scale, keynote speech *Proc. 1st ICPT (Hamamatsu, Japan, June 2004)*

[3] Yamamoto M, Kanno I and Aoki S 2000 Profile measurement of high aspect ratio micro structures using a tungsten carbide micro cantilever coated with PZT thin films *Proc. 13th Int. Conf. on Micro Electro Mechanical System* pp 23–7

[4] Yu Z, Masuzawa T and Fujino M 1998 Micro-EDM for three-dimensional cavities development of uniform wear method *J. CIRP Ann.: Manuf. Technol.* **47** 169–72

[5] Sheu D Y 2005 Micro-spherical probes machining by EDM *J. Micromech. Microeng.* **15** 185–9

[6] Sheu D Y 2004 Multi-spherical probe machining by EDM: Combining WEDG technology with one-pulse electro-discharge *J. Mater. Process. Technol.* **149** 597–603

[7] Deladi S, Iannuzzi V J and Schreuders H 2006 Carving fiber-top optomechanical transducers from an optical fiber *J. Micromech. Microeng.* **16** 886–9

[8] Guijun J, Schwenke H and Trapet E 1998 Opto-tactile sensor for measuring small structures on coordinate measuring machines *Proc. 18th ASPE* pp 25–8

[9] Muralikrishnan B, Stone J A and Stoup J R 2006 Fiber deflection probe for small hole metrology *Precision Eng.* **30** 154–64

[10] Ji H *et al* 2005 Concept design of a novel tactile probe tip for down scaled 3D CMMs *SPIE Microelectronics, MEMS, and Nanotechnology (Brisbane, Australia, December)* vol 6037 paper No 28
[11] Halfpenny D R and Kane D M 1996 Electric-arc cleaning of optical-fiber endfaces *J. Appl. Opt.* **35** 4516–7
[12] Hatakeyama I and Tsuchiya H 1978 Fusion splices for optical fibers by discharge heating *J. Appl. Opt.* **17** 1959–64
[13] Tachikura M 1984 Fusion mass-splicing for optical fibers using electric discharges between two pairs of electrodes *J. Appl. Opt.* **23** 492–8
[14] Quan C, Wang S, Tay C J, Reading I and Fang Z P 2003 Integrated optical inspection on surface geometry and refractive index distribution of a micro lens array *Opt. Commun.* **225** 215–22
[15] Wang S, Quan C, Tay C J, Reading I and Fang Z P 2004 Measurement of a fiber end surface profile using phase-shifting laser interferometry *Appl. Opt.* **43** 49–56
[16] Fan K C *et al* 2006 Development of a low cost micro-CMM for 3D micro/nano measurements *Meas. Sci. Technol.* **17** 524–32
[17] Yin D C, Wakayama N I, Harata K, Fujiwara M, Kiyoshi T, Wada N, Arai S and Tanimoto Y 2004 Formation of protein crystals (orthorhombic lysozyme) in quasi-microgravity environment obtained by superconducting magnet *J. Cryst. Growth* **270** 184–91