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REVIEW

Ball Tips of Micro/Nano Probing Systems: A Review

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Abstract To satisfy the measuring demands for the micro components of the industry, micro/nano probing systems with various ball tips have been developed. However, most of them cannot be used to measure the real micro geometrical features high precisely because the parameters of the ball tips are not appropriate. The ball tips with a diameter of less than 100 μm, a sphericity and eccentricity of far less than 1 μm are required urgently. A review on the state-of-the-art of ball tips of micro/nano probing systems is presented. The material characteristics and geometric parameters of now available ball tips are introduced separately. The existing fabrication methods for the ball tips are demonstrated and summarized. The ball tips' future trends, which are smaller diameter, better sphericity and smaller eccentricity, are proposed in view of the practical requirements of high-precision measurement for micro geometrical features. Some challenges have to be faced in future, such as the promotion and high-precision measurement for the small ball tip's sphericity and eccentricity. Fusion method without the gravity effect when the molten ball tip solidifying is a more suitable way to fabricate a small diameter ball tip together with a shaft.

Keywords Ball tip · Probe · Micro/nano CMMs · Micro components

1 Introduction

Since 1980s, ultra-precision machining, as one of the core technologies of nanometer technology, has been constantly improved, thus promoting the rapid progress and development of various new disciplines, such as micromachines and micro-electromechanical systems (MEMS). Currently, precision optical components, microelectronic devices, and MEMS devices are produced in a wide range [1–3]. The minimum size of the ultra-precision machining technology devices is up to 1 μm, the highest machining dimension precision is up to 10 nm, and the surface roughness is up to 1 nm [4, 5]. Consequently, the geometric dimensions of these micro devices need to be measured by high-precision micro/nano-measuring instruments.

High-precision micro/nano-measuring instruments comprise two types, namely, non-contact optical measuring instruments and contact measuring instruments. Concerning non-contact optical measuring instruments, the optical beam is used as a probe. The receiver can then obtain the surface topography data of the measured device according to the reflected light [6]. The widely used non-contact micro/nano optical measuring instruments currently include atomic force microscope, scanning tunneling microscope, white-light interferometer, and holographic digital micro-scope [7–10]. The resolution of this type of optical measuring instrument is in the range of nano- to pico scales. The optical measurements have many advantages, such as high measuring speed, high vertical resolution, and non-destruction. Their disadvantages include the

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following: (1) small measuring range; (2) affected by the tested material and diffraction limit; (3) cannot measure the features with high aspect ratio, such as deep holes, lateral-walls and micro grooves.

On the contrary, contact type measuring instruments show powerful functions under the circumstance. The probe of contact measuring instruments makes physical contact with the measured device and generates a physical deformation instantaneously. The sensor detects the physical deformation and transfers it into electrical signals, which are calibrated and output 3D surface data. The contact measuring instruments have the characteristics of measuring a large-angle profile. At present, the high-precision contact measuring instruments are mainly CMMs.

The definition of micro/nano CMMs was first proposed by Takamasu(*Tokyo University, Japan*) to measure the sizes of micro-holes and microgrooves. According to the definition, the specifications of micro/nano CMMs should be 1/100 to 1/1000 of the ones of the traditional CMM [11, 12]. Fig. 1 illustrates the concept of the micro/nano CMM. In order to achieve high-precision metrology of micro/nano CMMs, the probing head needs a highly precise ball-ended stylus tip with accuracy in the sub-micro order. The use of a probe is a key technique for high-precision measurement and such a probe is one of the core components of micro/nano CMMs [13, 14]. In this study, the core-sensing component of probe comprises ball tip and probe shaft, as shown in Fig. 2. The CMM performance depends considerably on the parameters of the ball tip, such as sphericity, diameter, and material. Therefore, a ball tip with a small diameter, high sphericity, and small eccentricity plays a crucial role in improving the accuracy of micro/nano CMMs.

2 Material and Application of Ball Tips

The common probe ball tips are made of ruby, glass fiber, and tungsten carbide. The characteristics of each material and its applications are reviewed as follows.

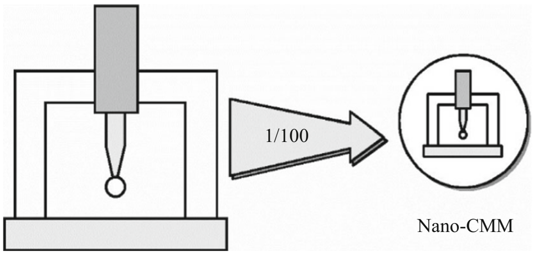


Fig. 1 Concept of the nano CMM

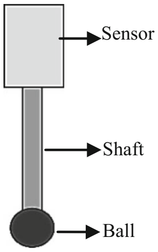


Fig. 2 Schematic diagram of a traditional probe

2.1 Ruby

Ruby is one of the hardest materials known. This material also has a good surface finish and excellent compressive strength and collision resistance. However, if the measured object is made of a high-strength aluminum material, a phenomenon called adhesive wear will happen during the touching process. The surface of ruby may also be worn when the measured material is cast iron. The minimum diameter of the synthetic ruby ball can be 0.3 mm, and its precision can reach IT5.

Ruby is a good candidate as the material for CMM probe by many research institutions, such as the Triskelion Probe of *IBS Precision Engineering* [15, 16], the 3D probe based on silicon thin film of *Physikalisch-Technische Bundesanstalt (PTB)* [17–19], the contact probe of *Hefei University of Technology(HFUT)* [20–22], the high-precision micro/nano CMM (M-CMM) of *the Advanced Industrial Science and Technology(AIST)* [23, 24], the Zeiss F25 probe [25] and the 3D probe of *MEATS* [26].

2.2 Glass Fiber

Glass fiber has many advantages, such as low price, high elasticity coefficient, and great rigidity. High elongation in the elastic limit and high tensile strength contribute to large attack energy absorbed. Glass fiber is also widely used as the material of the probe, such as the large-scanning-range contact probe of *HFUT* [27], the PTB fiber probe [17–19], the Fiber Deflection Probe of *the National Institute of Standards and Technology(NIST)* [28–30], the probe for large-scale dimensional measurement from *Tohoku University* [31], the static tri-switches tactile probe from *National Taipei University of Technology, China(NTUT)* [32] and the high-sensitivity optical touch trigger probe of *the University of South Australia(Unisa)* [33].

2.3 Silicon Nitride

Silicon nitride is a hard and wear-resistant material, which can be processed into the ball with high-precision surface polishing. Adhesive wear will not happen because silicon nitride and aluminum material will not attract each other. However, silicon nitride can be easily worn when the probe sweeps the steel surface. It is used in the micro probe of *National Physical Lab(NPL)* [34–36].

2.4 Tungsten Carbide

The hardness of tungsten carbide is similar to that of diamond. Nevertheless, given that tungsten carbide contains carbon and tungsten, air chambers will appear and make it fragile. Tungsten carbide has high hardness, abrasion resistance, refractory properties, filament, low wear rate, and toughness. The application of this material is presently relatively rare.

2.5 Alumina

Alumina has high strength, high hardness, high wear resistance, high melting point, high temperature stability, and resistance to corrosion. However, it can only be found in traditional CMM nowadays.

A variety of CMM' probes have been reported in the literature, whose materials and geometric parameters are summarized in Table 1.

3 Fabrication Methods of Ball Tip

The present fabrication methods for ball tip can be categorized into adhesion method, material removal method and fusion method.

3.1 Adhesion Method

A hybrid gluing and assembling process on micro electrical discharge machine (EDM) has been carried out to produce micro ball tips for micro CMM's probing heads by SHEU, et al [37, 38]. A micro electrode with a diameter of 40 μm could be easily fabricated using the wire electro-discharge grinding (WEDG) technology. In order to increase the adhesion strength, an arc-shaped cavity was fabricated in front of electrode on the same micro EDM. Epoxy glue with a layer of about 0.05 mm thickness was sprayed on the metal plate. The epoxy glue adhered to the electrode easily through the low-voltage detecting function of EDM. After completion of step 1 and step 2, the electrode feeds down toward the micro ball,which was held on the gripper manipulator,in order to accomplish position alignment. The gluing and assembling processes are shown in Fig. 3. Under the observation of charge-coupled device(CCD) 1 and CCD2, a micro glass ball with a diameter of 70 μm could be glued onto the electrode with a diameter between 40 μm and 50 μm successfully. The experimental results show that the roundness of the largest micro ball tip with a diameter of 70 μm could be as small as 0.613 μm. The adhesion strength of the gluing stylus tip is approximately 12 mN.

Fig. 4 shows the photograph of the shear-mode micro probe. The micro stylus is composed of a micro glass shaft and a micro glass ball. The stylus shaft is made of a capillary glass tube, which is thermally pulled by using a commercially available glass pipette puller. A micro glass ball with a nominal diameter of 52.6 μm is attached to one

Table 1 The materials and geometric parameters of several typical probes

Institute (item name)	Material of probe ball	Material of probe shaft	Diameter of probe ball *d*/μm	Length of probe shaft *l*/mm
IBS (Triskelion probe)	Ruby	Tungsten carbide	500	8.5
PTB (ruby probe)	Ruby	Glass fiber	300	5
Zeiss (F25)	Ruby	Glassy carbon	120	4
MEATS	Ruby	NA	100–1000	NA
HFUT	Ruby	Tungsten	500	10
AIST (M-CMM)	Ruby	Tungsten carbide	30	2
Eindhoven probe	Ruby	Titanium	1000–4000	30
NIST	Glass fiber	Glass fiber	75	20
HFUT	Glass fiber	Glass fiber	300	10
PTB (Werth fiber probe)	Glass fiber	Glass fiber	25	NA
Unisa	Glass fiber	Glass fiber	300–400	5
Tohoku University	Glass fiber	Glass fiber	52.3	NA
NTUT (Static Tri-Switches Tactile Probe)	Glass fiber	Glass fiber	120	NA
NPL	Silicon nitride	Tungsten carbide	300	1–3

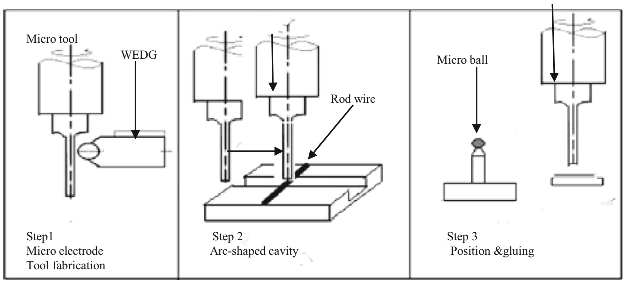


Fig. 3 Micro glass ball-ended stylus gluing and assembling process

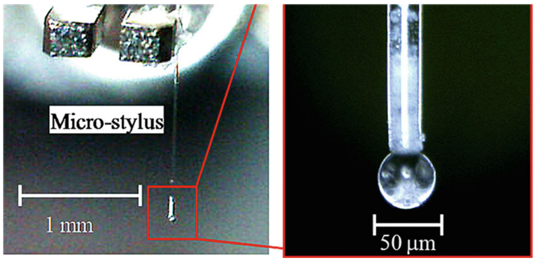


Fig. 4 Photograph of shear-mode micro-probe

end of the glass micro-stylus by thermosetting resin [31]. The optical fiber stylus, which was developed by the *NIST* and *the University of North Carolina*, was also fabricated by this method [28–30].

In order to scan the surface appearance, two types of ball tips were manufactured by GAO Wei from *the Tohoku University* [39]. The probe shafts are made from glass tube and stainless steel separately. Fig. 5(a) shows the first type of probe, which is composed of a glass probe shaft and a glass ball tip. The probe shaft is made of a capillary glass tube that is thermally pulled by using a commercially available glass pipette puller. The ball tip is made by the fusion method.

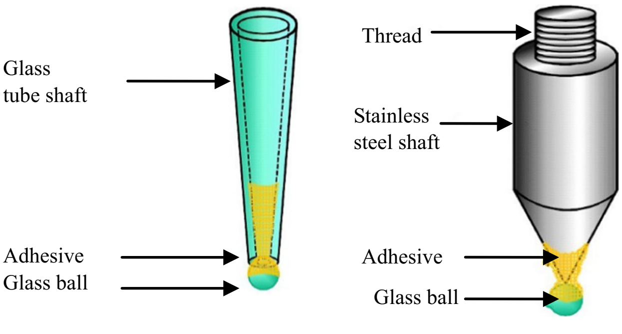
High-precision glass ball tip with a nominal diameter of 52.3 μm was glued to the front end of the thin needle bar by thermosetting resin. The adhesion process requires the use of precision assembly system to accurately locate the ball tips and probe shafts. Fig. 5(b) shows the stainless steel probe. Its assembling method is similar to that of the glass probe. The only difference is that the material of probe shaft is stainless steel.

The low-force 3D touch probe from *the Federal Institute of Metrology METAS* also adopts the same adhesion method [26]. The ball tip and probe shaft were first fabricated separately. The probe shaft was then inserted into the blind hole on the ball tip and fixed in the blind hole with adhesive. The views about the extended set of probes ranging from 1 mm to 0.125 mm are shown in Fig. 6. Nearly all probing styluses with a ruby ball tip in the market are made by this way. The diameters of the most advanced ruby ball tip in the sale are at least 300 μm.

The disadvantages of the adhesion method lie in that the sphericity of ball tip will be reduced when the blind hole is processed on the ball tip or the ball is stuck to the probe shaft. When the diameter of the ball tip becomes small, the eccentric error deviation between the ball center and the probe shaft central line is difficult to be reduced because of the adhesive-bonded processing. In addition, the dynamic triggering force should be smaller than adhesion strength when the ball tip touches micro objects. Some epoxy will drip onto micro ball surface, resulting in reduced profile accuracy.

3.2 Material Removal Method

In this method, a round bar is used as a probe shaft, which is machined directly a ball tip at the end of the probe shaft by material removal and melt condensation polymerization. This method mainly includes two types. One is the electrical discharge machining(EDM) combining wire electro-discharge grinding(WEDG) with one-pulse electro-discharge(OPED). The other one is the micro electro-chemical machining (micro-ECM)-OPED.



(a) Glass tube probe **(b)** Stainless steel probe

Fig. 5 Two types of glass ball probes

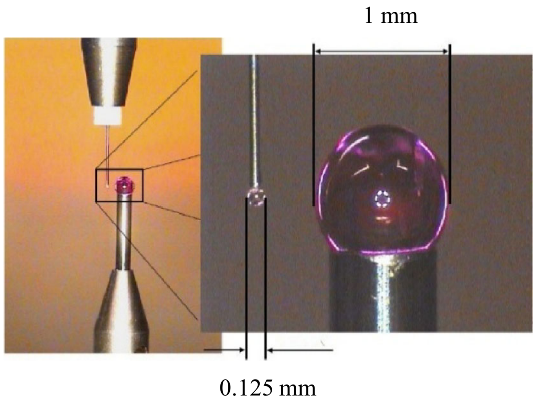


Fig. 6 Extended set of probes ranging from 1 mm to 0.125 mm

3.2.1 *EDM Combining WEDG with OPED*

Micro-structures have been manufactured at the end of metal bar with the development of WEDG [40]. Based on the principle of electric discharge, SHEU proposed a hybrid technique combining the WEDG technology with OPED [41–43]. Fig. 7 shows the fabrication procedure of the WEDG-OPED. The tungsten wire is rough machined from the diameter of 300 μm to 30 μm with WEDG. The end of the tungsten wire melts with OPED and is fabricated into a tungsten ball with a diameter of 40 μm. The experimental results suggest that the deviation in diameter and roundness tolerances of micro ball tips are about 1 μm and 3 μm, respectively.

However, the disadvantages are as follows. Not only the surface roundness of the machined micro-spherical stylus tip is not good enough, but the machining time is too long and the cost of processing is heavy because the nature of this method is the denudation of a layer by a layer. In addition, the cylindrical electrode, which has a diameter under 15 μm that makes it become a limited problem to fabricate a micro-spherical stylus tip in the after process, is difficult to machine. Sphericity is difficult to be controlled as well.

3.2.2 *Micro-ECM-OPED*

MENG Dong proposed a new technology combining micro-ECM and OPED to fabricate micro ball tip in micro-ECM tool [44]. The processing device diagram of micro-ECM-OPED is shown in Fig. 8. A micro cylindrical electrode was first manufactured with micro-ECM. A micro-spherical stylus tip was then fabricated in the front of the cylindrical electrode. The experimental results show that a micro ball tip with a diameter of 30 μm has been fabricated at the end of a tungsten shaft with a diameter of 15 μm.

A hybrid manufacturing process of ECM and OPED to fabricate micro CMM's tactile ball tips has also been carried out by SHEU [45]. The schematic structure is shown in Fig. 9. The isolated small tank was equipped in an EDM table combined with ECM. The shaft-pin can feed downward through the small hole of stainless plat, which was fixed to the cathode, in order to increase the dimensional controllability. The structure determines that chemical erosion occurs only surrounding the small hole where the alkaline electrolyte such as NaOH and electro field distributed. By the CCD image measurement method and adjusting the parameters of ECM, the main target diameter of micro pin can be processed into approximately 40 μm. As illustrated in Fig. 10, the micro ball tips with a diameter of 63 μm could be produced easily with single-pulse electro discharge after micro shaft-pin fabrication on the same machine. The sphericity deviation of ball tips is approximately ± 2 μm.

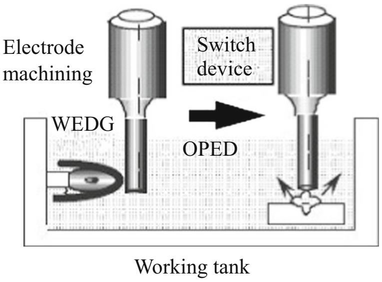


Fig. 7 Procedure of the WEDG-OPED

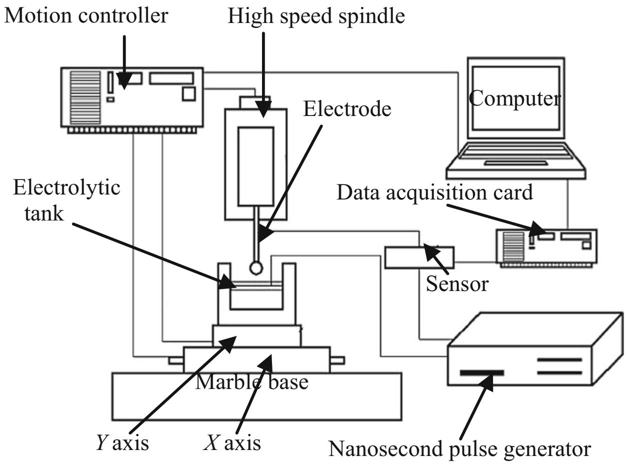


Fig. 8 Processing device diagram of micro-ECM-OPED

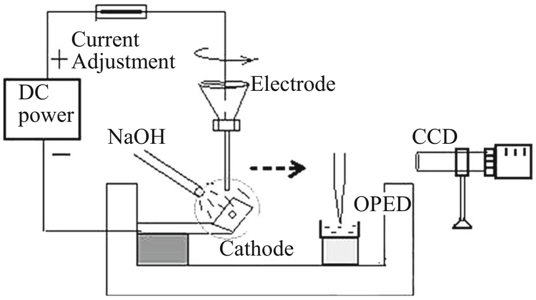


Fig. 9 Micro spherical stylus tip fabrication by hybrid ECM and OPED processes on micro EDM machine

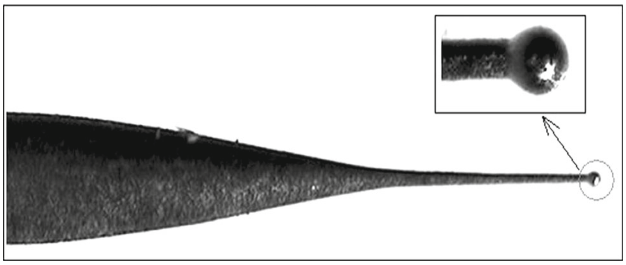


Fig. 10 Micro spherical stylus tips by ECM and OPED processes

3.3 Fusion Method

The fusion method is mainly to form a ball tip by fusing the shaft. This method includes arc discharge, laser beam machining(LBM), and oxy-propane gas torch.

3.3.1 Arc Discharge

A new processing method was developed, adopting commercial single-mode (SM) fiber fusion splice and glass fiber, to fabricate optical fiber ball tip by FAN from *the National Taiwan University, China* [46–49]. Based on the principle of arc discharge of fusion splice, the end of the glass fiber would be melted in a short time [50, 51]. Owing to the physical phenomenon of the surface tension and contraction, the melt part would be solidified into a micro ball. The image of the actual fabrication of ball tip is shown in Fig. 11. The experimental system added a 3D moving platform to adjust the position of the optical fiber, optical fiber fixture, and rotating platform. The “Taguchi” was utilized to optimize the parameters of the optical fiber-fusing process in experiments. The geometric characteristics of the optical fiber ball tip could be controlled. The micro 3D optical fiber probe of micro/nano contact measurement could be attained. In this experiment, a single mode glass fiber, with a diameter of 125 μm after removing the coating layer, was used as the raw material. The experimental results show that the optical ball with a diameter of 310 μm can be attained by the arc discharge at the electrode tip. The sphericity error is less than 1 μm. The offset distance between the ball center and the stem central line is less than 1 μm.

An integrated optical fiber micro ball is also fabricated at the end of the optical fiber tape by HUANG Qiangxian from *HFUT* [52]. The structural diagram of the experimental device is shown in Fig. 12. A single mode optical fiber, which has a diameter of 125 μm, was processed into a parabolic object with the tapering technique. A micro ball with a diameter within 100 μm could then be attained at the end of the optical fiber tape by melting method. The sphericity is 0.5 μm. The 2D eccentric error deviation between the fiber shaft central line and the micro ball tip center is less than 0.65 μm.

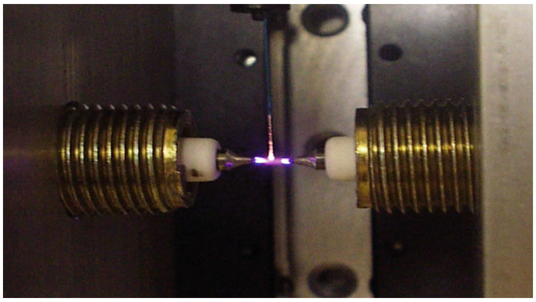


Fig. 11 Image of the actual fabrication of ball tip

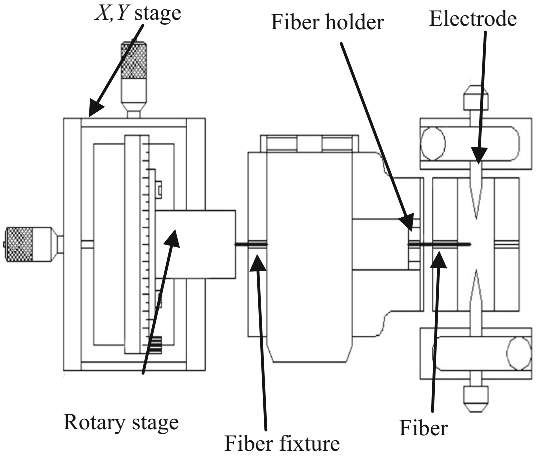


Fig. 12 Experimental arrangement of National Taiwan University, China

The advantage of this approach is that the fiber end can be melted easily in a short duration of time. The heating area can be limited in the end region, and the discharge intensity can be controlled by the current size. Low cost, high efficiency, and clean discharge are also concerned.

3.3.2 LBM

LBM is a non-traditional subtractive manufacturing process in which a laser beam is directed toward the work piece for machining. This process uses thermal energy to remove material from metallic or nonmetallic surfaces.

A micro glass fiber ball with a high degree of roundness was fabricated by FU Qiang of *the Saitama University* fabricated with LBM [53, 54]. The schematic of the LBM-processed micro ball is shown in Fig. 13. Owing to the small diameter of the laser beam, a micro ball could be produced at the front end of the glass fiber. When the laser beam was irradiated to the front end of the glass fiber, the

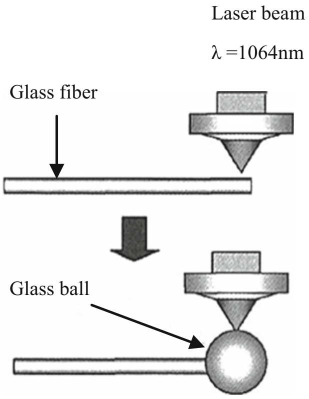


Fig. 13 Schematic of the LBM-processed micro ball

temperature of the front end of the glass fiber could reach 1300 °C or above, and the front end of the glass fiber is changed. At this point, the melting glass fiber formed a liquid droplet because of surface tension. After cutting off the laser, the liquid droplet was cooled into micro solid glass balls in a very short duration of time. In this experiment, Nd: YAG (Nd: $Y_3Al_5O_{12}$) laser was used as heat source, the laser wavelength is 1064 nm, the maximum output power is 18 W, and the laser beam diameter is approximately 31 μm. The minimum diameter of the micro sphere produced by the laser method is 39.48 μm, the maximum diameter is 39.38 μm, and the true roundness is 50 nm. VAIDYA Anil and HARRINGTON James A from *the Rutgers University* also fabricated a micro ball at the end of silica fiber by using this method [55, 56].

The LMB method has the following advantages: high energy density, fast processing speed, and local processing. No influence or effect exists on the non-laser irradiation site.

4 Future Trends and Challenges

Substantial challenges need to be addressed to expand the use of micro contact coordinate metrology for a large number of industrial applications.

The majority of commercially available micro/nano CMMs are equipped with stylus tips of approximately 125 μm in diameter [32]. Such a size would render a micro/nano CMM incapable of measuring the micro device whose size is below 125 μm. Hence, a ball tip with a smaller diameter and higher sphericity should be developed.

As the ball becomes significantly small, probe integration is especially important because the offset distance between the ball center and the probe shaft central line by gluing is difficult to be reduced. As a result, the probe integration is the development trend.

Although many small ball tips are used for commercial micro/nano CMMs, its sphericity error of straight morphology cannot be given. Up to now, only the actual radius of the ball tips could be measured, but in the practical cases of measuring, the sphericity deviation must be considered because of the imperfect shape. The sphericity measurement is thus important. When the ball diameter becomes considerably small, the influence of sphericity error of actual measurement becomes obvious. In the future research, therefore, the sphericity measurement with high accuracy of the micro ball tip is also a challenge.

Given that the end of the probe shaft is in the molten state during the ball tips fabrication, the melting part is vertical to the gravity direction and then solidifies. Therefore, the gravity error causing non-round shape of the ball tips has to be compensated. In future research, studying gravity compensation will be a significant issue. The precision of the ball tip will remarkably improve after eliminating the influence of gravity.

5 Conclusions

(1) The measurement for the micro geometrical features requires the ball tips with a diameter of less than 100 μm, a sphericity and eccentricity of far less than 1 μm.
(2) The materials of the current ball tips include ruby, glass fiber, silicon nitride, tungsten carbide and alumina. The fabrication methods of the current ball tips include adhesion, material removal and fusion. It is more convenient to fabricate a monolithic stylus with a small diameter ball tip by melting a wire of glass fiber or tungsten carbide.
(3) Much more works need to be conducted in future, such as the measurement for the small ball tip's sphericity and eccentricity, the compensation for the negative effect caused by gravity before the liquid state ball tip solidifying.

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