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Fabrication optimization of a micro-spherical fiber probe with the Taguchi method

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Abstract
This paper describes a low-cost and efficient method to fabricate a micro-spherical fiber probe using a commercial fiber fusion splicer based on the Taguchi method. Based on the principles of electric arc discharging energy absorption and the surface tension phenomenon, a microsphere can be formed at the end of the optical glass fiber. The optimum parameters to control the geometrical accuracy of the probe were selected according to the Taguchi method with the signal-to-noise ratio and the analysis of variance processes. From the results, a spherical probe about 310 μm in diameter with less than 1 μm in roundness error could be produced using a 125 μm diameter single-mode optical fiber. The offset distance between the ball center and the fiber stylus central line due to the gravity effect could also be controlled to less than 1 μm after optimization of the parameters. The microprobe can be used for the contact-type stylus head to enhance the resolution and extend the capability of measuring meso- to micro-objects.

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

1. Introduction

Dimensional inspection of any workpiece is carried out by contact- or non-contact-type measurement. In the contact type, the size of the tip radius of the probe depends on the size and geometry of the measured part, while the sphericity and center offset of the tip ball will affect the measurement accuracy. The contact probe is a key component in the coordinate measuring machine (CMM). The CMM is a popular device that makes the dimensional inspection of sophisticated workpieces possible. However, with the ongoing miniaturization in mechanical and optical products there is an urgent demand for measurements of meso- to micro-scaled parts. Even with all the advancements in non-contact three-dimensional measurement technologies and the ability to accurately measure into the submicron range [1], there is still a need for contact probing to achieve the true three-dimensional measurement on microstructures, such as the edge and surface detection of the side wall of a high aspect ratio hole, step height or groove. The contact probe tip of current CMMs is manufactured by attaching a spherical metal or ruby ball to a metal stem. The smallest ruby ball is about 0.3–0.5 mm in diameter [2]. As the ball becomes smaller, the sphericity and center offset of the ball to stem are difficult to be proportionally downscaled. The design and manufacturing of a microtouch trigger probe in a single piece is necessary to satisfy the aforementioned requirements.

Fusing the stem end to form a spherical probing tip can minimize the errors introduced by the traditional assembling process. Microelectronic mechanical system (MEMS) based microprobes are expected to have superior feasibilities, but are expensive to manufacture and the material is restricted to a silicon substrate. One feasible way is to use the micro-electro

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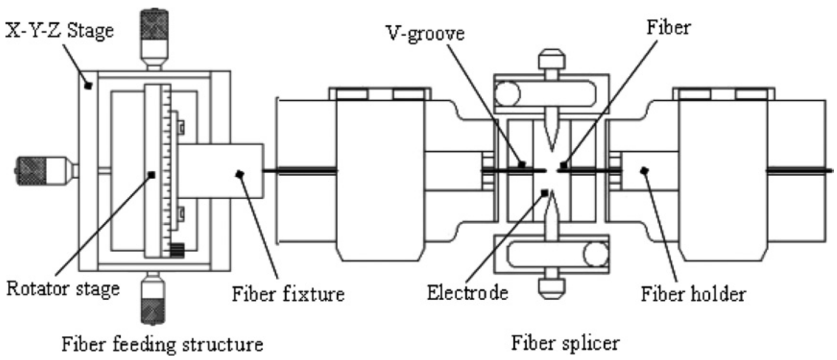

Figure 1. A fiber fusion splicer and fiber feeding structure.

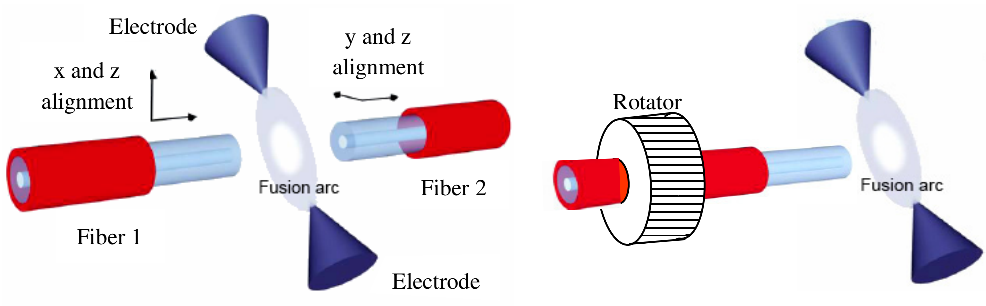

Figure 2. Principle of electrode discharging: (*a*) principle of fusion splicing, (*b*) principle of the fusion fiber probe.

discharge machining (micro-EDM) method to manufacture complex 3D parts and microprobes [3, 4]. However, it 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 micro-spherical probes, has been proposed recently [5, 6], but the geometrical accuracy needed for the measurement requirements has not been achieved. Direct fabrication on the fiber end to form a monolithic microstructure as a particular sensor is another possible approach [7, 8], but the deviation of the probe center from the centerline of the stylus has not been overcome. Various technologies for the formation of an integrated optical fiber tip based on the methods of fusion have been reported, but the fabrication process of a good fiber probe is not clear [9].

This paper describes an advanced approach based on previous work [8]. With a similar experimental setup, the microball tip is directly fabricated on an optical fiber utilizing the cleaning feature of a commercial fiber fusion splicer. The forming geometry of the sphere can be monitored with a vision system *in situ*. The dimension and the quality of the fused fiber tip are affected by several process parameters, and different combinations of these parameters will yield different results. The parameters include the selection of arc power, cleaning arc power offset, cleaning time. It requires intermittency for dimension check to control the ball droop due to microgravity. It was very time consuming for iterative fusion of the probe and checking its dimension. Some human-induced errors are the major causes for large roundness and center offset errors. In this study, the Taguchi method is employed. A robust design for improving the function of the process results in the optimal ball tip geometry. The details are addressed in the following.

2. Experiments

2.1. Optical glass fiber and fusion splicing

The smaller the diameter of the fiber, the smaller the ball tip can be made. The single mode (SM) glass fiber with 125 μm diameter was selected to manufacture the ball tip. This material is easily obtainable from the communication market. The glass fiber also has sufficient mechanical strength to perform contact measurements. The viscosity of pure vitreous silica is a function of the temperature, the straining point of the glass fiber is 1108 °C, the annealing point is 1190 °C and the softening point is about 1670 °C [10]. When the temperature rises up to the softening point, the fiber tip melts instantaneously. Due to the surface tension, the localized melting part of the fiber starts to form a spherical tip gradually during solidification.

A fusion splicer for single mode fiber (FITEL S199S model) is the basic apparatus employed in this experiment, as is shown in figure 1. The left and right V-grooves are used to align the fibers. The left and right fiber clamps hold the fibers in the grooves. The electrodes stimulate an electric arc that heats up the fibers so they will fuse, and the region where the splicing actually takes place is shown in figure 2. The fiber fusion splicer provides the cleaning feature to remove any contaminant from the fiber end and the arc check feature to optimize the splicing conditions [11]. The arc check function is the pre-fusion procedure, during which the fiber ends are

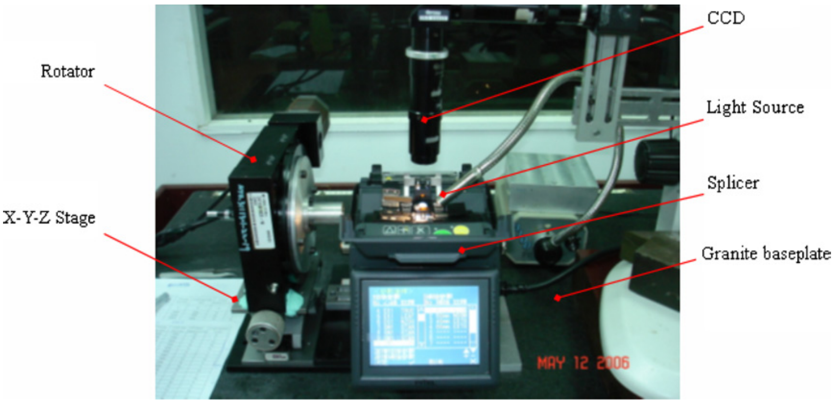

Figure 3. Prototype of the experimental set-up.

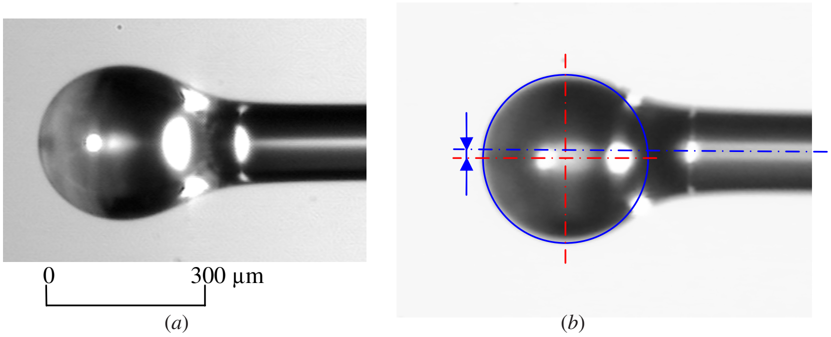

Figure 4. Bad ball formation: (*a*) elliptical shape, (*b*) center offset.

heated by absorbing the electric arc discharging power to soften the joining fiber ends but not splice one SM fiber to the other. If the pre-fusion temperature is high enough to cause excessive fiber-end deformation and change the glass geometry, the micro-sphere can be formed feasibly at the end of the fiber tip.

2.2. Experimental setup and procedure

The fiber fusion splicer was modified to conduct the experiments of fusing a fiber end effectively and accurately by adding an *XYZ* linear stage at one side of the groove to precisely position the fiber and a rotary stage to rotate the fiber to compensate for the gravity effect of the formed ball tip during the fusion process. The other side of groove was not in use. In addition, a CCD image system is equipped to in-process monitor the fiber position and the geometrical quality of the growing microball. Figure 3 shows the photo of the prototype setup. The precise dimension of the probe is measured by an external image vision coordinate measuring machine, which has higher resolution and accuracy than the equipped *in situ* image system.

The original operation of a ball tip formation on the optical fiber consists of three steps: the fiber preparation process, the fiber loading process and the fiber formation process [8]. It is, however, necessary to measure the ball profile during the fusion cycles. In this study, the three operational steps are modified to the fiber preparation process, the ball formation process and the probe measurement process respectively. The first step actually combines the fiber preparation and loading processes as before, which includes the stripping-off of the fiber, cleaning, cleaving, loading and clamping. The second step is to fabricate the ball tip by setting parameters of arc power, cleaning arc power offset and cleaning cycle, which have been proved to be important factors to form the microball tip [8]. A good spherical probe for precision measurement requires three critical characteristics: uniform ball diameter, good roundness and small center offset of the ball from the stylus. The first two characteristics can be achieved by adjusting the arc discharging parameters. Too low pre-fusion temperature may result in an elliptical ball tip, as is shown by a CCD image in figure 4(*a*). On the other hand, too high pre-fusion temperature and long fusing duration will increase the offset of the ball to the fiber stem attributed to the influence of the gravity effect during the ball formation, as is shown in figure 4(*b*). Therefore, the third step of process intermittent measurement is necessary to monitor the geometric profile of the probe after the second step with the image-version-type coordinate measuring machine. It is then able to estimate the bending direction and the offset value of the current probe. The second step is then repeated with proper parameters, with proper parameters after rotating the fiber stylus opposite to the bending direction. Steps two and three shall be iterated until a fine probe with a good roundness and center offset is achieved.

With such a procedure, it is time consuming to get a good probe with both of its roundness and center offset within 1 μm. Furthermore, the image version coordinate measuring machine is independent. The fiber has to be removed out

Table 1. Manufacturing parameters and their levels for the Taguchi method.

Level	Fusing times (180°) Stage 1 (N_1) A	Fusing times Stage 2 (N_2) B	Arc power (units) Stage 1 (P_1) C	Arc power (units) Stage 2 (P_2) D	Cleaning arc power offset (units) Stage 1 (C_1) E	Cleaning arc power offset (units) Stage 2 (C_2) F	Cleaning time (ms) Stage 1 (T_1) G	Cleaning time (ms) Stage 2 (T_2) H
1	2	4	170	90	170	200	10 000	400
2	3	5	200	100	200	215	20 000	500
3		6	230	110	230	230	30 000	600

of the holder after each fusion cycle to measure the current profile of the probe. One crucial influence is that the clamping force, when re-engages the fiber into the holder each time, will induce friction so as to alter the ball droop orientation. As a result, the rotating degree of the fiber stylus is not exactly 180°. This is the main cause why the previous work could only control the form and the offset up to several microns [8]. It is not a scientific experiment if its results are not repeatable. Therefore, the Taguchi method was adopted in this study to redesign the experiment.

3. Experiment redesign and results

3.1. Redesign of the experiment

The Taguchi method considers three stages in process development: (1) the system design, (2) the parameter design and (3) the tolerance design. In the system design, engineers use scientific and engineering principles to determine the basic configuration. In the parameter design, the specific values for the system parameters are determined. The tolerance design is applied to specify the best tolerances for the parameters [12]. Among these stages, the parameter design is the key step in the Taguchi method to find the optimal factors which affect the final product quality or cost. To obtain high forming performance in the micro-spherical fiber probe fabrication process, the parameter design approach proposed by the Taguchi method was adopted in this study.

In this study, the factor interaction is not considered, i.e. factors are assumed to function independently. Based on the aforementioned experiments, eight influential fabricating factors were selected, including fusing times (N_1, in times), arc power (P_1, in units), cleaning arc power offset (C_1, in units) and cleaning time (T_1, in ms) in the first step to obtain a spherical tip with required diameter and roundness; fusing times (N_2), arc power (P_2), cleaning arc power offset (C_2) and cleaning time (T_2) in the second step were included to obtain a small center offset. To evaluate these factors, the first factor was considered with two levels and the remaining factors were considered in three levels. The involved factors and their levels are shown in table 1. The total degrees of freedom is $(2 - 1) + 7 \times (3 - 1) + 1 = 16$. These 16 degrees lead to the choice of an L_{18} ($2^1 \times 3^7$) orthogonal array according to Taguchi's suggestion.

If the full factorial experimental design were used, it would require 4374 ($2^1 \times 3^7$) trials for all possible combinations of these factors to get the optimum result. By using the Taguchi orthogonal array L_{18} for an experimental design, the number for trials is reduced to 18-group simple and effective experiments. Table 2 illustrates the orthogonal array L_{18} ($2^1 \times 3^7$) in which 18 runs are carried out to investigate the effects of the eight factors.

Table 2. Experimental layout of an L_{18} ($2^1 \times 3^7$) orthogonal array.

L_{18}	N_1	N_2	P_1	P_2	C_1	C_2	T_1	T_2
1	2	4	170	90	170	200	10 000	400
2	2	4	200	100	200	215	20 000	500
3	2	4	230	110	230	230	30 000	600
4	2	5	170	90	200	215	30 000	600
5	2	5	200	100	230	230	10 000	400
6	2	5	230	110	170	200	20 000	500
7	2	6	170	100	170	230	20 000	600
8	2	6	200	110	200	200	30 000	400
9	2	6	230	90	230	215	10 000	500
10	3	4	170	110	230	215	20 000	400
11	3	4	200	90	170	230	30 000	500
12	3	4	230	100	200	200	10 000	600
13	3	5	170	100	230	200	30 000	500
14	3	5	200	110	170	215	10 000	600
15	3	5	230	90	200	230	20 000	400
16	3	6	170	110	200	230	10 000	500
17	3	6	200	90	230	200	20 000	600
18	3	6	230	100	170	215	30 000	400

3.2. S/N analyses

As an evaluation tool for determining robustness, the signal-to-noise (S/N) ratio is the most important component of a parameter design. In the Taguchi method, the term 'signal' represents the desirable target for good products and the term 'noise' indicates the undesirable value. The S/N ratio is used to measure the quality characteristic deviating from the desired value. The S/N ratio is defined by

$$S/N = -\log(\text{MSD}), \tag{1}$$

where MSD is the mean square deviation of the quality characteristics.

Usually, there are three categories of quality characteristics in the analysis of the S/N ratio, i.e. the smaller the better, the bigger the better and the nominal the best. The probe diameter, roundness and the center offset in this study are the quality characteristics with the objective 'smaller the better'. The mean square deviation for the smaller-the-better quality characteristic is given by

$$\text{MSD} = \frac{1}{n}\sum_{i=1}^{n} y_i^2, \tag{2}$$

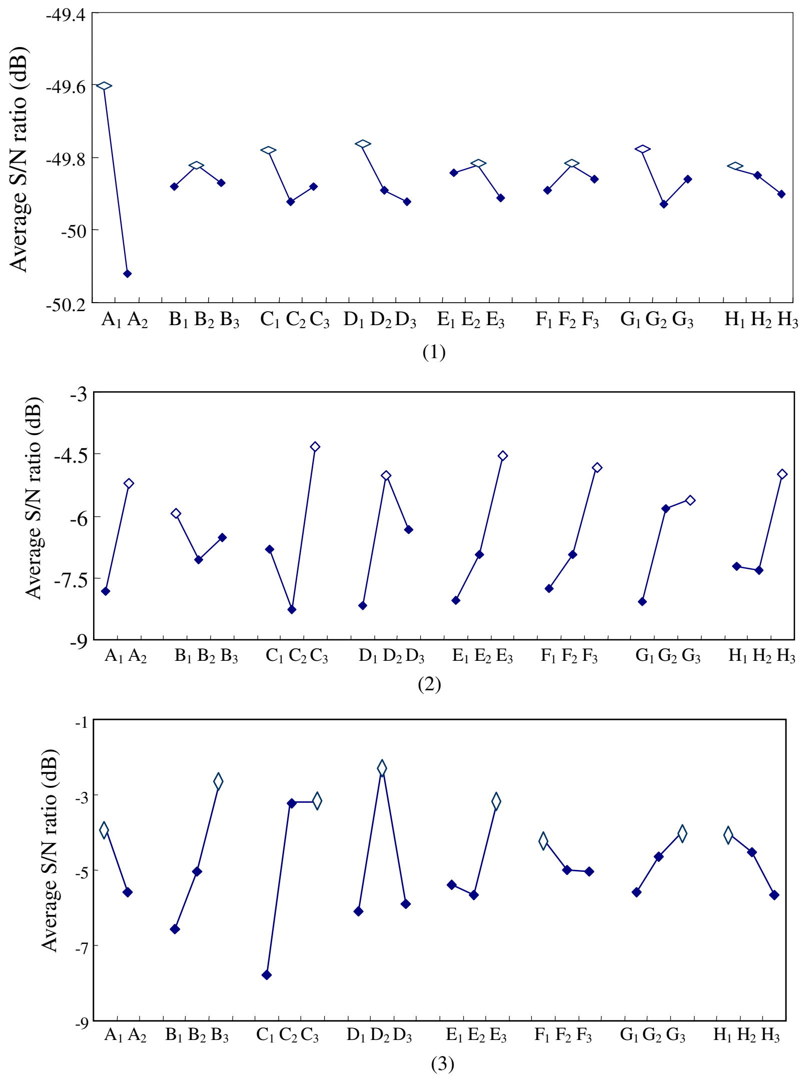

Figure 5. Average S/N ratio responses for probe feature. (1) Average S/N ratio response graph for probe diameter, (2) average S/N ratio response graph for probe roundness, (3) average S/N ratio response graph for probe center offset.

where n is the number of experiments in the L_{18} orthogonal array and y_i is the ith measured value. It is suggested that the quality characteristics are optimized when the S/N response is as large as possible.

After carrying out the experiments and applying S/N analyses, the results of the experiments and S/N ratios of the 18 trial conditions were calculated using equations (1) and (2), as listed in table 3. The average S/N ratio for each level of the fabricating factors is summarized and is called the S/N responses for the probe features. Figure 5 shows the S/N responses for the probe diameter, probe roundness and center offset separately.

In this study, it is the smaller-the-better case, which means that the smallest diameter, smallest roundness and smallest center offset would be the ideal situation. Also, the largest S/N ratio would be preferred. Following these criteria, the graphs in figure 5 were used to determine the initial set of parameters for the following optimum search by the ANOVA analysis, i.e. ($A_1B_2C_1D_1E_2F_2G_1H_1$) for getting a smaller probe diameter, ($A_2B_1C_3D_2E_3F_3G_3H_3$) for getting smaller probe roundness and ($A_1B_3C_2D_2E_3F_1G_3H_1$) for getting a smaller center offset.

3.3. ANOVA analyses

In order to investigate the effects of the forming parameters quantitatively, the ANOVA is carried out. The ANOVA tests for the significant differences between the parameters by comparing variances. It calculates the sum of squares of the difference between the mean S/N ratio and the individual S/N ratio.

The overall mean S/N ratio is expressed as

$$\overline{S/N} = \frac{1}{k}\sum_{i=1}^{k}(S/N)_i, \qquad (3)$$

where k is the number of tests in the orthogonal array and $(S/N)_i$ is the S/N ratio of the ith test. The sum of squares of individual S/N from the mean S/N ratio is

$$SS = \sum_{i=1}^{k}((S/N)_i - \overline{S/N})^2. \qquad (4)$$

Table 3. Experimental results and S/N ratios for diameter, roundness and center offset.

	Average diameter (μm)	Smaller-the-better S/N ratio (dB)	Average roundness (μm)	Smaller-the-better S/N ratio (dB)	Average offset (μm)	Smaller-the-better S/N ratio (dB)
1	293.83	−49.36	5.96	−15.94	5.36	−11.56
2	305.01	−49.69	3.16	−10.08	2.02	−3.73
3	309.10	−49.80	1.19	−0.31	1.58	−5.46
4	293.92	−49.36	2.22	−7.04	2.01	−7.66
5	302.32	−49.61	1.83	−5.48	0.56	3.25
6	306.91	−49.74	2.51	−7.13	1.01	−1.36
7	303.88	−49.65	1.72	−4.70	1.58	−5.05
8	305.65	−49.70	3.54	−11.24	1.15	−1.27
9	297.15	−49.46	2.62	−8.41	1.07	−1.94
10	322.14	−50.18	1.13	−1.83	2.07	−8.31
11	319.63	−50.10	1.99	−6.26	1.89	−6.09
12	322.87	−50.16	0.93	−1.12	1.63	−4.34
13	318.46	−50.10	1.76	−5.64	2.01	−5.57
14	320.08	−50.10	3.49	−11.18	3.06	−10.51
15	316.78	−50.00	1.95	−5.84	2.40	−8.41
16	316.32	−50.00	2.04	−6.33	2.65	−8.49
17	328.04	−50.30	1.64	−5.46	0.99	−0.89
18	321.53	−50.10	1.34	−3.05	0.75	2.22

Table 4. ANOVA for probe diameter, probe roundness and center offset.

	Probe diameter			Probe roundness			Probe center offset		
	Degrees of freedom	SS_i	Contribution P_i (%)	Degrees of freedom	SS_i	Contribution P_i (%)	Degrees of freedom	SS_i	Contribution P_i (%)
A	1	0.270	82.04	1	3.432	9.67	1	1.497	3.73
B	2	0.002	0.64	2	0.640	1.80	2	8.184	20.42
C	2	0.024	7.17	2	8.055	22.69	2	13.862	34.59
D	2	0.005	1.37	2	5.001	14.09	2	9.527	23.77
E	2	0.013	3.80	2	6.486	18.27	2	3.778	9.43
F	2	0.003	0.76	2	4.595	12.94	2	0.477	1.19
G	2	0.011	3.43	2	3.760	10.59	2	1.345	3.35
H	2	0.003	0.79	2	3.5300	9.94	2	1.405	3.50

The sum of squares of $(S/N)_i$ from the mean S/N ratio for the ith factor is

$$SS_i = \sum_{j=1}^{l} T_j \times (\overline{(S/N)}_{ij} - \overline{S/N})^2, \qquad (5)$$

where l is the number of the factor levels ($l = 3$ in this study), T_j is the number of the tests of the ith factor at the jth level and $\overline{(S/N)}_{ij}$ is the mean S/N ratio of the quality characteristic for the ith factor at the jth level. The percentage of contribution of the ith factor is given by

$$P_i(\%) = \frac{SS_i}{SS} \times 100 \qquad (6)$$

The results of the ANOVA for the probe diameter, the roundness and the center offset are shown in table 4. From the contribution percentage, it can be seen that the significant parameters influencing the probe diameter are the fusing times (180°) and the arc power, the critical factors affecting the probe roundness are the arc power and the cleaning power offset of the first stage, and the important factors influencing the probe center offset are the fusing times of the second stage and the arc power of both stages.

3.4. The optimum parameters and confirmation experiments

Based on the S/N ratios and ANOVA analyses, the optimal levels of all the manufacturing parameters' combination were identified. For the diameter required, considering the importance of the factors affecting the probe roundness and the center offset, both of the final manufacturing parameters' combination were found as A_1 (2 times), B_3 (6 times), C_3 (230 units), D_2 (100 units), E_3 (230 units), F_3 (230 units), G_3 (30 000 ms) and H_3 (600 ms).

The confirmation experiment was carried out at the optimum setting of the significant forming parameters. This strategy has been applied to fabricate a number of microprobes. Figure 6 shows the diameters of ten fiber probes, which are repeatable around 314 μm with all the roundness and center offset less than 1 μm. The images of one of the probes viewed at four angular positions are shown in figure 7, and the corresponding measured results are summarized in table 5.

It is clearly seen that the droop of the probe tip and the bending of the fiber have been significantly reduced. This implies that the parameters' design based on the Taguchi method does work to the extent that the existing experimental apparatus can handle. Both the roundness error and the center

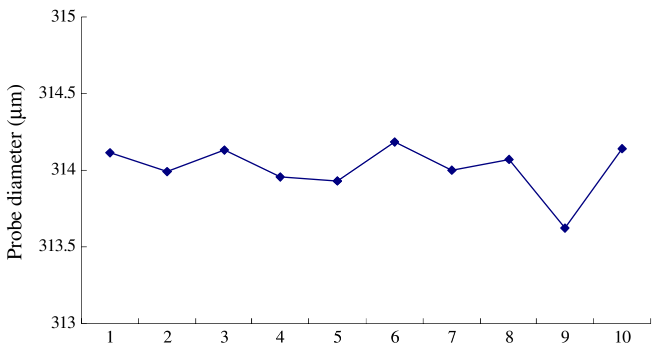

Figure 6. Diameters (in μm) of ten fiber probes.

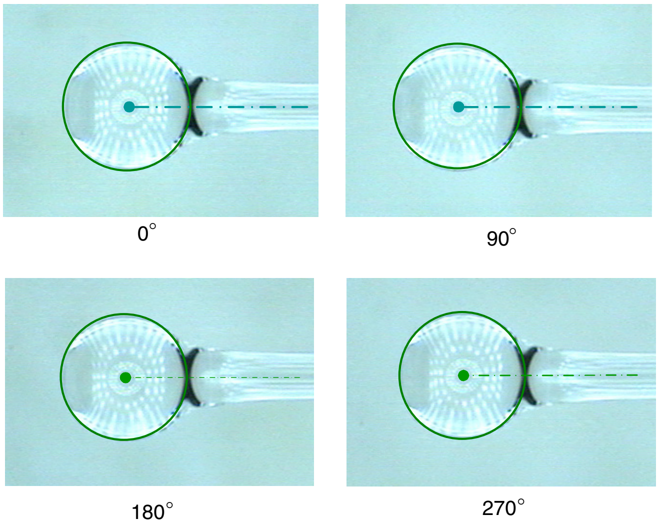

Figure 7. Images of the fiber probe.

Table 5. Measurement results of the tip at various rotational angles (in μm).

Angle of view	0°	90°	180°	270°
Diameter	314.07	313.84	314.05	313.89
Roundness	0.54	0.82	0.37	0.61
Center offset	0.37	0.96	0.28	0.72

offset of the probes can be controlled to within 1 μm with repeated fabrications under the same condition.

4. Discussion

The probe size will be required in different diameters for different holes. According to the accuracy requirements of microparts, the geometrical accuracy of the probe will also be required to different degrees.

(1) For the time being, the roundness and the center offset of the probe can both be controlled to within 1 μm. These characteristics have met industrial requirement. They also almost reach the instrument limit of the image vision measuring machine. Further improvement of this specification is be possible if a higher resolution instrument would be used, such as the x-ray image system or the SEM.

(2) As to the further reduction of the ball diameter, our experience shows that the minimum diameter which can be formed is about two times of the fused fiber diameter. For our case of 125 μm single mode fiber for 1550 nm wavelength, the minimum ball which can be formed is about 250 μm. If it is intended to fabricate an even smaller ball, other means should be employed, such as fusing thinner fiber, using wet etching technique, etc. It is expected that a reliable and cost-effective microprobe, within 100 μm diameter and 100 nm form errors, can be achieved in the near future.

(3) One special feature of this outcome over our previous solution is the finding of the optimum parameter combination by the Taguchi method. By this means, intermittent measurement with moving in and out of the fiber from the setup is no more necessary. Once the parameters are set, the final ball of predicated characteristics can be fabricated automatically.

(4) Another special feature of this outcome over other microprobes that are made by gluing a microsphere to a microstem is the monolithic structure of our probe. The uncertainty of the center offset error could be minimized.

5. Conclusions

This paper demonstrates the feasibility of utilizing a commercially available fiber fusion splicer to fabricate a micro-spherical fiber probe based on the Taguchi method. With the optimization design, the optimum parameters were assigned in the procedure to produce a good microball. The redesign experiment first focused on producing a probe with required diameter and roundness by applying the stage 1 parameters. It then concentrated on compensating the offset due to the gravity force by applying the stage 2 parameters. Based on the S/N ratio and ANOVA analyses, the best process parameters for required ball diameter, roundness and center offset were obtained from the experimental redesign that considerably reduced the number of experiments. With the combination of the optimum parameters, the optimal shape of the microprobe has been achieved after a series of confirmation experiments. Measurement results show that an optical fiber probe with diameter close to 310 μm and roundness and center offset of less than 1 μm has been achieved.

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