Research on Defect Detection Method of Whole Surface of Small Ball Based on Field Scan

Runze Zheng¹, Xin Chen¹*, Xiaoyu Cai², Jiasi Wei², Yuan Li²

¹ School of Electronic Information and Electrical Engineering, Shanghai Jiaotong University, Shanghai, China
² Shanghai Institute of Measurement and Testing Technology, Shanghai, China

*Corresponding author e-mail: cxshcn@163.com

Abstract. This paper introduces a detection method that uses a white-light interference microscope to scan along the circle of latitude line to detect defects on the entire surface of microsphere with a diameter of 2mm. The surface of the microsphere is exposed under the white light interference microscope from the top to the equator in turn according to the annular belts of different latitudes to make the acquired image cover the entire surface of the ball. The topography data is processed, the defects are identified, and the number of defects of different horizontal and vertical sizes is counted, so as to achieve the quantitative evaluation of the surface defects of the small ball.

1. Introduction

With the continuous progress of micro-nano processing technology, microspheres with diameters of tens of micrometers to several millimeters are widely used in fields such as micromechanics, micro-optics and inertial confinement fusion [1]. The detection and evaluation of surface defects on microspheres has always been the focus of research.

In the field of precision machinery, bearing failures caused by defects such as pits and scratches on the surface have reached 65% [2]. In the field of controlled nuclear fusion scientific research, the National Ignition Facility set relevant technical indicators for the target surface isolated defects [3]. In recent years, the detection of the surface quality of microspheres has mostly adopted digital holography [4], eddy current wave detection [5,6], optical fiber sensing [7] and other detection technologies. But these are not suitable for the quantitative characterization of small surface defects. Non-contact optical measurement methods have received widespread attention.

This article uses white light interference detection method to detect microspheres, but currently commercial white light scanning interferometer can only meet the measurement of plane and aspheric surface [8]. In this paper, by "latitude circle band coverage", the images covering the entire ball can be obtained and by processing collected data, the defects can be identified and their sizes can be calculated, and the number of defects with different horizontal and vertical sizes can be counted to achieve the purpose of quantitative evaluation of surface defects of small ball.
2. Detection principle

2.1. Measurement trajectory

To realize the detection of the entire surface of the microsphere without omission, it is necessary to make the surface of the ball exposed to the detection instrument one by one in a certain way, and then process the spherical data to evaluate the overall shape of the spherical surface.

At present, the trajectory detection schemes for the topography of small balls with a diameter of less than 5 millimeters mainly include three methods: the orthogonal circle method, the equally spaced meridian method, and the latitude circle method. The orthogonal circle method only takes points on three orthogonal circles, and the isolated defect points between the trajectories will be ignored, which has the limitation of low information amount. And through equally spaced meridian method to achieve the omission-free detection of the overall surface morphology of the ball, the measurement process requires multiple rotations of the ball between two orthogonally placed axis systems. The operation is cumbersome and introduces a large number of mechanism motion errors.

In order to solve the above technical problems, this paper adopts latitude circle method to cover the surface of the ball. The measurement trajectories are latitudes at different latitudes of the ball, and the surface topography data of a circle of latitude line can be obtained each time the ball rotates 360°.

2.2. Measurement process

Because the range of image acquired by the white light interferometry microscope is limited, it is necessary to use the main and auxiliary dual axis systems to rotate the microsphere at a regular sequence, so that the partial spherical surface is sequentially exposed to the white light interferometric probe, then completing the image acquisition, and finally cover the entire sphere.

The schematic diagram is shown in Figure 1. The entire microsphere surface is scanned sequentially at different latitudes in a certain order. The measurement method and steps are as follows: Step 1. The main axis nozzle sucks the microsphere, and the rotation platform drives the main axis to rotate to a vertical position; step 2, adjust the axis of the white light interference probe to the center of the microsphere, take an image to obtain a single measurement topography; step 3, the rotation platform drives the main axis to rotate clockwise by a certain angle α, Repeat step 2, the main axis self-rotation motor drives the main axis to rotate a certain angle β, repeat step 2, continue to make the main axis rotating angle β and shoot until obtain all images of the current latitude circle; step 4, repeat step 3 Until the main axis is turned to the horizontal position to complete the detection of the hemisphere; Step 5, adjust the X-Y micro-movement platform and Z-direction micro-movement platform of auxiliary axis system, align the auxiliary axis nozzle with the microsphere on the main axis nozzle, and exchange the microsphere to auxiliary axis, the auxiliary axis rotation motor drives the auxiliary axis to rotate 180 degrees, flip the microsphere, and then exchange it back to the main axis; step 6, change the rotation direction of the main axis platform to counter-clockwise, and repeat step 3 until main axis rotating back to vertical position, complete the image acquisition work that covering the whole microsphere surface.

![Fig 1. Schematic diagram of measuring method principle](image-url)
Calculating $\alpha$ and $\beta$ accurately according to the size of the microsphere and the single-shot image of white light interference, so that at least 20% coverage can be achieved between adjacent acquisition images at the same latitude and between adjacent latitude images, and whole surface topography data without leakage can be acquired.

2.3. Resolution calculation

The image acquisition module consists of a CCD camera and its corresponding data acquisition system. The resolution of CCD is 1024px×1024px, the pixel size is 5.5μm×5.5μm.

The resolution is a key parameter of the white light interference probe. According to the Rayleigh criterion, the lateral resolution of the white light interference probe can be obtained:

$$\varepsilon_o = \frac{0.61\lambda}{NA}$$

(1)

In the formula, $\lambda$ is the wavelength of the white light source, and NA is the numerical aperture of the objective lens.

The lateral resolution of the white light interference system is not only related to the resolution of the probe, but also affected by the CCD resolution. The calculation formula for the resolution $\varepsilon_c$ is:

$$\varepsilon_c = \frac{2S_p}{M}$$

(2)

In the formula, $S_p$ is the CCD pixel size, and $M$ is the magnification. Compare $\varepsilon_o$ and $\varepsilon_c$, and take the larger one as the lateral resolution of the measurement system.

The axial resolution of the system is affected by the minimum light intensity change $\varepsilon_i$ that can be detected by the system, which is related to the number of sampling bits $N$ of the CCD:

$$\varepsilon_i = \frac{I_{max} - I_{min}}{2^N}$$

(3)

It is known that the corresponding phase change of $I_{max} - I_{min}$ is $\pi$. Accordingly, the minimum phase change that the system can resolve is:

$$\Delta \varphi \geq \frac{\pi}{2^N}$$

(4)

Therefore, the minimum height change that the system can distinguish is:

$$\Delta h \geq \frac{\lambda}{4\cdot2^N}$$

(5)

In this paper, a 50x interference objective lens is used. At this time, NA is 0.7. Therefore, the lateral resolution of the system is 0.51μm and the axial resolution is 0.58nm.

3. Data processing

The data collected by the white light interference system is the relative height of the surface of the measured object. Only the z-direction data is accurate, the x-y direction is the ideal array coordinate.

There is a lot of high-frequency noise in the original data. In this paper, the identification of microsphere surface defects is based on the relative height of the spherical surface. The curved surface itself has certain height information, which will interfere with the extraction of defects. Therefore, reasonable filtering and spherical fitting of the original data is the key part of preprocessing.

3.1. Denoising

Median filtering can better eliminate noise, and at the same time, the edge details of the image are preserved, avoiding the disadvantages that the mean filtering and Wiener filtering will blur the boundaries and details of the image.

By comparison, it is concluded that the median filtering of the 5×5 template is better. Using a large-scale template median filter can get a strong effect of removing noise, but it reduces the sharpness of the details of the image, which causes the loss of image details and the accuracy. Therefore, selecting a median filter window of an appropriate size can remove image noise while maintaining the maximum image detail characteristics.
3.2. Nonlinear least squares spherical fitting

Assuming \((x_i, y_i, z_i)\) is the data point on the surface of the microsphere, the ideal spherical equation is

\[
(x - x_0)^2 + (y - y_0)^2 + (z - z_0)^2 = R^2
\]

Where \((x_0, y_0, z_0)\) is the ideal sphere center, and R is the ideal sphere radius. Construct function

\[
H(x_0, y_0, z_0, R) = \sum_{i=1}^{N}((x_i - x_0)^2 + (y_i - y_0)^2 + (z_i - z_0)^2 - R^2)^2
\]

According to the least squares method, to minimize \(H\), \((x_0, y_0, z_0)\) and \(R\) need to satisfy the following four equations

\[
\frac{\partial H}{\partial x_0} = 0, \quad \frac{\partial H}{\partial y_0} = 0, \quad \frac{\partial H}{\partial z_0} = 0, \quad \frac{\partial H}{\partial R} = 0
\]

The non-linear least squares method is used to estimate the center of the spherical surface, and the corresponding ideal surface is obtained. The measured data is subtracted from the ideal surface to expand into a plane. Based on the positive and negative height information on the plane, the protrusion and depression of the defect can be determined. The topography of the microsphere after filtering and surface flattening is shown in Figure 2.

![Figure 2. Results after filtering and surface flattening](image)

(a) Original data  (b) Effect after filtering and flattening

3.3. Defect identification

After removing the noise and flattening the surface topography data, the method for defect detection is as follows: Query the convex and concave parts according to the height information to get the corresponding connected area. Set the threshold. If the Unicom area is larger than this value, it is judged as a defect, and the identified defect is mapped on the original image, marked with red color, as shown in Figure 3.

![Figure 3. Recognition of microsphere surface defect](image)

4. Experiment results

The median filtering is performed on the original data, and then a spherical fit is performed using the non-linear least square method, and then developed into a plane, and then the SIFT algorithm is used for feature matching. The collected multi-latitude annulus images are stitched together, and the
defects are identified as a whole. The size of the defects is extracted and the number of defects with different horizontal and vertical dimensions is counted. The statistics are shown in Table 1. From the processed surface topography data, it is calculated that the proportion of defective pixels on the stitched microspheres accounts for 5.89% of the total pixels.

### Table 1. Statistics of defects on microsphere surface

| Vertical size (nm) | Horizontal size (μm) | (0,10] | (10,20] | (20,30] | (30,∞) |
|-------------------|----------------------|--------|---------|---------|--------|
| (-∞, -1081]      | 10                   | 1      | 0       | 1       |
| (-1081, -825]    | 5                    | 0      | 0       | 1       |
| (-825, -669]     | 5                    | 0      | 1       | 1       |
| (-669, 0)        | 23                   | 12     | 0       | 3       |
| (0, 669]         | 245                  | 134    | 34      | 3       |
| (669, 825]       | 45                   | 56     | 14      | 2       |
| (825, 1081]      | 19                   | 16     | 11      | 1       |
| (1081, ∞)        | 9                    | 6      | 14      | 28      |

5. Conclusion

This paper is based on the trajectory of the latitude circle, using a white light scanning interferometer to measure the entire surface of the silicon nitride spheres with a diameter of 2mm. Obtain the surface topography data of the ball and complete the defect detection and quantitative statistics of defects on the entire surface. Experiments verify the reliability and practicability of the method. The detection method of the surface defect of the small ball proposed in this paper has a good application prospect for some special application scenarios today, such as special material microspheres such as laser fusion targets that are very sensitive to surface isolated defects.

6. Acknowledgments

This work was financially supported by Scientific Programs of Shanghai Municipal Bureau of Quality and Technical Supervision (No. 2018-06).

References

[1] Huang Qiangxian, Hu Xiaojuan, Bian Yakui, Mei Jian, Zhang Liangsheng, Chen Lijuan. Advances in Sphericity Measurement Technology of Micro Sphere [J]. China Mechanical Engineering, 2016, 27(09):1271-1277.
[2] Zhou Hangchao, Dong Chenchen, Chen Feng, Cheng Li, Wu Chunjie, Weng Haizhou. Review of Detection Methods for Surface Defects of Steel Balls [J]. Equipment Manufacturing Technology, 2018(10):7-11.
[3] Project Staff. Inertial confinement fusion target component fabrication and technology development support[R]. General Atomics Report (GA-A25649), 2006.
[4] C. Hermerel, A. Choux, L. Jeannot, et al. Characterization of the micro-shell surface using holography[J]. Fusion Science and Technology, 2011, 59(1): 110-115.
[5] Zhang H, Zhong M, Xie F, et al. Application of a Saddle-Type Eddy Current Sensor in Steel Ball Surface-Defect Inspection[J]. Sensors, 2017, 17(12):2814.
[6] Xie FQ, Xiao LJ, Lu YP, et al. Design of the Eddy Current Sensor of Steel Ball Nondestructive Detection[J]. Applied Mechanics and Materials, 2013, 271-272:842-846.
[7] Wang CL, Ai CS, Li GP. Optical Fiber Sensor System for Detecting the Steel Ball Surface Quality[J]. Applied Mechanics and Materials, 2014, 654:245-249.
[8] Katsuichi K. Recent trends in white light interferometry. Proc. of SPIE, 2006, 6382: 1-10