NANO-POSITIONAL DETECTION USING LASER TRAPPING PROBE FOR MICROPARTS

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1. INTRODUCTION

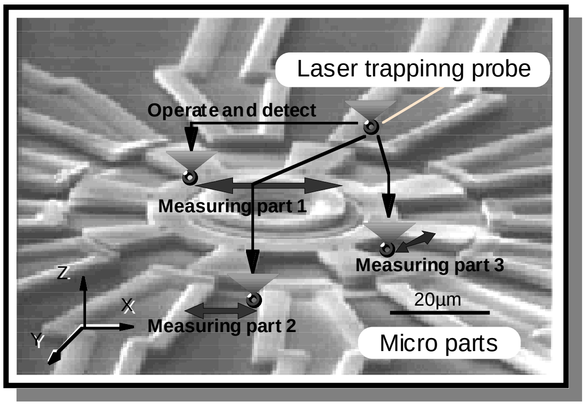


Fig. 1 Conceptual drawing of nano-positional detection using laser trapping probe

Over the recent years, steady progress of microfabrication or micromachining technology is seen with the enhancement of photolithography technology for creating miniature three-dimensional (3D) structures with dimensions ranging from millimeters to submicrometers. In order to obtain and maintain compatibility of standardized microcomponents in practical use, it is necessary to assess the geometrical properties of micromachined 3D shapes based on coordinate metrology at an accuracy of the nanometer order. For this a nano-CMM (Coordinate Measuring Machine)[1] is required, and a nano-CMM which is 1/100 or 1/1000 the size of a conventional CMM has been proposed for the coordinate metrology of microparts by positional probing. Fig. 1 shows the concept of the nano-CMM. In the use of the nano-CMM, the dimensions and other geometrical properties of the microscale 3D shapes of microcomponents must be evaluated in the nanometer order by probing the measurement points using a three-dimensional sensing microprobe. The microprobe must satisfy harsh specifications such as probe sphere size in the micrometer order, 3D positional detection sensitivity of higher than 10nm and measuring force of less than 10^{-5} N. New probing techniques for achieving nano-positional detection using a microprobe are therefore required. To answer to this need, the authors have developed a new probing technique for the nano-CMM, called a laser trapping probe [2] whose principle is based on the single-beam gradient-force optical trapping technique [3] and microscope interferometers. The work reported in this paper deals with the fundamental characteristics of the practical positional detection and measurements of a glass microsphere with a NIST traceable mean diameter of about 160μm using the laser trapping probe.

2. PRINCIPLE OF 3D POSITIONAL SENSING

An optically trapped small dielectric particle in air [4] is used as the microprobe sphere. It is sensitive to external force generated by interactions with a workpiece and has the same dynamical properties as a positional detection probe. Fig. 2 shows the dynamical behavior of an optically trapped small dielectric particle. The probe sphere retains a stable position when applied with trapping force $\mathbf{F}_t$, which is the resulting force of all radiation pressures $\mathbf{f}_i$ produced by the focused laser beam, as shown in Fig. 2(a). When an external force $\mathbf{F}_e$ is applied to the probe sphere (Fig. 2(b)), the dynamical balance is broken and the probe sphere shifts. At this moment, the trapping force changes with the radiation pressure distribution depending on the illumination conditions of the probe sphere position. When $\mathbf{F}_e$ is released (Fig. 2(c)), the probe sphere is accelerated in the direction of the stable position and is finally returned to the initial position precisely. As discussed above, an optically trapped small dielectric particle has the same dynamical properties as a probe sphere, which is sensitive to external force generated by interactions with a workpiece.

3D positions in the coordinate system can be measured by detecting the shift of a probe sphere caused by the external force $\mathbf{F}_e$ at the position approximating to the workpiece. The Linnik type microscope interferometer senses displacement with high accuracy;for example detecting displacement δ of P_o on the probe sphere's top surface indicates a shift Δ in an arbitrary direction as shown in Fig.4. Fig. 4(a) shows the fundamental configuration of the Linnik type microscope interferometer. The two waves divided by a beam-splitter are united and a concentric circular fringe pattern is produced on the detector. A microprobe sphere with a diameter of less than 8.0μm as shown in the SEM image of Fig.4(b) is used as the probe sphere. The fringe pattern employed which reflects displacements at not just one point but everywhere on a probe sphere's top surface promises high sensitivity.

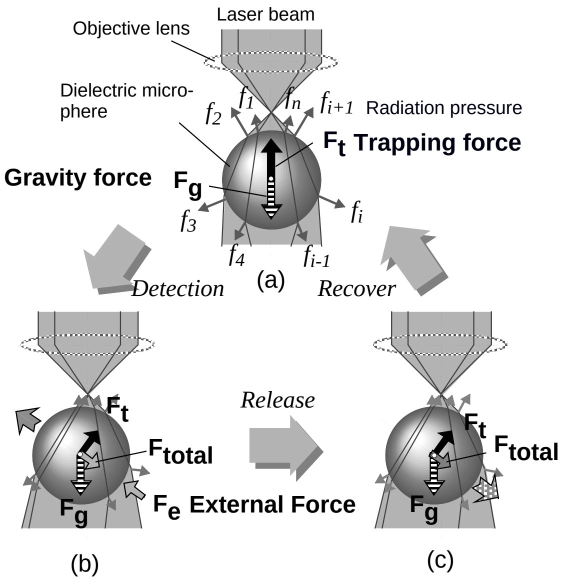
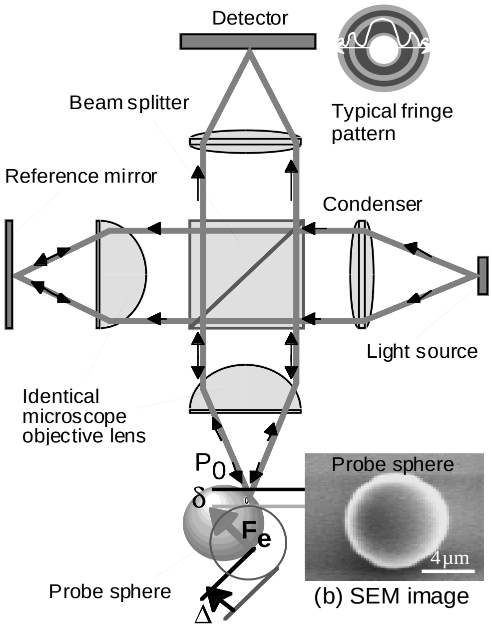


Fig. 2 Dynamical behavior of laser trapping probe



(b) SEM image

(a) Linnik interferometer

Fig. 3 Configuration of Linnik interferometer

3. LASER TRAPPING PROBE SYSTEM

Fig. 5 shows the schematic diagram of the measurement system specifically designed for trapping particles in air, observing the trapped particles and measuring the fringe pattern. The system is composed of a laser trapping optical system with a Q-switch/Nd:YAG laser with wavelength of 1064nm, Linnik type microscope interferometer consisting mounting a microscope objective lens 1 with a numerical aperture (N.A.) of 0.95 and an xyz-stage with positioning accuracy of 5nm, which is driven by PZT actuators. The YAG laser beam is deflected by a dichroic mirror toward the microscope objective lens 1, then focused on silica particle used as a probe sphere. The silica particle can only be levitated in air with the concentration of the high energy of the Q-switch pulse emission, after which the probe sphere can be maintained at a stable position in the CW emission mode with a low power of less than 100mW. A He-Ne laser with a wavelength of 633nm is utilized as the interference light source. The beam travels through an optical fiber and is deflected by a cube beam-splitter. A dichroic mirror divides the wave into two; one segment travels to a reference mirror with a flatness of 1/10 the wavelength and the other to the probe sphere. The reference mirror is positioned using a PZT stage with the same positioning accuracy as the xyz-stage. The top view of a trapped probe sphere with the fringe is obtained using the microscope component with a magnification rate of 500X. The fringe image data detected by the CCD area sensor is processed by a personal computer with an image memory. Manipulation of the probe is observed using the microscope unit in the lateral direction.

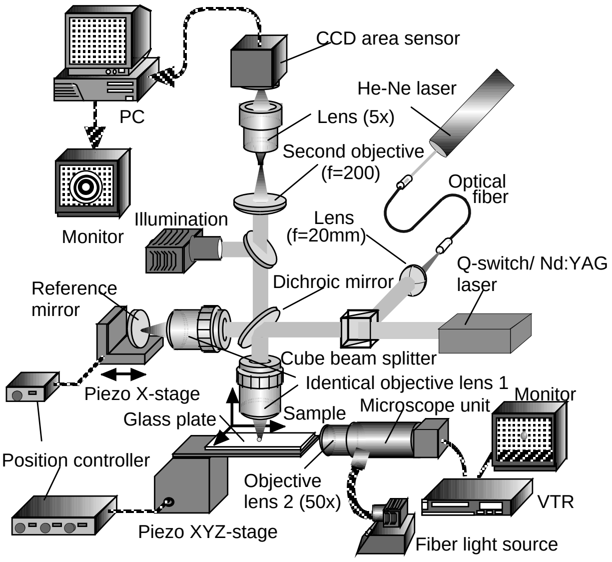


Fig. 4 Schematic diagram of laser trapping probe experimental system

4. FUNDAMENTAL EXPERIMENTS

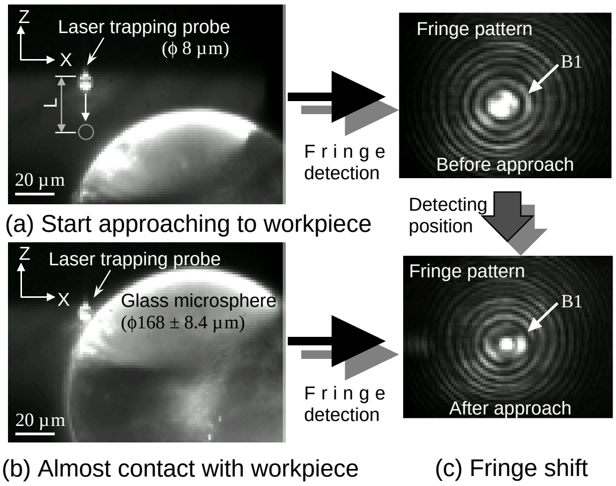
Fundamental experiments were carried out to find the fringe properties with a probe approximated to the workpiece. A glass microsphere (see Chapter 5) was used as the workpiece. Fig. 5 shows the microscopic images of the three-dimensional trapped probe sphere in air and the approach to the workpiece with the corresponding fringe patterns. The probe moves in the z-direction to the workpiece as shown in Fig. 5 (a). When the probe sphere is at the nearest position to the workpiece as shown in Fig. 5(b), the fringe intensity meets the turning-over indicated in Fig. 5(c). The initial position was set at about 20μm away from the workpiece surface, and the first bright fringe intensity B1 changing with distance L from the initial position was measured. Fig. 6 shows the measured results. The normalized intensity was found to decrease steadily from about L=10μm as the probe was about to come in contact with the surface. Finally the intensity reached the minimum value at about L=18μm. These fringe properties enable non-contact sensing of the position of the workpiece. The laser trapping probe can detect position according to changes in the fringe intensity such as the turning-over of the first bright fringe.

5. MEASUREMENTS OF A GLASS MICROSPHERE

To verify the validity of the positional detection method based on changes in the fringe intensity, the coordinate measurement of a uniform glass microsphere was carried out. Figs. 7(a) and (b) show the measured cross sections and nominal values of a uniform glass microsphere as the workpiece. The probe position was fixed and the workpiece was moved relatively by the xyz-stage on which the workpiece was set. Each position was measured twice by probing in the z-direction. Five cross sections of parts A to E were measured. The glass microsphere had a calibrated mean diameter of 168±8.48μm traceable to the Standard Meter through the National Institute of Standards and Technology (NIST). Fig. 8 shows the measured point data plot, the regression circle calculated using the least square method and deviations of the individual measured points from the regression circle. Fig. 8(a) shows that the diameter d1=121.7μm of the regression circle for the measured part A (Y=60μm) agrees with the nominal circle diameter of D1=117.6μm within uncertainty range. The measured points more or less fit the regression circle within the maximum deviation of 2.0μm. Figs.8 (b) and (c) show the measured results for part B (Y=50μm) and part C (Y=40μm) respectively. The regression circle diameter, the nominal circle diameter, and maximum deviation obtained were as follows; d2=157.8μm, D2=135.0μm, 4.0μm for part B and d3=157.9μm, D3=147.7μm, 6.0μm for part C. A regression sphere with diameter of 168.4μm was obtained from 60 measured points. This agreed well with the nominal diameter of 168±8.48μm within uncertainty range. Consequently, these measured results demonstrate the potentials of the laser trapping probe as a positional detection probe for the nano-CMM, which can measure submillimeter size 3D shapes of microparts with nanometer order accuracy.

6. CONCLUSIONS

To establish a nano-positional detection probe technique for evaluating the geometrical properties of the microscale 3D shapes of microcomponents, a laser trapping probe applying an optically trapped small dielectric particle in air and Linnik interferometer has been developed. The fringe properties with probe access to the workpiece were experimentally investigated. A microprobe sphere was displaced by less than 160nm by interactions between the microprobe sphere and workpiece. To verify the validity of the positional detection method based on changes in the fringe intensity, measurements of a glass microsphere with a NIST traceable mean diameter of 168±8.48μm were carried out. A regression sphere with a diameter of 168.4μm was obtained from 60 measured points. This agreed well with the nominal diameter within uncertainty range. The measured results demonstrate the potential of the laser trapping probe as a nano-positional detection probe for evaluating the submillimeter size 3D shapes of microparts with nanometer order accuracy.



(a) Start approaching to workpiece

(b) Almost contact with workpiece

(c) Fringe shift

Fig. 5 Change in fringe pattern while close to glass microsphere

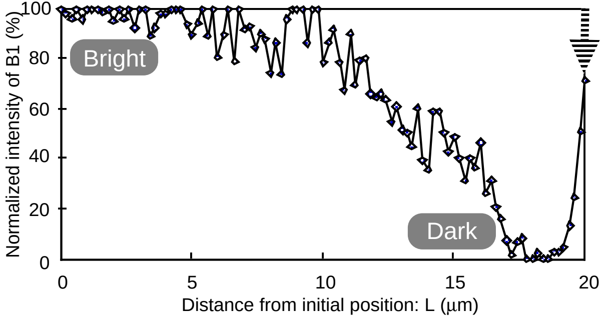
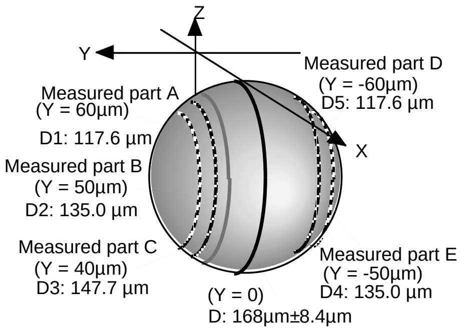


Fig. 6 Changes in fringe intensity according to probe approach

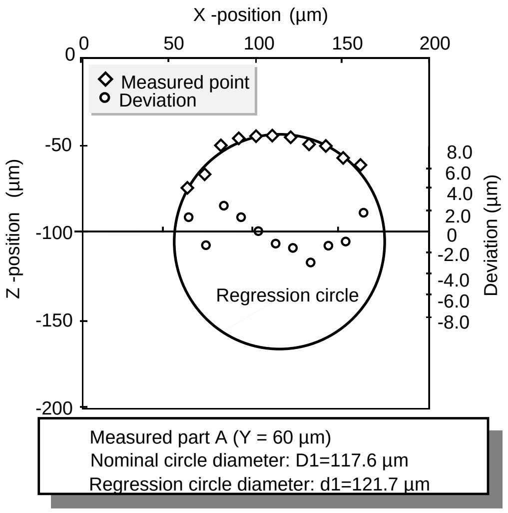


(a) Measured cross sections

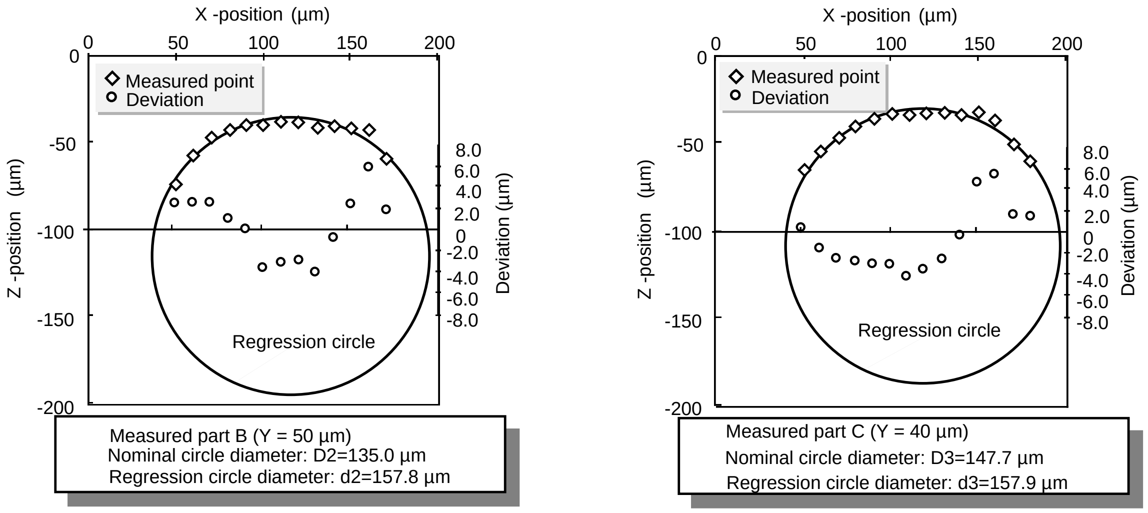
(b) Specification of glass microsphere

Certified Mean Diameter	168µm±8.4µm
Standard Deviation	7.5µm
Index of Refraction	1.51@589nm
Composition	Soda lime glass

Fig. 7 Measured cross sections and nominal values



(a) Measured result of measured part A



(b) Measured result of measured part B

(c) Measured result of measured part C

Fig. 8 Measured results of glass microsphere using laser trapping probe

ACKNOWLEDGMENTS

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REFERENCES

[1] K. Takamasu, et al., "Basic Concepts of Nano-CMM (Coordinate Measuring Machine with Nanometer Resolution)", *Proc. of The Japan-China Bilateral Symposium on Advanced Manufacturing Engineering*, pp.155-158(1996).

[2] Y. Takaya, H. Shimizu, S. Takahashi, T. Miyoshi, "Fundamental Study on The New Probe Technique for The Nano-CMM based on The Laser Trapping and Mirau Interferometer", *Measurement*, **25**/1, pp.9-18(1999).

[3] A. Ashkin, J. M. Dziedzic, J. E. Bjorkholm and S. Chu, "Observation of a single-beam gradient force optical trap for dielectric particles", *Opt. Lett.*, **11**, pp.288-290(1986).

[4] Y. Takaya, S. Takahashi, T. Miyoshi and K. Saito(2), "Development of The Nano-CMM Probe based on Laser Trapping Technology", *CIRP ANNALS* , **48**/1, pp.421-424(1999).