Research Article

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Fundamental validation for surface texture imaging using a microsphere as a laser-trapping-based microprobe

Abstract: A surface imaging technique using a laser-trapped microsphere is proposed. The goal of this research is to image the surface texture, while simultaneously measuring the position of the engineered surfaces using the laser-trapping-based microprobe. This paper presents an investigation of imaging characteristics for the microsphere technique. Depending on the distance from the surface to the microsphere, the available images could be either real or virtual. Virtual images had a higher contrast than real images. Contrast and magnification varies depending on the positions of the focal point of the objective lens and surface.

Keywords: laser trapping; microlens; microsphere; surface texture.

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1 Introduction

In the past several decades, several types of microfabrication techniques have matured, including micro-mechanical machining [1], laser fabrication [2], lithography [3], and micro-electro-discharge machining (EDM) [4], as well as manufactured microstructures such as micro-holes and micro-grooves. These fabrication techniques form different surface textures on the microstructures in accordance with the processing technique. At micro-scales, surface texture highly affects the functionality of the products [5, 6]. Therefore, both the dimensions and surface texture are crucial determining factors for product performances. Thus, evaluating the surface characteristics of a microstructure along with its dimensions and geometry is important. Many techniques, such as optical techniques [7], surface profiling, and scanning-probe microscopy have been developed thus far. However, these techniques have mainly been developed for use with relatively flat surface textures. Generally, either a micro-coordinate measuring system [8] or micro-X-ray computed tomography [9] is used to characterize the dimensions of a sample. Different data points are measured separately and then combined during postprocessing [9, 10]. However, evaluating the surface texture and dimensions of a microstructure is not easy to do simultaneously.

We have developed a surface-sensing probe for micro-coordinate metrology using the laser-trapping technique [11–14]. An optically trapped microsphere acts as a sensor for detecting the surface features. Here, we propose a new technique for imaging the microstructure surface texture using a laser-trapped microsphere. This enables the simultaneous measurement of the surface position and surface texture. For surface imaging, the microsphere serves as a microlens to focus on the image surface. To establish this imaging technique, the basic principles for surface imaging are investigated in this paper.

2 Laser-trapping-based microprobe

2.1 Surface sensing

Laser-trapping-based microprobe was originally developed for coordinate metrology [11–14], which has tactile and scanning operating modes. An optically controlled microsphere is brought close to the surface. In the vicinity of the surface, the probe dynamic behavior changes as a result of its interaction with the surface. In the tactile mode (Figure 1A) [11, 12], the surface is detected by monitoring the probe

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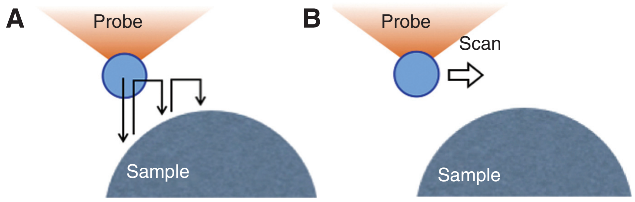

Figure 1 Schematics of the laser-trapping-based microprobe for coordinate metrology.

dynamics. In the scanning mode, light transmitted via the microsphere is reflected from the surface of the microstructure. This retro-reflected light and trapping laser interferes with each other, which results in an optical standing wave along the optical axis. This is called the standing wave scale (SWS). The spatial phase difference of the SWS corresponds to the surface topography. The optically trapped microsphere can be used to detect the phase shift of the SWS, thereby enabling the measurement of surface topography in the scanning mode (Figure 1B) [13, 14].

2.2 Surface imaging

Surface texture is imaged using the trapped microsphere. The trapped microsphere is brought close to the surface, but not in contact with the surface because of the optical radiation pressure generated by the retro-reflected beam. Consequently, the microsphere is trapped a few hundred nanometers away from the surface. As such, the microsphere serves as a microlens to optically transfer information about surface texture to an imaging device.

Depending on the position of the trapped microsphere, the imaging device receives either a real or virtual image. Recent studies of imaging with a microsphere mainly use the virtual image for high-resolution imaging [15, 16]. These studies assume that the microsphere is in contact with the surface. The principles behind imaging a surface through a microsphere with a gap between the surface and microsphere have not yet been understood. In this paper, the properties of using the microsphere to image a surface without direct contact are investigated using a finite-differential time domain (FDTD) numerical simulation and experiment.

3 Lensing effect analysis

3.1 Model

FDTD analysis was used to understand how the microsphere propagate light from the surface to the objective lens. A point source is considered as an ideal surface point. The light-propagating conditions are different depending on the distance, d, between the microsphere and point source. The simulation conditions are as follows: The wavelength of the point source was considered to be 632.8 nm. The cell size was set to 40 nm with an analytical region of 21.3 µm (x)×21.3 µm (y)×13.3 µm (z). A glass microsphere with a diameter of 8 µm was assumed. The refractive index of the glass material was set to 1.44. The electromagnetic field was calculated as a function of the distance between the microsphere and point source, which ranged from 0.1 to 3.0 µm. The simulated model is depicted in Figure 2A.

3.2 Simulation result

The simulated results are shown in Figure 2B–D, which are of cross-sectional planes along the XY plane, centered on the microsphere Z-axis. The red circles indicate the surface boundary of the microsphere. With the point source close to the microsphere (Figure 2B), the light diverges after the microsphere. Once the point source is a few micrometers away from the microsphere, the light converges after the microsphere (Figure 2C, D). The imaging scheme of the surface texture is related to these propagating conditions of the microsphere. Converged light can be imaged as a real image (Figure 3A). In this case, the focal point of the objective lens has to be above the microsphere. On the contrary, in the field far away from the microsphere, the propagating light diverges for all cases in Figure 2. When the focal point of the objective lens is below the microsphere, the diverging light can be imaged as a virtual image (Figure 3B), which is possible with either narrow or wide gap distance, d. Therefore, both real and virtual images are obtainable, depending on the configurations of the microsphere-surface gap distance and focal point of the objective lens.

4 Fundamental characteristic

4.1 Experimental setup

The characteristics of surface imaging with the proposed method were experimentally investigated. As a basic test, the microsphere was not optically trapped but held using a micropipette, which was adhered by a vacuum force, as shown in Figure 4. It is known that the presence of the micropipette does not affect the imaging performance [15]. The diameter of the microsphere was 22 µm for this

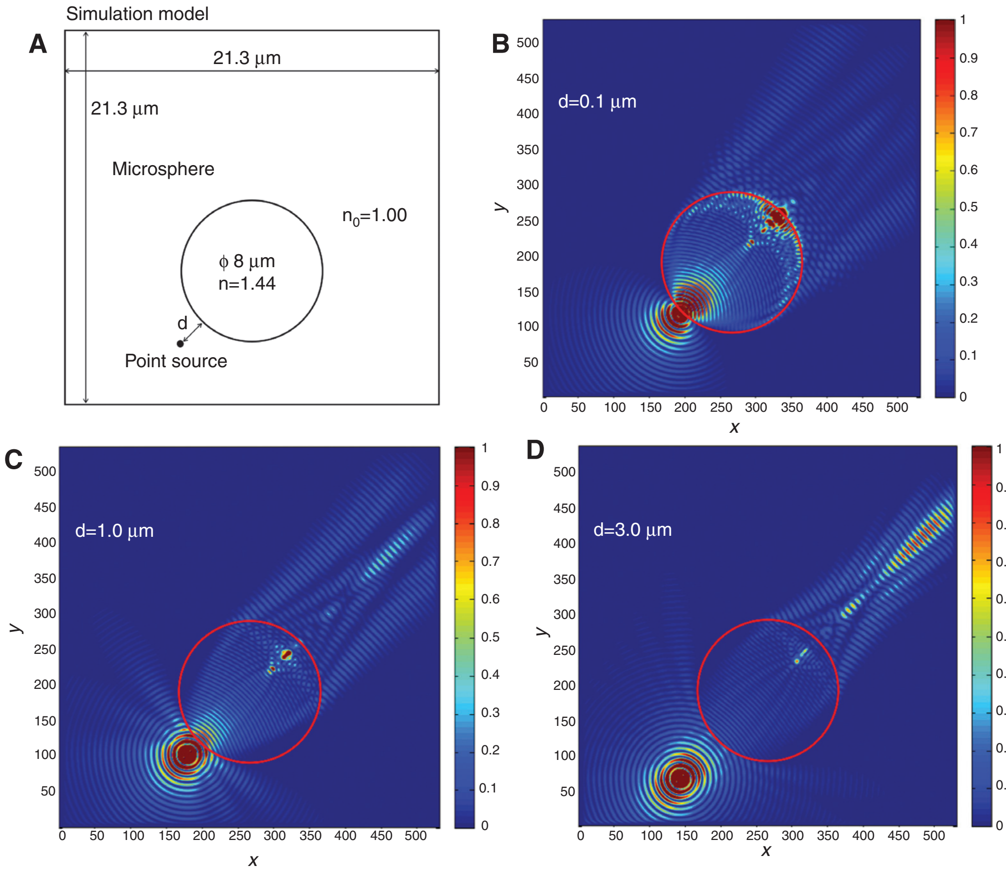

Figure 2 Simulated results for the lensing effect of the microsphere.

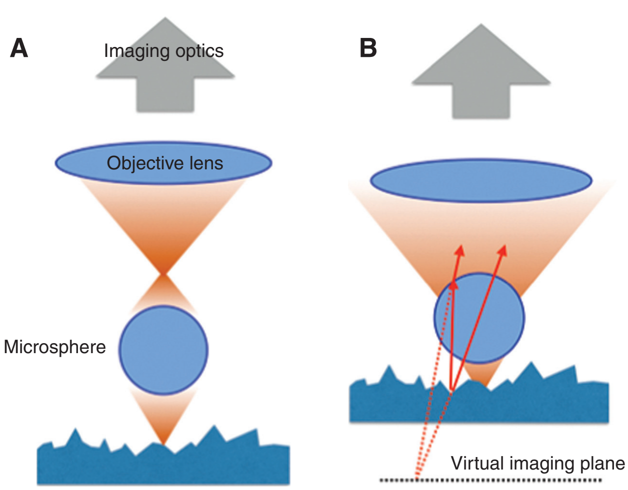

Figure 3 Conceptual illustration of surface texture imaging with a laser-trapping-based microsphere.

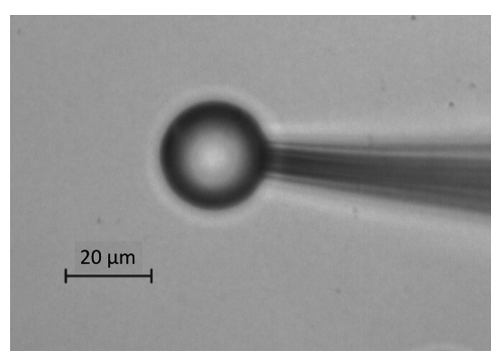

Figure 4 Microsphere held by micropipette.

case. Figure 5 shows the experimental setup. The held microsphere was brought underneath the objective lens of an optical microscope system. The measured sample was placed on the XY stage. The micropipette was set on an XYZ fine manipulation system (resolution: 1 µm). The objective lens was vertically adjusted (Z-axis) with 1.0-µm resolution. The numerical aperture of the objective lens used was 0.45. Diffraction gratings served as the measured surface. We used two different groove pitches, i.e., 2400 and 1800 grooves/mm, and the average pitches and depths of the gratings were measured using atomic force microscopy (Table 1). The surface of the diffraction grating was coated with aluminum.

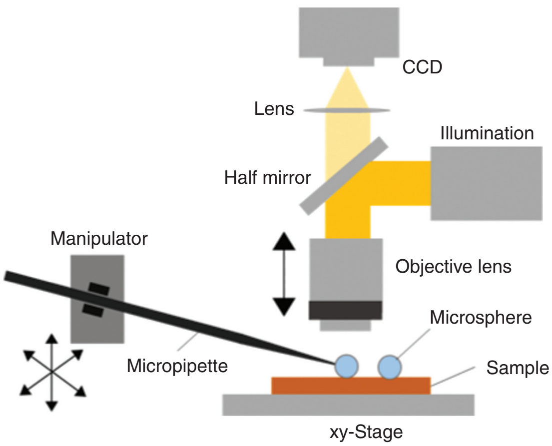

Figure 5 Experimental setup.

Table 1 Measured surface.

Specifications (grooves/mm)	Pitch (nm)	Depth (nm)
1800	597	55
2400	453	53

4.2 Image contrast

Surface images were taken under several conditions. The relevant parameters are the following two distances: the distance, Δz, between the focal point of the objective lens and surface, and the distance, h, between the microsphere and surface, as shown in Figure 6. Representative images of a diffraction grating with 1800 grooves/nm are shown in Figure 7. First, the objective lens is placed above the microsphere (positive Δz) to obtain a real image, which is shown in Figure 7A, where the left pictures show the captured image, and the right figures show the intensity profile along the white-dotted line in the left image. The distance h was set to 2 µm. The periodic pattern of the diffraction grating was very slightly evident, but it is difficult to recognize in the intensity profile. Second, a virtual image was captured. The distance h was set to 1 µm or 2 µm, which is shown in Figure 7B and C, respectively. The focal point of the objective lens was underneath the surface (negative Δz). As h decreases, Δz becomes more negative, as the simulation predicted. The obtained contrast was equivalent for both values of h. Compared to the real image, the virtual image exhibits a higher contrast. In the case of laser trapping, trapping the microsphere is difficult when the focal point of the objective lens is above the microsphere because of the scattering force [17]. Therefore, the virtual image is a better choice for our purpose, i.e., considering the imaging performance and laser trapping.

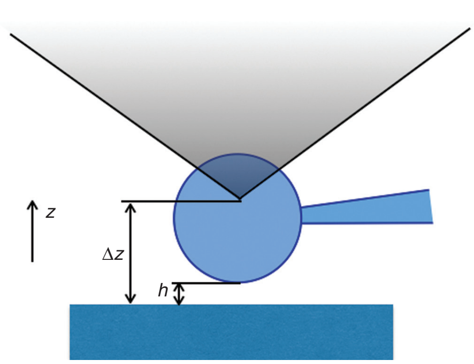

Figure 6 Controlled experiment parameters.

4.3 Configuration

The characteristics of the obtained image depend on the relationships among the positions of the focal point, microsphere, and surface. Below, we investigate the magnification and contrast of the obtained virtual images with a variable Δz and fixed h.

The distance, h, between the microsphere and surface was fixed at 2 µm, and the objective lens' focal point position was varied. In these conditions, the virtual images were captured and compared. Figure 8 shows three images taken at different positions. As noted above, the pitches of the periodic pattern of the diffraction grating were different. Thus, the magnification of the virtual image changed depending on the focal position of the objective lens. Figure 9 shows the measured magnifications related to the focal position. As the objective lens moved closer to the surface, the magnification decreased. This change in the rate of the magnification is because the length per pixel changed by 2.7 µm when the focal position was changed 10 µm.

In Figure 8, it is clear that the contrasts of the images were different. The brightness of the image is complex due to the illumination conditions and reflection from the surface and microsphere itself, which influences the image contrast. Figure 10 shows the image contrast. The contrast was evaluated as the averaged amplitude of the periodic patterns of the intensity profile. From 60 to 80 µm, the contrast was relatively high and was stable from 80 µm to 100 µm. In that stable range, the brightness of the image was more uniform.

From this investigation of the magnification and contrast, it is clear that the positions of the apparatus must be fixed. For the measurements using a laser-trapping-based microprobe, the surface position has been measured

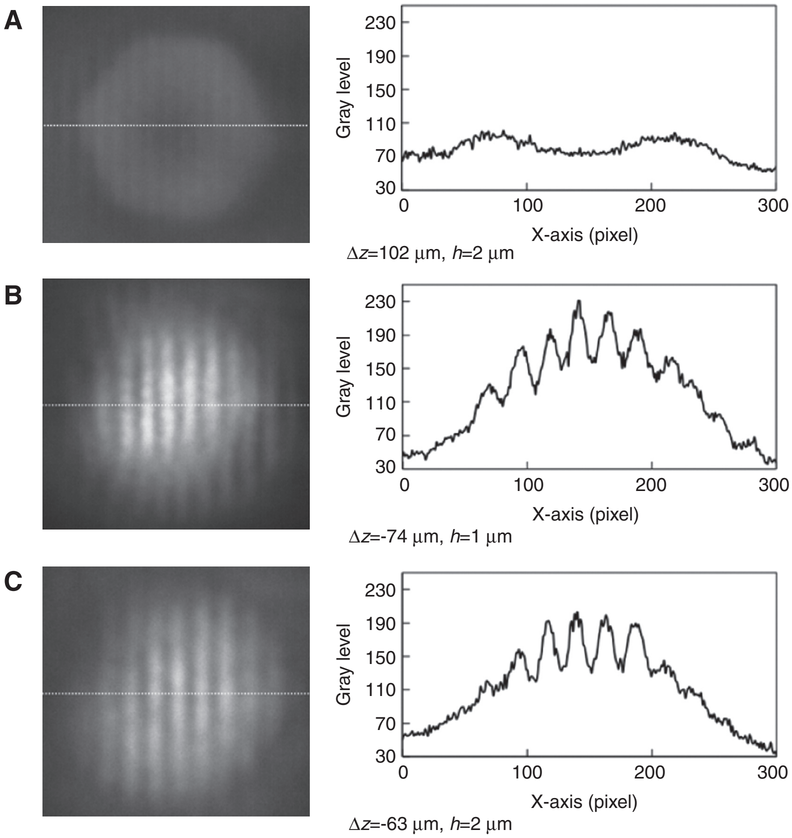

Figure 7 Obtained real and virtual image and its intensity profile.

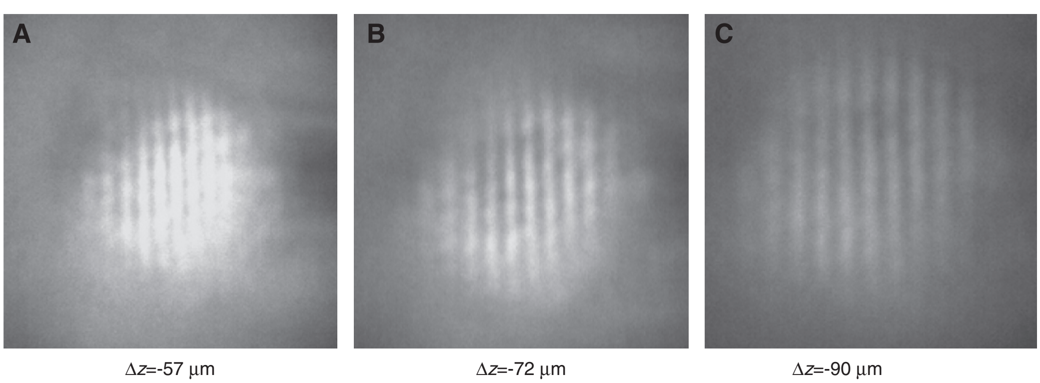

Figure 8 Virtual image with different defocusing.

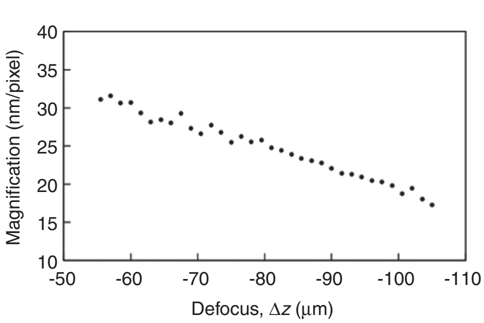

Figure 9 Magnification of the image dependence on the focal point position of the objective lens.

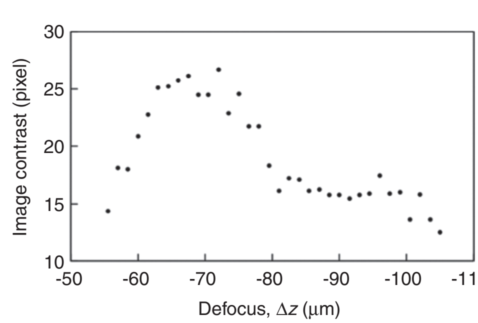

Figure 10 Contrast of the image dependence on the position of the objective lens focal point.

using a function of the surface sensing, which has 30-nm resolution [12], and the position of the microsphere has also been finely measured with >10-nm resolution [11]. Therefore, these positional relationships are manageable.

Beside, size effect of the microsphere was considered. The microsphere with a diameter of 22 μm was used in the experiments. Typically, a diameter of the microsphere for the laser-trapping-based microprobe is 8 μm [11–14]. Increasing the size of the microsphere widens the virtual imaging field of view [18]. It is also predicted that effect of aberrations due to the use of a smaller sphere as a lens becomes notably high. Consequently, the diameter of the microsphere is desired as large as possible for the application of the laser-trapping-based microprobe.

5 Conclusion

We proposed a surface texture imaging technique using a laser-trapping-based microprobe. In this paper, the fundamental characteristics of using a microsphere as a microlens for imaging were investigated. The findings are summarized as follows:

1. Surface images could be obtained using the microsphere with a gap between it and the surface. Therefore, this scheme is applicable for a laser-trapping-based microsphere.
2. Depending on the positions of the microsphere and focal point of the objective lens, either a real or virtual image of the surface texture was available. The contrast of the virtual images is higher than that of real images.
3. Magnification and contrast also depend on the imaging configuration. Therefore, to measure surface texture, the positions of the surface and microsphere must be precisely measured.

As future works, configuration of the laser-trapping-based microprobe must be optimized to address the aberrations and the spatial frequency response as an imaging system.

Author's contributions: Masaki Michihata wrote the main text. Kosuke Takami, Masaki Michihata, and Terutake Hayashi contributed to conceptual development. Kosuke Takami contributed to the experimental work. Yasuhiro Takaya and Terutake Hayashi contributed equally to the intellectual development of this paper.

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