Measurement 107 (2017) 165–171

Contents lists available at ScienceDirect

Measurement

journal homepage: www.elsevier.com/locate/measurement

A non-imaging optical system for characterisation of ball-shaped micro-indenters

Zhi Li [*], Uwe Brand, Febo Menelao, Mona Herdin, Andre Felgner

Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany

ARTICLE INFO

Article history:
Received 17 October 2014
Received in revised form 8 June 2016
Accepted 5 July 2016
Available online 6 July 2016

Keywords:
Confocal microscopy
Micro- and nanoindentation
Indenter
Rockwell indenter
Ball-shaped indenter
Radius measurement

ABSTRACT

To quantitatively determine the tip radius of spherical/conical and Rockwell micro-indenters, a practical tip radius measurement system is presented. Realization of the optical system has been detailed, including its theoretical and actual resolution and error sources. For the purpose of experimental investigation of the performance of the non-imaging radius measurement system, a sapphire sphere with a nominal radius of 200 μm has been measured. Detailed data analysis indicates that higher-order form deviation of the object under test might be one of the key error sources within the calibration setup. Further experiments indicate that the prototype of the non-imaging system is able to measure real conical and Rockwell indenters with adequate resolution.

1. Introduction

Hardness testing is one of the important approaches to determine the mechanical properties of materials. With the help of Finite Element Analysis more mechanical properties, like Young's modulus and yield strength, can be interpreted from those typical indentation testing data [1,2]. The measurement uncertainty of hardness tests is, however, subject to a few factors, in which the form error of the indenter in use is always one of the significant error sources. To improve the measurement uncertainty, it is therefore strongly suggested to calibrate the geometric form of indenters before being used [3].

Typical means for geometrical characterisation of an indenter can be classified into two types: reference material method and direct calibration approach. In the former approach, a indenter under calibration is firstly used to make series of indents on reference materials (i.e. materials with known mechanical properties), its tip area function (and geometrical deviation) can then be determined from the measurement data with different mathematical methods [3,4]. The reference material approach is therefore flexible and cost-effective. However, the calibration accuracy of this approach depends, to a large extent, on the effectivity of the evaluation models in use [5]. Direct measurement of the tip geometry of an indenter hence gains more and more interest in the past years, especially for interpretation of indentation data with 3-D finite element modeling.

Typical means for calibration of the microform of an indenter is to employ micro-coordinate measuring machines [6–8], or even a nanomeasuring machine [9], which features large measurement ranges (up to tens of mm) with nanometer resolution, to measure directly the 3D topography of a micro-indenter. This calibration approach features therefore relatively high universality, and can be applied for almost all kinds of indenters. In the mean time, as demonstrated in [9,10], this method suffers from such shortages as being time-consuming and complicated data evaluation.

Optical imaging methods and instruments, including interference microscopy and confocal microscopy, demonstrate high resolution and relatively easy operation, and therefore have also been applied for characterisation of various indenters[12,11]. However, due to its relatively small lateral and vertical measurement range for curved surfaces, a conventional interference or confocal microscope is suitable for direct measurement of the overall topography of a micro-indenter. To obtain the 3D geometry of an indenter, one of the usual ways is to use the image stitching technique to put together numbers of sub-region images of the indenter, which would, in return, impose high requirements to the 3D scanning system [13,14].

In this manuscript, for the purpose of cost-effective characterisation of ball-shaped micro-indenters, especially for evaluation of the tip radius of spherical indenters, Rockwell indenters, or conical indenters with tip rounding, a non-imaging optical system is pre-

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* Corresponding author.
E-mail address: zhi.li@ptb.de (Z. Li).

http://dx.doi.org/10.1016/j.measurement.2016.07.019
0263-2241/

sented. The fundamental principle of this system is detailed in Section 2. System realization is discussed in Section 3. Experimental investigation of the measurement capability of the calibration setup is demonstrated and discussed in Section 4. Further development of this system is outlined in Section 5.

2. Principle

The non-imaging tip radius measuring system is developed on basis of a confocal position-sensing method [15]. The fundamental optical principle of this system is illustrated in Fig. 1: monochromatic light with a plane wavefront is delivered into the optical system to illuminate the sample to be measured, yielding a focused spot on the focal plane of the objective. The reflected light coming from an object under test is collected by the same objective and then focused in the back focal plane of a tube lens, and finally detected by a point-like photo-detector.

For a spherical object, assuming that the sphere radius R be far larger than the focused spot size, the maximum signal intensity would appear when

(a) the top surface of the object is in the focal plane of the microscope objective (z = Pos1), or when
(b) the center of the sphere under test is located in the objectives focal plane (z = Pos2), as illustrated in Fig. 1.

Obviously, in the case of an ideal optical system (e.g. without lens aberrations and positioning and alignment errors) and an ideal sphere under test (e.g. highly reflective, no form deviation, fully smooth, etc.), the radius of the sphere under test can be determined by measuring the distance between positions Pos1 and Pos2, i.e. $R = z_{\mathrm{Pos2}} - z_{\mathrm{Pos1}}$.

2.1. The axial resolution of the confocal positioning system with respect to different indenters

In the case of measuring a flat surface at the position $z = z_{\mathrm{Pos1}}$ or an ideal sphere at $z = z_{\mathrm{Pos2}}$, the theoretical axial resolution of the optical system using an aberration-free objective in air amounts to [16]

$$\delta z = \frac{1.26\lambda}{A_N^2}. \qquad (1)$$

where λ is the illumination wavelength used in the microscope. Obviously, the axial resolution of a confocal microscope would decrease radically if the numerical aperture A_N of the employed microscope objective is reduced slightly. Taken as examples, in case of $A_N = 0.75$ with $\lambda = 632.8$ nm, a perfect confocal position sensor would reach an axial resolution of 1.42 µm, and when $A_N = 0.5$, its axial resolution becomes about 3.2 µm.

The real axial confocal resolution of the optical system for measuring a real indenter at the position $z = z_{\mathrm{Pos2}}$ is also subject to the geometrical form of the object under test (and its spatial holding status [15]). Taken as an example, for a Rockwell indenter with its mounting axis parallel to the optical axis of the objective, as shown in Fig. 2, the effective A_N of the objective (and the measurement system) is reduced to be 0.5, since the reflected light from the shoulder of the indenter could not be collected by the objective.

2.2. A practical approach to improve the resolution of confocal position sensor for determination of the tip radius of a Rockwell indenter

As detailed in Fig. 2, a Rockwell indenter would have a spherical surface only within the semi-apex angle of 60°, which determines actually the ultimate axial resolution of a confocal position sensor. For the purpose of resolution enhancement, one can apply a few sophisticated approaches to improve the axial resolution of confocal microscopy, e.g. proposed in Ref. [[17,18]], which are either complicate for preparation or inconvenient for operation.

Here a simple strategy is suggested to improve the positioning accuracy of the calibration system, as illustrated in Fig. 3: a Rockwell indenter under calibration is firstly rotated relative to its central point with an angle φ, and then mounted into the optical system. The actual numerical aperture of the measuring system $A_{N_{\mathrm{eff}}}$ can now be effectively enhanced, since the reflected light from the indenter surface can now illuminate the high aperture part of the objective.

Given a well-corrected objective obeying the so-called sine condition (s.a. Fig. 1), i.e. $r = f \cdot n \cdot \sin\theta$, where f is the focal length and $n \cdot \sin\theta = A_N$ the corresponding numerical aperture of the objective, respectively, the maximum $A_{N_{\mathrm{eff}}}$ for detecting the position Pos2 can be achieved if the in-plane rotating angle φ of the Rockwell indenter under test can amount to

$$\varphi = \arcsin(A_N) - 30^\circ. \qquad (2)$$

3. System design, data evaluation and measurement error analysis

The optical system of the calibration setup is shown in Fig. 4. It consists of two parts: a confocal position-detecting system, and an auxiliary microscope for viewing the object under test.

The light coming from a point-like source (e.g. single-mode/multi-mode fiber) is firstly collimated by an achromatic lens, and delivered to the microscope objective by means of a relay-lens pair $R_1 - R_2$. The diameter of the collimated beam can be adjusted by an iris aperture. An additional polarizer can be used to optimize the polarization properties of the illumination beam, if a multi-mode fiber is used as the light source.

After passing through a polarizing beamsplitter (PBS), the input beam (measurement beam, p-polarized) would be focused onto the object under test. The reflected measurement beam shall be collected by a tube lens, and focused on a CCD camera (Pixelink, PL-B952, pixel size 4.65 µm × 4.65 µm), acting as the point detector for confocal imaging. A polarizer in front of the camera helps to control the light intensity focused on the camera.

3.1. Positioning system

A three-axis positioning stage (NanoMax 303, Thorlabs) [19] with two differential micrometers for x–y axis and a stepper-motor drive for z-axis is employed in the measurement system for pre-adjustment and fine positioning of the object under test.

The two manual micrometers of the stage for lateral positioning feature a resolution of about 1 µm. The achievable z-axis incremental movement resolution with the stepper motor can be up to 60 nm, however the actual repeatability is found to be not better than 0.5 µm. In addition, the cross-talk of this stage for a small positioning range of 500 µm amounts to about 2 µm [8].

3.2. Data evaluation

During the pre-adjustment and fine positioning of the object under test, the lateral position of the focal point of the reflected light on the CCD camera can be determined.

The confocal response of the measurement system close to the interested positions Pos1 and Pos2 of the object under test is acquired by measuring the intensity variation of the reflected light with respect to the z-axis position of the spherical object.