

CLAIMS

1. A method of generating a composite image of a non-flat surface of a test object using a microscope, the method comprising:

acquiring, using the microscope, a plurality of three-dimensional images of different areas of the non-flat surface, where each image comprises a region of overlap with at least one adjacent image, the microscope having sufficient resolution to image in the overlap region and in three dimensions a microstructure on the non-flat surface having a lateral dimension of 10 microns or less and a height of 10 nm or less;

identifying, for each region of overlap, a corresponding microstructure having a lateral dimension of 10 microns or less and a height of 10 nm or less;

determining, for each of the images, a set of rigid body parameters relating a position and an orientation of the test object in the image to a common coordinate system, where the set of rigid body parameters is determined by fitting the resolved microstructure in the overlap region in the image with the corresponding microstructure in the overlap region of the adjacent image,

wherein fitting the resolved microstructure in the overlap region in the image with the corresponding microstructure in the overlap region of the adjacent image is performed for a series of adjacent image pairs, and

wherein, for each adjacent image pair, the fitting results in an intermediate set of rigid body parameters relating a relative position and orientation of the test object between the images in the image pair;

performing a global optimization to obtain a final set of rigid body parameters that best matches the intermediate sets of parameters; and

combining the plurality of images based on the final set of rigid body parameters to generate a composite image of the surface.

2. The method of claim 1, wherein the non-flat surface comprises at least two locations having respective normals that form an angle greater than 20 degrees, greater than 30 degrees, greater than 45 degrees, or greater than 60 degrees.

3. The method of claim 1, wherein the final set of rigid body parameter comprises at least two translation coordinates and at least two angular coordinates.

4. The method of claim 1, wherein the final set of rigid body parameters comprise at least five coordinates.

5. The method of claim 4, wherein the final set of rigid body parameters comprise six coordinates.

6. The method of claim 1, wherein the final set of rigid body parameters is sufficient to relate the orientations of at least two locations of the non-flat surface to one another, wherein the at least two locations have respective normals that form an angle greater than 10 degrees, greater than 20 degrees, greater than 30 degrees, greater than 45 degrees, or greater than 60 degrees.

7. The method of claim 1, wherein the final set of rigid body parameters comprise three orthogonal rotation angles.

8. The method of claim 1, wherein the different areas of the plurality of three dimensional images comprise at least two locations having respective normals that form an angle greater than 10 degrees, greater than 20 degrees, greater than 30 degrees, greater than 45 degrees, or greater than 60 degrees.

9. The method of claim 8, wherein acquiring the images with the microscope comprises sequentially orienting that test object so that the locations have their respective normals substantially parallel to an axis of the microscope.

10. The method of claim 9, wherein the microscope comprises a mount configured to hold the test object and orient it over a range of orientations sufficient to sequentially make normals of the locations substantially parallel to the axis of the microscope.

11. The method of claim 1, wherein an area of the composite image is larger than a field of view of the microscope.

12. The method of claim 1, wherein the test object is translated relative to the microscope for successive images.

13. The method of claim 1, wherein the test object is rotated relative to the microscope for successive images.

14. The method of claim 1, wherein the test object is rotated based on a curvature of the non-flat surface to orient a portion of the non-flat surface in a field of view of the microscope appropriately for imaging using the microscope.

15. The method of claim 13, wherein a relative rotation of the test object for at least some of the images is 10° or more.

16. The method of claim 1, wherein the non-flat surface has a RMS surface roughness of 1 nm or less.

17. The method of claim 1, wherein the non-flat surface is an optically smooth surface.

18. The method of claim 1, wherein the test object is an aspheric lens.

19. The method of claim 1, wherein determining the set of rigid body parameters comprises calibrating the plurality of three-dimensional images prior to fitting resolved microstructure.

20. The method of claim 19, wherein calibrating the plurality of three-dimensional images comprises:

acquiring, using the microscope, an image of a reference mirror; and

subtracting the reference mirror image from each of the three-dimensional images.

21. The method of claim 19, wherein acquiring the plurality of three-dimensional images comprises detecting the images using a multi-element detector, and wherein calibrating the plurality of three-dimensional images comprises:

detecting at the multi-element detector an image of a reference sample comprising a pre-defined periodic surface pattern;

determining an error in a pixel pattern of the measured reference sample; and compensating each of the three-dimensional images for the error in the pixel pattern.

22. The method of claim 19, wherein acquiring the plurality of three-dimensional images comprises detecting the images using a multi-element detector, and wherein calibrating the plurality of three-dimensional images comprises, for each three-dimensional image:

determining, for each pixel of the three-dimensional image, a surface slope along two orthogonal directions;

calculating, for each pixel of the three-dimensional image, a corresponding retrace error function; and

subtracting the retrace error function from the corresponding pixel in the three-dimensional image.

23. The method of claim 1, comprising acquiring the plurality of three-dimensional images using an optical microscope.

24. The method of claim 1, comprising acquiring the plurality of three-dimensional images using a coherence scanning interferometry microscope, a phase-shifting interferometry microscope, a confocal microscope, a focus-scanning microscope, a digital holography microscope, a structured-illumination microscope, or a chromatic confocal microscope.

25. The method of claim 1, wherein acquiring the plurality of three-dimensional images comprises using coherence scanning interferometry to obtain a topography map of each of the different areas of the non-flat surface.

26. The method of claim 1, wherein acquiring the plurality of three-dimensional images comprises using a stylus to measure a topography map of each of the different areas of the non-flat surface.

27. The method of claim 1, wherein the composite image is a three-dimensional image.

28. A system for generating a composite image of a non-flat surface of a test object, the system comprising:

a microscope, the microscope having a resolution sufficient to image in three dimensions a microstructure on the non-flat surface having a lateral dimension of 10 microns or less and a height of 10 nm or less;

a stage for arranging the test object relative to the microscope, the stage having at least one rotational degree of freedom relative to the microscope and having an angular range of 10° or more for varying an angular orientation of the test object relative to the microscope; and

an electronic processor in communication with the microscope,

wherein during operation the microscope acquires a plurality of three-dimensional images of different areas of the non-flat surface, where each image comprises a region of overlap with at least one adjacent image and at least some of the images are acquired for different angular orientations of the test object with respect to the objective, and the electronic processor being programmed

to receive the images from the microscope,

to identify, for each region of overlap, a corresponding microstructure having a lateral dimension of 10 microns or less and a height of 10 nm or less,

to determine, for each of the images, a set of rigid body parameters relating a position and orientation of the test object to a common coordinate system, where the set of rigid body

parameters is determined by a) fitting the resolved microstructure in the overlap region in the image with the corresponding microstructure in the overlap region of the adjacent image for a series of adjacent image pairs, wherein for each adjacent image pair, the fitting results in an intermediate set of rigid body parameters relating a relative position and orientation of the test object between the images in the image pair, and b) performing a global optimization to obtain a final set of rigid body parameters that best matches the intermediate sets of parameters, and to combine the plurality of images based on the final set of rigid body parameters to generate a composite image of the surface.

29. The system of claim 28, wherein the final set of rigid body parameter comprises at least two translation coordinates and at least two angular coordinates.

30. The system of claim 28, wherein the final set of rigid body parameters comprise at least five coordinates.

31. The system of claim 28, wherein the final set of rigid body parameters comprise six coordinates.

32. The system of claim 28, wherein the final set of rigid body parameters is sufficient to relate the orientations of at least two locations of the non-flat surface to one another, wherein the at least two locations have respective normals that form an angle greater than 10 degrees, greater than 20 degrees, greater than 30 degrees, greater than 45 degrees, or greater than 60 degrees.

33. The system of claim 32, wherein the microscope is configured to acquires the plurality of three-dimensional images by sequentially orienting that test object so that the locations of the non-flat surface object have their respective normals substantially parallel to a measurement axis of the microscope.

34. The system of claim 33, wherein the microscope and the stage are configured to orient the test object over a range of orientations sufficient to sequentially make normals of locations on the test object substantially parallel to the optical axis of the microscope.

35. The system of claim 28, wherein the microscope and stage are configured to translate the test object relative to each other between successive images of the plurality of three-dimensional images.

36. The system of claim 35, wherein the stage comprises one or more actuators for translating the test object relative to the microscope.

37. The system of claim 28, wherein the microscope and stage are configured to rotate the test object relative to each other between successive images of the plurality of three-dimensional images.

38. The system of claim 37, wherein the stage comprises one or more actuators for rotating the test object relative to the microscope.

39. The system of claim 28, wherein the microscope further comprises a multi-element detector for detecting the plurality of three-dimensional images, and wherein the processor is configured to calibrate the plurality of three-dimensional images detected by the multi-element detector.

40. The system of claim 28, wherein the microscope is an optical microscope.

41. The system of claim 28, wherein the microscope is a CSI microscope.

42. The system of claim 28, wherein the microscope is a PSI microscope, a confocal microscope, a focus-scanning microscope, a digital holography microscope, a structured-illumination microscope, or a chromatic confocal microscope.

43. The system of claim 28, wherein the microscope comprises a stylus configured to measure a topography map of the test object.

44. The system of claim 28, wherein the microscope comprises a first sensor configured to detect the microstructure and a second sensor configured to detect a surface form of the test object.

45. The system of claim 28, wherein the composite image is a three-dimensional image.