Computerized Interferometric Measurement of Surface Microstructure

James C. Wyant and Joanna Schmit

WYKO Corporation, 2650 E. Elvira Road
Tucson, Arizona 85706, USA
www.wyko.com
&
Optical Sciences Center
University of Arizona
Tucson, Arizona 85721, USA
www.opt-sci.arizona.edu

ABSTRACT

The addition of modern electronics, computers, and software to an interference microscope greatly increases the surface height measurement capability of the interference microscope. The RMS repeatability of surface microstructure measured using a computerized phase-shifting interference microscope can be less than 0.1 nanometer. While phase-shifting interferometry having sub-nanometer height precision has limited dynamic range, the dynamic range of an interference microscope can be extended to hundreds, or even thousands, of microns by using vertical scanning coherence peak sensing techniques. This paper describes the measurement capabilities of an interference microscope employing both phase-shifting phase measurement capability and coherence peak sensing. Typical measurements obtained using phase-shifting and coherence peak sensing are illustrated. Techniques for extending the measurement capability of computerized interference microscopes are discussed.

Key Words: Interferometry, Interference, Interference Microscope, Metrology, Surface Measurement, Phase-shifting Interferometry, Coherence Sensing.

2. INTRODUCTION

While interferometry is an old science, modern electronics and computers have greatly increased the measurement capability of interferometers and hence the interest in interferometry. Without a doubt, one of the largest advancements in interferometry the last 50 years has been the introduction of phase-shifting interferometry (1-5). In phase-shifting interferometry three or more interference data frames are taken where the average phase difference between consecutive data frames is typically 90 degrees. It is easily shown that the point-by-point phase difference between the two interfering beams can be determined from the point-by-point irradiance of three data frames. Typically, 5 or 6 data frames are used instead of only 3 because the measurement sensitivity to the phase difference between consecutive frames is reduced as the number of frames is increased. Every month there are several papers published on new phase-shifting algorithms. While

0-8194-2168-5/96/$6.00

the algorithms are great, the real things that are making phase-shifting interferometry so powerful are the large CCD arrays and the powerful, low cost, computers, coupled with extensive data analysis software.

While phase shifting interferometry has great precision, it has limited dynamic range. It can easily be shown that the height difference between two consecutive data points must be less than $\lambda/4$, where λ is the wavelength of the light used. If the slope is greater than $\lambda/4$ per detector pixel then height ambiguities of multiples of half-wavelengths exist. One technique that has been very successful in overcoming these slope limitations is to perform the measurement using two or more wavelengths. If measurements are performed using two wavelengths, λ_1 and λ_2, it can be shown that the maximum height difference between two consecutive data points is $\lambda_{eq}/4$, where λ_{eq} is given by

$$\lambda_{eq} = \frac{\lambda_1 \lambda_2}{|\lambda_1 - \lambda_2|}$$

Thus, by carefully selecting the two wavelengths it is possible to greatly increase the dynamic range of the measurement over what can be obtained using a single wavelength. (6-8)

While using two wavelength phase-shifting interferometry works very well with step heights, it does not work especially well with rough surfaces. A much better approach is to use a broad range of wavelengths and the coherence peak sensing approach described below.

3. COHERENCE PEAK SENSING

In the vertical scanning coherence peak sensing mode of operation a broad spectral width light source is used. Due to the large spectral bandwidth of the source, the coherence length of the source is short, and good contrast fringes will be obtained only when the two paths of the interferometer are closely matched in length. Thus, if in the interference microscope the path length of the sample arm of the interferometer is varied, the height variations across the sample can be determined by looking at the sample position for which the fringe contrast is a maximum. In this measurement there are no height ambiguities and since in a properly adjusted interferometer the sample is in focus when the maximum fringe contrast is obtained, there are no focus errors in the measurement of surface microstructure. (9-13)

The major drawback of this type of scanning interferometer measurement is that only a single surface height is being measured at a time and a large number of measurements and calculations are required to determine a large range of surface height values. One method for processing the data that gives both fast and accurate measurement results is to use conventional communication theory and digital signal processing (DSP) hardware, or fast computers with efficient software, to demodulate the envelope of the fringe signal to determine the peak of the fringe contrast.

Figure 1 shows the irradiance at a single sample point as the sample is translated through focus. It should be noted that this signal looks a lot like an amplitude modulated (AM) communication signal. To obtain the location of the peak, and hence the surface height information, this irradiance signal is detected using a CCD array. The signal is sampled at fixed intervals, such as every 80 or 240 nm, as the sample path is varied. Low frequency and DC signal components are removed from the signal by digital highpass filtering. The signal is next rectified by square-law detection and digitally lowpass filtered. The peak of the lowpass filter output is located and the vertical position corresponding to the peak is noted. Interpolation between sample points can be used to increase the resolution of the instrument beyond the sampling interval. This type of measurement system produces fast, non-contact, true three-dimensional area measurements for both large steps and rough surfaces to nanometer precision.

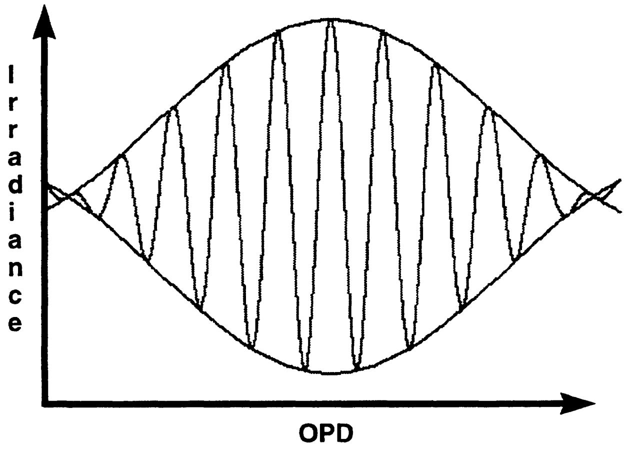


Figure 1. Irradiance at a single sample point as the sample is translated through focus.

4. OPTICAL PROFILOMETER

Figure 2 shows a simplified schematic of a phase shifting/coherence peak sensing interference microscope (called RST Plus). The configuration shown in Figure 2 utilizes a two-beam Mirau interferometer at the microscope objective. Typically the Mirau interferometer is used for magnifications between 10 and 50X, a Michelson interferometer is used for low magnifications, and the Linnik interferometer is used for high magnifications. A separate magnification selector is placed between the microscope objective and the CCD camera to provide additional image magnifications. A tungsten halogen lamp is used as the light source. In the phase shifting mode of operation a spectral filter of 40 nm bandwidth centered at 650 nm is used to increase the coherence length. For the vertical scanning mode of operation the spectral filter is not used. Light reflected from the test surface interferes with light reflected from the reference. The resulting interference pattern is imaged onto the CCD array. The output of the CCD array can be viewed on the TV monitor. Also, output from the CCD array is digitized and read by the computer. The Mirau interferometer is mounted on either a piezoelectric transducer (PZT) or a motorized stage so that it can be moved. During this movement, the distance from the lens to the reference surface remains fixed. Thus, a phase shift is introduced into one arm of the interferometer. By introducing a phase shift into only one arm while recording the interference pattern that is produced, it is possible to perform either phase-shifting interferometry or vertical scanning coherence peak sensing interferometry. The complete RST-Plus system includes a Pentium computer running Microsoft Windows for data analysis and graphics display.

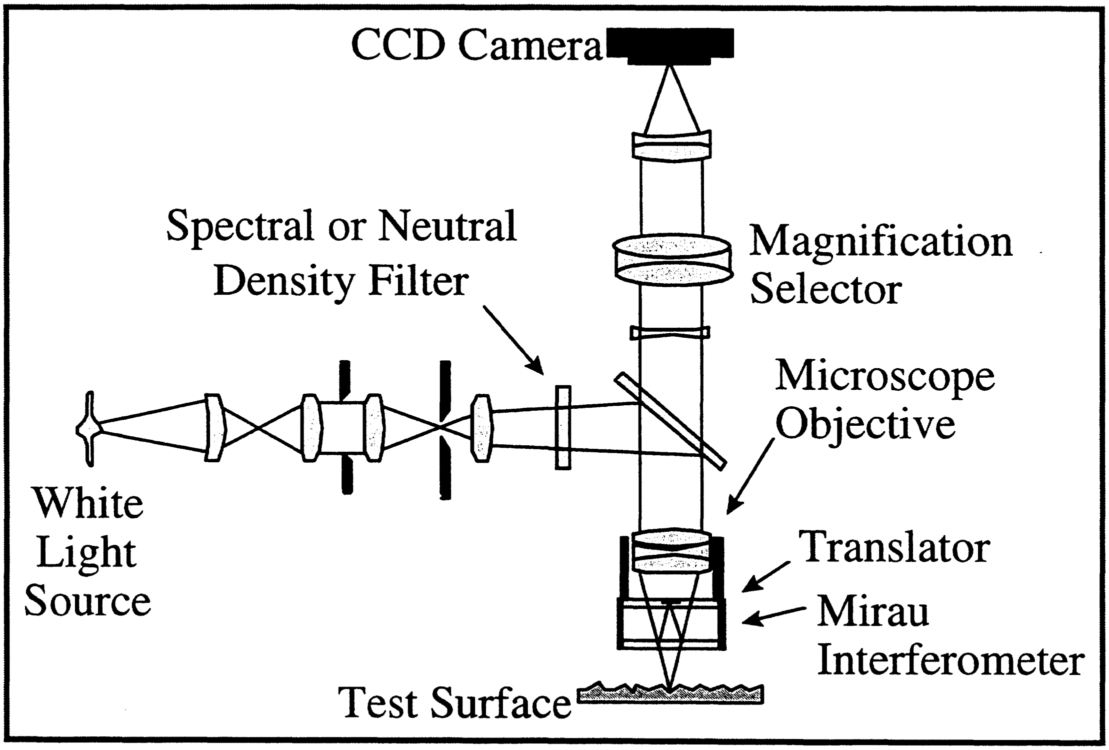


Figure 2. Optical schematic of interference microscope used for measurement of fine surface structure.

5. TYPICAL MEASUREMENTS

Figure 3 shows the point-by-point difference between two measurements performed using phase-shifting interferometry. The RMS difference of 0.04 nm clearly shows the high precision of the technique.

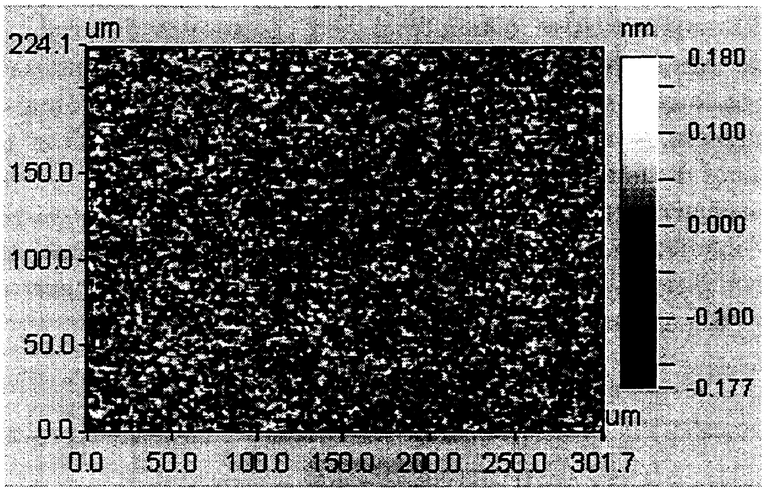


Figure 3. Point-by-point difference between two phase-shifting interferometry measurements. RMS of difference is 0.04 nm, P-V is 0.36 nm.

Figure 4 shows a phase-shifting measurement of the end of a fiber optic connector. In this example the optical fiber in the center of the connector is masked out to emphasize the surface quality of the connector.

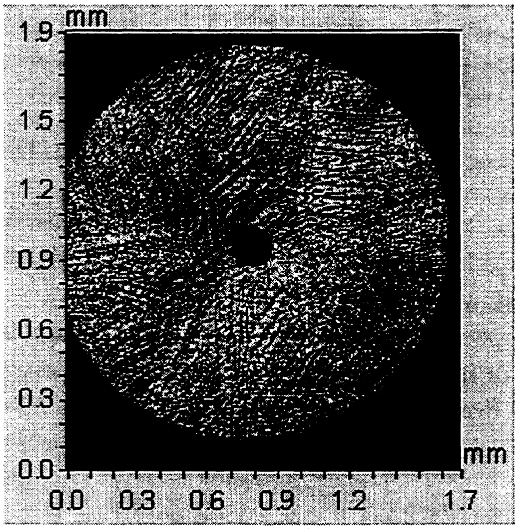


Figure 4. Fiber optic connector (RMS 108 nm, P-V 1.04 microns).

Figure 5 shows a vertical scanning coherence peak sensing measurement of a micromachined silicon part. For this example the RMS of the surface is 2.3 microns and the P-V is 6.16 microns.

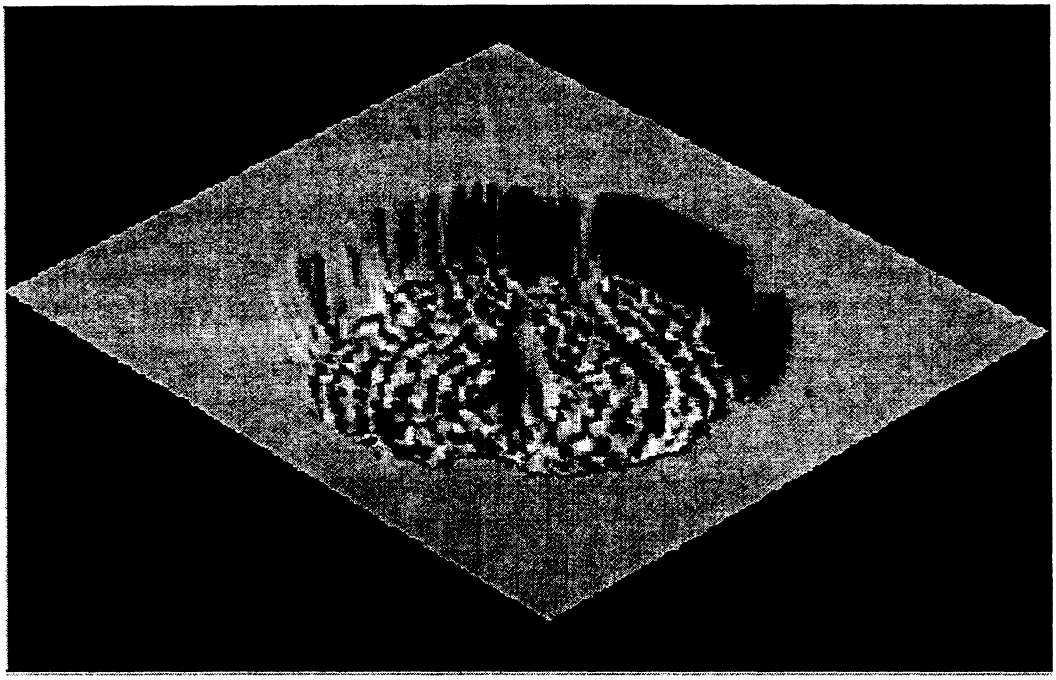


Figure 5. Vertical scanning coherence peak sensing measurement of laser etched silicon (RMS 2.30 microns, P-V 6.16 microns).

6. EXTENDING THE MEASUREMENT CAPABILITIES

An interference microscope having both phase-shifting measurement capabilities and coherence peak detection capabilities is found to be extremely powerful and it can measure the surface microstructure of almost anything. Sometimes the measurements are so amazing that they have to be seen to be believed. Due to the wide range of measurement capabilities it is sometimes convenient to modify the conventional interference microscope configuration to take full advantage of the measurement capabilities. Three modifications of interest are 1) portable system, 2) modify to fit inside of small areas, and 3) addition of computer controlled stage having optical encoders to enable the stitching together of several small field-of-view measurements to obtain a large field-of-view measurement having the spatial resolution of the smaller field-of-view measurement.

6.1 Portable interference microscope

Sometimes the part being measured is so large that it does not make sense to bring the part to the microscope, but rather it is necessary to take the interference microscope to the part. In such cases not only must the microscope be portable, but also often the interference microscope must be able to work in less than ideal environments. In interferometric measurements it is important that the vibration is sufficiently small that good measurements can be obtained. An approach that works well for reducing the effects of vibration is to couple the measuring instrument to the part being measured, and then while both the part being measured and the measuring interference microscope vibrate, they vibrate together.

Figure 6 shows a portable interference microscope (Rollscope) that can perform both phase-shifting and coherence-peak detection. If necessary, the Rollscope can be put on top of the part being measured to reduce the effects of vibration. The Rollscope has found to be very useful for the testing of printing rollers, where the rollers are often very large, and they are located in locations of high vibration.

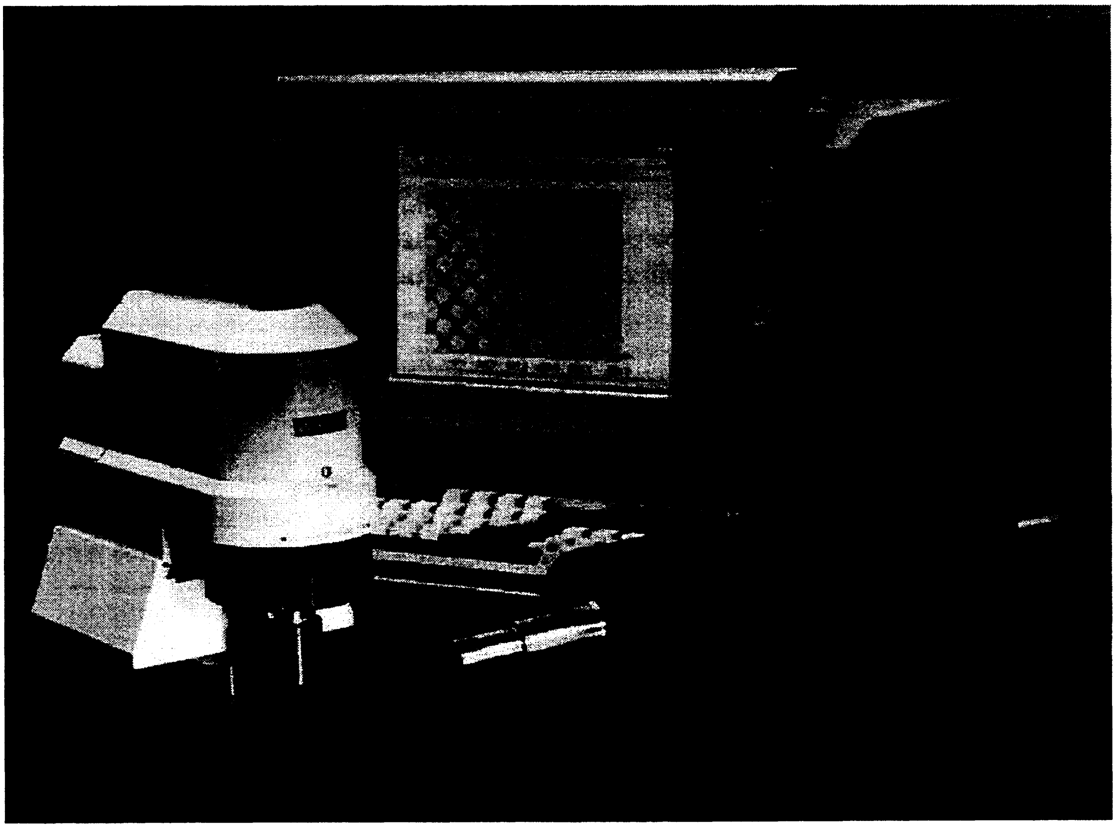


Figure 6. Portable interference microscope having phase-shifting and coherence peak sensing capability (Rollscope).

Figure 7 shows a vertical scanning measurement of a print roller. The pits in the roller are clearly measured, and the volume of these pits can be calculated if desired to give a measure of the performance of the print roller as the surface wears during use. The measurement works very well even though the light reflected off the roller back into the interference microscope varies greatly across the print roller cells as shown in the lower right corner of Figure 7.

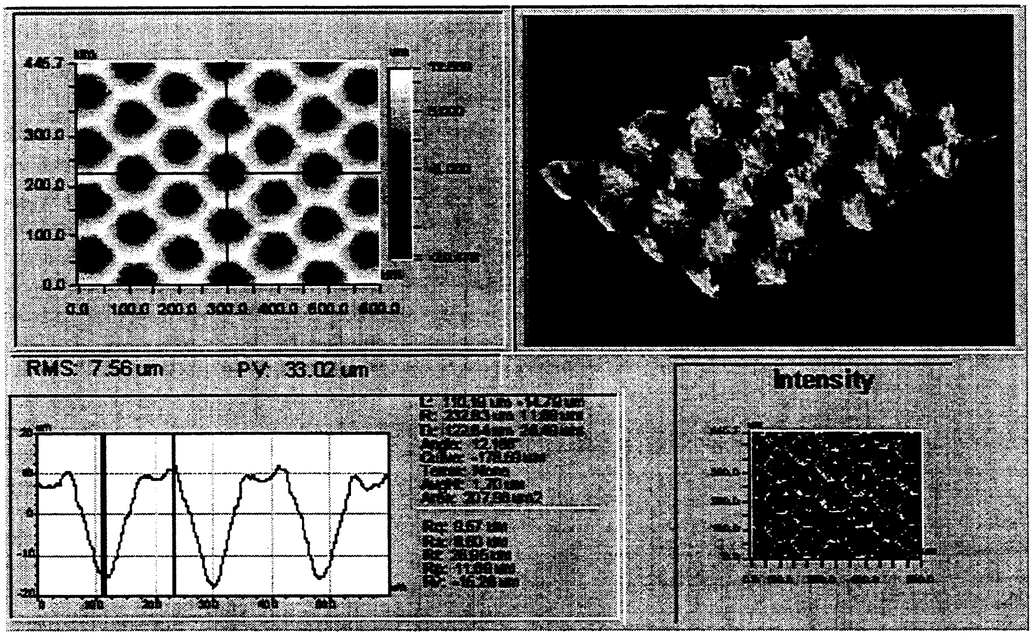


Figure 7. Vertical scanning coherence peak sensing measurement of print roller (RMS 7.56 microns, P-V 33.02 microns).

6.2 Measuring in small places

Sometimes it is desirable to perform microstructure measurements inside of a part. Of particular interest is the ability to measure the microstructure of the inside of an engine cylinder bore.

Figure 8 shows a version of the RST (Insight 2000) made to measure engine cylinder bores. In this case the vertical scanning coherence peak sensing is the preferred measurement technique. The measurement of the cross hatch angle of the surface structure is of particular interest. This cross hatch angle can be determined by calculating the power spectral density function (PSD) of the surface microstructure and finding the position of the peaks in the PSD. Figure 9 shows the results of calculating the cross hatch angle from the measurement of an engine cylinder bore.

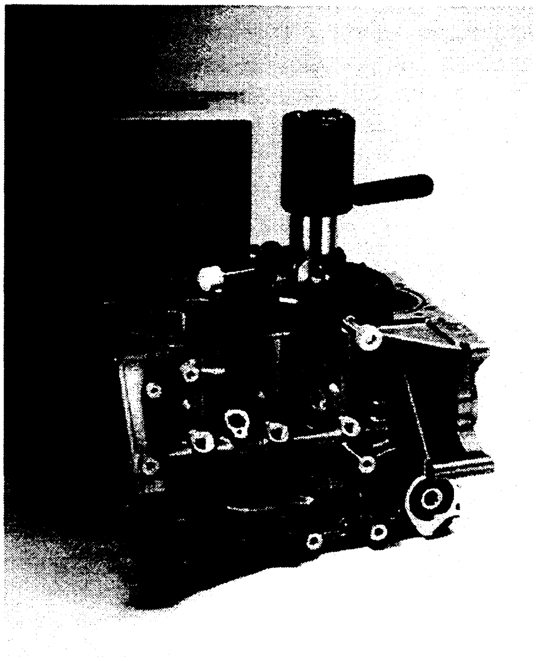
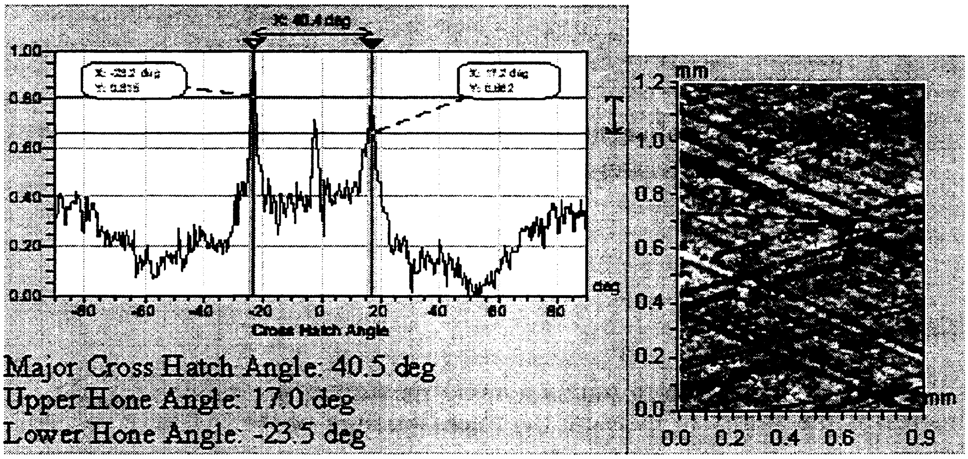


Figure 8. Insight 2000 in engine cylinder.



Major Cross Hatch Angle: 40.5 deg
Upper Hone Angle: 17.0 deg
Lower Hone Angle: -23.5 deg

Figure 9. Measurement of cross hatch angle in a cylinder bore.

6.3 Large FOV and high spatial frequency resolution - stitching

In the measurement of microstructure high spatial resolution is required. However, this means that the field-of-view must be small since the maximum number of data points that can be measured across a field of view is limited by the number of pixels in a CCD array to be on the order of 1000 points. However, if the sample is mounted on a computer controlled x-y stage having precision optical encoders, it should be possible to measure several small field-of-view images of the sample and stitch the images together to obtain a larger field-of-view measurement without significant loss in spatial or height resolution. Typically there needs to be some overlap between data sets so over the region of overlap the piston and tilt of the two measurements can be matched. We have found a 20 per cent overlap to be acceptable. The measurements of smooth surfaces obtained using phase-shifting interferometry and rough surfaces obtained using coherence peak sensing both give good results.

Figure 10 shows the results of measuring a thin film resistor. In this example 12 sub-regions were stitched together. We have stitched together as many as 80 sub-regions.

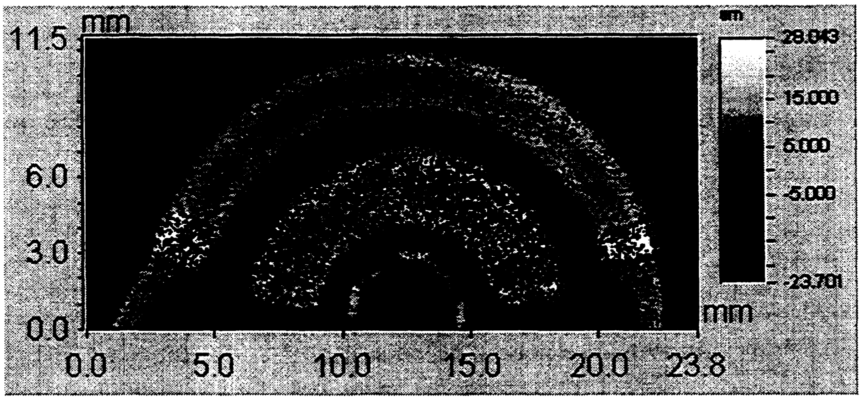


Figure 10. Thin film resistor. 6 x 2 stitched images. 23.8 x 11.5 mm FOV.

Figure 11 shows an example of the measurement of a thin, narrow, sample, in this case a lapping bar used in the making of magnetic heads. Both the overall shape and the microstructure are of interest. In this example 12 individual measurements were stitched together to measure the 56.2 mm length. The lower part of the figure shows a zoomed version of 5 % of the total length of the bar. In addition to a local overall curvature along the length of the bar, a lot of surface microstructure is observed.

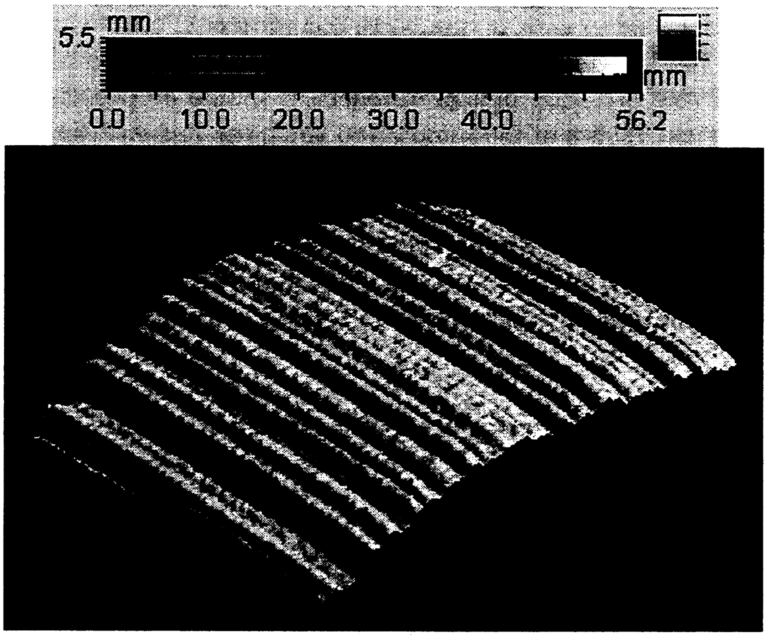


Figure 11. Lapping bar. Bottom picture shows 5% of the length of the bar.

7. CONCLUSIONS

By using phase-shifting interferometry for the measurement of the microstructure of smooth surfaces and vertical scanning coherence peak sensing for rough surfaces it is possible to measure the surface microstructure of almost any surface. Surfaces having a reflectance of less than 1 % can be easily measured. Portable systems that can make contact with the surface being measured can be used in environments having much vibration since both the surface under test and the instrument can be made to vibrate together. Interference microscopes can be made in several form factors so measurements can be performed in small places. By combining computer controlled stages having precision optical encoders with interference microscopes it is possible to stitch together many small field-of-view, high spatial resolution measurements to obtain a large field-of-view, high spatial resolution measurement.

8. REFERENCES

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