Phase shift reflectometry for sub-surface defect detection

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ABSTRACT

Phase Shift Reflectometry has recently been seen as a novel alternative to interferometry since it can provide warpage measurement over large areas with no need for large optical components. To confirm its capability and to explore the use of this method for sub-surface defect detection, a Chinese magic mirror is used. This bronze mirror which dates back to the Chinese Han Dynasty appears at first sight to be an ordinary convex mirror. However, unlike a normal mirror, when illuminated by a beam of light, an image is formed onto a screen. It has been hypothesized that there are indentations inside the mirror which alter the path of reflected light rays and hence the reflected image. This paper explores various methods to measure these indentations. Of the methods test Phase Shift Reflectometry (PSR) was found suitable to be the most suitable both in terms of the sensitivity and the field of view.

Keywords: Magic Mirror, Sub-surface defect, Microscope, Interferometer, Phase Shift Reflectometry

1. INTRODUCTION

Measurement of sub-surface defects is vital in precision optical components – especially the sub-surface damage. High hardness and the brittle nature of glass and ceramics make them difficult to machine and sub-surface cracks are thus unavoidable. There are various approaches that have been proposed both destructive and non-destructive [1]. Optical methods proliferate for non-destructive imaging of sub-surface defects. Of these laser scattering and confocal techniques were the first [2], followed by Total Internal Reflection Microscopy (TIRM) [3], and Optical Coherence Tomography [4] and white light interferometry. In most of these cases, the field of view is generally small since the feature to be detected is typically ~10 µm. Hence there is a need to develop technologies which have a larger field of view. Of these, techniques based on polarization of light [5] and phase shift reflectometry [6] seem to show promise. In this paper, we use a Chinese magic mirror as a test specimen to measure the indents just below the surface of the mirror. The magic mirror is a convex bronze mirror, an ancient artefact that dates back to the Han Dynasty. It is magical in a sense that when parallel light rays strike the polished convex mirror surface, an image appears on a screen in front of the mirror (Fig 1).

There are two schools of thought on the principle of the method. The first suggests that slight changes in surface curvature are generated due to differences in the rate of solidification of the cast bronze caused by differential thickness of the cast caused by pattern on the back [7]. The second approach which is more recent is that indentations on the back surface give minute protrusions on the front that forms the image by reflections [8]. This mirror provides some of the challenges which may be encountered in sub-surface imaging and hence has been used as a test sample.

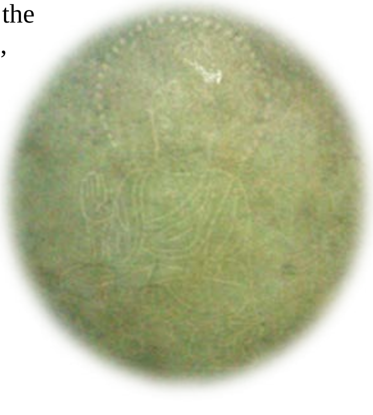

Figure 1 – Image from a Magic Mirror

2. EXPERIMENTAL METHODOLOGIES

2.1 Microscope

Microscopes provide high resolution images of the surface of the sample. However, these images are generally two dimensional pictures of the surface of the specimen or the specific plane which is to be imaged. The confocal microscope enables 3-D visualization of the surface but as with the microscope provides images over a very small field of view. The Atomic Force Microscope (AFM) or the Scanning Electron Microscope (SEM) also provides 3-D surface views with

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very high sensitivities but again at the cost of a very small field of view. None of these techniques were able to see any surface variations or the sub-surface indents on the magic-mirror. All that was observed as shown in fig. 2, were some intensity variations possibly caused by surface damage of the mirror. There were some indications of indents as in the SEM

Figure 2 (a) Microscope Image (b) Confocal Image (c) SEM image

2.2 Interferometer

Interferometers are widely used for testing of the surface profile of reflecting and refracting surfaces with very high resolution and over relatively large areas. Of the many types of interferometer, the Fizeau interferometer, schematically shown in Fig. 3(a) is the most widely used for optical testing due to its compact size and flexibility for testing various surfaces. Interferometers measure the optical path difference between the test sample and a reference surface. Usually the reference surface profile is similar to that of the test sample, which allows the interference fringes to be analyzed easily. Hence for flat surfaces, a flat reference is used. Such a flat reference would not work for the convex mirror surface and as the lab. did not have an appropriate reference, the results from the interferometer were inconclusive. In order to generate a suitable a reference an additional lens was introduced into the optical path of the interferometer which created a converging wave whose wavefront was similar to the sample to be tested. However, by inserting the lens, a new surface was introduced into the optical path and its characteristics had to first measured and then subtracted from the final result. Also since the curvature obtained from this lens (one which was available in the lab) was not exactly similar to the test surface and also since the aperture of this lens was small, only a part of the image could be observed. Figure 3(b) shows the difference image recorded by subtracting the wavefront of the additional lens. It clearly shows the profile of the surface which provides the image similar to that in Fig. 1.

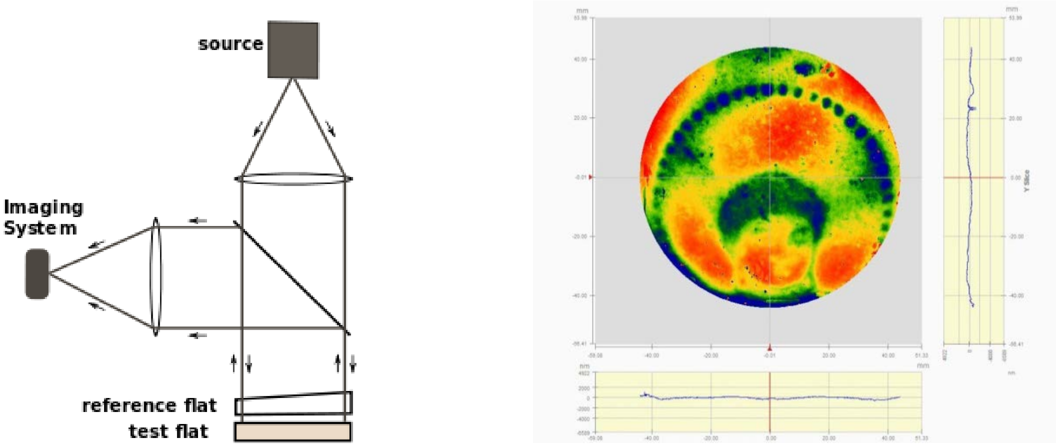


Fig. 3(a) Schematic of a Fizeau interferometer (b) Result of the magic mirror after subtracting wavefront of a beam shaping lens

2.3 Phase Shift Reflectometry

Phase shift reflectometry (PSR) is seen great advances in recent years, especially with the use of flat computer screens used to display gratings which were then reflected off the surface and imaged using a digital camera. A schematic of the system is shown in Fig. 4(a) and a photograph of the set-up is shown in fig. 4(b). Four or multiple phase shifted images

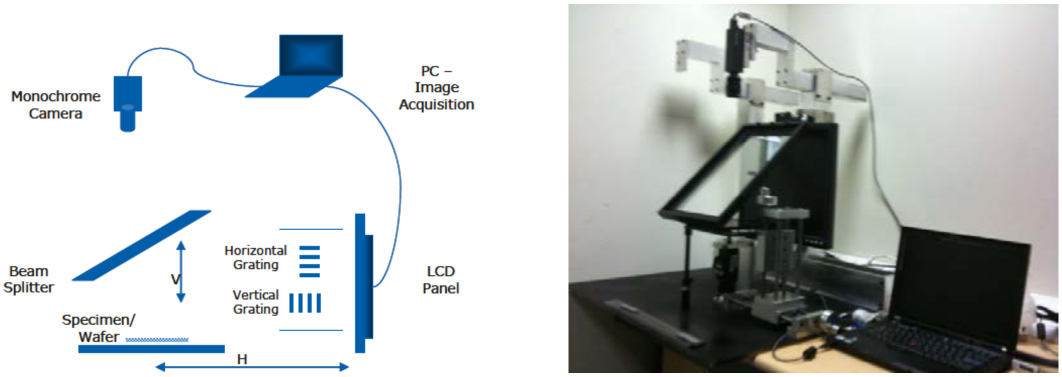
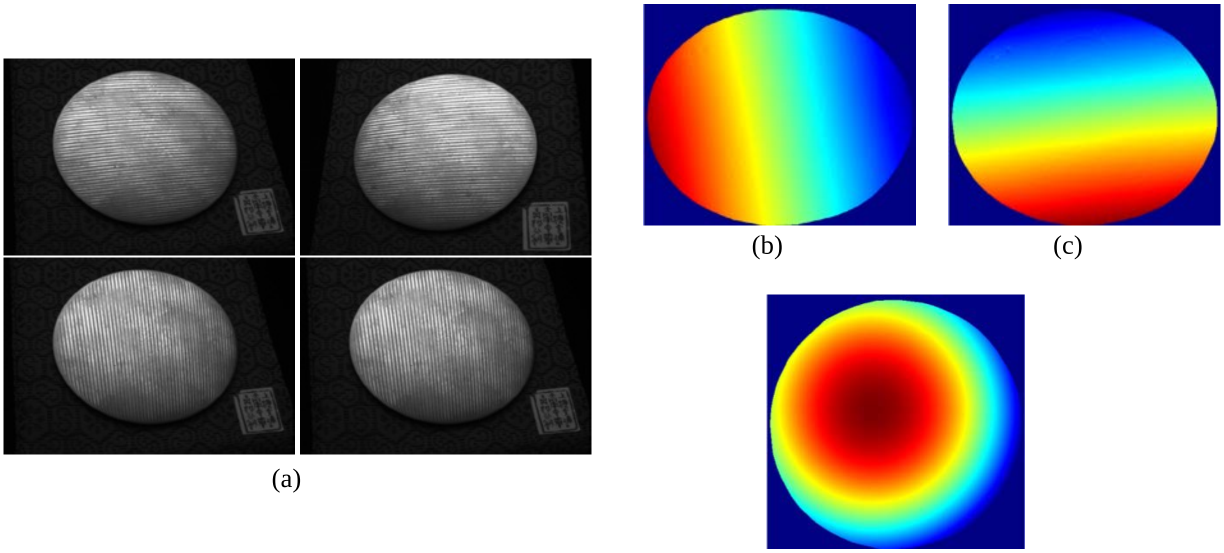


Figure 4 (a) Schematic of Phase Shift Reflectometry (b) Photograph of typical set-up.

can be recorded by suitable changing the displayed grating and the resulting phase map can be deduced using the standard phase shift algorithm. The phase shift images and the resulting phase pattern is shown in Fig. 5. The resulting phase is proportional to the slope of the surface. The slopes in two perpendicular directions are obtained by using cross gratings as shown in Figs. 5(b) and (c). Integrations of these images results in the surface warpage of the sample as shown in Fig. 5(d)


(b) (c)

(a)

(d)

Figure 5 (a) Phase shift images for vertical grating (b) resulting phase map (c) Phase map for horizontal grating (d) integration of the phase maps in (b) and (c).

The PSR was then used to image the magic mirror, the resultant phase map obtained profiles not only the surface of the mirror but also the small indentations or surface variations caused by the indents or sub-surface defects. Hence in order to measure these small variations, the global surface has to be subtracted, much like the case for the interferometer. The resulting surface variations are shown in Fig. 6. The indents or sub-surface dents of the magic mirror are clearly visible and take the shape of the projected image of Fig. 1. It is also noted that the indentations or surface variations caused by these dents are very small, typically less than 1 µm.

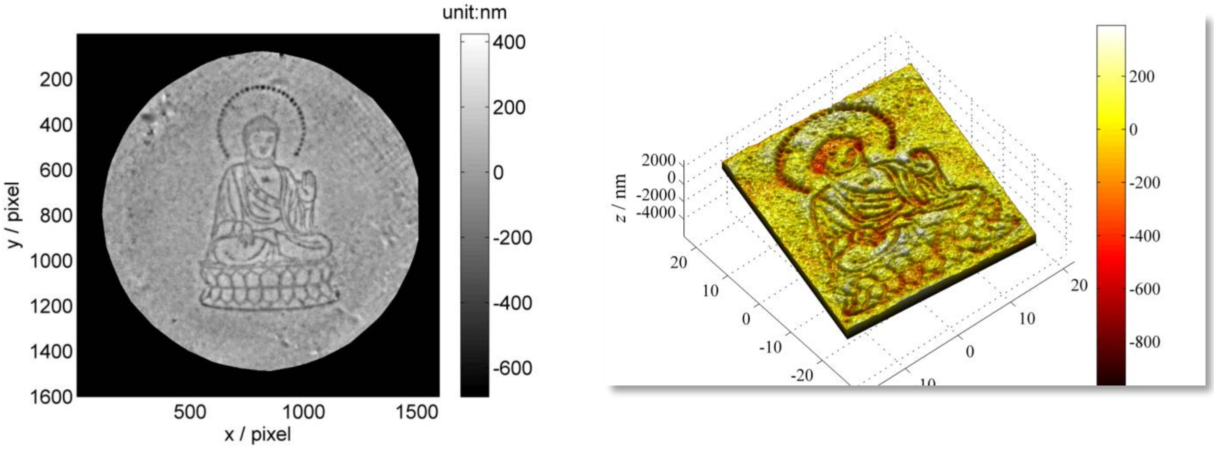


Figure 6 3-D profiles of the magic mirror indentations after removing the global profile of the mirror.

3. CONCLUSION

Phase Shift Reflectometry has shown great potential for measurement of large surfaces with very high resolution without the need for high quality and large reference optics as in the case of interferometers. However the system does has some ways to go in order to accurately quantify the profile of the surface. Specifically, there is an integration process involved in converting the recorded phase data to height profiles. This requires calibration of the optical parameters including the lenses and cameras – which is somewhat akin to 3D Phase Shift Profilometry. However, the system could be used in a manner similar to interferometers to get relative height differences between a test surface and a standard reference with similar profile. The large field of view of such system has made it amenable to measuring warpage and curvature of Si-wafers for residual stress and flatness profiling. It can also used for dynamic applications where the surface of liquids could be accurately mapped for distortions caused due to external perturbances. The Magic Mirror while appearing to be a simple object has infact a lot of intricate optical features which enable it to be used as a novel tool for encouraging youngsters to understand the diversity of optics and optical engineering much the same way as holograms provide an eye catching 3D display.

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