SPECKLE REFERENCING – Digital Speckle Pattern Interferometry (SR-DSPI) for Imaging of Non-Diffusive Surfaces

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ABSTRACT

Optical metrology has been widely employed as a key technique for modern industrial production, owing to its fast, precise and non-invasive measurement. Digital speckle pattern interferometry (DSPI) is one of these non-destructive testing methods that possess the abilities to measure surface deformation, vibration and profile. However, one of the challenges with DSPI is the incapability to address the imaging of non-diffusive surface, owing to the failure to form speckle pattern. In this paper, we demonstrate a modified DSPI system used for non-diffusive surface measurement. Experiment has been carried out to validate this modified DSPI by using metal-alloy surface as testing sample. The speckle fringe pattern generated by applying an external load was analyzed to obtain the 3-D surface deformation parameters.

Keywords: non-diffusive surface, laser speckle, digital speckle pattern interferometry, speckle referencing

1. INTRODUCTION

Recently the super-alloy has been increasingly used in aerospace and automotive industries owing to its superior properties such as high temperature strength, high stiffness, high wear resistance and high resistance to chemical erosion[1-3]. The measurement and analysis of the alloy surface are of great importance to evaluate its functionality and performance[4-5]. Optical metrology techniques have been widely and intensively explored for the measurement of engineering surface. Instead of using the stylus-based technique, optical techniques can obtain the surface information with high precision in a non-contact or non-invasive manner. As there is no such global solution to address all the surfaces regarding to their unique surface properties such as roughness, reflectance, shape complexity and dimension, various optical metrology systems have been proposed to address their particular scenario. Conventional interferometers, such as Fizeau[6-7], Twyman-Green interferometer[8-9], can measure the optically smooth surface with resolution down to nanometer, but might lose their feasibility when addressing non-spherical surface. Fringe projection and reflection techniques (FPT[10-11] and FRT[12-13]) are the good solutions to measure free-form surfaces, however FPT and FRT both have inherently limited working range regarding to the surface roughness[14]. The white light interferometry could be another solution to measure the free-form surface with rough or specular property[15-16]. However this method requires an axial scanning to seek the optical length matching, which is time-consuming especially when the surface has large dimensions. Digital speckle pattern interferometry (DSPI), as a full-field and scanning-free optical technique, can accurately measure the surface displacement[17-21], deformation[22-23], vibration[24-25], profile[26], and defects[27-28] for the further study of the engineering material. Recently with the advancing of manufacturing technologies, the surface finish of super-alloy can go down to the order of 1 µm or even lower[3, 29]. This makes the surface non-diffusive to laser light and not assessable with the conventional DSPI due to the failure to generate laser speckle pattern.

In this paper, we demonstrate to measure the deformation and superficial defect of titanium-alloy with non-diffusive surface finishing using a speckle referencing-digital speckle pattern interferometry (SR-DSPI) system. Rather than interfering the testing beam with a Gaussian distributed beam, we make a modification on the referencing optical path by illuminating a rough surface with a coherent light beam and taking the reflection from the rough surface to interfere with the testing beam. Doing this, a uniform speckle pattern can be effectively formed at the imaging plane, and speckle fringe pattern can be generated with external perturbation and subsequent image subtraction. The perturbation-induced phase change can be extracted using phase shifting technique. The adjustment of optical path, environmental refractive index or the illumination wavelength can result in the phase change. By extracting the phase change and through

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geometrical calculation, the surface information, such as deformation, strain or dimensional profile, can be obtained. Within the scope of this paper, the out-of-plane deformation of a titanium-alloy plate introduced by three-point bending was measured and analyzed through speckle referencing-digital speckle pattern interferometry (SR-DSPI). In order to simulate defect, a dent of depth of 100 µm and diameter 6 mm was created on the surface of this plate by drilling.

2. EXPERIMENTAL SETUP AND ANALYSIS METHOD

The optical setup of the SR-DSPI system is illustrated in figure 1. A fiber pigtailed laser of wavelength $\lambda = 635$ nm (OZ-2000, OZ Optics LTD) was used for the illumination of testing sample and the referencing. The laser beam was split into two beams using the beam splitter 1 with the object beam perpendicularly going to the testing surface1 and the reference beam guided to illuminate a rough reference surface through a piezoelectric transducer (PZT) actuated mirror. The two reflections respectively from the non-diffusive testing surface and the reference rough surface interfere with each other and effectively form a speckle pattern at the image plane, where the CCD camera was kept. A three-point bending can be applied to the testing sample to introduce the perturbation.

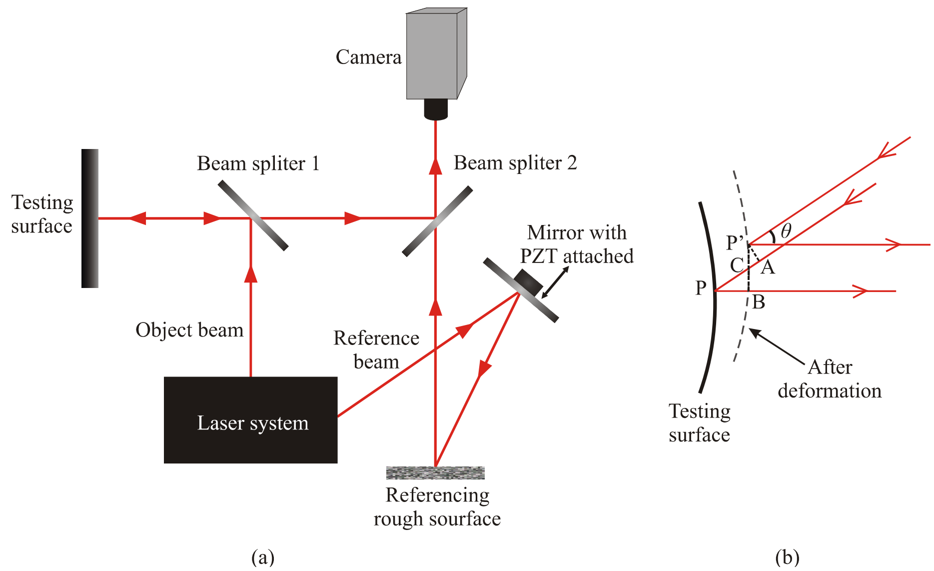

Figure 1 (a) Schematic experimental setup of SR-DSPI for out-of-plane deformation measurement. Unlike the conventional DSPI system, the reference beam is firstly guided to illuminate a reference rough surface, and the reflection from it is taken as the referencing. (b) Illustration of the optical path difference before and after surface deformation.

The perturbation would give a slight deformation to the testing surface that eventually would result in a phase change Δ to modify the intensity distribution of the speckle pattern. The subtraction of the two speckle patterns before and after the perturbation can generate a fringe pattern which is modulated by a sinusoidal carrier, and the spatial frequency of the fringe pattern is determined by the phase change Δ. And Δ can be interpreted by a simple ray-tracing model illustrated as figure 1 (b) for the out-of-plane measurement. The optical path difference (OPD) is contributed by both incident ray and reflection ray[30]:

$$\mathrm{OPD} = \mathrm{PA} + \mathrm{PB} \tag{1}$$

where PB is the out-of-plane displacement w, and P'B is the in-plane displacement u. By applying some geometrical properties, PA can be obtained as:

$$\mathrm{PA} = w\cos\theta + u\sin\theta \tag{2}$$

By the combination of eqn. (1) and (2), the OPD can be calculated as:

$$\mathrm{OPD} = w\,(\cos\theta + 1) + u\sin\theta \tag{3}$$

In the case that the incident angle θ is small, the second term in eqn. (3) can be neglected. Therefore the phase change becomes proportional to the out-of-plane displacement:

$$\Delta = \frac{2\pi}{\lambda} w\,(\cos\theta + 1) \tag{4}$$

The phase change can be evaluated using phase shifting techniques[31-32]. Generally for a phase shifting technique, a series of frames need to be recorded and a phase shift needs to be applied after recording each frame. The calculation through the combination of these frames can result in the phase map of the speckle pattern. In this work, *Carré* method, which is a self-calibrated phase shifting technique[33-34], has been employed to retrieve the phase maps before and after the surface deformation respectively. The subtraction of the two phase maps can yield the phase change *Δ*. And the out-of-plane deformation can be quantitatively evaluated using Eqn. (4).

3. EXPERIMENTAL RESULTS AND DISCUSSIONS

To validate the concept of speckle referencing-DSPI, a well-polished titanium alloy plate was used as the testing sample in the experiment. Firstly, two speckle fringe patterns were recorded using SR-DSPI and conventional DSPI respectively, which are shown in figure 2 (a) and (b). As observed, the speckle pattern formed using speckle referencing method consists of fine and uniform speckles (figure 1 (a)), nevertheless the speckles shown in figure 2 (b) aggregate as clusters and the intensities distributed unevenly over the entire field of view. This formation of the speckle clusters might result from the partially specular reflection from the non-diffusive testing surface. However with speckle referencing, the phase of this partial specular reflection can be randomized during the interference with the reference beam, and thus eventually a uniform speckle pattern with fine granular size can be generated and recorded by the camera. Figure 2 (c) and (d) show the intensity profiles along the dashed lines in figure 2 (a) and (b) respectively. A good fringe contrast is critically important for the extraction of phase[35-36]. The comparison of profiles shows that the fringe contrast obtained by SR-DSPI is much larger than the one obtained by conventional DSPI.

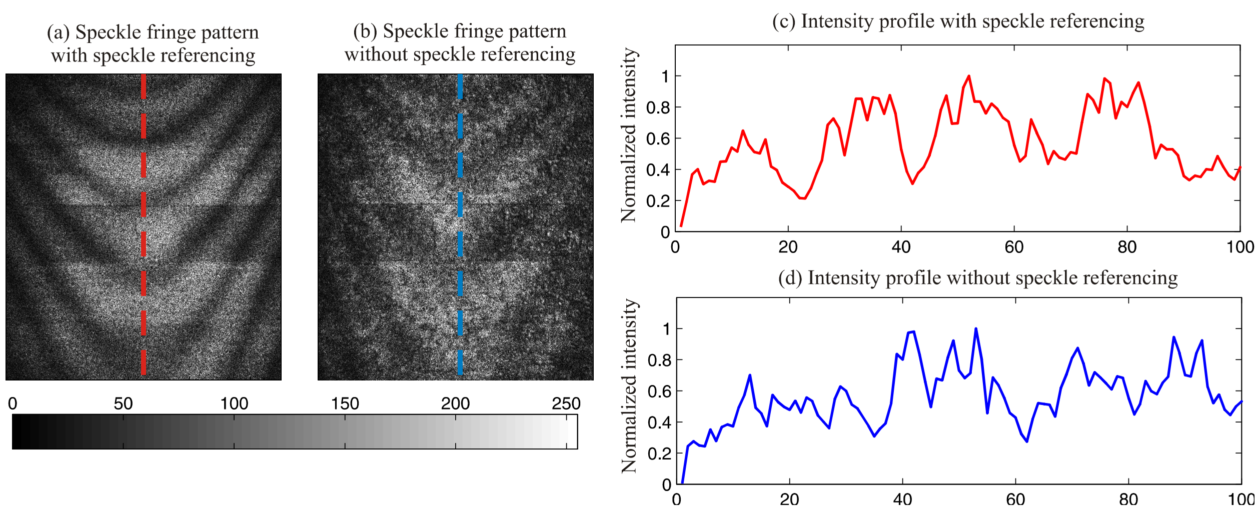

Figure 2 (a) Speckle fringe pattern obtained using SR-DSPI; (b) speckle fringe pattern obtained using conventional DSPI; (c) intensity profile along the dashed red line in (a); (d) intensity profile along the dashed blue line in (b).

To quantitatively evaluate the out-of-plane deformation, *Carré* algorithm was used for the phase-shifting technique to obtain the phase map of the speckle fringe pattern. A software package (isi-Studio, isi-sys GmbH, Germany) was used to do the filtering and demodulation of the unwrapped phase. Image pre-processing was firstly used to filter out the "*salt-and-pepper*" noise. The filter kernel size needs to be properly chosen so as that the features on the surface remain sharp after filtering. Figure 3 (a) shows the unwrapped phase map for an intact testing plate under *three-point* bending. In this experiment, the incident angle of the test beam was approximately 0^o to minimize the contribution from in-plane deformation, and thus Eqn. (3) can be simplified as:

$$\Delta = \frac{4\pi}{\lambda} w \tag{5}$$

After demodulation, the out-of-plane deformation can be obtained using Eqn. (5) and illustrated in figure 3 (b).

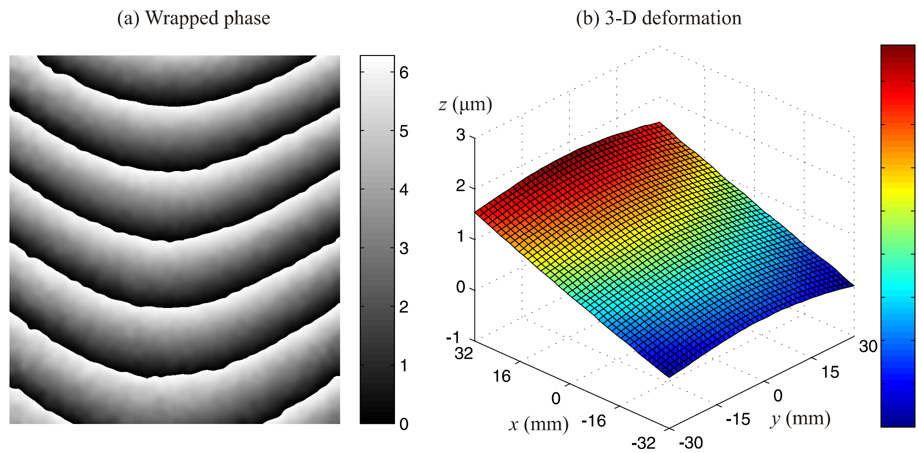

Figure 3 (a) Wrapped phase map for the fringe pattern obtained through phase shifting technique. The testing sample is an intact titanium-alloy plate under three-point bending. (b) The corresponding 3-D display of the out-of-plane deformation through unwrapping the phase map.

Besides the measurement of out-of-plane deformation for the non-diffusive surface, this SR-DSPI system is also capable to identify and locate the surface defect. To validate this, a dent with a diameter of 6 mm and depth of 100 µm was created on the surface of the titanium-alloy surface by drilling. The same procedures have been implemented to measure the deformation. Owing to the presence of the surface dent, the abnormity of rigidity might be introduced around the area of the surface dent. Therefore the external force might result in a surface deformation with discontinuity, which is illustrated in figure 4 (b) outlined by the dashed circle. This abnormity can also be observed in the wrapped phase map (shown in figure 4 (a)).

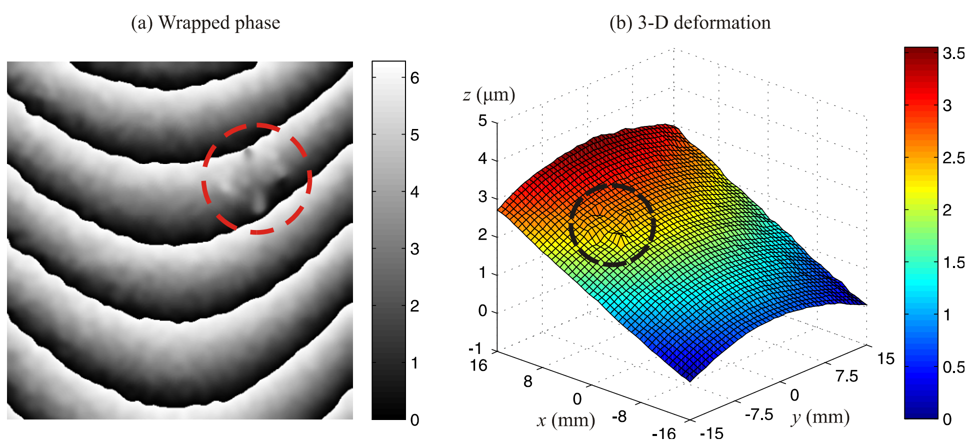

Figure 4 (a) Wrapped phase map for the fringe pattern obtained through phase shifting technique. The testing sample is a titanium-alloy plate with a surface dent outlined by the dashed circle. The surface dent has diameter of 6 mm and depth 100 µm. (b) The corresponding 3-D display of the out-of-plane deformation through unwrapping the phase map. The dashed circle illustrates the deformation abnormity owing to the presence of surface dent.

4. CONCLUSIONS

Owing to the advancing of the manufacture technology, the surface finishing of the aerospace and automotive components can go down to the order of 1 µm, which make the surface non-diffusive to the visible light and some of the laser metrology techniques then become hardly applicable. In this work, we propose and demonstrate a modified DSPI system by replacing the conventional reference beam with speckle referencing. This speckle referencing (SR)-DSPI system was validated through the measurement of a titanium-alloy plate. The measurement using conventional DSPI technique was also carried out for a comparison. The experimental results shows that a more uniform speckle pattern consisting of fine granular size speckles can be generated using the speckle referencing than the conventional method. *Carré* phase shifting method has been applied to retrieve the phase map of the speckle fringe pattern. After demodulation of the wrapped phase, the surface deformation of the alloy plate can be quantitatively evaluated using SR-DSPI, and the presence of surface defect/dent can also be identified through the observation of deformation abnormity.

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