THREE MOIRÉ TECHNIQUES UNDER A LASER SCANNING MICROSCOPE FOR MICRON/SUBMICRON-SCALE DEFORMATION MEASUREMENT

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Abstract:
Three moiré techniques based on a laser scanning microscope (LSM) were presented and compared for the first time, including the LSM scanning moiré method, our developed LSM overlapping moiré method, and our newly developed LSM secondary moiré method. The formation principles of these moiré patterns and the measurement principles for deformation measurement were introduced. The applicable conditions of these three techniques were analyzed. Some typical moiré fringes on a strain gauge, carbon fiber reinforce plastics, a polyimide film and a silicon wafer were illustrated. Our developed LSM overlapping moiré method and secondary moiré method are effective in eliminating the scanning distortion of the LSM. These three kinds of moiré techniques are able to expand the application range of the LSM in deformation measurement at the micron and the submicron scales.

Keywords: Laser scanning microscope, Moiré, Overlapping, Secondary, Deformation

1. INTRODUCTION

Moiré methods are non-destructive, full-field and robust optical methods for deformation measurement [1]. In the last several decades, moiré methods have been developed from the geometric moiré method and moiré interferometry to the charge coupled device moiré method, the sampling moiré method and the high-power microscope moiré methods [2, 3]. Owing to the high resolutions of high-power microscopes, the high-power microscope moiré methods work well in measuring the micron, the submicron and even the nano-scale deformation. The most commonly used high-power microscope moiré methods include the scanning electron microscope moiré method [4, 5], the laser scanning microscope (LSM) also called as laser scanning confocal microscopy (LSCM) moiré method [6, 7], the atomic force microscope moiré method and the transmission electron microscope moiré method.

Among the above mentioned methods, the LSM moiré method refers to the LSM scanning moiré method, which has drawn great attention because it does not need the vacuum environment, the resolution is higher compared with the optical microscope, and the specimen location is convenient [8-10]. However, the LSM scanning moiré method cannot be used for some specimen grating pitches due to the discontinuously of the magnification of the LSM objective lens. To overcome this shortcoming, we developed the overlapping-scanning laser microscope moiré method [11] also called as the LSM overlapping moiré method. Although the LSM overlapping moiré method can be applied for a wider range of specimen grating pitches, the view field is smaller than that of the LSM scanning moiré method. To address this issue, we developed a new moiré technique, i.e., the LSM secondary moiré method, which is suitable for a wider range of specimen grating pitches and has the same view field as the LSM scanning moiré method. In addition, the LSM secondary moiré is not influenced by the LSM scanning distortion. This study will compare and discuss the applicable conditions of these three LSM moiré techniques.

2. FORMATION AND MEASUREMENT PRINCIPLES

2.1 Principles of LSM Scanning Moiré Method

Figure 1 illustrates the formation principles of the three LSM moire techniques. The LSM scanning moire comes from the interference between the scanning lines and the specimen grating (Fig. 1a). Let us define p and T are the pitch of specimen grating and the spacing of the LSM scanning lines, respectively. LSM scanning moire will appear when there is a mismatch between the LSM scanning lines and the specimen grating. Usually T=0.8p-1.2p, and the angle between the specimen grating lines and the LSM scanning lines is less than 15°. The strain of the specimen grating relative to the LSM scanning lines in the vertical direction can be expressed by

$$\varepsilon_{p\text{-}T} = T/d \qquad (1)$$

where d is the spacing of the LSM scanning moire. If the specimen grating deforms, the LSM moire fringes will also change. The deformation can be calculated from both of the strains of the specimen grating relative to the LSM scanning lines before and after deformation.

2.2 Principles of LSM Overlapping and Secondary Moiré Methods

The LSM overlapping moire is caused by the superposition between the specimen grating before deformation and that after deformation (Fig. 1b). The specimen grating images without backgrounds before and after deformation can be respectively remembered by the

LSM in two scanning processes. When we record an image after two scanning processes, the two specimen grating images will be superimposed on the image background in the second scanning process. As a consequence, The LSM overlapping moire will emerge if there is a mismatch or misalignment between the two specimen grating images.

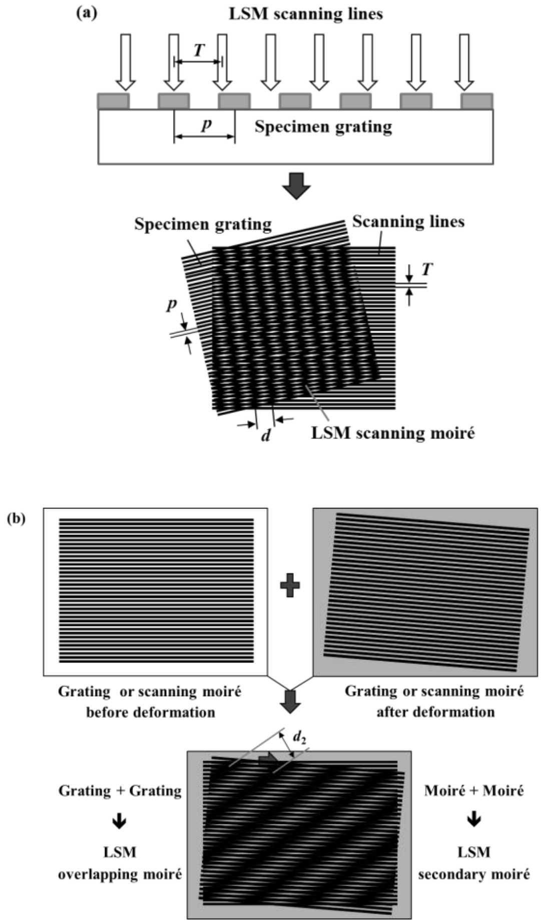

Fig. 1 Formation principles of (a) the LSM scanning moiré, (b) the LSM overlapping moiré and the LSM secondary moiré patterns

The LSM secondary moiré is resulted from the superposition between the LSM scanning moire before deformation and that after deformation respectively memorized by the LSM in two scanning processes (Fig. 1b). The recording process of the LSM secondary moiré is similar to that of the LSM overlapping moiré, except that the LSM scanning moiré fringes instead of the gratings are remembered before and after deformation. The deformation measurement principles of the LSM secondary moiré method and the LSM overlapping moiré method are the same. When the specimen grating pitch becomes p_2 from p_1 due to deformation, the LSM overlapping moiré or the LSM secondary moiré will arise with spacing of d_2. The strain in the principle direction of the specimen grating before deformation can be acquired from

$$\varepsilon_{p_2-p_1}=p_1/d_2 \quad (2)$$

A difference between the LSM secondary moiré method and the LSM overlapping moiré method lies in that the view field of the former is much greater than that of the latter for a certain specimen grating pitch. The detailed applicable conditions of the three LSM moiré techniques will be discussed in section 3.4. Besides, the LSM secondary moiré method is not affected by the scanning distortion because the deformation measurement is independent of the LSM scanning lines in this method as perceived from Eq. (2).

3. EXPERIMENTAL RESULTS AND DISCUSSIONS.

3.1 Generation of LSM Scanning Moiré Fringes

The LSM scanning moiré fringes have been observed on a strain gauge and a carbon fiber reinforce plastic (CFRP) specimen as shown in Fig. 2. The used microscope is a Lasertec LSM (1LM15). In Figs. 2a and 2b, the specimen grating on the strain gauge is a cross grating with pitch of 0.8 μm fabricated by the UV nanoimprint lithography. The spacing of the LSM scanning lines is 0.385 μm when the magnification of the objective lens is 50, about 0.48 times the specimen grating pitch. Both the parallel (Fig. 2a) and the rotational (Fig. 2b) LSM scanning moiré fringes are a kind of multiplication moiré with a higher density. However, the deformation measurement error will increase when the LSM scanning moiré fringes are very dense as in Figs. 2a and 2b. It is recommended to make the LSM scanning lines spacing is 0.8-1.2 times the specimen grating pitch to generate the primary LSM scanning moiré.

In Figs.2c and 2d, the pitch of the cross specimen grating on the CFRP specimen is 3.6 μm replicated from a UV nanoimprint mould. When the magnification of the objective lens is 5, the LSM scanning lines spacing becomes 3.85 μm, within 0.8-1.2 times the specimen grating pitch. Therefore, distinct LSM scanning moiré fringes can be found when the scanning lines are either parallel (Fig. 3c) or perpendicular (Fig. 3d) to the axis of CFRP after the sample is broken under three-point bending. From Eq. (1), the average strain of the specimen grating relative to the LSM scanning lines in the near-lateral direction is 0.039 and in the near-axial direction is 0.041. It should be noted that the upper part of the moiré fringes in Fig. 2d cannot be used because it has been affected by the scanning distortion of the LSM.

3.2 Generation of LSM Overlapping Moiré Fringes

The generated LSM overlapping moiré fringes on a polyimide film are presented in Fig. 3. The specimen grating is a cross grating with pitch of 3 μm made by the UV nanoimprint lithography. No matter what the LSM lens magnification is, the LSM scanning moiré is too dense. In this case, we can produce clear LSM overlapping moiré fringes for deformation measurement when the magnification of the LSM objective lens is 20, as seen in Fig. 3. The overlapping moiré fringes are caused by the superimposition between the specimen gratings before and after deformation. Using Eq. (2), the average strain in the principle direction of the specimen grating before deformation (vertical) is measured to be 0.037 from Fig. 3a and is 0.062 from Fig. 3b.

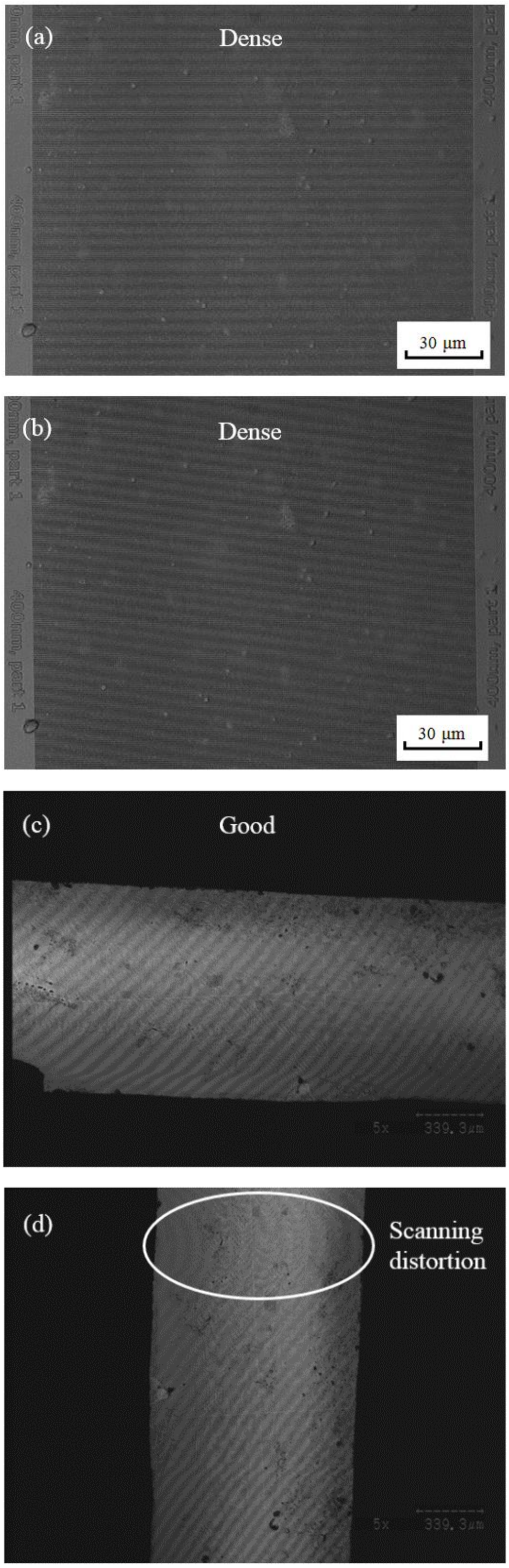

Fig. 2 Microscope images of LSM scanning moiré fringes. (a) Parallel moiré on a strain gauge, (b) rotational moiré on a strain gauge, (c) moiré when the scanning lines are parallel to the axis of CFRP, and (d) moiré when the scanning lines perpendicular to the axis of CFRP.

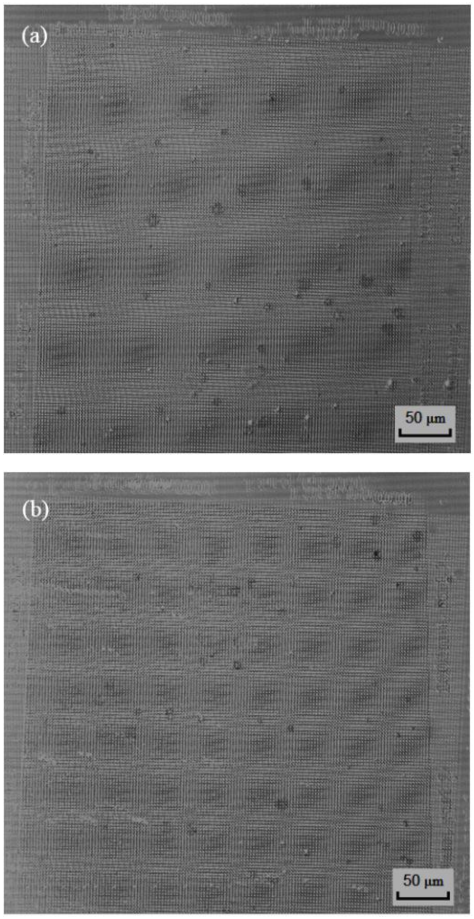

Fig. 3 Microscope images of LSM overlapping moiré fringes on a polyimide film. (a) When the deformation is smaller and (b) when the deformation is greater.

3.3 Generation of LSM Secondary Moiré Fringes

The formed LSM secondary moiré fringes and the corresponding LSM scanning moiré fringes before and after deformation are demonstrated in Fig. 4. The LSM secondary moiré in Fig. 4 is aroused from the superposition between the LSM scanning moiré before deformation in Fig. 4a and that after deformation in Fig. 4b. The specimen grating on a silicon wafer is a three-way grating with pitch of 2 μm fabricated by the electron beam lithography. The spacing of the LSM scanning lines is 1.925 μm when the magnification of the objective lens is 10. Although the LSM scanning lines spacing is in the range of 0.8-1.2 times the specimen grating pitch, the LSM scanning moiré is still dense when the angle between the specimen grating lines and the LSM scanning lines is greater than 15°. In the case that the LSM scanning moiré fringes are dense and a large view field is expected, we can generate LSM secondary moiré fringes as illustrated in Fig. 4c. When the deformation is greater, the spacing of the LSM secondary moiré fringes will decrease as in the example displayed in Fig. 4d. The average strain in the principle direction of the specimen grating before deformation (close to horizontal) is 0.019 from Fig. 4c and is 0.025 from Fig. 4d calculated by Eq. (2). Furthermore, the LSM secondary moiré fringes are not affected by the LSM scanning distortion.

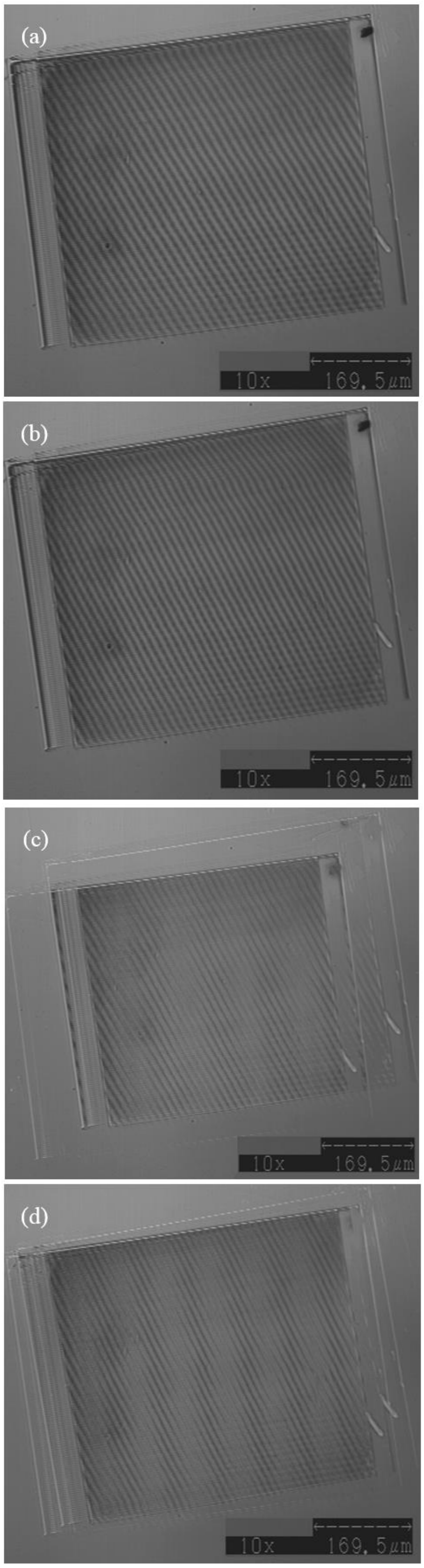

Fig. 4 Microscope images of LSM secondary moiré fringes generated from LSM scanning moiré fringes on silicon. (a) LSM scanning moiré before deformation, (b) LSM scanning moiré after deformation, (c) LSM secondary moiré formed by the interference between (a) and (b). (d) LSM secondary moiré when the deformation is greater.

3.4 Applicable Conditions of Three LSM Moiré Techniques

In this section, we will discuss the applicable conditions of the three LSM moiré techniques. Due to the discontinuity of the LSM magnification, the traditional LSM scanning moiré method cannot work well for some specimen gratings at the micron and the submicron scales. Our developed LSM overlapping moiré method and LSM secondary moiré method can overcome this shortcoming of the traditional LSM scanning moiré method. The reasonable combination of these three LSM moiré techniques will enable the deformation measurement regardless of the specimen grating pitch at the micron and the submicron scales. These three moiré techniques expand the application range of the LSM in the micron and the submicron-scale deformation measurement.

Figure 5 expresses the applicable conditions of the three LSM moiré techniques. The used LSM (Lasertec, 1LM15) is equipped with five objective lens with magnifications of 5, 10, 20, 50 and 100, respectively. The suitable ranges of the specimen grating pitch at different magnifications were plotted in Fig. 5. It can be seen that no matter what the specimen grating pitch is in the range of 0.2 μm to 40 μm, the deformation can be measured from one or more LSM moiré techniques. If the LSM scanning moiré cannot be formed, we can use the LSM overlapping moiré method. If the LSM scanning moiré fringes are too dense, we can choose one method from the LSM secondary moiré method and the LSM overlapping moiré method. When the specimen grating pitch is the same, the view field of the LSM scanning moiré method and the LSM secondary moiré method is greater than that of the LSM overlapping method. In all the three techniques, the deformation measurement sensitivity depends on the specimen grating pitch. Which LSM moiré technique should be utilized rests with the specimen grating pitch and the required view field.

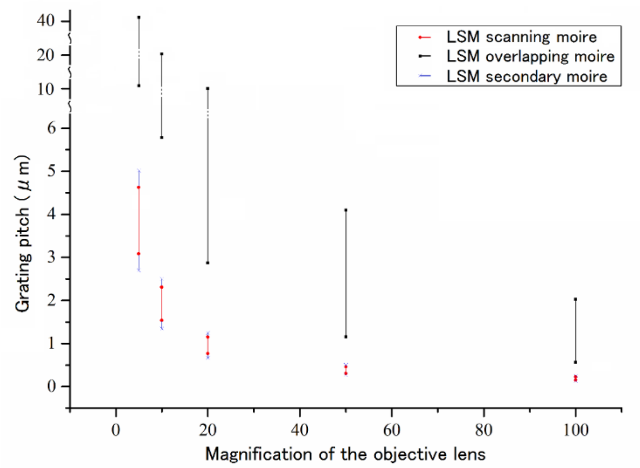

Fig. 5 Applicable ranges of the LSM moiré method, LSM overlapping moiré method

The ranges of the specimen grating pitch in Fig. 5 are the main scopes when the moiré fringes are distinct. In the LSM scanning moiré method and the LSM secondary moiré method in Fig. 5, the LSM scanning moiré only indicates the primary moiré and does not include the multiplication moiré.

In the LSM overlapping moiré method, the specimen grating pitch can reach 100 μm for a very large deformation.

4. CONCLUSIONS

We first compared and reported three LSM moiré techniques for deformation measurement, i.e., the LSM scanning moiré method, our developed LSM overlapping moiré method and the latest LSM secondary moiré method. The formation principles, measurement principles and some applications were explained. The applicable conditions and the selection criteria of the three LSM moiré techniques were discussed. Although the magnification of the LSM is discontinuous, a series of continuous specimen grating pitches can be used to measure the micron and the submicron-scale deformations by the combination of the three LSM moiré techniques.

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