Study on artificial strain induced by AFM scanning parameters using digital image correlation analysis

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AFM has been widely used in biological, physical, chemical, machinery, and other areas of nanoscale surface topography measurement. There is significant difference between the real topography and the measurement results because the features of the AFM system itself such as nonlinear, hysteresis and aging will cause the measurement error. Through the AFM images themselves, it is difficult to observe the difference between both sides. The Digital Images Correlation (DIC) technique can be used to obtain the displacement and strain fields of the target through calculating the relationship between two digital images. In the present study, the DIC technique is used to analyze the AFM images to study effects of the scanning parameters such as scan size, scan rate, scan time and stabilization time on the artificial strains in the AFM images. Their variation laws are investigated and the scales of each parameter during the measurement procedure are provided. Experimental results show that: after the system's booting time exceeds 60 minutes, the artificial strain induced by drift reaches to a minimum value. Scan size should be optimized according to the measured sample for the minimum measurement error. Scan rate in the range of 1Hz to 3Hz will lead to the 10^{-4} artificial strain. When changing scanning parameters (eg. scan rate and scan size), scanning more than 4 times is needed. After that, the system generates a stable and minimal artificial strain and the minimum measurement error can be obtained.

1. Introduction

The Digital Image Correlation (DIC) method is proposed by Japan's scholar Yamaguchi [1], and Peters and Ranson of the United States University of South Carolina [2-3]. The surface is directly tested before and after deformation. The obtained results are then changed to digital images of the gray scale which are utilized to calculate the displacement and strain fields of the measured area. DIC technology is now widely applied to the macroscopic deformation measurement [4]. With the improvement of microscopy and materials science, people focus on the microstructure of materials to explain the observed macroscopic deformation properties and the mechanical behavior of materials. For example, the DIC and scanning electron microscopy (SEM) are combined to study the deformation field of the welding head, to predict failure in the welded joints in electronic packaging, as well as provide a basis for shape design [5]. With the invention of the Scanning Tunneling Microscopy (STM) and Atomic Force Microscopy (AFM), the Scanning Probe Microscopy (SPM) technique in the nanometer scale and even atomic-scale morphology measurement has demonstrated a significant unique ability. People try to combine the DIC and the scanning probe microscopy. For example, STM is in conjunction with DIC to perform submicron deformation measurements [6-7]. Hui-Min Xie et al. [8] combined DIC with SEM to measure the single-walled carbon nanotube elastic modulus and tensile strength. Because sample material which can be measured by AFM is extensive, studies with AFM and DIC gradually become a research hotspot. Based on the *in-situ* tensile device, the tensile test on the tape is carried out. AFM is used to measure the micro topography of the fixed point on the tensile tape and the results are analyzed by the DIC technique. The local micro deformation of the tape during the tensile process is provided [9]. This technique can also be used to investigate the aging state of the magnetic recording media. In order to measure the deformation of the silicon beam, due to the small structure, techniques combined AFM with the DIC method has obvious advantages [10]. In addition, research in nano-wear by using this method has good prospects. Li Xiaodong et al. [11] applied this technique into studying the wear of gold films.

However, due to its key component, AFM PZT's properties of nonlinearity and hysteresis, and the effect of the control system response, changes of the whole system in the environment with the time will cause the greatly difference between the test results obtained by AFM and the real space morphology. And this difference is difficult to be distinguished by observing the AFM images directl y. Simultaneously, various scanning parameters used in the AFM system often needs to be changed. Up to now, there are still no relevant reports on the difference between the parameters changed before and after. Therefore, in the present study, the effects of the main scanning parameters of AFM such as scan size, scan rate, scan times, stabilizing time and the parameters changing on the measurement results which will cause the artificial strain are studied in detail with the DIC technique.

2. Experimental methods

The DIC software used in the present study is Moire Analysis software (MoireSoftware) which is provided on the website for free. Atomic Force Microscope is Dimension 3100 (U.S. Veeco Company). The tip and cantilever is the Si_3N_4. The cantilever spring constant is about 0.5N / m, and the tip radius is less than 30nm, which are provided by the manufacture.

The procedure by using the DIC and the AFM images to study the artificial strain is explained as follows: Choose a specific speckle pattern characteristic of samples which is measured by AFM with different testing parameters, and then save acquired images. Two gray scale pictures are selected to calculate the strain or displacement fields by the DIC software. Because of the sample is not deformed by external forces, the obtained strain is the artificial strain which is in duced by the changes of the scanning parameters. This artificial stain may cause measurement errors to the results. A greater error of results shows that the greater difference between the real topography and the measured one. In the present study, the errors induced by the correlation coefficient expression, the implementation process and other relevant factors of the DIC software itself are ignored. More detail procedures of DIC analysis of AFM images can be found in many previous articles [9-11], which are ignored here.

3. Experimental results and discussions

The sample used in this study is Y_2O_3 thin films deposited on the glass, whose thickness is about 1μm. AFM Works in the contact mode. Images are processed by the flatten method. Images with a resolution of 256 × 256 are obtained. 512 × 512 which is interpolated by the software is used for the DIC process. The middle part of 256 pixel × 256 pixel is used as the computational domain.

3.1 Effect of the stabilizing time of AFM system on the measurement results

Because of the thermal effect of the piezoelectric ceramic, after the system is powered on, the voltage applied to the ceramic will vary with the increasing in the temperature of the system, and thus, the displacement of the ceramic will correspondingly change, resulting in the measurement error into the AFM images. In order to evaluate the effect of the balance time of the whole system on the measurement results, the AFM's AutoScan function is used for continuous capturing a set of AFM images, and 14 pictures of them are analyzed with the DIC software. The adjacent images are compared and the artificial displacement and strain fields are calculated. Scan size is 40μm. Scan rate is 3Hz.

Fig. 1 (a) and (b) show the relationships between the drifting displacement, the average strain and the scanning time after the system boots up, respectively. As the Fig. 1(a) shown, for the slow scan direction Y, the drift value is slightly larger than the fast scanning direction X. But the drifting displacements in both directions can reach to a stabilization state after the system is working for about 60 minutes. The reason is that the ceramics reaches to a constant temperature slowly with the time. The whole measurement system including the mechanical and electrical parts has also reached to equilibrium. Thus, the drift caused by thermal effects is also stable. For the variation of the average artificial strain, because the sample is not deformed and the measurement parameters are not changed, the change of average strain is mainly due to the time of equilibrium. From the Fig. 1 (b), it can be seen that after the system's booting up for 60 minutes, the artificial average strain is less than 1×10^{-3} for both directions.

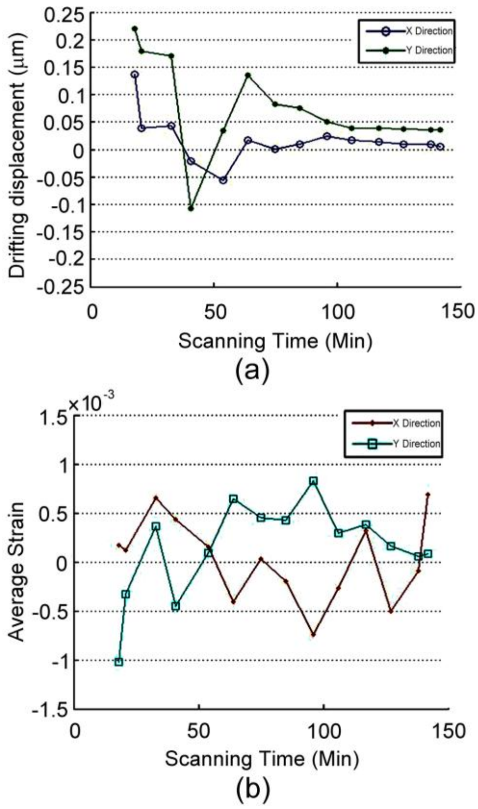

Fig. 1 Relationships between the drifting displacement, the average strain and the scanning time after the system powers on

3.2 Effect of the AFM scan size on the measurement results

Scan size are selected as 50μm, 40μm, 30μm, 20μm, 10μm, respectively. Scan rate is 2Hz. For each scan size, totally 6 ~ 7 images are captured. Scanning lines are 256 × 256. For the same size, two consecutive scans are compared to obtain the average strain data. Fig. 2 shows the relationship between the artificial average strain and the scan size. The figure shows the average strain of the slow scan direction Y is always less than 1×10^{-3}. For the fast scan direction X, when the scan size is greater than 20μm, the artificial average strain is less than 1×10^{-3}. For the scan size is less than 20μm, the artificial average strain is larger. The reason maybe as follows: For the small scan size, the speckle distribution provided by the surface morphology is less than that provided by the larger scan size. Simultaneously, the noise generated with a smaller scan size is relatively larger. This phenomenon results in a corresponding larger artificial strain. Therefore, using AFM image to perform DIC analysis, the appropriate scan size should be employed according to the morphology property of the sample. In the present study, the optimized scanning size is greater than 40μm for the sample used here. Then, the real topography of the sample can be achieved with a small artificial strain.

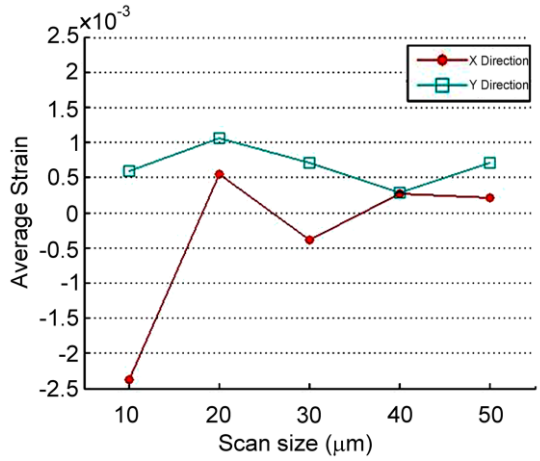

Fig. 2 Relationship between the artificial average strain and the scan size

3.3 Effect of AFM scan rate on the measurement results

Scan size is 50μm. Scan rate is from 1Hz to 5Hz, with the interval of 1Hz. For each scan rate, 6 ~ 7 AFM images are captured. Scan lines is 512 × 512. Two consecutive images are compared for the same scan rate. Fig. 3 shows the DIC analysis results of two consecutive AFM images at the scan rate of 5Hz, after the scanning and the system are both stable. Fig. 3 (a) and (b) represent the displacement fields of the X direction and Y direction, respectively. The displacement data can be further calculated to obtain the average strain fields of the X-direction and Y-direction, as shown in Fig. 3 (c) and (d), respectively. The average strain for the X direction is -1.207×10^{-3}. The average strain of the Y direction is $+2.059\times10^{-3}$. The overall strain distribution uniforms and the error is relatively small.

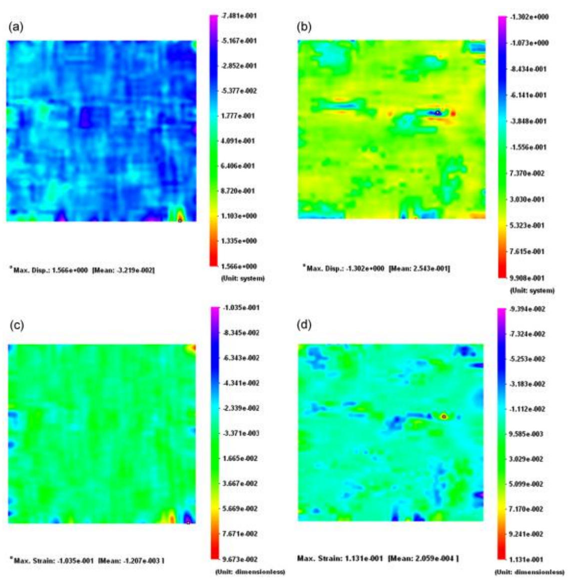

Fig. 3 DIC analysis results of two consecutive AFM images at the scan rate of 5Hz

For each scan rate, after stabilization, the artificial average stains in the X and Y directions with different scan rates are shown in Fig. 4. When the scan rate is less than 3Hz, the artificial average strain reaches to the magnitude of 10^{-4}, which shows that the difference between the measured result and the real topography is smallest. For the scan rates of 4Hz and 5Hz, there will be a lot of noise on the image because of the scan rate is relatively high, which will lead to a larger strain. For the ordinary measurement with AFM, the scan rate of 1-3Hz is ideal. This scan rate can not only meet the measurement accuracy, but also ensure the measurement efficiency.

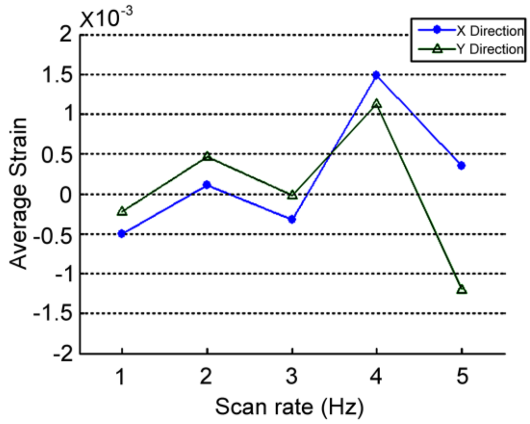

Fig. 4 Relationship between the artificial average strain and the scan rate

3.4 Effect of the scanning time after modifying scan parameters on the measurement results

When using AFM to measure the micro topography, specific requirements need to change scanning parameters from time to time such as measurement range, scanning rate and so on. However, such changing will bring the corresponding measurement error to the measured figures.

First, the artificial averaged strain induced by modifying the scan size is discussed. Fig. 5 shows the artificial average strains calculated from the continuous measured AFM images for both directions when the scan size just changes from 40μm to 30μm. As the figure shown, the average strains in X and Y directions have a greater artificial strain once the scan size changes for the first two times scanning. This is due to the hysteresis effect of piezoelectric ceramics which has the memory feature. When the third scanning is carried out, the artificial average strain decreases and tends to be a constant value. Therefore, after changing the scan size, three images need to wait to be captured in the AFM measurement process. The fourth figures should be captured for use with the minimum measurement error.

Second, Fig. 6 shows the relationship between the artificial average strain and the scanning times when the scan rate is changed. When the scan rate changes from 4Hz to 3Hz, AFM images are captured and DIC analysis is carried out. There is a significant effect of the scan rate on the results. The average strain calculated from the first two scans can reach up to 0.022. When scanning the sample for three times, the artificial average strain becomes dramatically smaller. Therefore, we can observe the same condition with that changing the scan size. When the scan rate just changes, the maximum error is achieved. It is needed to scan the sample for three times with the new scan rate, then the corresponding fourth image captured is very close to the real image.

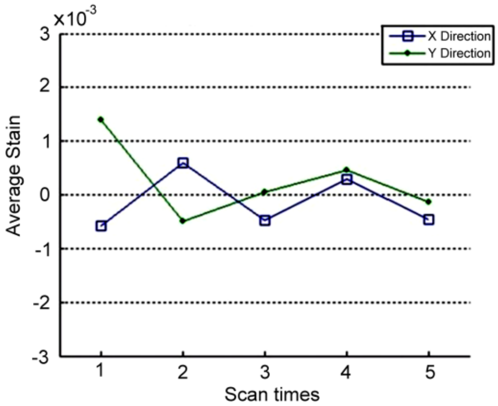

Fig. 5 Artificial average strains for X and Y directions with the scan size of 30μm

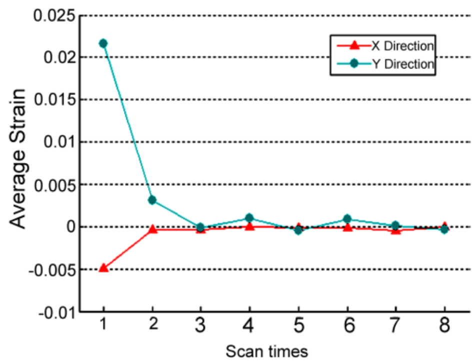

Fig. 6 Relationship between the artificial average strain and the scan times with the scan rate of 3Hz

4. Conclusions

In this paper, the DIC technique is employed to analyze the AFM images of the sample with zero strain. The artificial average strain and the displacement fields induced by the stabilizing time of the system, scan size, scan rate and modifying scanning parameters are studied. The optimized measurement parameters and process which can be used to achieve the real topography of the measured sample are provided. The following conclusions are obtained: After the system stabilizes for more than 60 minutes, the minimum drift and artificial average strain induced by the temperature drift and instability of the system can be achieved. For different samples, a proper scan size can be selected for the minimal measurement error. The effects of the scan rate are described as follows: for the scan rate from 1Hz to 3Hz, the artificial average strain is less than 10^{-4}. For the scan rate of larger than 3Hz, the artificial average strain will increase. Influenced by the response of the system control system and the property of the ceramic tube, after modifying the measurement parameters, four times scanning are needed for new parameters. Then the artificial average strain reaches to a minimum value and the measurement error is also minimum.

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