MEASUREMENT STRATEGIES IN OPTICAL 3-D SURFACE MEASUREMENT WITH FOCUS VARIATION

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Abstract: Focus variation is an optical contact-free method that allows the measurement of three-dimensional surface metrology using optics with limited depths of field and vertical scanning. It was documented in the ISO 25178-6 first time in 2010.As one method of image capture, it has very crucial influence to get an excellent quality image that some key parameters are selected correctly for different workpiece. Those key parameters are including the exposure time, contrast, filters and so on. In this paper, a few of applications were selected to demonstrate the capabilities of the system using different measurement parameters including measurements on cutting-insert tool, stainless steel ball, stepped workpiece and VDI standard workpiece with silver colour surface. Some principles were concluded for optical three-dimensional surface measurement with focus variation after comparing the practical results with different parameters, serving as measurement strategies.

Keywords: Image quality, 3-D Measurement, Parameters optimizing, High precision

1. INTRODUCTION

Surface texture plays a vital role in the functionality of a component. It is estimated that surface effects cause 10 % of manufactured parts to fail and can contribute significantly to an advanced nation's GDP. In the last century, surface texture was primarily measured by a method that involved tracing a contacting stylus across the surface and measuring the vertical motion of the stylus as it traversed the surface features. In most cases only a single line, or surface profile, was measured and this gave rise to enough information to control production, but was limited to identifying process change[4].

In recent years optical free-contact techniques for three-dimensional surface metrology have become increasingly important in contrast to traditional tactile measurement methods. Compared to other optical methods, focus variation is very new in the field of measuring surface texture although its principle was first published in 1924[1]. This method was documented in the ISO-25178 series first time in 2010 and the nominal characteristics were documented in 2011[3].

Based on the technology of focus variation, some commercial instruments were developed by Leica, Alicona, Werth and some other companies.

This paper was organized as follows: Section 2 presents the principle of focus variation technology and the working principle of an instrument named 'InfiniteFocus' produced by Alicona which is introduced from two aspects: hardware structure and software structure. Section 3 introduces some experiments on a wide range of workpieces under different parameters, as well as the result of each experiment. Section 4 concludes the measurement strategies after comparing the results.

2. FOCUS VARIATION TECHNOLOGY

2.1 Principle of focus variation measurement

Focus variation is a method that allows the measurement of areal surface topography using optics with limited depths of field and vertical scanning. The measurement principle works as bellow: at first images with difference focus are captured. This is done by moving the sample or the optics in relation to each other. Then for each position the focus over each plane is calculated and the plane with the best focus is used to get a sharp image. The corresponding depth gives the depth at this position[2].

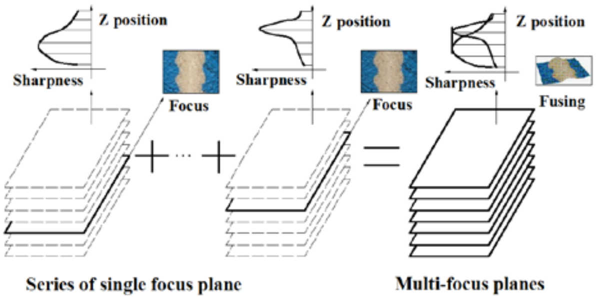

Fig. 1: Schematic diagram of the principle of focus variation

2.2 Working principle of 'InfiniteFocus' instrument

On the market, an instrument named 'InfiniteFocus' was developed for optical areal surface topography measurement by Alicona. Such a device has a series of advantages beyond tactile ones. First it does not touch and damage the surface, second it is able to measure whole areas instead of only surface profiles and third it is typically much faster for detailed measurements of large areas. But it also has a few disadvantages limited by its principle. First it cannot be used if the surface of the sample does not give structure in the image. This means it cannot be used for silicon wafers and glass. Second due to the limitation by optical diffraction of light, it has a high vertical resolution up to 10 nm but a poorer lateral resolution of about 500 nm after optimizing hardware and software components. The experiments mentioned in the article are based on this instrument.

More details of this instrument will be described both hardware structure and software structure as bellow:

2.2.1 Hardware structure

A detailed description of hardware structure of a typical measurement device based on focus variation which is documented from Reference [4] is shown in Fig. 2:

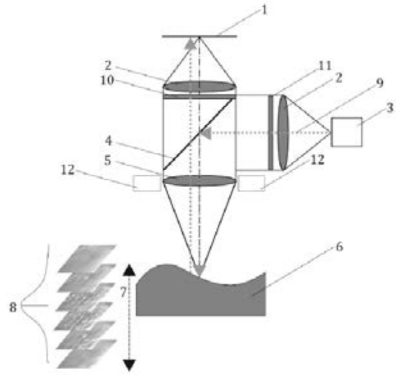

Fig. 2: Schematic diagram of a typical measurement device based on focus variation: (1) CCD sensor, (2) lenses, (3) white light source, (4) semi-transparent mirror, (5) objective lens with limited depth of field, (6) sample, (7) vertical movement with driving unit, (8) contrast curve calculated from the local window, (9) light rays from the white light source, (10) optional analyser, (11) optional polarizer and (12) optional ring light

White light from LED light sources is transmitted through the semi-transparent mirror and the objective lens to the sample. Due to variations in the topography and the reflectivity of the sample, the light is reflected in different directions. The reflected light is partly collected by the objective and projected through the semitransparent mirror and the tube lens to the charge-coupled device (CCD) sensor. Depending on the vertical position of the sample in relation to the objective lens, the light is focused to varying degrees on to the CCD sensor[4].

By moving the sample in the vertical direction in relation to the objective lens, the degree of focus varies from low to high and back to low again. This change of focus is related to a change of contrast on the CCD sensor. By analysing this contrast on the CCD sensor, the position where the sample was in focus can be measured. By repeating this for every lateral position on the CCD sensor, the topography of the sample in the field of view can be measured. In addition to measuring the position where the sample was in focus, the colour of the sample can be determined[4].

2.2.2 Software schematic diagram

As shown in Fig. 3, a flowchart of the principle of data processing by software in focus variation measurement device is given.

In Fig. 3, in each one of the image sequence acquired by vertical scanning on direction Z, only a small region of the object is sharply imaged in the same viewpoint. That means, only part of the depth information of the detected specimen is acquired. In order to perform a complete detection of the

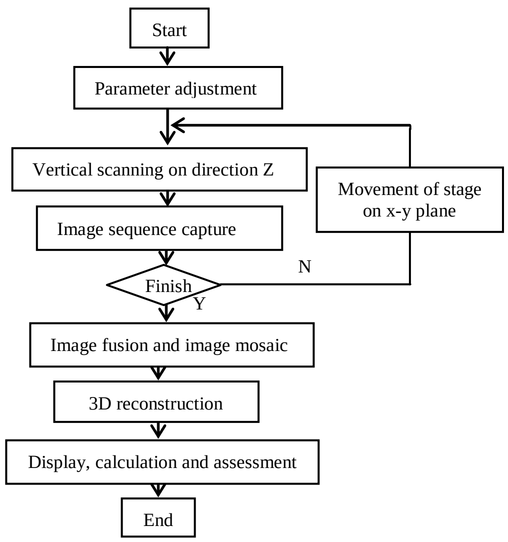

Fig. 3: Schematic diagram of the principle of data processing in focus variation measurement

surface, different sharply region of each image should be fused to an image, which is focused in all areas with adequate information by the help of image fusion technology. The function of image fusion is to ultimately obtain the accurate and abundant information from the fused images, which is not available in a single image. Another important technique of image processing is image mosaic technology. If one point of view fails to contain the whole detected area, the sample or the optics will move in lateral direction to capture more images. Then images captured from different viewpoints are fused to an integrated one, which contains adequate information of all regions. Afterwards, 3D reconstruction will generate a 3D model by virtue of the processed image sequence. Finally, the images and models are displayed and computing results and assessment are given.

3. EXPERIMENTS AND RESULTS

In this section, a few of experiments were launched to demonstrate the capabilities of the system using different parameters including measurements on cutting-insert tool, stainless steel ball, stepped workpiece and VDI standard workpiece with silver colour surface. Some strategies were concluded to measure different types of workpiece after comparing the practical results under different parameters.

3.1 The detection of cutting-insert tool

The Fig. 4 shows the detected workpiece and observed results under different parameters. Fig. 4(a) is the cutting-insert tool and Fig. 4(b) is the wear on the major cutting edge. Finally, appropriate measurement strategies of this kind of workpiece will be concluded.

It’s safe to draw the conclusion from Table 1 that when wear on tool major cutting edge is detected, magnification should be adjusted to 10X to capture more information.

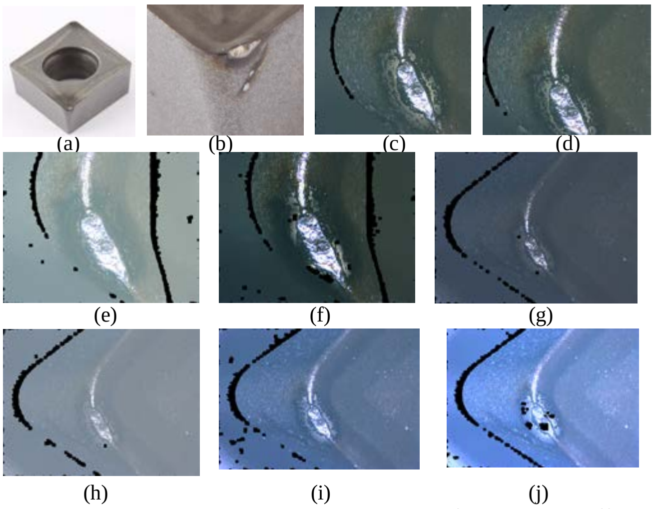

Fig. 4: wear on cutting-insert tooling and the figures under different parameters. (a) cutting-insert tool; (b) wear details of cutting insert tool on the major cutting edge; (c~j) the observed figures of the wear under different parameters. And relevant parameters and result assessment of each figure are shown in Table 1.

Table 1: parameters and result assessments of different tests

N	E t (ms)	C	M	I p	E
c	1.66	1	10X	No	Clear
d	1.75	1	10X	No	Clear
e	2	0.43	10X	No	Low contrast
f	2	1.5	10X	Yes	Invalid points exist
g	2.44	1	5X	Yes	Invalid points exist
h	2.55	0.43	5X	Yes	Invalid points exist; low contrast
i	4.88	1.6	5X	No	Clear
j	6	2	5X	Yes	Invalid points exist; colour distortion

In Table 1: N-Number; E t-Exposure time; C-Contrast; M-Magnification; I p-Invalid points; E-Effect; S f-Smartflash. The abbreviation rules will also apply to those in Table 2 and 4.

Meanwhile, exposure time should be adjusted to less than 2ms and better contrast is 1, considering the fact that when exposure time is fixed at 2ms, relatively low contrast like 0.43 in Fig. 4(e) leads to an insufficient contrast of colour and high contrast like 1.5 in Fig. 4(f) leads to more invalid points (black), which means useful information is lost.

When both worn and unworn regions are detected, magnification is increased to 5X. More exposure time and higher contrast in Fig. 4(g),(h)&(j) bring more invalid points on the wear. There will be no invalid points on a whole when exposure time is around 5ms and contrast is around 1.6 in Fig. 4(i).

3.2 The detection of through hole

The through hole shown in Fig. 5(b) has a small end with radius of 338μm and a big end with radius of 569μm.

In order to check the profile of the through hole, a profile path in red across the diameter of both small end and big end is used. And the profiles of surface are generated.

From the profile, especially the one of the big end, conclusion can be draw from it. The data in red boxes reflects that when a tilted surface with a big angle is detected, the data may be distorted if the angle exceeds the limitation of the instrument. Additionally, in the Fig. 5(d) and Fig. 5(f), the hole is full of invalid points. In this test, the angle of obliquity is 87.5 degree.

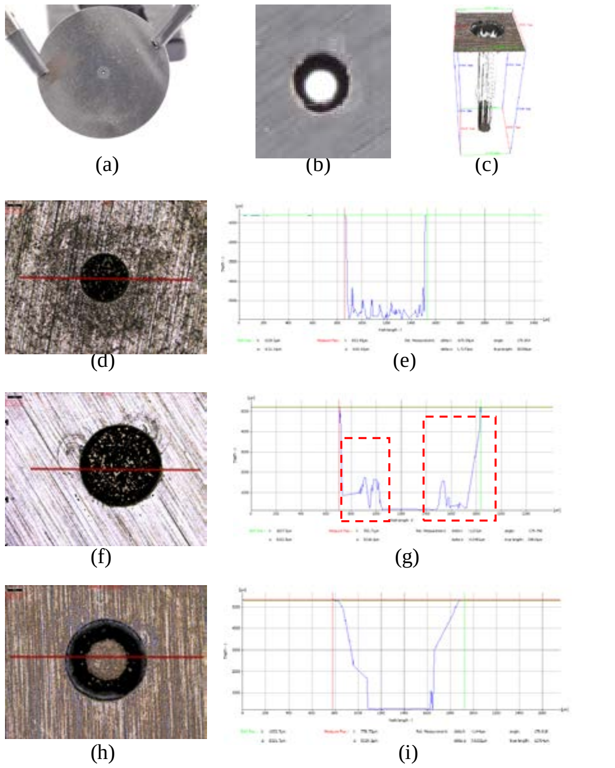

Fig. 5: through hole and the figures with relevant profiles under different parameters.(a) workpiece with through hole; (b) through hole; (c) 3D model; (d&e) small end of the hole and the profile generated; (f&g) big end of the hole and the profile generated; (h&i) big end of the hole and the profile generated with smartflash open.

The tests of Fig. 5(d) and Fig. 5(f) are without smartflash. In Fig. 5(h), when smartflash is open, a comparatively smoother profile with a much better effect can be acquired with less information distortion. But still, it's not an accurate result. The value of contrast is 1 in three times test, and the variation of exposure time has no obvious influence on the results.

3.3 The detection of spherical surface with high reflectivity

The spherical surface of the stainless ball in Fig. 6(b) is featured by decreasing reflectivity from the centre to the edge.

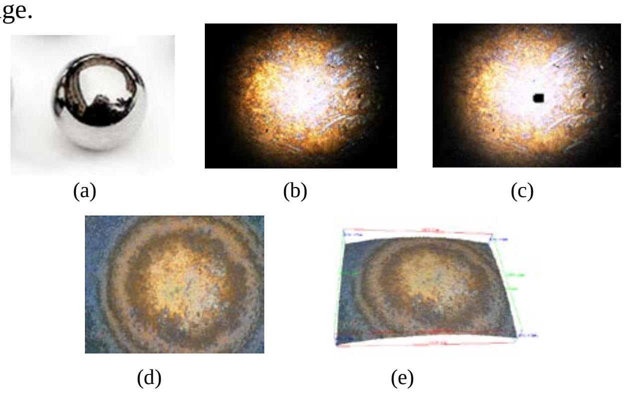

Fig. 6: a stainless ball and the figures under different parameters.(a) a stainless ball; (b~d) the observed figures of the spherical surface under

different parameters; (e) 3D model. And relevant parameters and result assessment of each figure are shown in Table 2.

Table 2: parameters and result assessments of different tests

N	E t (μs)	C	M	I p	S f	E
b	194	1.5	10X	No	No	Too bright in Central part and too dark in surrounding region
c	399	2.17	10X	Yes	No	Ditto; invalid points exist
d	199	1	10X	No	Yes	Clear

When a spherical surface is detected with smartflash off, it can only display a small region surrounding the centre of the ball in Fig. 6(b) and Fig. 6(c). The exposure time and contrast used don't have an obvious influence on the figures in which the central region is too bright, as a result of high reflectivity. After the smartflash is open, much better result is shown in Fig. 6(d). In this way, a clear image of the surface providing adequate information can be acquired.

3.4 The detection of stepped workpiece

In this experiment, a step with a height of 0.303mm on a workpiece in red box in Fig. 7(a) is detected.

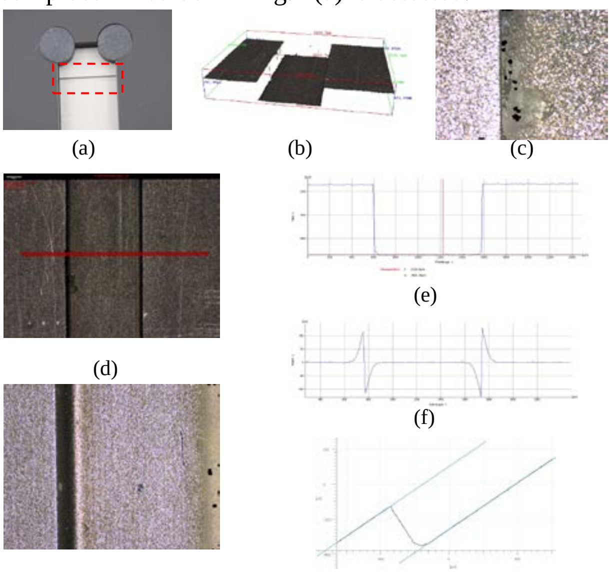

Fig. 7: stepped workpiece and figures with relevant profiles under different parameters. (a) step with a height of 0.303mm on workpiece; (b) 3D model; (c) 20X image with invalid points; (d) 5X image; (e) profile of 5X image; (f) profile of 5X image with data distortion; (g) 20X image of the stepped workpiece with tilt; (h) profile of 20X image of the stepped workpiece with tilt.

From the results above, we can find that when a stepped workpiece is detected vertically, the profile will be distorted sometime, as in Fig. 7(f). Additionally, invalid points will occur in the region around the vertical plane if magnification increased to 20X as shown in Fig. 7(c). To solve these drawbacks, another supplementary experiment is launched, in which the workpiece is given a tilt. From Fig .7(g)&(h), we find a clear image without invalid points and an accurate and smooth profile can be acquired. In another experiment using a workpiece with a 1mm step, the conclusion still holds true.

4. CONCLUSIONS

After finishing some experiments mentioned above, several strategies aimed at different types of workpiece are concluded as bellow, shown in Table 3:

Table 3: strategies to measure different types of workpiece

	Types	Strategies
1	Cutting-insert tool with wear	To detect the wear, appropriate parameters: exposure time is less than 2ms, contrast is around 1 and magnification is 10X. To detect the whole region, appropriate parameters: exposure time is around 5ms, contrast is around 1.5 and magnification is 5X.
2	Through hole on workpiece	When smartflash is open, a comparatively smoother profile with a better effect can be acquired with less information distortion than that without smartflash.
3	Spherical surface with high reflectivity	Smartflash is a necessity when this kind of workpiece is detected. If smartflash is open, the result can be clear without invalid points.
4	Stepped workpiece	If a stepped workpiece is detected, with the increasing of magnification, the information loss may occur, which can be remedied and supplemented by detecting the workpiece with a tilt.

4.1 The verification of the conclusions

Using the strategies we have acquired, a verification experiment on a VDI standard workpiece is conducted to verify the correctness of the conclusions. The VDI standard workpiece (VDI 3400 Ref.) shown in Fig. 8(a) has a row of regions in standard roughness. In this experiment, only Region 12 (Ra: 0.40μm, Rmax: 1.6μm), Region 18 (Ra: 0.8μm, Rmax: 3.2μm) and Region 24 (Ra: 1.60μm, Rmax: 6.3μm) are chosen to be detected.

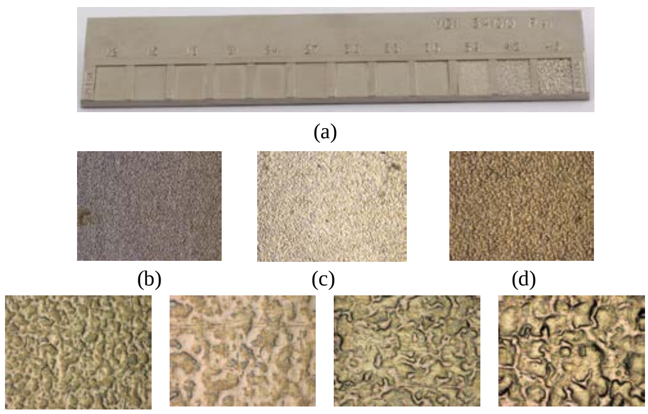

Fig. 8: VDI standard workpiece and figures under different parameters. (a) the VDI standard workpiece; (b~f) the observed figures of Region 12; (g) the observed figure of Region 18; (h) the observed figure of Region 24. And relevant parameters and result assessment of each figure are shown in Table 4.

From the observed results in Table 4, we can find that under the given parameters, all the areas are clear, containing accurate and adequate information. The results verify that the strategies we conclude from the experiments are appropriate and practical.

Table 4: parameters and result assessments of different tests

N	*E t (µs)*	*C*	*M*	*I p*	*E*
a	*572*	*0.8*	*5X*	*No*	*Clear*
b	*275*	*0.8*	*10X*	*No*	*Clear*
c	*208*	*0.8*	*20X*	*No*	*Clear*
d	*541*	*0.8*	*50X*	*No*	*Clear*
e	*372*	*0.8*	*100X*	*No*	*Clear*
f	*514*	*0.8*	*50X*	*No*	*Clear*
g	*250*	*0.89*	*50X*	*No*	*Clear*

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