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EVALUATION OF CMM FOR FLATNESS MEASUREMENTS

Coordinate measuring machine (CMM) is a universal measuring instrument in dimensional metrology. However, the CMM has many sources of errors and deviations that affect its precision and accuracy. Unfortunately, the accuracy of flatness measurement by the CMM is not studied which is very important feature in metrology and industry at present time. A method is introduced to evaluate the accuracy of the flatness measurement of the Zeiss CMM based on flatness measurement of an optical flat. The flatnesses of the optical flat are measured by four different techniques using the CMM. Moreover, the effects of CMM head probe's scanning speed and step width on flatness measurements are examined separately in special measuring subroutines. The flatness of the optical flat surfaces are calibrated using Zygo phase shifting interferometer since it is used as reference for this study. The experimental results show that the CMM's probing points technique can be used for accurate measurements of flatness.

Keywords: Flatness measurement, Coordinate Measuring Machine (CMM), Zygo phase shifting interferometer.

1. INTRODUCTION

Optical flats as reference standard pieces are most commonly used as test plates to evaluate the flatness of optical surfaces by placing it in contact with the reference optical flat under a monochromatic light. An optical flat is a glass, fused silica, Zerodur or sapphire disk polished to a high degree of flatness, typically within a few millionths of an inch. The methods of flatness measurements can be classified as mechanical and optical methods. The mechanical methods apply stylus or probe to contact the surface by measuring separate points or by scanning through lines or grids [1]. The optical interferometrical techniques are the most accurate methods for testing of flatness surfaces [2]. The optical methods are completely unsuitable to machined surfaces of spare parts and engines due to their curving, complicated surfaces and structures. For this reason O. A. Kruger applied the laser interferometer to Coordinate Measuring

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Machine (CMM) to enable the measurements of flatness and parallelism of a step gauge in 3 axes [3]. Machined surfaces have very strict dimensional and form tolerances in order to guarantee their proper operation, reduced fuel consumption and a long life time. For example, in order to evaluate cylinder head flatness, a large quantity of surface points has to be measured very accurately. These types of measurements require skilled operators and very accurate instruments. In this case the Zeiss CMM equipped with touch and scanning head probe VAST provide suitable solution for the problem. The CMM is an instrument measuring dimensions of various objects by determining some of its surface points in 3 coordinate system to measure object's dimentions. The application of CMM enables reliable and accurate measuring results. This is due to the CMM's possibility to measure in 3 axes applying hardware and software for real time measurements and can be programmed to work automatically in the CNC measuring mode. This feature is also useful for repeating the measurements several times which is useful for statistical parameters and measurement uncertainty evaluations. Unfortunately, the CMM has many sources of errors and deviations that affect its precision and accuracy which leads to the suggestion of various methods for assessment of CMM performance. The result of these efforts and suggestions was the issue of the International Standard ISO 10360-2, Geneva, International Organization for Standardization [4], 1994.

This method specifies special parameters and procedures to assess the performance of the CMM. The Volumetric Probing Error P, that is determined by measuring 25 points equally distributed on the surface of a precision sphere [5], ($P = R_{max} - R_{min}$), is an example. However, the parameter P specifies the CMM error at Form measurements, i.e. when measuring Straightness, Flatness, Roundness, Cylinder form and Contours [3]. It is obvious that this method does not provide a procedure for assessing the CMM flatness which is very important feature in metrology and industry at present time. Since the optical flat is used to test flatness of optical components and elements, we decided to use it for assessing the flatness of the CMM. In this article we study the flatness measurement techniques of Zeiss Coordinate measuring machine operated by Calypso software using reference optical flat. The flatnesses of the optical flat surfaces are calibrated using Zygo interferometer for comparison with the results of flatness measured by the Zeiss CMM. The experimental work of this article has been realized in the Laboratory of Engineering and Surface Metrology, Egyptian National Institute of Standards.

2. EXPERIMENTAL PROCEDURE

The optical flat is cleaned and aligned firmly on the CMM's table in the middle as shown in Fig. 1. The CMM is operated in stable environment condition of 20 ±1°C. The CMM is operated and programmed for flatness measurements of the optical flat.

The flatness measurement program on the CMM software is established by defining the measuring probe characteristics and defining the optical flat coordinate system by setting the alignment process. The measuring program contains the setting of the optical flat clearance planes to avoid collision and any harmful scratches to the CMM and the optical flat. The flatness measuring program corrects the errors of the environmental temperature by using the CMM temperature sensors [6]. The flatness of the optical flat is determined by measuring various points through various techniques using the Zeiss probe and scanning head VAST-shown in Fig. 2.

Fig. 1. The alignment process of the optical flat is on the CMM's table.

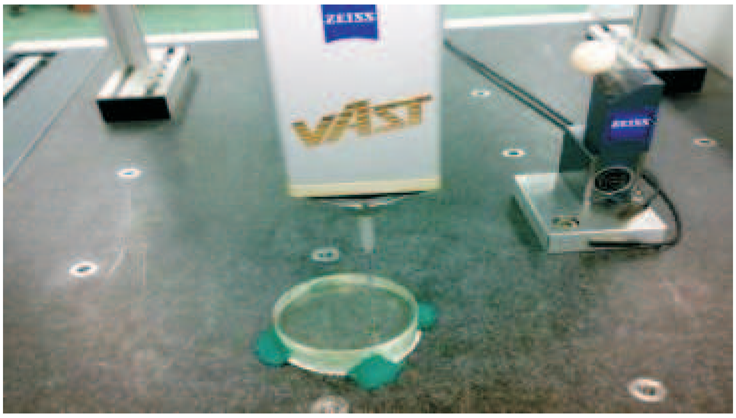

Fig. 2. Flatness measurements of the optical flat are realized by the Zies CMM using probing – scanning head Zeiss Vast.

The CMM Calypso software provides various techniques for flatness measurements that are classified to probing points and scanning methods. The scanning methods apply different techniques such as scanning across poly lines, grids and circles. This leads to four measuring techniques that are as follows: a) probing points method, b) poly line method, grid lines method and circles method. The probing method applies probing of 40 points equally distributed along the selected plane on the optical flat surface for flatness measurements. The scanning methods also apply various scanning speeds and step widths that affect flatness measurement results [6]. The flatness is measured in the program by creating four similar plane's characteristics on the surface of the optical flat, then the four flatness features are created with all the necessary information for CMM measurements. The four flatness features characteristics are classified as probing points method, scanning across poly lines, grids and circles as shown in Fig. 3. The measurement program is executed by the CMM automatically using the CMM software option Computer Numerical Control (CNC) to measure and evaluate flatness of the optical flat. The effect of the CMM head probe's scanning speed on flatness measurements is examined in special measuring subroutine with fixing of CMM head probe's scanning step width.

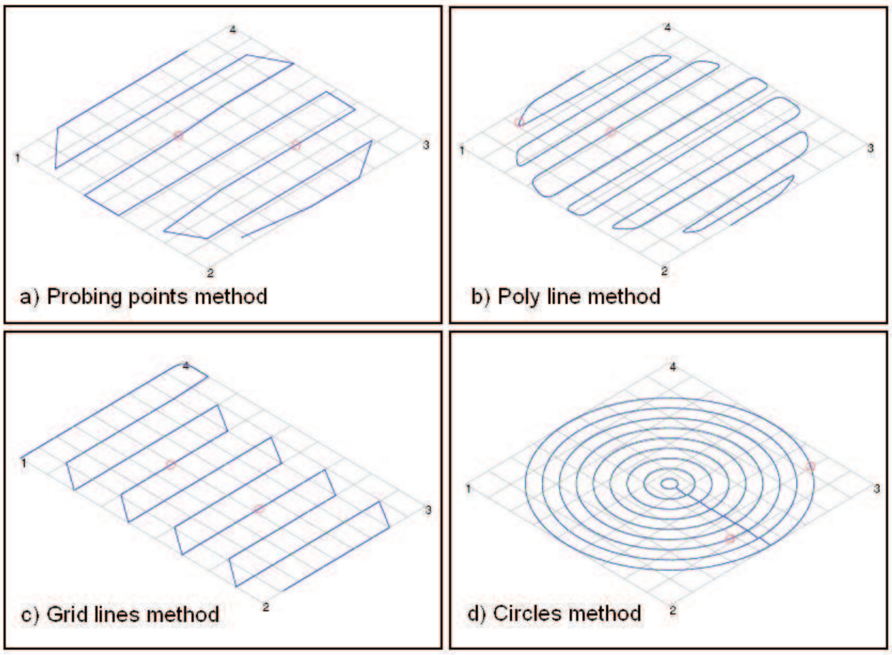

Fig. 3. Various Flatness methods of the optical flat that are measured by Zeiss CMM; a) probing points, b) poly line, c) grid lines and d) circles method.

Also, the effect of the CMM head probe's step width on flatness measurements is examined in another subroutine with fixed of CMM head probe's scanning speed. The flatnesses of the optical flat surfaces are calibrated using Zygo GPI-Xp phase shifting laser interferometer [7] since the optical flat is used as a reference piece for evaluation of the Zeiss CMM's flatness measuring accuracy. The Zygo GPI-Xp is a Fizeau laser interferometer used to calibrate the flatness of the optical flat surfaces by comparing it with a more accurate reference flat as shown in Fig. 4.

Fig. 4. The diagram shows the phase shifting laser interferometer Zygo GPI-Xp.

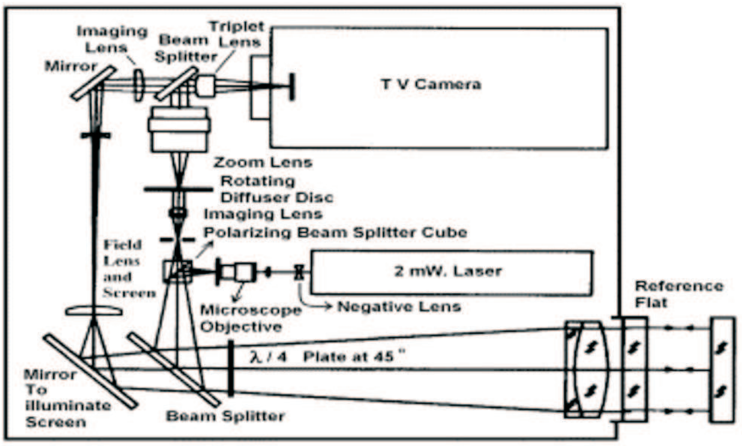

Fig. 5. The optical design of the Zygo GPI-Xp phase shifting interferometer.

The instrument works by He-Ne laser (λ = 632.8 nm) as a source of light, a CCD camera for recording the interference fringes and a computer-based data acquisition system to measure the fringe spacing and analyze the data to convert them to a large test aperture of 102 mm. Fig. 5 shows the optical design of the Zygo GPI-Xp interferometer produced by Zygo Corporation (USA). The interferometer provides high quality, non-contact measurement of a wide variety of surface types [7].

3. RESULTS AND DISCUSSION

The average results of flatness measurements evaluated by peak to valley parameters of both sides of the optical flat measured by the CMM, applying the four methods discussed in section 1 and 2 (Fig. 3.) are represented in Table 1. The flatness values of the 1st surface of the optical flat measured by the CMM vary from 0.046 μm to 1.58 μm. The highest flatness value is for the CMM 2nd method (poly line method) and the lowest value is for the CMM 1st method (probe points method). The flatness values of the 2nd surface of the optical flat measured by the CMM vary from 0.6 μm to 4.7 μm. The highest flatness value is for the CMM 4th method (circles method) and the lowest value is for the CMM 1st method (probe points method). The uncertainty of the flatness values measured by the CMM vary from ± 0.11 μm to ± 0.47 μm. The evaluation of the flatness uncertainties (Table 1) is realized with respect to ISO International Standard for the expression of uncertainty in measurement [8] applying the statistical distributions [9].

The results of flatness of the optical flat surfaces calibrated by the Zygo GPI-Xp laser interferometer are 0.026 μm, 0.838 μm for the 1st and 2nd surfaces respectively as shown in Table 1.

Table 1. The results of flatness of optical flat sides calibrated by Zygo interferometer and measured by the Zeiss CMM.

	Zygo Interferometer	Average of Flatness Results measured by the Four Zeiss CMM techniques ; μm			
Optical Flat side	Flatness; μm	1-Probe. Points	2- poly line	3-grid lines	4- circles
Face 1	0.026	0.46	1.58	0.96	1.12
Face 2	0.838	0.6	3.6	0.7	4.7
Uncertainty	±0.05	±0.16	±0.47	±0.11	±0.26

Since the flatness results of the optical flat (Table 1) vary due to the applied techniques, studying the effect of the CMM head probe's scanning speed and step width on flatness measurements is very important to determine the optimum technique, scanning speed and step width for determining the accurate flatness measuring method applying the Zeiss CMM. The flatness results of the effect of CMM head probe's scanning speed and scanning step width on flatness measurements, which are examined separately, are shown in Fig. 6 and Fig. 7 respectively. Fig. 6 and 7 show that the flatness results measured by scanning across poly lines and spiral methods have the highest values.

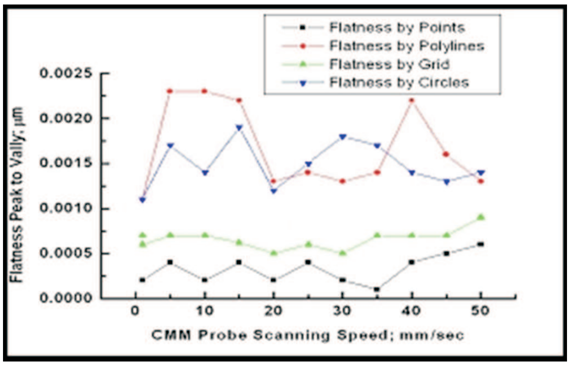

Fig. 6. The CMM head probe's scanning speed effect on flatness measurements.

The uncertainty of flatness measurements (Table 1) is evaluated using random and systematic uncertainties. The random uncertainty is evaluated by determining the standard deviation of the flatness results that are measured experimentally several times to allow for statistical evaluation of the uncertainty according to the method of the ISO International Organization for Standardization [8].

The systematic uncertainty is determined applying the software of the CMM and Zygo interferometer that evaluate various systematic factors such as the CMM and its probe head errors, the Zygo laser's wavelength, absorption and reflection coefficient of the optical flat glass, errors of the reference and calibrated optical flats, etc. The statistical uncertainty is calculated using the standard deviation of the mean of results [9] as follows:

$$u_j = \sqrt{\frac{1}{(n-1)} \sum_{j=1}^{n} (x_j - \overline{x})^2}, \tag{1}$$

where: n is the no. of measurements, x_j is the measured value, $\bar{x}$ is the mean value.

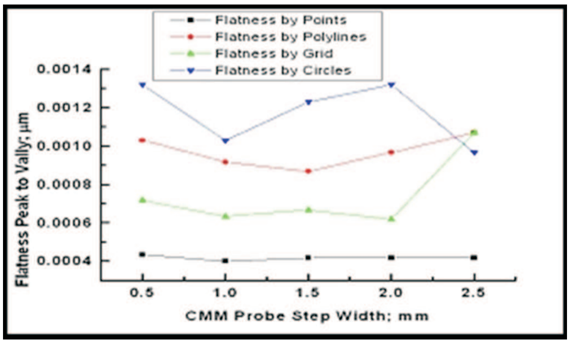

Fig. 7. The CMM head probe's scanning step width effect on flatness measurements.

The lowest flatness values are measured by probing points method. The flatness values measured by scanning across grid lines are the intermediate values slightly higher than probing point's method. The flatness results of the optical flat surfaces shown in Fig. 6 and 7 show that probing points method is more accurate than all scanning methods. Among the flatness scanning methods we found that the flatness measured by scanning across grid lines is the most accurate method.

The Zygo interferometer (Fig. 4, 5) calibrate the hole surface flatness of the optical flat in one single measurement and evaluates the optical flat radius of curvature and peak to valley values of the surface. This feature makes the calibration results of flatness of the optical flat by the interferometer determine which technique applied by the CMM is the most accurate, fast and reliable. The images of the optical flat surface flatness calibrated by the Zygo interferometer are shown in Fig. 8 and 9 for the 1st and 2nd surfaces of the optical flat.

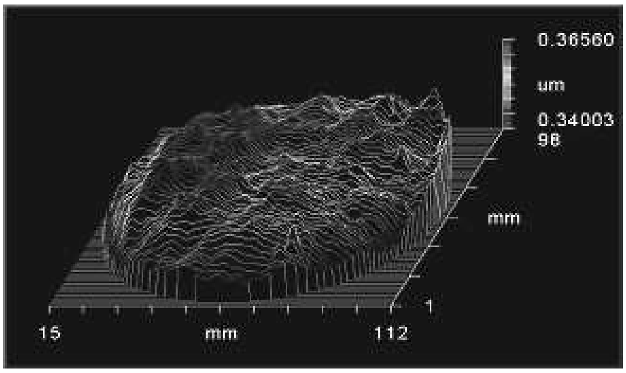

Fig. 8. Flatness of optical flat side 1 calibrated by Zygo interferometer; peak to valley = 0.026 μm.

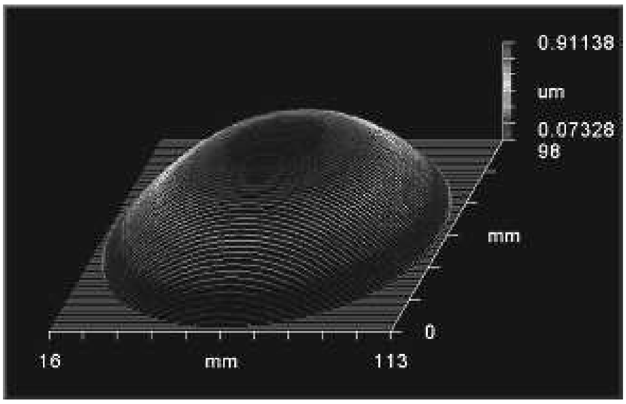

Fig. 9. Flatness of optical flat side 2 calibrated by Zygo interferometer; peak to valley = 0.838 μm.

Comparing the results introduced in Table 1 of flatness measurements by various techniques of the CMM with those calibrated by Zygo interferometer, one can see that the results measured by CMM probing points method are the nearest values to those calibrated by Zygo interferometer. This means in general that flatness measurements by the CMM scanning techniques are less accurate than those measured by CMM probing points technique. This shows an interesting feature for the measurements of flatness by using the CMM which can produce very accurate flatness results if the CMM has a high accuracy and provided with an accurate head probe that works in good environmental conditions with temperature 20 ±1.0°C.

4. CONCLUSIONS

The comparison of flatness results measured by the CMM and Zygo laser interferometer show that the measurements of flatness by the CMM can produce very accurate flatness results providing that the CMM has a high accuracy and working with an accurate head probe in stable environmental conditions with temperature 20°C±1.0°C.

The results of flatness measurements by the CMM applying probing points method are the most accurate since they are close to the flatness results calibrated by Zygo interferometer.

The flatness results measured by the CMM scanning techniques are less accurate than those measured by CMM probing points technique.

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