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Exploration of the Differences and Applicability of Contact and Non-contact Surface Roughness Measurement Methods

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Abstract

Surface roughness refers to the micro geometric unevenness of the machining surface of a workpiece with small spacing and small peaks and valleys. Surface roughness plays a very important role in the machining accuracy of products and ensuring the performance of mechanical parts. The measurement methods for surface roughness can be divided into contact measurement and non-contact measurement. This article uses a stylus surface roughness measuring instrument and a white light interferometer to measure the surface roughness parameter Ra of the same set of multi groove templates with multiple nominal values. We compare the measurement results of the two methods, analyze the reasons for the differences in measurement results from the perspectives of measurement principles and processes, and provide the applicability of the two measurement methods.

Keywords

Surface Roughness; Multi Groove Template; Non-contact Measurement; Residual Profile.

1. Introduction

In the actual machining process, friction, metal tearing, mechanical vibration, and temperature changes can leave uneven marks such as micro peaks and valleys on the surface of the machined parts, resulting in a micro geometric shape composed of small spacing and peaks and valleys. The geometric shape characteristics formed by the amplitude and density of these peaks and valleys are called surface roughness. Surface roughness is an important indicator used to evaluate the surface manufacturing quality of workpieces.

Surface roughness not only affects the accuracy of processed products, but also affects the glossiness and texture of the surface. Therefore, surface roughness is an important factor affecting product image and brand. Especially in the field of ultra precision machining, not only is machining accuracy required, but also high surface treatment ability is required, so the parameter of surface roughness is very important.

Surface roughness has an important impact on the wear resistance, compatibility stability, fatigue strength, corrosion resistance, sealing performance, and surface optical properties of parts. For example, in terms of its impact on wear resistance, the rougher the surface, the smaller the effective contact area between mating surfaces, the greater the pressure, the greater the frictional resistance, and the faster the wear. In terms of sealing, rough surfaces cannot tightly adhere to each other, and gas or liquid leaks through the gaps between the contact surfaces. Therefore, surface roughness also has an important impact on the sealing performance of the product; In terms of the impact on measurement accuracy, especially in precision measurement processes, the surface roughness of the measured surface of the parts and the measuring surface of the measuring tools will directly affect the measurement accuracy; The failure of parts subjected to alternating loads is mostly caused by

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surface fatigue cracks. Fatigue cracks are mainly caused by stress concentration caused by surface micro peaks and valleys. The rougher the surface of the part, the deeper the valley, and the more severe the stress concentration. Therefore, surface roughness can affect the fatigue resistance of the parts. Therefore, when designing the geometric parameter accuracy of parts, it is necessary to propose reasonable surface roughness requirements to ensure the performance of mechanical parts.

Figure 1. Metal object images with different surface roughness

With the development of technology, the demand for surface performance of components is becoming increasingly high. Surface roughness measurement technology plays an important role in fields such as microelectromechanical systems, precision optical systems, and semiconductors.

The measurement methods for surface roughness can be divided into contact measurement and non-contact measurement. The contact measurement method is mainly based on the stylus measurement method, which generally includes comparison method, impression method, and stylus method; Non contact measurement is mainly based on optical principles, and the main measurement methods include optical interferometry, real-time holography, speckle method, and measurement using atomic force microscopy.

2. Contact and Non-contact Measurement of Surface Roughness

Surface roughness is often represented by the parameter *Ra*, which is the arithmetic mean roughness. The concept of parameter *Ra* is intuitive and reflects the contour characteristics of surface roughness with a large amount of information. Moreover, the parameter *Ra* value is relatively easy to obtain using a stylus profilometer in the early stages of roughness measurement development, so it is widely used.

$$Ra = \frac{1}{l}\int_0^l \left|Z(x)\right| dx \tag{1}$$

In the formula, *l* is the sampling length, and within the sampling length *l*, *Ra* is the arithmetic mean of all vertical coordinates.

2.1 Contact Measurement of Surface Roughness

The typical method of contact measurement is to use a stylus surface roughness measuring instrument to measure the surface of the sample. In 1936, E.J. Abbott of the United States successfully developed the first profilometer for measuring surface roughness used in production sites; In 1940, Taylor Hobson, a British company, successfully developed the first surface roughness measuring instrument, opening the door to modern surface roughness detection [1]. Subsequently, various countries successfully developed modern instruments for measuring surface roughness. At present, the relatively famous international instruments of this kind are a series of mature products launched by Taylor Hobson in the UK.

The driver of the stylus surface roughness measuring instrument drives the sensor to slide along the direction perpendicular to the processed texture at a constant speed on the measured surface. The mechanical stylus at the front end of the sensor contacts the measured surface. The stylus is usually made of diamond, with a conical shape and a needle tip radius of (0.1-10) μm. The micro roughness of the workpiece surface will cause the stylus to move up and down. The movement of the stylus is induced by the sensor and converted into an electrical signal by the measurement bridge. After amplification and demodulation, the micro profile of the sample's measured section will be obtained, thereby obtaining the measured values of shape error, waviness, and surface roughness of the measured surface. The principle of a stylus surface roughness measuring instrument is shown in Figure 2.

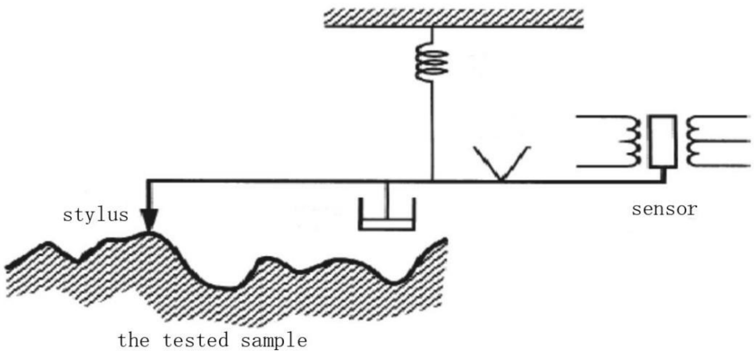

Figure 2. Principle of a stylus surface roughness measuring instrument

2.2 Non Contact Measurement of Surface Roughness

With the advancement of science and technology and the increasing demand for roughness measurement accuracy, contact measurement methods are not suitable for some surfaces that do not allow scratching, relatively soft metal and non-metal surfaces, and some device surfaces that contain information. Therefore, non-contact measurement methods have emerged. Among them, white light interference method has the advantages of high stability, and the measurement results are less affected by external disturbances and changes in the output power of the light source.

The application of white light interference has a long history, but the first three-dimensional surface morphology measurement system that truly uses the principle of white light interference for measurement was proposed by N.Balasubramanian in 1980. Since then, many experts and scholars in the field of surface morphology measurement have developed various measurement devices based on this principle internationally[2-4]. Currently, ZYGO Company in the United States is well-known in this field, and its three-dimensional surface morphology measurement instrument has been widely used.

The illumination beam of the white light interferometer is divided into two beams through a semi reflective and semi transparent spectroscope, which are respectively projected onto the surface of the sample and the surface of the reference mirror. The two beams of light reflected from these two surfaces are then combined into one beam through a splitter, and the imaging system forms two superimposed images on the photosensitive surface of the CCD camera. Due to the interference between two beams of light, interference fringes of light and dark can be observed on the photosensitive surface of the CCD camera. Piezoelectric ceramics (PZT) drive the movement of the aspherical objective lens group, and the accurate position is fed back by capacitive sensors. By

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combining interference image photos at different heights, the microscopic image of the surface structure of the tested sample can be analyzed. The principle of a white light interferometer is shown in the Figure 3.

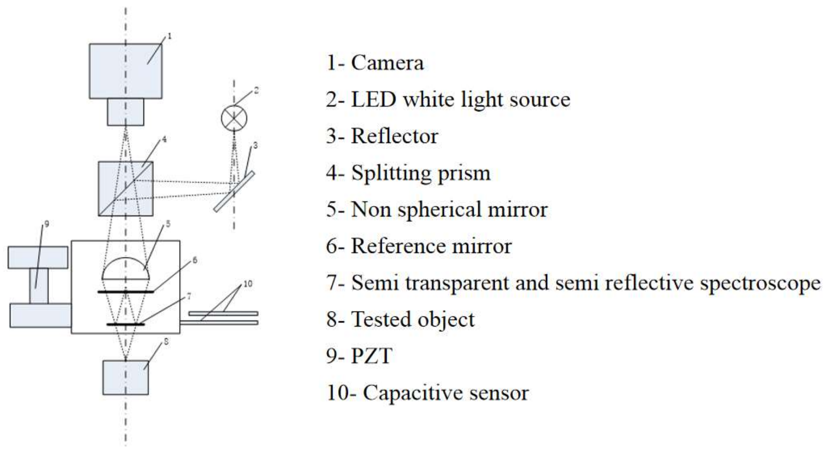

Figure 3. Schematic diagram of the principle of white light interferometer

We conducted preliminary discussions on the measurement results and applicability of the contact and non-contact measurement methods for roughness through comparative experiments.

3. Experiment and Analysis

To investigate the influence of contact and non-contact measurement methods on the measurement results of surface roughness, Taylor Hobson's stylus surface roughness measuring instrument and Zygo's optical surface morphology measuring instrument were used for measurement in this comparative experiment.

This experiment measured the surface roughness of a set of multi groove surface roughness templates. The multi groove template is a measuring instrument composed of periodic or random multi groove lines with a certain range of grooves, as shown in Figure 4.The periodic profile can be obtained on the section perpendicular to the groove of the multi groove template. The average distance from each point on the profile to the centerline within the sampling length is the roughness parameter *Ra* of the multi groove template.The nominal values of the multi groove templates used in this experiment are 0.0125 μm, 0.025 μm, 0.05 μm, 0.1 μm, 0.2 μm, and 0.4 μm, respectively.The parameter *Ra* value of the multi groove template should be measured at 6 evenly distributed positions within the working area of the template working surface.

Figure 4. Physical image of multi groove template

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During the experiment using two measurement methods, the measurement length and the sampling length selected for calculating the roughness *Ra* value were kept consistent, and both were calculated and analyzed according to the Table 1. The measurement length was set to seven times the sampling length.

Table 1. Reference table for selecting sampling length

The nominal value of parameter *Ra* (μm)	Sampling length *l* (mm)
0.0125	0.08
0.025, 0.05, 0.1	0.25
0.2, 0.4	0.8

3.1 Measurement Method Using a Stylus Type Surface Roughness Measuring Instrument

Place the tested multi groove template on the workbench of the preheated stylus surface roughness measuring instrument, with the measurement direction perpendicular to the direction of the grooves of the multi groove template. Measure at 6 evenly distributed positions on the template in sequence. After analysis and filtering, take the average *Ra* value as the measurement result. The measurement data obtained using a stylus surface roughness measuring instrument are shown in Table 2.

Table 2. Measurement results of samples using a stylus measuring instrument

Sample number	Measurement values of parameter *Ra* at different positions (μm)						average value (μm)
	1	2	3	4	5	6	
1#	0.0121	0.0120	0.0121	0.0122	0.0120	0.0123	0.0121
2#	0.0246	0.0244	0.0239	0.0242	0.0246	0.0242	0.0243
3#	0.0548	0.0546	0.0543	0.0544	0.0544	0.0544	0.0545
4#	0.0971	0.0975	0.0971	0.0966	0.0975	0.0971	0.0972
5#	0.2461	0.2466	0.2461	0.2460	0.2461	0.2491	0.2467
6#	0.4306	0.4301	0.4316	0.4306	0.4316	0.4311	0.4309

3.2 Measurement Method Using White Light Interferometer

Place the tested multi groove template on the workbench of the white light interferometer, select a 10X objective lens, adjust the height of the objective lens until clear interference fringes can be observed, adjust the interference fringes to be perpendicular to the direction of the multi groove template, and adjust the interference fringes of the template to the zero level fringe position.Similar to the contact measurement method, measurements are taken sequentially at 6 evenly distributed positions on the sample, and the scanning range and number of splices are determined based on the sampling length and measurement length.

In the process of data analysis, select a straight line from the measurement data results and obtain the measured roughness parameter *Ra* on this straight line. The measurement data obtained using a white light interferometer are shown in Table 3.

From the experimental data, it can be observed that the results of using a white light interferometer to measure the parameter Ra of the multi groove surface roughness template are all smaller than those of a stylus surface roughness measuring instrument.

We analyzed the measurement principle and process, and found that contact measurement may produce certain deviations during the contact between the stylus and the sample, as well as during signal transmission and processing. We classified it as residual profile. We obtained the original profile by experimentally measuring an ideal smooth surface. We selected ultra smooth monocrystalline silicon to measure the residual profile of the stylus surface roughness measuring instrument, and the result obtained was 0.003 μm.

Table 3. Measurement results of samples using a white light interferometer

Sample number	Measurement values of parameter *Ra* at different positions (μm)						average value(μm)
	1	2	3	4	5	6	
1#	0.0075	0.0078	0.0081	0.0077	0.0076	0.0071	0.0076
2#	0.0222	0.0221	0.0223	0.0222	0.0221	0.0222	0.0222
3#	0.0507	0.0505	0.0507	0.0507	0.0504	0.0506	0.0506
4#	0.0933	0.0935	0.0936	0.0937	0.0939	0.0941	0.0937
5#	0.2372	0.2369	0.2339	0.2359	0.2349	0.2356	0.2357
6#	0.4211	0.4188	0.4205	0.4199	0.4205	0.4206	0.4202

The residual profile accounts for a significant proportion in the measurement results of multi groove templates with smaller nominal values. For example, in the template with a nominal value of 0.0125 μm, it reaches a proportion of 24%, and in the template with a nominal value of 0.025 μm, it reaches a proportion of 12%.For samples with parameter *Ra* values greater than 0.1 μm, the white light interferometer measurement method requires more splicing times and the resulting error will gradually increase.

4. Conclusion

The non-contact measurement method reduces the residual profile and other errors introduced by the measurement method itself due to avoiding direct contact between the stylus and the measured surface. When measuring surface roughness parameters with smaller nominal values, non-contact optical measurement methods are more suitable, which can truly reflect the surface roughness data of the sample. For example, for multi groove templates, when the nominal value Ra is less than 0.1 μm, non-contact measurement methods are more suitable. However, as the surface roughness parameter *Ra* gradually increases, the required measurement length and number of splices increase. Non contact optical measurement methods also introduce certain splicing and calculation errors.

The contact measurement method has the characteristics of mature and stable methods, large range, simple instrument operation, low labor and instrument costs, and can ignore the residual profile introduced during the measurement process for samples with larger nominal roughness values. Therefore, for samples with larger nominal surface roughness *Ra* values, the contact measurement method can be used for measurement. For example, for multi groove samples, when the nominal value is greater than 0.1 μm, using a stylus surface roughness measurement instrument is more suitable.

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