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Paper:

Development of On-Machine Measurement System Utilizing Line Laser Displacement Sensor

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Demand for precision machining of dies and molds with complex shapes has been increasing. Though high performance CNC machine tools are widely utilized for precision machining, machining error compensation is still necessary to meet accuracy requirements. For precision measurement, a workpiece must usually be unloaded from a CNC machine tool. Then, the workpiece is measured by a precision measurement device, such as 3D CMM. After the machining error is clarified according to the measurements taken, the workpiece must be re-clamped for the necessary error compensation machining. This error compensation machining is costly and time consuming, and it requires a highly skilled machinists. The re-clamping of the workpiece also causes positioning errors. Therefore, demands for on-machine measurement have been increasing. In this paper, an on-machine measurement device that consists of a line laser displacement sensor is developed. This measurement device, attached to the spindle head of a machine tool with magnetic clamps, has special features, such as non-contact, multi-point, high-speed measurement capabilities. Additionally, a sequential multi-point method, an extension of the two-point method, is applied for shape measurement accuracy.

Keywords: on-machine measurement, line laser displacement sensor, sequential two-point method, sequential multi-point method

1. Introduction

Demand for the precision machining of dies and molds with complex shapes has been increasing. Although CNC machine tools are widely utilized for precision machining, machining error compensation is still necessary to meet machining accuracy requirements. However, machining error compensation is costly and time-consuming, and it requires the skills of an experienced machinist. The main problems associated with precision machining can be summarized as follows:

(1) Highly skilled machinists are required for machining error compensation.

(2) Off-line measurement using a 3D Coordinate Measuring Machine (CMM) to detect machining error is both costly and time-consuming.

(3) Positioning errors and workpiece deformation after re-clamping of the machined workpiece make machining error compensation difficult.

In our previous study, we proposed a new method of compensating for machining error to solve problem (1). In this method, the machined workpiece is measured and the machining error found is used to modify the 3D surface model of the part being machined [1]. This modified 3D surface model is generated by subtracting the machining error from the measurements of the original 3D surface model. A new Numerical Control (NC) program for machining error compensation is generated from the modified 3D surface model. The difference between the original and the modified 3D surface models corresponds to the machining error generated. Moreover, a special fixture is used in order to reduce positioning error and workpiece deformation.

The transporting of large, heavy workpieces is cumbersome, and re-clamping them exaggerates positioning errors. Therefore, the demand for an on-machine measurement system has been increasing. One solution to this problem has been investigated with an on-machine measurement method using a CCD laser displacement sensor [2, 3]. This is called a non-contact method. However, there is no difference in measurement time between the traditional contact measurement method and the non-contact method. Additionally, an NC program is required for measuring, and measuring time and loss of efficiency are not negligible. In this study, a measuring device employing a line laser displacement sensor was developed for an on-machine measurement system in order to improve measuring speed and accuracy.

2. On-Machine Measurement

2.1. Comparison of On-Machine Measurement Sensor

There are two methods for on-machine measurement systems: the contact and non-contact methods. For con-

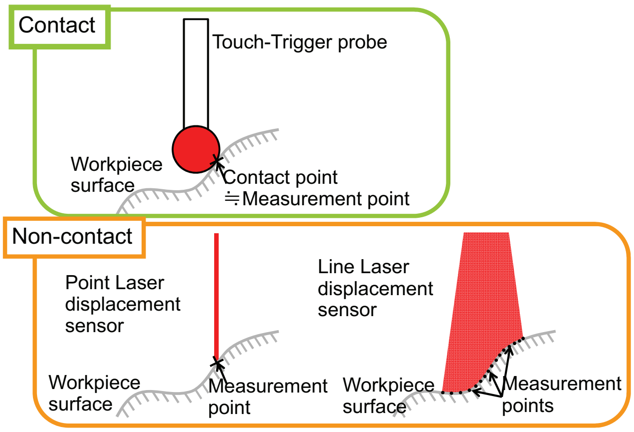

Fig. 1. Comparison of on-machine measurement sensors.

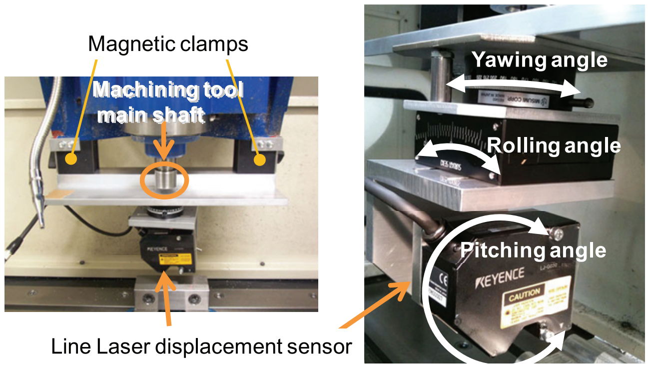

Fig. 2. On-machine measurement device.

Table 1. Specifications of line laser displacement sensor.

Reference distance			30 mm
Measuring range	Z-axis		±10 mm
	X-axis (Width)	Near	20 mm
		Reference distance	22 mm
		Far	25 mm
Light source		Kind	Red semiconductor laser
		Wavelength	650 nm
		Output	0.95 mW max
Spot diameter(at reference distance)			approx. 40 μm×25 mm
Repeatability		Z-axis(Height)	1 μm
		X-axis(Width)	5 μm

tact measurement methods, a touch-trigger probe called the stylus is used for the sensor. An example of the touch-trigger probe is shown in **Fig. 1**. In order to detect the measurement point precisely, a contact point between the stylus and the workpiece is calculated by the radius compensation of the stylus. However, the accurate calculation of the contact point is very difficult for an unknown surface, such as a machined surface including machining error. In order to improve measuring accuracy, multi-point measurements are required to detect 3D coordinates on the surface. However, the touch-trigger probe is not suitable for scanning the surface for multi-point measurements. In this study, a line laser displacement sensor is applied for multi-point measurements without surface contact.

2.2. On-Machine Measurement Device

The on-machine measurement device, shown in **Fig. 2**, consists of a high-precision line laser displacement sensor (LJ-G030; Keyence) attached with magnetic clamps to a machine tool spindle head. Specifications of the line laser displacement sensor are listed in **Table 1**. The line laser displacement sensor fixture can rotate around both the vertical and horizontal axes, and the sensor can assume suitable postures for taking non-contact measurements of the vertical surface and the steep slope of the workpiece. The scanning motion of the sensor is controlled by an NC program, and the sensor can detect the surface profile at a sampling rate of 46000 points/sec.

2.3. Data Processing

Data from the on-machine measurement device are output through a sensor controller and a data logger. The output data are then converted into 3D point data. The coordinate system of the line laser displacement sensor for measurements is shown in **Fig. 3**. The data-processing procedure is summarized in **Fig. 4**. First, the output data, ZL, are provided as time-series data. YL is generated from the scanning speed and the trigger interval, and 2D cross-section point data are calculated. The origin of 2D

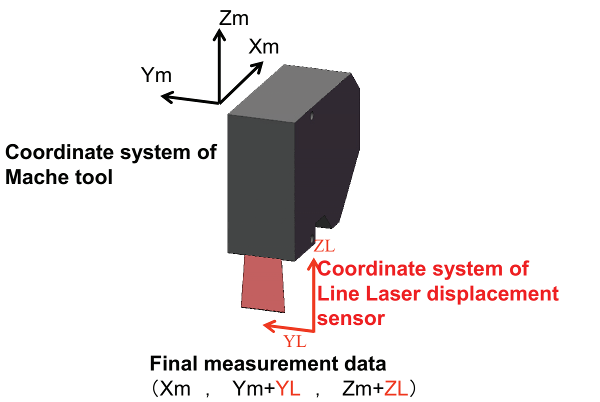

Fig. 3. Coordinate system of the line laser displacement sensor.

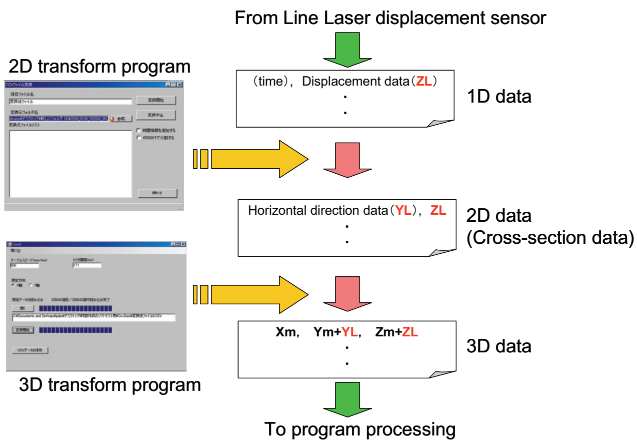

Fig. 4. Outline of data-processing procedure.

point data is set to the center of the cross-section. Finally, YL and ZL are converted to Ym and Zm, respectively, and Xm is generated from the feed speed of the machine tool and the scanning pitch of the line laser displacement sensor. The origin of the 3D point data is set to the starting point of measurement.

2.4. Equipment Used in the Experiment

In this study, a high-speed milling machine (ASV-400, Toshiba Machine) is used for the machining and on-machine measuring, and a 3D CMM (Prismo5, Carl Zeiss) is used to evaluate the accuracy of the measurement data. The equipment used in the experiment is shown in **Fig. 5**.

The estimated measurement efficiency data are summarized in **Table 2**. 0.1 million points in a 20×20 mm area are measured by the line laser displacement sensor, the on-machine measuring touch-trigger probe, the 3D CMM, and the on-machine measuring CCD laser displacement sensor, respectively. The results show that the line laser displacement sensor employed in the on-machine measurement device in this study can achieve the highest measurement efficiency.

2.5. Verification of Measurement Error Caused by Laser Line Width

The measurement principle of the line laser displacement sensor [4] is shown in **Fig. 6**. The light receiving device detects the intensity of the scattered light that is reflected off the workpiece surface. When the workpiece surface height rises ε, the maximum intensity point of scattered light moves Δg. Thus, the workpiece surface height is measured by the motion of the maximum intensity point on the light receiving device. In this case, it is assumed that the line laser beam has infinitesimal width theoretically.

However, the line laser beam has finite width practically. The scattered light intensity of the laser beam that is reflected off the workpiece surface has a Gaussian distribution. The Gaussian distribution usually has a maximum value in the vicinity of the center. The irregular condition of the workpiece surface disturbs the scattered light intensity, and the maximum intensity point moves Δg. This is the cause of the measurement error in detecting the workpiece surface height ε.

Figure 7 shows the relation between the measurement error and the laser beam width. When the scattered light intensity is at the maximum at point C (an edge of laser beam width), the light receiving device recognizes that the laser beam is reflected at point B. Therefore, the sensor detects the measurement error $+\varepsilon_1$ compared with the actual surface height. Similarly, when the scattered light intensity is at its maximum at the point F, the sensor detects the measurement error $-\varepsilon_2$ compared with the actual surface height.

Figure 8 shows the estimated measurement errors ε_1 and ε_2 under the influence of angle γ. For the laser sensor

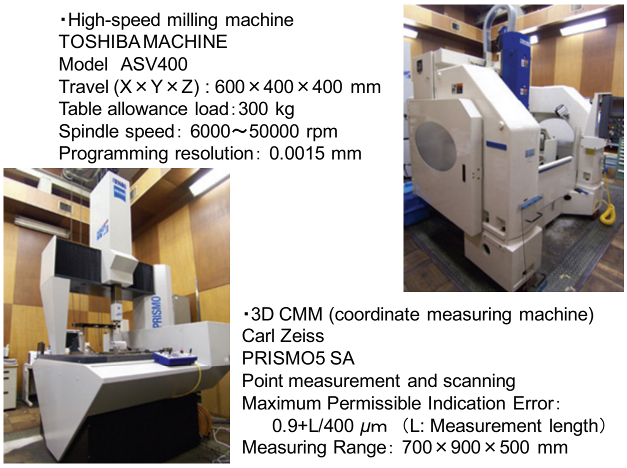

Fig. 5. Equipment used in the experiment.

Table 2. Comparison of estimated measurement efficiency.

	Measuring time	Estimated feed speed (mm/min)	Comparison of measurement efficiency (times)	Remarks
Line laser displacement sensor	~2.5 sec	500	1	In this study
Touch-Trigger Probe	~ 86 h	0.66	~ 120,000	measuring 1 point/3 sec on-machine measuring
3D CMM	~ 19 min	180	~ 1,400	scanning speed 3 mm/sec
CCD laser displacement sensor	~ 102 sec	2,000	~ 40	sampling time 1 ms on-machine measureing

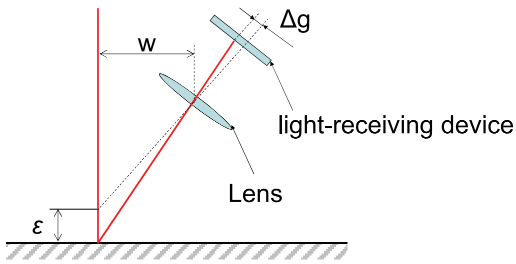

Fig. 6. The measurement principle of line laser displacement sensor.

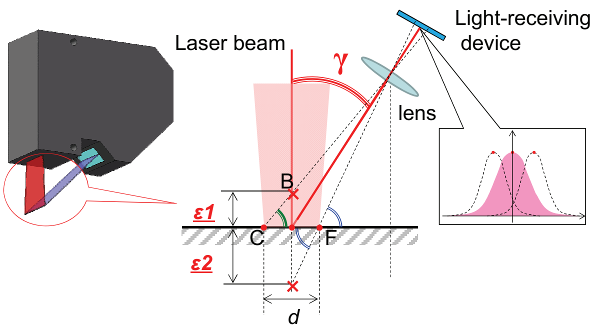

Fig. 7. The error due to laser beam width.

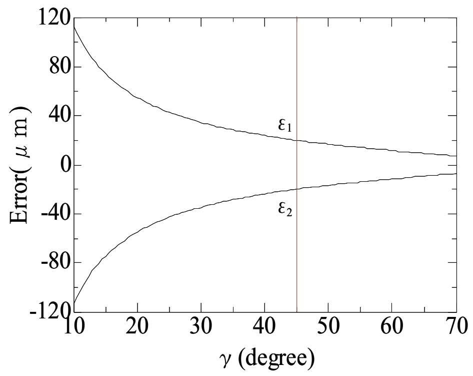

Fig. 8. Influence of tilt γ on maximum error.

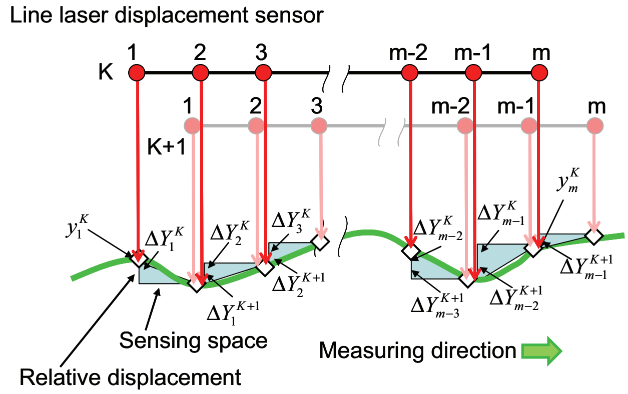

Fig. 9. Principle of sequential multi-point method.

applied in this study, the angle γ is 45 degrees, and the estimated measurement error is ± 20 μm.

In this study, the sequential multi-point method, which is an extension of the sequential two-point method for shape measurement, is applied to reduce measurement error.

3. Sequential Multi-Point Method (SMPM)

This method is an extension of the sequential two-point method [5, 6] for shape measurement. The sequential two-point method was developed to evaluate the amount of error in the straightness of the movement of a machine tool. In this method, two displacement sensors are attached to the machine tool spindle at a prescribed distance in the direction of table movement. A workpiece is measured in the direction of table movement at all prescribed distances. From the relative displacements between the two displacements measured by the two sensors, the straightness of machine tool and the shape of workpiece can be evaluated separately. Above all, the motion error of machine tool can be eliminated through this method.

The laser sensor detects random noise that is caused by scattered light, and this worsens the accuracy of measured relative displacements. In this study, a line laser displacement sensor is utilized as a multipoint displacement sensor. The Sequential Multi-Point Method (SMPM), which is based on the sequential two-point method, is proposed to reduce measurement error caused by random noise.

3.1. Principle of Sequential Multi-Point Method

Figure 9 shows the measurement principle of this method. It is assumed that the line laser displacement sensor at position K can detect m displacements y_j^K $(j = 1 \sim m)$ in a moment, and $m-1$ relative displacements ΔY_j^K $(j = 1 \sim m-1)$ that correspond to the difference between two displacements measured by neighboring sensing points. According to scans made by the laser displacement sensor from position K to $K+m-1$, $m-1$ times, measurement of relative displacement can be performed. Resultant relative displacement ΔY_K can be calculated using following equation:

$$\Delta Y_K = \frac{1}{m-1}\sum_{i=1}^{m-1} \Delta Y_{m-i}^{K+i-(m-1)} \qquad \ldots\ldots \quad (1)$$

The measurement shape of the workpiece can be represented by successive resultant relative displacements

3.2. Verification of Measurement Accuracy

The precision cylinder gauge 20 mm in diameter is measured to verify measurement accuracy. The measurement data is compared with the 3D CAD model to evaluate the accuracy of measurement. The measurement direction and the precision gauge for the measurement are shown in **Fig. 10**. The laser sensor moves across the axis of the gauge. The maximum number of sensing points the line laser displacement sensor can have is 800 points. The sensing points are 33 microns apart. The sampling time is adjusted to get scanning data every 33 microns.

The measurement data are adjusted to the origin of the 3D CAD model data by the least squares method. After that, the measurement error is evaluated. The circularity of the precision gauge is under 1 micron, measured by CMM. It means that form error is negligible. Therefore, the 3D CAD model data is used for comparison with the measurement data. The result is shown in **Fig. 11**. The upper graph in **Fig. 11** shows a 3D CAD model of the precision gauge; the lower graph shows measurement error calculated by comparison of measurement data with CAD data. In this case, the gauge surface, with its steep angle, could not be detected properly, because the laser light reflects in the wrong direction. Measurement errors were evaluated at 3.12 μm RMS for the SMPM data (500 points using) and 7.89 μm RMS for the original data. This method is effective to reduce measurement error.

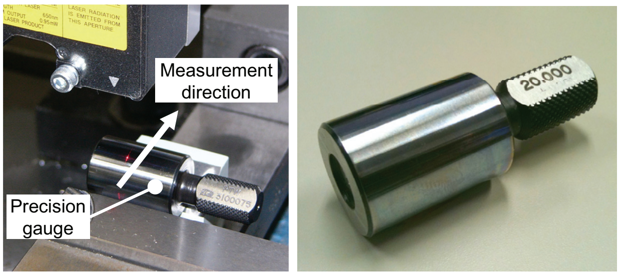

Fig. 10. The experimental set up and the precision cylinder gauge for the measurement.

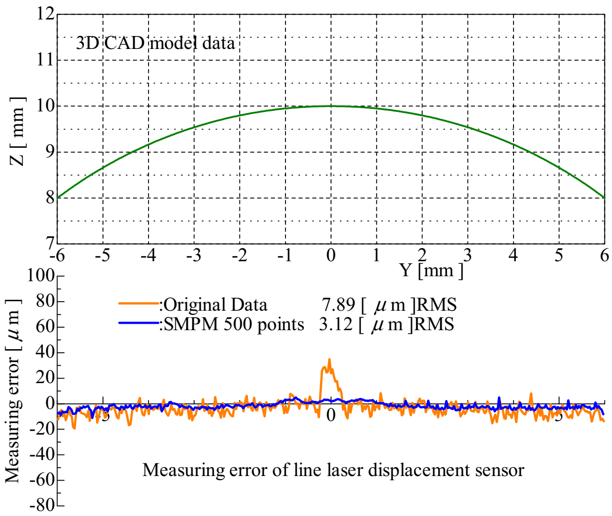

Fig. 11. Comparison of SMPM and 3D CAD data.

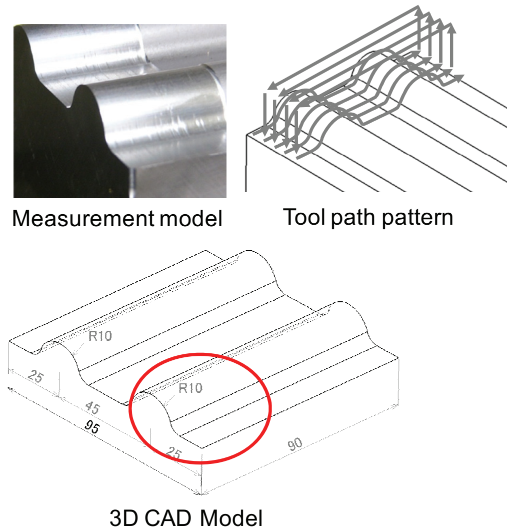

Fig. 12. Measurement model for case study.

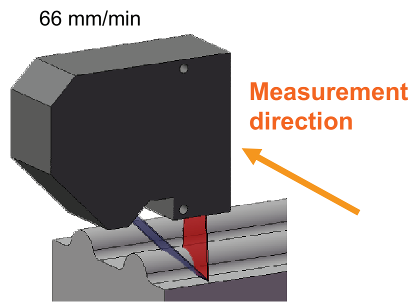

Fig. 13. Direction of measurement in the case study.

4. Case Study

Figure 12 shows the measurement model for the case study. This model is machined under the following conditions:

- Workpiece material: Aluminum Alloy A5052
- Tool: ball end mill 3R
- Spindle speed: 30000 min^{-1}
- Feed speed: 1000 mm/min
- Pick feed: 0.5 mm (rough), 0.1 mm (finish)
- Depth of cut: 0.5 mm (rough), 0.1 mm (finish)
- Temperature: 20 ± 1 °C

Figure 13 shows the direction of measurement. Measuring conditions are as follows:

- Feed speed: 66 mm/min
- Trigger interval: 30 ms
- Number of data for SMPM: 500 points
- Measuring time: 24.5 sec
- Temperature: 20 ± 1 °C

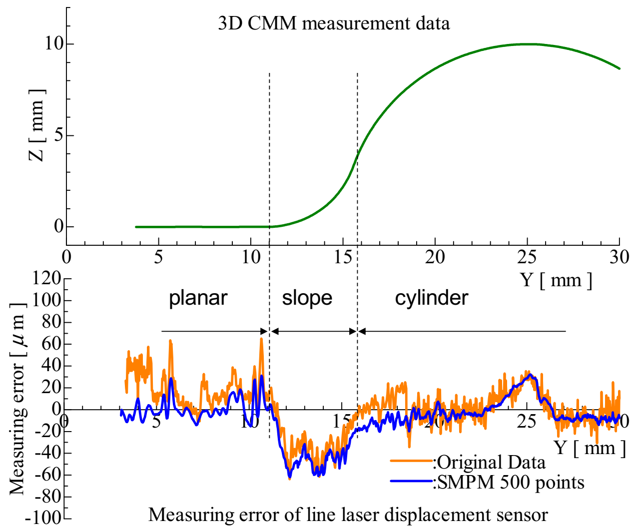

Fig. 14. Comparison of measurement error.

Figure 14 shows the comparison of measuring error in Case study. The measurement results are summarized in **Table 3**. In both results, the measurement error at slope portion is larger than the other portions. The scattered light intensity that is reflected at slope portion of the workpiece is decreased.

Table 3. Comparison of measurement error deviation.

Measurement error deviation RMS[μ m]

	whole	planar portion	slope portion	cylinder portion
Original Data	22.06	25.01	34.85	13.25
SMPM 500 Points	20.79	9.75	43.00	12.06

The measurement errors in SMPM are better than original one at planar and cylinder portion. But the measurement error is larger than the original one at slope portion. It means that the relative displacements vary widely.

The measurement error increases with machining surface roughness because the roughness of the machining surface affects the intensity of the scattered laser beam. **Fig. 15** shows the measurement roughness of the precision cylinder gauge surface and machining surface, as measured by 3D optical surface profilers (NewView6300, Zygo). Areas measured are 0.70×0.52 mm.

The machining surface roughness is 0.064 μm R_a and 2.013 μm PV, and the precision cylinder gauge surface roughness is 0.076 μm R_a and 1.991 μm PV, respectively. The surface roughness results (R_a, PV) of these surfaces are almost the same, but the surface conditions or textures are quite different. The rectangle shown in **Fig. 16** corresponds to the laser beam width. **Fig. 16** is a close-up view of the surface roughness conditions within the width of the laser beam.

The surface condition of precision cylinder gauge is homogeneous. It means that the scattered light intensity might be regular. On the other hand, the surface condition of machining surface is heterogeneous. It means that the scattered light intensity might be irregular. The heterogeneous surface condition makes measurement error large. It means that the measurement error is very sensitive to surface roughness or surface condition. Further investigation for selecting suitable sensing space, number of data points and measuring direction is required to reduce measurement error caused by laser beam scatter.

5. Conclusions

A measuring device consisting of a Line laser displacement sensor is developed for on-machine measurement of machining surfaces. The measurement results of a machined workpiece using the developed system are summarized as follows:

(1) The sequential multi-point method in this study is effective to reduce the measurement error than original data.

(2) The heterogeneous surface condition makes measurement error large. It means that the measurement error is very sensitive to surface roughness condition.

Further investigation is required to reduce the measurement error caused by laser beam scatter on the machining surface.

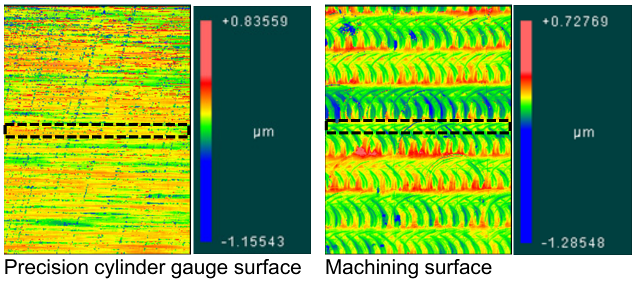

Fig. 15. Measured roughness of precision cylinder gauge surface and machining surface.

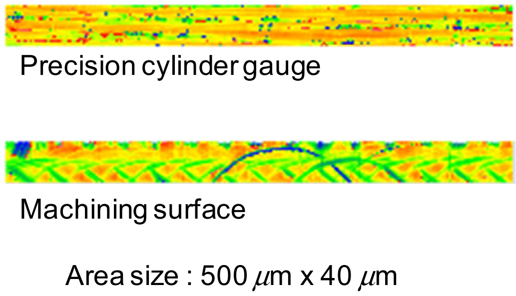

Fig. 16. Surface conditions within laser beam width.

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