Non-Contact Type On-Machine Measurement System for Turbine Blade

S. Nishikawa\textsuperscript{a}, K. Ohno\textsuperscript{a}, M. Mori\textsuperscript{a}, M. Fujishima\textsuperscript{*}

\textsuperscript{a}DMG Mori Seiki Co., Ltd., 2-35-16 Meieki, Nakamura-ku, Nagoya City, Aichi 450-0002, Japan

\textsuperscript{*} Corresponding author. Tel.: +81-595-45-5603; fax: +81-595-45-4173. E-mail address: fujisima@dmgmoriseiki.co.jp

Abstract

In turbine blade machining from a near net shape (e.g., forged workpiece), it is difficult to use a touch trigger probe for measuring the mounting angle of the workpiece due to its uncertain free-form surface. Therefore, non-contact measurement is required to determine the setup condition of the workpiece. Recently, a high-performance laser displacement sensor has been able to measure glossy metal surfaces because of the progress in its sensing device. Using such a high-performance sensor, the non-contact type on-machine measurement system has been developed. It was installed on the multi-functional machine tool to determine validity of the system. This system measured the turbine blade cross-section to compare with CAD data and the measurement data by coordinate measuring machine (CMM). As a result, validity of this system for measuring a turbine blade was proved. We have proposed some application using this measurement system. The application enables optimal machining of a turbine blade from a near net shape at an appropriate phase. This contributes to minimizing the size of expensive material and the machining time.

1. Introduction

Nickel-base superalloy is widely used for turbine blade [1,2]. This material is 20 times more expensive than SC steel. Therefore, it is important to reduce removal amount in turbine blade machining. Machining from a near net shape (e.g., forged workpiece) proactively contributes to reducing waste of material. To machine a specified shape from an uncertain shaped forged workpiece, it is inevitable to accurately define the position of the workpiece that is mounted on the machine. Currently, to accurately define a workpiece position, a special fixture is used to hold the workpiece at the specified position, or a reference area is provided on the workpiece in advance for position measurement using a touch trigger probe [3]. However, manufacturing special fixtures for each turbine blade shape is costly, and additional time is required for designing and manufacturing these special fixtures. Moreover, the whole workpiece shape cannot be recognized by a touch trigger probe because it measures a reference area only. Due to this uncertainty in measurement, the near net shaped workpiece is manufactured larger than the actual dimension, which results in extra material cost.

To reduce this extra cost, the whole workpiece shape needs to be defined on a machine tool. Although a non-contact sensor is preferable, a widely known laser displacement sensor based on triangulation is not applicable to glossy metal surface measurement without powder splayed on the specular machined surface. Therefore, using a laser displacement sensor on a machine was not realistic [4].

On the other hand, controlling laser output for measuring glossy metal surfaces in real time is a recent trend [5]. In this paper, a non-contact type on-machine measurement system has been developed. This system enables to measure glossy metal surface by employing the latest laser displacement sensor with laser output control function and
higher sensitivity of light receiving element. This system has been installed on the multi-functional machine tool.

The robustness for on-machine measurement was assessed through measuring a glossy metal surface of a gauge block, which used to be impossible to be measured with a conventional laser sensor. This system also measured the turbine blade cross-section to compare with CAD data and the measurement data by CMM. The comparison result proved the validity of this system for measuring a turbine blade.

This system can measure a workpiece whole shape clamped by the chuck on a machine tool. Furthermore, this paper shows solutions to determine the reference posture for machining by measuring multiple cross-sections of the turbine blade with this system.

2. Development of non-contact on-machine measurement system

The non-contact type on-machine measurement system developed in this paper has been installed on the NT4250 DCG multi-functional machine tool, which is widely used for turbine blade machining. Principal components of this system are follows:

- Sensor head mounted on the tool spindle
- Interface to upload measurement data using the sensor head and its position data to the control unit of a machine tool
- Time-delay circuit to synchronize timings for obtaining measurement data and sensor head position
- Software to calculate the 3D coordinate of a measurement point on a material surface from the measurement data and the sensor head position

An overview of this system is shown in Fig. 1. Details of the main parts are described in the following sections.

![Fig. 2. Overview of sensor head](image)

2.1. Sensor head

The sensor head developed in this paper for this system is shown in Fig. 2. This head composed of a tool shank, which is clamped to the tool spindle of a machine tool, a laser displacement sensor, and an interface cable for power supply and data transfer. This head is mounted on the tool spindle and the interface cable is connected to the machine, so that the laser beam is emitted from the laser displacement sensor to start measurement based on the principle of triangulation [6]. A safety circuit is incorporated in the system to detect cable connection and control rotation of the tool spindle. The sensor head always has a little inclination with respect to the tool spindle axis. When a phase of the tool spindle changes, the spot at which the laser beam is emitted is shifted. Therefore, the tool spindle is always oriented to the same rotary position during measurement.

Major specifications of the laser displacement sensor are shown in Table 1. In the triangulation method based on diffuse reflection detection, measurement ability for a glossy metal surface depends largely on laser power and sensitivity [7]. Using laser displacement sensor has the highly sensitive CMOS sensor in the light receiving unit, which enables the laser displacement sensor to control laser output so that the light receiving unit always receives optimum amount of light. Therefore, even if a small amount of light is reflected from specular machined surfaces to the light receiving unit, measurement values can be obtained due to enhanced laser output and sensibility of the CMOS sensor. This sensing function plays a crucial role in non-contact type on-machine measurement.

<table>
<thead>
<tr>
<th>Reference distance</th>
<th>50mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement range</td>
<td>20mm (+/- 10mm)</td>
</tr>
<tr>
<td>Spot diameter at reference distance</td>
<td>50μm</td>
</tr>
<tr>
<td>Repeatability</td>
<td>0.025μm</td>
</tr>
</tbody>
</table>

The laser displacement sensor has a measurement range of 20 mm, which makes it possible to measure surface profiles smaller than its measurement range with linear motion only (Fig. 3).
2.2. Synchronous circuit and synchronous method

It is necessary to synchronize timings for obtaining measurement data from the sensor head and its position data from the CNC unit. This system obtains the coordinate position of the head every 8 msec from the CNC unit and transmits a trigger signal for measuring timing to the sensor head so that the timings can be synchronized. However, this is not enough because a trigger signal has some delay. Measuring timing has also some delay due to the timing for obtaining the sensor head position. This delay varies depending on the CNC unit. For example, if this delay is 4 msec and the sensor head is moved horizontally at a feedrate of 360 mm/min as shown in Fig.3, a difference between a position of obtaining measurement data and a position of obtaining its position data is calculated to be 24 \( \mu \text{m} \). The lower the feedrate is, the less the shift amount becomes, but the measurement time is longer. Eliminating this gap in timings is important to obtain a profile rapidly by taking advantage of non-contact measurement.

This system has been developed by utilizing the synchronous method as shown in Fig.4.

A machine tool obtains position data at an interval of the clock cycle (8 msec) in parallel with transmitting a trigger signal for synchronization to the time-delay circuit. The timing for transmitting the trigger signal is delayed by the time-delay circuit for the predetermined period of time and the trigger signal is transmitted to the sensor head. Setting the delay time enables to synchronize the measuring timing by the sensor head with the next PLC clock cycle. Therefore, measurement data of the sensor head is paired with the position data of one clock cycle before.

Delay time \( N \), which is set in the time-delay circuit, is calculated by measuring reciprocating movement of the reference sphere’s center. Delay time \( N \) is calculated by the following equation under the condition that constant velocity is \( V \) and the difference of reference sphere’s centers between the back and forth movements is \( D \).

\[
N = \frac{(D/V)}{2} \quad (1)
\]

According to these above circuits, to collect the head position data in synchronization with the measurement data of sensor head has been possible at 8 msec cycle (125 points/sec).

2.3. Three-dimensional coordinate calculation method

A sensor head is attached on the tool spindle as shown in Fig.5.

Vector \( \vec{L} \) shows the positional relation between spindle datum point, the coordinate of the head, and sensor’s zero position, the measuring zero point by the laser displacement sensor. Vector \( \vec{T} \) shows the unit vector of the laser beam to be emitted from the laser displacement sensor. Vector \( \vec{L} \) and vector \( \vec{T} \) can be calculated by method [8].

The three-dimensional coordinate of the measurement point \( P_m \) is calculated from spindle datum point \( P_s \) and measurement data \( d \) by the laser displacement sensor using equation (2).

\[
P_m = P_s - \vec{L} + d \cdot \vec{T} \quad (2)
\]
3. System verification

First, a surface of a polished metal gauge block was measured by the laser displacement sensor to determine if a glossy metal surface can be measured without prior processes such as spraying. Next, the turbine blade cross-section blade was measured as an integrative test to verify the data synchronous method and three-dimensional coordinate calculation method.

3.1. Measuring method for glossy metal surface

To evaluate performance of the laser displacement sensor on a glossy metal surface, a gauge block with a specular finished surface is used as the measurement target. Characteristics of the gauge block are shown in Table 2. If this sensor can measure the surface of the polished metal gauge block, this sensor can be used for measurement of ordinary machined surfaces because the diffuse reflection of gauge block is smaller than ordinary machined surfaces.

Table 2. Characteristics of gauge block (ISO 3650:1998).

<table>
<thead>
<tr>
<th>Grade 0</th>
<th>Nominal Length (mm)</th>
<th>Deviation of length from nominal length any point μm</th>
<th>Variation in length μm</th>
</tr>
</thead>
</table>

The gauge block and the laser displacement sensor were set as shown in Fig. 6(a). The laser displacement sensor was installed so that the laser emission unit is located on the back side and the laser receiving unit on the front side. The surface was measured by scanning at a measurement interval of 1μm pitch while the laser displacement sensor moved a distance of 5 mm in the X-axis direction at a feedrate of 7.5 mm/min. Furthermore, the gauge block was inclined with respect to the laser displacement sensor from 0 degrees to 15 degrees as shown in Fig. 6(b) to perform scanning in the same way.

![Fig.6. Laser displacement sensor and gauge block](a) 0 = 0 degrees; (b) 0 = 10 degrees.)

Fig.6. Laser displacement sensor and gauge block

![Fig.7. Measuring results of the gauge block surface](a) 0 = 0 degrees; (b) 0 = 5 degrees; (c) 0 = 10 degrees; (d) 0 = 15 degrees.)

Fig.7. Measuring results of the gauge block surface

3.2. Measuring results of glossy metal surface

Measuring results of the gauge block surface are shown in Fig. 7. In each graph, the horizontal axis shows the laser displacement sensor position in the X-axis direction and the vertical axis shows displacement obtained by the sensor.

When the inclination angle is 0 degrees (a), displacements were measured continuously according to the specified measuring path. Up to 10 degrees of inclination (5 degrees (b) and 10 degrees (c)), displacements were continuously measured as is the case in the inclination angle of 0 degrees. When the inclination angle is 15 degrees (d), points where the laser displacement sensor cannot measure due to insufficient diffuse reflectance were determined by the sensor itself. These results are quantified in Table 3.

Table 3. Valid data ratio of 5,000 points measuring

<table>
<thead>
<tr>
<th>Inclination angle [degrees]</th>
<th>Valid points</th>
<th>Valid data ratio [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>5,000</td>
<td>100.0</td>
</tr>
<tr>
<td>5</td>
<td>4,602</td>
<td>92.0</td>
</tr>
<tr>
<td>10</td>
<td>2,984</td>
<td>59.7</td>
</tr>
<tr>
<td>15</td>
<td>258</td>
<td>5.2</td>
</tr>
</tbody>
</table>

Valid points means the number of displacements which were measured free of influence of low diffuse reflectance. The maximum number of measuring points was 5,000 because a distance of 5 mm was measured at 1μm measuring pitch.

Valid data ratio is a ratio of valid points, which is calculated by dividing valid points by the maximum number of measuring points.
3.3. Measuring method for turbine blade profile

The turbine blade profile was measured by this system on the NT4250 DCG multi-functional machine tool as an integrative test. The axis configuration of this machine is shown in Fig. 8. The turbine blade was mounted on C1 and C2 axes. The sensor head was mounted on the tool spindle. The positional relation between the turbine blade and the sensor head is shown in Fig. 9.

The turbine blade used for the evaluation of this study was made of aluminum (AlMg2.5) and machined from bar material of ø200 × 400 mm. The machined workpiece was 264 mm in length and 125 mm in width.

The measurement path does not need automatic measurement path generation software such as CAM, and is generated by simple linear interpolation (G01) and 4 C-axis index commands as shown in Fig. 10. The feedrate was 30 mm /min (i.e., 4μm measurement pitch) at edges and 500 mm/min (i.e., 66.7μm measurement pitch) along the diameter. Actual indexing movement is manipulated by rotation of the C1 and C2 axes in the synchronized state.

3.4. Measuring result of turbine blade profile

Measuring results along the cross-sectional lines of the turbine blade by this system and CMM are shown in Fig. 11. This system measured all the cross-sectional parts of the turbine blade: inner diameter (ID); outer diameter (OD); leading edge (LE); and trailing edge (TE). On the other hand, CMM measured only gentle sloping surfaces such as ID and OD, and was not able to measure steep sloping surface such as LE and TE. Measuring results of this system and CMM are shown in Fig. 12.
This system needed 8 msec for measuring 1 point, whereas CMM needed 1.5 sec. This system measures at an interval of several μm to several dozen μm. Although CMM can perform the same measurement in principle, enormous amount of time is required. Therefore, CMM’s measurement pitch was from 4 to 5 mm. Measuring results of this system are almost the same as those of CMM. This system has proven that the data synchronous method and the three dimensions coordinate calculation method are effective.

Next, the measuring results of TE part by this system is shown in Fig. 13. This system also measured an inclined surface of over 45 degrees on a machined surface of an aluminum workpiece continuously. This result also has proven that this system can be put into practical use as on-machine measurement by using the high performance laser displacement sensor.

4. Conclusion

The laser displacement sensor was used for this system to measure a glossy metal surface of a turbine blade on a machine tool. It was made possible by advances in sensing device. Powder spray for measurement is not necessary anymore. Enormous amount of data of material surface positions is obtained by non-contact measurement using this system in a short time. Therefore, small amount of data loss does not affect the measurement result.

Not only the accuracy can be check after machining a workpiece but also a profile of a near net shape workpiece can be measured before machining it with this system. It is difficult to measure LE or TE of a turbine blade by a touch trigger probe due to its uncertain shape. Therefore non-contact measurement with this system is useful for a turbine blade. By measuring a turbine blade cross-section including LE and TE, the rotary phase of near net shape can be obtained. Material setting to machine tool becomes easy. The setting process is shown in Fig. 14.

First, a near net shape turbine blade is mounted on the chuck on the machine tool in Step 1. Its rotary position is optional. Next, the sensor head moves to the above of the near net shape turbine blade in Step 2. Then, LE and TE positions are sensed by this system while the turbine blade is rotating in Step 3. After that, the turbine blade is positioned as shown in Fig. 10 and the cross-section shapes of different positions are measured in Step 4. The most appropriate rotary angle for machining a turbine blade is determined through these steps. The application software for automating the above mentioned steps can contribute to the cost reduction in the aerospace industry. The development of this application software with this non-contact type on-machine measurement system is authors’ next challenge.

Fig. 13. (a) Comparison with the measurement data by CAD; (b) Zoomed view of white square in (a).

Fig. 14. Solution to adjust the phase of the turbine blade

References