426 Development of a Practical High-Performance Laser-Guided Deep-Hole Boring Tool: Performance Test

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Abstract: The practical laser-guided deep-hole boring tool of 110mm diameter is produced for application and higher performance on the basis of the experimental results of the prototype tool. The practical tool consists of a counter-boring head, piezoelectric actuators for its attitude control, an active rotation stopper and a laser system for detecting its attitude. Experiments are conducted to examine the performance of this tool in detail using a duralumin (A2017-T4) workpiece with a prebored 108-mm diameter hole. To improve guiding accuracy, a guiding axis is optically arranged to bring in line with a desired one. Rolling of the tool is restricted by a rolling proof apparatus for detecting and controlling its attitude precisely. Results show that the practical tool can be guided to go straight through along the desired axis. The tool can be practically used to bore a precise hole using a rolling proof apparatus.

Key Words: Deep hole boring, Laser, Adaptive control

1. INTRODUCTION

In deep hole boring, hole deviation due to unavoidable reasons, e.g., nonhomogeneity of work material, misalignment of machining systems, deflection of boring bar and so on. To prevent the hole deviation, the tool should be controlled to correct the hole deviation. On this point of view, a prototype laser-guided deep-hole boring tool is developed. By using the tool, counter-boring of duralumin workpiece (JIS A2017-T4) is performed with straightness of ±10 μm over 700mm [1].

On the basis of the experimental data, the practical boring tool is made. Performance of each component of the tool is examined [2]. It is cleared that each component works with high accuracies. Then simulation for the tool guiding is performed [3]. It is cleared that the tool can be used as a guided tool.

In this paper, three kinds of guiding tests are performed to improve the guiding accuracy.

![Fig.1 Practical high-performance laser-guided deep-hole boring tool](image-url)
2. SETTING OF THE GUIDING AXIS

Figure 1 shows the tool which is composed of a counter-boring head for cutting, six actuators for its attitude (position and inclination) control, a laser diode for detecting its attitude and a rotation stopper for preventing its rolling and correcting. The actuators and the laser diode are fixed on an actuator holder. In this experiment, a rolling proof apparatus is used instead of the rotation stopper.

Figure 2 shows the experimental apparatus. The experiments are conducted on a deep-hole boring machine. A guide bush and the workpiece is set on the machine table. The optical apparatus for setting desired axis is put in front of the tool head. The optical apparatus for detecting tool attitude is next to a head stock and behind the tool. Generated chips are absorbed through the tool center and boring bar by an ejector type cleaner.

The following sections 2.1, 2.2 and 2.3 explain how to set the desired axis and guiding axis.

2.1 Setting of the desired axis

The desired axis is determined by a laser beam as follows. A PSD (Position-Sensitive Detector) is fixed on a steel block of a rectangular parallelepiped (Fig.3). The center of the PSD is on the desired axis when the block is set on the machine table along the side guide for workpiece setting. The position and inclination of the laser diode are arranged so that its spot is kept on the center of the PSD even if the machine table moves back and forth.

2.2 Setting of PSD1 and PSD2

A mirror is fixed on the block instead of the PSD (Fig.4). Then the block is set on the machine table along a side guide for workpiece setting. A laser beam is radiated from the laser diode and reflected by the mirror. The reflected beam is deflected by a half mirror. The deflected beam is divided into two beams by a beam splitter. One of
the beam passes through a beam splitter and reaches PSD1 and another beam is reflected and reaches PSD2. The two spots are arranged to the centers of the two PSDs by moving them.

2.3 Setting of PSDₘ and PSDᵢ

The mirror is replaced on the front end surface of the tool (Fig.5). The tool is inserted into the hole of the guide bush. Six actuators protrude equally to the guide bush. A laser beam is radiated from the diode laser toward the mirror. If the transmitted and reflected beams do not reach the centers simultaneously of the PSD1 and PSD2, respectively, the rear three actuators of the tool work so that the two beams reach the two PSDs.

After the tool setting, the laser beam is radiated toward PSDₘ and PSDᵢ from the laser diode fixed in the rear end of the tool. The two PSDs are arranged so that the laser spots come to their centers.

3. EXPERIMENTAL PROCEDURE

Experiments are conducted using the rotating tool-stationary workpiece system. Rotational speed N is 270 rpm. Feed f is 0.125 mm/rev. Duralumin workpiece with a prebored 108-mm diameter hole is used. Oil is supplied to the cutting area from the front of the tool at a rate of 150 mL/min. The hole deviation is measured by an electric microdisplacement sensor using the rolling proof apparatus on the deep hole boring machine [2].

The performance of the tool is examined by the experiments stated in the following sections.

3.1 First experiment (Without adjustment of optical axes)

The first experiment is performed after following setting of the tool. The tool is set in the guide bush. Six actuators protrude equally to guide bush. Then laser beam is radiated backward from the laser diode fixed on the rear end of the tool. Reference origins of the PSDₘ and PSDᵢ for detecting tool position and its inclination are decided. After the tool enters the workpiece to a depth of 2 mm, then forward three actuators extract.

3.2 Second experiment (With adjustment of optical axes)

The second experiment is performed after guiding axis is arranged on the desired axis (a spindle rotation axis) as stated in Section 2.

Forward three actuators extract at a depth of 2 mm as in the first experiment.

3.3 Third experiment (After resetting of the Y guiding axis)

The third experiment is carried out after the inclination of the guiding axis out of the desired axis, which caused the hole deviation in Y direction of the second experiment, is corrected by a computer program. Further the following items are improved to improve the guiding accuracy.

The back taper of the counter-boring head is modified to improve controllability. In the first and second experiments, it is 2 µm/mm over the guide pad length of 30 mm. In this experiment, the back taper over the front end of the guide pad to 6.5 mm is 2 µm/mm and 6 µm/mm over 6.5 to 30 mm.

After the tool entering the workpiece, three forward actuators keep to push the head by a force.
of 30 N during boring in order to refrain from regenerative chatter vibration.

4. RESULTS AND DISCUSSIONS

4.1 First experiment

Figures 6 and 7 show the variations of tool position and hole deviation, respectively. Figure 6 shows that the tool is guided along the guiding axis because the tool positions in \( X \) and \( Y \) directions keep zero level. However hole deviations occur in \( X \) and \( Y \) directions. It means that the guiding axis inclines to the desired axis. The inclination stems from the following causes.

1. The hole axis of the guide bush deviates and/or inclines to the desired axis.
2. The surface of mirror fixed to the front end surface of the tool is not perpendicular to the tool axis.

4.2 Second experiment

Figures 8 and 9 show the variations of tool position and hole deviation, respectively. The hole deviation in \( X \) direction in the first experiment is corrected, but the one in \( Y \) direction worse. This error mainly occurs during the adjustment shown in Fig.5. Mirror is fixed vertically with respect to the desired axis. However the tool axis (the guiding axis) is inclined to the desired axis. In this case, the tool moves toward the direction of the tool axis.

4.3 Third experiment

Figures 10 and 11 show the variations of tool position and hole deviation, respectively. Figure 11 shows that the hole deviation in \( Y \) direction of the second experiment is corrected. Although a hole depth of 400 mm is longer than 185 mm in the
second experiment, the hole deviation decreases to 26 \( \mu \)m from 97 \( \mu \)m.

However the hole deviation in \( X \) direction becomes 88 \( \mu \)m over a hole depth of 400mm. The reason is explained as follows. After the second experiment, the tool is removed from the deep hole drilling machine to measure the hole deviation. The third experiment starts from resetting of the PSD\( \alpha \) and PSD\( \beta \) (Fig.5). In this setting, the positions of the two PSDs deviate from those of the second experiment because the mirror cannot be fixed exactly same as in the second experiment.

5. GUIDING ACCURACY

5.1 Theoretical guiding accuracy

The distance \( \delta D \) between the guiding and desired axes shows guiding error (Fig.12). The theoretical error \( \delta D \) is written as:

\[
\delta D \leq \frac{(D - d)}{2}
\]  

(1)

where \( D \) and \( d \) are diameters of the guide bush and the tool, respectively. In this experiment, \( D \) and \( d \) are 19.980 and 19.960 mm, respectively. \( \delta D \) becomes less than 10 \( \mu \)m. If the guide bush shifts from the desired axis, the error increases by the amount.

5.2 Causes affecting guiding errors

**Fixing error of mirror**

In the third experiment, the guiding axis deviates and inclines out of the desired axis even if the guiding axis is arranged on the desired axis by the computer program. Because the positions of the origins of the PSD\( \alpha \) and PSD\( \beta \) in the third experiment differ from those in the second as the tool is replaced for the measurement of the hole deviation after the second experiment.

If the hole deviation is measured by an apparatus to evaluate the hole deviation without using the deep hole boring machine, high accuracy for guidance can be obtained. For this purpose, a deep hole evaluating probe is also developed together with the tool [2,4].

**Mismatching of spindle rotation and feed**

Data to control the tool are acquired once for every rotation of the spindle from PSD\( \alpha \) and PSD\( \beta \). The time for one revolution is counted by a signal from an encoder for measuring feed of the machine table. A rotational speed 270 rpm of the spindle is measured by a tachometer. The machine table is fed by a hydraulically-operated lead screw. Therefore spindle rotation has no linkage with table feed. In this experiment, a trigger for detecting one rotation of the spindle is set by a pulse corresponding to a feed of 0.125 mm. A real rotation of the spindle corresponding to a feed of 0.125 mm differs by a few percent from a rotational speed of 270 rpm. The shift results in the miscontrol of the tool.

**Lack of tool accuracy**

Multi-cornered hole are sometimes formed when bored by the tool. In the hole deviation of the third experiment, the waviness occurs due to multi-cornered hole which forms when the cutting condition is unstable (Fig.11). The causes are not cleared yet. However the following are doubted.

The spring supporting the dead load of the tool encourages the regenerative vibration which leads to the multi-cornered hole.

A sheet metal is put between the body of the head and each guide pad. The sheet metal is one of the causes of the vibration. Circumferential grinding of the counter-boring head is done to keep height of the guide pad at the same level after setting the metal.

Parallelism of an axis of the actuator holder to
that of the shaft of the counter-boring head lacks an accuracy after fixing two bearings on both sides (Fig.1). It results in that the counter-boring head does not rotate smoothly, which leads to the regenerative vibration.

5.3 Improvement of guidance

If a corner cube prism and a mirror are fixed on the steel block as shown in Fig.13, the error stated in Section 5.1 disappears [1]. By using the corner cube prism, the deviation from the desired axis can be measured and corrected.

6. COMPARISON OF TWO METHODS FOR DETECTION OF TOOL ATTITUDE

It is possible to guide the tool from the front using a corner cube prism and mirror [1]. Here the two guiding methods are compared.

6.1 Detection from the rear end surface

The laser diode for detecting the tool position and its inclination is set away from the center of the tool (Fig.1). This results in the interference between the signal due to the rolling of the tool and that due to its deflection [3]. The interference is to be corrected. As the laser diode does not rotate, data for controlling can be acquired continuously. It means that the continuous monitoring is possible.

The effect of the oil mist on the laser beam is less than that from the front end.

Solid boring is possible because the prebored hole, which the laser beam passes through, is not necessary.

An optical construction for detecting tool attitude is more simple than that from the front end. However the tool position and its inclination are obtained through a numerical computation.

6.2 Detection from the front end surface

The optical head for detecting the tool position and its inclination is set in the center of the tool [1]. The signal due to the rolling of the tool does not interfere with that due to the tool deflection [3].

As the optical head rotates, data for control can be acquired once for every rotation of the counter-boring head. The tool consists of the counter-boring head and an actuator holder (Fig.1). The optical head is fixed to the counter-boring head.

7. CONCLUSIONS

A practical laser-guided deep-hole boring tool is developed. As a result of the performance tests, the following can be cleared.

1. The tool can bore a straight hole by being guided by a laser.
2. Guiding accuracy is increased by using a corner cube prism and mirror.

Further the tool can be used practically after several performance tests using steels together with improvement of computer programs.

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