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Wireless cutting force sensing system mounted on a rotary cutting tool holder using a semiconductor strain sensor

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Abstract
This study describes the development of a tool holder that can measure cutting force and torque and that transmits data and supplies power wirelessly. In recent years, substantial growth has been achieved in intelligent and high-tech processing technologies, such as industry 4.0 and IoT. An essential technology at the foundation of such technological innovation is the monitoring technology of the processing conditions. In machining, monitoring the conditions of tool damage is essential for improved productivity and reduced costs. In this study, a new semiconductor strain sensor and wireless power supply and communication circuit board were developed and installed in the tool holder. When the system was used for drilling, it was possible to detect damage to the drill that could not be detected by measuring the spindle power of the machine tool. In addition, in a small-diameter drilling experiment, it was possible to detect damage to a drill with a diameter of 4 mm. These results suggest that the developed wireless cutting force sensing system has the potential to monitor machining conditions in drilling at a lower cost and with higher accuracy than conventional methods.

Semiconductor strain sensor, tool wear monitoring, wireless, tool holder

1. Introduction

Intelligent and high-tech processing technologies, such as industry 4.0 and IoT, have substantially grown in recent years. Online monitoring of tool and chip removal conditions during cutting operations is required to improve the productivity at production sites [1]. Various methods have been proposed for monitoring cutting operations, including those that use cutting force, spindle power, cutting noise, and acoustic emissions, but all of these methods have issues such as resolution and accuracy [2]. This paper proposes a low-cost and highly reliable cutting force measurement method using a semiconductor strain sensor mounted on a rotary tool holder. A previous study demonstrated that abnormalities such as tool breakage can be detected from the output of a strain sensor that is attached to a tool fixed on a lathe [3]. This study developed a wireless system for supplying power to the sensor and communicating with it; then, the system was applied to monitor the drilling process.

2. Wireless cutting force measurement holder

The developed wireless cutting force measurement holder is shown in Figure 1. The sensor part is a 2.5 mm square semiconductor chip that includes a semiconductor strain sensor, temperature sensor, and A/D converter and can measure strain with a minimum resolution of ±1 με. In addition, the built-in temperature drift compensation circuit can be used to compensate for drift in the measured values due to temperature changes. The sensor consumes less than 3 mW, enabling low-power operation. The sensor was attached to the straight shank portion (diameter 20 mm) of the tool holder, as shown in Figure 1 (middle). A total of two sensors were mounted, one in the direction of the rotation axis for thrust force measurement and the other mounted at a 45° angle for torque measurement. The sensor's signal line was connected to the secondary circuit board, which was attached to the holder and rotated with the spindle. A primary circuit board was fixed to the spindle of the machine tool to enable wireless power supply and data transmission to and from the secondary circuit board. This eliminated the need for battery replacement and enabled measurement and monitoring over long periods of time.

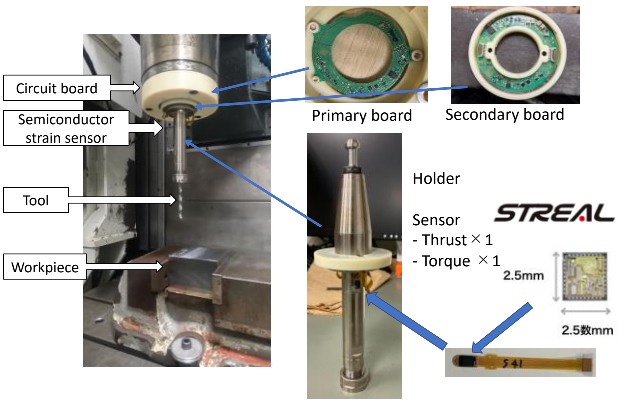

Figure 1. Wireless cutting force sensing system

3. Experimental results and discussion

3.1 Detection of tool damage in drilling

Drilling was performed using the developed wireless holder (hereinafter referred to as "sensor holder"). In the experiment, a carbide twist drill with a diameter of 6 mm (point angle of 118 degrees) was used to drill holes in carbon steel under the conditions listed in Table 1. After each hole was drilled, the tool

Table 1 Cutting conditions

Cutting speed	51 m/min
Feed	0.1 mm/ver
Depth of hole	10 mm
Workpiece	C50 (ISO)
Atmosphere	Dry

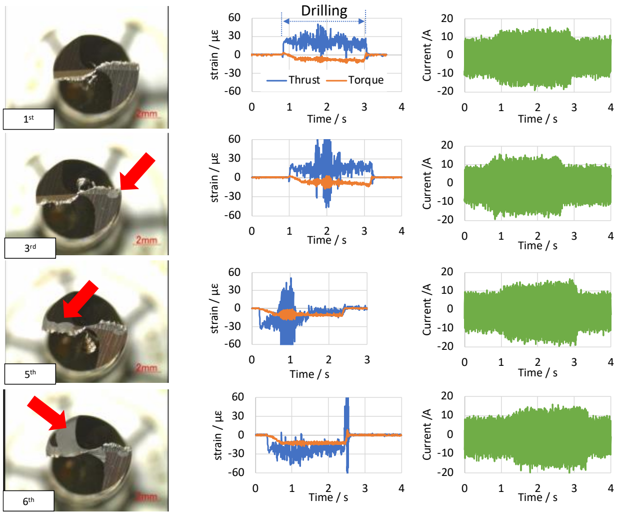

Figure 2. Drill (left) and strain sensor (middle) and spindle power (right)

was observed, and the semiconductor sensor readings and the spindle power of the machine tool were recorded. Figure 2 shows examples of the measurement results. The figure (left) shows that chipping occurred at the margin of the drill during the drilling of the third hole in red arrow part in the figure. By observing the sensor values at this time, changes in thrust and torque values can be seen in the middle of the machining process. In particular, a large variation in the thrust value is observed, indicating that chipping has occurred at this point. In the fifth hole, the cutting edge of the drill is defective, and the sensor also shows a large change in value at around 1.5 s, indicating that the sensor is able to detect the defect. In the sixth hole, the tool has an even larger defect, but the thrust value of the sensor fluctuates significantly at the end of machining. This indicates that the defect occurred when the tool was pulled out of the hole after drilling was completed. For comparison, the Figure on the right shows the measured spindle power under the same conditions. No change was observed in the values under any of the conditions, indicating that the above-mentioned tool damage had almost no effect on the spindle power. These results demonstrate that the sensor holder can detect tool damage during drilling that cannot be detected by the spindle power value and can accurately detect the moment when such damage occurs.

3.2 Detection of tool damage during small-diameter drilling

We attempted to detect tool damage during small-diameter drilling using a drill with a diameter smaller than that used in the experiment described in the previous section. The drills used were 5 mm and 4 mm in diameter, and the cutting edge geometry was the same as that used in the experiments in the previous chapter. The feed rate was set to 0.071 mm/rev for ϕ5 and 0.056 mm/rev for ϕ4 to take into account the decrease in rigidity due to the smaller drill diameter. Other cutting conditions were the same as in the previous experiment.Figure 3 shows the experimental results for a 5-mm-diameter drill.

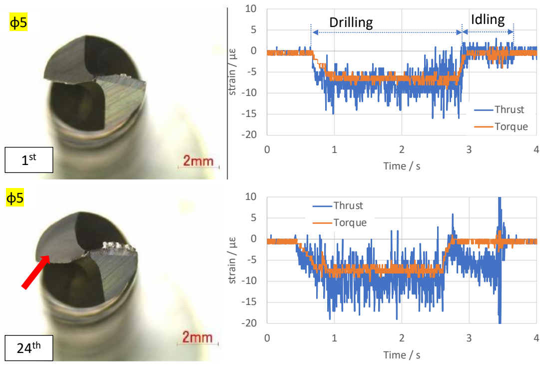

Figure 3. Tool and sensor values during drilling of 5 mm diameter

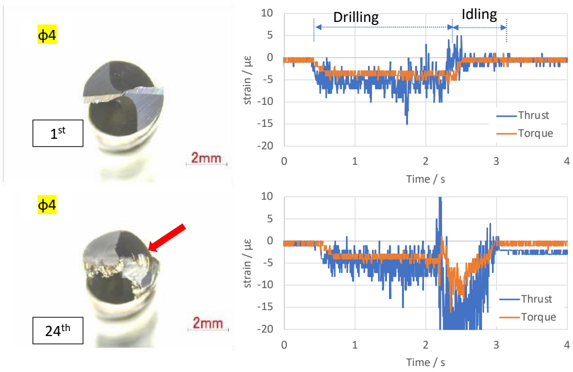

Figure 4. Tool and sensor values during drilling of 4 mm diameter

When drilling holes with this drill, the waveform shown in the figure (1 hole machined) is generated when drilling is performed well. As the number of holes increased, the cutting edge became defective at the 24th hole. From the sensor output (thrust), it can be seen that a waveform clearly different from the normal state was generated when the spindle was idle after the end of drilling, indicating that a defect was generated at this time. Furthermore, in the drilling of a 4 mm diameter hole shown in Figure 4, it can be seen that a waveform showing similar defects occurs when the spindle is idle and when the tool is withdrawn from the hole at the 24th hole. These results demonstrate that the sensor holder can detect tool damage in small-diameter drilling up to 4 mm in diameter.

4. Summary

In this study, a cutting force measurement holder with a built-in semiconductor strain sensor that can supply power and transfer data wirelessly was developed and used to detect tool damage during drilling. The results demonstrated that the sensor holder can detect tool damage during drilling that cannot be detected by the spindle power value and can accurately detect the moment when such damage occurs. Furthermore, it was found that tool damage could be detected up to a drill diameter of 4 mm.

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