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In-situ tool wear monitoring using semiconductor strain sensor in diamond cutting

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Abstract
Herein, the development of inexpensive cutting force monitoring technology is discussed using a semiconductor strain sensor that has high rigidity, sensitivity, and frequency response. In the experiment, cemented carbide was machined via a turning tool with a semiconductor strain sensor and either polycrystalline diamond (PCD) or nano-polycrystalline diamond (NPD) tool. The cutting force was detected, and tool damage observed. Sudden chipping and regular wear in the tool were successfully detected using the developed system without changing the composition or the rigidity of the machine. Furthermore, while machining the cemented carbide using the NPD tool, the cutting force as small as 20 N was detected. Based on these findings, the cutting force monitoring system has the potential to replace conventional dynamometers.

semiconductor strain sensor, tool wear monitoring, diamond cutting, cemented carbide

1. Introduction

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 particular, in the precision machining of hard materials using diamond tools, high precision processing is required, and the tools are expensive; hence, controlling tool damage is particularly important. Measurement of the cutting forces is a general method of examining tool damage; strain gauge dynamometers and piezoelectric dynamometers are often used to measure cutting force. However, the former has low measurement sensitivity and frequency response. Moreover, there can be a tangible decrease in the rigidity of the attaching part. The latter is superior in these aspects; however, its per-use cost is extremely high. Based on this background, in this study, a newly developed semiconductor strain sensor was attached to the machining tool to establish a new cutting force measurement method that resolves the problems associated with conventional dynamometers. Cemented carbide was machined using an unmodified machining tool with a semiconductor strain sensor and a PCD tool. The cutting force was obtained based on the previously obtained calibration value and compared to the measurement results of a quartz dynamometer. The semiconductor strain sensor was used to detect sudden damage and regular wear. To monitor the processing condition, the proposed method was also applied to the finishing process of the cemented carbide using an NPD tool.

2. Semiconductor strain sensor

Figure 1 shows the exterior of the sensor developed in this study. The sensor comprises a semiconductor strain detection part, bridge circuit, amplifier, A/D converter, and control circuit, all contained in a chip of approx. 2.5-mm size. The system has lower power consumption compared to conventional strain gauges, the ability to measure the minute strain of scale 1 με, and high measurement sensitivity. It also has a temperature control sensor that maintains the output fluctuation at 1% or less under an ambient temperature range of −40°C to 120°C, thus rendering a highly stable system [1].

3. Experimental method

As shown in Figure 2 (left), semiconductor strain sensors were attached to the four surfaces of the tool. While the cemented carbide was machined via a general-purpose lathe, an attempt was made to measure the cutting force and detect the condition of the tool wear. The cutting conditions were set to cutting speed of 15 m/min, feed 100 μm/rev, depth of cut of 200 μm. The output values of the semiconductor strain sensor and that of a Quartz 4—Compoment Dynamometer (KISTLER 9272) were recorded in a synchronized manner.

4. Calibration

To measure the cutting force using a semiconductor strain sensor, the calibration of sensor output to cutting force is necessary. Herein, the output value of the sensor was the

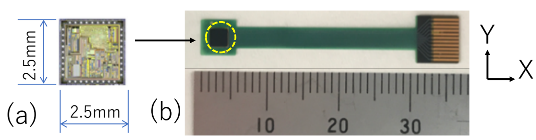

Figure 1. External view of the semiconductor sensor (a) microscopic image (b) whole view

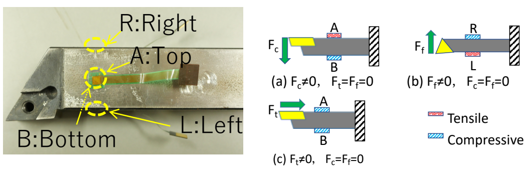

Figure 2. Cutting tool with semiconductor strain sensor (left) and direction of strain applied to the tool during cutting (right)

difference between the X and Y components shown in Figure 1. For the semiconductor strain sensors attached to the tool, as shown in Figure 2 (left), the strain in X and Y directions are denoted by εX and εY, respectively. The output value S is expressed by the Poisson's ratio v as follows:

$$S = \varepsilon X - \varepsilon Y = \varepsilon X(1 + \upsilon) \qquad (1)$$

. If F denotes the force in the X direction and K denotes the calibration coefficient, the following equation can be expressed:

$$KS = F(1 + \upsilon) \qquad (2)$$

. Considering the tool to be a cantilever, as shown in Figure 2 (right), and applying equation (2) to the semiconductor strain sensors attached at the four locations (top, bottom, left, and right), the cutting forces can be expressed as follows:

$$K_A S_A = (F_c - F_t)(1 + \upsilon) \qquad (3)$$

$$K_R S_R = \left(-F_f - F_t\right)(1 + \upsilon) \qquad (4)$$

$$K_B S_B = (-F_c - F_t)(1 + \upsilon) \qquad (5)$$

$$K_L S_L = \left(F_f - F_t\right)(1 + \upsilon) \qquad (6)$$

Here, F_c denotes the cutting force, F_t is the thrust force, F_f is the feed force, and the subscripts, A, R, B, and L correspond to top, right, bottom, and left, respectively. Based on equations (3)–(6), the cutting force F_c, thrust force F_t, and feed force F_f are expressed by equations (7), (8), and (9), respectively.

$$F_c = \frac{K_A S_A - K_B S_B}{2(1+\upsilon)} \qquad (7)$$

$$F_f = \frac{K_L S_L - K_R S_R}{2(1+\upsilon)} \qquad (8)$$

$$F_t = \frac{-K_A S_A - K_B S_B}{2(1+\upsilon)} \qquad (9)$$

υ was set to 0.3, and K_A, K_B, K_L, K_R were obtained by a calibration experiment. In the experiment, the tool was pressed against the workpiece in a single axis direction while increasing the pressing force stepwise, and it was performed for each of the three component forces. As in the measurement example in the feed force direction shown in Figure 3, the calibration coefficient was calculated from the slope of the approximation line. Using the calibration coefficient obtained in the calibration experiment and that from equations (7)–(9), the semiconductor strain sensor outputs were converted to cutting forces.

5. Experimental results and observations

Figure 4 shows the relationship between the cutting distance and the maximum flank wear. A linear increase is observed in the flank wear as the cutting distance increases. Figure 5 shows the results of the semiconductor strain sensors and that of the dynamometer measurements at the initial stage of the cutting; it can be observed that the results of the cutting forces calculated from the strains obtained from the semiconductor strain sensors have a good correspondence. The differences in the average values obtained from the dynamometer and that obtained from the semiconductor strain sensor are 18 N, 13 N, and 16 N for the cutting force, feed force, and thrust force, respectively. These values indicate minimized errors in detecting the cutting forces, and It is thought that this error can be reduced by improving the calibration method. When a strain gauge is used for strain measurements, the attachment part of the gauge is typically designed to possess low rigidity to generate strain. However, no modification processing on the tools was performed, and the typical machine composition was used before attaching the sensors to the tool. Based on the fact that the measurement resolution of the semiconductor strain sensor was 1 με, it was possible to detect a cutting force of approximately 100 N despite the high rigidity of the machine composition. From the wear width of the tool shown in Figure 4, it was observed that there were chippings of approximately 0.4-mm scale around the cutting distance of 55 m. Figure 6 shows the results obtained from the measurements by the semiconductor strain sensors at this point. A rapid increase in the value of the measured force at the initial stage of the cutting is observed. The maximum frequency resolution of the sensor was 20 kHz, which enabled the detection of such changes caused by sudden chipping. Beyond this point, the increase in the cutting force with the cutting distance due to tool wear was successfully detected by the semiconductor strain sensor.

Furthermore, Figure 7 shows the values of the cutting forces when the NPD tool was used to machine the cemented carbide under the finishing process conditions. It is observed that the semiconductor strain sensor detected the cutting force of the scale as small as 20 N, and the waveforms of the semiconductor strain sensor and the dynamometer were almost the same.

5. Conclusions

Herein, a method of measuring the cutting force using a semiconductor strain sensor was proposed as a potential replacement for the conventional cutting force measurement methods. The semiconductor strain sensor attached to a tool can detect the strains and calculate the cutting forces. While cutting the cemented carbide with the PCD tool using the proposed system, the real-time cutting force along with the regular wear and sudden damage were detected. Furthermore, the system can detect a small cutting force of the scale of approximately 20 N in the finishing process of the cemented carbide using the NPD tool. These results indicate a possibility of inexpensive cutting force monitoring with high sensitivity and frequency response, without a reduction in the rigidity of the machine.

References

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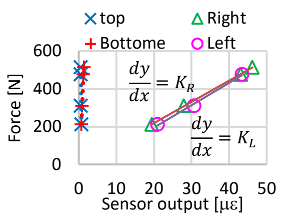


Fig.3 Sensor output and pressing pressure (F_f direction)

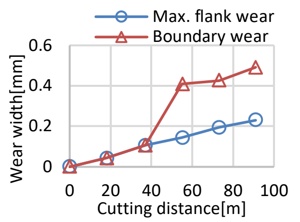
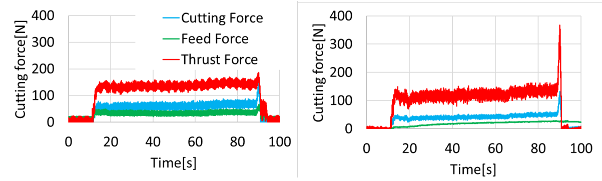
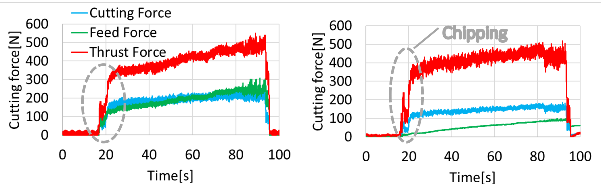


Fig.4 Transition of tool wear with increasing cutting distance



(a)Dynamometer (b)Strain sensor

Fig.5 Cutting distance and cutting force (cutting distance 0 to 18 m)



(a)By Dynamometer (b)By Strain sensor

Fig.6 Cutting distance and cutting force (cutting distance 37 to 55 m)

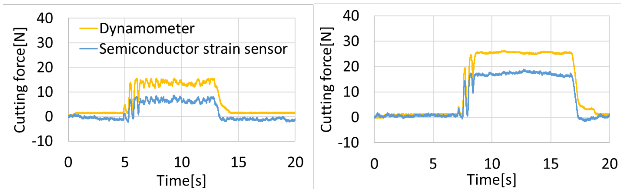


Fig.7 Cutting force when cutting the cemented carbide with NPD tool (v=20 m/min, f=100 μm, Depth of cut=20:left, right 60 μm)