Basic Research on Development of Magnetostrictive Sensor for Detecting Cutting Force

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1. Introduction

Monitoring of cutting processes is indispensable and important technology to realize a flexible and autonomous manufacturing system. A lot of works on monitoring technology have been done so far. However, most of the works were only effective for restrictive the cutting conditions, the restrictive machine tool, and so on. Then it is still desired to develop sensors and data processing methods for establishing a practical monitoring system.

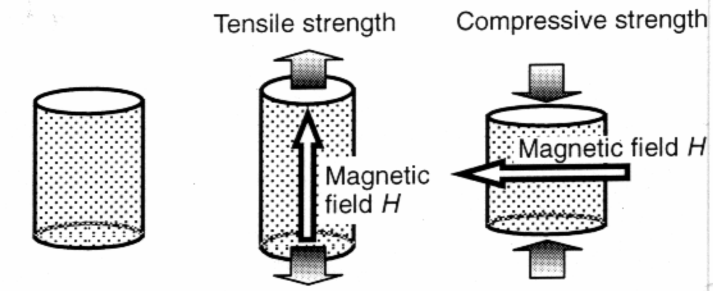
The main targets of identification of cutting processes are tool wear, tool chipping, tool failure, and chatter. These items directly influence cutting force so that it is one of the most effective methods for monitoring them to detect cutting force. Cutting force can be traditionally detected by the table type sensor or the spindle attaching type sensor. The table type sensor is not suitable for practical use under considering viewpoints of the measurement range and fixing operation for each workpiece. The spindle attaching type sensor has the problem on rigidity in practical application. Cutting torque can also be estimated from the electric current of the main spindle. However, in this case, detection sensitivity of the cutting torque is not enough. Thus, authors have developed the magnetostrictive torque sensor [1] which is installed in the tool holder and has very high detection sensitivity.

In order to make more advanced actions according to the monitored information, it is desired to detect not only cutting torque but also x, y, and z components of cutting force. The final objective of this study is to develop a magnetostrictive force sensor which can detect x, y, and z components of cutting force, cutting torque, and deflection of the cutting tool with high detection sensitivity. To achieve this objective, in this paper, a coil-sensor to detect magnetostrictive effect and the force sensor using the coil-sensors are proposed and the characteristics of the coil-sensor and the force sensor are made clear by the experiments.

2. Coil-Sensor to Detect Magnetostrictive Effect

2.1 Magetostrictive Effect

A magnetic material has two kinds of magnetostrictive effect; one is the Joule effect and the other is the Villari effect. When a magnetic field with the intensity and the direction is given to a magnetic material, the magnetic material extends in the direction of the magnetic field in the case of positive magnetostriction and shrinks in the case of negative magnetostriction. This phenomenon is called as the Joule effect. On the other hand, as shown in Fig. 1, when tensile strain is given to a magnetic material with positive magnetostriction, the material has a magnetic filed *H* with the magnetic direction and the magnetic intensity. The magnetic direction is the same with the tensile direction and the magnetic intensity depends on the given strain. When compressive strain is given to a magnetic material with negative magnetostriction, the magnetic direction and intensity according to the strain arises in the perpendicular direction for the compressive direction. This phenomenon is called as the Villari effect.

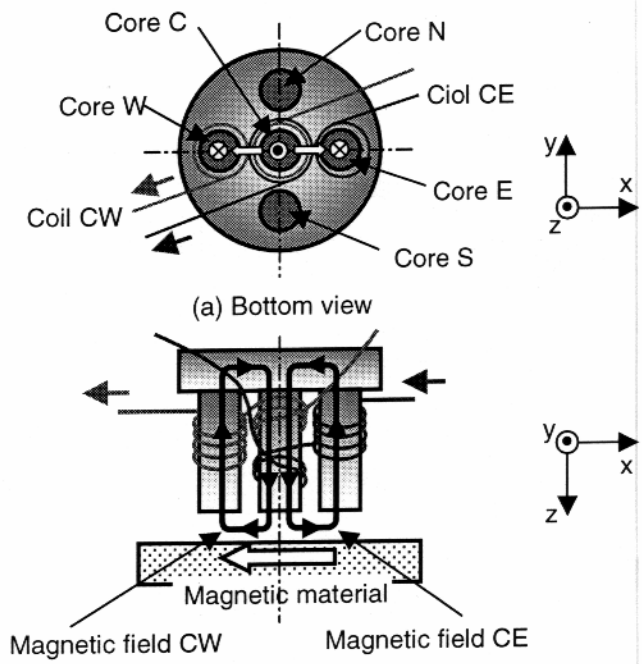


(a) No strain (b) Tensile strain (c) Compressive strain

Fig. 1 Villari effect (in the case of positive magnetostriction)

2.2 Coil-Sensor to Detect the Magnetostriction

As Mentioned above, the magnitude and the direction of applied force on a magnetic material can be identified from the intensity and the direction of the magnetic field generated in the magnetic material by the Villari effect. The intensity of the magnetic field in a direction can be detected as the impedance change of a coil. In this paper, a coil-sensor which detects the intensity of the magnetic field in the two perpendicular directions is proposed.



(a) Bottom view

(b) Side view

Fig. 2 Structure of the coil-sensor

Figure 2 shows the structure of the proposed coil-sensor. The coil-sensor is composed of the five cores C, N, S, E, and W and the four coils CN, CS, CE, and CW. As shown in Fig. 2, the coil CE is made by winding Nichrome wire around the cores C and E and the coil CW is formed by winding Nichrome wire around the cores C and W. In the same manner as the coils CE and CW, the coils CN and CS are made by winding Nichrome wire around the cores C and N and the cores C and S. The winding directions of the coils are determined to make the magnetic field from the center core C to the outside cores N, S, E, and W or the reverse magnetic field under alternation current flow.

As shown in Fig. 2, when the magnetic material has the magnetic field of the magnetic direction from +x to −x and the coils makes the magnetic field from the center core C to the cores E and W, the impedance of the coil CE will be increased and the impedance of the coil CW will be decreased. In the case that the electric current flows in reverse, the impedance change will be opposite. The coil-sensor shown in Fig. 2 detects the intensity of the magnetic filed in the x direction by the coils CE and CW. Also, the intensity of magnetic filed in the y direction is detected by the coils CN and CS. As a result, the proposed coil-sensor can detect the intensity of the magnetic field in x and y directions.

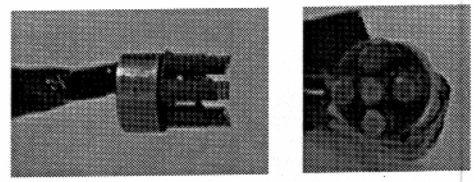


Fig. 3 Coil-sensor

3. Basic Characteristics of the Coil-Sensor and the Signal Detection System

Figure 3 shows the developed coil-sensor. Since the impedance change of the coil-sensor by the magnetic field change is extremely small, the signal form the coil-sensor is detected by using a lock-in amplifier and a direct current amplifier with a bridge circuit as shown in Fig. 4.

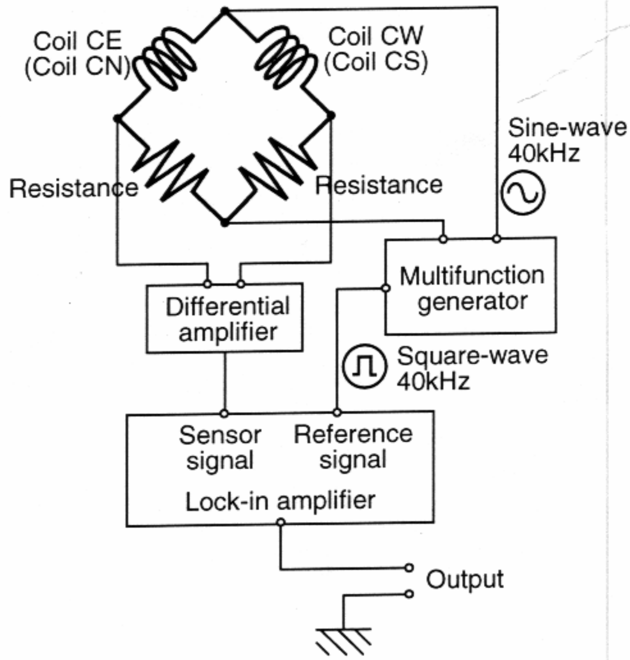


Fig. 4 Signal detecting system

A film of magnetic material Fe-Ni-Mo-B was deposited on a test piece with the size of 110*20*10 mm by thermal spraying. The magnetic field change of the film surface was detected by the coil-sensor under different tensile strain for the test piece. Figure 5 shows the characteristic of directionality of the coil-sensor. In Fig. 5, the abscissa means the angle between the force direction applied on the test piece and the detecting direction of the coil-sensor. Thus it became cleat that the output depends on the detecting direction and the force applied on the test piece. And it is understandable that the output is also influenced by the gap between the coil-sensor and the magnetic film.

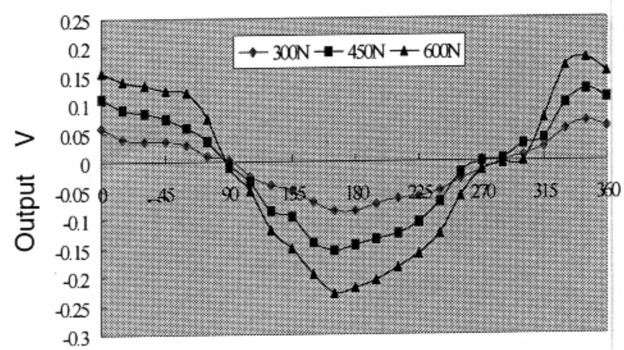


Fig. 5 Directionality of the coil-sensor

4. Magnetostrictive Sensor to Detect Cutting Force and Cutting Tool Deformation

The structure of the proposed magetostrictive force sensor is shown in Fig. 6. The sensor can detect x, y, and z components of cutting force, cutting torque, and the deformation of the cutting tool. The four coil-sensors N, S, E, and W are arranged with the directionality shown in Fig. 6 around the magnetic film of Fe-Ni-Mo-B which is deposited on the tool shank surface by thermal spraying.

Each coil-sensor has the two output signals corresponding to the magnetic field. When the output signals from the coil-sensors N, S, E, and W are V_{n1}, V_{n2}, V_{s1}, V_{s2}, V_{e1}, V_{e2}, V_{w1}, and V_{w2}, respectively, x, y, and z components *Fx*, *Fy*, and *Fz*, cutting torque *T*, deformation in x and y directions *Dx*, and *Dy* are derived from the following equations.

$$Fx = \frac{V_{n1} + V_{n2} + \sqrt{2}V_{s1} + (2-\sqrt{2})V_{s2}}{2} \quad (1)$$

$$Fy = \frac{\sqrt{2}V_{w1} - (\sqrt{2}+2)V_{w2} - V_{w1} - V_{w2}}{2} \quad (2)$$

$$Fz = \frac{V_{n1} + V_{n2} + (2+\sqrt{2})V_{s1} - \sqrt{2}V_{s2}}{2} = \frac{V_{e1} + V_{e2} + (2-\sqrt{2})V_{w1} + \sqrt{2}V_{w2}}{2} \quad (3)$$

$$T = \frac{V_{n1} - V_{n2}}{2} = \frac{V_{e1} - V_{e2}}{2} \quad (4)$$

$$Dx = \frac{V_{n1} + V_{n2} + \sqrt{2}V_{s1} - \sqrt{2}V_{s2}}{2} \quad (5)$$

$$Dy = \frac{\sqrt{2}V_{w1} - \sqrt{2}V_{w2} - V_{e1} - V_{e2}}{2} \quad (6)$$

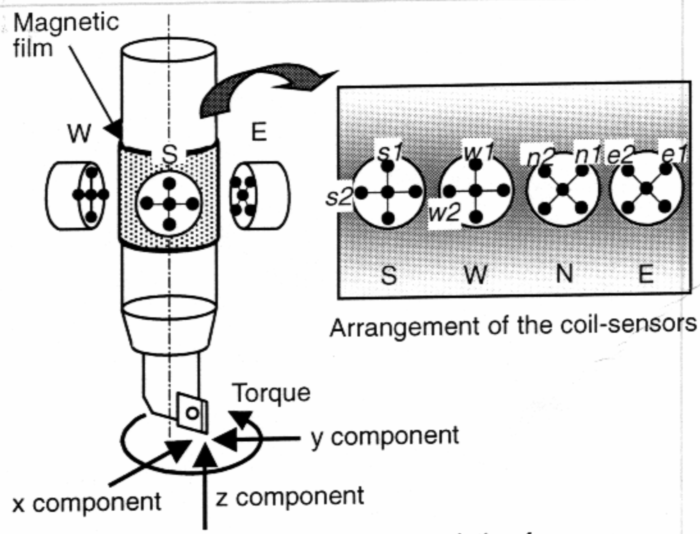


Fig. 6 Structure of the magnetostrictive force sensor

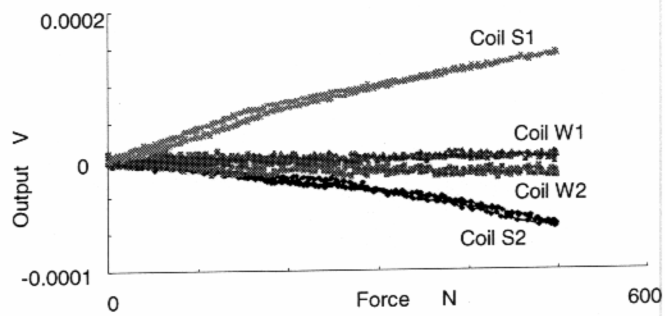


Fig. 7 Relationship between force and sensor output

Figure 7 shows the output signals *s*1, *s*2, *w*1, and *w*2 of the coil-sensors S and W when the horizontal force is statically applied on the cutting edge against the coil-sensor S.

5. Conclusions

(1) Strain can be measured by detecting the magnetic field change generated by magnetostrictive effect.

(2) The coil-sensor to detect the magnetic field change with directionality was proposed and developed.

(3) The measuring system to amplify the extremely weak signal from the coil-sensor was constructed by using a lock-in amplifier and a direct current amplifier with a bridge circuit

(4) The characteristics of the coil-sensor were made clear by basic experiments.

(5) The force sensor based on the magnetostrictive effect was proposed to detect x, y, and z components of cutting force, cutting torque, and deformation of the cutting tool.

(6) The detecting principle of the force sensor was theoretically explained with equations and its basic characteristics were made clear by the experiments.

References

[1] Hideki AOYAMA, et al.: Prediction of Tool Wear and Tool Failure in Milling by Utilizing Magnetostrictive Torque Sensor, Technical Papers of the North American Manufacturing Research Institution of SME (1998), pp125-130.