RAPID ON-MACHINE MEASUREMENT OF SURFACE FINISH FOR CYLINDRICALLY GRINDING WORKPIECE

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INTRODUCTION
The strict control is required in the surface finish, which is the typical evaluation criterion for finished surface qualities, as well as the shape and size. The flowchart of production process, from grinding (manufacturing) to shipment, is shown in Figure 1. In the actual manufacturing processes by grinding, the post-process measurement of surface finish is carried out after finishing as shown in (a). In addition, the surface finish is generally measured by the surface roughness tester with lower stylus tracing speed of zero point several millimeters per second. Therefore, the surface finish of all parts manufactured in a lot is generally judged based on the measured results of only few parts by the acceptance sampling.

However, if the surface finish measurement is carried out in the grinding process or immediately after the process on the machine tool as shown in (b), the surface finish of all manufactured parts can be checked. It’s very useful from the viewpoint of not only quality control of ground parts but also manufacturing efficiency. We propose the novel rapid on-machine measurement of surface finish for cylindrically grinding workpiece and investigate the measurement characteristics.

PRINCIPLE OF SURFACE FINISH MEASUREMENT WITH THERMOELECTRIC EFFECT
The surface finish measurement proposed in this study utilizes the thermoelectric effect as the fundamental principle of thermocouple by which we often measure the temperature. Figure 2 shows the principle of thermocouple and surface finish measurement. The fundamental thermocouple circuit based on thermoelectric (Seebeck) effect is shown in (a). When the temperature at either junction (hot junction) rises in a close circuit composed of a certain metal wire A and wire B of other materials, it will generate a voltage. A pair of different metal wires, for example Chromel / Alumel, Chromel /
Constantan and so on, is often used in the measurement of temperature as thermocouples. When the wire C made of the material different from wires A and B is connected into the circuit with equal temperatures $T_1$ at both wire ends as shown in (b), the circuit generates the voltage as large as that without wire C [1]. When the wire C places between wire A and wire B as shown in (c), it doesn’t affect the generated voltage with the temperature at both wire ends as large as that at the hot junction.

If the ground workpiece is replaced with wire C as shown in (d), the generated voltage reflects the temperature at the points on finished surface contacting with both wires [2]. Furthermore when the workpiece rotates with the contact with both wires on a machine tool, the voltage caused by the frictional heat will be included in that by the temperature of workpiece surface. So if the surface finish has the relationship with the frictional heat with a certain rotating speed of workpiece, the surface finish can obtained by the generated voltage in thermocouple circuit.

**EXPERIMENTAL PROCEDURE**

Figure 3 shows the developed rapid measurement system with the surface finish sensor. Chromel and Alumel wires, having no junction each other, are fixed on the sensor body made of acrylic resin with a certain tension, and the sensor makes contact with workpiece surface rotating at about the same rate in grinding process with a constant load. We have an assumption that the workpiece surface is wet during the measurement in or immediately after grinding process, and the coolant is supplied onto the workpiece surface during the experimental tests. The sensing signal, the electromotive force (EMF) generated in the thermocouple circuit, is transmitted to PC after amplification. The workpiece surfaces are ground to several surface finishes. Table 1 shows main conditions in surface finish measurement.

**RELATIONSHIP BETWEEN SURFACE FINISH AND EMF**

Figure 4 shows the variations of electromotive force, which are generated at points on workpiece surface in contact with each thermocouple wire of sensor as shown in Figure 3, when workpiece starts rotating with a certain speed. EMF at room temperature is defined as zero in this paper.

The signals of EMF increase to be stable immediately after turning on the switch of workpiece rotation, and they depend on the surface finish of workpiece $R_a$. EMF of about 170$\mu$V immediately generates by rotation of workpiece with 0.6$\mu$m $R_a$ as shown in the figure, and EMF of about 110$\mu$V generates by rotation.

**TABLE 1. Conditions in surface finish measurement**

<table>
<thead>
<tr>
<th>Workpiece</th>
<th>SUS304 (φ100 x 10 mm, Ground surface, 0.2-1.1 $\mu$m $R_a$)</th>
</tr>
</thead>
</table>
| Thermocouple       | Chromel / Alumel
|                    | Chromel / Constantan (φ0.32 $\mu$m) |
|                    | Iron / Constantan |
| Workpiece speed    | $V_w=0.16 - 0.88$ m/s |
| (Measuring speed)  |                                    |
| Measuring load     | $F=0.19 - 0.98$ N |
| Lubrication        | Soluble type coolant (diluted by 1.25%) |

**FIGURE 3.** Developed rapid measurement system with the surface finish sensor utilizes the thermoelectric effect

**FIGURE 4.** Variations of electromotive force EMF in measurement on workpiece surface
FIGURE 5. Relationship between surface finish and EMF

FIGURE 6. Relationship between surface finish and EMF at several measuring speeds

of workpiece with 0.3\( \mu m \) \( R_a \). Such difference in EMF suggests the difference in surface roughness. Therefore, the system can immediately obtain the surface finish on grinding machine.

Figure 5 shows the relationship between surface finish and EMF by the measurement system as shown in Figure 3. The arithmetical mean deviation of profile \( R_a \) as a surface finish parameter is investigated in follows because it is considered that the sensor output is difficult to reflect very small measured area in the roughness curve differently from the maximum height of profile \( R_y \). EMF approximately has a linear relationship with the surface finish as shown in the figure. This relationship suggests that the frictional heat, generated at the points on workpiece surface in contact with thermocouples wires, increases with an increase of surface finish. Therefore, the surface finish can be estimated by the EMF with the relationship in this figure.

FIGURE 7. Relationship between surface finish and EMF by several thermocouple types

EFFECT OF MEASURING CONDITIONS

Measuring Speed (Peripheral Speed of Workpiece)

Figure 6 shows the relationships between surface finish and EMF at several peripheral speed of workpiece \( V_W \), which is the measuring speed. EMF approximately has linear relationships with surface finish at any measuring speeds and the sensitivity increases with an increase of measuring speed. These relationships suggest that the frictional heat generated at points contact on workpiece surface increases with increasing peripheral speed of workpiece.

Thermocouple types

Figure 7 shows the relationships between surface finish and EMF of three types of thermocouple. EMF approximately increases linearly with increasing surface finish by any thermocouple types like that shown in Figure 5 and the gradient of EMF, which means the sensitivity, is higher in the order, Chromel/Constantan thermocouple, Chromel/Alumel, Iron/Constantan. Therefore, it seems effective to use Chromel/Constantan thermocouple as the developed contact sensor because of its high sensitivity.

Measuring Load

Figure 8 shows the variations of EMF in measurement on workpiece surface, which is ground to 0.5\( \mu m \) \( R_a \), at 0.30N and 0.19N in measuring load \( F \). In these measurement processes, the workpiece rotates after setting the sensor on workpiece surface and stops rotating by switch-off of main spindle after steady rotation of workpiece for about 4 seconds.
EMF varies so violently that the signal has lots of spikes at 0.19N as shown in (b). The spikes in signal are also generated after the stop of workpiece rotation. In contrast, EMF immediately increases up to a certain voltage and gradually decreases down to the original amount with decreasing rotation speed of workpiece after switch-off of main spindle as shown in (a). Therefore, it is necessary for this measurement system to apply the measuring load so large that thermocouple wires keep steady contact with workpiece surface.

Figure 9 shows the effect of the measuring load on the sensitivity. The sensitivity at 0.98N is higher than that at 0.29N as shown in the figure. Such difference of sensitivity is considered to result from the increase of frictional heat based on frictional force at points on workpiece surface contact with thermocouple wires with an increase of measuring load.

CONCLUSIONS
We propose the novel measurement technique of surface finish for rotating ground workpiece with the thermoelectric effect and experimentally investigate its availability and measurement characteristics. Main conclusions obtained in this paper are as follows:

(a) The rapid on-machine measurement technique of surface finish for ground workpiece with thermoelectric effect is developed.
(b) The output from the developed contact sensor with thermocouple wires approximately has the liner relationship with surface finish.
(c) The sensitivity improves with an increase of measuring speed, peripheral speed of workpiece, and the system can obtain the surface finish of workpiece rotating at practical peripheral speed region in grinding.
(d) Chromel/Constantan thermocouple is best suited to the measurement with high sensitivity.
(e) It is necessary for this measurement system to apply the measuring load so large that thermocouple wires keep steady contact with workpiece surface.

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