Real-Time Evaluation of Tool Flank Wear by In-Process Contact Resistance Measurement in Face Milling*

Mitsuaki MURATA**, Syuhei KUROKAWA**, Osamu OHNISHI**, Michio UNEDA*** and Toshiro DOI**
**Department of Mechanical Engineering, Graduate School, Kyushu University
744 Motooka, Nishi-ku, Fukuoka, Japan
E-mail: mrt4@nifty.com
***Department of Mechanical Engineering, Kanazawa Institute of Technology
7-1, Ohgiga-oka, Nonoichi-machi, Ishikawa, Japan

Abstract
This paper reports in-process detection of tool wear by using tool-work thermo-electromotive force (E.M.F.) as a sensor signal in face milling. In the case of using a single cutting edge, E.M.F. at the beginning of cut increased slowly corresponding to the width of tool flank wear. We assume this phenomenon is due to variations in electric resistance by increase of the contact area between the workpiece and the tool, so electric current between tool and workpiece was also detected. The variations of contact electric resistance calculated from both the E.M.F. and the electric current reveal that the electric resistance decreases as the tool flank wear progresses because contact areas between tool and workpiece increase. We developed a measurement system of variations of the contact resistance during face milling process. By monitoring the contact resistance using this system, the real-time detection of the width of tool flank wear can be achieved stably during intermittent cutting operations.

Key words: Signal Processing, In-Situ Monitoring, Flank Wear, Face Milling, Thermo-Electromotive Force, Electric Resistance

1. Introduction

Three dimensional cutting by using a machining center has been the mainstream as a high-efficient and cost-effective processing method, which is typical in today's metallic mold manufacturing. In a long time machining process including unattended machining, progress of the tool wear or unexpected tool chipping is one of the important problems. If tool wear progresses during cutting operations, shapes of manufactured products will differ from the designed tool paths generated by CAM, and it will take quite long time in finishing process by grinding or polishing. To avoid accuracy deterioration, the real time detection of tool wear, in other words in-situ wear monitoring becomes very important in intermittent cutting processes.

Researches have been carried out for many years on in-process tool wear detection using signal variations of Acoustic Emission (AE)\(^1\)\(^-\)\(^3\), cutting force\(^4\)\(^-\)\(^6\), acceleration\(^7\), and their combinations. Those methods however have some weak points such as changes of sensitivity depending on types of machine tools as well as sensor mounting positions.

When a tool cuts the workpiece, tool-work thermo-electromotive force (E.M.F.) is generated by the cutting heat. The interface between tool and workpiece is a direct source of
this signal. So the E.M.F. is regarded as the sensor signal for direct phenomenon at the closest position to cutting edges. It is known that E.M.F. has a lot of information on cutting phenomena. It is reported that E.M.F. can be used to monitor information on tool-work chatter vibration as well as information of chip cutting frequency.\(^8\)\(^-\)\(^10\) It is also reported that response frequency of E.M.F. signal is over 40kHz. It is therefore considered that by using E.M.F. as a sensor signal, it is possible to retrieve some information associated with the progression of tool flank wear in good response rate.

In the case of monitoring the tool wear using such as acoustic emission (AE), acceleration sensor or tool dynamometer, cutting vibration when the tool approaches the workpiece makes the monitoring difficult. Therefore the measurement system becomes complicated and it is difficult to apply those sensors to intermittent cutting. On the other hand, the monitoring system using E.M.F. is able to be relatively-easily applied to intermittent cutting because the principle of measurement is simple. However, the difficulty of tool wear detection that uses the E.M.F. as a sensor signal is that the DC component of the E.M.F. increases if the cutting temperature rises. That means the E.M.F. strongly depends on the cutting speed.\(^{11}\)\(^{12}\) Because the conventional researches utilise the E.M.F. signal for detection of the tool wear, the cutting speed dependency must be considered. For instance, it is tried to detect the tool flank wear from the change rate of the DC component of E.M.F. with new cutting edge and worn cutting edge.\(^{13}\) In our experiment, however, we utilise the contact resistance which is independent to the cutting speed and evaluated as the combination of the E.M.F. and thermal current. This technique is available for real-time evaluation of tool flank wear.

2. Measurement system and the detected signals

2.1 Measurement of E.M.F.

Figure 1 shows the experimental system to obtain E.M.F. between the cutting tool and the workpiece in the face milling. E.M.F. generated at the cutting tool and the workpiece interface is outputted through the mercury contact on the top of the spindle axis and the isolated workpiece. E.M.F. is led to the DC amplifier and amplified by three hundredfold.

Fig. 1 Measurement system of E.M.F.
Amplified E.M.F. is converted to the digital signal by the built-in A/D converter on the memory recorder and recorded with the proximity sensor signal output pulse per rotation.

When the cutting tool and the workpiece are not in contact, the measurement circuit goes into an open state. In such an open state, the whole circuit comes to an antenna and amplified AC power frequency and high frequency noise are added to the original signal. The noise was removed without the increase of impedance and lowering the response frequency of the entire circuit by switching the terminator with an analog switching circuit. When the measuring circuit is in an open state, the value of the terminator is assumed to be 10kΩ, and the noise is suppressed. When the E.M.F. is generated by the tool coming in contact with the workpiece, the analog switch is driven by the binarization signal of E.M.F. and the terminator is replaced to 510kΩ. The terminator changes back to 10kΩ again when one cutting edge finishes cutting. It is thought that the influence on E.M.F. by switching the terminator can be ignored because the duration for switching is only 600ns at the maximum and the leak current according to the switching is less than 5nA.

In this experiment, carbide tips are used as cutting edges and S45C carbon steel is used for the workpiece. By choosing those materials, the polarity of the workpiece becomes a positive and the cutting tool becomes a negative electrode. Considering the invasion of noise from the outside, it is better to cover the whole system with the ground signal to bring the potential of milling machine body into the ground state of the measuring system. So the workpiece is isolated with milling machine nip by insulator material between the vice and the workpiece. The insulator between the vice and the workpiece is the polypropylene sheet of 0.2mm thickness. The E.M.F. waveform was observed from the beginning of cutting cycle within the period that only one cutting edge was acting on. The milling machine and the cutting tools used in the experiment are listed in Table 1.

<table>
<thead>
<tr>
<th>Table 1 Measurement equipment</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>NC milling machine</strong></td>
</tr>
<tr>
<td><strong>Face mill</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td><strong>Carbide tip</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td><strong>Workpiece material</strong></td>
</tr>
<tr>
<td><strong>Cutting condition</strong></td>
</tr>
</tbody>
</table>

Cutting conditions used in the experiment are as follows: the feed rate \( f \) is 0.1mm/edge, 0.15mm/edge and 0.20mm/edge, cutting speed \( V \) is 98m/min, 138m/min and 180m/min and depth of cut \( t \) is 0.5mm, 1.0mm and 2.0mm in each cutting speed and feed rate.

The cutting position is set so that the center of rotation of the face mill is exactly concentric with the center of the workpiece. There is a possibility that the following waveform analysis becomes complex because the engagement angle changes at every moment during cutting. However, considering the practical use of the in-process monitoring of the tool wear, it is necessary to examine under the conditions used at actual factories. In many factories, the position of the tool and workpiece is not taken into consideration because the engagement angle is regarded to be constant.
In the cutting tool and the cutting conditions used by the actual experiment, the crater wear was not observed at all. In the face milling, the tool wear is dominated by the flank wear. Therefore, this paper examines the relationship between each monitored waveform and the tool flank wear width. Fig. 2-a shows an E.M.F. waveform obtained with new cutting edge ($V=138\text{m/min}$, $t=1.0\text{mm}$) and the photograph of the appearance of cutting edge, and Fig. 2-b shows that obtained with worn cutting edge (with flank wear of $V_b=0.6\text{mm}$, $V=138\text{m/min}$, $t=1.0\text{mm}$) and the photograph of the appearance of cutting edge. The delay in rising waveform with progresses of tool flank wear was observed at the start of rising edge that corresponds to starting point of cutting. This delay indicated a similar tendency at the cutting speed of 98m/min and 180m/min as shown in Fig. 3. This change in rising waveforms was also observed at depth of cut of 0.5mm and the delay rate of the rising edge was more apparent than at the depth of cut of 1.0mm. It is thought that this phenomenon is related to the progress of flank wear because it appears even if the cutting speed changes. The following hypothesis was set up as a cause of the change in rising of the E.M.F. waveform: In the case of a new cutting tool, the interface where tool is in contact with the workpiece is only rake face when the cutting edge acts from the beginning to the end of cutting. In contrast, when the tool flank wear progresses, the contact region is not only on the rake face but also at tool flank wear area. That is, as the tool flank wear progresses, contact areas between the workpiece and the cutting tool increase. Especially, when a worn cutting edge approaches the workpiece, the contact areas at both the rake face and the flank change gradually during cutting. The total contact area between the tool and the workpiece therefore changes at every moment. The electric resistance decreases when the contact area increases. For these reasons, rising waveform of E.M.F. changes.

![Waveforms and photographs of cutting edge](image-url)

**Fig. 2** Waveforms of thermo-electromotive force and photographs of cutting edge ($V=138\text{m/min}$, $f=0.1\text{mm/edge}$, $t=1.0\text{mm}$)
2.2 Measurement of Thermal Current

To prove the rising delay of E.M.F. caused by the increase of contact areas with the progress of the flank wear, we observed the electric current induced by E.M.F. (thermal current). The experimental system has changed to measure the thermal current as shown in Fig. 4. A specified resistance (shunt resistor, 0.14mΩ) is connected between the vice and the isolated workpiece to construct closed-loop circuit during the cutting process. By measuring the voltage drop in the shunt resistor, the current waveform that flows in the closed-loop circuit is obtained. To confirm whether the current flows properly or not, the non-contact current sensor is used. Voltage drop in the shunt resistor is amplified five hundredfold. It is converted to the digital signal by the built-in A/D converter on the memory recorder and recorded.

Figure 5 shows the thermal current waveform superposed; each waveform is captured with a new tool, and worn tools with flank wear widths of 0.2mm, 0.4mm, 0.6mm and 0.8mm at cutting speed of 138m/min and cutting depth of 1.0mm (Fig. 5-a), with flank wear width of 0.3mm, 0.4mm, 0.5mm and 0.7mm at cutting depth of 0.5mm (Fig. 5-b). It can be seen that the current in the closed-loop increases as the progress of the tool wear. From the increase of this thermal current, it is concluded that contact resistance goes down due to the progress of the tool flank wear. On the other hand, focusing on the current waveform in a state of progressive flank wear, the current waveform does not indicate steady-state value from the start of cutting to the end of cutting. According to the progress of flank wear, the cutting edge becomes blunt. Thus large amount of heat is generated during cutting. The heat generation due to the edge blunt may result in this steep thermal current waveform.
The change of thermal current shown in Fig. 5 has very good correlation with the width of tool flank wear. Therefore, we examined the relationship among thermal current, tool flank wear and cutting speed when the cutting condition is sufficiently steady. To plot the thermal current waveform variations by the progress of the tool wear, the average of the waveform was taken every 1ms. Those averaged values are plotted in Fig. 6 as thermal current values in each cutting condition with respect to the width of flank wear. It is found that the current value at any cutting speed increases rapidly from the flank wear width of 0.4mm to 0.5mm that corresponds to almost tool life. This graph also reveals the remarkable differences on cutting speed. Thermal current also includes the influence of cutting temperature since current value is also relatively large as cutting speed become faster. From the fact, it is not easy to use thermal current for a universal tool wear judgment because it depends on the cutting speed. The contact resistance by using the E.M.F. and the thermal current will be therefore another candidate for tool wear judgment.

3. Development of Tool-Work Contact Resistance Measurement System

In the measurement system shown in Fig. 1, the E.M.F. can be measured by taking the terminator close to infinity. On the other hand, the thermal current can be measured by taking the terminator close to zero as shown in Fig. 4. It has been understood that the resistance is calculated from the voltage divided by the current. Then, the measuring system was developed to measure tool-work contact resistance from E.M.F. and thermal current waveforms during the cutting cycle. The principle of this measurement system is to output
the contact resistance derived from the E.M.F. and thermal current using Ohm’s law. In conventional measurement, two special probes for measurement of the E.M.F. and the thermal current were prepared and each probe was used alternately by exchanging the connection between the vice and the workpiece manually. It is necessary to exchange these probes at high speed and arbitrary timing automatically to obtain the contact resistance during the cutting cycle. For exchanging the E.M.F. measurement and the thermal current measurement by using only one probe in arbitrary timing, it has been assumed that the terminator is selected with the switch that could be controlled by logic signal from outside. To realize the switch, the on-resistance value of the switch must be taken into account at the current measurement mode. Examples of on-resistance values of commercial switches are as follows.

<table>
<thead>
<tr>
<th>Switch Type</th>
<th>On-Resistance Value</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical Relay</td>
<td>50mΩ ~</td>
<td>(Many chattering)</td>
</tr>
<tr>
<td>Photo MOS Relay</td>
<td>30mΩ ~</td>
<td>(Slow switching speed)</td>
</tr>
<tr>
<td>Mercury Relay</td>
<td>50mΩ ~</td>
<td>(Slow switching speed)</td>
</tr>
<tr>
<td>CMOS analog switch</td>
<td>450mΩ ~</td>
<td>(Large on-resistance)</td>
</tr>
</tbody>
</table>

These switches however cannot be used because they have relatively large values of resistance compared to the electrical resistance value of the entire system including the tool-work contact resistance. The variation of contact resistance caused by the progress of tool flank wear is less than 1mΩ. Then, a super-low on-resistance switch that has two or more power MOSFETs was developed as shown in Fig. 7. The on-resistance of FET used in this switch is 1.5mΩ at the maximum. By connecting eight FETs in parallel, the total on-resistance of the switch is 0.1875mΩ at the maximum. There is no chattering during switching and the switching can be done only in 200ns at the maximum because it is a semiconductor switch. In this switch, the resistance value between both terminals including the switching resistance is only 0.29mΩ. It becomes possible to exchange the terminator to 1kΩ (measurement of E.M.F.) and 0.29mΩ (measurement of thermal current) alternately to use this super-low on-resistance switch.

Fig. 7 Super-low on-resistance switch with non-contact current sensor

The reason in selecting the terminator of 1kΩ at the E.M.F. measurement mode is the existence of the electrostatic capacity always parasitic between gates and sources of MOSFET. The total electrostatic capacity becomes 37.6μF as it connects with 8 pieces in parallel because each FET has the electrostatic capacity of 4700pF. The switch becomes a very large capacitor, and the capacity of 37.6μF is a problem in composing the circuit. In
the E.M.F. measurement mode by the super-low on-resistance switch being turned off, if the resistance of large value like 510kΩ is selected as the terminator, the electric charge stored in the capacitor of FET array won’t be completely discharged in slight opening time of the circuit. Therefore, E.M.F. remains to a certain value when a cutting edge finishes the cutting. The E.M.F. waveform does not drop down to zero, and the E.M.F. waveform outputs will shift in the next cutting. In such a state, it is difficult to judge the timing of the beginning or end of cut. Therefore, the terminator value is selected to be 1kΩ, and the electric charge stored in the capacitor is discharged quickly though the frequency response of E.M.F. is somewhat sacrificed.

The timing of the switching E.M.F. measurement mode and thermal current measurement mode by super-low on-resistance switch is set at every one rotation according to the timing that the tool is not in contact with the workpiece. This timing signal for the switching is generated by the binarization signal of E.M.F. or thermal current output in each cutting edge and by the proximity sensor signal output pulse per revolution.

The block diagram of the contact resistance measurement system is shown in Fig. 8. When the super-low on-resistance switch turns off (E.M.F. measurement mode), E.M.F. generated by each cutting edge is converted to the digital signal by the A/D converter at the sampling frequency of 25kHz and stored in the memory of the microcomputer. After the main spindle rotates by one rotation, the super-low on-resistance switch is turned on and it

![Fig. 8 Block diagram of tool-work contact resistance measurement system](image)

![Fig. 9 Relation between switching pulse and output signals](image)
changes into the thermal current measurement mode. Under this mode, E.M.F. waveform stored in the memory of the microcomputer is outputted from the D/A converter according to the timing of rising of the thermal current waveform with each cutting edge. Thermal current is led to the analog dividing circuit at the same time. E.M.F. waveform and thermal current waveform are thus obtained on the same cutting edge. However these waveforms have just one rotational delay with each other. In the analog dividing circuit, the contact resistance is calculated by using two waveforms in accordance with Ohm's law. The above-mentioned operation is repeated by one cycle in two rotations of the main spindle. Figure 9 shows the waveforms obtained with this system. E.M.F. waveform is outputted in the first rotation. After the rotation at a certain timing where the circuit is in an open state, the waveform changes to the thermal current waveform and contact resistance waveform is also outputted at the same timing as thermal current output.

Figure 10-a shows the tool-work contact resistance waveforms calculated by using Ohm's law from the E.M.F. and thermal current that measured separately in each measurement circuit. Figure 10-b shows tool-work contact resistance waveforms of the entire measurement circuit resistance including the change in the contact resistance by the new tool and worn tool with flank wear of $V_{f}=0.53\text{mm}$ at the cutting depth of 1.0mm.
outputted from newly developed measuring system. For the convenience of the measuring circuit, contact resistance waveform outputs from this system have the negative sign. However compared with these two waveforms, output result shows almost similar tendency including the absolute value of tool-work contact resistance becoming small by the progress of the tool flank wear and the contact resistance being independent to the cutting speed.

4. Result and Discussion

The contact resistance waveform of each cutting edge measured with the developed tool-work contact resistance measuring system is processed further; first extracting approximately 20% of each waveform duration and next it is numerically averaged by calculating the least square approximation. The width of tool flank wear was measured at every constant cutting time, and the relation between actual tool flank wear width and tool-work contact resistance was obtained.

Figure 11 shows the relation between tool flank wear width and tool-work contact resistance output in different depths of cut. The cutting speed is 138m/min (Fig.11-a) and 180m/min (Fig.11-b) and both feed rates are 0.10mm/edge. It is found that when the depth of cut \( t \) gets smaller, the change in the contact resistance according to the progress of tool flank wear becomes larger. Moreover, this tendency is almost similar in spite of different cutting speeds. In addition, the corresponding absolute values themselves in both figures seem to be almost
the same, that means they are independent to the cutting speed.

Figure 12 shows relation between tool flank wear width and tool-work contact resistance in different cutting speeds. The depth of cut \( t \) and the feed rate \( f \) are \( t=0.5\text{mm} \) and \( f=0.10\text{mm/edge} \) in Fig.12-a and \( t=2.0\text{mm} \) and \( f=0.20\text{mm/edge} \) in Fig.12-b. It is clear that in both finish cutting condition (Fig.12-a) and rough cutting condition (Fig.12-b) the resistance values are independent to the cutting speed.

Figure 13 shows the relation between the tool flank wear width and tool-work contact resistance in different feed rates at the same cutting speed of 138m/min in rough and finish cutting conditions. In the case of finish cutting condition \((t=0.5\text{mm})\), the differences of contact resistance among different feed rates get larger when the cutting edge condition gets closer to the new state. When the tool wear progresses, there is no difference in different feed rates. On the other hand, the influence of the feed rate is not observed in all flank wear widths in the case of rough cutting condition \((t=2.0\text{mm})\).

From the above-mentioned results, it is concluded that the previous assumption is right, that means contact resistance variations occur due to the progress of the tool wear. However, when a contact area necessary and sufficient for the current flow in the closed loop circuit is secured, it is not possible to measure the change in the contact resistance value even if the contact area increases more. As shown in Fig. 11 and Fig. 12, the contact area required for the current flow in the closed loop circuit is ensured even at the new cutting edge in the rough cutting condition. Therefore, the change in the contact resistance value is small even if the tool wear progresses in the rough cutting condition.

In the case of new cutting edges under finishing conditions, a minute change in the contact area in different feed rates appears remarkably in the contact resistance value because the contact area becomes small. Under the condition that the tool wear progresses and the contact area of tool flank wear has increased, or under the rough cutting condition, there is little change in the contact resistance in different feed rates. The fact that the contact resistance is directly related to the tool-work contact area indicates clearly that the tool-work contact resistance is not affected by the cutting speed.

5. Conclusion

The possibility of the in-situ monitoring of the tool flank wear by using E.M.F. as a sensor signal was investigated. It was found that there is some delays caused by the progression of tool flank wear at the rising edge of the E.M.F. when a cutting edge of the tool starts the cutting.
We assume the cause of this rising delay of E.M.F. is the change in electrical resistance by increasing the contact area due to the change of tool flank wear width, and measured the electric current between the tool and the workpiece. As a result, it is found that the thermal current increases as the tool flank wear progresses, and the thermal current is also affected by the cutting speed.

The in-process tool-work contact resistance measurement system was developed, and tool-work contact resistances are automatically calculated with the E.M.F. and thermal current waveforms measured under the same cutting cycle by change the terminator resistances. As a result, tool-work electrical contact resistance decreases along with the increase the width of tool flank wear, and the contact resistance is independent to the change of the cutting speed.

The conventional researches using E.M.F. mainly aim for detecting cutting temperature between the tools and workpiece. The proposed method here is directly useful to detect tool wear which is independent to the cutting speed.

The developed system enables to achieve robust measurement of tool flank wear during processing of the cutting cycle.

References

(10)H. Hirota, N. Shinozaki, T. Narita, Recognition of Chip Treatment States and Control : A Method of Recognition and Examples of Adaptive Control on Feed, Journal of the
