In-process tool wear detection by measuring the slip of AC induction motor in intermittent cutting process

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Abstract

The molds used in the manufacture of many industrial products are mainly manufactured by cutting with a machining center. Since the cutting time is very long in these cutting processes, it is important to judge the tool life and know the appropriate timing for tool change. The authors of this study have been investigating in-process detection of tool wear using tools and the work material itself as sensors, and good results have been obtained. In this method, since the work material and the cutting edge of the cutting tool themselves become sensors, therefore the detection system can be constructed at low cost and does not affect the actual work. In this study, the focus was on the slip of the AC induction motor for driving the spindle of a milling machine. This detection method can also construct the detection system at low cost and does not affect the actual work. By measuring it, it was possible to investigate whether tool wear can be detected in-process. It was found that there is an excellent relationship between the progress of tool flank wear and the slip of the AC induction motor.

Keywords : Tool wear, Slip of AC induction motor, In-process detection, Intermittent cutting

1. Introduction

The use of artificial intelligence (AI) technology has spread rapidly during the past few years. It has also been applied to various devices and fields—for example, face authentication for unlocking smartphones, software for automatically managing addresses and names by recognizing characters, such as on business cards, and automated driving technology that is developing rapidly. Most of these AI technologies are learning/recognition technologies that have been used for a long time using neural networks.

The cutting field is still supported by many experts. In die cutting, the lead time from the start to the end of cutting tends to be long. Under such circumstances, recognition of abnormal conditions during cutting, such as tool wear, tool breakage, and chatter vibration, depends largely on the intuition and experiences accumulated by experts — that is, the expert perceives the state during cutting and searches for a similar situation that he or she has experienced. The expert then judges whether the state is abnormal. Therefore, it is truly the same as AI technology.

In cutting machines equipped with automatic tool changers, such as machining centers and turning centers, a part of the tool-wear detection system called “interprocess” has been applied in practical applications. In the tool wear measurement of the interprocess, tool wear width is measured at the time of tool change or at a constant machining time. “In-process” cutting tool state recognition, which determines the tool state during cutting, has not yet been put to practical use. In-process measurement of cutting tool wear has been performed by various approaches, but all are laboratory-level methods and have not been put to practical use. To measure the tool wear, installing sensors at various points on the milling machine or installing expensive measuring equipment, such as a cutting dynamometer, interferes with the work

of the machine operator and reduces efficiency. Above all, incorporating the tool wear measuring device causes the cutting machine itself to become quite expensive.

The authors have conducted research to solve these problems. As mentioned above, embedding sensors into milling machines must be inexpensive and must not reduce work efficiency. Previous studies have investigated whether the tool–work thermoelectromotive force (EMF) or tool–work contact electric resistance can be used as a sensor signal for tool-wear detection during the intermittent cutting process. As a result, it was found that a peculiar waveform change appears in these signal waveforms with the progress of tool wear (Murata et al., 2012; Murata et al., 2013; Gouarir et al., 2016). These measuring methods do not select the model of the milling machine and do not reduce the work efficiency of the operator. Furthermore, measurement is possible by installing only inexpensive sensors. However, in order to deep-learn these signal changes in AI and determine the tool life from them, it is necessary to add additional detection signals.

In this study, following the measurement method described above, the focus was on the slip of the AC induction motor, which is the main-shaft rotation power of the milling machine. It is believed that this measurement method can also be used as a tool-wear detection method that does not reduce work efficiency, and measurement can be performed with an inexpensive sensor. Various characteristics of a three-phase AC squirrel-cage motor change depending on the load applied to the motor. While most of them fluctuate like a quadratic curve, the slip ratio changes almost linearly with the load (Akatsu, 2012). In a previous article, it was reported that the cutting power was estimated from the slip of the AC induction motor in continuous cutting with a lathe (Hirota and Shinozaki, 1977). However, no study has examined the slippage of AC motors in intermittent cutting with a short cutting time per edge, and no report has been found on in-process tool-wear detection using this signal. Therefore, whether this slip signal of the AC induction motor is effective as an in-process detection signal for tool wear in an intermittent cutting process was investigated.

2. Measurement of the slip of the AC induction motor

An AC induction motor rotates in synchronization with the frequency of the three-phase AC when there is no load. When the load is applied to the motor, the rotation of the rotor lags behind the frequency to be synchronized as the load increases. This is called the “slip” of the AC motor. The slip (slip rate) with respect to the load changes almost linearly. However, according to the literature, the commercial power supply frequency in Japan is 50 or 60 Hz, which varies depending on the region; however, the frequency actually provided varies by approximately $\pm 5\%$ with respect to these rated frequencies (the power supply frequency in the authors’ area is rated at 60 Hz) (IEEJ, 2002). Therefore, if measurement is not performed based on this variation, the waveform change caused by the progress of tool wear may be buried, and measurement may not be possible. First, the method of measuring the slip of an AC induction motor was examined with reference to previous work.

Figure 1 shows the experimental setup of the slip of the AC induction motor measurement. A rotary encoder of 8000 ppr was attached to the spindle rotating motor of the milling machine. The transmission gear for the spindle was set to neutral to rotate the motor. In that state, the number of output pulses from the rotary encoder at each reference gate time was counted. The gate used in this experiment was an accurate 1-s gate made of quartz (hereinafter referred to as a “quartz gate”) and a gate that counts 60 cycles of a commercial power supply cycle for 1 s (hereinafter referred to as a “power

Fig. 1 Experimental setup of the slip of AC induction motor

supply gate”). In other words, the quartz gate had an accurate 1 s, while the power supply gate had a fluctuation of $\pm 5\%$ with respect to 1 s — i.e., “almost 1 s.” However, because the rotation speed of the AC induction motor also fluctuates owing to fluctuations in the power supply frequency, the gate time of the power supply gate was synchronized with the rotation speed of the AC induction motor. Figure 2 shows the result of counting the number of pulses output from the encoder in 1 s created by each gate. The horizontal axis of the graph shows the number of pulses per second displayed on the seven-segment light-emitting diode (LED) display, and the vertical axis shows the frequency at which the numerical value appears. Figure 2a shows the measurement results with the quartz gate, and Figure 2b shows the measurement results with the power supply gate. The number of pulses per second was measured 300 times at each gate. This figure shows that, when the measurement results of the quartz gate and the power supply gate are compared, the count using the power supply gate has less variation in the number of counts. The standard deviation at this time was 105.6 for the quartz gate method and 23.9 for the power supply gate method. This result is consistent with previous results. Moreover, the rotation speed of the AC induction motor driven by the commercial power supply varies correspondingly—that is, when the slip of an AC induction motor directly driven by a commercial power supply is measured, the gate for counting the number of pulses must use a power supply gate based on the frequency of the commercial power supply.

Next, a similar experiment was conducted by driving the AC induction motor with an inverter. The AC induction

Fig. 2 Relation between number of pulses and frequency depending on the drive power supply

motor was driven at frequencies of 45, 60, and 70 Hz, and the quartz gate method was used to count the number of pulses per second 300 times each, as before. Figure 3 shows the variation in the number of output pulses from the rotary encoder when the AC induction motor is driven at each frequency by the inverter. Each axis is the same as in Fig. 2. Figure 3a shows the results when the inverter drive frequency is set to 45 Hz. Similarly, Fig. 3b shows the results at 60 Hz, and Fig. 3c shows the results at 70 Hz. The variation in the number of counts is equal to or smaller than the result measured by directly driving the AC induction motor with the commercial power supply and using the power supply gate shown in

Fig. 3 Relation between number of pulses and frequency depending on the drive frequency of inverter output

Table 1 Cutting conditions

Condition	Rough	Finish
Cutting tool	$\phi 100$ Face mill with One cutting edge Axial rake angle : 15° Radial rake angle : 3° Cutting edge angle : 45°	
Tool material	Toshiba Tungaloy P-class cemented carbide No chip breaker	
Work piece	JIS carbon steel S45C 60mm square-bar	
Cuttig speed V : (Spindle rotation)	100m/min (318.5min^{-1})	150m/min (477.7min^{-1})
Feed rate f : (Table feed speed F :)	0.10mm/edge (31.9mm/min)	0.10mm/edge (47.8mm/min)
Depth of cut t :	1.0mm	0.2mm
Engage / Dis engage angle	$36.9^\circ / 36.9^\circ$	
Cutting lubrication	- (Dry cutting)

Fig. 5 Measurement timing of each signal

Therefore, it is difficult to obtain the correlation between the state of the cutting edge and the measured value. As a result, this experiment was performed with only one cutting edge. Two cutting conditions were used in this experiment. Rough cutting conditions of cutting speed $V = 100$ m/min, feed rate $f = 0.1$ mm/edge, and depth of cut $t = 1.0$ mm and a finishing

cutting condition of cutting speed $V = 150$ mm/min, feed rate $f = 0.1$ mm/edge, and depth of cut $t = 0.2$ mm were assumed. Both the AC motor for the spindle and the AC motor for the table feed were driven by using an inverter, and the output frequency of the inverter was adjusted to achieve the desired cutting conditions. The work material was JIS carbon steel S45C with a square cross section of 60 mm on a side. It was in a dry cutting condition using a Toshiba Tungaloy P-class cemented carbide cutting edge. The isolation between the vise and the work material was to obtain the tool–work thermoelectromotive force that serves as the cutting start and end signals of the cutting edge, and a 0.2-mm-thick polypropylene sheet was used.

Each time the surface of the work material was cut under the specified cutting conditions, the tool–work thermoelectromotive force, the number of output pulses, and the F – V conversion waveform were recorded in the memory recorder. Every time one cutting cycle was completed, the state of the cutting edge was photographed with a charge-coupled device microscope, and the maximum flank wear width was measured from the photograph. The cutting distance for one cycle was the value calculated geometrically using the shape of the cutting tool with a diameter of 100 mm and the shape of the work material with a square cross section of 60 mm on each side. Generally, the maximum flank wear width is about 0.5 mm for rough cutting condition, and the maximum flank wear width is about 0.3 mm for finish cutting condition is judged as the tool life. In this tool wear experiment, the maximum flank wear width from a new cutting edge is increased to the tool life plus 0.1 mm, that is, the maximum flank wear width is 0.6 mm for rough cutting condition and the maximum flank wear width is 0.4 mm for finish cutting condition. During that time, if the chipping occurs, the cutting edge shall be replaced with new one and the tool wear experiment shall be conducted from the beginning. After the maximum flank wear width reached the target flank wear width, the experiment was continued as it was even if the cutting edge was chipped as a reference value.

4. Tool wear experiment results and discussion

Figure 6 shows the relationship between the cutting distance, the maximum tool flank wear width, and the number of encoder output pulses under rough cutting conditions. The horizontal axis shows the total cutting distance of the cutting edge. The left vertical axis shows the maximum flank wear width of the cutting edge, and the right vertical axis shows the encoder pulse number. In this experiment, once the material surface is cut, cutting data for about 29 rotations (28 rotations depending on the timing of cutting of the cutting edge) can be obtained. Each plot point in Fig. 6 is the average value of multiple data obtained in one cutting. The tool flank wear progressed according to the cutting distance, and the number of encoder output pulses also decreased accordingly. Figure 7 shows the conversion into the relationship between

Fig. 6 Relationship between maximum tool flank wear width, pulse count of encoder output, and distance of cut in rough cutting condition

Fig. 7 Relationship between maximum tool flank wear width and pulse count of encoder output in rough cutting condition

the maximum flank wear width and the number of encoder output pulses from Fig. 6. This figure reveals that the load on the AC induction motor increased as the flank wear progressed; therefore, the slip of the AC induction motor also increased. The relationship between the maximum flank wear width and the number of output pulses changed linearly to a maximum flank wear width of 0.6 or 0.7 mm, which is generally called the “tool life” in rough cutting. When the maximum flank wear width exceeded 0.7 mm, the variation in the number of output pulses became extremely large. The circled plot in Fig. 7 shows the data for every 0.1 mm from the flank wear width of 0 mm. Figure 8 shows the F – V converted waveforms extracted at each circled plot point of Fig. 7 and superimposed. This figure shows that a clear change occurred in the F – V converted output waveform as the tool flank wear progressed.

Fig. 8 Relationship between tool–work thermoelectromotive force, F – V conversion signals, and time of cut

Fig. 9 Relationship between maximum tool flank wear width and pulse count of encoder output in finish cutting condition

Figure 9 shows the relationship between the maximum tool flank wear width and the number of encoder output pulses under the finish cutting conditions. Even if the depth of cut were small, the same relationship as under the rough machining conditions would be measured. The above results indicate that this measurement method is quite sensitive.

However, the need for some improvements has become apparent because the sensitivity is too high. Figure 10 shows the relationship between the main-shaft gear shifting and the number of rotary encoder output pulses when the main spindle is idling. The number of output pulses was measured 20 times at 1-min intervals at each gear position. The vertical axis represents the number of output pulses from the rotary encoder for 1 s, and the horizontal axis represents the number of measurements. The output pulse number of the rotary encoder was changed just by shifting the transmission gear, even without cutting. This means that, when learning the F - V conversion waveform changes in AI, it is necessary to remove the level shift of the initial value because of the shift of the main-shaft gear.

Next, regarding the timing of the pulse number measurement, in this experiment, the number of pulses was counted for 25 ms after 5 ms from when the cutting edge started cutting. However, the relationship between the tool-work thermoelectromotive force waveform and the F - V conversion waveform indicates that the peak of the pulse number changed when the progress of flank wear occurred slightly later than that timing. This delay is considered to be caused

Fig. 10 Relationship between spindle gear position and output pulse number when not cutting

by the inertia of the rotor of the AC induction motor; however, it is also thought that the timing changes depending on the motor model. Therefore, it is necessary to improve the measurement system so that the peak of the pulse number change can be detected automatically. In this regard, the frequency characteristics of the self-made F – V conversion circuit used in this experiment are slow. Thus, it is necessary to change to a faster F – V conversion circuit.

In Fig. 7 and Fig. 9, it can be seen that the variation in the pulse count value becomes large after the maximum value of the maximum flank wear width targeted in this experiment is exceeded. In addition, a temporary increase in the pulse count value was observed in the same area. When the state of tool wear was reconfirmed with the photograph, evidence of chipping on the tool was confirmed. Therefore, it is considered that this increase in the pulse count value causes the cutting edge to temporarily sharpen due to the tool chipping, and as the result, the cutting resistance is considered to have decreased.

5. Conclusion

It has been shown that there is a clear correlation between the progress of tool flank wear and the cutting force. By measuring the relationship between the slip of the AC induction motor and the tool flank wear width, it was possible to verify the relationship again.

The rotation speed of the AC motor depends on the power supply frequency. Therefore, when using this method, if the spindle motor of the milling machine is directly driven by the commercial power supply, it is necessary to perform measurement using the AC power gate. When the spindle motor is driven by using an inverter, there is no problem in counting the number of pulses using a quartz gate.

The slip of the AC induction motor was found to be extremely sensitive, and it was found that the progress of tool flank wear can be detected in-process by measuring it.

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