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Monitoring of End-mill Temperature with Infrared Thermography and Wireless Tool Holder System

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Keywords: end-mill process, tool temperature, infrared imagery, thermography, process efficiency, process monitoring.

Abstract. Nowadays, infrared thermographic technology has been attracting attention in various industrial fields. We therefore focus on it as a novel method for monitoring tool temperature to improve end-milling conditions for difficult-to-cut materials. However, a problem has emerged; it is difficult to measure the tool temperature when there is a coolant because the coolant prevents monitoring of the surface of the end-mill tool. Thus, we developed a wireless tool holder system equipped with a thermocouple in the end mill to monitor the tool temperature under coolant conditions. In this report, we compared the temperature measured by infrared thermographic imagery with that measured by a wireless tool holder system when end milling the stainless steel under dry coolant conditions. The thermocouple, which has a small diameter of 0.12 mm, was used to ensure high response measurement in the proposed wireless tool holder. We obtained the tool temperatures by infrared thermographic imagery and by wireless tool holder equipped with a thermocouple at a sampling time of 1/30 of a second. We confirmed that the temperature measured by the wireless tool holder agrees with that measured by infrared thermographic imagery. As a result, we demonstrated that the developed method with a wireless system is effective to estimate the tool temperature in end-milling processes and makes it feasible to measure it under coolant conditions.

Introduction

Nowadays, manufacturing companies have been requested to develop new technologies to determine the machining conditions in the agile and trial manufacturing fields. The cutting force and the cutting temperature must be monitored to estimate machining conditions sufficiently accurately. Recently, it has become easy to measure the cutting force with a piezoelectric sensor on the machine tool table whereas the cutting temperature is difficult to measure because measuring with a thermocouple sensor is considered to be the only effective and practical method [1, 2]. Few recent reports have dealt with measuring the tool temperature with an infrared temperature sensor [3]. However, an insufficient temperature distribution was obtained because these methods are based on a point measuring method. Additionally, infrared thermography is considered to be an effective method to obtain the tool temperature distribution during the shallow drilling process [4]. We proposed a method to estimate the tool temperature in the end-mill process by infrared imagery with high speed thermography [5]. In this study, we developed a wireless tool holder system equipped with a thermocouple in the end-mill to monitor the tool temperature under coolant conditions. This method was also expected to be effective to monitor the drill tool temperature during the more deeper hole drilling process. We compared the temperature by infrared thermographic imagery with that measured by the wireless tool holder system when end milling the stainless steel under dry coolant conditions. The thermocouple, which had a small diameter of 0.12 mm, was used to ensure high response measurement in the proposed wireless tool holder. We obtained the tool temperatures by infrared thermographic imagery and by the wireless tool holder equipped with a thermocouple at a sampling time of 1/30 of a second. We confirmed that the temperature measured by wireless tool holder agrees with that measured by infrared thermographic imagery. As a result, we demonstrated that the developed method with a wireless system is effective to estimate the tool temperature in end-mill processes.

Setup for monitoring end-mill process

Measurement of tool surface temperature. Figure 1 shows the setup for monitoring the end-mill process. The thermography used in the experiment is infrared ray technology H2640 made by Nippon Avionics Co. The minimum space resolution is 0.18mm at 0.3m working distance, which means the spatial resolution 0.6mrad, temperature resolution is 0.03°C, and the maximum measureable temperature is equal to or lower than 500°C. The thermography can transfer continuous images to a computer. Depending on the function, the thermography can also obtain frame imagery images at 30 images per second. The thermography was set up next to the machining center. We monitored the end-mill process at an angle of 150° in the direction of tool movement. The distance between the end-mill and thermography was 1500 mm. The workpiece was a 100 (cutting length) × 100 × 50 mm sheet of heat-resistant steel (JIS SUS310S, 25Cr-20Ni). The tool diameters were 6 mm and 10 mm (type: WXL-EMS, OSG Corporation). The twist angle was 30 degrees. The number of cutting teeth was four. The emissivity of the end-mill surface was 0.4. The machining conditions were a 1450 rpm rotating speed, 0.05 mm per tooth feed amount, 0.6 mm cutting width, and 12 mm cutting depth. The coolant was dry air.

Figure 2 shows infrared imagery of the end-mill process. You can easily and finely obtain the temperatures of the holder, end-mill, workpiece, and machining chips by observing infrared imagery during temperature distribution. The reflected image of the cutting edge close to the processing point is reflected on the glossy surface of the workpiece, and it can be seen that the analysis can be performed while considering the change in the infrared emissivity. This figure shows that the monitoring method effectively estimated the end-mill process by using a high response infrared thermograph that can continuously transmit frame images to a personal computer.

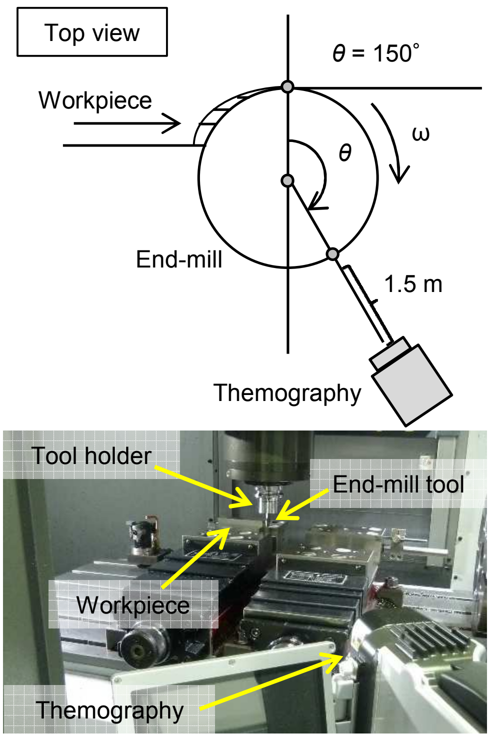
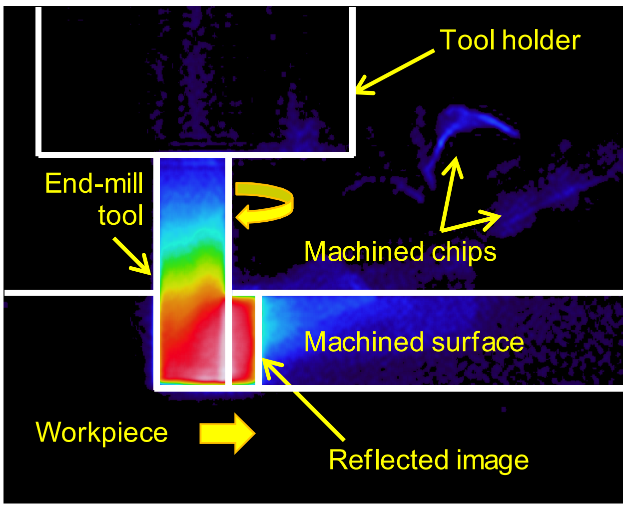


Fig. 1 Setup for monitoring end-mill process



Workpiece: JIS SUS310S
Cutting tool: OSG WXL-EMS D = 10 mm, 4 flute
Machining conditions:
V_c = 45 m/min, f_z = 0.05 mm/tooth,
Ad = 12 mm, Rd = 0.6 mm, dry air

Fig. 2 Infrared imagery of end-mill process

Tool for measuring internal temperature. Figure 3 shows the schematic diagram of the wireless measurement tool holder system. If the measurement object was a rotating tool, there was the problem that the wire wound around the spindle when it rotated at high speed. Therefore, we have developed a wireless measurement tool holder system. First, we inserted the thermocouple into the hole in line with the tool center axis . Next, we placed the amplifier, A/D converter, micro-controller, and transmitter in the tool holder. The tool temperature measurement results were wirelessly and continuously transmitted to a computer that is connected to the receiver. The thermocouple was K type with a wire diameter of 0.12 mm. Depending on the function, the wireless measurement tool holder system could also obtain thermal data at 30 times per second. The responsiveness and sampling period of the wireless measurement tool holder system and the thermography were almost the same. The workpiece was a 100 (cutting length) × 100 × 50 mm sheet of heat-resistant steel (JIS SUS310S, 25Cr-20Ni). The tool diameter was 6 mm (type: WXL-EMS, OSG Corporation). The twist angle was 30 degrees. The number of cutting teeth was four. The machining conditions were a 1450 rpm rotating speed, 0.05 mm per tooth feed amount, 0.6 mm cutting width, and 12 mm cutting depth. The coolant was dry air.

Figure 4 shows the wireless measurement tool holder system. By using this measurement system, we could monitor the processing temperature, even if the cutting edge was not visible, for example, in a drilling or cutting fluid environment.

Figure 5 shows the discharge machining electrode and end-mill tool. The total length of the end-mill tool was 50 mm. The diameter of the discharge machining electrodes was 1 mm. We had a micro-deep hole of 49 mm (L / D = 49) from the shank part of the central axis of the end-mill tool. We inserted a thermocouple into the micro-deep hole. The position of the tip of the thermocouple was 1 mm short of the bottom edge of the end-mill tool.

Figure 6 shows a cross-sectional schematic view of the temperature measurement tool. The left side represents the flute part, and the right side represents the shank part. The volume of the flute part is smaller than that of the shank part because the flute part of the end-mill tool has a chip pocket. The cross-sectional area perpendicular to the axis decreases gradually towards the flute part. In addition, the core thickness of the end-mill tool is less than the diameter of the flute part. The diameter of the thermocouple insert hole should be less than the tool core thickness. Because the diameter of the thermocouple insert hole is 1 mm, we thought that the limit of the tool diameter could be measured by using the wireless measurement tool holder system, which is around 2 mm in diameter.

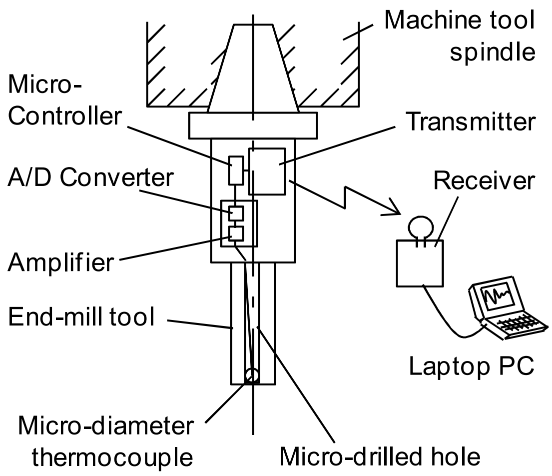


Fig. 3 Schematic diagram of wireless measurement tool holder system

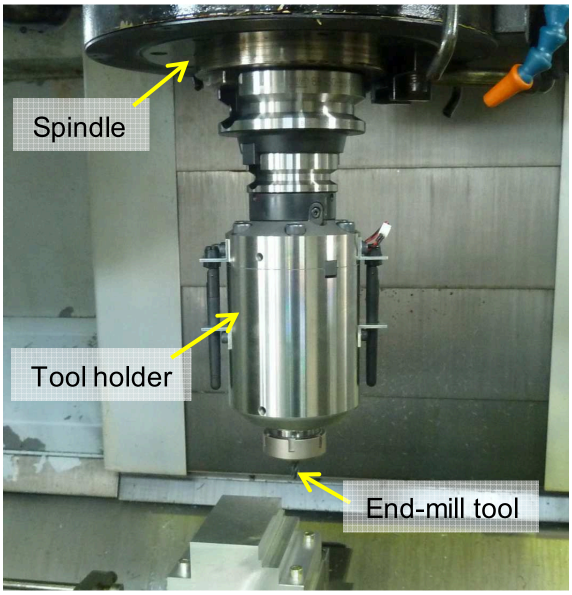


Fig. 4 Wireless measurement tool holder system

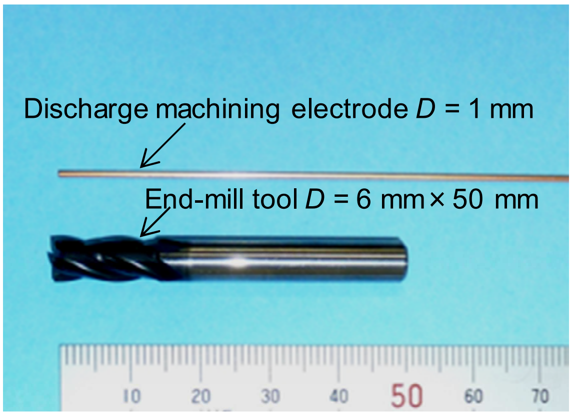


Fig. 5 Discharge machining electrode and end-mill tool

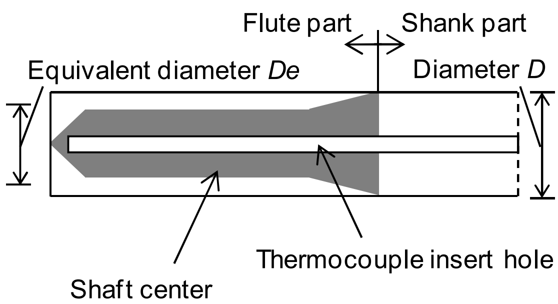


Fig. 6 Cross-sectional schematic view of temperature measurement tool

Results and discussions

Effect of processing time on tool temperature. Figure 7 shows the effect of processing time on the temperature distribution. The end-mill tool temperature rose if the cutting time increased. The results show that heat storage occurs.

Figure 8 shows the relationship between the tool temperature and processing time. The machining conditions were the same except for the tool diameter. This figure shows that the maximum temperature of the tool increased and converged to a constant temperature with time. The converged temperature was different when the diameter of the tool was different. This is expected to be shown by the model close to the first order time delay of these phenomena.

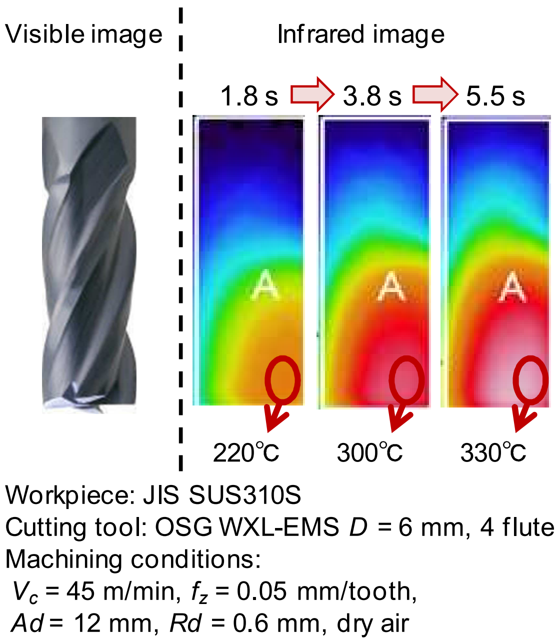


Fig. 7 Effect of processing time on temperature distribution

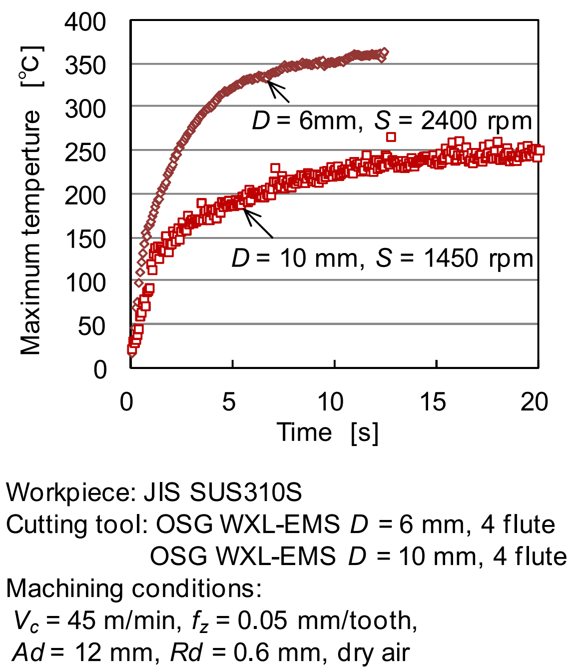


Fig. 8 Relationship between tool temperature and processing time

Temperature response model based on first order time delay. Figure 9 shows the temperature response model based on the first order time delay. The heat storage action of the tip of the tool explains the model of the first order lag system [6]. This figure also shows the heat capacity in the tip of the tool. We consider a column of infinite length. The density is defined by ρ, specific heat by C, outside thermal conductivity by α, primary temperature of the column by T_0, and step temperature (assuming it changes rapidly) by T_s.

$$\rho C(\frac{\pi D^2}{4})(\frac{dT}{dt}) = \pi D\,\alpha(T_s - T) \quad (1)$$

The left side shows the change of thermal energy per unit time, and the right side shows the amount of heat transferred from the surface per unit length. The end-mill process is intermittent cutting. However, the end-mill rotating speed is much faster than the transient heat transfer. Therefore, an end-mill process that can approach the model of perimeter was considered. Differential equation (1) was solved as a primary condition if $T = T_0$ when $t = 0$ as the left side is dimensionless temperature.

$$\frac{T - T_s}{T_0 - T_s} = \exp(-\frac{4\alpha}{\rho CD}t) \quad (2)$$

Therefore, if $T_m = \rho CD/4\alpha$,

$$T = T_s + (T_0 - T_s)\mathrm{esp}(-t/T_m)\ . \quad (3)$$

T_m is the damping time constant of the first order time delay and is proportional to heat capacity. Figure 10 shows a comparison between the measurement result of the tool surface maximum temperature by infrared thermography and the internal temperature by the wireless measurement tool holder system. The tool internal temperatures are indicated by circles. It was confirmed that the cutting heat was transmitted with a slight delay because the position of the tip of the thermocouple was some distance from the cutting point. We were able to confirm that the internal temperature converged to the same extent as the surface temperature, and this was a reasonable result.

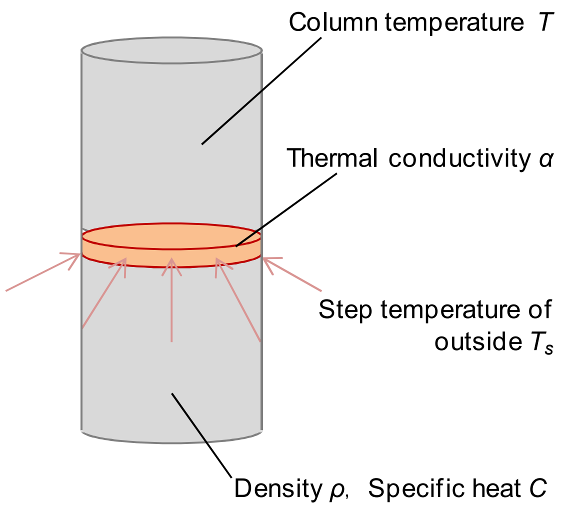
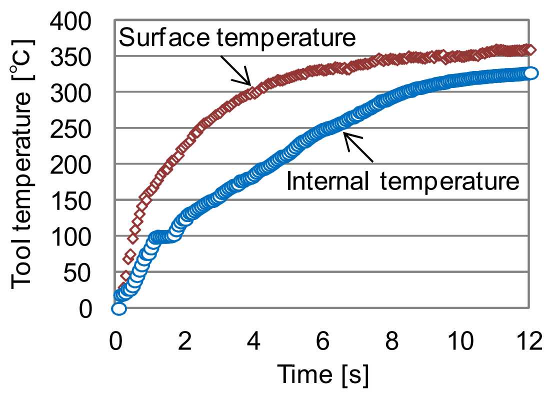


Fig. 9 Modeling by first order time delay



Workpiece: JIS SUS310S
Cutting tool: OSG WXL-EMS D = 6 mm, 4 flute
Machining conditions:
V_c = 45 m/min, f_z = 0.05 mm/tooth,
Ad = 12 mm, Rd = 0.6 mm, dry air

Fig. 10 Comparison between surface temperature and internal temperature

FEM analysis of temperature by axial symmetry model. Figure 11 shows the FEM analysis of the end-mill model considering the decrease in heat capacity in the flute part. We use the axial symmetry model and consider that its element size is almost the same as that of the image element of thermography. In reality, the volume of the flute part is smaller than the shank part of the end-mill. Therefore, we used a model with the equivalent diameter for the flute part. We charged the heat source at the tip of the cutting edge of the side surface. The rest of the boundary is insulation. The material of the holder is steel, and that of the shank and equivalent cutting part is cemented carbide. A density of 14,800 kg/m^3, specific heat of 0.21 kJ/(kg·K), and thermal conductivity of 80W/(m·K) were used for the physical property values of the tool. A density of 7860 kg/m^3, specific heat of 0.50

kJ/(kg・K), and thermal conductivity of 42 W/(m・K) were used for the physical property values of the holder.

Figure 12 shows the FEM analysis result of the temperature by using the axial symmetry model. The dotted line shows the temperature analysis result of the thermocouple insert position on the center line of the FEM model. The heat input was determined from the measurement result of the surface temperature by infrared imagery. We confirmed that the measured values substantially agree with the analysis results.

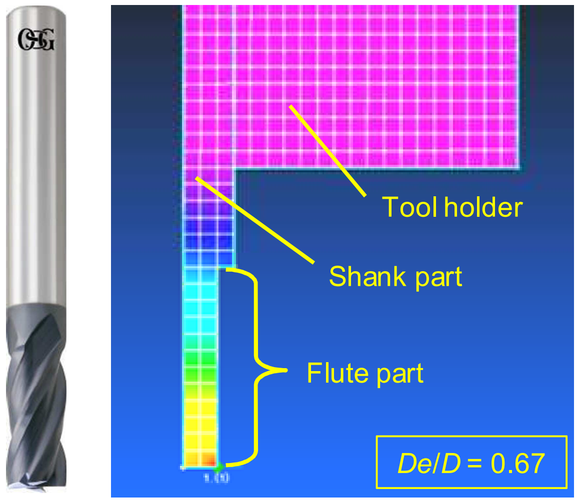


Fig. 11 FEM model with equivalent diameter

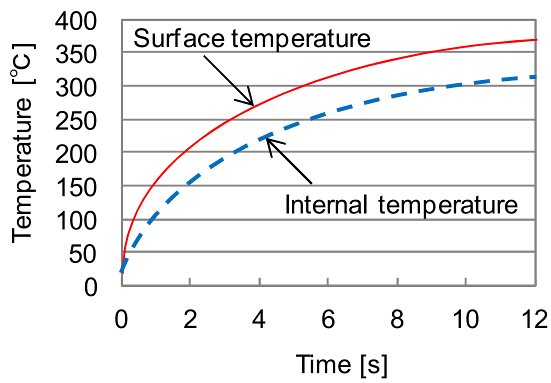


Fig. 12 FEM analysis result of temperature by axial symmetry model

Summary

Measurement by infrared imagery is effective in the analysis of the temperature distribution from the cutting edge of the end-mill tool to the shank part. On the other hand, we developed a wireless tool holder system equipped with a thermocouple in the end-mill to monitor the tool temperature under coolant conditions. As a result, we have confirmed that the wireless measurement tool holder system is also effective.

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