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Monitoring of End-Mill Process Based on Infrared Imagery with a High Speed Thermography

Masatoshi SHINDOU[1,a *], Hiroyuki KODAMA[2,b], Toshiki HIROGAKI[2,c] and Eiichi AOYAMA[2,d]

[1] Research and Development Group, Yamamoto Metal Technos Co., Ltd.
4-7 Setoguchi, 2-chome, Hirano-ku, Osaka 547-0034, Japan

[2] Department of Mechanical Engineering, Doshisha University
1-3 Miyakodani, Tatara, Kyotanabe-shi, Kyoto 610-0321, Japan

[a] shindou@yama-kin.co.jp, [b] etl1302@mail4.doshisha.ac.jp,
[c] thirogak@mail.doshisha.ac.jp, [d] eaoyama@mail.doshisha.ac.jp

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Abstract. In this study, we perform the end-mill process of a difficult-to-cut material (JIS SUS310 stainless steel) and observe it with high performance infrared thermography. Considering the rotating angle of end-mill tool, a pixel temperature in each frame is investigated to obtain the tool temperature variation after cutting of each tooth in end-mill process. The tool temperature distribution can be analyzed at each rotating tool position in end-mill process from imageries, considering the relationship between the time duration of each frame and the rotating speed of an end-mill tool. Moreover, the tool/holder shape and the number of cutting teeth can be seen to affect the cutting temperature because the tool heat capacity and the heat input are different. The examination and analytical results show this method to be effective to estimate the tool temperature in the end-mill process sufficiently.

Introduction

Nowadays, manufacturing companies have been requested to develop new technologies to determine the machining conditions in agile and trial manufacturing fields. The cutting force and the cutting temperature must be monitored to estimate machining conditions sufficiently. The cutting force has recently become easy to measure with a piezoelectric sensor on the machine tool table, whereas the cutting temperature is difficult to measure because a thermocouple sensor is considered the only effective method to obtain it practically [1] [2].Few recent reports have dealt with measuring the tool temperature with an infrared temperature sensor [3]. However, insufficient temperature distribution was obtained because these methods are based on a point measuring method. Additionally, an infrared thermography is considered to be an effective method to obtain the tool temperature distribution during the drilling process [4]. We therefore attempt to develop an estimating method for end-mill process from an infrared imagery to measure the cutting temperature easily. We especially focus on a high response and high speed monitoring thermography, which makes it possible to obtain 30 frames per second and continuously forward them to an analyzing computer. In the present report, we perform the end-mill process of a difficult-to-cut material (JIS SUS310 stainless steel) and observe it with this high performance infrared thermography. Considering the rotating angle of end-mill tool, a pixel temperature in each frame is investigated to obtain the tool temperature variation after cutting of each tooth in end-mill process. The tool temperature distribution can be analyzed in images of each rotating tool position in the end-mill process by considering the relationship between the time duration of each frame and the rotating speed of an end-mill tool. In addition, we perform a temperature response analysis based on a Finite Element Method (FEM) model. By comparing experimental and analytical results, the tool/holder shape and the number of cutting teeth can be seen to affect the cutting temperature because the tool heat capacity and the heat input are different. These results show this method to be effective to estimate the tool temperature in the end-mill process sufficiently.

Setup for monitoring of end-mill process

Figure 1 shows the setup for monitoring the end-mill process. 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. As shown in Fig.1, the thermography is set up next to machining centers. We monitored the end-mill process at an angle of 150° in direction of tool movement. The distance between end-mill and thermography is 1500mm. The workpiece was SUS310, which is a difficult-to-cut material. The tool diameter was 10mm(Type: WXL-EMS,WXL-2D-DE, OSG Corporation). Twist angle is 30 degree. The numbers of cutting teeth are two and four. The emissivity of end-mill surface is 0.4. The machining conditions are a 1450rpm rotating speed, a 0.05mm per tooth feed amount, a 0.6mm width of cutting, and a 12mm depth of cutting. The coolant is dry-air.

Figure 2 shows an infrared imagery of the end-mill process. As shown in Fig.2, you can easily and finely obtain the temperatures of the holder, end-mill, workpiece, and machining chips by observing infrared imagery during temperature distribution. Figure 2 shows that the monitoring method effectively estimates the end-mill process by using high response infrared thermography equipped with a function for continuously transmitting frame imagery to a personal computer.

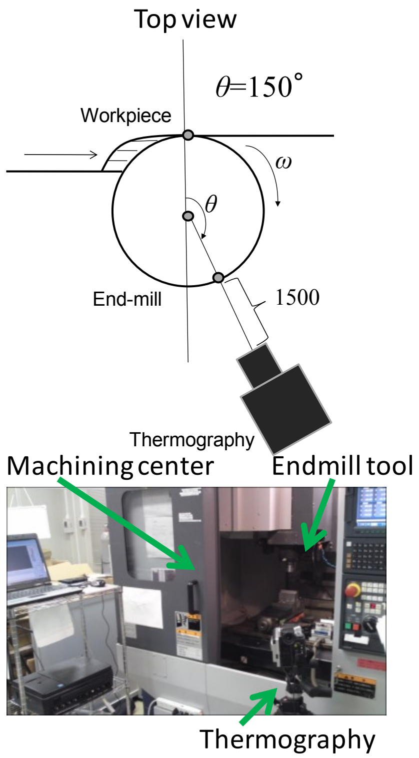

Fig. 1 Setup for monitoring of end-mill process

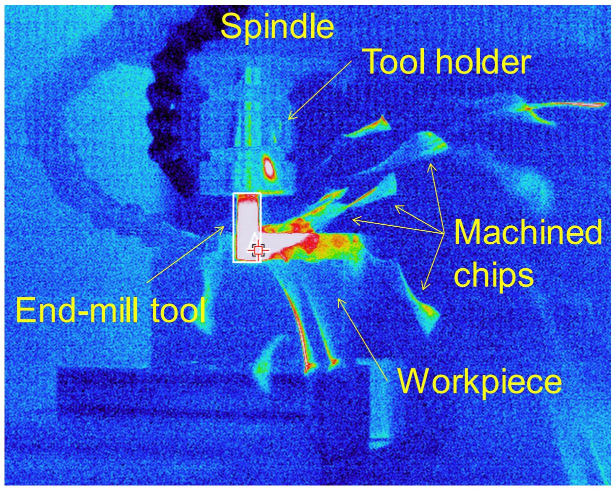

Fig. 2 Infrared imagery of end-mill process

Results and discussions

Influence of tool rotational angle on temperature distribution. Figure 3 shows the definition of tool rotational angle and its influence on the imagery of the end-mill process. Machining conditions are listed above. Temperature distribution changes slightly if tool rotational angle on end-mill process

changes. We consider the relationship between frame time in the imagery and tool rotating angle. In Fig. 3, angle α, which shows a phase of the cutting edge, is defined as the tool rotating angle when cutting edge is 0° in the normal direction relative to the shoot direction through the central axis.
If frame rate is defined by f(fps) and tool rotating speed by N(rpm), tool rotating speed per frame n is equation (1)

$$n=(N/60)\cdot(1/f). \tag{1}$$

If it assumes that there is no difference in the form of all teeth of the end-mill, the degree of changing the phase of cutting edge at m frame is defined by ε, the number of teeth of the end-mill by Z, and gauss symbol by [ ].
ε can be shown equation (2).

$$\varepsilon=m\cdot n\cdot Z-[m\cdot n\cdot Z]. \tag{2}$$

Thus, tool rotating angle α_m at m frame is equation (3)

$$\alpha_m=\varepsilon\cdot(360/Z). \tag{3}$$

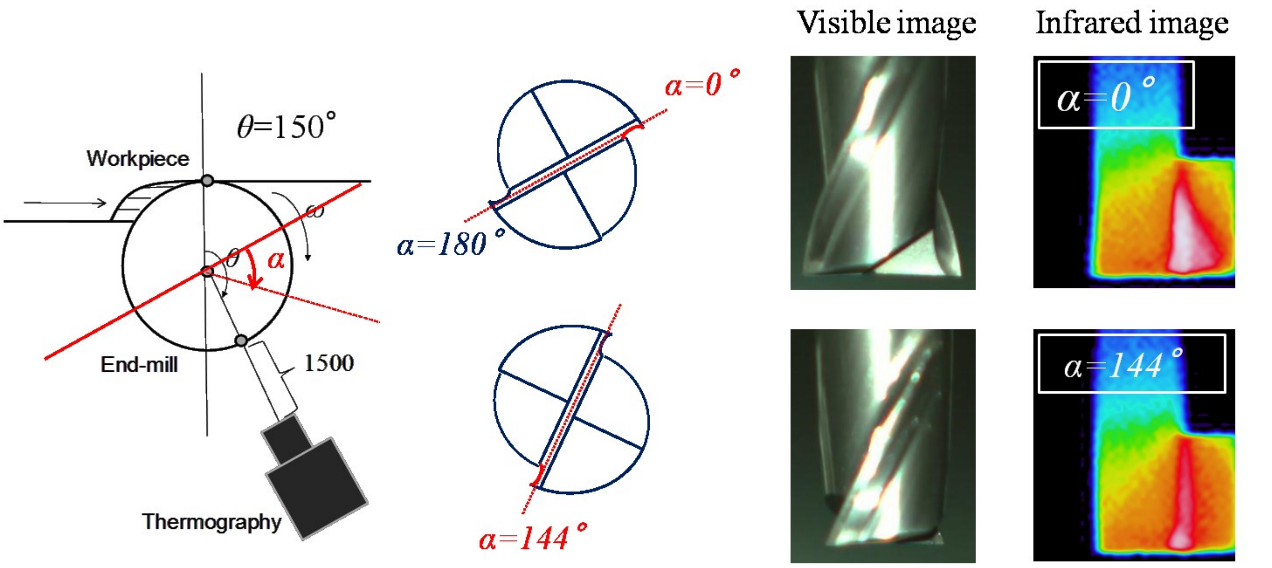

Fig. 3 Definition of tool rotational angle and its influence on the imagery of end-mill process

Figure 4 shows the relationship between the rotational angle as defined in Fig.3, tool temperature, and processing time. Here, the 15 fps sampling time is set to prevent the high frequency noise in Fig.4 (b). Change of the rotational angle and tool temperature is well in agreement. Therefore, we found that we can estimate the influence of changing the position of the cutting edge by tool rotating from getting the infrared imagery.

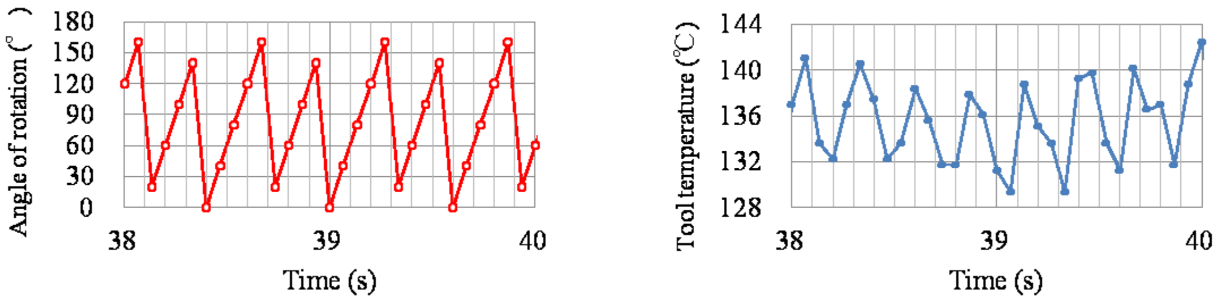

Fig. 4 Relationship between the rotational angle, tool temperature, and processing time

Influence of processing time on tool temperature. Figure 5 shows the influence of processing time on the temperature distribution. The end-mill temperature rises if cutting time increases. The results show that the heat storage action occurs.

Figure 6 shows the relationship between the tool temperature and the processing time. This figure shows that the converged temperature is different when the number of teeth is different. This is thought to be because only half as much heat is input to the tool of the end-mill per unit time when there are half as many teeth.

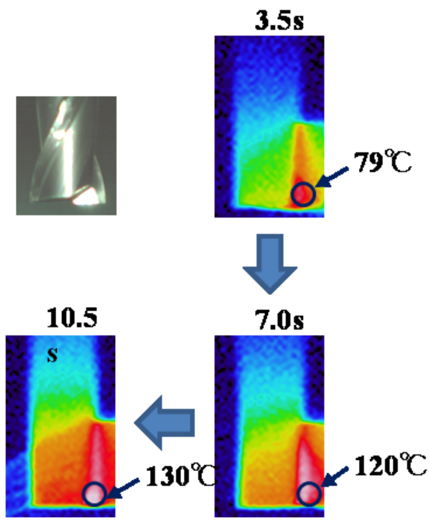

Fig. 5 Influence of processing time on the temperature distribution

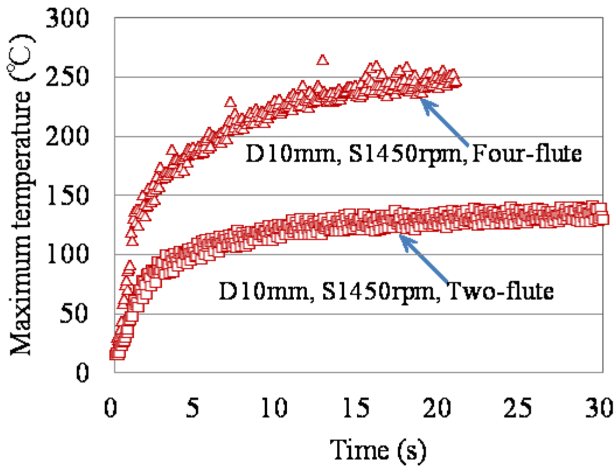

Fig. 6 Relationship between tool temperature and processing time

Temperature response model based on time delay of first order and FEM. Figure 7 shows a temperature response model based on time delay of first order. Heat storage action of the tip of the tool explains the model of the first order lag system [5]. Figure 7 shows the definition of 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, thermal conductivity concerning the outside by α, primary temperature of the column by T_0, and step temperature outside of the step reply, assuming it changes rapidly, by Ts.

$$\rho C\left(\frac{\pi d^2}{4}\right)\left(\frac{dT}{dt}\right)=\pi d \alpha (Ts-T) . \tag{4}$$

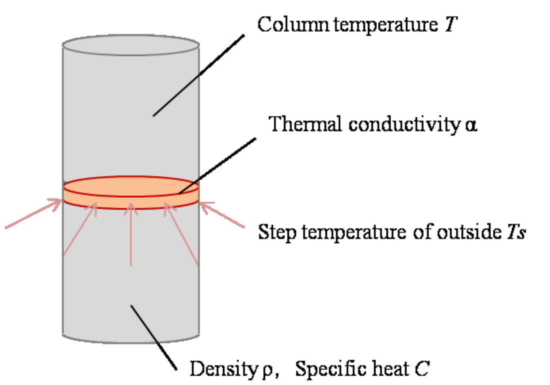

Fig. 7 Modeling by time delay of first order

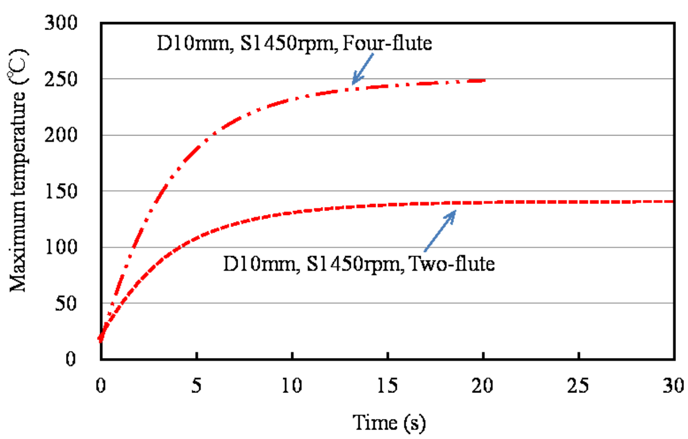

Fig. 8 Temperature based on time delay of first order

The left side shows the changing of thermal energy per unit time, and the right side shows the amount of heat transferred from surface per unit length. The end-mill process is intermittent cutting. However, the end-mill rotating speed is much faster than the phenomenon of transient heat transfer of energy. Therefore, an end-mill process is considered that can approach the model of perimeter.
Solve a differential equation (4), as a primary condition, if $T=T_0$ when $t=0$, as the left side is dimensionless temperature.

$$\frac{T-Ts}{T_0-Ts}=\exp\left(-\frac{4\alpha}{\rho Cd}t\right) . \tag{5}$$

Therefore, if $Tm=\rho Cd/4\alpha$,

$$T=Ts+(T_0-Ts)\exp(-t/Tm) \tag{6}$$

Tm is damping time constant of time delay of the first order. Tm is proportional to heat capacity. Figure 8 shows a temperature response based on time delay of the first order. The results in Fig.8 are almost the same as those in Fig 6.
Figure 9 shows a FEM end-mill model considering the decrease in heat capacity in the tooth part. We use the model of axial symmetry, and consider its element size is almost same as image element of thermography. In reality, the volume of tooth part is smaller than the shank part of the end-mill. Therefore, we use the model for changing the average diameter of the tooth part. Thus, we use the model in which the average diameter of the tooth part is changed. We charged the heat source to the depth of the cutting part that was distributed all-round. The rest of the boundary is insulation. The material of a holder part is steel, and that of a shank and an equivalent cutting part is cemented carbide. Density of 14800kg/m^3, specific heat of 0.21kJ/(kg・K), and thermal conductivity of 80W/(m・K) were used for the physical-property values of the tool part. Density of 7860kg/m^3, specific heat of 0.50kJ/(kg・K), and thermal conductivity of 42W/(m・K) were used for the physical-property values of the holder part.

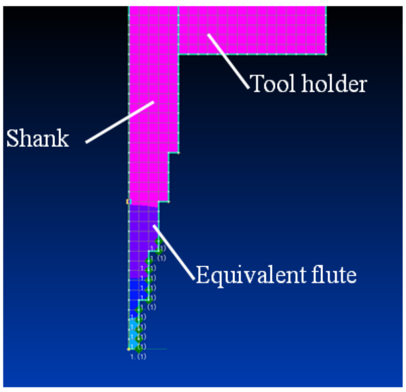

Fig. 9 FEM model with an equivalent diameter

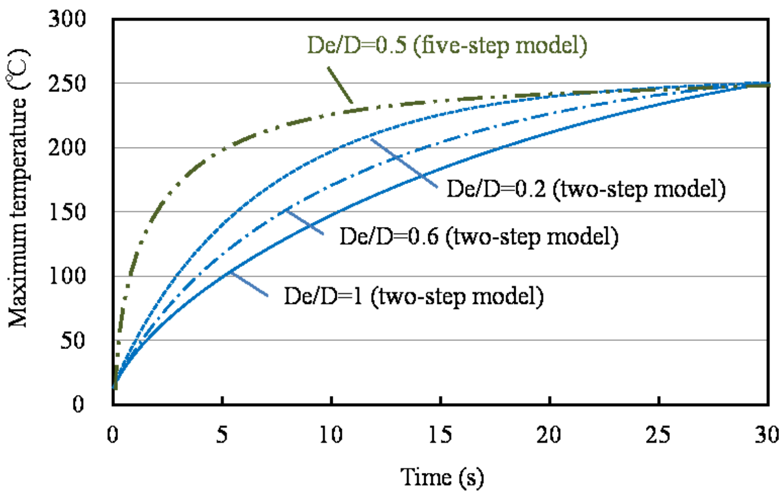

Fig. 10 Influence of equivalent diameter

Figure 10 shows the influence of equivalent diameter on the time constant. These are the results of a 10-mm-diameter tool and four cutting teeth. We found that responsiveness is improved as the equivalent diameter decreases. From Fig.10, the calculated results do not agree well with the experimental ones when a two-step model is used that has a constant equivalent diameter in the flute part. Thus, we used a five-step model with a multi diameter in the flute part as shown in Fig.9, and its

calculated results agree well with the experimental ones in Fig.6. The amount of heat input in the five-step model was set to 15.5W.
Figure 11 shows the influence of the number of teeth on tool temperature. Two-flute is the results when heat input is half of four-flute. They are almost the same as the results in Fig.6. Thus, the proposed monitoring method can enable estimation of the end-mill temperature.

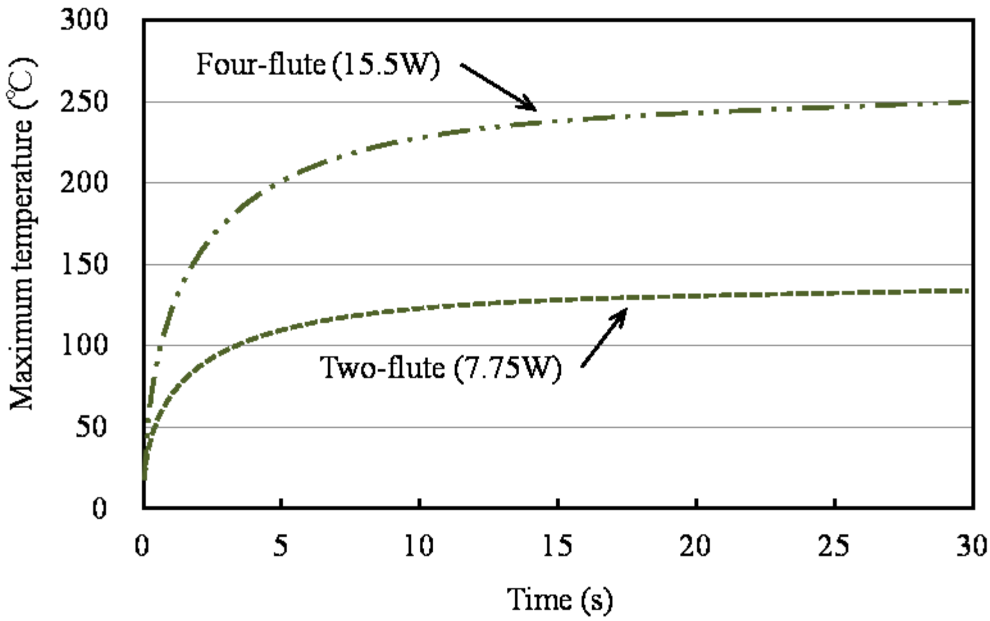

Fig. 11 Influence of number of teeth on tool temperature

Summary

We proposed a novel temperature monitoring method for end-mill process from infrared imagery with a high response and resolution infrared thermography to improve the processing of difficult-to-cut material. By comparing experimental results and analytical ones, these temperatures were confirmed to agree well. As a result, this method is found to be effective to estimate the tool temperature in the end-mill process sufficiently.

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