Measurement of tool temperature in burnishing using diamond tip

Masato OKADA*, Masayoshi SHINYA**, Hidetake TANAKA***
Naoki ASAKAWA**** and Masaaki OTSU*

*Faculty of Engineering, University of Fukui
3-9-1 Bunkyo, Fukui-shi, Fukui 910-8507, Japan
E-mail: okada_m@u-fukui.ac.jp

**Graduate School of Natural Science and Technology, Kanazawa University
Kakuma-machi, Kanazawa-shi, Ishikawa 920-1192, Japan

***Faculty of Science and Technology, Sophia University
7-1 Kioi-cho, Chiyoda-ku, Tokyo 102-8554, Japan

****Institute of Science and Technology, Kanazawa University
Kakuma-machi, Kanazawa-shi, Ishikawa 920-1192, Japan

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Abstract
This paper proposes a method for measuring the tool temperature during burnishing by using a diamond tip. The proposed method was used to examine the influence of tool wear behavior and burnishing conditions on the tool temperature. The experiment focused on the inner circumferential surface of a cylindrical geometric workpiece rotated by the main spindle of a lathe. The tool temperature was measured by using a two-color pyrometer with an optical fiber as a noncontact thermometer. An optical fiber was embedded in the workpiece in the radial direction, and it was rotated with the workpiece. The optical fiber accepted the infrared rays that radiated from the burnishing point of the diamond tip. Another optical fiber that was fixed on the outside of the lathe guided the accepted infrared rays to the two-color pyrometer. The accelerometer was fixed on the tool shank to detect the position of the burnishing point. The output pulses from the two-color pyrometer and accelerometer were stably observed during each rotation of the workpiece. The influence of the tool wear behavior on the tool temperature was observed. The tool temperature increased when the profile of the wear region of the diamond tip became rough. In contrast, the tool temperature decreased during the initial stage of burnishing. The circumferential speed of the target surface (burnishing speed) and the indentation force of the diamond tip on the target surface influenced the tool temperature.

Key words: Surface finishing, Burnishing, Diamond tip, Tool temperature, Two-color pyrometer

1. Introduction

A burnishing process that uses a ball, roller, and hemispherical tip as a tool is a micro-plastic forming method employed for generating smooth surfaces (Okada, et al., 2015). The method can also be expected to improve the abrasion resistance and fatigue strength of a target surface layer owing to work hardening and the creation of compressive residual stress. In addition, this method does not require dedicated equipment because it can be performed using the same machine tools as those commonly used for cutting. Diamond tip burnishing, which uses a hemispherical diamond tip as a tool, offers high processing efficiency for the burnishing of a hard material workpiece, compared to other processes such as grinding. Thus, various investigations on diamond burnishing have been performed. Konefal, et al. (2013) investigated the corrosion resistance of a burnished surface using the potentiodynamic method. Luo, et al. (2006) performed a study on the burnishing of aluminum alloy using a PCD tool experimentally and theoretically.

In diamond tip burnishing, the influence of the surface integrity of the top of a diamond tip that is in contact with a workpiece on a burnished surface roughness is very strong. Therefore, a study that concerns tool wear in diamond
burnishing has been reported (Korzynski, et al., 2011). In addition, the temperature at the contact point between the diamond tip and workpiece material is an important factor for determining diamond tip wear because diamond has characteristics such as oxidation under high-temperature and high-pressure atmosphere (Minton, et al., 2013). In particular, the diamond tip is subjected considerable wear owing to sliding with a ferrous material under high-temperature atmosphere (Shimada, et al., 2004). With diamond tip burnishing, however, it is very difficult to measure the tool temperature because of the amount of heat and size of the heated portion are very small. Moreover, the tool or workpiece is rotated by the main spindle of a machine tool. Furthermore, because the diamond tip is an electrical insulator, a tool-work thermocouple configuration cannot be applied.

The authors developed a two-color pyrometer with an optical fiber. The developed pyrometer has a high response speed of approximately 100 kHz and a small measurement area, which is almost equal to the diameter of the optical fiber, in contactless mode (Okada, et al., 2006). The authors clarified the influence of the coating film material and base material of the insert of the end mill on the tool flank temperature in hard milling using the developed two-color pyrometer (Okada, et al., 2011). The authors also investigated the cutting-edge temperature in drilling (Okada, et al., 2014a, 2014b). Moreover, Hosokawa et al. (2010) measured the tool temperature during turning using a rotary tool under MQL cutting, and Furumoto et al. (2015) measured the laser spot of a silicon wafer using the thermal stress cleaving technique.

In this paper, a method for measuring the temperature of a diamond tip during the burnishing process using a two-color pyrometer with an optical fiber is proposed. In addition, the influence of the tool wear behavior and burnishing conditions on the diamond tip temperature is investigated.

2. Experimental method
2.1 Diamond burnishing tool

Figures 1 (a) and (b) show the external view and schematic illustration of the diamond burnishing tool. This diamond burnishing tool is designed for processing the inner circumferential surface of a cylindrical workpiece. The diamond tip is fixed on the top of the diamond tip holder. A spring is located inside the main body of the tool, and it is linked to the diamond tip holder through a cam. Therefore, the indentation force of the diamond tip on the target surface can be controlled through the intended distance of the diamond tip to the target surface. The preload of the spring can be also controlled via the adjust bolt. Figure 2 shows a close-up view and schematic illustration of the diamond tip. The diamond tip has a hemi-spherical shape, and the tip radius is 1.5 mm.

![Diamond burnishing tool](image)

Fig. 1 External view and components of burnishing tool are shown. This tool is designed for processing the inner circumferential surface of cylindrical workpiece. A spring is built in the tool to control the indentation force of the diamond tip on the target surface.
Fig. 2 A close-up view of diamond tip is depicted. The diamond tip is fixed on the top of the diamond tip holder shown in Fig. 1. The diamond tip has a hemi-spherical shape, and its tip radius is 1.5 mm.

2.2 Two-color pyrometer with optical fiber

Figure 3 shows the schematic illustration of the two-color pyrometer with an optical fiber. In this pyrometer, the infrared rays radiated from the target surface are accepted and guided to the two-color detector by the optical fiber. The two-color detector is constructed using InAs and InSb photodetectors, and the infrared energy guided by the optical fiber is converted into electric signals as outputs of the two-color detector. These electric signals are amplified by the amplifier circuit, and two types of voltage output can be obtained. Using this two-color pyrometer, the changing of the emissivity of the measurement target during processing and influence of disturbance, such as oil mist, can be canceled by taking the ratio of the output pulses from the two-color detector. Therefore, the diamond tip temperature can also be measured, even when the diamond tip is undergoing wear. In addition, we confirmed that this pyrometer can detect the maximum temperature in the measurement area (Ueda, et al., 2001). The measurement area of the two-color pyrometer is determined by the core diameter of the optical fiber (\(\phi 500 \mu m\)), acceptance angle of the optical fiber (\(\varepsilon = 23.6^\circ\)), and distance between the end face of the optical fiber and target surface. Figure 4 shows the calibration curve of the two-color pyrometer obtained by the experimental values and the theoretical curve. The theoretical curve was calculated from the spectral sensitivity characteristics of the two-color detector. As shown in the figure, the precise calibration curve was obtained between 100 °C and 410 °C.

Fig. 3 The fundamental structure of the two-color pyrometer with an optical fiber is illustrated. The infrared rays radiated from the target object are accepted and led to the two-color detector by the optical fiber. The two-color detector converted the infrared energy to the electrical signal and the amplifier circuit amplified it.

Fig. 4 Calibration results of the two-color pyrometer are depicted. The calibration curve is obtained by the experimental values and the theoretical curve. The theoretical curve is calculated from the spectral sensitivity characteristics of the two-color detector.
2.3 Experimental setup

The setup for measuring the tool temperature is shown in Fig. 5. The inner circumferential surface of the cylindrical workpiece, rotated by the main spindle of the universal lathe, is the target object used in the experiment. The rotated probe, a small brass grooved pin that houses an optical fiber, is fixed to the workpiece in the radial direction, as shown in Figs. 6 (a) and (b). The diameter and groove width of the brass pin is φ3 mm and 1 mm, respectively. The position of the optical axis of the rotated probe is adjusted with the optical axis of the other optical fiber attached to the two-color pyrometer by an accurate positioning stage. Therefore, the infrared rays emitted from the burnishing point of the diamond tip are accepted by the rotated probe and transmitted to the other optical fiber through non-contact coupling. Thus, the infrared rays are transmitted to the pyrometer at the instant when the burnishing point, rotated probe, and optical fiber attached to the two-color pyrometer are aligned on the same axis. An accelerometer is mounted on the shank of the burnishing tool to detect the micro-vibrations caused by the diamond tip passing on the rotated probe. The electrical output from the accelerometer is amplified by the charge amplifier, and its output waveform is recorded by a data logger simultaneously with the waveform from the two-color pyrometer.

![Diagram of experimental setup](image_url)

Fig. 5 The experimental setup is depicted. The burnishing process focuses on the inner circumferential surface of the cylindrical workpiece. A universal lathe is used as a machine tool, and the universal lathe rotates the cylindrical workpiece. The burnishing tool is fed in the direction of the rotational axis of the workpiece rotation.
Fig. 6 The positional relationship of the diamond tip, the rotated probe, and the optical fiber attached to the pyrometer is depicted. As shown in (b), at the instant when the burnishing point, the optical fiber fixed on the brass grooved pin, and the optical fiber attached to the two-color pyrometer are aligned on same axis, the infrared rays radiated from the diamond tip are transmitted to the pyrometer.

2.4 Experimental conditions

Table 1 lists the experiment conditions. As a workpiece material, a hardened stainless steel JIS SUS420J2 with 53 HRC hardness is used. The hardened stainless steel has high hardness and low thermal conductivity, implying that the diamond tip temperature can be increased easily. The roughness of the preliminary surface of the diamond tip burnishing has a strong influence on the burnishing characteristics (Korzynski, 2007). Therefore, the roughness of the inner circumferential surface of the workpiece is arranged at approximately Ra = 1.0 μm by turning with a cBN tip. The inner and outer diameters of the workpiece are approximately 110 mm and 120 mm, respectively. The center of the rotated probe is positioned at 20 mm in the axial direction from the end face of the workpiece. The burnishing speed is defined as the circumferential speed of the inner surface of the workpiece, and it corresponds to the sliding speed between the inner surface of the workpiece and the diamond tip. The indentation force indicates the compressive force between the inner surface of the workpiece and the diamond tip, and it can be controlled by the method described in Section 2.1. The feed rate indicates the feed speed of the burnishing tool in the direction of the workpiece rotation axis. Lubrication is not supplied.

<table>
<thead>
<tr>
<th>Tool</th>
<th>Diamond tipped tool DT2D1, Sugino Machine Ltd., Tip radius R = 1.5 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Workpiece</td>
<td>Hardened stainless steel (JIS SUS420J2) 53HRC, Ra ≈ 1.0 μm</td>
</tr>
<tr>
<td>Burnishing speed</td>
<td>vb = 100, 150, 200 m/min</td>
</tr>
<tr>
<td>Indentation force</td>
<td>F = 90, 140, 180 N</td>
</tr>
<tr>
<td>Feed rate</td>
<td>f = 50 μm/rev</td>
</tr>
<tr>
<td>Lubrication</td>
<td>Dry</td>
</tr>
</tbody>
</table>
3. Verification of measurement of diamond tip temperature during burnishing process

Figures 7 (a)–(c) show the typical output waveform from the two-color pyrometer and accelerometer. Figure 7 (a) shows the entire view of the output waveform when the diamond tip passes on the rotated probe. Figure 7 (b) shows a close-up view of region A of (a), and Fig. 7 (c) shows a close-up view of region B of (b). The revolution speed of the workpiece and the feed rate of the burnishing tool were \( N = 590 \text{ min}^{-1} \) and \( f = 29.5 \text{ mm/min} \), respectively, and thus, the time required to complete one rotation of the workpiece was approximately 0.1 s; the diamond tip passes on the rotated probe multiple times during the burnishing process. The output pulses from the two-color pyrometer and accelerometer of each rotation of the workpiece were obtained at approximately \( \Delta t = 0.1 \text{ s} \), as shown in Fig. 7 (b). Therefore, it can be confirmed that the two-color pyrometer and accelerometer can detect infrared energy from the diamond tip and small vibrations during each rotation of the workpiece, respectively.

Figures 8 (a)–(c) show a schematic illustration of the cross section, from the perspective of the y-axis direction of the burnishing process while the diamond tip is passed on the rotated probe. Figures 9 (a) and (b) show the schematic illustration, from the perspective of the z-axis direction.

In region I in Fig. 7 (a), only the output pulses from the two-color pyrometer were observed, whereas those from the accelerometer were not observed. Accordingly, the positional relationship between the diamond tip and rotated probe in the tool feed direction of region I is shown in Fig. 8 (a). The reason for the output pulses being obtained from the two-color pyrometer regardless of whether the diamond tip passes on the rotated probe, as shown in Fig. 8 (a), is attributed to the influence of the reflection of the infrared rays radiated from the diamond tip. Therefore, the output pulses of region I in Fig. 7 (a) were omitted from the results of the temperature measurement. In region II in Fig. 7 (a), the output pulses from the accelerometer were observed with those from the two-color pyrometer. Therefore, the output pulses in this region corresponded to the output pulses when the diamond tip was passed on the rotated probe, as shown in Fig. 8 (b). The tool temperature was calculated using the 21 output pulses obtained from center of region II in Fig. 7 (a), from the two-color pyrometer. In addition, the output pulses from the two-color pyrometer of region III in Fig. 7 (a) corresponded to Fig. 8 (c). Consequently, the output pulses of region III were also omitted from the results of the temperature measurement for the same reason the output pulses of region I were omitted in Fig. 7 (a).

In point IV in Fig. 7 (c), the output from the two-color pyrometer was observed, and that from the accelerometer was not observed. Therefore, the moment of point IV corresponded to the positional relationship shown in Fig. 9 (a), and after that, it also corresponded to the positional relationship shown in Fig. 9 (b) because the output from the accelerometer was observed from the diamond tip passing on the groove of the brass pin. From these results, the positional relationship between the diamond tip and rotated probe can be identified through the above method, and the tool temperature during the burnishing process can be measured accurately.
Fig. 7  The typical output waveforms from the two-color pyrometer and accelerometer are shown. The periodic output pulses are obtained from the two-color detector and accelerometer. The pulses have frequencies based on the time required to complete a rotation of the workpiece.

Fig. 8  The positional relationship between the rotated probe and diamond tip from the perspective of y-axis is shown. As the burnishing process progresses, the diamond tip passes on the rotated probe and through the light-receiving region of the optical fiber fixed on the brass-grooved pin.
Fig. 9  The positional relationship between the rotated probe and the diamond tip from the perspective of z-axis is illustrated. At every workpiece rotation, the rotated probe passes on the diamond tip. The rotated probe accepts infrared rays from the diamond tip as it passes on it, and generates micro vibrations.

4. Experimental results and discussion

4.1 Tool temperature variation during each rotation of workpiece

Figure 10 shows the tool temperature $\theta$ in 21 rotations of the workpiece, and the 0 in the axis representing the number of workpiece rotations shows the moment when the diamond tip passes on the center of the rotated probe in the tool feed direction, as shown in Fig. 8 (b). With respect to the burnishing conditions, the burnishing speed, the indentation force, and the burnishing length were set as $v_b = 200$ m/min, $F = 140$ N, and $L_b = 250$ m, respectively. The burnishing length $L_b$ is defined as total sliding distance between the diamond tip and the target surface. The distance between the center of the rotated probe and the start point of the burnishing in tool feed direction was 13mm. During each rotation of the workpiece, the mean, the maximum, and the minimum values of tool temperature $\theta$ were 155 °C, 167 °C and 140 °C, respectively. In this case, the standard deviation of the results shown in Fig. 10 is 6.9 °C.

![Graph showing tool temperature variation](image)

**Fig. 10**  The tool temperature variation during each rotation of the workpiece is shown. The tool temperatures across 21 rotations of the workpiece are measured. The moment when the diamond tip passes on the center of the rotated probe in the tool feed direction is indicated by 0 on the axis representing the number of workpiece rotations.

4.2 Tool temperature and tool wear behavior during progress of burnishing length

Figure 11 shows the influence of the burnishing length $L_b$ on the diamond tip temperature $\theta$. Figures 12 (a)–(e) show a close-up view of the sliding point of the diamond tip for each burnishing length. Figures 13 (a)–(e) show the profile curve of the burnished surface for each burnishing length. The burnishing conditions, $v_b = 200$ m/min, $F = 140$ N, and $f = 50$ $\mu$m/rev were employed in this study, and the tool temperature values shown in Fig. 11 were calculated by the averaged value of 21 pulse outputs when the diamond tip passes on the optical fiber of the rotated probe, as shown in Fig. 10. The diamond tip chipped at $L_b = 1500$ m, as shown in Fig. 12 (e). From Fig. 11, we observe that $\theta$ decreases with increasing $L_b$. However, $\theta$ increases with $L_b$ beyond $L_b = 500$ m. From Fig. 12, we observe the wear region caused by sliding with the target surface from $L_b = 250$ m, and the scratch marks in the wear region in the rotational direction of the workpiece material become clear and are magnified with an increase in $L_b$. From Fig. 13, we observe that the profile curve of the burnished surface deteriorates as $L_b$ increases, and fine irregularities are noticeable at $L_b = 1470$ m, which is
prior to the fracture of the diamond tip. The fine irregularities at \(L_b = 1470\) m were due to the transfer of the scratch marks in the wear region of the diamond tip. From these results, we infer that the increase in the diamond tip temperature after \(L_b = 500\) m was due to micro-cutting generated at the burnishing point because of the formation of fine irregularities on the wear region of the diamond tip. Conversely, it can be seen that the change of the contact pressure, the frictional area, and the thermal conductive condition between the diamond tip and target surface resulted in the decreasing tendency of the diamond tip temperature before approximately \(L_b = 500\) m. This was because the burnishing point of the diamond tip was flattened by the wear progress. From these results, we deduce that the proposed measurement method can accurately measure tool temperature during the burnishing process. In addition, the tool life of the diamond tip was approximately \(L_b = 1500\) m in this experiment, which is very short. The hard burnishing conditions such as high burnishing speed, hard workpiece material, and no lubricant application resulted in the abrasive wear as shown in Figs. 12 (b)–(d). However, the diamond tip fracture observed in the crack and chipping that determined the tool life at \(L_b = 1500\) m was due to the impact behavior that occurred when the diamond tip was passed on the rotated probe. The diamond tip used in the experiment shown in Fig. 11 fractured when it passed on the rotated probe. Therefore, it is important to recognize that this method influences shortened tool life through the diamond tip fracture. However, the burnishing process was performed normally otherwise when passing around the rotated probe because an improvement in the surface roughness is obtained when the profile curve before and after burnishing was compared as shown in Figs. 13 (b)–(e). Moreover, the influence of the impact behavior on the abrasive wear behavior of the diamond tip was negligible because the abrasive wear as shown in Figs. 12 (b)–(d) was also observed in the case when the target surface was used without the probe.

![Fig. 11](image)

**Fig. 11** The relationship between the burnishing length and the tool temperature is shown. The tool temperature increases with increases in the burnishing length beyond approximately \(L_b = 500\) m. However, the tool temperature decreases with burnishing length below \(L_b = 500\) m. The diamond tip fractures when the burnishing length reaches \(L_b = 1500\) m.
Fig. 12  The wear behavior of the diamond tip for each burnishing length is shown. Abrasive wear is observed below $L_b = 1000$ m. The wear area increases with the burnishing length. Scratch marks in the sliding direction with the workpiece are observed on the wear region.

Fig. 13  The surface profiles of the preliminary surface and the burnished surface for each burnishing length are shown. The surface profiles are measured in the axial direction of the workpiece. Fine irregularities can be observed as the burnishing length increases.
4.3 Influence of burnishing conditions on tool temperature

Figure 14 (a) shows the relationship between burnishing speed \( v_b \) and tool temperature \( \theta \), and Fig. 14 (b) shows the relationship between indentation force \( F \) and tool temperature \( \theta \). Error bars are shown in both figures. A diamond tip was used when the burnishing length was approximately \( L_b = 250 \) m. The influence of \( v_b \) and \( F \) on \( \theta \) was clearly observed, and \( \theta \) increased along with \( v_b \) and \( F \). The tool temperature \( \theta \) in either burnishing conditions was distributed at approximately 125-180 °C. The burnishing speed \( v_b \) is directly related to the sliding speed between the diamond tip and target surface. Therefore, the increase in tool temperature with an increase in burnishing speed was caused by increasing the frictional heat. Similarly, the indentation force is directly connected to the contact pressure between the diamond tip and target surface. From these results, we derive that the burnishing speed and indentation force influence the tool temperature strongly, and that the tool temperature is lower than 200 °C, unless there is no tool wear progress.

![Figure 14](image)

(a) Influence of burnishing speed  
(b) Influence of indentation force

Fig. 14 The relationship between the burnishing conditions and the tool temperature is illustrated. Each plot also shows the error bars obtained by 21 output pulses from the pyrometer. The tool temperature increases with the burnishing speed and indentation force.

5. Conclusions

This study proposed a method for measuring the tool temperature during burnishing with a diamond tip and investigated the influence of tool wear behavior and burnishing conditions on tool temperature. The temperature of the diamond tip when burnishing the inner surface of a cylindrical workpiece was measured using a two-color pyrometer with an optical fiber because the optical fiber was set in the radial direction of the workpiece as a rotated probe. The positional relationship between the diamond tip and rotated probe was also identified; this relationship was used to confirm that the proposed method could measure the tool temperature during each rotation of the workpiece. The tool temperature increased when the surface profile of the burnishing point on the diamond tip became rough, although the tool temperature decreased as tool wear progressed. The tool temperature was also strongly influenced by the burnishing conditions of burnishing speed and indentation force, and the tool temperature increased with an increase in the burnishing speed and indentation force.

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