Improvement of Removal Amount Estimation Method in Multistage Superfinishing of Sapphire

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Abstract. In this study, high accuracy and high efficiency processing of sapphire was investigated. In order to attain the target surface roughness 2 nmRa equivalent to lapping process, multistage superfinishing with plural diamond superabrasive stones was carried out. In our past work, superfinishing with four different grain size stones was examined. The multistage process was capable of producing surface roughness of 2 nmRa in 8 min. To improve multistage superfinishing, removal amount estimation method considering elastic deformation during superfinishing was developed. However, measured removal amount in long time superfinishing was smaller than that of estimated amount. It was considered that superfinishing efficiency decreased after pre-finished surface roughness was removed. Therefore, removal amount estimation method was improved by changing removal amount estimation formula after removing total height of roughness profile Rt of pre-finished surface. Results indicated that estimated removal amount approximated to the measured amount in long time superfinishing with SD20000 stone.

Introduction

Sapphire is used as LED substrate because of its excellent optical, chemical and mechanical properties [1]. Major processing method of sapphire is lapping and polishing, and those methods take a long time because sapphire is hard [2-3].

In this study, superfinishing with diamond superabrasive stones was carried out to improve accuracy and efficiency of sapphire processing. In our past work [4], multistage superfinishing with four different grain size diamond superabrasive stones was examined. The multistage process was capable of producing surface roughness of 2 nmRa equivalent to lapping process in 8 min. In our past study [5], removal amount estimation method was also developed to apply Preston’s empirical rule to superfinishing process. Removal amount was estimated in consideration of elastic deformation of stone and contact area ratio of sapphire to calculate working area ratio of stone. The removal of SSD required removal amount of 1.6 times of total height of the roughness profile Rt from our past experiments [6].

In this study, long time superfinishing for removing double amount of Rt of pre-finished surface was carried out. However, measured removal amount was smaller than that of estimated amount. It was considered that superfinishing efficiency decreased after pre-finished surface roughness was removed. Therefore, removal amount estimation method was improved.

Materials and methods

Fig. 1 shows centerless flat superfinishing machine (SEIBU JIDO KIKI, STK-50FSC). The workpiece was supported by two rollers and a shoe system. The diameter of the workpiece was 30 mm.
The diameter of the stone was 50 mm, and 25 segments, each 5 × 5 mm, were arrayed on the circumference of the 50-mm circle. The workpiece was face-finished by the rotating abrasive stone with oscillating motion. Table 1 shows experimental conditions.

Removal amount estimation method was used as follows. Removal amount was estimated using the following equation:

\[ q(t) = k \cdot v \cdot \Delta t \cdot \sum_{r=0}^{t} \left[ \frac{P_S}{\eta(\tau) \cdot tp(q(\tau))} - P_{RC} \right] \]  

(1)

where \( q(t) \) denotes the removal amount, \( k \) is the proportionality constant, \( v \) is the superfinishing velocity, \( \Delta t \) is infinitesimal time interval, \( P_S \) is the stone pressure, \( \eta \) is the working area ratio of stone, \( tp \) is the load length ratio, and \( P_{RC} \) is the critical real contact pressure. Estimated proportionality constant \( k \) and the critical real contact pressure \( P_{RC} \) for each stone are shown in Table 2. Fig. 2 and Fig. 3 show the changes in the working area ratio \( \eta \) and the load length ratio \( tp \) during superfinishing.
respectively. The working area ratio for each stone was approximated linearly from the measured value because the changes were small. The load length ratio for each stone was estimated from the cutting level of \( q + d \), where \( d \) is the depth of cut of each stone. The load length ratio during superfinishing increased as the removal amount increased. In the process of SD2000, the removal amount was set to 5 μm by considering deep scratches of pre-finishing. Relationship between superfinishing time and the estimated removal amount is shown in Fig. 4. Superfinishing time was determined at the estimated removal amount of 5 μm in the process of SD2000. In the processes after

![Graphs showing working area ratio and load length ratio](attachment:image1.png)

Fig. 2. Working area ratio during superfinishing with each stone.
SD4000, the removal amount was set to double amount of Rt of pre-finished surface. Fig. 4 (b), (c) and (d) show the estimated removal amount in each process of SD4000, SD6000, and SD20000, respectively. Table 1 shows the estimated superfinishing time of each stone equivalent to the above-mentioned removal amount.

Fig.3. Change in load length ratio of the sapphire during superfinishing with each stone.

Fig.4. Estimated removal amount with each stone.
Table 3 Parameters used for modified removal amount estimation method.

<table>
<thead>
<tr>
<th>Stone</th>
<th>SD2000</th>
<th>SD4000</th>
<th>SD6000</th>
<th>SD20000</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k_1$ [mm$^2$/N]</td>
<td>4001</td>
<td>360</td>
<td>96</td>
<td>40</td>
</tr>
<tr>
<td>$k_2$ [mm$^2$/N]</td>
<td>3693</td>
<td>290</td>
<td>75</td>
<td>15</td>
</tr>
<tr>
<td>$P_{RC}$ [MPa]</td>
<td>36.1</td>
<td>49.1</td>
<td>33.5</td>
<td>48.0</td>
</tr>
</tbody>
</table>

Fig. 5. Surface roughness in multistage superfinishing of sapphire.

Fig. 6. Removal amount in multistage superfinishing of sapphire.

Fig. 7. Comparison of removal amount by conventional and proposed method with each stone.
Results and discussion

Fig. 5 shows surface roughness Ra in multistage superfinishing of the sapphire. The multistage process was capable of producing less than 2 nm Ra, equivalent to a lapped surface. Fig. 6 shows the estimated removal amount and measured value of each stone. Measured removal amounts of SD2000 stone and SD4000 stone were much larger than estimated amounts. It was considered that fracturing of stones occurred continuously and removal amounts became larger because these processes exceeded the critical pressures. In superfinishing with SD6000 stone, less than the critical pressure, the measured value was almost the same as the estimated one. In the process of SD20000 stone, though which was also less than the critical pressure, the measured value was larger at 60 s and smaller at 300 s. It was thought that after pre-finished surface roughness was removed, real contact pressure decreased and superfinishing efficiency decreased considerably. Therefore, modification of the removal amount estimation method was required after pre-finished surface roughness was removed.

Improvement of removal amount estimation method

Equation (1) was revised to estimate the removal amount properly before and after total height of roughness profile Rt was removed. The proportionality constant $k_1$ was used until removal amount $q$ reached Rt. Until then, roughness of pre-finished surface remained on the surface. After removal amount $q$ reached Rt, the proportionality constant was changed to $k_2$. After that, scratches with each stone will remain. Modified equations corresponding to two states are as follows:

$$q(t) = k_1 \cdot v \cdot \Delta t \cdot \sum_{\tau=0}^{t} \left[ \frac{P_s}{\eta(\tau) \cdot tp(q(\tau))} - P_{RC} \right] \quad (q < Rt) \quad (2)$$

$$q(t) = k_2 \cdot v \cdot \Delta t \cdot \sum_{\tau=0}^{t} \left[ \frac{P_s}{\eta(\tau) \cdot tp(q(\tau))} - P_{RC} \right] \quad (q \geq Rt) \quad (3)$$

In order to estimate the removal amount in equations (2) and (3), $k_1$, $k_2$ and $P_{RC}$ were determined so that the difference between measured value and the estimated value became minimum. Table 3 shows determined proportionality constant $k_1$, $k_2$ and the critical real contact pressure $P_{RC}$ of each stone. Fig. 7 shows comparison of estimated removal amount by conventional method and proposed method with each stone. In SD2000, SD4000, and SD6000 stone, $k_1$ and $k_2$ relatively close. On the other hand, in the process of SD20000 stone, $k_2$ was smaller than the half of $k_1$. As a result, the estimated value approximated to the measured value.

Conclusions

To improve multistage superfinishing of sapphire with vitrified-bonded diamond superabrasive stones, a long time superfinishing was carried out and the removal amount estimation method was modified.

The constant values used for the removal estimation method were renewed after the estimated removal amount reached pre-finished roughness Rt. In the process of SD20000 stone, modified value of estimated removal amount approximated to the measured amount, and simulations for longer superfinishing became possible.

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References


