Experimental Study on ELID Grinding of Silicon Nitride Ceramics for G5 Class Bearing Balls

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Abstract: This study has focused on analyzing the impact of material characteristics and grinding conditions on the surface roughness in ELID grinding of ceramic materials intended for bearing balls. The main research objective was to examine the feasibility of achieving the required surface roughness for G5 class bearing balls through a high-efficiency and high-precision ELID grinding process. Three types of silicon nitride specimens and two types of grinding wheels with cBN and diamond abrasives were prepared for the experiments. An HP (high-pressure) specimen was fabricated through high-temperature and high-pressure sintering at 1700 °C for 2 h, containing a composition of Y2O3 and MgO in Si3N4, while GPS 1hr and GPS 6hr specimens were prepared using gas-pressure sintering for 1 h and 6 h, respectively. From the experimental results, it has been confirmed through surface morphology and surface roughness analysis that material characteristics and grinding parameters affect the surface roughness of silicon nitride ceramics during the grinding process. The surface ground with a #2000 diamond wheel is at a level that can satisfy the required surface roughness, 0.014 um or less in G5 class bearing balls. Based on the analysis of surface morphology and roughness in grinding processes, the #325 cBN wheel exhibited excellent performance in rough grinding, while the #2000 diamond wheel demonstrated highly effective surface finishing performance, indicating that the combination of these two abrasives can be effectively utilized for high-efficiency and high-precision nanosurface machining of silicon nitride ceramics.

Keywords: surface roughness; ball bearing; silicon nitride (Si3N4); ELID grinding; nanosurface

1. Introduction

Silicon nitride (Si3N4) is a prominent non-oxide ceramic material known for its advantageous properties. It has a low density, making it lightweight, and its coefficient of thermal expansion is similar to that of silicon. Silicon nitride exhibits high strength, hardness, and fracture toughness, along with excellent resistance to wear, oxidation, thermal shock, and thermal fatigue. These outstanding mechanical, thermal, and chemical characteristics make it a versatile material suitable for structural components and electronics applications. Silicon nitride is a functional material with exceptional mechanical, physical, and chemical properties, and it holds significant potential for a wide range of applications, including extreme environmental conditions, making it a material with immense future prospects. As a structural material, silicon nitride boasts outstanding properties such as high strength, hardness, chemical stability, high-temperature strength, wear resistance, thermal conductivity, and a low coefficient of thermal expansion. It finds extensive applications in various fields, including power electronics components for electric vehicles, heat sinks, automotive bearings, semiconductors, and aerospace components [1]. Silicon nitride has been developed as hypersonic guided munition material, leveraging its excellent dielectric properties, mechanical strength, thermal shock resistance, and particle erosion resistance [2]. As an
electrical and electronic material, silicon nitride (Si$_3$N$_4$) is expected to find applications in the semiconductor industry, particularly in the production of next-generation memories such as DRAM (dynamic random access memory) and flash memory. It is anticipated to be used in a thin-film format, serving as an insulating layer, passivation treatment, diffusion prevention mask, and more [3]. Research has also been conducted to improve the adhesion of the electrode layer when forming it through a wet process on silicon nitride ceramic substrates, which exhibit excellent electrical properties and high thermal conductivity [4]. Silicon nitride is also known to be a suitable ceramic material for bearing applications due to its favorable mechanical and physical properties, as well as its reliability in terms of rolling fatigue life [5–10]. It exhibits excellent material characteristics such as high density, strength, and heat resistance. When used as a rolling element in bearings, silicon nitride reduces centrifugal load owing to its low density and enhances bearing rigidity due to its low elastic modulus [10]. Moreover, its outstanding friction characteristics lead to low heat generation and a low coefficient of thermal expansion. However, it is essential to note that silicon nitride is a challenging material to sinter due to thermal decomposition at high temperatures and its low diffusion coefficient with a 70% strong covalent bonding ratio. The densification of silicon nitride ceramics occurs through the reaction of silica on the surface of silicon nitride particles, resulting in the formation of a low-melting liquid phase. During the densification process, the liquid phase generated at the grain boundaries remains in an amorphous glassy phase after cooling. This phenomenon significantly influences the growth, fracture toughness, and high-temperature properties of silicon nitride crystals, leading to a deterioration of silicon nitride’s properties. The rolling fatigue life of silicon nitride is improved when it possesses a uniform and small particle microstructure with no pores and secondary phases, as well as fewer grain boundary phases [11–13]. Recent research has been focused on low-temperature densification sintering to achieve a uniform fine particle structure, aiming to enhance mechanical properties such as wear resistance, strength, and hardness, which are crucial for bearing rolling components. To increase the strength reliability of silicon nitride ceramics for bearing balls, three types of hot-press sintering processes were proposed. Additionally, the correlation between the microstructure and strength reliability was studied to produce high-density and high-strength silicon nitride [14]. Ceramic removal machining techniques are categorized into three main methods: fixed abrasive processing utilizing grinding wheels, flow abrasive processing using abrasive slurry, and high-energy special processing employing laser or discharge phenomena. Fixed abrasive processing is a machining method that can achieve a high material removal rate and excellent shape accuracy. However, it has the disadvantage of frequently causing brittle fracture due to the aggravation of surface damage during the process. Flow abrasive processing is another machining method primarily used for ceramics, as it causes minimal surface damage [15–18]. Nevertheless, it suffers from a low material removal rate, difficulty in controlling shape accuracy, and extended processing time. On the other hand, high-energy special processing is not suitable for ceramic parts requiring high shape precision and surface quality, such as ceramic bearing balls. This is because the severe degree of thermal surface damage and the complexity of controlling shape accuracy pose challenges. Ceramic bearing balls are classified into 11 grades, ranging from G3 to G200, depending on their shape and surface roughness levels [19]. G5 class ceramic bearing balls demand high shape accuracy and surface roughness, with a ball diameter variation and spherical deviation of 0.13 um or less, and a surface roughness of 0.014 Ra or less. To efficiently process brittle materials with high shape accuracy and surface quality, it is crucial to adopt processing technology that reduces processing time while achieving an excellent surface without surface damage [20]. Electrolytic In-process Dressing (ELID) grinding [15,21–24] is well suited for high-precision processing of brittle materials such as ceramic ball bearings. It combines the advantages of fixed abrasive processing with a high material removal rate and excellent shape accuracy, and flow abrasive processing, which offers superior surface roughness and low surface damage [25–27]. The ELID grinding method involves the generation of pulsed power in the electrolytic power supply, accompa-
nied by a non-linear electrolytic phenomenon, to achieve continuous dressing during the grinding process. This balances the electrolytic characteristics of the metal bond grinding wheel and the passivation of the oxidized layer. Due to the electrolytic phenomenon, the binder in the wheel oxidizes, allowing the abrasives to protrude. In this electrolytic process, after the dissolution of a few micrometers, an insulating layer rapidly forms on the surface of the grinding wheel due to the generation of ferrous hydroxide and ferric oxide passivating agents, effectively preventing excessive dissolution. As grinding commences, the workpiece comes into contact with the passivated layer, causing it to be gradually removed as the grinding wheel wears. Consequently, the insulating properties of the passivated layer diminish, leading to the redissolution of the binder and the repeated exposure of abrasive particles, resulting in continuous dressing. This cyclic process is referred to as the ELID cycle. The continuous dressing effect during grinding has a significant impact on the machining of brittle materials such as ceramics because it helps maintain a consistent grinding pressure, significantly reducing the maximum grinding force [21,22,24]. This study conducted basic grinding experiments using ELID grinding technology to achieve the required surface roughness for silicon nitride ceramic bearing balls. The impact of material properties and grinding parameters on the surface quality of ground silicon nitride ceramics was investigated and compared through the assessment of surface defects and surface roughness.

2. Materials and Methods

Surface defects that occur during the ceramic grinding process are a result of brittle fracture caused by an increase in cutting force. Therefore, it is necessary to perform surface grinding at a low and constant cutting force to eliminate these defects. The gradual increase in cutting force during the grinding process is caused by the loading phenomenon. Hence, performing periodic dressing to remove chips before loading occurs is essential. However, the time loss incurred by dressing work is substantial, and determining the periodicity of the dressing cycle proves to be highly challenging due to its variation depending on the grinding conditions. ELID grinding is well suited for surface machining of brittle materials such as ceramics because it maintains a low and constant cutting force, preventing the occurrence of the loading phenomenon and eliminating the need for separate dressing work due to the continuous dressing effect during grinding [21–24]. In this study, separate ELID grinding experiments were conducted to analyze both the impact of silicon nitride ceramics’ properties on the ground surface and the influence of grinding conditions on the ground surface. The evaluation of the ground surface was divided into two categories: a quantitative evaluation, achieved through the measurement of surface roughness, and a qualitative evaluation, performed by analyzing surface photographs using a surface magnifying microscope [28–31] and FE-SEM (Field Emission Scanning Electron Microscope) device.

2.1. Specimens of Silicon Nitride

Three types of silicon nitride ceramic specimens were prepared for the experiment: HP, GPS 1hr, and GPS 6hr. The hot-pressed (HP) specimen has a composition of $\text{Si}_3\text{N}_4 + \text{Y}_2\text{O}_3$ (2 wt.%) + MgO (5 wt.%) and was sintered under high-temperature and high-pressure conditions at 1700 °C for 2 h. The gas-pressure-sintered (GPS) specimens were created by subjecting the HP specimens to additional gas-pressure sintering at 1900 °C for 1 h and 6 h, resulting in two types of specimens: GPS 1hr and GPS 6hr. These specimens were prepared to analyze the effect of material properties on the ground surface. In general, as the gas-pressure sintering time increases, the particles tend to agglomerate, and the porosity content becomes more significant. Figure 1 shows the surface images of each specimen captured using an FE-SEM device. In the HP specimens, it is difficult to observe the presence of pores, and the particle size is relatively small. However, as the gas-pressure sintering time increases in GPS specimens, it can be observed that the particle sizes become larger, and the porosity content ratio increases. Figure 2 shows the results of measuring material properties and sintered particle sizes for each specimen. The particle size of the
HP specimen was the smallest, and its fracture toughness and flexural strength were higher than the others.

![Figure 1. FE-SEM image of specimens’ surface structure for experiments.](image1)

(a) Fracture toughness and flexural strength  
(b) Particle size

Figure 2. Material test results for: (a) material properties, (b) particle size of specimens.

The starting Si$_3$N$_4$ powder (E10, UBE Corporation, Japan, $D_{50} = 0.3$ $\mu$m) was mixed with two sintering additives, MgO (Sigma-Aldrich, $D_{50} < 0.1$ $\mu$m) and Y$_2$O$_3$ (Grade C, H.C. Starck, Germany, $D_{50} = 0.9$ $\mu$m), via the ball-milling process. The mixing media was Si$_3$N$_4$ ball (Nikkato, Japan, Diameter = 5 mm), and the liquid medium for mixing was anhydrous ethanol. The microstructural difference was from the material loss by the reaction between Si$_3$N$_4$ and grain boundary phases, SiO$_2$-based amorphous glass. At high temperatures over 1500 °C, Si$_3$N$_4$ is prone to react with SiO$_2$ to produce a gaseous phase, which induces the material loss from the Si$_3$N$_4$ body [32]. As a result of the prolonged heat treatment at a higher temperature, the above reaction also keeps going to further weight loss. The as-hot-pressed Si$_3$N$_4$ sample was sintered under the confined mold to prevent outgassing of SiO(g) and N$_2$(g), a by-product of the reaction (1). However, during the heat treatment in the GPS furnace at 1900 °C, the Si$_3$N$_4$ samples are exposed to atmosphere without any protection. Hence, the material loss occurred via producing the resultant gases, so a number of pores were generated in the sintered Si$_3$N$_4$ bodies. Moreover, the weight loss of the heat-treated Si$_3$N$_4$ was measured as 0.88, 1.76, and 2.49 wt % for increased soaking duration from 1, 3, and 6 h, respectively. The trend of increasing weight loss is consistent with the expected result from the reaction (1), and the microstructural evolution of increasing the number of pores can be rationalized. For sintered Si$_3$N$_4$ ceramics, the mechanical properties such as flexural strength and fracture toughness are strongly dependent on the microstructure. Typically, the distinct bimodal distribution of grain size is advantageous for enhancing the flexural strength as well as the fracture toughness [33]. The HPed Si$_3$N$_4$, with higher strength and toughness, has distinct bimodal distribution of grain size, whereas the microstructure of heat-treated Si$_3$N$_4$, with lower strength and toughness, shows all the enlarged grains with a thick columnar shape. This phenomenon is well matched with those of the above reference, that the crack propagation can be effectively deflected along the grain boundary of randomly distributed columnar grains, but the crack propagation can be relatively
straightforward for too-enlarged grains. Moreover, the pores generated from the material loss by reaction (1) can act as critical flaws which degrade the mechanical properties.

\[
\text{Si}_3\text{N}_4(s) + 3\text{SiO}_2(s) \rightarrow 6\text{SiO}(g) + 2\text{N}_2(g) \quad (1)
\]

2.2. Experimental Conditions

This study conducted experiments on the grinding characteristics of silicon nitride ceramics for three types of silicon nitride specimens under limited grinding conditions, specifically, the depth of cut (hereafter referred to as DOC), grit number of the grinding wheel, and type of abrasive. The grinding conditions, including the rotational speed of the grinding wheel and rotary table, feed rate, and the ELID conditions, such as current, voltage, and duty ratio, were predefined for this research. As shown in Figure 3, the experimental setup for ELID grinding was assembled on a conventional reciprocating grinding machine, incorporating an ELID power supply and monitoring system. The specimens were securely fixed on the rotary table and rotated during the process. Metal-bonded diamond wheels and cBN (cubic boron nitride) wheels with a diameter of 162 mm were employed for the experiment, utilizing grit sizes #325, #1200, and #2000 for each wheel type. The DOC conditions for the experiment were selected based on the grit size of the grinding wheels, as indicated in Table 1. The rotational speeds of the grinding wheels and the rotary table were set at 1900 rpm and 100 rpm, respectively. Additionally, the vertical feed rate of the grinding wheel was set at 84 mm/min, considering the width of the grinding wheel.

![Figure 3. Setup for ELID grinding experiments and schematic diagram for the grinding process.](image)

Table 1. Depth of cut (DOC) for ELID grinding experiments.

<table>
<thead>
<tr>
<th>Abrasives</th>
<th>Grit Size</th>
<th>DOC, (d) (µm)</th>
<th>Number of DOC</th>
<th>Total DOC, (g) (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diamond and cBN</td>
<td>#325</td>
<td>10</td>
<td>5</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6</td>
<td>5</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>#1200</td>
<td>4</td>
<td>5</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>5</td>
<td>10</td>
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<tr>
<td></td>
<td></td>
<td>1</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>#2000</td>
<td>2</td>
<td>5</td>
<td>10</td>
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<td></td>
<td></td>
<td>1</td>
<td>5</td>
<td>5</td>
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<tr>
<td></td>
<td></td>
<td>0.5</td>
<td>5</td>
<td>2.5</td>
</tr>
</tbody>
</table>

2.3. Measurements and Devices

Surface roughness measurements were conducted using a surface profilometer (Taly-surf series 2, Taylor Hobson). Qualitative analyses were performed using an FE-SEM and
an optical microscope. The surface roughness measurements were taken by moving the probe in the perpendicular direction to the grinding direction, with 9 repeated measurements at each location on the specimen. The maximum, minimum, and average values were compared to assess the surface roughness. For evaluating the fracture toughness of ceramic materials, the Indentation Fracture (IF) method was employed [34]. The IF method determines the fracture toughness by evaluating the size of cracks formed by indenting a Vickers hardness indenter (Mitutoyo) under an applied load. This method is particularly valuable for measuring the fracture toughness of small and brittle materials, as it enables the assessment of crack growth reactions in a highly localized range. Figure 4 presents the images of the test results for each specimen. The fracture toughness \( K_{IC} \) of brittle materials can be expressed using Equation (2), which relates the critical crack length \( a \), fracture stress \( \sigma_f \), and geometric coefficient \( Y \). When the critical crack length is the same, fracture stress is proportional to the fracture toughness.

\[
K_{IC} = Y \sigma_f (\pi a)^{1/2}
\]  

(2)

![Figure 4. Measurement of fracture toughness by indentation fracture method.](image)

3. Ground Surface Morphology

Ground surface morphology analysis is valuable for evaluating the condition of ground surfaces. To investigate the ground surfaces, ELID grinding experiments were conducted under uniform conditions, maintaining a fixed initial DOC of 2 \( \mu \)m (total DOC: 10 \( \mu \)m). Each experiment involved performing ELID grinding with different abrasive sizes, types of abrasive, and workpiece materials. The ground surfaces were meticulously examined and subjected to comparative analysis using optical microscopy and FE-SEM imaging. In general, ground surfaces exhibit two primary machining modes: ductile mode and brittle mode. Ductile mode machining results in smooth cutting surfaces, with the traces of the abrasive path faithfully replicated, making surface roughness prediction relatively straightforward. In the case of larger abrasive sizes, distinct peaks and valleys align with the direction of abrasive movement, while exceedingly small abrasive sizes yield an exceptionally smooth surface, making it challenging to differentiate between peaks and valleys. On the other hand, brittle mode machining results in irregular and random grinding marks, arising from the brittle fracture of the material within transgranular or intergranular regions. Particularly with larger abrasive sizes, the grinding marks are discontinuous with the direction of abrasive advancement, and the height difference between peaks and valleys is significant, making them relatively easy to identify. Ground surfaces demonstrate a combination of both ductile and brittle mode machining, with the proportions varying significantly based on factors such as abrasive size, type, grinding conditions, and workpiece material characteristics. Notably, grinding wheels with larger abrasive sizes exhibit a relatively higher proportion of brittle mode surfaces. As described, the ground surfaces of each experimental specimen were subjected to a comparative analysis using ground surface morphology images.
3.1. Grinding Marks and Traces

Table 2 presents a compilation of microscopic surface images captured from the ELID-ground surface. The ground surface of the #325 grinding wheel (Table 2, images a to f) exhibited the most distinct grinding marks along the direction of abrasive movement. For the #1200 grinding wheel’s ground surface (Table 2, images g to l), there were also some visible grinding marks, but they appeared significantly fainter compared to the #325 grinding wheel. As for the #2000 grinding wheel’s ground surface (Table 2, images m to r), it was challenging to identify grinding marks along the overall direction of the abrasive movement. In the case of the cBN grinding wheel’s ground surface (Table 2, images p and q), localized areas that were presumed to be grinding marks were found.

3.2. Ductile Mode and Brittle Mode

The ground surface of the #325 grinding wheel on the HP specimen (Table 2, images a,d) exhibited a relatively higher proportion of ductile mode machining surfaces. In contrast, for the GPS specimens (Table 2, images b–f), the proportion of brittle mode machining surfaces gradually increased with longer sintering times. The traces of peaks and valleys were more pronounced on the ground surface of the diamond abrasive (Table 2, images a–c) compared to the cBN abrasive’s ground surface. A similar observation was made for the #1200 grinding wheel’s ground surface; however, the traces of peaks and valleys were much fainter compared to #325. For the #2000 grinding wheel, it was challenging to conduct a comparative analysis of the machining modes using optical microscopy; therefore, confirmation was made through FE-SEM imaging. Tables 3 and 4 provide a compilation of FE-SEM images for the #2000 grinding wheel’s ground surface, taken at different magnifications. Table 3 (image a) and Table 4 (image a) display the ground surface of the HP specimen processed with a diamond abrasive. As described in Section 2.1, the HP specimen has a relatively small average particle size and minimal porosity, while the GPS specimen exhibits an increase in average particle size and higher porosity with longer gas-pressure sintering times.

In the images of the ground surface processed with a diamond abrasive (Table 3 (image a) and Table 4 (image a)), a smooth cutting surface can be observed. On the other hand, when the cBN abrasive was used (Table 3 (image b) and Table 4 (image b)), numerous fracture marks were observed. It was evident that their size was somewhat larger compared to the size of the inherent pores in the material. The cracks observed on the cBN abrasive’s ground surface of the HP specimen are likely attributed to surface cracks generated during brittle mode machining. The surface cracks seen on the cBN abrasive’s ground surface (Table 3 (image d,f) and Table 4 (image d,f)) of GPS specimens are much larger compared to the pore size, suggesting that they are likely due to cracks resulting from brittle mode machining. Even on the ground surface of the GPS specimen processed with a diamond abrasive (Table 3 (image c,e) and Table 4 (image c,e)), the fine marks are observed, indicating a high possibility of exposing the pores generated during the gas-pressure sintering process. This suggests that the pores formed during the gas-pressure sintering process are likely to be exposed after machining with the diamond abrasive. This inference is supported by the fact that the size of the fine marks observed on the diamond abrasive’s ground surface (Table 4 (image c,e)) closely matches the size of the pores observed in Figure 1 for the GPS specimens, which are approximately 1 micrometer in diameter. The condition of the ground surfaces from the analysis of ground surface morphology has been compared and examined. The diamond grinding wheel demonstrated a ductile mode machining, resulting in smooth cutting surfaces where the traces of the abrasive path were faithfully replicated. In the case of relatively large grit sizes of diamond grinding wheels (#325 and #1200), the ground surface exhibited more distinct peaks and valleys compared to the cBN abrasive’s ground surface, and the proportion of ductile mode surfaces was higher than the cBN wheel. For the diamond #2000 grinding wheel, it was difficult to detect traces of abrasive paths, and the majority of the ground surface was processed in the ductile mode.
As a result of this confirmation, the diamond wheel achieved a superior ground surface compared to the cBN wheel.

Table 2. Microscopic surface image of the ground surface.

<table>
<thead>
<tr>
<th>Grit Size</th>
<th>Abrasives</th>
<th>HP</th>
<th>GPS 1hr</th>
<th>GPS 6hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>#325</td>
<td>Diamond</td>
<td><img src="image" alt="a" /></td>
<td><img src="image" alt="b" /></td>
<td><img src="image" alt="c" /></td>
</tr>
<tr>
<td></td>
<td>cBN</td>
<td><img src="image" alt="d" /></td>
<td><img src="image" alt="e" /></td>
<td><img src="image" alt="f" /></td>
</tr>
<tr>
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<td>Diamond</td>
<td><img src="image" alt="g" /></td>
<td><img src="image" alt="h" /></td>
<td><img src="image" alt="i" /></td>
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<tr>
<td></td>
<td>cBN</td>
<td><img src="image" alt="j" /></td>
<td><img src="image" alt="k" /></td>
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<tr>
<td>#2000</td>
<td>Diamond</td>
<td><img src="image" alt="m" /></td>
<td><img src="image" alt="n" /></td>
<td><img src="image" alt="o" /></td>
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<tr>
<td></td>
<td>cBN</td>
<td><img src="image" alt="p" /></td>
<td><img src="image" alt="q" /></td>
<td><img src="image" alt="r" /></td>
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Table 3. 1 kx FE-SEM image for the analysis of the #2000 ground surface.

<table>
<thead>
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<th>Specimen</th>
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<th>cBN</th>
</tr>
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<tr>
<td><strong>HP</strong></td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
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<tr>
<td></td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
</tr>
<tr>
<td><strong>GPS 1hr</strong></td>
<td><img src="image5.png" alt="Image" /></td>
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<tr>
<td></td>
<td><img src="image7.png" alt="Image" /></td>
<td><img src="image8.png" alt="Image" /></td>
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<tr>
<td><strong>GPS 6hr</strong></td>
<td><img src="image9.png" alt="Image" /></td>
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Table 4. 10 kx FE-SEM image for the analysis of the #2000 ground surface.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Diamond</th>
<th>cBN</th>
</tr>
</thead>
<tbody>
<tr>
<td>HP</td>
<td><img src="image_url" alt="image a" /></td>
<td><img src="image_url" alt="image b" /></td>
</tr>
<tr>
<td>GPS 1hr</td>
<td><img src="image_url" alt="image c" /></td>
<td><img src="image_url" alt="image d" /></td>
</tr>
<tr>
<td>GPS 6hr</td>
<td><img src="image_url" alt="image e" /></td>
<td><img src="image_url" alt="image f" /></td>
</tr>
</tbody>
</table>

4. Comparative Analysis of Surface Roughness

ELID grinding is known as a suitable technique for grinding brittle materials due to its capability to reduce and maintain consistent grinding resistance through the continuous dressing action of the electrolytic process, enabling prominent protrusion of abrasive particles. To analyze the surface quality of the ground material based on the grit size and abrasive type of the grinding wheel, ELID grinding experiments were conducted using diamond and cBN as abrasive materials. Grit size #325 was used for the rough grinding
stage, while grit sizes #1200 and #2000 were employed for the finish grinding stage. The ground surfaces were quantitatively compared by measuring the parameters $R_a$ and $R_{\text{max}}$ using a surface roughness measuring instrument. ELID grinding experiments were carried out on three types of silicon nitride materials, following the conditions in Table 1, and the surface roughness was measured. The DOC specified in Table 1 was set to be below 30% of the average abrasive size for each corresponding grit size.

4.1. Machining Conditions

Determining the optimal grinding conditions based on the workpiece material and grinding wheel type requires a substantial investment of time, experience, and effort. The impact of grinding conditions on surface roughness was compared and analyzed. Figure 5 presents a graph summarizing the experimental results for each abrasive grit size. As the DOC increases, the surface roughness ($R_a$) also increases. The analysis reveals a direct correlation between the DOC and surface roughness across all three grit sizes. As the DOC increased, the surface roughness further increased. In the case of the #325 grinding wheel, the surface roughness ($R_a$ and $R_{\text{max}}$) increased proportionally with the increase in the DOC. The range of surface roughness was notably more prominent for the diamond abrasive than the cBN abrasive.

For the #1200 grinding wheel, no significant difference in surface roughness ($R_a$ and $R_{\text{max}}$) was observed between a DOC of 1 $\mu$m and 2 $\mu$m. However, a substantial increase in surface roughness was observed at a DOC of 4 $\mu$m. In this instance, the difference in surface roughness based on the type of abrasive was not prominently evident; however, $R_{\text{max}}$ was slightly higher for the diamond grinding wheel. For the #2000 grinding wheel, an increasing trend in surface roughness was observed with the increase in the DOC. The surface roughness based on the type of abrasive demonstrated significant superiority for the ground surface processed with the diamond grinding wheel compared to the cBN grinding wheel. This correlation can be attributed to a higher proportion of surfaces affected by ductile mode machining in the ground surface processed with the diamond grinding wheel, as observed through the analysis of ground surface images in Tables 3 and 4. Meanwhile, the range of surface roughness represents the difference between the maximum and minimum values of the measured data, which allows for the evaluation of ground surface variability and distribution. Figures 6–11 present graphs depicting the average values and ranges of surface roughness, $R_a$, based on the DOC. Figure 6 illustrates the measurement results for #325 diamond and cBN grinding wheels. For the #325 grinding wheel, the diamond abrasive showed significantly larger differences between the maximum and minimum surface roughness values compared to the cBN abrasive. In the case of the #1200 grinding wheel, no significant difference was observed in the average value and range of surface roughness. As for the #2000 grinding wheel, although the range of surface roughness showed no difference, the average value for the diamond abrasive ground surface was remarkably low. These outcomes can be attributed to the diamond abrasive’s effective involvement in the complete cutting of silicon nitride particles, clearly revealing the traces of abrasive passing through the peaks and valleys. In contrast, the cBN abrasive generated a ground surface with a rubbing action on the silicon nitride surface, resulting in a lower proportion of involvement in ductile mode machining. Thus, significant improvement in the ground surface beyond the #1200 grit size using cBN abrasive is challenging to expect. The ground surface of the #325 cBN grinding wheel exhibited superior surface roughness compared to the diamond ground surface. This phenomenon is believed to be influenced by factors such as chip formation during machining and the cutting match between the abrasive and the workpiece material. However, the exact cause will be investigated further in subsequent research. Figure 9 compares the results of experiments conducted with the same DOC, 2 $\mu$m, to analyze the impact of grit sizes #325, #1200, and #2000 on surface roughness. For the diamond abrasive, the surface roughness for grit sizes #325, #1200, and #2000 were in the ranges of $0.166–0.189$ $\mu$m $R_a$, $0.025–0.046$ $\mu$m $R_a$, and $0.0031–0.0069$ $\mu$m $R_a$, respectively. Particularly, for the #2000 grinding wheel, nanosurface machining with
roughness below 7 nm Ra was achievable. For the cBN abrasive, the surface roughness for grit sizes #325, #1200, and #2000 were in the ranges of 0.094–0.123 μm Ra, 0.025–0.045 μm Ra, and 0.0217–0.0275 μm Ra, respectively. Unlike the diamond-ground surface, the surface roughness for cBN #2000 did not show significant improvement compared to cBN #1200. In grinding processes, the choice of abrasive is a critical factor in obtaining clean cutting surfaces based on the correlation of hardness, strength, and other mechanical properties with the workpiece material. Figure 10 is a graph reorganized based on the abrasives, which can be utilized to facilitate the selection of a suitable abrasive for silicon nitride grinding in the grinding process. For grit size #325, cBN demonstrated excellent surface roughness, while for #1200, both diamond and cBN showed similar performance. The results demonstrated that the ground surface processed with the #2000 grit size diamond abrasive was significantly superior to the cBN abrasive. In summary, it was found that the surface roughness increased as the DOC increased. In terms of grit size, for #325, it was possible to achieve superior surface roughness with the cBN abrasive compared to the diamond abrasive. For #1200, no significant difference was observed between the two abrasives, but for #2000, the ground surface processed with the diamond abrasive exhibited significantly superior surface roughness compared to the cBN wheel.

4.2. Material Properties

The grinding process is characterized by a relatively small DOC and a significantly higher normal force than the tangential force compared to the cutting process. It is known that material properties such as fracture toughness and flexural strength influence the fracture characteristics of both ductile mode and brittle mode grinding processes in ceramics machining. The fracture toughness of ceramic materials is typically measured using the IF (Indentation Fracture) method. The IF method calculates fracture toughness by assessing the size of median cracks formed by the indentation of a Vickers hardness indenter and the applied load. This method is primarily employed for measuring the fracture toughness of ceramics with high brittleness, as it allows for the evaluation of crack growth responses in a very small range. Grinding processes involve a small depth of cut and exhibit significantly higher normal force compared to the tangential force. Therefore, fracture toughness determined by the IF method can be effectively utilized to analyze and evaluate the machining mode characteristics of ceramic surfaces in grinding processes with a low depth of cut [15]. Lee et al. [15] previously reported that specimens with high fracture toughness exhibited superior surface roughness in ELID (Electrolytic In-Process Dressing) grinding experiments using #325 and #1200 grit wheels. Fracture stress is inversely proportional to the square root of the critical crack length, meaning that larger internal voids in the material result in lower fracture stress. Additionally, when the critical crack length is the same, materials with lower fracture toughness exhibit lower fracture stress. Consequently, it was reported that grinding materials with low fracture toughness leads to an increase in surface roughness due to the higher frequency of ductile mode fractures induced by machining pressure. Although there is a regrettable omission regarding the impact of particle size and void content on surface roughness, this study is significant as it confirms the influence of fracture toughness on surface roughness. In this experiment, ELID grinding characteristics were analyzed for three specimens with varying particle size and pore content, all composed of silicon nitride ceramic material with the same composition. Avoiding internal pores in ceramics during the sintering process is challenging. As observed in Figure 2, the GPS specimens exhibit relatively larger and more numerous internal pores compared to the HP specimens, resulting in lower flexural strength and fracture toughness in the GPS specimens. Figure 11 provides a graph comparing fracture toughness, surface roughness (Ra), and the range of surface roughness (ΔRa). The HP specimen, with the highest fracture toughness, shows the lowest surface roughness Ra, demonstrating an inverse correlation between fracture toughness and the range of surface roughness ΔRa.
Figure 5. Surface roughness measurement results by grit size of grinding wheels.

For the #1200 grinding wheel, no significant difference in surface roughness (Ra and Rmax) was observed between a DOC of 1 µm and 2 µm. However, a substantial increase...
Figure 6. Comparison for range of surface roughness (Ra) using #325 wheel for HP specimen.

Figure 7. Comparison for range of surface roughness (Ra) using #1200 wheel for HP specimen.

Figure 8. Comparison for range of surface roughness (Ra) using #2000 wheel for HP specimen.
Figure 8. Comparison for range of surface roughness (Ra) using #2000 wheel for HP specimen.

Figure 9. Comparison of surface roughness by grit size.

Figure 10. Comparison of surface roughness by abrasive.

Figure 11. Comparison of surface roughness, range of surface roughness, and fracture toughness by specimen.
The increase in surface roughness $R_a$ and the wider range of surface roughness $\Delta R_a$ with lower fracture toughness can be attributed to the facilitated occurrence of brittle mode fracture. Figure 12 compares the measured results of flexural strength, surface roughness $R_a$, and $R_{max}$ based on the specimen type. The HP specimen with the highest flexural strength exhibits the lowest surface roughness ($R_a$). Lower flexural strength is associated with higher surface roughness $R_a$, and the consistent trend of higher $R_{max}$ with lower flexural strength is observed between the HP and GPS specimens. However, for the #325 grinding wheel, no significant difference in $R_{max}$ between the GPS 1hr and GPS 6hr specimens was observed. The experimental findings demonstrate that higher fracture toughness and flexural strength tend to result in superior surface roughness.

![Comparison of surface roughness and flexural strength](image)

**Figure 12.** Comparison of surface roughness and flexural strength by specimen.

5. Conclusions

The ceramic silicon nitride specimens for ceramic bearing balls were prepared, and ELID grinding experiments were conducted to compare and analyze the influence of material properties and grinding conditions on the quality of the ground surface. The results of ground surface morphology analysis revealed the following:

1. Diamond abrasives exhibited smooth cutting surfaces due to ductile mode machining, where the traces of abrasive passing through were faithfully transferred onto the machined surface.
2. For the diamond abrasives at lower grit sizes (#325 and #1200), the ground surface exhibited distinct peaks and valleys compared to the cBN ground surface, indicating a higher proportion of ductile mode fractured surface than brittle mode.
3. At a higher grit size (#2000), the ground surface showed almost no evidence of brittle mode fractured surface, resulting in a smoother ground surface compared to cBN.

Surface roughness comparison analysis yielded the following conclusions:

1. It has been confirmed that an increase in the DOC led to an increase in surface roughness under the same grinding conditions.
2. The analysis of surface roughness based on different grit sizes revealed that the #325 cBN abrasive showed a superior ground surface compared to the diamond abrasive, #1200 showed no significant difference between the two abrasives, and #2000 showed a significantly superior surface when ground with the diamond abrasive compared to cBN.
3. Based on the comparison between material properties and surface roughness, it was observed that higher fracture toughness and flexural strength were correlated with superior surface roughness. Ground surface morphology analysis visually confirmed the cutting performance of diamond and cBN abrasives on silicon nitride ceramics.
It has been confirmed that the material characteristics and grinding parameters affect the surface roughness of silicon nitride ceramics during the grinding process through surface morphology and surface roughness analysis after ELID grinding experiments. Expanding the applicability of results derived from this experiment, through surface roughness comparison analysis, it was observed that in the roughing process, using low-grit-size cBN wheels such as #325 at deeper depths of cut can increase grinding efficiency while enhancing the quality of the ground surface. On the other hand, in the finishing process, using high-grit-size diamond wheels such as #2000 allows for the achievement of nanosurfaces, providing a more efficient and effective approach for high-efficiency machining and nanosurface fabrication. The surface ground with the #2000 wheel is at a level that can satisfy the required surface roughness, 0.014 μm or less in G5 class bearing balls.


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