Study on the low energy & pollution manufacturing of micro cutting tools by powder injection molding process

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Abstract. In this paper, micro cutting tools were manufactured by the powder injection molding process. Most of cutting tools are manufactured by bulk-molding and grinding methods but, the fabrication of micro cutting tools is very difficult because of their minute flute shapes and cutting edges. Therefore, a powder injection molding (PIM) process was used to fabricate the green part of a micro cutting tool with zirconia mixer feedstock and the de-binding and sintering processes were performed. Besides, the grinding processes can be dropped by PIM. Finally, the micro cutting experiment using the newly manufactured tool by PIM was executed for verifying the utility of manufactured tool.

1. Introduction

As the trends of sub-miniature and slim products are recently accelerating in many industries, including machining, electric appliance, electronics, and bioengineering industries, interest in MEMS and high precision micro processing technologies is increasing. Especially in future-oriented industries such as information technology (IT), miniature/sub-miniature fuel cells, and bio-chips, micro-processing technology is emerging as an essential element, and many studies are being conducted on micro processes for the prototyping and mass production of products and parts that have sub-miniature functional micro patterns and shapes [1-4].

In the initial stage, micro processing technology was mainly the simple application of semiconductor manufacturing processes, but with the development of manufacturing technology for high precision processing equipment and tools, the applications of micro cutting technology in related industries are increasing. The quality of this cutting technology, which is based on the mechanical material removal mechanism, may be poorer than that of chemical or electrochemical processing methods. However, due to such advantages as accurate control of processing dimensions, 3-D micro shape processing, and diversity of processing materials, micro cutting is very useful for the manufacturing of micro injection and press molds and light metal parts that require mechanical hardness in MEMS.

In micro end milling, which is a representative micro cutting process, the micro endmill is the core element. The micro endmill determines the limits of the shape size that can be processed, and the geometry and properties of tools, such as smooth discharge of chips and wear resistance, have a direct effect on the shape processing quality. At present, most micro endmills are made of hard materials such as tungsten carbide and ceramics. Hard materials are appropriate for tools for their thermal...
characteristics and hardness, but as they are typically difficult-to-cut materials, high production costs are required to achieve various geometries of endmill, such as helix and relief angles. Furthermore, as micro endmills are manufactured through multiple processes, such as ion beam process, molding, turning and grinding, they cause such production process problems as increased energy of production process and the generation of by-products and dust from the turning and grinding processes.

On the other hand, manufacturing micro tools through powder injection molding (PIM) using metal and ceramic powders is advantageous for high quality mass production, and can reduce production energy consumption compared to existing tool manufacturing processes, and fundamentally solve the by-product problem by omitting the turning and grinding processes. Therefore, in this study, micro cutting tools that provide ease of manufacturing of tool blades and better structural hardness were designed and manufactured through the PIM process using zirconia ceramic materials with excellent wear resistance and hardness. Furthermore, the efficiency of the manufactured micro tool was verified through a micro cutting experiment with Cu as an electrode material.

2. Design of micro cutting tool and powder injection mold

2.1 Design of micro cutting tool

In this study, two types of micro cutting tools, flat-type and ball-nosed type, were designed by reviewing the existing micro tools and considering the characteristics of the micro cutting process. The flat-type tool was designed with a diameter of 500 µm, a blade length of 1 mm (double the tool diameter), and a tool relief angle of 5 degrees, to minimize cutting resistance at the bottom surface of the tool during processing. The ball-nosed type tool was designed with a radius of 250 µm and the same blade length as that of the flat type (double the tool diameter). Figure 1 shows the designed tool shapes.

To examine the micro cutting effectiveness of the designed tools, prototype tools were manufactured using hard materials before the PIM molds for the micro cutting tools were designed. The prototype tools with hard materials were designed with the same shape and geometry as the tools designed using turning and grinding processes (Figures 2 and 3). Tool geometry measurement and visual observation using a tool microscope found that the tool shape reproducibility was relatively good and the tool manufacturing error was 0.02 mm or less in diameter.
Table 1 shows the conditions for micro cutting experiment using the prototype tools. The cutting experiment was performed with commercial micro endmills under the same processing conditions to compare the processing results. As a result, it was found that the micro tool shapes designed in this study could perform the micro cutting process and provide relatively good micro-slot bottom surface quality. However, the processing quality of the ball-nosed type prototype tool was poorer than that of the flat-type tool, as it generated many cusps. Thus, it appears to be poorer than the general commercial hard endmills with respect to bur generation (Figure 4).

Figure 5 shows the width measurements of micro slots that were processed using the ball-nosed type prototype tool. The measurements revealed a shape processing error of up to 1.2 μm. The processing precision was relatively good, but as mentioned above, the bur generation quality was somewhat poor when the tools designed in this study are used. However, as micro cutting tools...
manufactured with ceramic materials through PIM have relatively good wear resistance, their utility as rough grinding tools is expected to be high.

![Image](a) (b) (c)

**Figure 4.** Micro cutting features. (a) micro endmill (s-flutes), (b) prototype flat micro cutting tool, and (c) prototype ball-nosed micro cutting tool.

![Image](a) (b) (c)

**Figure 5.** Measurements of micro slot widths. (a) entrance position, (b) center position, and (c) end position.

### 2.2 Design of powder injection mold

In this study, PIM molds were manufactured for molding the designed cutting tools. The general mold structures were designed to be similar to general plastic injection molds, and the flow system was designed in consideration of the PIM process characteristics (Figure 6). As PIM products contract through debinding and sintering after molding, the final product is smaller than the first molded (green) part. Thus, the molding shape size inside the core was increased by a factor of 1.3267 by considering the contraction characteristics of the debinding and sintering processes as well as the contraction characteristics of the feedstock materials used in the PIM process.

![Image](a) (b)

**Figure 6.** 3D design of powder injection mold for micro cutting tools.

**Figure 7.** Fabricated powder injection mold. (a) upper part and (b) bottom part.
3. Fabrication of micro cutting tools by PIM process

3.1 Powder injection molding
To manufacture the micro cutting tools using the designed molds, zirconia ceramic material was chosen as the feedstock. Table 2 shows the characteristics of the chosen material. This material was found to be appropriate for molding micro cutting tools as it had excellent thermal expansion, hardness, and wear resistance properties. Table 3 shows the molding conditions for manufacturing micro cutting tools and Figure 8 illustrates the shapes of the injection molded micro cutting tools.

| Table 2. Material properties of zirconia ceramics. |
|-----------------------------------------------|
| **Physical characteristics**                  |
| Crystallite size [nm]                         | 26   |
| Granule size [µm]                             | 60   |
| Bulk density [g/cm³]                          | 1.2  |
| **Process characteristics**                   |
| Green density [g/cm³]                         | 2.50 |
| Sintered density [g/cm³]                      | 5.50 |
| Bending strength [MPa]                        | 1900 |
| Fracture toughness                            | 5.0  |
| Hardness [Hv10]                               | 1400 |

| Table 3. Powder injection molding conditions. |
|----------------------------------------------|
| **Item**                                     |      |
| Injection temperature [°C]                   | 170  |
| Mold temperature [°C]                        | 70   |
| Injection time [sec]                         | 0.92 |
| Injection pressure [MPa]                     | 37   |
| Packing pressure [MPa]                       | 37   |
| Packing time [sec]                           | 3    |
| Cooling time [sec]                           | 25   |

[Figure 8](#). Molded parts of micro cutting tools. (a) flat micro cutting tool and (b) ball-nosed micro cutting tool.
3.2 Debinding and sintering process

The debinding process of the injection molded body (green part) in this study consisted of first catalysis debinding and second thermal debinding. The first catalysis debinding used n-hexane solvent at a temperature of 50°C and holding time of 12 hours. The second thermal debinding process consisted of raising the temperature to 250°C at 2°C per min, holding for 2 hours at 250°C, raising the temperature to 450°C at 1°C per min, holding for 2 hours at 450°C, raising the temperature to 700°C at 1°C per min, and holding for 1 hour at 700°C.

After debinding, a sintering process was performed to manufacture the final tool. For sintering, a sintering machine that could sinter at temperatures up to 1700°C was used. The sintering process consisted of raising the temperature to 1550°C at 100°C per hour, holding for 2 hours at 1550°C, and cooling to room temperature at 200°C per hour. Figure 9 shows the final micro cutting tools that were fabricated through sintering.

To test the dimensional precision of the tools manufactured through the injection molding-debinding-sintering process, measurements were taken using a tool microscope. As shown in the measurement results in Figure 10, the maximum shape error of the sintered part of the flat-type tool was 0.037 mm compared to the designed value, and the size of the sintered part was reduced by about
22% compared to the molded part. Figure 11 shows the measurement results of the ball-nosed tool. The maximum shape error was 0.055 mm and as with the flat-type tool, the size of the sintered part was reduced by about 22% compared to the molded part.

![Figure 12](image1.png)

**Figure 12.** Inspection of micro cutting feature fabricated by the flat micro cutting tool. (a) measurement of rib width and (b) sideview image of the micro feature.

![Figure 13](image2.png)

**Figure 13.** Inspection of micro cutting feature fabricated by the ball-nosed micro cutting tool. (a) measurement of rib width and (b) sideview image of the micro feature.

4. Micro cutting experiments and results

To analyze the processing characteristics of ceramic micro cutting tools fabricated through PIM, the same experiment as the micro cutting experiment of the prototype tools was conducted. After the cutting experiment, the processed shape was examined and the processed micro rib width was measured. For tool wear analysis, the tool blade images were analyzed before and after processing.

Figure 12 shows the measurements of the micro rib shape that was processed with the flat-type micro tool. The reproducibility of the processed shape was good, but the maximum slot width processing error was 7.29 µm. The cause of this excessive shape processing error seems to be that, through the debinding and sintering after PIM, the tool was bent vertically, in the longitudinal direction of the tool, which worsened the runout error which occurs during tool setup. Figure 13 shows the measurements of the shape processed with the ball-nosed micro cutting tool. The shape processing quality is poorer and the processing error is greater than those of the flat type. The reason for this seems to be that the ball-nosed micro cutting tool has a different cutting load on the tool at different cutting depths, which causes irregular tool deformations during the process such as tool bending and runout.

Figures 14 and 15 show blade images before and after processing with the micro cutting tools that were fabricated through PIM. As shown in these figures, there was almost no tool wear. This excellent
wear resistance was made possible by fabricating ceramic tools through PIM, and the wear resistance is better than that of hard materials. Micro cutting in general has the shortcoming of uneven processing quality for large or long area processes due to tool wear, but ceramic single-blade tools with excellent wear resistance will be more advantageous for rough grinding processes that have relatively large cutting volumes and loads. As a result, the cutting load is reduced in the post-processing, which reduces processing energy consumption and allows excellent processing quality. Above all, the reduction of the fabrication process and the omission of turning and grinding processes for micro cutting tools can reduce production energy consumption and establish a clean production process.

![Figure 14. Tool wear image comparison of the flat micro cutting tool. (a) new micro cutting tool and (b) used micro cutting tool.](image)

![Figure 15. Tool wear image comparison of the ball-nosed micro cutting tool. (a) new micro cutting tool and (b) used micro cutting tool.](image)

5. Conclusions
In this study, micro cutting tools were fabricated through PIM with zirconia ceramic material with excellent wear resistance and hardness, and their efficiency were verified through cutting experiments. For this purpose, micro cutting tools were designed which are appropriate for the PIM process and offer relatively high hardness. Furthermore, the tool designs were verified through the manufacturing of prototype tools and cutting experiments. The PIM molds were designed and manufactured by considering the final tool designs, and the micro cutting tools with zirconia ceramic material were finally manufactured through the molding-debinding-sintering process. The micro cutting experiments with the fabricated tools revealed somewhat poor processing precision due to tool bending in the manufacturing process. However, as the tool has excellent wear resistance, it will be very useful as a rough grinding tool for large area micro cutting processes.

Micro cutting tools are generally manufactured through multiple production factories. This causes high production costs and energy consumption, as well as by-products due to turning and grinding. However, as the proposed micro cutting tool manufacturing process with PIM in this study can mass produce micro cutting tools only through molding, debinding, and sintering, not only the product cost and energy consumption can be reduced, but also the turning and grinding processes can be omitted.
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