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ORIGINAL ARTICLE

Experimental investigation on microgrooving characteristics of ceramics using electroplated diamond wire tools

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ABSTRACT – For precision machining such as slicing and grooving of hard and brittle materials, wire tools with electroplated diamond abrasives have been widely used. Slicing with electroplated diamond wire tools, in particular, is quickly becoming a common method for machining hard materials. Many studies have been published on the machining properties of electroplated diamond wire tools. However, there are very few reports on the tool wear of wire tools. In particular, the influence of work material on the machining and wear characteristics of electroplated diamond wire tools is still unclear. Fundamental grooving experiments are used to investigate the effect of the workpiece's material properties on the grooving characteristics and the wear characteristics of the wire tool. Two types of ceramics, alumina (Al_2O_3) and zirconia (ZrO_2), were used as work materials in this study. The grooving experiments revealed that the workpiece material affects the machining characteristics. Alumina, which is brittle, was found to be more machinable than zirconia, which has a high toughness for the same hardness. The wear of the electroplated diamond wire tools, on the other hand, showed no significant difference.

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INTRODUCTION

Slicing with a multiwire saw is one of the best methods for precision slicing of hard and brittle materials like semiconductors and optical components. Slicing methods using a multiwire saw can be broadly classified into loose abrasive machining using slurry as the cutting tool and fixed-abrasive machining using fixed abrasive wire tools as the cutting tool [1, 2]. In general, loose abrasive machining is superior in terms of machining accuracy, while fixed-abrasive machining is superior in terms of machining efficiency; however, in recent years, fixed-abrasive machining's machining accuracy has also improved. In fixed-abrasive machining, diamond abrasives are often electrodeposited on wire tools, but there are also those in which diamond abrasives are fixed with resin [3].

Electroplated diamond wire tools have recently become popular as precision cutting tools for hard and brittle materials. It has become a popular tool for slicing hard materials, especially SiC. Hardin et al. [4] demonstrated the damage to SiC caused by slicing with electroplated diamond wire tools. Gao and Chen have developed a finite element model of wire saw cutting of SiC single crystals containing spherical void defects, and have shown the effect of the relative position and size of the defects on the stress concentration during slicing with electroplated diamond wire tools [5]. Studies on the machining characteristics of electroplated diamond wire tools have also been actively pursued, with Suzuki et al. demonstrating the effects of high-speed machining with electroplated diamond wire tools on work materials [6]. Furthermore, research is being conducted to extend the tool life of electroplated diamond wire tools to deal with technological issues such as thinner and larger diameter wafers, which require lower costs, and the processing of difficult-to-cut materials such as SiC and sapphire. Among those who have contributed to this work are Suzuki et al. proposed a new coating method to improve the adhesion strength of diamond abrasive grains and electrolytic nickel bonding in electroplated diamond wire tools [7]. Muraoka and Suzuki also demonstrated the machining properties of single-crystalline silicon using electroplated wire tools with a new coating [8]. Several studies on the tool wear of electroplated diamond wire tools have been published [9]. However, the influence of machining conditions and work materials on the wear of electroplated diamond wire tools have not been reported, and there are currently no standards for determining tool life. Furthermore, many aspects of the relationship between machining characteristics and wear characteristics of electroplated diamond wire tools remain unclear.

We have studied in detail the machining characteristics of electroplated diamond wire tools not only on hard and brittle materials but also on wood materials [10] and composite materials [11, 12]. Tool wear of electroplated diamond wire tools during ceramic machining was also studied [13]. They also observed the wear state of electroplated diamond wire tools after slicing hard and brittle materials like borosilicate glass, monocrystalline silicon, polycrystalline silicon, and sapphire [14]. Moreover, the wear characteristics of the electroplated diamond wire tools were compared using metallic and hard, and brittle materials as work materials [15]. However, many aspects of the effects of machining

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conditions and workpiece material on the machining and wear characteristics of electroplated diamond wire tools remain unknown.

Grooving experiments were carried out in this study with two different types of ceramic materials as workpieces to investigate the effects of machining conditions and workpiece characteristics on the machining and wear characteristics of electroplated diamond wire tools.

EXPERIMENTAL METHOD

Experimental Setup

Grooving experiments were performed on a modified tabletop CNC milling machine. Figure 1 depicts a simplified schematic diagram of the experimental setup, while Figure 2 depicts a schematic diagram of the machining process as seen from the Z-axis. The workpiece is fixed to the spindle (Z-axis) via a work holder, and rotational motion is applied. This rotation of the workpiece generates a relative velocity between the wire tool and the workpiece. Grooving experiments were conducted in this study using the relative velocity of the wire tool and the workpiece. Furthermore, the wire tool is fixed to the X–Y table with constant tension and reciprocates in the X-axis direction at an extremely slow speed, extending the length of the wire tool that contributes to the grooving. The workpiece is pressed against the wire tool beforehand (pressing distance is 5 mm) and is not fed in the Y-axis direction during grooving.

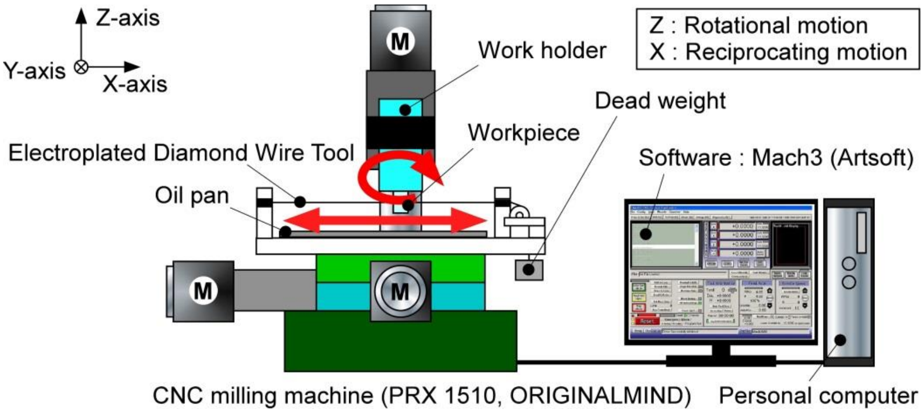

Figure 1. Schematic diagram of the experimental setup, which is a modified tabletop CNC milling machine

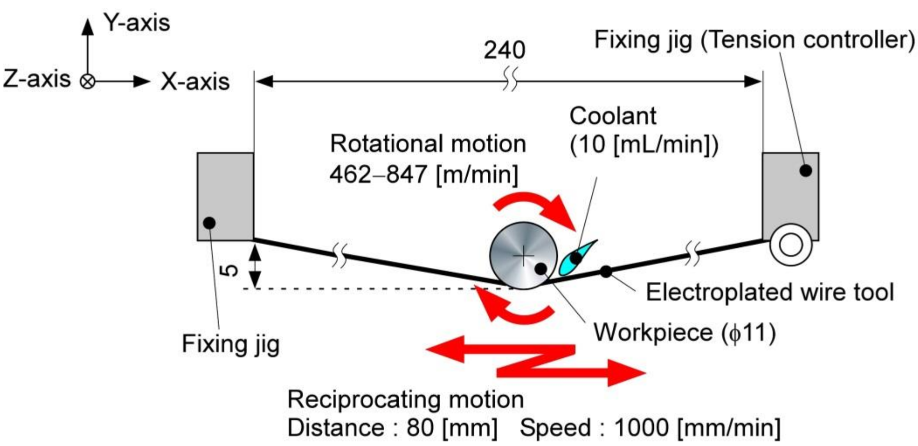

Figure 2. Schematic diagram of the machining process viewed from the Z-axis direction

Experimental Conditions

The materials used in the experiments and the main experimental conditions are summarized in Table 1. To prevent wire breakage and excessive tool wear, the tension on the electroplated diamond wire tool was set to a low value. The wire tool tension was set to 8.5 N in this study. Workpieces were 11 mm diameter alumina round bars and zirconia round bars. A solution-type water-soluble working fluid was used as the coolant, and it was intensively supplied to the grooving area at a rate of 10 mL/min. The rotational speed of the workpiece was 462–847 m/min. The travel distance of the electroplated diamond wire tool in the X-axis direction was set at 80 mm, and the travel speed was set at 1000 mm/min. The maximum machining time was set at 20 minutes, and various measurements were taken at 5-minute intervals.

An electroplated diamond wire tool is shown in Figure 3. In this figure, the electroplated diamond wire tool is unused. The core wire has a diameter of 200 μm and is electroplated with diamond abrasive grains with an average diameter of 30–40 μm. The electroplated diamond wire tool had a diameter of 265 μm at its widest point. Table 2 summarizes the simple composition and strength of the workpiece. The values were provided by the manufacturer. The zirconia used in the experiments is stabilized zirconia containing yttrium oxide. When compared to alumina, zirconia has higher bending strength and density values, indicating that it is a tougher material. Alumina and zirconia have comparable hardness in general, but alumina is more brittle [16, 17].

Table 1. The material used and main experimental conditions

Electroplated diamond wire tool	Material of abrasive grains	Synthetic diamond
	Diameter of abrasive grains (Diameter of the material itself)	30–40 [μm]
	Material of core wire	SWRS82A (JIS G 3502)
	Plating	Nickel plating
	Diameter of core wire (Diameter of the material itself)	200 [μm]
	Outermost diameter of the wire tool	265 [μm]
	Applied tension	8.5 [N]
Workpiece	Material	Alumina, Zirconia
	Shape	Round bar
	Diameter	11.0 [mm]
	Rotational speed	462, 616, 847 [m/min]
Working fluid	Type of coolant	Solution type
	Supply amount	10 [mL/min]
X–Y table	X-axis travel distance	80 [mm]
	Moving speed	1000 [mm/min]
	Machining time	5, 10, 15, 20 [min]

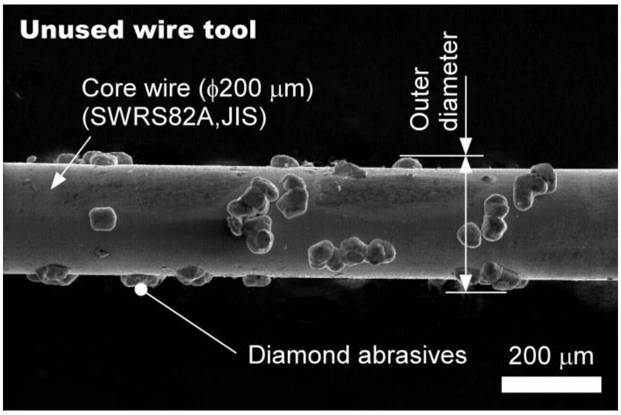

Figure 3. Appearance of an unused electroplated diamond wire tool

Table 2. Properties of the ceramic materials used

	Alumina	Zirconia
Chemical composition	Al_2O_3 (99.9%)	ZrO_2 (3 mol% Y_2O_3)
Bending strength	380 [MPa]	1200 [MPa]
Bulk density	3900 [kg/m^3]	6000 [kg/m^3]

Definition of Wear Amount in this Study

Figure 4 shows the definition of the amount of wear of the electroplated diamond wire tool in this study. The amount of wear on the electroplated diamond wire tool was defined as the difference in grain height between the unused and used electroplated diamond wire tools. It would be ideal to continuously monitor the wear of the same abrasive grain, but this is difficult in practice due to the need for specialized equipment and software. Therefore, the measurement range (distance) of the electroplated diamond wire tool was set to 1.2 mm, about 32 abrasive grains were observed, and the average value of the abrasive grains that contributed to the grooving was used in this study. The average abrasive grain height of the unused electroplated diamond wire tools in this study was 32 μm.

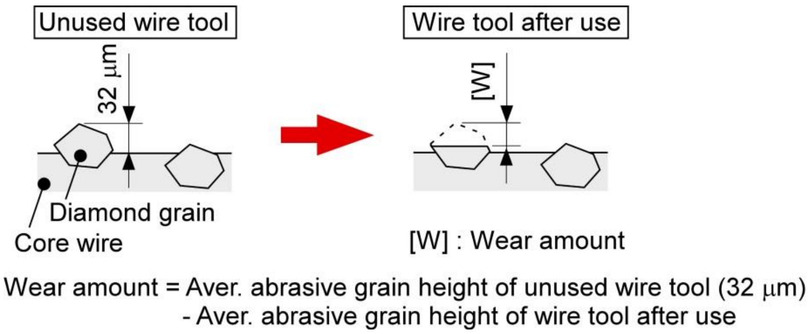

Figure 4. Definition of the amount of wear of the electroplated diamond wire tool in this study

EXPERIMENTAL RESULTS AND DISCUSSION

Influence of Machining Time

In this section, grooving experiments were carried out by varying the machining time up to 20 minutes to investigate the effect of machining time. Every 5 minutes, different measurements were taken. The data for alumina is shown in the filled circle (blue circles), while the data for zirconia is shown in the white circles. The rotational speed of the workpiece was set to 462 m/min.

The effect of machining time on groove depth is shown in Figure 5. The groove depth increased with the machining time for both alumina and zirconia groovings. The groove depth increased significantly with machining time, indicating good machinability, particularly in the grooving of alumina. On the other hand, the groove depth of zirconia also increased with machining time, but the groove depth was shallower than that of alumina. In other words, zirconia has lower machinability than alumina. In both cases, the groove depth increased almost linearly with machining time, indicating that the machining performance of the electroplated diamond wire tool could be maintained until the end of machining in this experiment. The difference in groove depth between alumina and zirconia, which have almost the same hardness, is due to the characteristics of the materials. In other words, when grooving alumina, which has more brittle properties, diamond abrasive caused a microscopic fracture of the work material, causing the groove depth to increase. On the other hand, the grooving of zirconia, which has high toughness, does not cause workpiece microfracture. Therefore, the groove depth was not very deep in the grooving of zirconia.

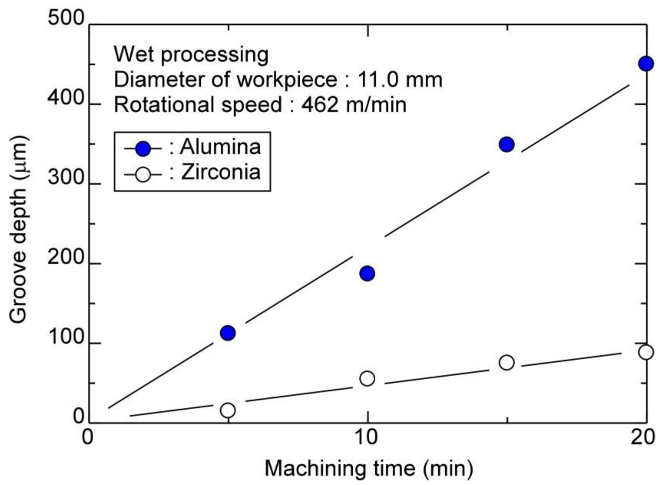

Figure 5. Relationship between machining time and groove depth

Figure 6 shows the influence of machining time on the wear of the wire tool. It is clear from this figure that the tool wear is progressing as the machining time passes. The amount of wear during the first 5 minutes (initial wear) is significant, and after that, wear progress at a nearly constant rate. The surface of the electroplated diamond wire tool is nickel-plated. This nickel coating wears off during the grooving process. One of the reasons for increased wear in the early stages of grooving is this. There was a significant difference in machining efficiency between alumina and zirconia grooving, but no significant difference in wear was observed. When alumina and zirconia are compared, alumina has slightly higher hardness but lower toughness [16, 17]. Machining efficiency depended on the toughness of the work material, and alumina with low toughness was superior, but there was no significant difference in the wear of the electroplated diamond wire tools. The hardness of the workpiece determined the wear of the electroplated diamond wire tool, and no significant difference was found between alumina and zirconia with similar hardness.

Figure 7 shows the influence of machining time on the groove width. The dashed line (red line) in this figure shows the outermost diameter of the electroplated diamond wire tool. This figure shows that the groove width is independent of the machining time. The groove width is slightly narrower for zirconia, which has higher toughness, but no discernible difference exists depending on the workpiece material. The width of the groove is approximately 118% of the outermost diameter of the electroplated diamond wire tool used. The increase in groove width is attributed to the vibration of the electroplated diamond wire tool associated with grooving. The accuracy and rigidity of the grooving equipment also have an effect.

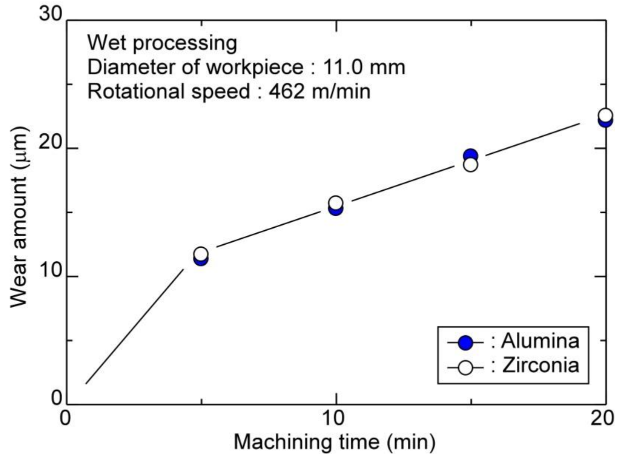

Figure 6. Relationship between machining time and the wear of the electroplated diamond wire tool

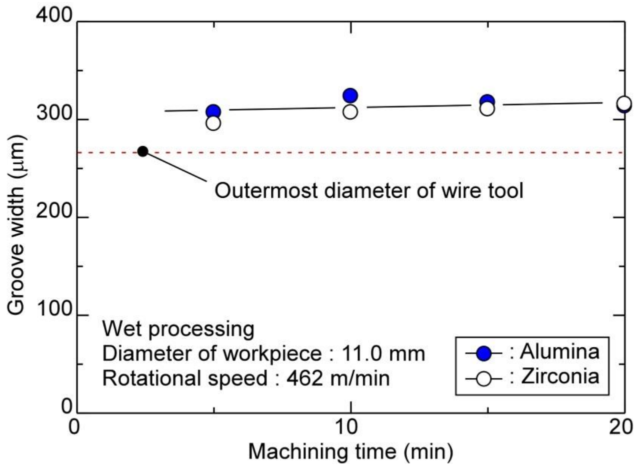

Figure 7. Relationship between machining time and the groove width

Influence of Relative Speed

The relative speed between the workpiece and the electroplated diamond wire tool is varied in this section by varying the workpiece's rotational speed. The workpiece's rotational speeds were set at 462, 616, and 847 m/min, respectively. The filled circle (blue circles) show the data for alumina and the white circles show the data for zirconia. The machining time (grooving time) is 15 minutes.

Figure 8 depicts the effect of the workpiece's rotational speed on the groove depth. The groove depth increases linearly in both alumina and zirconia grooving. Alumina grooving, in particular, significantly increases groove depth when compared to zirconia grooving. This is because alumina is a more brittle material than zirconia. In other words, as the rotational speed of the workpiece increases, the relative speed between the workpiece and the electroplated diamond wire tool increases. The diamond abrasive grains impact the workpiece at high speed as the relative speed increases, and in the grooving of alumina, which has brittle properties, the groove depth increases due to microbrittle fracture. Grooving on zirconia, on the other hand, does not increase groove depth as much as grooving on alumina.

Figure 9 shows the influence of the rotational speed of the workpiece on the amount of wear of the electroplated diamond wire tool. The amount of wear of the electroplated diamond wire tool decreased slightly with increasing the rotational speed of the workpiece, but no significant trend was observed. In short, the amount of wear on the electroplated diamond wire tool is nearly independent of the rotational speed of the workpiece. The slight decrease in the amount of wear of the electroplated diamond wire tool with increasing rotational speed of the workpiece can be attributed to an increase in the relative speed between the workpiece and the electroplated diamond wire tool, which slightly improved machinability. The amount of wear on the electroplated diamond wire tool was slightly higher for the alumina, but there was no significant difference between the workpieces. For the workpiece used in this study, alumina has a slightly higher hardness. As a result, the wear of the electroplated diamond wire tool was slightly higher for alumina. In other words, the amount of wear on the electroplated wire tool is thought to be independent of the workpiece's rotational speed but dependent on its hardness.

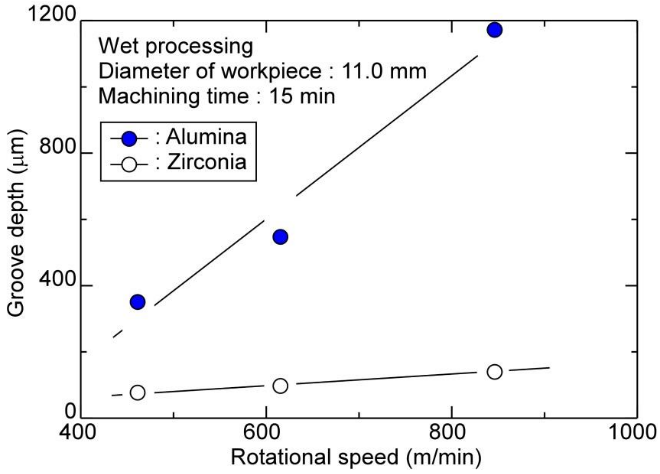

Figure 8. Relationship between the rotational speed of the workpiece and the groove depth

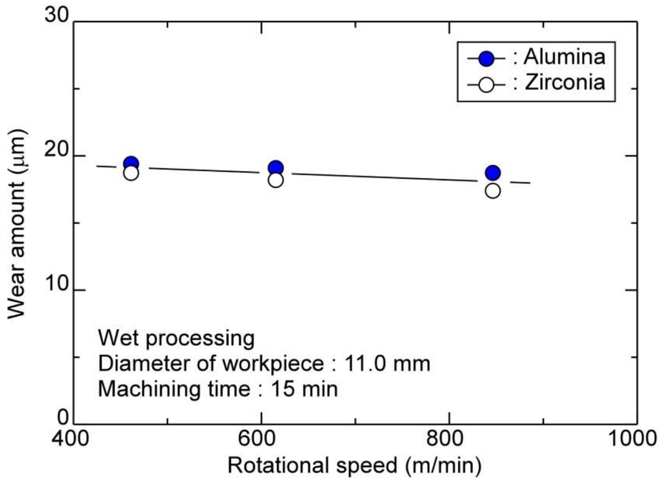

Figure 9. Relationship between the rotational speed of the workpiece and the wear of the wire tool

Figure 10 shows the influence of the rotational speed of the workpiece on the groove width. The dashed line (red line) in this figure shows the outermost diameter of the electroplated diamond wire tool used. From this figure, it is clear that the groove width does not depend on the rotational speed or the type of workpiece. The groove width is greater than the diameter of the electroplated diamond wire tool used, which is approximately 119% of the tool's outermost diameter. The groove width is affected by the vibration of the electroplated diamond wire tool during grooving and the accuracy and rigidity of the grooving machine. To put it another way, the groove width can be reduced by using a high-precision, high-rigidity grooving machine and increasing the tension applied to the electroplated diamond wire tool.

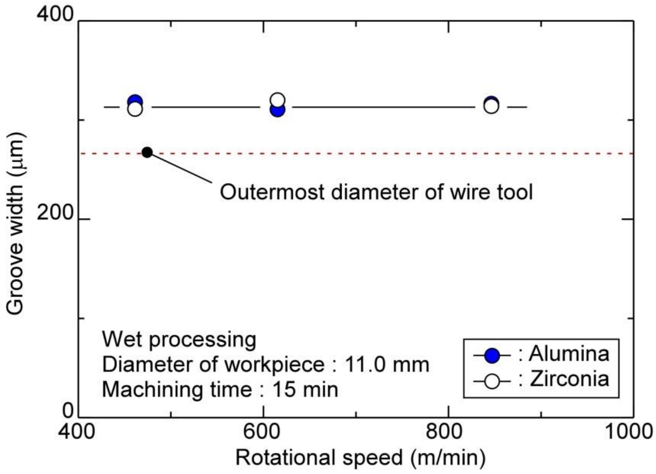

Figure 10. Relationship between the rotational speed of the workpiece and the groove width

CONCLUSION

The main purpose of this study was to clarify the influences of machining conditions and characteristics of workpieces on the grooving characteristics, including the wear of electroplated diamond wire tools. Grooving experiments were carried out on two different types of ceramic materials, alumina, and zirconia, as workpieces, by varying the machining time and the relative speed between the workpiece and the electroplated diamond wire tool. Although the hardness of alumina and zirconia used as workpieces is nearly identical, their toughness is vastly different. The main results obtained by the grooving experiments and wire tool observations are as follows:

1. As the machining time and rotational speed of the workpiece increased, so did the groove depth. A microbrittle fracture occurs during the grooving process, especially when alumina, which has brittle properties, is used. Therefore, the machinability of alumina is higher than that of zirconia, which has higher toughness.
2. The abrasive wear of the electroplated diamond wire tool is large in the initial stage of grooving. Thereafter, the wear rate decreases, but the amount of wear of the wire tool increases as the machining time passes. The amount of wear on the wire tool is almost independent of the rotational speed of the workpiece (relative speed between the workpiece and the electroplated diamond wire tool), but it decreases slightly as the relative speed increases. Furthermore, the amount of wear on wire tools is unrelated to the toughness of the workpiece. The amount of wear of the electroplated diamond wire tools seems to be slightly dependent on the hardness of the workpiece.
3. The groove width was greater than the outermost diameter of the electroplated diamond wire tool used and was independent of machining time or workpiece rotational speed. Additionally, there was no significant difference depending on the material of the workpiece.

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