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Micro Machining of High-Hardness Materials Using Magnetic Abrasive Grains

Sang-Don Mun[1,#]

1 Division of Mechanical Design Engineering, Chonbuk National University, 664-14, Duckjin-dong, Duckjin-gu, Jeonju, Seoul Korea, 561-756
Corresponding Author / E-mail: msd@jbnu.ac.kr, TEL: +82-63-270-4762, FAX: +82-63-270-2460

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If processing speed is increased and processing time is lengthened, a magnetic abrasive system can be used as a tool both for finishing and precise dimensional control of manufactured products at the micro-level, and for mirror face processing. In this study, a micro machining system that can change its high rotational speed was developed. Using micro machining with a high speed magnetic abrasive system, the diameter of difficult-to-cut materials with high hardness could be controlled almost linearly by changing the rotational speed, the frequency of magnetic poles, and the size of diamond particles. By changing machining conditions, the surface roughness of the mirror face level could be obtained. To improve roundness, a higher rotational speed improved processing time and dimensional precision, and 20,000 rpm was the optimum speed in this experiment. Roundness was obtained up to 0.15 ㎛. Before and after the processing, there was almost no change in the WC(tungsten carbide) and Ni components of the material, and there were no remains of mixed-type particles such as iron and diamond on the material.

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NOMENCLATURE

Ra = arithmetical mean deviation of the profile
Ry = maximum height of the profile
LSC = least square circle center
ACOD = accumulated change of diameter
ARW= accumulated removal weight
f = magnetic pole frequency
ds = diamond particle size

1. Introduction

The development of high precision and high efficiency mirror finishing technology is needed not only in machine-related manufacturing but also in the semiconductor, biomedical, electronics, and nuclear energy industries. The magnetic abrasive method is a flexible processing method that can enhance surface precision using particle brushes. This method is used a lot in the precise grinding of cylinder surfaces, inner surfaces of pipes, the plane of mold and parts of complex shapes.[1-9] Shinmura[10-11] developed a sintered magnetic abrasive and investigated its influence on the grinding characteristics of precise machining of high hardness material, the shape of magnetic poles, and the distance between magnetic poles. Chang[12] used an unbonded magnetic abrasive which mechanically mixed SiC abrasive and steel grit, and performed precise machining of cylindrical materials to confirm its machinability. Jain[13] clarified that working gap and rotational speed affect material removal and surface roughness in the magnetic abrasive finishing of cylindrical stainless steel. Yamaguch[14-17] used a magnetic abrasive method to manufacture clean pipes for semiconductor production and the medical industry. By performing precise machining on the inner surface of pipes using this method, he developed a variety of machining methods for hollow materials and investigated how the type of magnetic abrasives, shapes of magnetic poles, and magnetic flux density affect precision machining. Kim[18] investigated how the machining conditions affect on surface roughness by applying magnetic abrasive using WC-Co abrasive particles to the inner surface of STS 304 pipe and clarified that the surface roughness gets improved as the magnetic flux increases. Vahdati[19] used a NC machine to perform precise machining of the surface of aluminum alloy flat plate, obtained a surface roughness of Ra 0.6 ㎛ using a Nd-Fe-B permanent magnet and a magnetic abrasive tool, and reported that the optimum distance between a rotating pole and the workpiece is 5 mm. Park[20] fabricated a magnetic abrasive device that incorporated a magnetic pole vibration method to perform inner abrasion of pipe. And he reported that adding vibration to a magnetic pole increases the abrasion amount than the case of not adding vibration, and the surface roughness gets improved as a result. Kim[21] clarified that magnetic abrasive polishing could be useful to remove burrs in magnesium alloy.

Recently, many types of magnets have enabled the finishing of various materials using machining technologies under 3,000 rpm.[1-13] However, if machining speed is increased and the time is slightly lengthened, the magnetic abrasive method can be used both for finishing and the precise dimensional control of manufactured products at the micro-level. A magnetic abrasive micro machining system with high and changeable rotational speed was developed for this study. We considered the micro machining characteristics of high-hardness bars, a difficult-to-cut material in terms of rotational speed, vibration frequency, and particle size.

2. Experiment System and Method

Our experimental equipment consisted of a high speed spindle, a magnetic abrasive unit, and an electric slider. Fig. 1 shows the experimental layout.

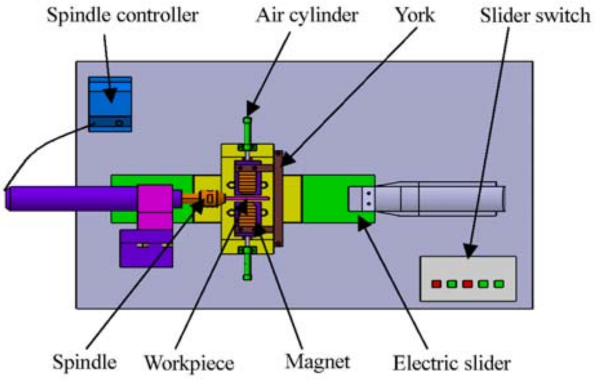


Fig. 1 Main appearance of micro magnetic abrasive machine

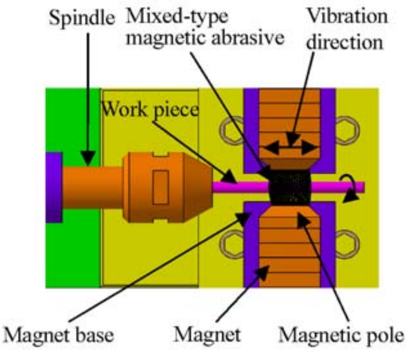


Fig. 2 Micro magnetic abrasive unit

The workpiece was attached to the high-speed spindle of the main axis and rotated on a magnetic abrasive unit. The speed of spindle could be adjusted in the range of 1,000 to 25,000 rpm. As shown in Fig. 2, the magnetic abrasive unit had mixed-type abrasive particles filled between the north-south (N-S) poles. The workpiece was inserted into the particle brush of the mixed-type abrasive and rotated. At the same time, the poles arranged on the magnetic base resulted in vibration in the parallel direction parallel to the axis of the spindle. With this procedure, the outer surface of the cylinder was micro machined. Axial vibration of the magnetic abrasive unit was caused by the vibration of the electric slider unit. Through the control of this electric slider, the frequency of the magnetic pole could be adjusted.

Table 1 shows the experimental conditions and the mechanical characteristics. The rotational speed was 1,000, 10,000, 20,000, and 25,000 rpm, which is considered fairly high in the magnetic abrasive field. The workpiece was non-magnetic tungsten carbide on which the precise machining was made with the centerless grinder. Shape precision and surface precision of tungsten carbide are hard to acquire due to its high abrasion resistance and hardness. For the micro machining of this material, we used the unbonded mixed-type magnetic abrasive (hereinafter, “mixed-type magnetic abrasive”) which is a mechanical mixture of diamond paste, iron powder, and light oil. The processing width of the magnetic poles for the micro machining was 10 mm, and the interval between the material and the pole was 0.7 mm.

Table 1 Experimental conditions

Rotational speed	1,000, 10,000, 20,000, 25,000 rpm
Magnet	Permanent magnet (Nd-Fe-B): 20×10 mm
Axial vibration of magnetic pole frequency	0, 3, 10, 20 Hz (amplitude: 1 mm)
Magnetic abrasive tool (unbonded)	Diamond paste (0.2 g) + iron particles (0.8 g) + light oil (7 ml)
Diamond particle size	0.5, 1, 3, 6, 15 ㎛
Iron particle mean size	75 ㎛
Clearance (working gap)	0.7 mm
Processing time	0, 20, 40, 60, 80, 100, 120, 140, 160 sec
Workpiece	Nonmagnetic tungsten carbide: ϕ 3 mm × 50 mm ^{L} Hardness: 88.0 HR$_{A}$ Density: 14.3 g/cm^{2}
Magnetic flux density	0.41 T

3. Experimental Results

Because magnetic machining is a technology still in development, workability under diverse conditions has not yet been clearly established. In the case of outer surface processing, magnetic machining at 3,000 rpm or higher has never been carried out. In this study, a magnetic micro machining system which has a changeable high rotational speed of 10,000 rpm or higher was produced for the application of high efficiency and high precision. In addition, the effect of high machining speeds on the characteristics of the surface roughness and the roundness and the processing instruments were examined.

3.1 Micro machining characteristics of difficult-to-cut hard workpiece according to change in rotational speed

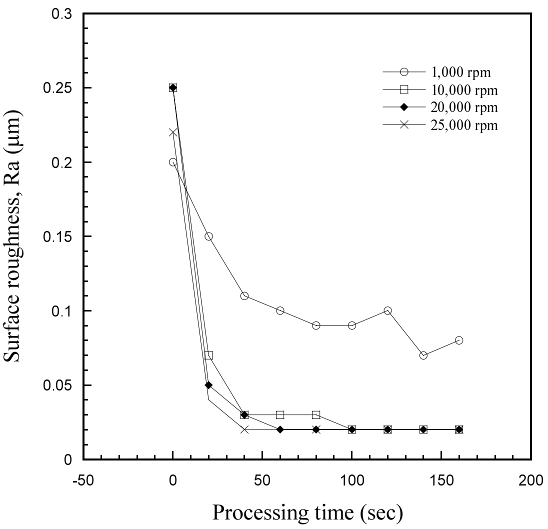
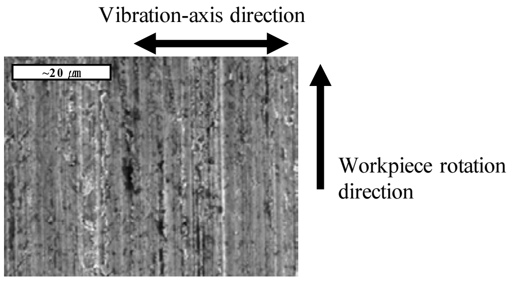


Fig. 3 Variations of surface roughness vs. processing time (magnetic pole frequency: 10 Hz, diamond particle size: 0.5 ㎛)

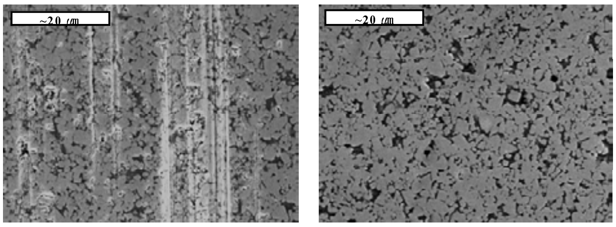
Fig. 3 shows the relationship between processing time and surface roughness (Ra) for various values of rotational speed. The frequency of the magnetic pole was 10 Hz, the interval between the pole and the workpiece was 0.7 mm, and the rotational speed of main spindle was 1,000, 10,000, 20,000 and 25,000 rpm respectively. As a reference for the characteristics of surface roughness at the high speeds, a low speed condition of 1,000 rpm was also included. In case of 10,000 rpm or higher, the speed of improvements in surface roughness was far faster than that of 1,000 rpm, and the deviation was smaller in general. At high rotational speed, it was found that the surface roughness value converged within 60 sec, and did not improve further. This process was a finishing process to remove unevenness on the surface of the workpiece. The process after this is a machining process in which most of unevenness is removed and the machining is performed on the workpiece. The surface roughness is not improved further and the change in diameter occurs only by machining. In the experiment, the surface roughness was obtained up to 0.02 ㎛.

Fig. 4 shows scanning electron microscope (SEM) images of the surface of the workpiece (2,000 x) before and after magnetic machining while changing the rotational speed. As the workpiece was processed with the centerless grinder, traces of plowing and grinding can be seen. It was found that the scratches generated by preprocessing had not been removed on the machining surface. Scratches were seen on the finished surface. We judged that the scratches had enlarged the amplitude of surface roughness at 1,000 rpm. In the cases of (c), (d), and (e), the surface roughness of the workpiece was improved tenfold or more. The traces of grinding were all removed and the scratches on the finish were hardly seen.

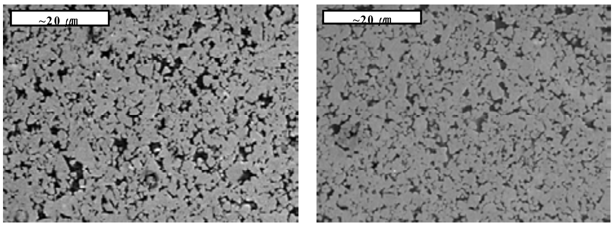
Fig. 5 shows the improvement in roundness versus the change in machining time. In the improvement of roundness, the case of 1,000 rpm was the slowest. Among the four conditions, the speed of improvements in roundness was best at 20,000 rpm and the next were 25,000, 10,000 and 1,000 rpm in order. Comparing roundness with the converging time of surface roughness in Fig. 3, the surface roughnesses all converged within 100 sec, but the roundness continued to improve even after 100 sec. It seems that because this experiment is a micro removal processing which removes the material so small, it takes more time than the time for improvement of surface roughness.



(a) Unfinished surface (0 sec, Ra: 0.25 ㎛)



(b) 1,000 rpm (Ra: 0.08 ㎛) (c) 10,000 rpm (Ra: 0.02 ㎛)



(d) 20,000 rpm (Ra: 0.02 ㎛) (e) 25,000 rpm (Ra: 0.02 ㎛)

Fig. 4 Photos of workpiece surface before and after magnetic machining (case a: 0 sec, case b, c, d: 160 sec)

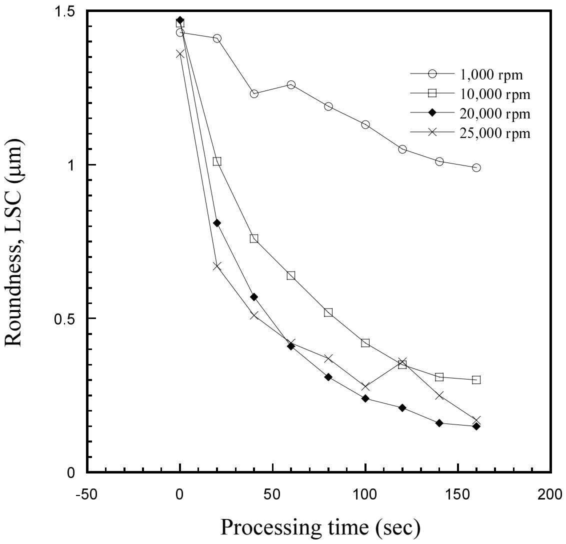
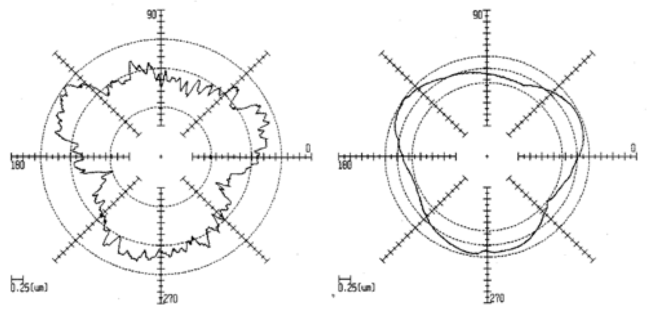


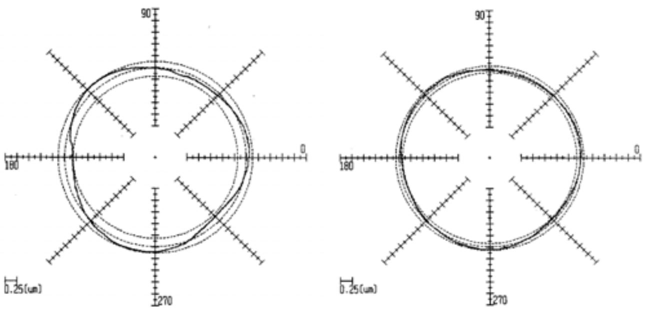
Fig. 5 Variations of roundness vs. processing time (magnetic pole frequency: 10 Hz, diamond particle size: 0.5 ㎛)

Fig. 6 shows the improving procedure of roundness in case of 20,000 rpm. As (a) shows, the sections with the greatest degree of unevenness are 0°~45°, 135°~180° and 225°~315°. It can be thus understood that preferential removal of these sections will enable the roundness to be improved. (b)~(d) are processes where the workpiece is machined in radial direction after removing the uneven section, it is found that the roundness is improved mainly on the high level section as pointed in (A).



(a) Roundness: 1.47 ㎛
Processing time: 0 sec

(b) Roundness: 0.57 ㎛
Processing time: 40 sec



(c) Roundness: 0.31 ㎛
Processing time: 80 sec

(d) Roundness: 0.15 ㎛
Processing time: 160 sec

Fig. 6 Improvement tendency of roundness (rotational speed: 20,000 rpm, diamond particle size: 0.5 ㎛, magnetic pole frequency: 10 Hz)

Fig. 7 shows the relationship between processing time and accumulated change of diameter at various rotational speeds of main spindle. At 1,000, 10,000, and 20,000 rpm, the change of accumulated diameter in proportion to the speed increase is clearly seen in the change of the slope. At 20,000 and 25,000 rpm, the phase was different. It was confirmed that under the experimental conditions, the case of 20,000 rpm showed the highest slope in the change of the micro diameter. On the other hand, since the magnitude of the magnetic field (a permanent magnet was used) and the diameter of workpiece were constants in this experiment, the friction force between the workpiece and the particles was constant regardless of the increase in rotational speed. However, the circumferential speed increased as the rotational frequency increased, and it is believed that the increase in sliding phenomenon resulted in the decrease of abrasion amount for the case of 25,000 rpm. Furthermore, as shown in Fig. 8, the accumulated removal weight versus the processing time had an almost a linear tendency. At 20,000 rpm, the slope of the micro-weight change was excellent. Thus, it is understood that the outer surface of the nonmagnetic tungsten carbide can be linearly processed for finishing/machining in a shorter time using a magnetic abrasive device rotating at high speed with a relatively simple structure.

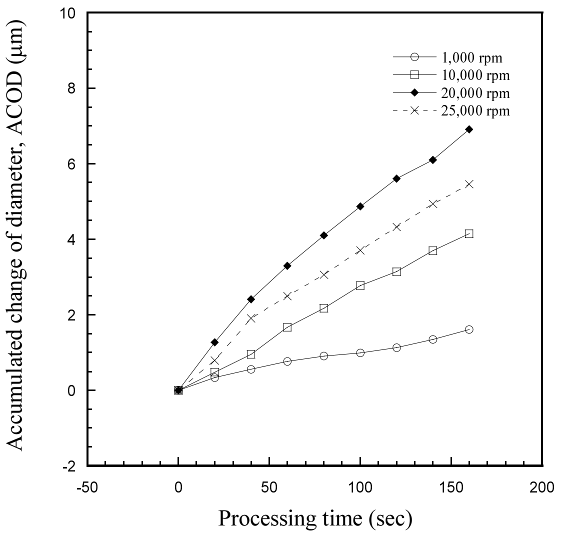


Fig. 7 Variations of accumulated change of diameter vs. processing time

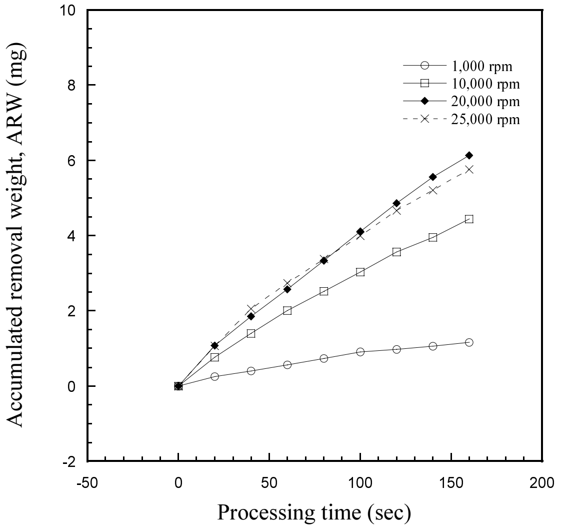


Fig. 8 Variations of accumulated removal weight vs. processing time

3.2 Characteristics of micro machining in accordance with frequency change of high-hardness workpiece

This section deals with the effect of micro machining in accordance with the frequency change imposed on the workpiece at high speed. Fig. 9 shows the relationship between processing time and surface roughness for change of frequency. The frequency of the magnetic poles was 0 Hz, 3 Hz, 10 Hz, and 15 Hz, and the rotational speed of main spindle was 20,000 rpm. The graph shows that the improving slope of surface roughness was relatively greater during the initial stage. This was apparently because the cylindrically-ground product had much surface unevenness prior to magnetic machining, and the unevenness was rapidly removed while improving the roundness relatively quickly. Under the four conditions, the surface roughness was classified into two groups of 0 Hz and 3/10/20 Hz. In the case of 0 Hz, as shown in Fig. 10(a), the processing traces were made in the same direction as the rotational direction of the workpiece. We note that the surface roughness, which was measured in the same direction and the 90° direction, was worse than that of 3 Hz, 10 Hz, and 20 Hz cases. In the graph, the frequency of the magnetic poles with the fastest improvement of surface roughness is 10 Hz. In this case, the surface roughness converged to 0.02 ㎛ after 60 sec. In the case of 20 Hz and 3 Hz, it converged to 0.02 ㎛ after 80 and 100 sec, respectively. Our results showed that in case of 3, 10, and 20 Hz, the change in frequency had no impact on the change of surface roughness but did affect the processing time.

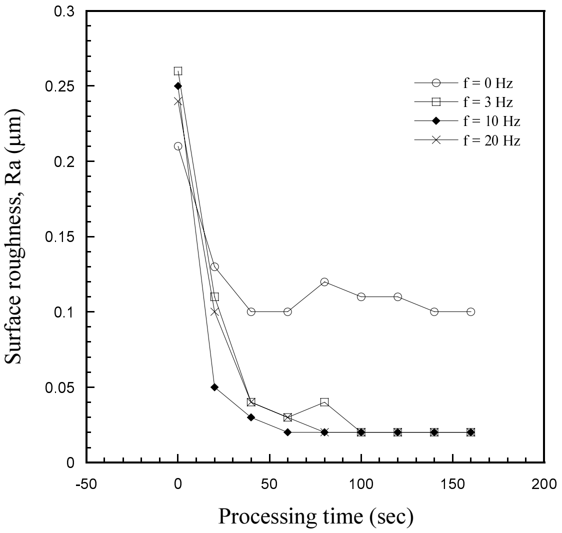
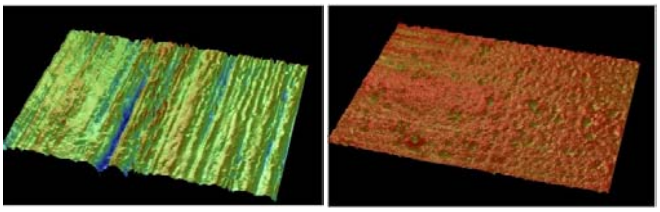
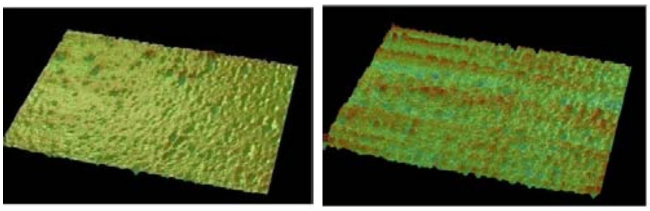


Fig. 9 Variations of surface roughness vs. processing time (rotational speed: 20,000 rpm, diamond particle size: 0.5 ㎛)



(a) Magnetic pole frequency: 0 Hz

(b) Magnetic pole frequency: 3 Hz



(c) Magnetic pole frequency: 10 Hz frequency:10Hz

(d) Magnetic pole frequency: 20 Hz

Fig. 10 Image showing the improved surface state in accordance with the frequency change of magnetic pole (160 sec)

Fig. 11 shows the micro-scale change in workpiece diameter in accordance with the change of frequency. In four conditions, the diameters were controlled in a micro scale. At 10 Hz, the change in diameter was excellent. At 20 Hz, the change of diameter was relatively smaller than that of 10 Hz. Magnetic abrasive machining is accompanied by vibration movement. However, if the vibration increases beyond a certain level, the friction between the workpiece and the abrasive particles decreases. Accordingly, it is judged that the abrasive effect at 20 Hz would decrease rather than for the case of 10 Hz.

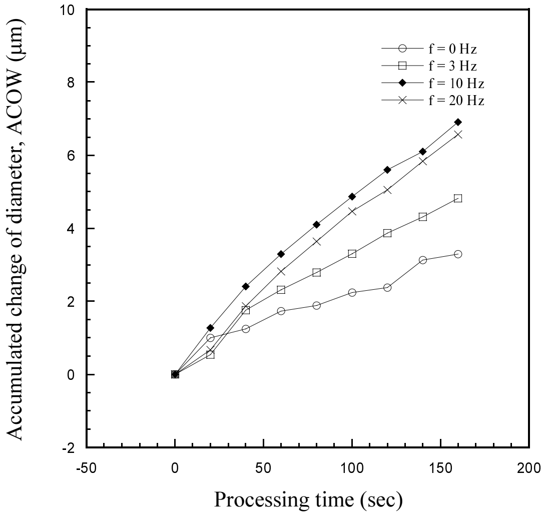


Fig. 11 Variations of accumulated change of diameter vs. processing time

At 0 Hz where no vibration was imposed on the magnetic pole, the ability to control the diameter was lowest. Therefore, vibration helps increase the diameter processing speed for appropriate diameter control.

3.3 Micro machining characteristics of the workpiece in accordance with particle size

Fig. 12 shows the relationship between processing time and surface roughness (Ra) for change of diamond particle size. The particle sizes were 0.5, 1, 6, and 15 ㎛, the rotation speed of the

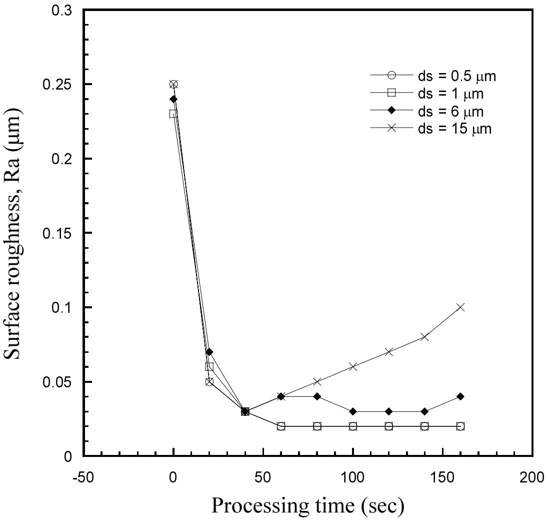
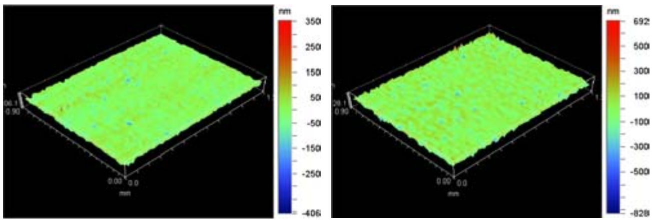
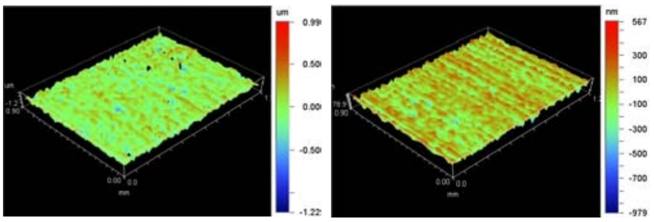


Fig. 12 Variations of surface roughness vs. processing time (rotational speed: 20,000 rpm, magnetic pole frequency: 10 Hz)

material was 20,000 rpm, and the interval between the workpiece and the magnetic pole was 0.7 mm. The figure shows that the improvement in surface roughness around 0~40 sec was very great because the initial unevenness was rapidly removed and a steep slope was formed. The process after 40 sec was analyzed to be a micro machining process where the workpiece was machined in micro-scale instead of a finishing process where most of the uneven sections are removed. In the case of large particle sizes, therefore, the surface roughness was not improved, and the machining by particles caused an inferior surface roughness. When machined by particles with sizes of 0.5 and 1 ㎛, the surface roughness was 0.02 ㎛, which is an excellent value. The surface roughness converged within approximately 60 sec under general conditions, which means that the time required to improve the surface roughness was very short.



(a) Diamond size: 0.5 ㎛ (b) Diamond size: 1 ㎛



(c) Diamond size: 6 ㎛ (d) Diamond size: 15 ㎛

Fig. 13 Surface state of workpiece in accordance with size change of diamond particles (processing time: 160 sec)

After processing for 160 sec, the finishing process was completed, leading to the micro machining stage where the surface roughness depends on the particle size. Fig. 13 shows an image obtained from the surface of the workpiece using a 3-D optical profiling system. In (a) and (b), ultra-precise size diamond particles were used, and there is no relative difference in the distribution of height on the surface due to low evenness on the surface. (c) and (d) used 6 ㎛ and 15 ㎛ particle sizes, respectively, and their surface status was not excellent due to higher unevenness than (a) and (b). In particular, a significant degree of unevenness can be observed in the case of 15 ㎛, largest particle size.

Fig. 14 shows the relationship between processing time and accumulated change of diameter at various size of diamond particles. Here, we note that it is linear in general. If the particle size increases, the processing slope of the diameter tends to increase. When the diameter was 15 ㎛, its micro machining ability was excellent. The average diameter machining ability was 3.0 ㎛ per 20 sec. When the diameter was 0.5 ㎛, its average diameter machining ability was 0.16 ㎛ per 20 sec. And, when the diameter was 1 and 6 ㎛, the ability was 0.67 and 2.16 ㎛, respectively.

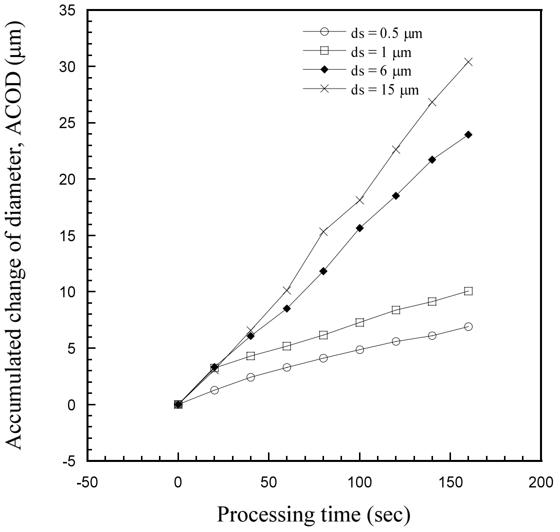


Fig. 14 Variations of accumulated change of diameter vs. processing time

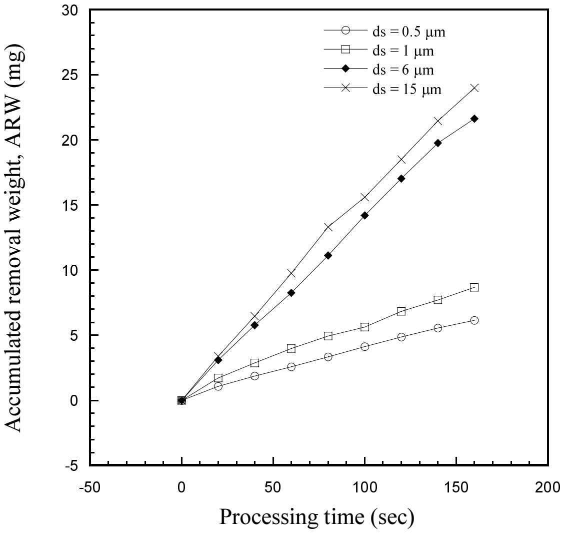


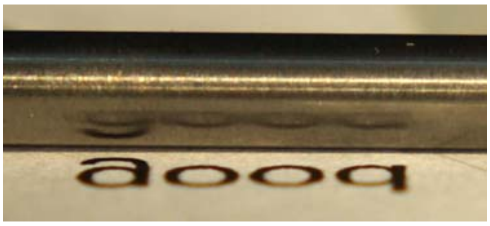
Fig. 15 Variations of accumulated removal weight vs. processing time

Fig. 15 presents the change in accumulated removal weight versus processing time. At the initial stage of machining, a large particle size and a small particle size were clearly differentiated. In the machining section after 20 sec, however, it depends on the size of tools (particles). Thus, micro machining is possible because the removal amount at high hardness tends to increase linearly, depending on the particle size.

3.4 Surface removal characteristics of workpiece

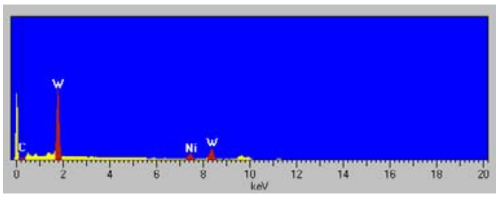
Fig. 16 shows surface photos before and after the micro machining, and the EDX test result from the electron microscope. (a) and (b) compare the processing state of the surface through a mixed-type magnetic abrasive with a diamond particle size of 0.5 ㎛. (a) is the surface before the processing: its surface roughness was Ra 0.25 ㎛ and Ry 2.2 ㎛. (b) is the surface after processing: its surface roughness was Ra 0.02 ㎛ and Ry 0.2 ㎛. The processed surface is a mirror face clearly reflecting the bottom letters. (c) and

(d) are the EDX test graphs on the surfaces of (a) and (b) by SEM. Before processing, the WC component was 89.87% and the Ni component was 10.13%. After processing, the WC component was 89.68% and the Ni component was 10.32%. Thus, there was almost no change of components. The components of iron and diamond were not left on the material.

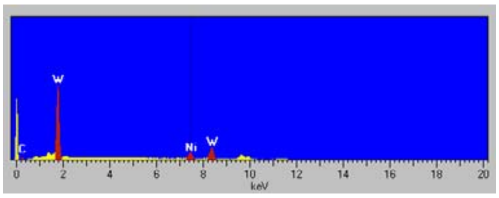


(a) Before micro machining

(b) After micro machining (20,000 rpm, 10 Hz, 0.5μm)



(c) Before micro machining



(d) After micro machining (20,000 rpm, 10 Hz, 0.5μm)

Fig. 16 Surface photos before and after micro machining and EDX test result

4. Conclusions

A high-speed magnetic abrasive system that can control rotational speed was developed. The impact of a wide range of high processing speeds on the dimensional precision and surface precision of high-hardness material was examined, along with the processing equipment.

1. By changing the rotational speed, the vibration frequency of the magnetic pole, and the micro machining diamond particle size, the diameter of difficult-to-cut material with high hardness could be controlled in an almost linear way.
2. Through a change in processing condition, a surface roughness of mirror face level could be achieved. The best surface roughness was Ra 0.02 μm.
3. To enhance roundness we used a high rotational speed, which improved the processing time and the dimensional precision. Under our experimental conditions, 20,000 rpm was the optimum speed, and roundness was obtained up to 0.15 μm.
4. For micro-unit processing of the workpiece diameter, it was advantageous to give the vibration in reducing the processing time. 10 Hz was the optimum frequency in reducing the processing time.
5. Micro machining ability was best at a diamond size of 15 μm, and its average processing ability per 20 sec was 3.00 μm. When the size was 0.5 μm, its ability was 0.61 μm/20 sec. When the size was 1 and 6 μm, it was 0.67 and 2.16 μm, respectively.
6. Before and after the machining, there was little change in the WC and Ni components of material, and there was no residues of mixed-type magnetic abrasive components such as iron and diamond on the material.

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