ABSTRACT
This paper describes a newly developed mechanochemical superabrasive stone containing CeO$_2$ abrasive. The effect of CeO$_2$ abrasive on their performances was evaluated through the superfinishing of optical glass. It was found that soft CeO$_2$ abrasive rubs the surface of optical glass producing smooth surfaces with fewer scratches than diamond abrasive. The addition of CeO$_2$ abrasive improves the surface integrity of optical glass because it reduces production of scratches by diamond abrasive.

INTRODUCTION
Abrasion machining using bonded abrasives provides rapid material removal and high dimensional accuracy. In addition, using mechanochemical stones [1], which have interfacial reaction with works, they provide better surfaces. On the basis of this way of thinking, some mechanochemical stones, containing cerium oxide, CeO$_2$, have been developed [2, 3]. Authors have developed new vitrified-bonded superabrasive stones, which contains the abrasive CeO$_2$, and have investigated the chemical reaction between CeO$_2$ and Fe theoretically and experimentally [4]. The abrasive CeO$_2$ is softer than the optical glass but reacts chemically with them [5]. Using these stones, it was possible to obtain a smooth surface with fewer scratches, which was not possible when using conventional diamond stones.

In this paper, the performances of CeO$_2$ stone, diamond stone, and diamond stone containing CeO$_2$ abrasive are evaluated and compared through superfinishing experiments of optical glass.

PERFORMANCE OF MECHANOCHEMICAL SUPERABRASIVE STONE
Test Stones
A Mechanochemical superabrasive stone was developed for superfinishing of optical glass. It consists of CeO$_2$ 20000-grit size with vitrified bond. In this paper, this is referred to as CeO$_2$ stone. In addition, a mechanochemical superabrasive stone, which consists of CeO$_2$ of 20000-grit size and synthetic diamond of 4000-grit size with vitrified bond, was developed. This is referred to as SD/CeO$_2$ stone in this paper. A conventional vitrified SD stone was also prepared to investigate the effect of the CeO$_2$ abrasive on the performance of stone.

Experimental Procedures
All tests were performed on a centerless flat surface lapping machine. The machine is shown in Fig. 1. The workpiece was face-finished by a rotating cup-shaped superabrasive stone with oscillating motion. Table 1 tabulates the superfinishing conditions that were used.
Results and Discussions
CeO₂ Stone
If the CeO₂ abrasive actually reacts on an optical glass workpiece in the superfinishing process, the material removal rate of the stone containing the CeO₂ abrasive will obey the Arrhenius equation, because of the temperature dependence of chemical reaction rate.

\[ k = A \exp \left( -\frac{E}{RT} \right) \]  

where \( k \) is the reaction rate, \( A \) is the pre-exponential factor, \( E \) is the activation energy, \( R \) is the gas constant, and \( T \) is the absolute temperature.

The removal rate of the CeO₂ stone was analyzed based on this empirical law for coolant temperature from 283 K to 313 K. Fig. 2 shows the Arrhenius plot of the logarithm of the removal rate against the reciprocal of the temperature. The removal rate of the CeO₂ stone increase almost linearly as the temperature increases. Calculating the apparent activation energy from the slope of the straight line gives 10.9 kJ/mol for the CeO₂ stone.

Fig. 3 shows the finishing ratio against the temperature. The finishing ratio of the CeO₂ stone increase almost linearly as the temperature increases because of the increase of the removal volume and the decrease of the stone wear volume. These results indicate that the CeO₂ abrasive reacts on an optical glass workpiece in the superfinishing process.

Fig. 4 shows the roughness values, \( Ra \), of the surfaces generated by the CeO₂ stone. The CeO₂ abrasive hardly scratches the surface of optical glass but only rubs it, because of its friability. Nevertheless, the CeO₂ stone effectively generates a smoother surface.

Fig. 5 shows the superfinished surface of BK7 with the CeO₂ stone. The surface has fewer scratches than conventional diamond stones. In some case, however, few scratches, which were generated with diamond abrasive during pre-finishing process, remains after superfinishing.

<table>
<thead>
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<th>TABLE 1. Superfinishing conditions.</th>
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FIGURE 5. Superfinished surface of BK7 with CeO2 stone. PV=56.6 nm, rms=2.3 nm, and Ra=1.5 nm.

**SD/CeO2 Stone and SD Stone**

As mentioned above, pre-finishing-process-oriented scratches sometimes remained after superfinishing with CeO2 stone. To improve the integrity of the finished surface, it is necessary to reduce such scratches.

From this standpoint, we investigated the performances of SD/CeO2 stone and SD stone using method of experimental design.

Table 2 tabulates the superfinishing conditions that were used. Superfinishing conditions were arranged following orthogonal table of L25(5^4), i.e. four factors (superfinishing pressure $P$, stone speed $V_2$, workpiece speed $V_1$, and superfinishing time $t$) with five levels respectively. After superfinishing, removal rate $S$, wear ratio $W_{ratio}$, roughness value $Ra$, and scratch depth $R_{P-V}$ were analyzed with multiple linear regression analyses.

The multiple-regression models obtained are as follows:

removal rate $S \propto V_2^\alpha P^\beta t^{-\gamma}$  \hspace{1cm} (2)
wear ratio $W_{ratio} \propto V_2^{-\epsilon} P^{-\delta} t^{-\epsilon}$  \hspace{1cm} (3)
roughness value $Ra \propto V_2^\phi P^{-\eta}$  \hspace{1cm} (4)
depth of scratch $R_{P-V} \propto V_2^{-\nu} P^{-\sigma}$  \hspace{1cm} (5)

From these formulae, when superfinishing at the same superfinishing time, all of those finishing characteristics just depend on superfinishing pressure $P$ and stone speed $V_2$. Therefore, we can estimate optimum superfinishing condition to maximize removal rate with certain constraint conditions.

Fig. 6 shows an example of an optimum superfinishing condition of SD/CeO2 stone at $t=180$ s, $Ra=0.02 \mu m$, $R_{P-V}=0.15 \mu m$, and $W_{ratio}=0.5$. The optimum condition is $V_2=452$ m/min and $P=0.49$ MPa, and the removal rate $S=3.6$ mm^3/min.

**TABLE 2. Superfinishing conditions for method of experimental design.**

| Superfinishing pressure | 0.09-0.49 MPa |
| Stone speed            | 113-452 m/min |
| Workpiece speed         | 66-132 m/min  |
| Frequency of oscillation| 16.7 Hz       |
| Amplitude               | 0.5 mm        |
| Superfinishing fluid    | Dilute solution of rust inhibitor in water, Concentration=1% |
| Temperature             | 293 K         |
| Superfinishing time     | 60-180 s      |
| Workpiece material      | BK7           |

**FIGURE 6. Optimum condition of SD/CeO2 stone.** $t=180$ s, $Ra=0.02 \mu m$, $R_{P-V}=0.15 \mu m$, $W_{ratio}=0.5$, $V_2=452$ m/min, $P=0.49$ MPa, $S=3.6$ mm^3/min.

**FIGURE 7. Superfinished surface of BK7 with optimum superfinishing condition of SD/CeO2 stone.** PV=90.2 nm, rms=8.4 nm, and Ra=6.4 nm.
estimated is \( S = 3.6 \, \text{mm}^3/\text{min} \).

Fig. 7 shows an example of a superfinished surface of BK7 with optimum superfinishing condition of SD/CeO\(_2\) stone. Using the optimum condition, it was possible to produce smooth surface without deep scratches in high removal rate and in one minute. This is probably due to both chemical removal with the CeO\(_2\) abrasive and mechanical removal by the diamond abrasive.

**SCRATCHLESS SURFACE FINISHING PROCESS**

Fig. 8 shows scratchless surface finishing process with SD stone, SD/CeO\(_2\) stone, and CeO\(_2\) stone. This process does reduce process time and improves the surface integrity. Thus, this process maybe much useful to larger optical glass, such as reflecting mirrors of next generation extremely large telescopes.

**CONCLUSIONS**

The SD/CeO\(_2\) stone produces smooth surface with less scratch, good roughness, and small stone wear, and high removal rate; that is, the SD/CeO\(_2\) stone is suitable for pre-finishing. The CeO\(_2\) stone reacts with optical glass surface and produces a smooth surface with less scratch that is suitable for finishing process of reflecting mirrors. Add to these results, the total finishing time of the process is shorter than two minutes. Consequently, it is concluded that the process chain has a superior finishing performance.

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**REFERENCES**