1. INTRODUCTION

The roughness of rolling bearings operating under a mixed or boundary lubrication region is detrimental to the fatigue life of the bearings. Thus, their surfaces are finished to increase the elastohydrodynamic lubrication (EHL) oil film parameter. But, the current view gaining support is that smooth surfaces with negative skewness, i.e., ones with valleys, lengthen the bearing life [1]. However, such a surface morphology cannot be produced by ordinary superfinishing because a chemical action would be required. By combining the rubbing action by soft and reactive abrasives with the scratching action by hard abrasives, it is possible to produce a smooth surface with valleys. In order to realize this process in a vitrified-bonded superabrasive stone, some fundamental and practical questions were examined, as follows.

First, the soft abrasive reaction with the steel was examined by considering the degree of chemical equilibrium. Second, basic experiments were performed to check whether the selected abrasive reacts with the steel in actual practice. And last, in order to examine whether the expected surface morphology could be produced, superfinishing experiments were conducted using superabrasive stones made by mixing the reactive abrasive with the superabrasive.

2. SELECTED REACTIVE ABRASIVE AND ITS CHEMICAL REACTION

CeO$_2$ has the property of storing oxygen, and releasing and uptaking oxygen due to the following reversible reaction [2]:

\[ 2\text{CeO}_2 = \text{Ce}_2\text{O}_3 + \frac{1}{2}\text{O}_2 \]  

Taking this reaction into consideration, it is expected that the reduction of CeO$_2$ to Ce$_2$O$_3$ and oxidation of Fe to FeO, Fe$_3$O$_4$ or Fe$_2$O$_3$ occur simultaneously when CeO$_2$ is in contact with Fe under the oxygen-lean condition. Hence, both thermodynamic simulations and experimental observations were carried out.

Figure 1 shows the Gibbs free energy change $\Delta G^0_T$ in the oxidation of iron by CeO$_2$ as a function of the atmospheric temperature. Since $\Delta G^0_T < 0$ in this figure, it can be predicted that CeO$_2$ forms various iron oxides in association with O$_2$. Moreover, since $\Delta G^0_T < 0$ at temperatures higher than 450 K or 800 K, it can be predicted that CeO$_2$ together with H$_2$O produces the iron oxide. Thus, it is confirmed in principle that CeO$_2$ oxidizes Fe in conditions in

![Figure 1. Change in Gibbs free energy in reduction of CeO$_2$ and oxidation of Fe.](image-url)
which oxygen is in short supply. Nevertheless, it is necessary to confirm whether such chemical reactions occur in practice; therefore, simple experiments were performed.

Two Fe specimens were heated at 773 K for 6 h in a high vacuum of $4.2 \times 10^{-3}$ Pa; one specimen was embedded in CeO$_2$ powder, but the other was not. Although the specimen surface with heat only was hardly damaged, the one inside CeO$_2$ powder with heat cracked and came off in scales. From this finding, it is obvious that the scales that formed under the reducing condition resulted from CeO$_2$. The scales were analyzed by X-ray diffractionmetry to determine the type of ferric oxide.

Figure 2 shows the X-ray diffraction pattern of the scale. In the diffraction pattern, peaks of Fe$_3$O$_4$ together with $\alpha$-Fe are seen, so it is concluded that CeO$_2$ powder in contact with the steel forms an oxide layer of Fe$_3$O$_4$ under the oxygen-lean condition. The diffraction pattern also gives vital information about the chemical change of CeO$_2$. Three diffraction peaks are seen at the diffraction angles $2\theta$=$28.20^\circ$, $32.68^\circ$ and $46.80^\circ$, which relate to the interplanar spacings $d=3.162$ Å, $2.738$ Å and $1.940$ Å, respectively. These interplanar spacings differ from those of CeO$_2$ [3] and are slightly larger than those of the unused CeO$_2$ powder. Therefore, the peaks are thought to be an oxide of cerium in the range of CeO$_2$-CeO$_{1.714}$, i.e., the oxygen-deficient non-stoichiometric oxide [2]. Many predictions have been made as to the formation of Fe$_3$O$_4$ by CeO$_2$, as depicted in Fig. 1. The process can be represented in the following equation:

$$4\text{CeO}_2 + 3\alpha\text{Fe} \rightarrow 4\text{CeO}_{2-x} + x\text{Fe}_3\text{O}_4 \ (2)$$

3. SUPERFINISHING CHARACTERISTICS

3.1 Experimental Procedures

Mechanochemical superabrasive stones were made experimentally by mixing CeO$_2$ powder, called CeO$_2$ abrasive in this paper, with CBN abrasive. Since the CeO$_2$ abrasive is thermally unstable, the special vitreous bond of a low melting point less than 1000 K was developed. In addition to the above CBN/CeO$_2$ stone, a conventional vitrified CBN stone and a vitrified CeO$_2$ stone that consists of only bonded CeO$_2$ abrasive were prepared in order to investigate the effect of the CeO$_2$ abrasive on the superfinishing characteristics.

Figure 3 shows SEM micrographs of the structure of the CeO$_2$, CBN/CeO$_2$ and CBN stones. In the CBN stone, it seems that CBN grit with sharp edges and smooth faces is anchored by bond posts, while in the CBN/CeO$_2$ stone, it seems that CBN grit attaching CeO$_2$ grits is retained by bond posts. In contrast with these two stones, the CeO$_2$ stone is different in the structure. It seems that agglomerate CeO$_2$ grits are dispersed into the bond posts.

All tests were performed on a flat superfinishing machine. The end of the workpiece was secured to the work spindle, then face-finished by the rotating cup-shaped abrasive stone without...
oscillating motion. During the superfinishing process, water-based superfinishing fluid was used as a coolant that would exclude any chemical reaction. Table 1 tabulates the superfinishing conditions that were used.

3.2 Results and Discussions
In general, the chemical reaction rate tends to increase with a temperature rise, and this temperature dependence is described by an Arrhenius equation of the following form [4]:

\[ \kappa = A \exp \left( -\frac{E}{RT} \right) \]  \hspace{1cm} (3)

where \( \kappa \) is the reaction rate, \( A \) is the frequency factor, \( E \) is the activation energy, \( T \) is the absolute temperature and \( R \) is the gas constant. If the reaction rate is taken into account, the material removal rate of stones containing CeO\(_2\) abrasive is presumed to depend on the temperature of the superfinishing fluid. Therefore, the removal rate of CeO\(_2\) stone was examined over the temperature range from 298 K to 333 K, then compared to that of CBN stone. Figure 4 shows the Arrhenius plot of the removal rate versus the temperature of the superfinishing fluid. In the CBN stone, there is almost no change in removal rate. In contrast, in the CeO\(_2\) stone, the increase in removal rate is almost linear with increasing temperature, so that the apparent activation energy can be calculated to be 32.8 kJ/mol. This means obviously that the CeO\(_2\) stone has the ability to chemically remove a steel workpiece during the superfinishing process.

Figure 5 shows the roughness profiles of the superfinished surfaces and the corresponding height distribution functions. The interaction of CBN abrasive cutting points with the workpiece leaves overlapping scratches on the workpiece surface, so that the roughness profile is very rugged and generally has a symmetrical height distribution. On the other hand, since the CeO\(_2\) abrasive exerts the combined action of a chemical attack and mechanical abrasion on the workpiece surface, the roughness profile is truncated and has clearly an asymmetrical height distribution.
The skewness, which is a third-order measure of the symmetry of a profile, offers a convenient way to illustrate the feature of the profile shapes and height distribution functions. Therefore, the profiles generated by three different stones were evaluated in terms of the skewness, as shown in Fig. 6. It is found that the valley-covered surface generated by the CeO$_2$ stone gives a negative skewness, whereas the bump-covered surface generated by the CBN stone gives a slightly positive skewness. In comparison with these two stones, the CBN/CeO$_2$ stone is found to generate a normal surface, i.e., it is neither a valley-covered surface nor a bump-covered surface, and gives a zero skewness. Therefore, an appropriate CeO$_2$ abrasive content will result in the generation of a smooth surface with negative skewness that is suitable for bearings.

The feature of the superfinished surfaces generated by the stones of different kinds is also reflected in the roughness, as seen in Fig. 7. The CBN stone has Ra surface roughness values in the range of 0.02-0.03 µm, whereas the CeO$_2$ stone has values in the range of 0.05-0.1 µm because of the persistence of the valleys of the roughness profile. However, the CBN/CeO$_2$ stone with the scratching and chemical actions seems better for the surface roughness than the other stones. The CBN/CeO$_2$ stone has roughness values in the range of 0.015-0.02 µm. Hence, it can be understood that the addition of CeO$_2$ abrasive to a superabrasive stone is effective in smoothing the steel workpiece surface.

4. CONCLUSIONS
The present study was an attempt to develop a vitrified-bonded superabrasive stone for mechanochemical superfinishing of bearing steels. Cerium oxide CeO$_2$, when in contact with steel under the oxygen-lean condition, forms an oxide layer of Fe$_3$O$_4$ on the steel surface. On the basis of this interesting point, a vitrified CeO$_2$ stone and a superabrasive stone containing CeO$_2$ abrasive, i.e., CBN/CeO$_2$ stone, were made experimentally and their performance was evaluated with respect to the superfinishing characteristics of bearing steel. As a result, it was found that the CeO$_2$ abrasive can react chemically on a steel workpiece in the superfinishing process because of the temperature dependence of the removal rate of CeO$_2$ stone, as described by the Arrhenius equation. Moreover, it was disclosed that the rubbing action by the friable CeO$_2$ abrasive can produce a smooth surface with negative skewness. Hence, it is concluded that the CBN/CeO$_2$ stone, which made the best use of the synergistic effect of the mechanical action of the CBN abrasive and the chemical action of the CeO$_2$ abrasive, is superior in surface finishing in comparison with conventional CBN stone.

REFERENCES