Micro-Scale Friction and Wear at Orthorhombic BaSO₄(0 0 1) Surface

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(Manuscript received 23 August 2015; accepted 06 June 2016; published 15 September 2016)
(Presented at the International Tribology Conference Tokyo 2015, 16-20 September, 2015)

To study relationship between friction and plastic deformation modes of single crystals, wear patterns were analyzed for BaSO₄, an orthorhombic crystal having various cleavage faces and slip systems. Upon scanning a sapphire stylus along the *b*-axis at (0 0 1) face, formation of triangular deformation patterns extending outside the wear track were observed with optical microscopy. Atomic force microscopic analysis revealed that the triangular areas were elevated, and the two sides were formed by {2 1 0} cleavage steps, starting within the track, and continued by {1 1 0} slip steps outside the track. Upon scanning with heavier normal loads, lots of {0 1 1} slip steps were formed inside the triangles, presumably due to horizontal compression given by the stylus to the triangular areas isolated from the rest of the surface. Mechanism of the wear pattern formation was proposed. When the stylus was scanned along the *a*-axis, the wear tracks were segmented into short strips by {1 0 1} slips. Under heavier normal loads, the segment structures were partly destroyed by the stylus, presumably by (0 0 1) slip and cleavage, producing debris on both sides of the track. The changes in deformation patterns under heavier normal loads caused steeper increase in friction curves measured in the two directions. Different deformation modes were activated depending upon the scan directions, normal loads and locations relative to the stylus.

Keywords: deformation modes, wear patterns, atomic force microscopy, frictional anisotropy, slip systems, BaSO₄

1. Introduction

In friction measurements using friction force microscopy (FFM) at single crystal surfaces, such as (0 0 1) faces of alkali halides (NaCl, NaF, LiF, KCl) and MgO, frictional anisotropy due to different periodicities of atoms has been clearly observed [1,2]. The smaller friction observed with all the crystals mentioned above along the [1 1 0] directions, where the same kind of atoms, anions or cations, are aligned, was explained by considering the oscillation of the electrostatic interaction potentials between the tip of the stylus and the surface atoms during the scan. The simple results suggest that the observed anisotropy in friction is an intrinsic surface property.

In conventional friction measurements using sharp diamond styluses under much heavier loads, Bowden and Brookes observed similar frictional anisotropy, [1 1 0] < [1 0 0], for LiF and MgO surfaces [3]. However,

reversed anisotropy, [1 1 0] > [1 0 0], has also been reported by Steijn [4] for NaCl and KBr, and by Kobayashi, Okui and Miura [5] for KCl. The complexity in the classical measurements comes from participation of bulk deformation modes of the crystals including slip activated by the intense stresses applied.

To understand friction in relation to the atomic structures of the materials, it is important to know at which stress levels the contribution from surface properties are overwhelmed by that of bulk properties. We have detected transition between the two regimes in the case of calcite (CaCO₃) [6]. At the cleaved (1 0 -1 4) surface of the crystal, frictional asymmetry has been observed with FFM in ±[4 2 -1] directions due to triangular CO₃²⁻ ions tilted to the same direction at the surface [7]. With a conventional friction apparatus, similar asymmetry was observed under the normal loads smaller than 50mN. Under heavier loads, however, friction in -[4 2 -1] direction started to increase rapidly and the sign of asymmetry was reversed. Optical

microscopic observation revealed that the transition was accompanied by activation of slip on (0 0 0 1) surfaces, inclined by 45 degrees from the surface, followed by cleavage on other {1 0 -1 4} surfaces.

The atomic-scale friction measured with FFM has been interpreted as dissipation process of mechanical energy stored in the spring system including the probe tip, the cantilever and the surface atoms, during the horizontal stick-slip action [8-11]. In μm -scale measurements of friction, especially under heavier normal loads, surface abrasion will become the main process of energy dissipation. However, plastic deformation modes in crystalline materials, such as slip actions having vertical components, will also consume the mechanical energy stored in the spring system made by the stylus and the strain gauge. The bulk deformation modes will modify the friction coefficients. Our previous observation of rapid increase in the friction force with the start of the (0 0 0 1) slip at the calcite surface supports the discussion. The slip occurred at only one side of the stylus because tensile force as well as shear force must work between the two sides of the slip plane.

In order to fully understand the contribution of plastic deformation modes in friction, we need to study competition between different modes depending upon the atomic structures, loading directions and locations on the surface relative to the loading point, and the orders of events. This time, we have chosen BaSO₄, a transparent crystal, as the sample. Various modes of deformation including cleavage, slip and twinning deformation have been reported for this crystal [12]. By analyzing deformation structures formed, we will be able to discuss how various modes are activated in respective conditions.

The atomic structure of (0 0 1) cleavage face of this orthorhombic crystal (space group *Pnma*), having lattice parameters of $a = 0.88842$, $b = 0.54559$, and $c = 0.71569$ nm [13], is shown in Fig. 1, together with expected traces of deformation modes. Several different modes may be activated at the same surface during friction measurements with a stylus. We will, then, be able to discuss relative importance of different modes of deformation.

Among the two slip modes reported in literature at room temperature [12], {0 1 1} <0 -1 1> will be activated either by vertical or horizontal compression given by the stylus at the (0 0 1) face. The slip face is inclined 52.7 degrees from the surface. Likelihood of activation of a slip mode depending upon stress directions can be partly evaluated by the Schmid factor $\cos\phi \cdot \cos\theta$, with ϕ and θ being the angles made by the stress direction with the slip plane normal, and with the slip direction, respectively [14,15]. The value of 0.482 calculated for the {0 1 1} slip under the normal load at the (0 0 1) face is fairly close to the maximum possible value of 0.5. The slip seems to be highly probable. This mode will make steps along the *a*-axis.

Fig. 1 Atomic structure of BaSO₄(0 0 1) surface and the traces of deformation modes observed. Only the {0 1 1} <0 -1 1> slip should make height differences at the surface

It should be noted here that the stylus gives not only vertical stress but also horizontal stress around the contact point. Scanning of the stylus also gives additional horizontal stress especially on the front side. Combined stress should be considered to evaluate the Schmid factors. For example, the other slip mode (0 0 1) [1 0 0] reported at room temperature cannot be activated at the (0 0 1) face solely by vertical compression since $\cos\theta = 0$. However, horizontal stress given by the scanning of the stylus along the *a*-axis may activate the slip by changing θ .

Three slip modes {1 0 1} <0 1 0>, (0 1 0) [1 0 0], and {1 1 0} <-1 -1 0> have been reported at elevated temperatures [12]. The first one, illustrated in Fig. 1, may be activated at the (0 0 1) face if considerable amount of horizontal stress is added to the normal load. The latter two will be activated mainly by horizontal stress because both the slip surface normal and the slip directions are on the (0 0 1) face. Traces of the {1 1 0} <-1 -1 0> slip, making an angle of 58.4 degrees with the *b*-axis, are shown in Fig. 1. None of the three slip modes make steps at the (0 0 1) face because the slip directions are parallel to the surface. They need to be accompanied by other modes of deformation to be detected as steps.

The traces of cleavage on {2 1 0} faces, making an angle of 39.1 degrees with the *b*-axis, are also shown in Fig. 1. The cleavage will occur when there is non-uniform stress in horizontal direction. Imperfect cleavage at (0 1 0) face has also been reported [12].

2. Experimental methods

The crystal structure in Fig. 1 was drawn using Diamond 4 structure visualization software of Crystal Impact. The software was also used for checking feasibility of the slip modes reported. Stress directions making angles of $\theta = \phi = 45$ degrees giving the maximum Schmid factor were determined for each slip system using an Excel program. Likelihood of activation

of slip modes depending on the locations around the stylus was, thus, evaluated.

The $\text{BaSO}_4(001)$ faces were prepared by cleaving a natural crystal and by mechanically polishing with 1.0 μm alumina suspension. Removal of large cleavage steps by the polishing gave smaller friction forces, and made minor traces of deformation more clearly visible with optical microscopy. Unpolished surfaces, however, were mainly used for surface profiling with atomic force microscopy (AFM) to avoid disturbance by scratches formed in the polishing process.

Friction measurements were performed using a Bowden-Leben apparatus (HEIDON 18 LFW) with a sapphire stylus with the cone angle of 60 degrees and the curvature radius of 50 μm . The Moh's hardness 9 of sapphire (corundum) is much larger than 3.3 reported for BaSO_4 and the sample surface is relatively easily abraded. The length of 2 mm was scanned at the speed of 24 mm/min. Only a single scan was performed at one position. Results of 3-5 scans were averaged for the friction measurement. The stylus was scanned mostly along the b -axis ([0 1 0] direction) and the a -axis ([1 0 0] direction) with the normal loads of 9.8-980 mN.

With the small crystal samples, the scan directions can be initially set only within the accuracy of ± 3 degrees. However, the angles made between known slip lines can be accurately measured in microscope images and be calculated from the crystal structure. Misalignment, if any, in the scanning can be easily evaluated.

The wear tracks were observed with Keyence VHX-2000 and HiRoX 7700 digital microscopes. Detailed analyses of step structures were performed with AFM (Digital Instruments, NanoScope III) in contact mode. In addition to height images, deflection images were also recorded. The latter are kind of differentiated images and step structures are emphasized. However, the step signs, upward or downward, can be determined only with height images. We have previously used deflection images to show cracks and large slip steps formed at CaF_2 surfaces [17]. Since the steps formed in the wear processes often have heights of several hundred nm, the

height range was set at 0.5-2.0 μm full-scale in AFM imaging. No filtering nor plane-fitting was applied to the images obtained.

3. Results and discussion

3.1. Friction force measurements

Friction forces measured along the b - and a -axis, namely, in [0 1 0] and [1 0 0] directions, are plotted in Fig. 2 against the normal load. In the lower normal load range smaller than 490 mN, friction forces in the two directions both increased linearly with the normal load. Stronger friction was observed along the [1 0 0] direction on the polished samples. With the normal load larger than 490 mN, however, the friction curves in both directions showed steeper increase, suggesting participation of additional modes of deformation. In order to determine the deformation modes concerned, wear patterns formed in the two directions were analyzed using optical microscopy and AFM.

3.2. Deformation patterns formed upon scanning along the b -axis

The optical microscope image in Fig. 3(a) was observed when the stylus was scanned in the [0 1 0]

Fig. 2 Friction forces measured in [0 1 0] and [1 0 0] directions plotted against the normal load applied to the stylus. The slopes of the curves both began to increase at the normal load of *ca.* 490 mN

Fig. 3 Wear patterns formed upon scanning the stylus in [0 1 0] direction at $\text{BaSO}_4(001)$ surface. (a) Optical microscope image observed after scanning with the lower normal load of 392 mN. (b,c) AFM height and deflection images (97.4 μm sq.), respectively, observed after scanning with the higher load of 784 mN. Traces of $\{210\}$ cleavage and $\{110\}$ and $\{011\}$ slip are recognized. The blue arrow in (b) shows the most effective stress orientation to cause the $\{110\}$ slip

direction at the (0 0 1) face applying normal load of 392 mN. Triangular deformation patterns extending outside the track of the stylus were repeated along the scan direction. The pattern was observed in smaller scale even with the normal load of 196 mN. It should be noted that two sides of each triangle are slightly curved, which was not observed in the case of calcite [6].

The AFM images in Fig. 3(b,c) were recorded after scanning the stylus with the normal load of 784 mN. The steps outside the wear track in (b) run in at least two directions. The step segments formed by $\{2\ 1\ 0\}$ cleavage, starting inside the track, seem to be continued further by steps parallel to $\{1\ 1\ 0\}$ slip directions outside the track. Presence of steps in the two directions most probably gives the curved appearance of the sides of the triangles imaged in Fig. 3(a).

It is also noticed in Fig. 3(b) that the triangular areas are at higher levels (brighter contrast) compared to the outer areas. That is why the traces of $\{2\ 1\ 0\}$ cleavage and $\{1\ 1\ 0\}$ slip are clearly visible as steps. Similar elevation of triangular areas has been observed for MgO(0 0 1) surface [16]. In that case, series of upward $\{0\ 1\ 1\} \langle 0\ -1\ 1 \rangle$ slip steps with the heights of 2-3 nm were observed inside the triangular areas.

The main feature of the triangular pattern formation looks nearly the same in the lower and the higher normal load ranges. However, a marked difference is noticed in the AFM deflection image in Fig. 3(c) observed under the heavier load of 784 mN, in which many traces along the *a*-axis were observed only inside the triangles. This indicates that the triangular areas should have been separated from rest of the surface by the $\{2\ 1\ 0\}$ cleavage, prior to the formation of the crowded traces. The traces are attributable to the $\{0\ 1\ 1\} \langle 0\ -1\ 1 \rangle$ slip steps, which can be activated effectively either by the normal stress or by horizontal compression along the *b*-axis. Since only small parts of the traces of the $\{0\ 1\ 1\}$ steps were seen in the height image in (b), they should be much lower than other steps. The steps were most probably created by horizontal compression applied by the stylus at the apex of each triangle. Similar activation of slips by horizontal compression was clearly observed in the case of CaF₂ crystal [17].

The stylus thumbing the apexes of triangles seems to explain the elevation of the triangular areas. The traces of the $\{0\ 1\ 1\}$ slip were also observed with optical microscopy after scanning with the normal load of 490 mN or larger. The mechanical work consumed in the slipping process is most probably the main reason for the steeper increase in the friction force under heavier loads in the $[0\ 1\ 0]$ direction shown in Fig. 2.

Knowing that the $\{0\ 1\ 1\}$ slip is easily activated, it will be reasonable to assume that the slip is the first mode of deformation to be activated within the wear track by the normal load, as illustrated in Fig. 4(a). Once a high $\{0\ 1\ 1\}$ slip step is formed, horizontal stress along the *b*-axis, applied by the stylus on the step-edge, will give the shear stress required to activate the $\{2\ 1\ 0\}$

Fig. 4 Mechanism of wear pattern formation at BaSO₄(0 0 1) surface proposed for the scratch along the *b*-axis

cleavage as shown in Fig. 4(b). The horizontal compression given to the triangular areas, freed from other part of the surface, will further activate the $\{0\ 1\ 1\}$ slips as in Fig. 4(c). At the end points of the $\{2\ 1\ 0\}$ cleavage outside the track, horizontal stress will cause $\{1\ 1\ 0\}$ slip as shown in Fig. 4(d). As indicated by a blue arrow in Fig. 3(b), horizontal stress inclined 45 degrees from the slip direction is ideal for the slip.

The deformation sequence proposed above explains all the features observed in Fig. 3. However, the traces of $\{0\ 1\ 1\}$ slip, presumably activated first inside the track, were overridden by the stylus and did not remain in Fig. 3(b). In order to keep the evidence of the first slip, the stylus needs to be scanned off the *b*-axis. However, the maximum normal load of 1 N allowed for the friction apparatus is not sufficient to cause the slip in less favorable scratch direction.

The optical microscope image in Fig. 5(a) was observed after scratching the (0 0 1) surface with metallic tweezers in the direction making the angle of 45 degrees with the *b*-axis. The wider wear track observed, compared to Fig. 3 or the other images in Fig. 5, indicates that much higher normal load was applied.

Quite many traces of the $\{0\ 1\ 1\}$ slip were detected both inside and outside the wear track. The slip direction is indicated by a white arrow pointing 52.7 degrees downward from the (0 0 1) surface. The fact that the slip is easily activated by the normal load with or without direct contact of the stylus supports activation of the first $\{0\ 1\ 1\}$ slip proposed in Fig. 4(a).

On the other side of the wear track in Fig. 5(a), traces along the *b*-axis were observed inside. Among the deformation modes reported, only the $\{1\ 0\ 1\} \langle 0\ 1\ 0 \rangle$ slip mode can give traces in that direction. We cannot determine, at present, which of the two slip faces, $(1\ 0\ 1)$ or $(-1\ 0\ 1)$, is participating. We can say, at least, that fairly strong stress by direct contact with the stylus is required to activate the slip.

3.3. Deformation patterns formed upon scanning along the *a*-axis

The optical microscope image in Fig. 5(b) was observed at the (0 0 1) surface after scanning the stylus

Fig. 5 Optical microscope images of wear patterns formed at $\text{BaSO}_4(0\ 0\ 1)$ surface. (a) The surface was manually scratched with steel tweezers in 45 degrees direction measured from the b -axis. Traces of $\{0\ 1\ 1\}$ slip were recognized both inside and outside the wear track, while the traces of $\{1\ 0\ 1\}$ slip were found only inside. White arrows indicate slip directions. The one for the $\{0\ 1\ 1\}$ slip is pointing downward by 52.7 degrees. (b,c) The surface was scratched with the sapphire stylus along the a -axis with the normal loads of (b): 392 mN and (c): 490 mN, respectively. The wear tracks were segmented by $(-1\ 0\ 1)$ slip in $\pm[0\ 1\ 0]$ directions shown with the white arrows. The blue arrows pointing 33.4 degrees downward from the $(0\ 0\ 1)$ face show the stress directions giving the maximum Schmid factor to activate the slip. (c) Under the heavier normal load, the upper layers of the track were abraded leaving lots of debris on both sides of the track

in $[-1\ 0\ 0]$ direction with the normal load of 392 mN. The wear track was segmented by the traces along the b -axis, into short strips having the width of about 3 μm . The traces are attributable to the $\{1\ 0\ 1\} \langle 0\ 1\ 0 \rangle$ slip observed in Fig. 5(a). Even when the scan direction was slightly rotated by ± 20 degrees from the a -axis, the traces observed always ran along the b -axis, supporting the assignment.

The surface profiling with AFM along the wear track revealed that upward steps with the heights of ~ 70 nm were created. It suggests that the $\{1\ 0\ 1\}$ slip was activated on the front side of the moving stylus. In the case of Fig. 5(b), $(-1\ 0\ 1)$ slip was activated, not $(1\ 0\ 1)$ slip.

The blue arrows in Fig. 5(b), pointing downward by 33.4 degrees from the sample surface, indicate the most effective stress orientations to cause the slip on the $(-1\ 0\ 1)$ face in the two directions, $[0\ 1\ 0]$ and $[0\ -1\ 0]$, indicated by white arrows. Since the stress components given by the stylus in the most effective directions will be small, the slip occurs only within the wear track, where the crystal axes are rotated by elastic deformation of the sample surface. The segment pattern, however, was recognized even under the normal loads of 98 mN and 196 mN, although the track widths were smaller. Friction due to the pattern formation is a part of the linear increase in the friction force in the lower normal load range in Fig. 2.

Traces of $\{2\ 1\ 0\}$ cleavage starting at the edges of the wear track were also observed in Fig. 5(b). As in the case of Fig. 3, horizontal stress given by the stylus causes the cleavage. However, traces of the $\{0\ 1\ 1\}$ slip along the a -axis were not detected this time.

The $\{0\ 1\ 1\}$ slip direction illustrated in Fig. 4(a) is making an angle of 52.7 degrees with the $(0\ 0\ 1)$ surface, and the $\{0\ 1\ 1\}$ surface normal is perpendicular to the slip direction. The stress direction giving the maximum Schmid factor is, thus, inclined by 7.7 degrees from the c -axis. The elastic deformation of the surface during the scan of stylus in b -direction will rotate the c -axis to favorable directions for the slip. That is why the $\{0\ 1\ 1\}$ slip occurred easily in the b -scan. This does not occur upon scanning the stylus along the a -axis.

Among various deformation modes reported, the $\{1\ 0\ 1\}$ slip seems to give the largest contribution to the friction along the a -axis. However, some other mode of deformation should be considered to explain the steeper increase in the friction force curve in Fig. 2 at higher normal loads.

The microscope image in Fig. 5(c) was recorded after scanning the stylus with the normal load of 490 mN. Compared to (b), the segment structure along the wear track was partly destroyed and lots of debris were piled up on both sides of the track. The segments were most probably abraded off the surface by the slip and cleavage at the $(0\ 0\ 1)$ face. The damage on the wear track became severer with the increase in the normal load. The steeper increase in the friction along the a -axis most probably corresponds to the abrasion.

4. Conclusions

Different modes of deformation were activated upon scanning the stylus along the a - and the b -axes at $\text{BaSO}_4(0\ 0\ 1)$ surface. In the scanning along the b -axis, $\{0\ 1\ 1\} \langle 0\ -1\ 1 \rangle$ slip was first activated in the wear

track, followed by $\{2\ 1\ 0\}$ cleavage extending outside the track, and then, by $\{1\ 1\ 0\}$ slip, finally giving elevated areas in triangular shapes. Under the normal loads of 490 mN or larger, dense traces of $\{0\ 1\ 1\}$ slip, presumably formed by horizontal compression of the triangular areas, were observed, corresponding to steeper increase in the friction plotted against the normal load. A mechanism was proposed for the pattern formation. In the scanning along the a -axis, $\{1\ 0\ 1\} \langle 0\ 1\ 0 \rangle$ slip made periodic segment structures inside the wear track. With the normal loads of 490 mN or larger, the segment structures were partly abraded by slip and cleavage at the (0 0 1) face producing debris, which corresponded to the steeper increase in the friction force plotted against the normal load. Various modes of deformation were activated depending upon the scan directions, normal load range and the locations relative to the stylus. Although frictional anisotropy was observed, the shapes of the friction curves in the two directions against the normal load were not very different.

Acknowledgements

This work was supported by JSPS KAKENHI Grant Numbers 24510144, 20510097, 20225002 and The Institute of Science and Engineering, Chuo University.

References

- [1] Namai, Y. and Shindo, H., "Frictional Force Microscopic Anisotropy on (001) Surfaces of Alkali Halides and MgO," *Japanese Journal of Applied Physics*, 39b, 2000, 4497-4500.
- [2] Karino, W. and Shindo, H., "Frictional Force Microscopic Detection of Anisotropy at NaCl(100), (110) and (111) Surfaces," *Tribology International*, 40, 2007, 1568-1573.
- [3] Bowden, F. P. and Brookes, C. A., "Frictional Anisotropy in Nonmetallic Crystals," *Proceedings of the Royal Society A*, 295, 1966, 244-258.
- [4] Steijn, R. P., "Friction and Wear of Single Crystals," *Wear*, 7, 1964, 48-66.
- [5] Kobayashi, S., Okui, T. and Miura, S., "Microscopic Deformations in KCl Single Crystals by Indentation and Scratching with Steel Ball and Pyramidal Indenters," *Wear*, 162-164, 1993, 92-101.
- [6] Niki, K., Kobayashi, M. and Shindo, H., "Frictional Asymmetry and Wear Pattern Formation by Slip and Cleavage Detected at Directional $r\{10\text{-}14\}$ Face of Calcite (CaCO₃)," *Tribology Online*, 7, 2012, 8-12.
- [7] Kwak, M. and Shindo, H., "Frictional Force Microscopic Detection of Frictional Asymmetry and Anisotropy at (10-14) Surface of Calcite," *Physical Chemistry Chemical Physics*, 6, 2004, 129-133.
- [8] McClelland, G. M., "Friction at Weakly Interacting Interfaces," in Grunze, M. and Kreuzer, H. J. eds., "Adhesion and Friction," Springer, Berlin, 1990, 1-16.
- [9] McClelland, G. M. and Glosli, J. N., "Friction at the Atomic Scale," in: Singer I. L. and Pollok, H. M., eds., "Fundamentals of Friction: Macroscopic and Microscopic Processes," Kluwer, Dordrecht, 1992, 405-425.
- [10] Tománek, D., Zhong, W. and Thomas, H., "Calculation of an Atomically Modulated Friction Force in Atomic-Force Microscopy," *Europhysics Letters*, 15, 1991, 887-892.
- [11] Tománek, D., "Theory of Atomic-Scale Friction," in: Wiesendanger, R. and Güntherodt, H.-J., eds., "Scanning Tunneling Microscopy III," Springer-Verlag, Berlin Heidelberg, 1993, 269-292.
- [12] Palache, C., Berman, H. and Frondel, C., "Dana's System of Mineralogy," Vol. 2, 7th ed., Wiley, New York, 1951, 410.
- [13] Hill, R. J., "A Further Refinement of the Barite Structure," *Canadian Mineralogist*, 15, 1977, 522-526.
- [14] Callister, W. D., "Materials Science and Engineering, An Introduction," 2nd ed., Wiley, New York, 1991, 162-163.
- [15] Hummel, R. E., "Understanding Materials Science," Springer, New York, 1998, 60.
- [16] Kasahara, E., Niki, K. and Shindo, H., "Effects of Slip Systems upon Friction and Wear at (001) Faces of Rock Salt-type Single Crystals," *Proc. World Tribology Congress 2013, Torino*, PS3-FW-31.
- [17] Niki, K., Mochimaru, G. and Shindo, H., "Participation of $\{100\} \langle 011 \rangle$ Slip Steps in Sliding Friction at (001), (111) and (110) Surfaces of Fluorite (CaF₂) Crystal," *Tribology Online*, 7, 2012, 81-86.