# DIRECTIONAL GRINDING HARDNESS IN DIAMOND*

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Abstract

In order to measure the relative variation of grinding hardness in single diamond crystals, two mechanisms have been constructed. One, which might be called a hardness comparator, permits the simultaneous cutting of two crystals. One crystal is oriented in an arbitrarily chosen unit hardness direction. The cutting rate of the second crystal is compared with the cutting rate of the reference crystal.

To facilitate the measurements a second apparatus has been designed to prepare spherical surfaces of predetermined radii on the diamonds. This apparatus was used in connection with hardness variation measurements on the cube face. The remainder of the planes investigated were studied on pyramidally faceted stones, because of the very slow operation of the sphere grinder.

Hardness curves were plotted, hardness against grinding azimuth, for the cube, dodecahedron, and octahedron, and for intermediate planes in the zones containing these three planes.

Hexoctahedral symmetry was assumed since no evidence of lower symmetry has been obtained from hardness measurements.

Errors inherent in the method are discussed.

The fact that certain directions in a diamond may be readily cut with diamond dust on a cast iron wheel while other directions can not be cut or polished is well known to the diamond cutting trade. A thorough qualitative investigation has been carried out by Slawson and Kohn.[1] The purpose of this research is to compare quantitatively the abrasion rates on single crystal diamonds for a series of planes in the three principal crystallographic zones.

If a diamond is cut in a relatively easy grinding direction ("on grain" in the professional cutter's parlance), the diamond itself tends to replenish the abrasive and the wheel will remain in good cutting condition almost indefinitely. If, on the other hand, a hard or "off grain" direction is cut, the abrasive is not replenished and the quality of the lap surface deteriorates rapidly. When this occurs, the diamond is no longer cut and the wheel becomes badly scored. In order to minimize the effects of this variation, two diamonds were cut simultaneously. One was used as a reference diamond. Its orientation was unchanged during the entire study. The other diamond was oriented so that special planes in the three principal zones were ground. A series of azimuths across each of these planes was investigated. The two diamonds were mounted on spindles provided

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[1] Slawson, C. B., and Cohn [sic], J. A., Maximum hardness vectors in the diamond: *Industrial Diamond Review*, **10**, June, 1950, 168–172.

with graduated azimuth circles. To avoid scoring the lap and to assure that both diamonds were ground under nearly equal conditions, they were moved back and forth on opposite sides of the center along a diameter of the lap. The thrusts of both diamonds on the lap surface were the same. In most tests the thrust was maintained at two kilograms, although in a few instances lighter thrusts were used. The relative rates of removal of material from the two stones provided a measure of the relative grinding hardness for each direction under consideration. Four micron diamond dust in olive oil was used for all grinding operations. Figure 1 shows the slide bar supporting two spindles over the wheel. The cam which oscillates the bar may be seen below the table in the left foreground.

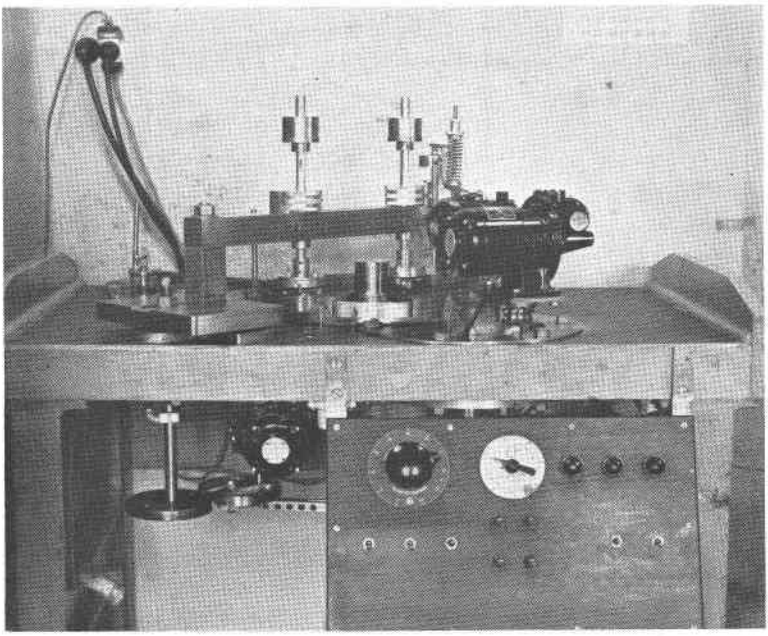

FIG. 1. Diamond hardness comparator and sphere grinder.

A grinding constant, $k$, was determined for each cut. The relation used was $k=v/TF$, in which $v$ represents the volume of diamond removed; $T$, the time of grinding; and $F$, the thrust force exerted upon the lap. A value of $k$ was determined for both the reference diamond and the diamond under test. If $k_1$ represents the grinding constant of the test diamond and $k_2$ represents the constant of the reference diamond, then $H$, the relative grinding hardness, equals $k_2/k_1$. This hardness is reciprocal to the relative ease of grinding. It should be noted that the values of $H$ are purely relative and that they are not to be considered as indicative of the grinding hardness on an absolute scale.

The hardness of the diamond crystal in some crystallographic directions is equal to, or greater than, the hardness of the diamond dust particles, which presumably are oriented with the octahedral plane parallel to the lap surface. Therefore, when one of the directions being compared is a hard direction of the diamond, small absolute hardness differences may cause large variations in grinding rate.

As a reference direction of assumed unit grinding hardness, the cube face in the direction of an *a*-axis was chosen. This relatively easy cutting direction tends to reduce the damage to the lap when directions are compared, because, as the cube surface is worn away, it replenishes the lost abrasive. Also a sufficiently large advance of cut is assured to minimize the effects of error of measurement. In addition, this direction is readily oriented on the crystals of octahedral habit used in this investigation.

The determination of the volume of diamond removed by grinding necessitates the measurement of the areas of the surfaces before and after grinding and also the measurement of the depths of the cuts. Because of the extreme hardness of diamond, it is not feasible to measure the depth directly. In order to measure the depth and the area of the cuts, it was decided to generate spherical surfaces on the diamonds. Then, the radius of curvature being known, the areas and depths could be readily determined by measuring the diameters of the flats.

An apparatus has been designed to grind the spherical surface. The diamond is mounted on a rotating spindle, oscillated about a horizontal axis, which lies above the lap surface at a distance equal to the radius of the sphere being ground. The spindle is spring-loaded so that it can slide parallel to its length. This sliding motion is limited in the direction toward the lap by an adjustable stop. The diamond should be bounded by a spherical surface when the sliding motion rests against the stop. Were it not for certain extremely hard grinding directions on certain planes, such an arrangement would generate a spherical cap. For each element of the surface of the sphere there are one or more optimum grinding directions, and there may be directions that can not be ground. In order that each point on the sphere be cut in all directions, the whole apparatus was mounted on a third (vertical) axis. A 90° oscillation about this third axis insures that all points on the sphere will be ground in a large number of directions. In order to grind a large number of directions on each element of the spherical surface, these three motions must have an irrational relationship with each other. Furthermore, the third axis oscillation makes it possible to utilize most of the wheel surface. The surface of the cutting wheel tends to be grooved at the innermost and the outermost points where the wheel grinding radius is momentarily unchanged during the end- and mid-points of the third axis oscillation. To lessen this difficulty the outer and inner parts of the wheel are beveled so that the diamond does not rest on the wheel during the time of reversal.

In order to generate a spherical surface, it is necessary first to approximate the surface with a series of small flats. For grinding a 50° cap on the cube position, the grinding process requires about 80 hours, during which time the lap must be resurfaced several times, even though two diamond flats in optimum grinding position are cut simultaneously. Surfaces prepared in this manner showed profiles constant in radius to about 10 per cent. Because of the great amount of time required, only the cube face was studied with the aid of the spherical surfaces. Figure 2 is a photograph of the sphere grinding apparatus.

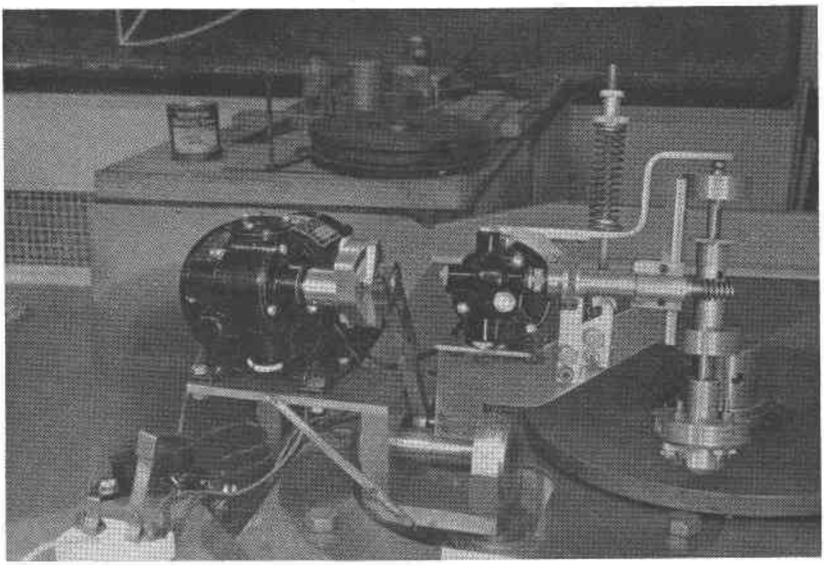

FIG. 2. Diamond sphere grinder.

Planes other than those parallel to the cube were studied from abraded frustrums of pre-formed pyramids. The pyramids were so shaped that the surfaces being abraded had rectangular outlines. Measurements made in this manner are consistent with those made with the aid of spherical surfaces. These ground surfaces of the diamonds were examined under a reflecting microscope and the facets were drawn with a camera lucida. An ocular micrometer, previously calibrated, was used to determine the scale of each drawing. In each instance it was found necessary to focus the microscope critically so that the image of the surface fell exactly in the plane of the micrometer scale. Otherwise parallax introduced serious errors. By this means the slight changes in scale of the drawings due to unavoidable changes in projection distances were measured. The areas were determined with a planimeter. Depths of cuts were determined from the changes in edge lengths of the ground facets.

The diamonds used were about $1\frac{1}{2}$ carat, clear yellow, exceptionally well crystallized, nearly ideal octahedrons with smooth plane surfaces. Because of the fine quality of the surfaces, the crystals could be oriented on the goniometer with a high degree of accuracy. They showed no external evidence of twinning and possessed low double refraction. As the study progressed, it became apparent that some twinning was present, even in these specially selected crystals. The twinned portions of the crystals appeared as occasional fine lamellae on the lapped surfaces parallel to the trace of an octahedral plane. Since the grinding rate on the surface of the twinned areas differs from that of the main untwinned portion of the crystal, a polishing relief is developed. Because of the slight undulations present on some of the polished surfaces, on planes nearly parallel to the octahedron, the twin lamellae appeared as discontinuous crescentic arcs.

The twinning caused uncertainty of the measurement of some of the "softer" grinding directions. Even a very small twinned area which presents a hard grinding direction will seriously retard the advance of a cut on what should be a fast cutting direction. Where possible, twinned areas were avoided.

The variation of the lap condition is not serious in the study of the directions of low grinding hardness. However, in the case of the directions of high grinding hardness, the effect is of considerable importance. As the wheel surface deteriorates, the cutting rate along relatively hard directions is greatly reduced by this condition. The reference diamond which is oriented in an on-grain position will continue to be cut on a relatively poorly charged wheel. Ultimately, if the wheel is not continuously recharged, even the reference diamond fails to advance. The effect can be reduced to a minimum by simultaneously cutting several additional stones in on-grain positions. During the testing of the hard directions, the surface of the lap must be liberally supplied with olive oil and diamond dust. The usual effect of the result of lap deterioration is an apparent increase in relative grinding hardness. The magnitude of this effect is uncertain.

Certain grinding directions are particularly sensitive to orientation errors. An error of 30 minutes in the location of the cube plane will seriously disturb the four-fold symmetry of hardness vectors which that plane exhibits. Undoubtedly the general experience of cutters that only one direction on the cube facet will present optimum cutting conditions[2]

[2] Grodzinski, Paul, Diamond and gemstone industrial production methods: Part XIII, *Industrial Diamond Review*, **9**, 154 (1949).

is due to small errors in the location of supposedly cube facets. Similar statements could be made concerning other planes. To avoid such errors it is necessary to check the position of facets after each grinding operation to make sure that the diamond has not changed position in its dop during grinding.

The relatively soft directions cut rapidly enough so that measurable increases in area can be obtained in a few minutes of grinding. However, in the case of the harder directions, even though the grinding continues for up to two-hour periods, the increment of area is so slight as to be close to the limit of accuracy of the measurements. Therefore, it was impossible to obtain satisfactory measurements for the hardest directions. It is for this reason that the curves are dotted in the region of greatest grinding hardness. The high hardness values have a probable error of about 25 per cent. The low values have a probable error of 10 per cent or less. In computing the probable errors some extreme values were eliminated. These extreme values were associated with prominent twinned areas or poor wheel condition.

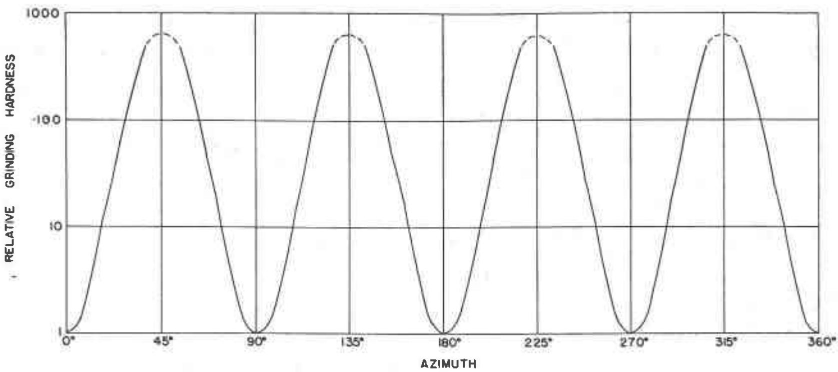


FIG. 3. Cube.

The results of the tests are shown in a series of curves. The curves are based upon measurements in one hundred lapping directions distributed among the several faces. The values were duplicated in successive tests. In the more difficult cutting directions, five or more determinations were made. Orientation of the planes was checked frequently, both by the goniometer and by grinding rates. Grinding rates are accurate checks only when symmetry relationships require that they be equal. The curves are plotted as relative grinding hardness (on a logarithmic scale) against azimuth.

Figure 3 shows the curve for the cube plane. The zero for the azimuth scale is the grinding direction parallel to a crystallographic axis. This direction was chosen as one of unit hardness. Measurements were made at 10-degree intervals up to 40° azimuth. At 45° the cutting is so slow (or the wheel surface deteriorates so rapidly) that no satisfactory measurements can be obtained for this, one of the hardest directions. The 40° azimuth possessed the greatest hardness that could be measured with reasonable certainty.

The extrapolation from 40° to 45° is purely conjectural. All of the directions of the crystal which yielded reasonably consistent results showed the hardness to be a continuous rather than a discontinuous property. Since in general hardness seems to be a continuous property, the extrapolations on this and other faces are drawn so as to avoid discontinuities in the curves. Any alternative extrapolations that involve discontinuities seem unlikely. If there exists a real discontinuity in the curves—assuming that good measurements might be made in the very hard directions in the future—it is a result of the technique employed. Were a harder abrasive available, the apparent discontinuities should disappear.

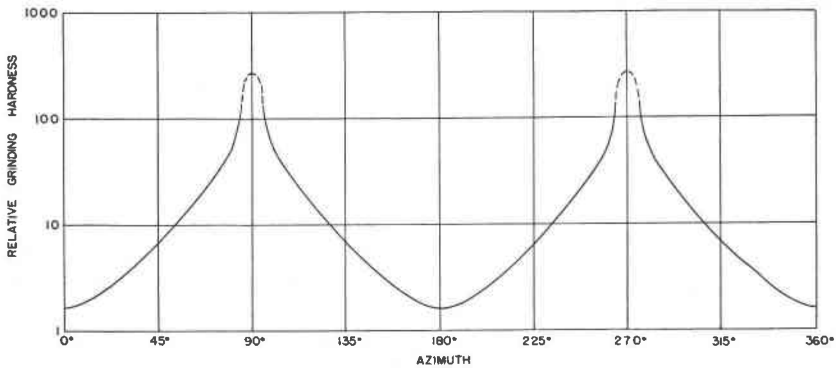


FIG. 4. Dodecahedron.

The only other plane studied that shows hardness magnitudes of the same order is the dodecahedron. The relative grinding hardness curve for the dodecahedron is plotted in Figure 4. The zero azimuth is taken as a direction parallel to a crystallographic axis. In the optimum cutting direction (toward the octahedron), this plane shows a hardness only slightly in excess of the reference direction. When the grinding is toward the cube (parallel to the direction of the long diagonal of a dodecahedron face), the relative grinding hardness is several hundred-fold that of the soft direction. It must be remembered that this does not imply a variation in absolute hardness of such a magnitude. The average rate of change of hardness per degree of azimuth is only about half that of the cube face. No satisfactory measurements were made between azimuths of 80 and

100 degrees. An attempt was made to compare the hardest directions of the cube and dodecahedron directly. Since such tests were inconclusive, it remains in doubt as to whether the cube or dodecahedron possesses the hardest of all known surfaces with respect to grinding.

A curve for the octahedron is not shown as all of the measurements made on this plane, because of its excessive hardness, are unsatisfactory. In general, relative hardness values between 10 and 100 times that of the reference direction were found. These values seem low. The error is tentatively assigned to unfavorable variation in the grinding condition of the wheel. While all of the directions on this face are very hard, none is so hard as the hardest directions on the cube and dodecahedron.

Slawson and Kohn[3] found the maximum hardness to be toward the cube, while the present study showed inconclusively that the direction

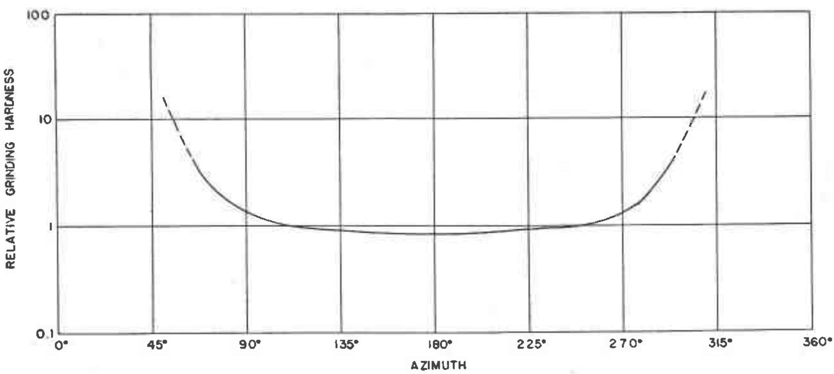


Fig. 5. Zone [010] 23° from Cube.

toward the dodecahedron is the harder. No evidence of the assymmetry reported by Tolkowsky[4] has been encountered either by Slawson and Kohn or by the present writer.

The octahedron is especially sensitive to orientation errors. If the plane being ground is one degree from the true octahedron position, the hardness curve will show quite low values, in part. In such a case the curve will indicate the orientation error, rather than the approximate hardness variation on the octahedron itself. In the present research the orientation error was kept within 15 minutes. Slawson and Kohn deduced the qualitative relative hardness indicated above by observing the hardness on a series of planes close to the octahedron in the zones

[3] Slawson and Cohn [sic], *op. cit.*

[4] Tolkowsky, M., Research on the abrading, grinding, or polishing of diamond: (*Unpublished Doctoral Dissertation, University of London,* 1920), cited by Paul Grodzinski, *op. cit.*, Part XII, pp. 118–124.

[$\bar{1}$01] and [1$\bar{1}$0]. This indirect method probably leads to more reliable results than the direct method of attempting to grind on the octahedron used by the present writer.

The hardness curve for an intermediate plane 23 degrees from the cube in the [010] zone is illustrated in Figure 5. The direction toward the cube is chosen as zero azimuth. This face showed high relative grinding hardness for azimuths up to about 45 degrees. From azimuth 90 to 180 degrees, the face is very easily ground. Such a plane offers the cutter a large range of easy grinding azimuths. The measurements on the hardest directions could not be duplicated well enough to warrant extending the curve to zero azimuth.

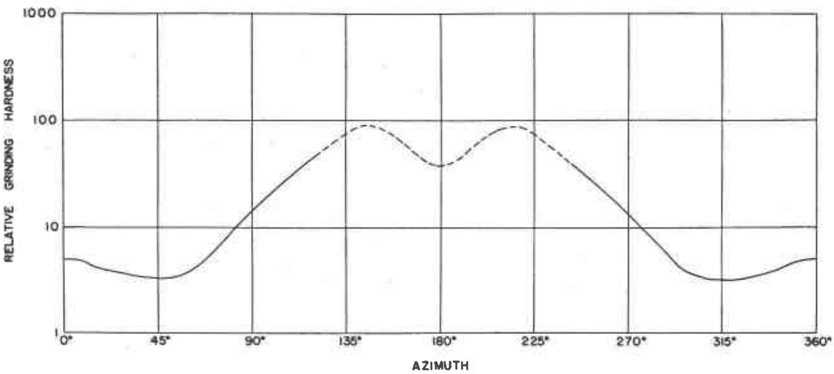


FIG. 6. Zone [1$\bar{1}$0] 39° from Cube.

In the [1$\bar{1}$0] zone the results on a plane 39 degrees from the cube are shown in Figure 6. All of the azimuths can be ground, but some only with difficulty. The zero azimuth is toward the cube. The optimum cutting direction lies at azimuth 45 degrees. This direction does not cut so readily as the optimum directions on the previously discussed planes, with the exception of the octahedron. The maximum hardness was found at about 145 degrees. While this represents a very hard direction, the diamond can be cut in this position. The face, obviously, can be cut more readily toward the cube than toward the octahedron. This plane is of interest since it lies at the edge of one of the lapping limits of Slawson and Kohn.[5]

Figure 7 shows the relative grinding hardness curve of a plane 15 degrees from the dodecahedron in the [$\bar{1}$01] zone. On this plane all directions can be cut. The direction toward the dodecahedron is the softest, while the direction of maximum hardness lies about 100 degrees from the former.

[5] Slawson and Cohn [sic], *op. cit.*

From the above series of examples it can be seen that it is not sufficient to define the relative grinding hardness merely in terms of the grinding direction within the crystal. For a given grinding direction, the relative grinding hardness depends upon the position of the plane being ground. It is for this reason that the relative grinding hardness can not be expressed as a three dimensional surface analogous to the optical indicatrix.

It should be emphasized that while all of the azimuths on the octahe-

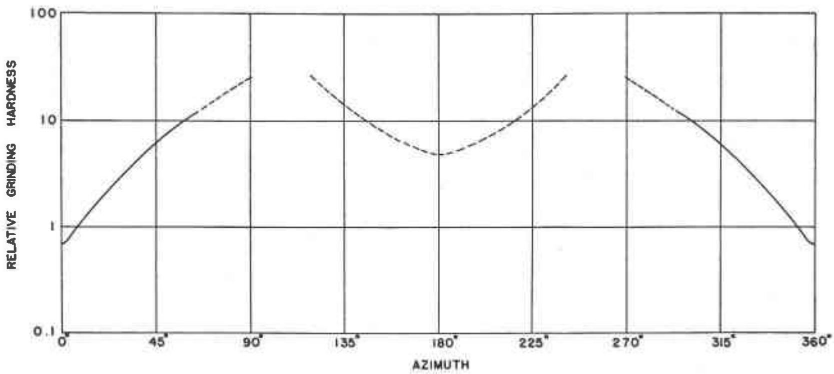


FIG. 7. Zone [$\bar{1}$01] 15° from Dodecahedron.

dron face are very hard, the hardest directions are on the dodecahedron plane toward the cube and on the cube toward the octahedron, and that these two hardest directions are parallel to each other. Which of the two latter directions is the harder is uncertain.

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