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ORIENTATION OF SYNTHETIC CORUNDUM FOR JEWEL BEARINGS[1]

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ABSTRACT

By a method similar to that used in petrofabric analyses, a correlation between crystallographic boule orientation and processing results is shown for synthetic corundum made in America by the well-known Verneuil process. For best processing results, the growth axis of a synthetic corundum boule should lie approximately normal to a second order pyramid face with indices $\{11\bar{2}2\}$. A second favorable orientation is close to $\{81\bar{9}0\}$. Boules grown normal to various faces in the zone of negative rhombohedrons generally show irregular to hackly fracture when split, and yield definitely inferior results in jewel-bearing manufacture. Economic savings could be effected if boule manufacturers would control the orientation of their product.

INTRODUCTION

Jewel bearings have long been used in fine watches and instruments to reduce friction on small pivots or axles which must turn easily if the instrument is to function properly. Such bearings usually take one of several shapes depending upon the purpose and service to which they are put. The simplest consists of a polished conical depression terminated at the apex by a spherical surface on which the pivot rides as shown in Fig. 1 at *A* and *E*. This is called a vee jewel. Wear resistance and durability in vibration and shock have been related to the position of the crystallographic *c*-axis in such jewels by several writers. Stott (1931, p. 54) states that the angle between a vee-jewel axis and the crystallographic *c*-axis should be over 30°, and probably less than 80°. Goss (1941, p. 814) prefers this angle to be between 80° and 90°. Grodzinski (1942, p. 167) states it should be either 45° to 48° or 60° to 90°. No exhaustive research has ever been published regarding wearing properties and orientation of the other types of jewel bearings, which are described below. A simple jewel bearing is shown in Fig. 1 at *B*. It consists of a flat plate of jewel material

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with one side polished, and with a polished cylindrical hole normal to the polished side. It is called a bar hole jewel. The hole serves to hold the pivot in place with respect to lateral stresses, and the polished flat surface serves as a thrust-bearing, as shown at *F* in the figure. Although simplest in design and use, the vee-jewel and the bar hole jewel have certain objectionable mechanical features that make two additional jewels useful at especially critical points, as in the escapement and balance wheel assembly of a fine watch or chronometer. These jewels are illustrated at *C* and *D* in the figure; they are called the olive hole jewel *C* and the endstone jewel *D*. The olive hole jewel is a more or less flat plate with a toric hole so shaped that the pivot can theoretically touch it only along a line of contact. This jewel is not suitable for sustaining end thrust and therefore the endstone jewel is provided as a complementary part, presenting a polished flat or convex surface against which the spherically-shaped polished end of the steel pivot rotates with a minimum of contact area. The relations of these two jewels and a pivot are shown at *G* in the figure.

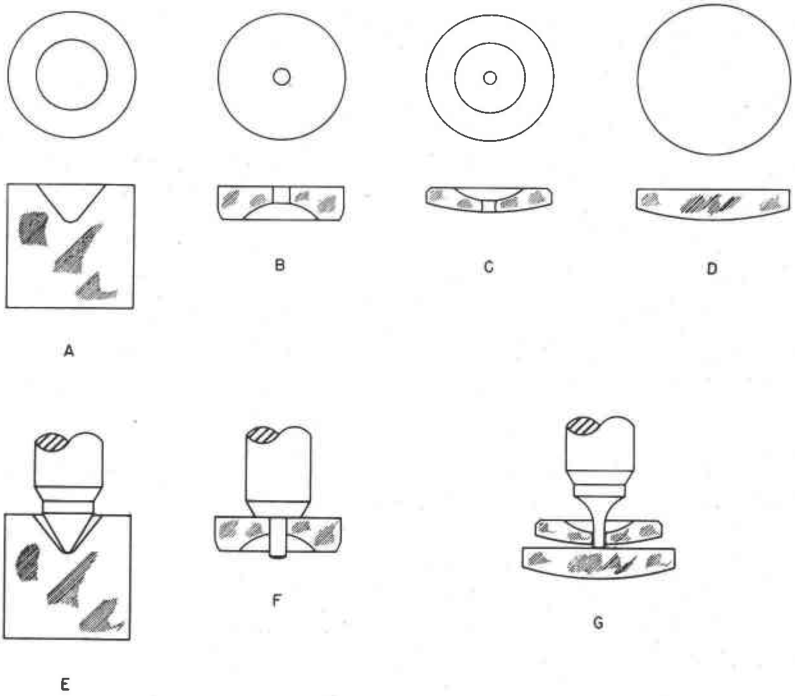

FIG. 1. Four recognized types of jewel bearings. *A*, Vee jewel; *B*, Bar hole jewel; *C*, Olive hole jewel; *D*, Endstone jewel; *E*, Assembly showing vee jewel and pivot; *F*, Bar hole jewel and pivot; *G*, Olive hole jewel, endstone jewel, and pivot.

JEWEL MATERIALS

Conventionally, the above-described jewel bearings are made from hard materials, either crystalline or vitreous; the commonest and most satisfactory material is synthetic corundum made by the Verneuil process which need not be described here. The raw material for jewels comes from the Verneuil furnace as a roughly cylindrical, homogeneous, gem-quality crystal or boule whose surface has no definite relation either in shape or in orientation to the lattice of the crystal of which it is composed. In synthetic corundum boules there are stresses which can be relieved only by breaking the boule. Boules of good quality invariably break lengthwise with a smooth, approximately plane fracture which will here be called the parting plane. Figure 2 shows several boules lying on their parting planes, and one in end view showing the shape after splitting. Experience shows that the parting plane is always that plane which contains both the growth axis (length) of the boule and the c-axis of the crystal. The angle between these axes may have any value whatever from 0° to 90°, although boules in which this angle is less than about 30° tend to be inferior. Because of the uniaxial character of corundum crystals, it is easy to measure this angle in polarized light; but it is impossible to determine by polarized light the relation between the parting plane or the growth axis and the minor crystallographic axes, a_1, a_2, a_3.

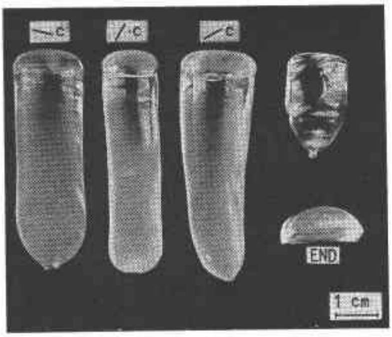

FIG. 2. American synthetic white corundum boules. The orientation of the c-axis is indicated above the three large boules. The small boule is an early specimen made before the technique reached its present efficiency. End view of a split boule.

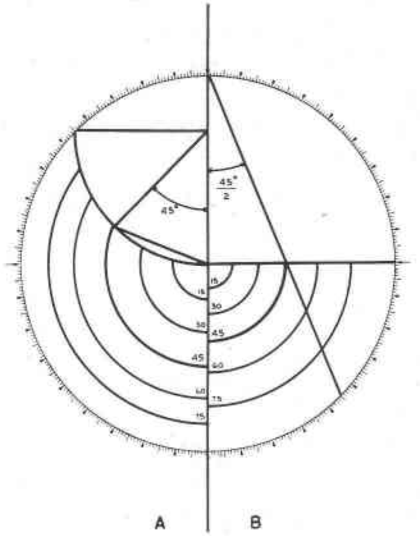

FIG. 3. Comparison and graphical construction of equal area (A) and stereographic (B) projections.

By x-ray diffraction methods it may be proved that there is no fixed relation between the orientation of the parting plane or the growth axis and that of the minor axes, although the parting plane must of course always lie in, or close to, the prism zone. Statistically, however, the parting plane is more often approximately parallel to a prism face of the first order, or to one of the second order, than to any other prism face; this may be deduced from the data to be given below.

MANUFACTURING PROCEDURE

The following steps will briefly outline the process of jewel manufacture. Needless to say, many operations are omitted here, but the omitted ones are of minor importance for the purposes of this discussion.

Small, round, flat discs are first cut from the boules. These discs are nearly always cut normal to the boule axis by three mutually perpendicular sawing operations yielding small squares. The squares are surfaced to standard thickness, and ground round in a centerless grinder. The resulting "roundels" are next drilled by fine wire drills rotating at high speed and charged with diamond powder. The holes are opened to size by stringing the jewel blanks on slightly tapered wires charged with diamond powder and abrading the holes until the proper size is reached. The above steps are relatively rough or vigorous, and it is sometimes assumed that this is desirable in order to break and eliminate any material that may be predisposed to break. Most of this "weak" material could probably be eliminated by a previous selection of boules, based on orientation as a primary criterion. Actual selection should be based upon more easily measured characters if possible. The finishing steps in jewel manufacture involve concentric grinding and various polishing and shaping operations to produce oil-holding depressions around the holes, lens-shaped surfaces instead of flat ones, polished surfaces, etc. Most of these steps are gentle, and spoilage due to broken jewels is relatively low in the finishing processes.

DEVELOPMENT OF AMERICAN INDUSTRY

When the war brought to an end the previous Swiss supply of jewel bearings for instruments and watches, the United Nations were temporarily hindered by a lack of jewels. It was necessary to develop quickly a source of synthetic corundum boules and a jewel making industry to fabricate them. Several American suppliers have developed boule manufacture to such a point that there is now very little danger that we might experience any shortage of synthetic corundum, The jewel-bearing industry has now attained a mass production basis in this country, so that the worst part of the jewel shortage is probably over. Partly on account of unfamiliar processing methods and partly on account of variable raw material, considerable loss was experienced at first, through waste of material, breakage, and other factors. It was therefore necessary to improve the mechanical processes of jewel production and also to study the jewel material itself to determine if it could be classified according to any scheme which might improve production efficiency. The latter studies constitute the subject of this paper.

ACKNOWLEDGMENTS

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THE ARGUMENT

The fundamental thesis of this discussion is the hypothesis that crystallographic orientation is an important aspect of the fabrication and use of all tools and products made from crystalline materials, and especially from single crystals of any material. This thesis has been argued by Kraus and Slawson (1939; 1941) for the special case of diamond. Hamilton experience has fully confirmed their general hypothesis in that case.

This hypothesis implies that boules having orientation "X" will in general give different results both in fabrication of jewels and in wearing ability of the product, when compared with boules having orientation "Y." Heretofore, it has been tacitly assumed that the differences, if any, are negligible; or that if not negligible, such differences are impracticable to determine. A simple criterion has been found for determining, at least approximately, the distinction between two important orientation-types of boules. This criterion enables one to predict with a fair degree of confidence, whether a given boule will be easily and efficiently processed, or will give more-than-average broken pieces (and less efficiency) in processing.

ORIENTATION STUDIES

There is only one criterion which can be used for separating boules into two or more groups without highly trained personnel. That is the smoothness of the parting plane. Parting planes can be classified as smooth and wavy, or as rough and hackly fractures. Intermediate grades of smoothness make the determination of quality on this basis somewhat arbitrary for about 25% of the boules, but most can be classified easily. To determine the usefulness of this criterion, the following test was made.

From a new quantity of 10 kilograms of boules, two groups totalling approximately 4,000 grams each were selected, the first containing the smoothest boules, and the second, the roughest. Two thousand grams of material from the original quantity was excluded from the test, mainly because of its intermediate smoothness.

Each of the 4,000 gram groups thus selected was divided into two lots, one lot of rough being paired with one of smooth boules for processing comparisons. Two sizes of jewel blanks were then produced from the two pairs of lots, one size from one smooth lot and its corresponding rough lot, and the other size from the other smooth lot and from its paired rough lot.

TABLE 1

SAWING RESULTS

Material Started	(%) Weight of Good Pieces Recovered			No. of Pieces Per Gram of Boules Started	
	Saw boules to slabs	Saw slabs to sticks	Saw sticks to blanks	Squares Sawn	Roundels
Size No. 1					
Smooth parting planes	69%	34%	15%	1.32	1.08
Rough parting planes	63%	38%	11%	0.84	0.62
Size No. 2					
Smooth parting planes	74%	48%	14%	2.10	1.75
Rough parting planes	71%	44%	14%	1.96	1.60

Table 1 shows the recovery, in weight percentages, from each sawing operation, and the number of pieces of each size obtained from a gram of boules started. The net recovery of roundels after sawing, surfacing, and grinding, was 1.08 roundels per gram for smooth boules versus 0.62 roundels per gram for rough boules in size number 1, and 1.75 and 1.60 roundels per gram, respectively, for size 2. The differences are not large, but they are consistent, not only in this experiment but also in an early one based on correlated data; further evidence below indicates that this same difference also continues through the drilling and opening operations.

The above experiment warranted further investigation. The complete orientation data for 24 of the smooth boules and for 25 of the rough ones were recorded in advance by means of back-reflection Laue diffraction patterns. The optic orientation of a considerably larger number of each type had also been determined. The optic orientation is not significantly different in the two types of boules, but the complete orientation with respect to both c-axis and a-axes shows very significant differences.

Method of orientation study. The methods of orientation study used here are based on x-ray diffraction patterns, usually combined with the rapid determination of extinction angle by means of polarized light; this angle is here designated "ρ" and is defined as the angle between the c-axis of the crystal and the growth-axis of the boule (or the geometrical axis of a jewel). The optical method is not an essential adjunct to the x-ray method, but serves as a useful check. As already noted, this angle may have any value from 0° to 90°. It is most often between 30° and 80° because that appears to be the range favored in the boule-manufacturing process. This angle is determined again by the x-ray method, but in addition, the latter method gives a second angular coordinate of orientation, designated "ϕ,"* which is the angle between (1) the plane containing the c-axis and an a-axis of the crystal, and (2) the plane containing the c-axis of the crystal and the growth-axis of the boule (that is, the parting plane). This angle, ϕ, may have any value between 0° and 120°, or by taking into account the symmetry planes of the rhombohedral class to which corundum belongs, ϕ may be limited to values between 30° and 90° if desired. Values larger than 120° would be but symmetrical repetitions of values less than 120° because of the ternary symmetry of the c-axis (see Ford, 1932, p. 120, or Winchell, 1943, p. 81). In accordance with the above definitions, (ϕ, ρ) are the 2-circle angular coordinates of the growth axis of the boule, or of the plane of a jewel cut in conventional manner from it. Remembering that the parting plane contains the c-axis and the boule-axis, its coordinates are then $(90°+\phi, 90°)$.

The x-ray method best adapted to the determination of the coordinates defined above is the back-reflection Laue technique, utilizing the general, or "white" radiation from the x-ray tube. The resulting pattern is related closely to the gnomonic and stereographic projections, and can often be interpreted by inspection. This pattern can easily be converted to a gnomonic projection in which the center of the projection represents the boule-axis or the jewel-axis to be determined, and it is relatively easy to determine the 2-circle coordinates of this point with respect to the crystallographic axes after location of the latter on the projection. The pseudo-cubic symmetry of corundum makes considerable care necessary in the construction and interpretation of these projections; it also makes the optical method of determining ρ independently very useful.

Presentation of orientation data. When many orientation data are to be studied it is convenient to use the Lambert equal area projection for plotting the 2-circle coordinates of the boule growth-axes, so that a contour diagram can be constructed from the summarized data. The relation of the equal-area, and the stereographic projection is indicated in Fig. 3.

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* The definition here given results in values of ϕ, 60° larger than those given for corresponding faces in the new edition of *Dana's System of Mineralogy*, volume 1, pp. 23–31. The difference is due to the choice of the positive end of an a-axis for $\phi=0$, versus the choice of the negative end therefor. Conversion is Winchell to Dana: $\phi'=\phi-60°$ and Dana to Winchell: $\phi'=\phi+60°$. This does not affect the value of ρ.

The azimuthal coordinate, ϕ, is measured by means of the scale of degrees around the primitive circle. The scatter diagrams (Figs. 4–10, A) show not only the points within the range $30 \leqq \phi \leqq 90$, but also all symmetrically equivalent points in the upper half of the rhombohedral crystal (See Ford, 1932, p. 120, or Winchell, 1942, p. 81).

Isopleths ("contour lines") are then drawn showing the density of point distribution on the scatter diagram, and therefore expressing the relative frequency of all possible boule (or jewel) orientations. This can be done because of the special property of equivalence of areas, possessed by the equal area projection. The lines are drawn in accordance with methods outlined in various books on structural petrology or petrofabrics (Sander, 1930, p. 118–135; Fairbairn, 1935, pp. 22–24). If the distribution is perfectly uniform, the concentration will be 1% all over the diagram, provided only that a sufficient number of points has been determined.

Orientations of boules with smooth and rough parting planes. Figure 4

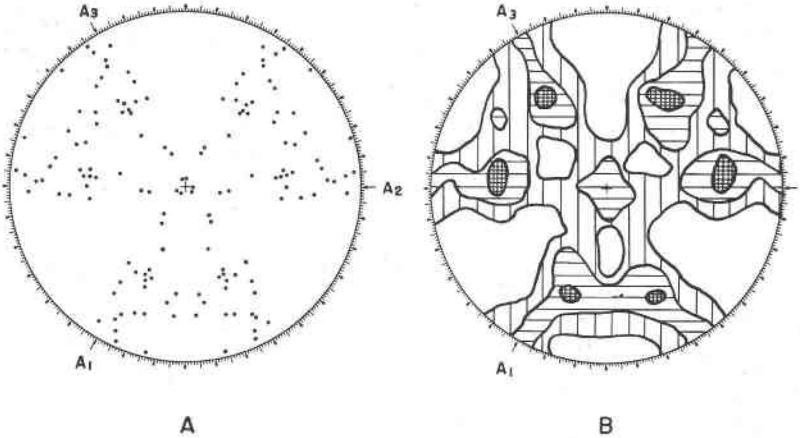


FIG. 4. Orientation of growth directions of 24 boules with smooth parting planes. *A*, Scatter diagram. *B*, Density diagram. 0–1–2–3%. Constructed with 2% movable area.

shows the orientation tendencies of boules having unusually smooth parting planes, representative of the boules cited in the experiment described above. Figure 5 represents the complementary boules with rough parting planes. It will be remembered that the smooth boules represented by Fig. 4 yielded consistently better results than the rough boules represented by Fig. 5, as shown in Table 1. It will be noted also that the extinction angles, ρ, indicate very little or no difference between the boules represented in Fig. 4, and those of Fig. 5. It is unfortunate that these same, identical lots cannot be traced through the remaining processing operations, to determine if smooth boules continue to be superior to rough ones. However, an analysis by the same methods, of orientations of jewel blanks that have passed through the most significant later steps of manufacture is possible and will be presented below, showing a very significant correlation with the smooth boules represented in Fig. 4.

General orientation tendencies of all boules. First, however, an analysis of general boule orientation regardless of the quality of the parting plane, extinction angle, or any other criterion, should be presented as background against which to compare observed orientation tendencies to be found in special groups. Figures 6, 7, and 8 show the results of x-ray orientation anaylsis of approximately 150 boules selected at random from three shipments, respectively of white boules from supplier "*X*," red boules from the same supplier, and red boules from supplier "*Y*." Shipments of boules from other suppliers have been too erratic to permit inclusion in this discussion, although individual boules still available in our specimen collections fall nicely into the pattern established by Figs. 6, 7, and 8. It will be noted that there are slight differences between the dominant orientations of "*X's*" white and red boules, but that "*Y's*" red boules show orientations somewhat similar to "*X's*" white ones. These differences probably result from differing orientation-control practices of the two suppliers, and not from any fundamental differences due to the crystallization of corundum boules.

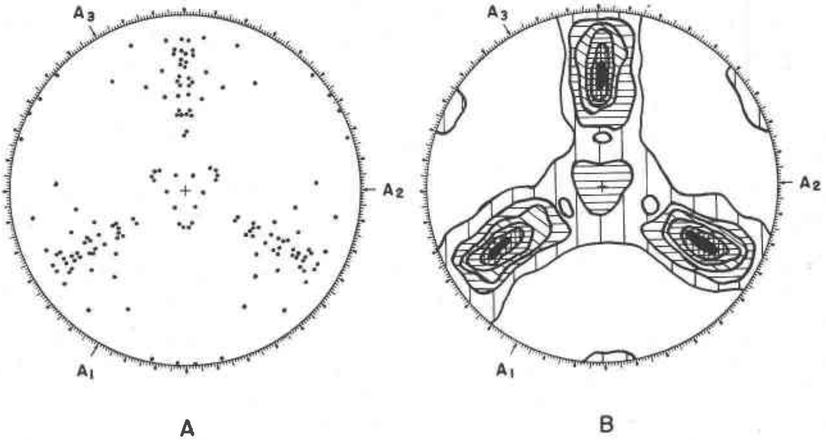


FIG. 5. Orientation of growth directions of 25 boules with rough parting planes. *A*, Scatte diagram. *B*, Density diagram. 0–1–2–3–4–5–6%. Constructed with 2% movable area. r

Orientations of successful vs. unsuccessful jewel blanks. This study was originally inspired by the writer's discovery of a box of jewel blanks which had proved themselves definitely superior to other blanks which broke

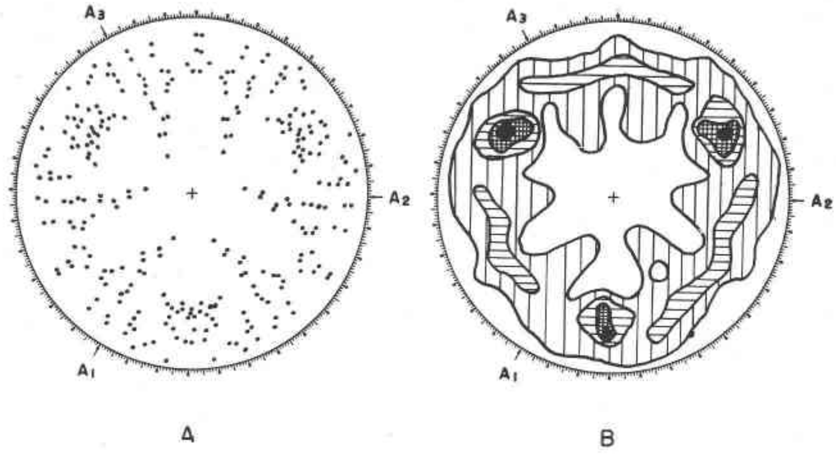


FIG. 6. Orientation of growth directions of 48 white boules from supplier "*X*." *A*, Scatter diagram. *B*, Density diagram. 0–1–2–3–4%. Constructed with 1% movable area.

under similar conditions. The superior jewel blanks were selected through the operation of a certain type of accident in the drilling operation, in which the drill becomes worn to a tapered point, then during drilling jams in the partially finished hole, and breaks off. Ordinarily, such ac-

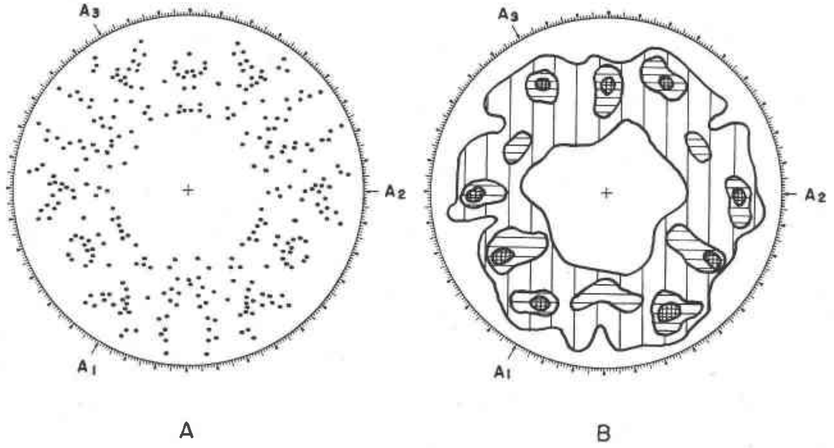
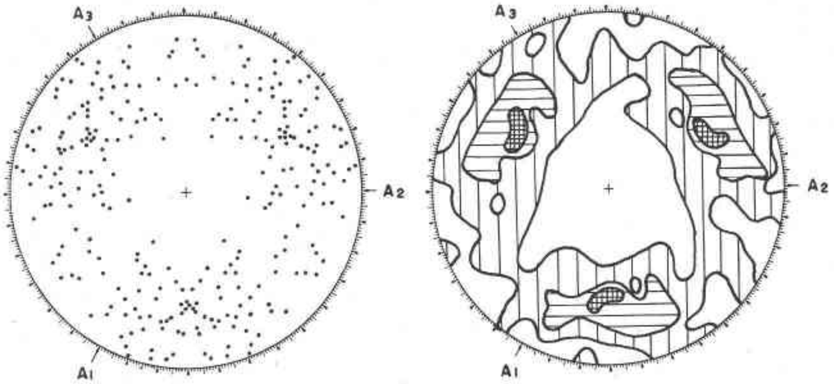


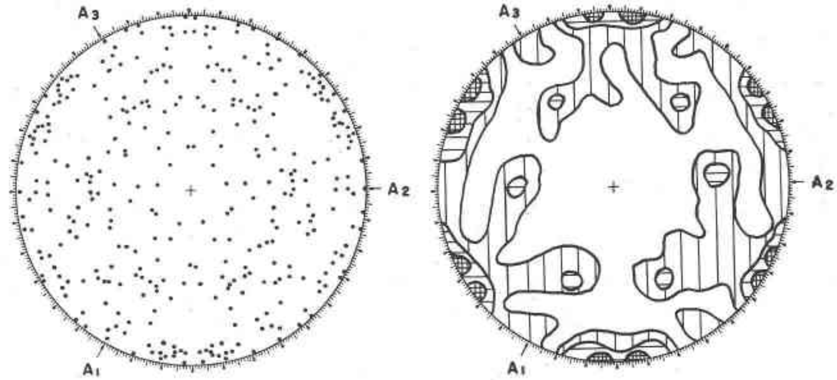
FIG. 7. Orientation of growth directions of 50 ruby boules from supplier "*X*." *A*, Scatter diagram. *B*, Density diagram. 0–1–2–3%. 1% movable area.



A B

Fig. 8. Orientation of growth directions of 46 ruby boules from supplier "*Y*." *A*, Scatter diagram. *B*, Density diagram. 0–1–2–3%. 1% movable area.

cidents result in broken jewels rather than broken drills. The following two figures make no pretense at showing orientations representative of the average jewel, but rather of orientation tendencies among remarkably strong, and among weak jewels.



A B

Fig. 9. Orientation of planes (or hole-axes) of 56 jewel blanks in which drills stuck without damage to the blanks. *A*, Scatter diagram. *B*, Density diagram. 0–1–2–3%. Constructed with 1% movable area.

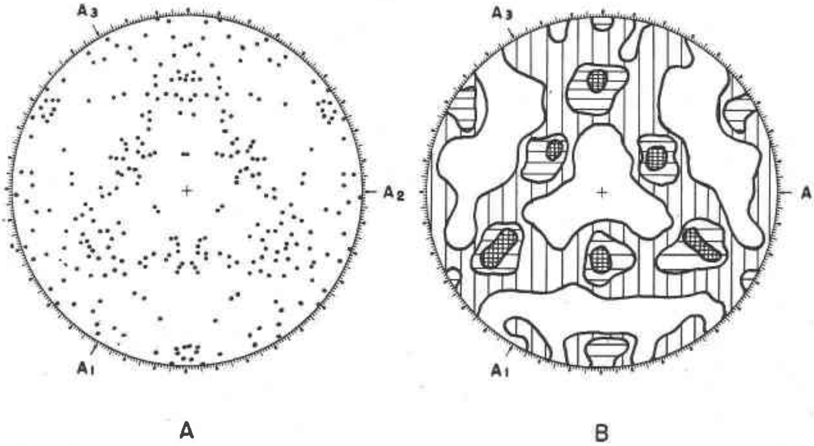


FIG. 10. Orientation of planes (or hole-axes) of 49 jewel blanks that broke during drilling or opening of the holes. *A*, Scatter diagram. *B*, Density diagram. 0–1–2–3%. 1% movable area.

Figure 9 shows the scatter and density diagrams of orientation of 56 jewel blanks in which drills were broken as just described. Figure 10 shows the corresponding diagrams for 49 broken jewel blanks. The force required to remove the broken drills mechanically is almost always enough to break the jewel blanks; in practice the drills are therefore removed chemically. All the jewel blanks represented by Figs. 9 and 10 had already withstood the tests of sawing, surfacing, and centerless grinding to make roundels. A comparison of the two diagrams therefore evaluates the strength of jewel blanks against expansive stresses set up in drilling and opening. On the other hand, comparison of Fig. 9 with Figs. 6, 7, and 8 indicates which of the boules were inferior in any of the operations from sawing through drilling. Moreover, it will be seen immediately that the boules with *rough* parting planes (Fig. 5) are strongly correlated with those jewel blanks which *broke* in drilling, (Fig. 10) even after surviving the preceding operations, and that the unusually *smooth* boules (Fig. 4) can be correlated excellently with the *strong* jewel blanks which survived the special accident of stuck drills (Fig. 9). For practical purposes, these conclusions show definitely that a material increase in rate of jewel production could be expected if the boule material should be especially selected for smooth parting planes in preference to rough, hackly surfaces.

CRYSTALLOGRAPHY OF SYNTHETIC CORUNDUM

A limited amount of fundamental information may be derived from the preceding data, in addition to the practical correlations to be found between jewel production rates and boule orientation. Moreover, the enunciation of such additional fundamental information may later lead to further conclusions of value to the manufacturer of jewels as well as to the manufacturer of boules.

Referring to Figs. 6, 7, and 8, it appears that certain crystal forms of corundum may have superior crystallizing power, a conclusion which the makers of the boules could probably confirm or refute in terms of amounts of gas required to grow a given weight of boules. It is understood that orientation control at the boule manufacturing plants is, or soon will be, an accomplished fact. Whether this intention may have resulted from fuel savings due to superior growth tendencies of corundum in certain orientations, or from the demands of the jewel manufacturing industry is known only to the boule makers. A study of energy-entropy relations and their correlation with crystallographic growth directions might lead to significant results, but such a study is outside the scope of this discussion. Conditions of crystallization obviously affect the crystal habit, and therefore the rate of growth of various crystal forms in nature; similarly, conditions of orientation and crystallization must affect the rate of crystal growth in artificially produced crystals.

An attempt to specify the various specially-marked growth axes in terms of Miller-Bravais indices or of Miller indices referred to rhombohedral axes might be valuable as an indication of which orientation should be preferred by jewel makers, and which orientation shunned. Table 2 gives in Miller-Bravais indices the nearest important crystallographic plane to each of the peaks shown in the density diagrams.

TABLE 2

Figure Number	Peak Concentration		
	ϕ	ρ	$h\,k\,\bar{i}\,l$
4	65	52	$33\bar{6}5$
5	30	55	$01\bar{1}1$
6	90	62	$40\bar{4}3$
6	−5 to 65	60±	
7	30	58	$01\bar{1}1$
7	60	65	$33\bar{6}4$
7	90	50	$40\bar{4}5$
8	90	52	$40\bar{4}5$
9	60	50	$11\bar{2}2$
9	85	90	$81\bar{9}0$
10	30	55	$01\bar{1}1$
10	90	30	$10\bar{1}2$

Information on cleavage and parting planes may be obtained from a study of Figs. 9 and 10. Figure 9 shows high concentrations of successfully drilled jewels at the point (85°, 90°), corresponding roughly to a plane with indices $\{10\bar{1}0\}$, or more exactly to $\{15.2.\overline{17}.0\}$. About 3 to 4 times as many drilled blanks showed this orientation as would have been the case had the orientation dots been distributed uniformly in all parts of the diagram. Ford (1932, p. 481) mentions a commonly developed parting parallel to the basal pinacoid $\{0001\}$. If such a weakness existed in these jewels, it could hardly have failed to show up through the breaking of the jewels in this orientation, and their consequent elimination from the class, "unusually strong in drilling." Figure 10 suggests by the distribution peaks that a likely plane of breakage is the second order prism $\{11\bar{2}0\}$. Breakage approximately parallel to this form could account for peaks of breakage of jewels whose axes lie 90° from it. The distribution of ridges in Fig. 10 suggests an alternative hypothesis, however, in the possibility that breakage occurred parallel to the planes of $\{01\bar{1}1\}$. If this were the one and only plane of weakness, practically all the broken jewels indicated in Fig. 10 would have had their holes drilled parallel to one or more of the faces of this form. Additional commentary on the possibility of a cleavage parallel to the second order prism is afforded by Fig. 5, in which almost all of the boules with rough, irregular parting planes are shown to have growth axes in the rhombohedral zone, and parting planes therefore parallel to the second order prism. It would be surprising if the poorest parting planes should be parallel to a good cleavage; quite the converse would be expected. Figure 4, on the other hand, in which growth axes of boules with smooth parting planes lie mostly in the second order pyramid zone, seems to indicate a tendency to break parallel to the first order prism $\{10\bar{1}0\}$.

Parting surfaces parallel to the unit rhombohedron $\{10\bar{1}1\}$ are sometimes developed very highly. When fracture occurs on such planes, the resulting surfaces may be perfectly flat over large areas, and always give excellent signals in the optical goniometer. This parting is frequently responsible for small chips out of corners and edges of jewel blanks, and indeed it sometimes gives much trouble in the processing of blanks for pallet stone jewels, which are shaped simply like tiny monoclinic crystals bounded by surfaces belonging to the three pinacoids. Such jewels are often as small as 0.5 mm. in thickness, and must have highly polished surfaces and perfect, unfrayed edges. The artificial production of such parallelepipedons to small dimensions from a brittle material like corundum offers a very nice problem in tool design, for the dimensional tolerances on these jewels are very limited. Vibration of saw blades in sawing boules or at other sawing steps, and vibration or too coarse diamond powder in laps used for surfacing small corundum pieces often seem to be responsible for development of the rhombohedral parting.

The exterior, convex surface of most boules is composed of myriads of tiny facets parallel with the faces of the basal pinacoid, the unit rhombohedron, and the first and second order prisms. As a result of this condition almost the entire convex surface of the boule glitters brightly under certain conditions of illumination. Under these conditions, slight imperfections of crystal structure along definite lines and bands are visible. This probably is the lineage structure described by Buerger (1934). The brightest reflection thus obtained is usually due to $c\{0001\}$. None of these reflections ever gives a very good signal in the optical goniometer.

Conclusions

The ratio of good jewels to corundum input can be correlated with crystallographic orientation of the raw material boules. An outstandingly poor orientation is more frequently found among boules with rough, hackly parting planes than among those with smooth ones. Such boules most often grow in a direction approximately normal to the planes, $\{01\bar{1}1\}$ and $\{10\bar{1}2\}$. Favorable orientations for boule axes are not so definitely located, but appear to be near $\{11\bar{2}2\}$ and $\{81\bar{9}0\}$ or $\{81\bar{9}2\}$. A uniform control of boule axes in one or the other of these orientations would probably result in a marked decrease in the rate of jewel breakage during fabrication.

One empirical method for partial control of boule orientation depends upon the fact that those with $\{01\bar{1}1\}$ orientation generally split with a rougher fracture than those with other orientations. This fact may indicate that the parting on $\{11\bar{2}0\}$ cited in reference books (Ford, 1932, p. 481), on the natural mineral is not so well developed in synthetic material as another parting, not mentioned in the textbooks, parallel to $\{10\bar{1}0\}$.

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