THE AMERICAN MINERALOGIST

JOURNAL OF THE MINERALOGICAL SOCIETY OF AMERICA

Vol. 32 JANUARY–FEBRUARY, 1947 Nos. 1 and 2

SOME PROPERTIES OF MATERIALS USED FOR JEWEL INSTRUMENT BEARINGS

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ABSTRACT

Information on the physical properties of materials used for jewel bearings which was obtained in the course of tests by the National Bureau of Standards for the Bureau of Aeronautics, U. S. Navy, is summarized. Inherent properties of the material which affect the ease of fabrication and the performance in use are described for the principal materials used for jewel bearings in aviation instruments, namely, synthetic and natural corundum (sapphire and ruby), synthetic spinel, and glass. Some incidental observations on the properties of synthetic spinel in relation to its use as a possible optical material are also included.

I. INTRODUCTION

In the course of an investigation on jewel bearings for instruments, conducted under authorization of the Bureau of Aeronautics, United States Navy,[1] the National Bureau of Standards made a number of tests and examinations of various materials used for this purpose. The present report summarizes the results of these laboratory tests so far as they give information on the suitability of the materials for the use intended as well as for other possible technical uses. Data are provided on the hardness, strength, homogeneity and structural defects in these materials. No attempt has been made in this investigation to evaluate the dimensions, shape and bearing surfaces of the jewels or the quality of the finish on the bearing surfaces.

The principal bearing materials investigated were corundum (sapphire and ruby), spinel and glass.

II. CORUNDUM

Corundum (αAl_2O_3) is the only one of the several forms of alumina which is used, either as a naturally occurring mineral or as a synthetic product for making jewel bearings. Detailed descriptions of the properties

[1] This work was done under order NAer 00076, NBS Project no. 6324.

and crystallography of corundum can be found in standard textbooks on mineralogy.[2] Strictly speaking, red varieties of corundum are called ruby, and blue varieties sapphire. Frequently, however, the name sapphire is given to any variety other than red and it is often used as a general name for all gem bearings made of corundum.

1. Natural crystals

The only natural corundum crystals submitted to this Bureau for examination and test were from a deposit in Montana and were submitted by the Defense Supplies Corporation. They were graded into sizes designated 5, 6 and 8, apparently corresponding to these sieve numbers. The crystals represented whole individuals or fragments in the form of partially waterworn, barrel-like prisms and thick plates. In color they were blue, green, pink, yellow, or lavender. No information was supplied by the Defense Supplies Corporation as to the source in Montana of these crystals. It is known that sapphire crystals have been obtained from at least two sources in that state, one at Philipsburg and the other at Yogo Gulch. It is understood that most of the supplies in recent years have come from Philipsburg.

The average percentage of stones rejected from purchased lots by the gem fabricators because of cracks, inclusions, etc., is not known. Two bearing manufacturers who appraised a lot of stones from the Defense Supplies Corporation at the request of the National Bureau of Standards agreed that about 60 per cent of these stones were suitable for bearing manufacture. As supplied to the bearing fabricators, natural corundum crystals are furnished in size grades depending on the size of the bearing to be cut. Even with size grading, however, the waste in cutting to size is probably at least as great as the waste in cutting synthetic boules of the conventional shape.

There is only one twinning plane in corundum, that parallel to the rhombohedral face $(10\bar{1}1)$. The twins produced may be of the interpenetration or repeated polysynthetic type. The crystals from the Montana source showed little external evidence of twinning.

While there is no good cleavage direction in corundum, there are two possible parting directions, one parallel to the base (0001) and the other parallel to the rhombohedron $(10\bar{1}1)$. The development of the parting along the rhombohedral plane appears to be greatly intensified by the presence of twinning along the same plane. The parting may affect the

[2] Dana's Textbook of Mineralogy, E. S. Dana and W. E. Ford, 4th ed. (John Wiley & Sons, New York, 1932).

Gems and Gem Minerals, E. H. Kraus and C. B. Slawson, 4th ed. (McGraw-Hill Book Co. New York, 1941).

usefulness of the natural crystals for instrument bearings because it may increase the breakage in fabrication.

The hardness of natural corundum, which is designated as 9 on the Mohs scale of scratch hardness, is more precisely rated by the Knoop and Peters[3] method, using a wedge-shaped diamond indenter impressed into the test material by a definite load. By this method the hardness number of corundum is found to vary with the relation of the indenter direction to the crystallographic direction. Measurements[4] were made on the finished lower surface of Montana sapphire instrument bearings in random directions with respect to the crystallographic *c* axis. For the 100 gram load the hardness numbers were found to range from 1700 to 2000 and for the 500 gram load from 1450 to 1730. This is about the range of hardness numbers obtained by indentations made in surfaces of synthetic sapphires. The variation in hardness with crystallographic direction is appreciable and significant. The indenter marks parallel to the *c* axis, or to its projection on the surface tested, usually are perfect, whereas those oblique or perpendicular to the *c* axis usually show fracture marks perpendicular to the *c* axis extending from the ends of the long axis of the indenter. These are probably cracks parallel to the basal parting plane caused by the pressure of the indenter.

Natural corundum may contain inclusions of liquid or of crystals such as rutile or hematite, but in general these are not a major cause of loss in the fabrication of gem bearings and such inclusions are rarely found in the finished bearings.

2. *Artificial Corundum*

As far as is known, all artificial corundum or artificial sapphire used for gem bearings is manufactured by methods which are basically the same as that of Verneuil.[5] By this method powdered raw material is introduced through the pipe of an oxyacetylene or oxyhydrogen blowtorch which is surrounded axially by a cylindrical furnace with insulated refractory walls. The raw material is usually very pure ammonium alum which is introduced into the blowpipe after reduction to a very fine powder by calcination. The raw material, melted in the flame of the blowtorch, impinges on a fire clay or other refractory base and there solidifies, building up from a small tip into a cylindrical or elongated pearshaped form called a boule. As the boule grows, the fire-clay base is lowered by

[3] A sensitive pyramidal-diamond tool for indentation measurements. Frederick Knoop, Chauncey G. Peters and Walter B. Emerson: *J. Research NBS*, **23,** 39 (1939); *RP* **1220.**

[4] Made by C. G. Peters, of the National Bureau of Standards.

[5] Verneuil, A. V. L., *Comptes rendus*, **150,** pp. 185–187. *Idem.*, U. S. Patents 988,230 and 1,004,505 (1911). Kraus and Slawson, *op. cit.*, pp. 124–134.

a mechanical or hand-operated screw until the required length is reached, when the flame is turned off and the boule is allowed to cool in the furnace for some time before removal to the open air.

With the exception of twinning bands in some boules, the corundum made by the process just described is essentially a single crystal and even the rod forms, which may be several feet long, are a single crystal from end to end.

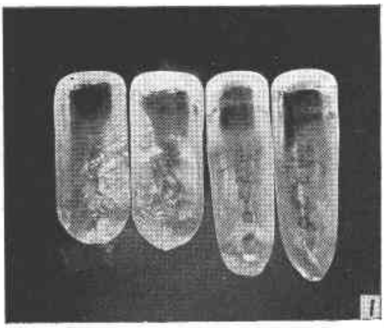
To color artificial corundum, small amounts of other oxides are added to the aluminum oxide in the raw material, one or two per cent of chromium oxide for ruby, and a mixture of iron oxide and titanium oxide for sapphire.

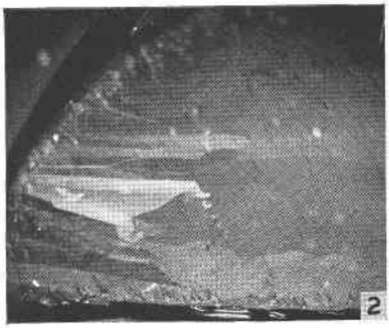
After removal from the furnace the elongated pear-shaped corundum crystals either split spontaneously or may be readily split into halves along the longitudinal axis (Fig. 1) by nipping off the small tip with a pair of pliers or by rapping the boule sharply on the tip with a hammer. The *c* axis almost without exception lies in the split plane.

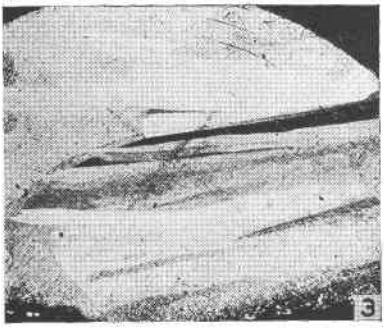
The splitting of boules on the plane containing the *c* axis may be explained by the differences in the coefficient of thermal expansivity in different crystallographic directions in corundum. As determined by J. B. Austin[6] for a blue Indian sapphire, the mean linear coefficient is 8.2×10^{-6} for the direction parallel to the principal axis (the crystallographic *c* axis) and 7.2×10^{-6} for the direction perpendicular to this axis over the temperature range 20° to 1,000°C. Preliminary determinations on oriented slices of an artificial corundum boule by A. S. Creamer, of the National Bureau of Standards, gave values which are essentially in agreement with those of Austin. Since the thermal expansivity of a crystallographically uniaxial crystal (such as corundum) may be represented by an ellipsoid of revolution with the *c* axis as the revolution axis, and since the boule shape also is a figure of revolution, the cooling of any boule in which the *c* axis is oblique to the boule axis results in a concentration of strain in the plane containing these axes, the release of which takes place by splitting along this plane.

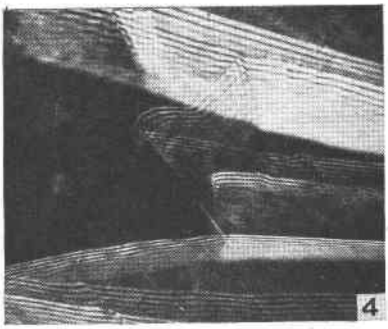
The orientation has been determined by *x*-rays at the National Bureau of Standards on a number of specimens of artificial corundum. Of the 56 boules of the pear-shaped type on which the orientation has been determined, 55 had the *c* axis lying in the split plane. Of the latter, 15 (or 27 per cent) had orientations such that the *c* axis made an angle of 80° or more with the boule axis, and 29 (or 53 per cent) had orientations such that the *c* axis made an angle of 70° or more with the boule axis. The number of specimens decreased with decrease in the angle and only one

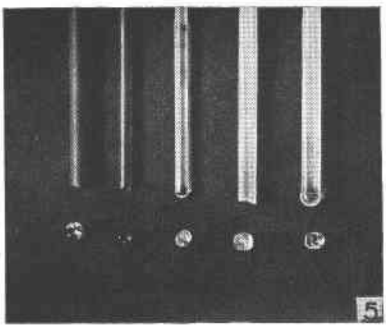
[6] *J. Am. Ceram. Soc.*, **14,** 795 (1941).











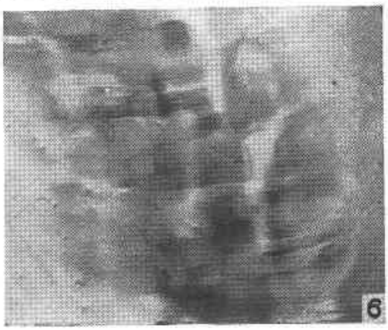


FIG. 1. Two artificial sapphire boules showing the split surface. 2/3 natural size.

FIG. 2. A transverse slice from a split corundum boule showing twinning bands and folds. Polarized light. Crossed nicols. Mag. $5\frac{1}{2}\times$.

FIG. 3. Cross-section of a sapphire boule showing banding and inhomogeneities. Polarized light. Crossed nicols. Mag. $5\times$.

FIG. 4. Same specimen as Fig. 3 at a higher magnification. Polarized light. Crossed nicols. Mag. $27\times$.

FIG. 5. Rod-shaped synthetic corundum and spinel boules. 2/3 natural size.

FIG. 6. Split surface of a sapphire boule showing striations and banding. Ordinary light. Mag. $7\times$.

was found with an angle of less than 20° between the *c* axis and the boule axis.

Winchell[7] has made a much more detailed analysis on a larger number of boules and has correlated the orientation with the behavior of the material in the process of manufacture of jewel bearings. Among other results of his work, he observed that boules with smooth parting planes gave lower loss in bearing fabrication than did those with rough or hackly parting surfaces. Our examination of only two or three of such boules indicates that hackly parting surfaces are related to areas in the boules in which repeated twinning takes place in the rhombohedral plane. In the boule containing the twinning bands shown in Fig. 2, the hackly portion of the split surface extends only as far as the twinning bands. Although these bands have rounded, irregular and convoluted terminations in the body of the boule as observed in slices approximately 1 mm. thick (Figs. 2, 3, and 4), alternate bands extinguish simultaneously, as in repeated or polysynthetic twinning, and the extinction angles between adjacent bands have the values to be expected from twinning on the rhombohedral twinning plane of corundum.

If, as appears probable from information from bearing fabricators, the ease and perfection of boule slicing depend on the direction of the saw cut with respect to crystallographic directions in the boule, the control of orientation would appear to be of practical importance. It is claimed by one fabricator of gem bearings that cutting with the diamond saw exactly parallel to the crystallographic basal plane of corundum takes place more rapidly and with less splintering of the material than in any other direction, although if the cut is made slightly off this plane, fracturing and splintering are worse than in any other direction. Cuts made approximately perpendicular to the basal plane take place with little fracturing, but the cutting is somewhat more difficult. This opinion is corroborated by the determination with the diamond indenter, which shows the softest direction parallel to the basal plane but with flaws extending out from the indenter mark parallel to this plane. In order to have easier control of orientation as well as to obtain a sample which gives less waste in cutting bearings, a domestic producer has modified the furnace operation so that long, thin rods $1\frac{1}{2}$ to 4 mm. in diameter are produced (Fig. 5) instead of the usual pear-shaped boule. The orientation is controlled by starting the formation in the furnace on a slice of corundum whose orientation has been determined. The new rod builds up on the "seed" with the same orientation. The manufacturer of the rod forms provides[8] the following

[7] Winchell, Horace, Orientation of synthetic corundum for jewel bearings: *Am. Mineral.*, **29**, 399–413 (1944).

[8] Personal communication from M. H. Barnes, of the Linde Air Products Co.

information concerning the most favorable orientation. Corundum rods which are to be worked thermally for such uses as thread guides should have orientations of from 30° to 75° between the *c* axis and the rod axis and preferably between 40° and 50°. Moreover, the plane of bending for such rods should coincide as nearly as possible with the plane containing the *c* axis and the rod axis. "For cutting and grinding operations synthetic corundum rods wherein the angle is between 30° and 80°, and preferably between 40° and 80°, are recommended for the maximum yield of usable products such as jewel bearing blanks."

While determination of the relation of crystallographic directions to the boule axis can be made most precisely by means of *x*-rays, there are some visual indications of the crystallographic orientation of the split surfaces of some boules. Figure 6 shows the split surface of such a boule at a magnification of 7 diameters. The fine parallel oblique striations (not to be confused with the nearly horizontal, broad bands) lie in the direction of the *c* axis. After a little practice these lines can be found with the unaided eye on the majority of boules having split surfaces.

The defects and impurities in artificial corundum are unlike those found in the natural material. Foreign crystals are rarely, if ever, observed in artificial corundum although gas bubbles are sometimes found. The gas bubbles, when present, are usually arranged in a zone paralleling one of the surfaces of the boule. Structure lines consisting of numerous fine parallel striations can sometimes be seen in artificial corundum, especially in the colored varieties. The cause of these striations is unknown, but they are probably due to an uneven distribution of the pigment.

Hardness determinations on synthetic corundum crystals made by the Knoop indenter agree quite well with those made on natural corundum crystals. A typical set of hardness numbers by the Knoop indenter as determined by C. G. Peters,[9] of the National Bureau of Standards, is given in the table below:

	100 grams	500 grams
Artificial corundum		
Indentation parallel to *c* axis	2000 P[1]	1670 P
Indentation perpendicular to *c* axis	1660 P	1525 F[2]

[1] P = perfect indentation.
[2] F = light fracture.

Although these values are within the range of those found by Winchell,[10] there are some discrepancies between the two sets of observations as to the relation of the Knoop number to orientation. In part, the discrep-

[9] Personal communication.

[10] Winchell, Horace, The Knoop microhardness tester as a mineralogical tool: *Am. Mineral.*, **30**, 583–595 (1945).

ancies may be the result of the apparent low hardness number parallel to the basal plane caused by the tendency to part along this plane. It is obvious, nevertheless, that experiments are necessary in which the direction of the indenter and the orientation of the plane on which the indentations are made are carefully controlled.

Optically, artificial corundum is not significantly different from natural corundum. The indices of refraction are practically identical and the colored varieties of artificial corundum, like the natural type, are pleochroic.

The specific electrical resistance of a single crystal of artificial corundum as measured at the National Bureau of Standards[11] was found to be 1 megohm at 1214°C. parallel to the *c* axis and 1 megohm at 1231°C. perpendicular to the *c* axis.

3. Corundum as Instrument Bearings.

Corundum (sapphire and ruby) has long been used as a bearing material in watches, chronometers, compasses, watt-hour meters and other instruments. As such, corundum has the advantage of its considerable hardness, toughness and resistance to impact. It has the disadvantage, however, that it is much harder than the metals commonly used for pivots. In bearings of the Vee type (having a conical surface) for instruments subject to vibration, this causes wear and deformation of the pivot. The accumulation of iron oxide resulting from the abrasion and rusting causes an increase in friction. Since the pivot with its attached parts is usually more difficult and expensive to replace than the bearings, there is a belief among some engineers that the bearing material should have approximately the same hardness as the pivot material. In ring bearings differential hardness may cause ellipticity in the opening, with consequent increase in frictional resistance.

III. Spinel

Another material having properties which make it suitable for use as gem bearings is the mineral spinel. While spinel in pieces large enough for gem bearings occurs in nature less abundantly than corundum, it can readily be made artificially.

Although the chemical formula of true spinel is $MgO.Al_2O_3$ with a composition by weight of 28.3 per cent MgO and 71.7 per cent Al_2O_3, Rankin and Merwin[12] have found that the composition of homogeneous spinels may be extended by solid solution of alumina to a limiting com-

[11] Geller, R. F., Yavorsky, P. J., Steierman, B. L., and Creamer, A. S., *J. Research NBS*, **36**, 277 (1946); *RP* **1703**.

[12] *J. Am. Chem. Soc.*, **38**, 568–588 (1916).

position of 7 per cent MgO, 93 per cent Al_2O_3. Rinne[13] has shown that spinels made by the Verneuil process show a continuous variation in physical properties up to a molecular composition of about $MgO.4Al_2O_3$. It has been found in commercial production that excess of magnesia over the composition $MgO.Al_2O_3$ causes the crystallization of periclase (MgO) with the spinel, which gives rise to the disruption of the boule during cooling. For this reason spinels are generally made with excess alumina.

So far as is known, natural spinel has not been used for instrument or meter bearings although it is well known as a decorative gem material.

Artificial spinel has been made for a number of years. It is produced with the same apparatus as artificial corundum. The raw material used is a mixture of magnesia and alumina, of magnesium carbonate and ammonium alum, or of similar materials which will give the required ratio of magnesia to alumina. The solidified material, like artificial corundum, occurs in the form of a pearshaped boule with a narrow stem below and a broad top. Artificial spinel boules, unlike artificial corundum, often have fairly well developed crystal faces corresponding to those of the cube, octahedron and dodecahedron. As the boule forms in the furnace, the rounded upper portion and the vertical sides are generally cube faces (Fig. 7) and the octahedral faces constitute the pyramidal planes (Figs. 7 and 8). The velvety matte appearance of the top surface of the boule is caused by the projecting pyramidal surfaces of microscopic crystals (Fig. 9).

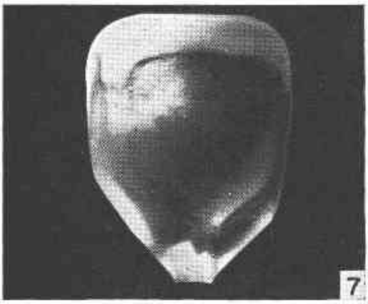
Spinel boules in the rod-shaped forms similar to those of corundum (Fig. 5) have also been manufactured in this country. These grow spontaneously with the fourfold axis (the cube axis) coincident with the rod axis.

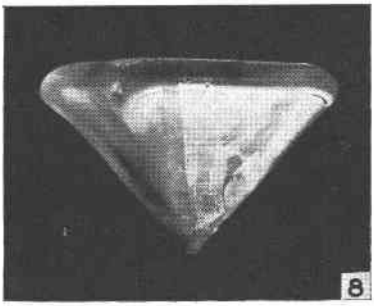
Blue spinels and green spinels are produced by the addition of small amounts of cobalt oxide and chromium oxide, respectively, to the batch mixture.

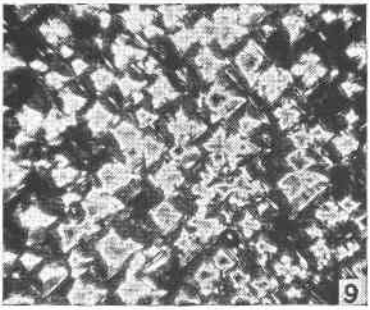
A detailed description of the artificial spinels, including the crystal faces observed as well as other physical and chemical properties, has been published by F. Rinne.[14]

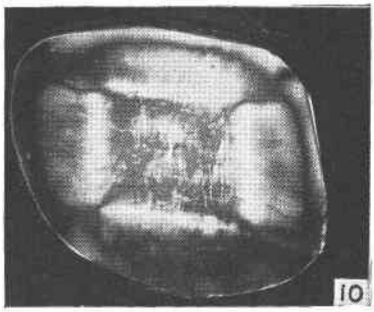
Since spinel is a compound, the crystals of which belong to the isometric (cubic) system, it should have no double refraction and, therefore, should show no interference effects between crossed polarizing prisms. As a matter of fact all synthetic spinels made and cooled in the usual manner in the furnace show marked double refraction and heterogeneous interference patterns. The double refraction appears to be due in part to

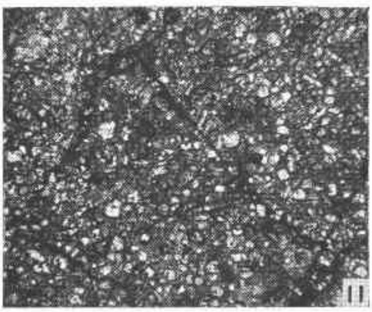
[13] *Neues Jahr. für Mineral., Geol.*, und *Pal.: Beilage Band* **58**, Abt. A, 43–108 (1928).
[14] *Op. cit.*











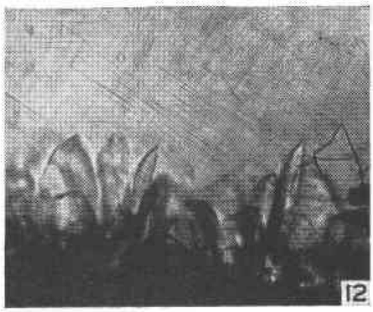


FIG. 7. Spinel boule showing crystal faces. Mag. about $1\frac{1}{3}\times$.

FIG. 8. Spinel boule showing crystal faces. $\frac{2}{3}$ natural size.

FIG. 9. Crown of a spinel boule showing projecting surfaces of microscopic crystals. Mag. 33×.

FIG. 10. Cross section of a spinel boule showing distribution of birefringent elements. Polarized light. Crossed nicols. Mag. $2\frac{1}{2}\times$.

FIG. 11. Crystallization in a slice from a spinel boule after heating at 1725°C. for one-half hour. Polarized light. Crossed nicols. Mag. 33×.

FIG. 12. Same slice as shown in Fig. 11 viewed on edge. Ordinary light. Mag. 80×.

the strain developed by rapid cooling. In part, however, it is related to the alumina content of the boule, the double refraction increasing with increase in the alumina content. The distribution and form of the strain patterns were studied at this Bureau on slices from a spinel boule which was furnished by a domestic manufacturer. This boule is understood to contain about 10 per cent MgO and 90 per cent Al_2O_3. It has a central core in which the birefringent components are distributed in a grating arrangement and an outer portion with a radiating fibrous structure (Fig. 10).

Determinations of hardness[15] made with the diamond indenter in the same manner as those made on the sapphire gave the following values:

Sample	*100 g*	*500 g*
Spinel #1, parallel to boule axis	1380 P[1]	1205 P
Spinel #1, 45° to boule axis	1339 P	1340 P
Spinel #2, parallel to boule axis	1339 P	1179 F[2]

[1] P = perfect indentation
[2] F = light fracture

Hardness is not significantly different for spinels of different colors or for different directions in a spinel crystal.

Because spinel has a hardness between that of sapphire and that of the hardest glass so far tested, it appeared to be promising for use as jewel Vee bearings. It was considered that the use of spinel would cause less deformation and fragmentation of the pivots than sapphire bearings and at the same time would provide a bearing less likely to fracture than glass. While preliminary tests appear promising, the only spinel bearings available for vibration testing with steel pivots had bearing surfaces so rough and so full of "blowholes" that data useful for comparison with data on glass and sapphire could not be obtained.

During examination of spinel for use as a bearing material, it was observed that spinel was a material with such high index of refraction and such low dispersion that it would be exceptional for use in certain optical installations provided other properties were satisfactory. The table below[16] gives the refractive index (n) for certain wave lengths of light, the Abbe value for the relative dispersion

$$\left(V=\frac{n_D-1}{n_F-n_C}\right)$$

and the mean dispersion (n_F-n_C).

[15] Made by C. G. Peters, of the National Bureau of Standards.
[16] Rinne, *op. cit.*, Tables 5 and 6.

Substance		$\lambda(A)$	n	V	$n_F - n_C$
$MgO \cdot Al_2O_3$	(C)	6563	1.7143		
(spinel)	(D)	5893	1.7182	60.86	0.0118
	(F)	4861	1.7261		
$MgO \cdot 5Al_2O_3$	(C)	6563	1.7243		
(spinel)	(D)	5893	1.7280	61.70	0.0118
	(F)	4861	1.7361		
Quartz (ω)	(D)	5893	1.5442	69.8	0.0078
Crown Glass	(D)	5893	1.5181	59.0	0.0088
Flint Glass	(D)	5893	1.6199	36.3	0.0171
Flint Glass	(D)	5893	1.727	28.8	0.0252

Unfortunately, the strain birefringence of artificial spinel is sufficient to destroy its optical homogeneity and to make it useless for most optical purposes. In consideration of the possibility of removing the strain by annealing, it was noted that a heat treatment of a boule at 1050°C. for a long period of time by Rinne[17] had resulted in the crystallization of corundum. An attempt at the National Bureau of Standards to remove the strain by annealing at 1750°C. also caused the crystallization of corundum as shown in Figs. 11 and 12. In a further attempt, annealing experiments were carried out on pieces of spinel rods furnished by the manufacturer, composed of MgO 10 per cent, Al_2O_3 90 per cent, and on a spinel prism of unknown composition and origin. They were heated by R. F. Geller, of the National Bureau of Standards, in a high-temperature resistor furnace of his design[18] at a temperature of 1950°C. for about 20 minutes. For the composition of the rod boule this temperature is close to the solidus as indicated by the diagram of Rankin and Merwin.[19] The heat treatment caused a very marked reduction in the birefringence (Figs. 13 and 14) of the rod specimens. The spinel prism was badly warped by heating at about the same temperature and there was considerable surface crystallization of corundum. Either the temperature distribution in the furnace was such as to cause partial melting of the spinel or the prism contained even more alumina than did the rods. These preliminary experiments indicate that suitable heat treatments can reduce the birefringence of artificial spinels very markedly without causing the crystallization of excess alumina and it seems probable that more can be done in this direction by further experiments. With the

[17] *Op. cit.*
[18] *J. Research NBS*, **27**, 555–566 (1941); *RP* **1443.**
[19] *Op. cit.*

strain birefringence removed, spinel should have many advantages for optical uses.

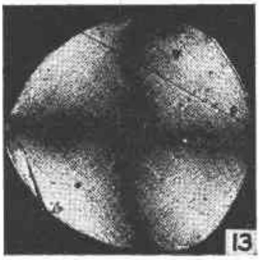


FIG. 13. Cross section of rod-shaped artificial spinel boule, as received. Polarized light. Crossed polaroids. Mag. 11×.

FIG. 14. Cross section of same boule as shown in Fig. 13 after annealing at 1950°C. for 20 minutes. Polarized light. Crossed polaroids. Mag. 11×.

IV. GLASS

For some time glass has been a recognized substitute for sapphire bearings in certain aviation installations where the weight of the pivot and indenter is kept below a specified maximum. Five types of glass used for this purpose have been tested by the National Bureau of Standards: an ordinary commercial soda-lime glass, two types of glass containing boric oxide (Pyrex brand) and two high-alumina glasses.

Of all the glasses tested the alumina glasses had the best performance records as Vee bearings. An approximate analysis of one of the latter was made at the National Bureau of Standards. The results are:

	Per cent	
SiO_2	57.0	
Al_2O_3	20.5	(including small amounts of Fe_2O_3 and P_2O_5)
CaO	5.5	
MgO	12.0	
B_2O_3	4.0	
Na_2O	1.0	

This is an unusually high Al_2O_3 content.

Using the same indenter method as that used on sapphire and spinel bearings, some measurements were made on glass bearings. The results are given below:

Material	*Hardness value*
Soda-lime glass (bottle glass)	440
Pyrex	400
High-alumina glass	560

For comparison, fused quartz has an indenter hardness value of 490.

Although all glass-bearing material is less resistant to fracture under impact than either sapphire or spinel, glass has the advantage that it is less liable to injure the pivot by abrasion. Even with molded surfaces, glass jewels are less abrasive than sapphires and spinels with polished surfaces.

Other properties of glass bearings that may affect their service are the presence of bubbles and the degree of strain. Bubbles when small in size, few in number and distant from the bearing surface probably have little or no effect on the life of the bearing. When abundant and large, how-

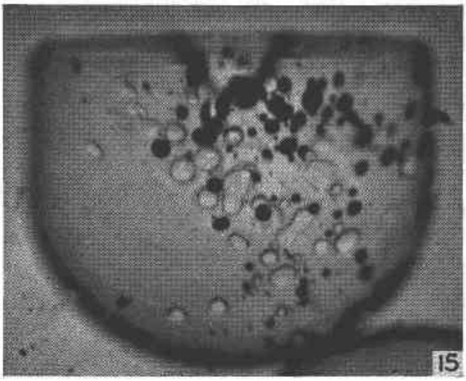


FIG. 15. Glass Vee jewel showing distribution of bubbles in glass. Mag. 29×.

ever, (Fig. 15), they are very likely to intersect the bearing surface, thus increasing the friction of the pivot by providing rough surfaces to abrade the pivot. Glass put under high compressive stresses by quenching is known to be tougher under some conditions than well annealed glass, but when subjected to impact by a sharp instrument (such as a pivot), it may shatter completely. Consequently it is considered better from a practical point of view to use well annealed rather than highly strained glass jewels. Other inhomogeneities such as striae (cords) and small "stones" (crystalline nuclei) are probably not of importance unless they produce high localized strain in the glass or unless the crystalline material occurs at the bearing surface.

V. Other Bearing Materials

Other nonmetallic bearing materials than those described above have been proposed, including vitrified porcelain and organic plastics. One sample of porcelain and one of organic plastic were examined at the

National Bureau of Standards. The surface of the porcelain even when well polished was still too rough to afford a satisfactory bearing surface. The organic plastic was too soft and too weak to be a satisfactory bearing material.

VI. Summary

This report provides a brief compilation and comparison of the significant properties of the three principal nonmetallic instrument bearing materials, corundum (sapphire), spinel and glass. Of the three, corundum has the greatest hardness and strength, but its hardness is so much greater than the usual steel instrument pivots that under continued vibration the pivots tend to deform, rust accumulates in the bearing and friction increases. Glass has about the same hardness as the steel pivots, but glass bearings may break under vibration and impact. Spinel is intermediate between corundum and glass in strength and hardness and, therefore, should have advantages as a bearing material, but sufficient data on actual vibration and wear tests of spinel bearings have not yet been accumulated to draw conclusions as to its service behavior. Some incidental observations on the physical properties of artificial spinel in relation to its use as a possible optical material are also included.