THIRD SYMPOSIUM ON DIAMONDS*

(1) INTRODUCTORY STATEMENT

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The exigencies of World War II greatly increased the demands for many minerals, and important new uses for some of them were developed. This is true of the diamond, especially of its use for industrial purposes. This expanded use of the diamond is of necessity based upon a fundamental knowledge of its crystallographic and structural properties. In this respect the diamond differs markedly from many other raw materials.

At the Boston meeting of the Mineralogical Society of America in December, 1941, the first symposium on diamonds was held. Eight persons participated in the program. The symposium was very well attended, and the discussion of the various papers was very gratifying, for much new information was given to those present. It was agreed that a second symposium should be arranged for the next annual meeting of the Society in 1942. Although no annual meetings have been held since 1941, papers for a second symposium were prepared. The papers of both symposiums were published in the March, 1942 and 1943, issues of *The American Mineralogist.* The demand for reprints in this country and from abroad has been unusually heavy. Since there has been no symposium since 1943, it was deemed highly desirable that papers discussing the present status and trends, as well as the new developments, some of which are truly remarkable, in the use of the diamond, should be prepared.

(2) DIAMOND PRODUCTION

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Now that the war is over, it may be said that the 2500-year-old diamond-mining industry under adverse conditions acquitted itself well in World War II. Staffs were depleted through enlistments, and supplies were none too abundant, but production not only held its own, but increased. The United Nations had enough industrial diamonds to speed up their machine grinding, to draw fine wire for their instruments, and to produce those perfect tolerances which permitted the interchange of similar parts of an aeroplane or other engine. The Axis Powers had too little. At one time, when Rommel and his tanks were rampaging through North

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Africa, some of us had the jitters. Were the Germans to win the diamond fields of Africa, producers of 95 per cent of the world's rough, which for two years were almost in their grasp? Fate and Montgomery decreed otherwise.

Not a plane, a tank or a big gun was made during the war without the use of industrial diamonds. It needed a war to persuade the average citizen that the diamond industry had passed from a luxury to a luxury-utility trade. Sir David Brewster, writing in 1835, had realized it 110 years ago, when he said, "Had the diamond not been placed at the head of the mineral kingdom from its invincible lustre and high value as an ornamental gem, it would have attained the same distinction from its great utility in the arts."

The production of diamonds for the years 1942 to 1944 (down somewhat from the 1939 to 1940 average of, in round numbers, 13,400,000 carats) is shown in the following table, with a rough break-down as to gem and industrial grades.

	1942 (*Carats*)	1943 (*Carats*)	1944 (*Carats*)
World production	9,283,000	8,353,000	11,402,000
Gem stones	1,949,000	1,754,000	2,280,000
Industrials	7,334,000	6,599,000	9,122,000

It will be noted that the production of industrials varied a bit more over the period than that of gem stones. The 1944 production was equivalent to 5026 pounds avoir., of which 4021 pounds were industrials and 1005 pounds gem material. All of the production in 1942 was alluvial, 98 per cent in 1943, and 95 per cent in 1944. In 1942, 98 per cent of the African production stemmed from pre-Cambrian sources and two per cent from Cretaceous sources. In 1943 and 1944, the proportions were, respectively, 96 and four per cent and 91 and nine per cent.

The Belgian Congo, a producer of both gem and industrial grades—but particularly of the latter—was, as to weight, by far the largest producer. This was largely due to the BCK mine, which alone produces 60 to 66 per cent of the world's diamonds, by weight, although, because its product is almost wholly crushing bort, the percentage of values is but one-third that. As to diamond content, it is by far the richest diamond mine in the world. The war history of the Belgian Congo is interesting: First, many of the staffs joined the armed forces; later, gold and tin being considered by the colonial authorites more important commodities than diamonds, the staffs were further decreased and equipment and labor were shunted to the gold and tin mines. When in 1942 our War Production Board foresaw a possible shortage of crushing bort, supplies and new equipment were sent out to the diamond mines, and both staff and crew were reinforced.

The production of the Gold Coast and Angola remained stabilized during the war years. The production of Sierra Leone in the early years of the war was forced, lest the mines fall into the hands of the Germans. From 1942 to 1944, the production of the Union of South Africa trebled, largely due to the "green light" given to pipe mining in 1943. Dutoitspan and Bulfontein were reopened. Two or three years hence the Premier Mine will again be producing, and perhaps shortly thereafter the New Jagersfontein. In consequence, by 1948 we can expect a larger supply of fine cuttables and excellent industrials. South West Africa is increasing its rather insignificant production, and Tanganyika Territory since 1936 has had a remarkable rebirth as a producer. Brazil, Venezuela and British Guiana, notwithstanding the fact that during the war, and due to it, they received double the price accorded other producers, remained static and accounted for but four per cent or less of the world's production. Russia (the Urals) produced a few carats, and stones were found for the first time in Bolivia. The Japs, desperately but unsuccessfully, tried to increase notably the production of Borneo.

Industrial diamonds are in part a by-product of gem mining, the exceptions being the crushing bort produced by BCK in the Belgian Congo and the insignificant carbonado production in Bahia, Brazil.

During the period Sierra Leone joined the charmed circle of producers of large gem stones (older members, India, Borneo, South Africa and the Bagagem district in Brazil). In 1944 Tanganyika Territory produced a rather large gem stone.

The market for diamonds was broad and sales for 1943 and 1944 were unusually large. From 1941 to 1943 they almost trebled. The industry now has two products to sell, industrials (24 to 39 per cent by value, 80 per cent by weight) and gem stones. As the war progressed, the demand for gem stones increased, thanks to high war wages.

From 1940 to 1945, the price of industrial stones was stabilized; that of small cut trebled or quadrupled, and that of fine large cut doubled in price. But the "carriage" trade is a thing of the past and the retailer's bread and butter is now the medium priced diamond.

During the war, many a war emigre who was lucky enough to escape from the Axis fiends lived off his stock of diamonds, and perhaps had enough left to establish a small business in his newly adopted land. During the war diamonds have been a prime investment.

During the war an attempt, only partially successful, was made to differentiate clearly gem stones from industrials. While it is admitted that some rough is so flawless and crystal-clear that it would be a sacrilege not to cut it into gems and that other rough, lacking beauty, can be used only industrially, there is annually a large intermediate caratage which is used as gems or as industrials, according to whether the demand for the first or the second dominates.

The growth of the use of industrial diamonds has been phenomenal. In 1923 our country imported but three or four tens of thousands of carats, in 1933 but 300,000 carats, and ten years later 12,172,025 carats.

In 1923, $24 was paid for a carat, but in 1943, due to the increased use of crushing bort, but $1.81. In 1943 and 1944, the consumption of industrials was almost double their production.

Stocks of diamonds above ground decreased during the war period and "sands" and large rough, among the cuttables, and many grades of industrials became in short supply. Indeed, several types of industrials have been scarce for eight years. Industrial diamond toolmakers are advised to turn to "inferior" grades of industrials, provided they decide to remain in business. From a cost standpoint, such use will benefit both manufacturer and purchaser.

Up to 1941 production equalled or exceeded consumption; since then stocks have been reduced to the danger point. As to industrials, the diamonds in overalls, our government has a fair stock and our industrialists a little. The total is, however, not impressive.

At the beginning of the war, the United Nations controlled some 96 per cent of the world's production and toward the end, 99.99+ per cent. In consequence, the munitions industries of the United Nations never lacked for industrial diamonds. Germany, and especially Japan, however, were short of this essential strategic mineral. As evidence, we may cite Germany's desperate attempts to smuggle diamonds into her domains and the exorbitant prices she paid for industrials in Switzerland, and Japan's futile attempts to increase the production of the Borneo deposits.

During the war the sale and distribution of industrial diamonds was administered in Great Britain by the Diamond Controller and in the United States by the War Production Board. These controls are now being relaxed.

The future of the industry appears to be satisfactory. Stocks are small, indeed, non-existent as to certain grades. The industry is well co-ordinated. The demand for gems is large and that for industrials should be satisfactory, once industry is reconverted, although for some time it can scarcely equal wartime consumption.

Before I close, may I add that our country produces no diamonds; they are produced far from our shores. Industrial diamonds are essential to efficient munitions production. Diamonds are among those minerals which should be stockpiled in adequate quantities to safeguard our country's future.

(3) GEM DIAMONDS

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The diamond cutting industry in the United States is in a precarious position, as we predicted before this assembly four years ago. The manufacturers of small, or melee, diamonds are feeling the rising competition of Belgium, and to a lesser degree, Palestine, Holland, South Africa, Brazil, and other countries. All of these countries have a lower wage standard than the United States, and in some cases are receiving aid from their governments to enable them to resume their pre-war position in diamond cutting and polishing.

Besides, American manufacturers are short of rough material. The rapidly expanding European industry is taking a large share of the world's limited rough diamond stocks, and replenishing these stocks is difficult now, since many diamond mines were shut down because of the war. Some of these mines have deteriorated in the interim, and will require up to a year and a half before they can regain full production. This shortage of diamonds is just beginning to become critical, and may well become disastrous for many during the coming year.

After the cessation of hostilities, it was found that the diamond cutting industry in Belgium was in a better position than had been generally expected. In Antwerp particularly, diamond cutting was the first industry to begin working effectively, and at present there are between ten and fifteen thousand diamond cutters already working with equipment and tools which had been hidden from the Germans throughout the long occupation. Belgium has always been a very productive and industrious country, but unfortunately, in some instances those qualities have been coupled with too much ingenuity, and the result has been the organization of a black market both in diamonds and other commodities, on a staggering scale. To give an example of the rapid recovery of the diamond cutting industry of Belgium, their legitimate exports to the United States were $750,000 in September; $1,000,000 in October; and $1,200,000 in November. These figures exclude the very considerable black market trade, which apparently is mounting much faster than the legitimate trade.

The exports listed above are currently competitive with domestic production in small-sized diamonds, but are based on a lower cost—when the diamond boom is over and prices sag, Belgium has already proved her ability to undersell American diamond cutters producing similar articles.

Belgium, also is in a better position to obtain rough than the United States. First, her traditional position is very strong; for generations one of her main industries was diamond cutting, an industry of almost negligible importance in the United States. At present, Belgium has almost no other export trade, and depends entirely on the diamond industry for the livelihood of a considerable proportion of its people. Secondly, Belgium actually owns many of the world's richest diamond mines and dictates the policy that the largest share of the available rough shall go to Belgium. However, the Belgian cutting is not comparable to the better American makes, since their tradition to sacrifice some brilliancy in the diamond in order to get more polished diamonds from their rough is well-established, and also because their present-day clientele, anxious to purchase diamonds of any kind, cannot afford to be too critical.

Holland fared far worse during the occupation than did Belgium and is recovering far more slowly. By contrast with the Belgian diamond industry, the Dutch had the greater part of their machinery confiscated and their workers deported and have only 500 men working. Since many of the bridges crossing the numerous Dutch canals were destroyed, transportation within that tiny country is almost impossible. Where Belgium has thousands of diamond cutters working, Holland, with a pre-war industry somewhat comparable to Belgium's has only 500 diamond polishers at work.

The British diamond cutting industry is prosperous, but on a relatively smaller scale. Palestine has established a large industry, particularly in small-sized diamonds, but will shortly also feel the pinch of a shortage of rough material. South Africa has a relatively small, but well-established diamond cutting industry which will probably grow, due to its important proximity to the diamond mines and the fact that native manufacturers do not pay the 10 per cent export duty on rough diamonds. Brazil has well over a thousand diamond workers, who will certainly also be short of work unless their government adopts laws restricting the export of Brazilian rough diamonds to other countries. Cuba's thousand diamond workers are already dormant. Puerto Rico is continuing to manufacture on existing stocks, but being in a position exactly parallel to the American mainland industry, will shortly be curtailed or stopped for lack of raw material.

The world situation, therefore, is as follows: The Diamond Trading Company finds itself in a dilemma. Every country which had a diamond cutting industry before the war is clamoring for the return of that industry now. At the same time, those countries which developed industries during the war are striving for their continuation. As explained above, diamond mining was and is curtailed because of the war. The result is that there simply are not enough diamonds to fill all needs, even with the best of intentions on the part of the Trading Company.

It must be pointed out that one of the reasons why the Low Countries are struggling so anxiously for a large share of the world's diamond cutting industry is that it is a perfect export industry for them under today's conditions. The main market for polished stones is the United States, and every European nation is anxious to secure more dollars to help them with their reconstruction problems. The diamond industry provides very lucrative employment for the citizens of those countries. In view of the critical shipping shortage, the shipments of diamonds, tiny in physical bulk, can be made, easily and conveniently, by airmail.

As above suggested, diamonds are today eagerly sought in almost every part of the world, and for widely differing reasons. In the United States, the demand can be traced to the great number of marriages, to the shortage of other consumer commodities, and to the large amount of easy money in circulation. In our opinion, the American public is buying a relatively small amount of diamonds as a hedge against inflation, although this is certainly a secondary motive in many purchases. The rest of the world seems to be in sharp contrast on this point. Distrust of the currency and fear of inflation are widespread in other parts of the world and lead to the purchase of large stocks as hedges against any emergency. In England, the Low Countries, and France, for example, diamonds actually command prices higher than in the United States; and in the case of black market transactions, are sold for prices two or three times their American values.

(4) BONDED DIAMOND WHEEL APPLICATIONS

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Since the 1943 Symposium on Diamonds, the use of bonded diamond products in industry has shown consistent growth with more diversified applications. Improvements have also been effected in efficiency as related to the older applications.

Precision grinding of cemented carbide tools has been definitely established as a diamond-wheel application: first, because of the freer and faster cutting action of bonded diamond products and secondly, because of their ability to grind with imperceptible wheel wear, thus making it possible to readily maintain precision dimensional tolerances.

Where the work is applied manually, as in off-hand grinding, and where the application involves grinding steel and brazing metal, large wheels containing silicon carbide as the abrasive are still used for the roughing operation. However, there is also demand for diamond wheels in the smaller shops where equipment is limited, because of the longer life and smoother action afforded by diamond wheels; also, with metal-bonded products, it is often possible to use the same wheel for both rough and finish grinding, which is an advantage. In most cases the finishing operation is carried out with diamond wheels.

The development of vitrified-bonded diamond wheels, which was mentioned in the 1943 Symposium, has resulted in still further economies. This is due to a fast cutting action comparable to resinoid-bonded products, with at least double the durability. The vitrified wheels show a much greater ability to grind steel, and therefore, superior results have been obtained on cemented carbide applications where the percentage of steel to be ground is high.

The superiority of diamond wheels in the grinding of quartz, gem stones, glass, granite, marble and ceramic materials is being well established. All commercial quartz cutting in the United States today is done with diamond wheels. The cutting and grinding of synthetic sapphire boules is definitely a bonded diamond application.

The use of bonded diamond lens generators for the roughing operation in the manufacture of ophthalmic lenses is widespread. To the degree that precision equipment becomes available, it is expected that the preparation of these lenses will be simplified and will require diamond lens generators for the rough and fine grinding operations.

The precision grinding of various types of plate glass and glass prisms is now generally done with bonded diamond products.

Another promising field of application is marble and granite cutting, where data indicate better economy and much greater speeds of cutting than has been possible with such abrasives as silicon carbide.

It is interesting to note that the use of a proper lubricant is extremely important for grinding quartz, synthetic sapphire, and glass. A paraffin base oil gives a much freer and faster cutting action than soluble oil and water.

Of paramount importance in all diamond wheel applications is the condition of the grinding machine. Where excessive vibration is encountered short wheel life and resultant poor economy may be expected.

Improvements in control of raw materials, in bond compositions and in manufacturing processes are being actively sought, the objective being to improve economies and to develop products suitable in new fields of application.

(5) VECTOR HARDNESS IN DIAMOND TOOLS

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INTRODUCTION

Early in 1942, shortly after the United States entered World War II, a possible shortage of industrial diamonds for dressing grinding wheels gave rise to an investigation of diamonds and their use for dressing grinding wheels. The investigation was sponsored by the Office of Production Research and Development of the War Production Board and was carried out in the Research and Development Laboratories of the Crane Company, Chicago, under the direction of the War Metallurgy Committee of the National Academy of Sciences. This paper, based on that work, has been released for publication by OPRD.

Although the research program was designed to determine the suitability of various grades of diamond under conditions that would be encountered in everyday industrial practice, the accumulated data yield upon examination some quantitative information in regard to the relative abrasion resistance offered by different directions within the diamond. These data have been assembled and are presented in this paper.

ABRASION TEST METHOD

A variety of industrial diamonds was tested ranging from sound, first quality, clear octahedrons and dodecahedrons to the opaque coated stones typical of the Belgian Congo fields.

DESCRIPTION OF STONES YIELDING VECTOR HARDNESS DATA

Specimen No.	*Description*
120	Grey white, clear octahedron
129	Brown, transparent rounded octahedron
141	Grey white, transparent dodecahedron
111	Yellow, transparent dodecahedron
43	Dark brown, translucent dodecahedron
136	Grey white, transparent octahedron-dodecahedron
139	Grey white, transparent octahedron-dodecahedron
84	Yellow, transparent rounded octahedron-dodecahedron
144	Belgian Congo, coated opaque octahedron-dodecahedron-cube
150	Belgian Congo, coated opaque octahedron-dodecahedron-cube
152	Belgian Congo, coated opaque octahedron-dodecahedron-cube
169	Belgian Congo, coated opaque octahedron-dodecahedron-cube
7	Belgian Congo, opaque cube
162	Belgian Congo, opaque cube

The comparison of the resistance of diamond to abrasion by grinding wheels presents a somewhat difficult problem since the diamond is exceedingly hard and wear on the diamond takes place at an extremely low rate. In order to measure the abrasion loss of diamond in a reasonable time interval, a test method was used which consisted of the continuous abrasion of the diamond with a grinding wheel and periodic measurements of the amounts worn off the diamond.

The essential parts of the test apparatus were a tool holder, so designed that any angular orientation could be given to the diamond, mounted on the table of a Brown and Sharpe No. 2 cylindrical grinding machine equipped with automatic feed, speed control, and traverse counter. Aluminum oxide grinding wheels twelve inches in diameter and one inch thick were used. Most of the tests were run on sixty mesh grit vitreous bonded grinding wheels, although some coarser wheels and some as fine as one hundred twenty grit were used, and some were resin bonded.

The diamond was mounted in a standard steel nib which in turn was mounted in the tool holder and oriented in the desired position. The tip of the diamond was then made to traverse across the face of the rapidly rotating grinding wheel removing 0.001″ from the face. After completing the traverse, the diamond was moved forward 0.001″ and then traversed back across the face of the wheel in the reverse direction. This process was automatically controlled and fifty passes across the face of the wheel constituted a test run.

Measurement of Abrasion Loss

The loss of weight in the diamond after such a series of dressings was so small that it could not be accurately weighed and so was computed from the volume removed. In order to determine the volume loss, the diamond, after being mounted in the nib and before the test run, was projected upon a screen with a 100× magnification, and a profile was drawn of the contour of the point of the diamond. After the completion of a test run, a second profile was made in the same position over the original profile. The outline of the facet or "flat" ground on the diamond was also traced under the same magnification and its area determined by tracing the outline with a planimeter.

The volume of the minute portion of the diamond removed was calculated as a pyramid whose height was given by the difference between the first and second profiles and whose base area was the area of the flat. The weight was computed using 3.52 as the specific gravity of the diamond. This method of computation assumes that the portion of diamond removed is a pyramid whose sides are flat surfaces. When, as is common in diamond crystals, the surfaces were curved or irregular, profiles of cross-sections at various positions were drawn and used in correcting the

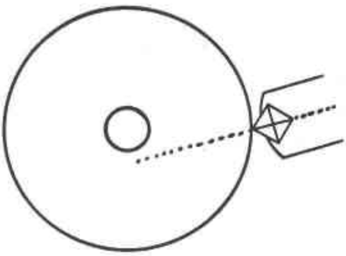

FIG. 1

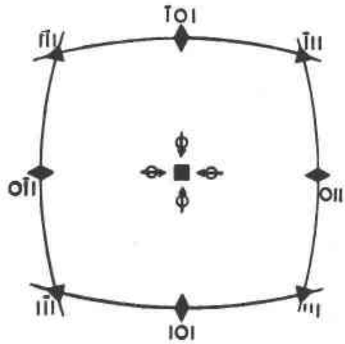

FIG. 2

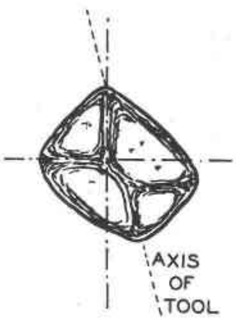

FIG. 3

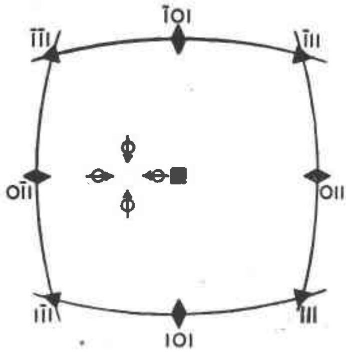

FIG. 4

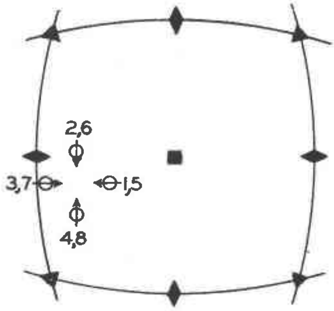

FIG. 5

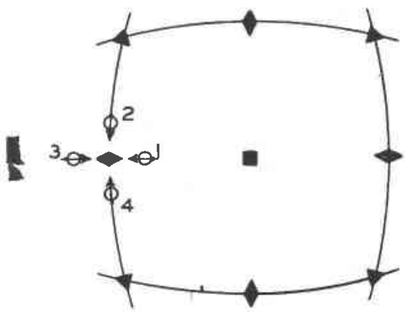

FIG. 6

volume determinations. An arbitrary *unit of wear rate* was established for comparative purposes by dividing the computed weight loss in carats by the volume in cubic inches of grinding wheel removed.

Orientation of Abrasion Directions

Following the standard procedures used in industry the longest dimension of the diamond was mounted parallel to the axis of the tool. The tool was applied to the grinding wheel with the axis of the tool directed below the center of the wheel (Fig. 1). This is known in industry as giving a "drag" to the tool. The "drag angle" was 15°. After each test run the tool was rotated 90° about its axis. Thus after a complete rotation of the tool a series of four "flats" would be worn all equally inclined to the tool axis at an angle equal to the drag angle.

With a symmetrically developed crystal its longest dimension would be parallel to the crystal axis, and the series of flats would be equally disposed about (001). The position of these flats and the directions of abrasion across them is indicated in Fig. 2. With an unsymmetrical crystal the longest dimension is not parallel to a crystal axis (Fig. 3) and the series of flats are unsymmetrically disposed about (001), and if the deviation from parallelism (Fig. 4) exceeds the drag angle, (001) lies outside the circle of generated flats. In the first instance, the direction of abrasion is always towards (001), a hard vector direction of the diamond, but in the last instance there is one position during the complete rotation in which the abrasion direction is away from (001), a soft vector direction. In these projections the ground facets are symmetrically related to the diamond crystal. In general, the axis of the tool will not lie in a plane of symmetry, and the circle of generated flats will not be symmetrically disposed to any of the crystallographic elements. While checking the orientation of the diamond from the relationship of crystal faces and cleavages to the tool shank, it soon became evident that the soft abrasion direction took a high polish while the hard direction developed a fine matte finish. This observation made rapid preliminary orientations possible.

In Table 1, the data of twenty-two tests on fourteen stones have been assembled. The values for wear rate ranged from 2 to 100×10^{-5} carat per cubic inch of grinding wheel removed, which is the equivalent of one part by weight of diamond abraded to 200,000 to 10,000,000 parts by weight of grinding wheel consumed. In the abrading of these large quantities of grinding wheel in a test the diamond lost between 0.05 to 0.2 mm. in height and facets 0.2 to 1.0 mm.^{2} in area were ground on the diamond. A great diversity of test conditions is represented, but for each test the conditions are comparable, and the ratio of soft to hard directions remains consistently around two. The low values were those obtained on resin-bonded wheels, the high values on coarse grit vitreous bonded wheels which were run dry, i.e., without flooding the tool with water, which is the common industrial practice. The values do not represent a comparison of the hardest to the softest directions, but a comparison of the average of all hard directions encountered to the soft directions. The soft directions, as indicated in Fig. 4, are on surfaces nearly parallel to cube faces, the so-called four-point grain of the diamond cutters.

TABLE 1. COMPARISON OF WEAR RATES BETWEEN "HARD" AND "SOFT" DIRECTIONS IN DIAMOND

Specimen No.	Wear Rate (Dry) in Carat$\times 10^{-5}$/cu. in.		Ratio $\frac{\text{Soft Dir.}}{\text{Hard Dir.}}$
	Hard Direction	Soft Direction	
111	41	95	2.3
120	38	58	1.5
7	36	59	1.7
141	30	55	1.8
152	26	80	3.0
162	22	54	2.4
120	22	32	1.5
150	22	35	1.6
129	17	38	2.2
139	16	31	1.9
136	14	40	2.9
169	13	27	2.0
144	9	20	2.2
162	5	13	2.5
7	5	8	1.6
84	4.2	14	3.3
43	3.5	8.4	2.4
144	3.3	5.1	1.5
84	2.7	5.1	1.9
141	2.6	5.4	2.1
84	2.4	7	2.9
84	2.0	3.8	1.9

Table 2 presents the data on a series of test runs, all on the same tool, which was rotated ninety degrees between each test. The abraded point was the intersection of the octahedron, dodecahedron, and cube (Specimen No. 152). The position of the flats developed and the directions of abrasion across these flats are shown in projection in Fig. 5. In tests 2 and

6, the vector direction of abrasion is towards the dodecahedron, and the flat developed is nearly parallel to a crystallographic axis. This is the so-called two-point cutting direction of the diamond cutters and gives high wear rates. Tests 4 and 8 are likewise towards the dodecahedron face, but the facet makes a considerable angle with the crystallographic axis; hence

TABLE 2. RELATIVE RATES OF WEAR RATE (DRY) OF DIFFERENT ORIENTATIONS OF DIAMOND

Test No.	1	2	3	4	5	6	7	8
Tool Rotation	0°	90°	180°	270°	0°	90°	180°	270°
Wear Rate $\times 10^{-5}$ ct./in.^{3}	18	68	22	27	40	94	25	47

while the wear rates are high, they are not as large as those obtained on tests 2 and 4. The other directions are hard directions.

In shaping the wheel for grinding threads, a very sharp point of a diamond is needed, because of the close tolerances to which these threads are held. Diamonds used for this purpose are known as thread dressers. Natural octahedrons with sharp points or lapped points with the apex at the end of a crystallographic axis are most suitable. When points are lapped on the ends of cleavage splinters, the wear rate on the diamond point was found to be as much as three times as great. These results were to be expected, because cleavage splinters are elongated parallel to a binary axis of symmetry. The binary axis of symmetry is normal to the dodecahedron face and the abrasion conditions are shown in projection in Fig. 6. The diamond abrades very rapidly along the direction of the so-called two-point cutting grain of the diamond cutters, 2 and 4, the softest direction on the surface of the diamond. The directions 1 and 3 are hard.

CONCLUSIONS

1. No significant differences in abrasion rates were revealed which can be attributed to color, transparency, size, shape, or geographical origin.
2. Those directions which are crystallographically weaker directions show higher losses due to abrasion.
3. Facets abraded along the softer directions acquire a high polish.
4. The preference shown in industry for well-formed octahedrons can be attributed to the fact that when the conventional methods of mounting and using the stones are followed, there is little likelihood that the softer directions will be presented to the wheel when dressing grinding

wheels. Distorted and ill-shaped stones will give equally good results if mounted with a crystallographic axis parallel to the axis of the tool.

(6) OBSERVATIONS ON ORIENTATION AND HARDNESS VARIATIONS

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As described by Whittaker and Slawson,[1] hardness is a vector property that varies considerably in diamond crystals. It is my purpose to describe some results obtained in the laboratories of the Hamilton Watch Company, indicating a probable ratio of 100 to 1 for the hardnesses of the hardest direction in the hardest surface and of the softest direction in the softest surface. These experiments were conducted under conditions of unidirectional rubbing of a flat diamond surface against stainless steel watch parts. A polished, flat diamond is used to burnish the watch parts by rubbing the two together under considerable pressure, and with no vibration. This condition of high pressure, vibrationless rubbing between diamond and metal would represent approximately the conditions of service that must obtain in wire dies, except for the complications due to the curved surfaces of the dies. It is probably not representative of the conditions of use encountered by diamond wheel-dressers, where at least some vibration and shock seem almost certain, and where the tendency of a pointed tool to fracture easily probably masks some parts of the range of hardnesses.

Kraus and Slawson[2] described the general pattern of hardness variations; their qualitative results now need to be augmented by quantitative studies. The beginning of such a program was undertaken by the Hamilton Watch Company in a successful effort to lengthen the life of certain diamond tools used in the factory.

The production that can be expected from a tool in which the softest direction of the softest surface is presented against the stainless steel parts, is less than 200 units; but the same tool, made with equivalent quality of diamond, but so oriented as to present the hardest direction of nearly the hardest surface, will consistently produce 20,000 such units; in one case characterized by unusually skillful handling by the machine operator, over 100,000 units of production was achieved. The stated ratio of 100 to 1 for the maximum range of hardnesses is therefore probably not too high.

[1] Preceding paper.

[2] Kraus, E. H., and Slawson, C. B., Variation of hardness in the diamond *Am. Mineral.*, **24**, 661–676 (1939).

Kraus, E. H., and Slawson, C. B., Cutting of diamonds for industrial purposes: *Am. Mineral.*, **26**, 153–160 (1941).

It is essential to be able to specify and measure the orientation of any direction in any surface of a diamond crystal. Perhaps I may compare the crystal with a sphere such as the earth. Crystallographers recognize a north pole in the diamond sphere just as geographers recognize one on the earth. Likewise there is a prime meridian on the diamond sphere, just as there is a prime meridian through Greenwich, England, on the earth. Crystallographers have long used these coordinates of longitude and latitude to locate points on spherical projections of crystals. Now let us suppose that our diamond sphere is touching a flat lap. The point of contact can be specified in terms of the coordinates of longitude and latitude just described. Moreover, just as a ship on the high seas steers along some course selected by the captain, so the surface of the lap is abrading the diamond sphere at the point of contact, in a certain direction called the azimuth of abrasion. Thus crystallographic longitude and latitude may be used to specify the orientation of a plane surface—artificial or natural—and crystallographic azimuth may be used to specify a direction in that surface. The measurement of these coordinates in a crystal may be likened to the fixing of a location at sea by astronomical observations. But navigation in crystallography is another subject and must be considered elsewhere.[3]

Observations of hardness or wear resistance have been collected for several years in the Hamilton laboratories. Hardness is expressed in terms of the number of similar units of production obtained by identically shaped, but differently oriented diamond tools. Each diamond was selected in the laboratory, and assigned its orientation. It was then polished on a mechanical fixture so as to obtain the best possible uniformity of shape and size. The polish and exact crystallographic orientation were then examined in the laboratory before forwarding the tool to the production department where it was used. When a tool ceased to be productive for any reason, it was returned to the laboratory. The reasons for failure generally belong to one of three groups: (1) the diamond surface is worn out; (2) the diamond was improperly set; (3) accidental damage occurred. Results that I am about to describe were obtained from diamonds that were rejected for the first reason—worn surface.

Figure 1 is a photomicrograph showing an extreme case of this condition. The diamond surface, as originally polished, would be perfectly smooth and featureless; after rejection for a worn surface, there are usually some fine lines or grooves across it in the direction of the motion of the work pieces. This photomicrograph shows more than the usual number of such lines, running from top to bottom. The diagonal lines are structural features of the diamond crystal, and would not be found on

[3] Winchell, H., Navigation in crystallography: *Geol. Soc. Am. Bull.*, (in press).

most crystals. As stated, this particular one was exceptionally badly worn. Most tests were concluded when the tool had light grooves that were deep enough to spoil the mirror finish desired on the metal work pieces, but not conspicuous enough to show clearly in a photomicrograph. The number of work pieces successfully produced by a tool is taken as the hardness of the diamond surface in the direction concerned.

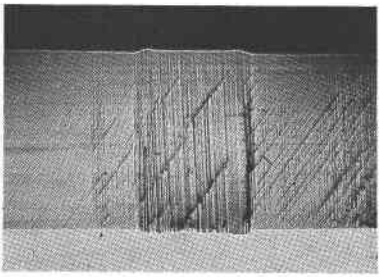

FIG. 1. Surface of diamond tool after exceptionally heavy groove had been worn across burnishing facet. Facet is 0.010″ wide from top to bottom.

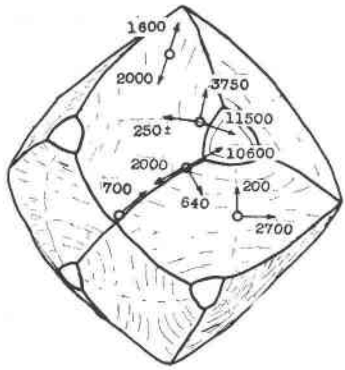

FIG. 2. Sketch of a rounded dodecahedral diamond crystal, schematically showing the approximate average relative resistance to abrasion in several directions at points indicated by circles.

The actual values of the hardness readings so obtained range from less than 200 to well over 20,000, depending upon the orientations of the diamond tools. In order to represent most of the observations on a simple diagram, I have grouped together all observations in certain ranges of orientation, and Fig. 2 shows the averaged results for these groupings. Note that the maximum range of hardness values shown is less than 100 to 1 because the highest hardnesses have been averaged with hardnesses obtained from other nearby orientations that were not so hard.

Surfaces crystallographically equivalent to various trisoctahedrons (*hhl*) and fairly close to the octahedron (111) were averaged together. Most of the observations on such surfaces were made in the direction toward the octahedron: their average is 11500. The opposite direction is indicated as approximately 250. This is probably a maximum hardness rather than a valid determination of the average, since considerably more wear is usually visible after producing these 250 pieces than after producing 20,000 in the hard direction. A third direction in surfaces of this type gave an intermediate hardness value, 3750.

Surfaces crystallographically equivalent to various trapezohedrons (*hll*) and also fairly close to the octahedron, were tested in several directions enough times to indicate appreciable variations in the hardness. Such surfaces, abraded toward the octahedron, yielded an average of 10,600 pieces before wearing out. The same surfaces abraded in the opposite direction gave only 2000 pieces. And if abraded at right angles to that direction, much trouble was encountered in setting up the tools, and the average production was only 640 pieces. It is not certain that this or the 2000 observation is a valid determination of the relative hardness.

Surfaces approximately parallel to the dodecahedron (110) gave widely varying hardnesses, depending as expected upon the direction of abrasion in the surfaces. Parallel to a crystallographic axis, in the "polishing grain" of the surface, the production averaged 200 units, although this is probably high, since much deeper grooves were generally worn in the surface while making this test than were produced in differently oriented surfaces or in other directions in this surface. This is probably the softest surface and direction of all. The hardness measured at right angles to this direction was about 2700, or more than 10 times as great.

Surfaces in the tetrahexahedral zones (*hk*0) and surfaces nearly parallel to the cube face (100) were not tested thoroughly. A few observations gave the results shown in the figure, but these are of a lower order of accuracy than the trisoctahedron, dodecahedron and trapezohedron tests.

In general, it is emphasized that these are all preliminary data, possibly subject to wide errors, even though their orders of magnitude are probably about right. The quality of polish on each of the surfaces tested was good, and as uniform as could be obtained, but the best polish was obtained on surfaces in the zone including the dodecahedron and the various trisoctahedrons. Octahedral faces themselves are practically impossible to polish. A few tests on a surface nearly parallel to an octahedron indicated the importance of a superior polish in the work, and pointed a warning that this factor must be carefully controlled.

Conclusion

Preliminary work on a diamond tool used for burnishing stainless steel watch parts has shown that crystallographic orientation largely controls the rate of wear, and therefore the ability of the tool to produce a large quantity of satisfactory work pieces. The best orientation for this type of tool utilizes the remarkably large variation of hardness of trisoctahedral surfaces to provide a very high hardness in the direction used for burnishing, and at the same time, a very easy "polishing grain" in the opposite direction. These results are sufficient for technological purposes, but only preliminary for purposes of accurate study of the variations of hardness.

(7) THE PREPARATION AND STANDARDIZATION OF DIAMOND POWDERS

HERBERT INSLEY AND B. L. STEIERMAN, *Bureau of Standards, Washington, D. C.*

INTRODUCTION

The investigations sponsored by the War Production Board on diamonds for use in the manufacture of war materials, such as wire-drawing dies, cutting tools and instrument bearings soon disclosed a need for the investigation of the diamond powder which was used in preparing the diamond articles. For example, diamond dies for wire drawing often showed detrimental grooves in the drawing cone (Fig. 1) which apparently were caused by the presence of over-size diamond particles in the dust used for drilling. Conversely, the presence of excessive amounts of very fine material often caused inefficient action.

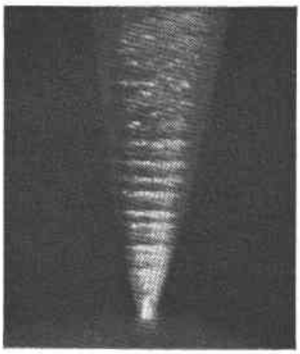

FIG. 1. Photomicrograph of the drawing cone of a diamond die for wire drawing showing grooves in the primary cone caused by oversize grains of diamond dust used in drilling. Magnification, 94×.

A microscopic examination of the diamond powders obtained commercially showed that (1) the classification of diamond powders for size was almost without exception poor, (2) diamond powders were in a few cases contaminated with lint, grease and inorganic impurities, and (3) the designation of size grades was non-uniform and without relation to the actual particle size.

In view of these conditions the War Production Board authorized the National Bureau of Standards, under the sponsorship of the War Metallurgy Committee, to undertake an investigation of diamond powders with the principal objects of (1) determining the efficiency of various methods of grading powders for size, (2) selecting a method of size fractionating which would be useful under commercial conditions, and (3) assisting in devising a standard of uniformity of fractionated powders which would be useful and commercially feasible. This paper is a condensed account of the methods used and the results achieved. A detailed description will appear in the Journal of Research of the National Bureau of Standards in the near future.

Methods and Results

As an essential first step in size fractionation or in determining particle size, it is necessary to find a medium in which diamond powder will disperse. A liquid medium to be effective must wet diamond and must develop an electric charge on diamond particles when the diamond and liquid are in contact. Other properties of the liquid such as viscosity and specific gravity are also of importance. Wettability was determined simply by observing whether a liquid, brought into contact with clean diamond particles, surrounded the particles or pushed them away. The development of an electrical charge was ascertained by observation under the microscope of the migration of diamond particles immersed in a liquid in a simple electrophoresis cell.

It was found that in all the liquids tried the diamond particles developed a negative charge. The liquids were judged on the basis of their dispersive power, i.e., on the basis of the absence of aggregates and the Brownian movement of fine particles, and were given a rating of excellent, good, fair, or poor. For the purpose of size fractionation, only two of the more than 30 liquids examined were given a grade of excellent. One of these was the general group of pine oils in various viscosity grades and the other was a 1/10 to $\frac{1}{4}$ per cent solution of gelatin in H_2O to which enough sodium carbonate had been added to give a *p*H of about 9. Ethylene glycol, glycol sebacate, hexaldehyde, oleic acid, olive oil and a $\frac{1}{5}$ per cent solution of calcium lignin sulfonate in water were found to be good dispersants although two were too viscous and one was too expensive to be practical for use in settling or elutriation procedures. It is interesting to note that ethyl alcohol, which apparently has been widely used commercially, was one of the poorest dispersants tried. Microscopic observation of diamond dusts fractionated commercially in alcohol almost invariably showed poor size grading.

In photomicrography, excellent mounts of well dispersed diamond powder are obtained by stirring the powder well into Canada balsam melted on the object slide. Hyrax also gives good mounts.

Separation Methods

The selection of a method of separation for commercial use is based principally upon the following considerations: (1) a quality of size fractionation which will meet the demands of the user, and (2) an economy in cost and operation of the machine which will make the apparatus commercially feasible.

The methods of separation considered fall into three general classes:* centrifuge methods, gravity settling and elutriation. The discontinuous centrifuge method when operated according to the specifications of the Research Laboratories of the British General Electric Company was known to give a product of excellent quality, but due to the amount of attention required by an operator for the amount of dust separated and to the expense of equipment and supplies, it did not appear suitable for commercial use.

Direct gravity settling gives good results when proper precautions are taken as to temperature uniformity, proper settling medium, proper methods of removing fractions, and requisite number of repetitions of the settling process, but the method is very time-consuming.

A modified form of the Cooke elutriator was finally selected as embodying features most useful in fractionating the diamond powders commercially. This instrument is described and illustrated in Report of Investigation #3333, *United States Bureau of Mines.* The modifications introduced in the diamond powder investigations, such as changes in the reservoir for maintaining constant head, will be fully described in the final report. For a dispersing medium, a 1/10 per cent solution of gelatin was used to which was added sufficient sodium carbonate to give a *p*H of about 9 and sufficient thymol to prevent bacterial growth.

In operation, a slurry of diamond powder and gelatin solution is placed in a can into which the gelatin solution flows at constant rate under constant head, adequate precautions being taken to prevent turbulent flow through the diamond suspension. The rate of upward flow through the diamond suspension determines the size of grain washed over the edge of the can. Assuming constant and non-turbulent flow with adeuqate stirring of the diamond dust in the can, all the diamond grains of one size can be separated provided sufficient time is allowed. The finer particle sizes are separated first by beginning with the slower flow rates.

The results were quite satisfactory and well within the tolerances of the commercial standard as finally proposed and adopted. Provided large enough reservoirs for liquid and for separated powder suspensions are furnished, the machine will operate with very little attention.

The liquid elutriation method has the advantage over the gravity set-

* This study was largely confined to sub-sieve sizes since the powders in the range of commercial sieve sizes were in general found to be well graded.

tling method that the former can theoretically separate completely in one operation all the grains within definite size limits whereas the gravity method can only approach asymptotically a complete separation with repeated mixings and settlings. The liquid elutriation method, moreover, requires the lesser attention of an operator for an adequate separation of sizes.

Commercial Standard

A Commercial Standard (CS123-45) drawn up by the National Bureau of Standards and put into operation on May 5, 1945, provides a basis for agreement beteeen purchaser and seller on uniform size and purity grades of diamond dust. It is principally valuable in that (1) it furnishes a designation for size grades of diamond dust based on the average particle size in microns, and (2) it provides size grades of dust with minimum and maximum limits which are adequate for the user and attainable by the producer. Seventeen size grades are provided beginning with 1 (minimum size 0, maximum size 2 microns), proceeding up the scale with graduated increase in size and in tolerance and ending with 400 (minimum size 250, maximum size 550 microns). This standard has already reduced the confusion in the buyer's mind caused by arbitrarily selected designations of powder sizes which had no relation to actual sizes in any mensural system.

(8) APPLICATION OF THE HIGH VOLTAGE ARC TO THE CUTTING, SAWING, AND DRILLING OF DIAMONDS

Chauncey G. Peters, *National Bureau of Standards, Washington, D. C.*

While the larger wire dies of both diamond and carboloy have been produced domestically for a number of years, all the small diamond dies of .002″ to .0004″ in diameter were imported from Europe. When the war completely cut off this supply and at the same time enormously increased the requirements for fine wire, the War Prodcution Board took active steps to encourage and assist domestic plants in the production of these critical dies. A report on the progress of this program is given in an article "Diamond Dies," Alexander Shayne, *American Mineralogist*, **28,** 145, 148 (1943). In spite of this effort it was found by January 1943 that the number and quality of the dies produced were below requirements and the assistance of the National Bureau of Standards was requested. Under Project NRC-535 a die laboratory was instituted at the Bureau with the purpose of reducing production time and cost, and improving the quality of dies.

Machines of the type in general use were installed and operated but it soon became apparent that no appreciable reduction in drilling time could be made over the average experience of the industry.

Fortunately, at that time, with the aid of apparatus previously used in the Interferometry Laboratory for depositing metallic films, holes about .020″ deep and .004″ in diameter were drilled in diamonds in about 15 minutes time. The arrangement of this high voltage apparatus as now being used is shown in Fig. 1. The leads from the 110 V, 60 cycle a.c.

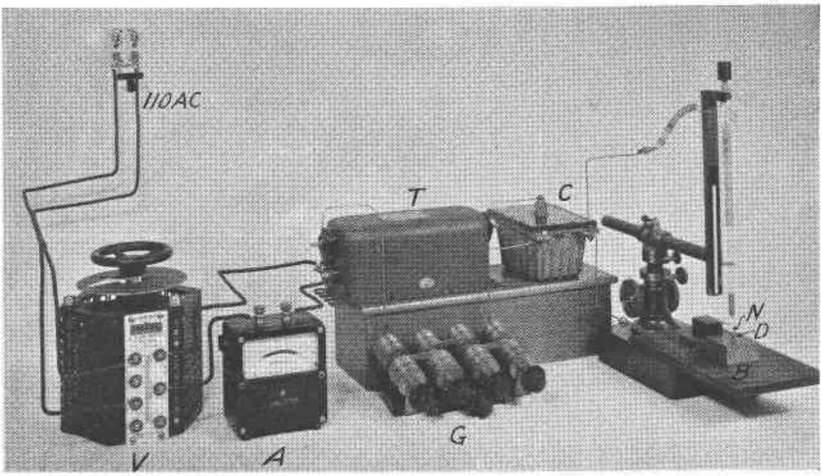

FIG. 1. Apparatus for high voltage, electrical fore-drilling.

outlet are connected to the primary of a 0 to 120 V output variac, *V*. The secondary of the variac is connected to the primary terminals of a 10,000 volt, 300 VA power transformer, *T*. In one of the primary connecting leads a variable rheostat, *P*, of 200 ohms (not shown in the figure) is placed and in the other an alternating current ammeter, *A*, of 2 ampere range. A capacitor, *C*, of about .0004 microfarad is connected across the secondary leads of the transformer. Control and speed of drilling is improved by inserting a quenched spark gap, *G*, in one secondary lead of the transformer.

One of the secondary leads of the transformer is connected to the brass base block, *B*, which supports the diamond, *D*, and the other lead is connected to the drilling needle, *N*, which is made of 0.020″ diameter, 70 per cent platinum-30 per cent iridium wire and contacts the diamond.

Adjusting the current to about one ampere by means of the variac, a white arc extends from the needle to the brass pillar and a hole of about .020″ depth shown in Fig. 2, is drilled in 8 to 10 minutes. The die is then transferred to a light drilling machine and the primary cone shown in Fig. 3, is reamed. (This operation requires about 45 minutes time.) The cone angle is controlled by the shape of the needle. By repeating the two operations a primary cone of about .040″ depth is produced.

The previous method of making dies has been essentially a star drilling operation, that is, the diamond is tapped rapidly by a sharp pointed needle covered with diamond powder. This action causes the point of the steel needle to almost immediately break down with but little effect on the diamond. For this reason, from 75 to 150 hours were required to drill through a die blank of .050″ thickness.

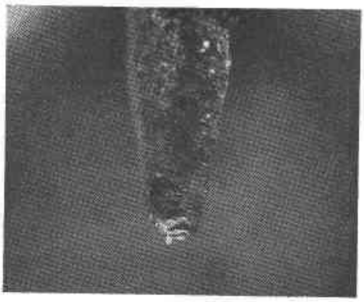

FIG. 2. Fore-drilled pilot hole. ×73.

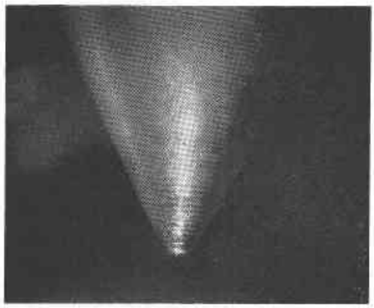

FIG. 3. Countersunk bell cone. ×73.

With the method here described the hole is fore drilled by means of the electric arc. The point of the drilling needle follows this pilot hole without coming in contact with the diamond and the rapidly rotating side of the needle cone charged with diamond powder, laps, or reams the primary cone to desired form.

The drilling and polishing of the secondary cone and bearing is discussed in the second part of this report. (See following paper.)

Applying the high voltage arc to the lapping machines used for cutting flat facets on diamond, the cutting rate is materially increased for all orientations of the diamond and good progress can be made directly on a natural octahedron face, where cutting without the arc is almost impossible. The arrangement of the apparatus is shown in Fig. 4 which is the same as for Fig. 1 except that variac and quenched spark gap can be dispersed with.

One secondary lead of the transformer is connected to the dop, F, which, holds the diamond, D, and is supported by the insulating arm, B. The other lead is connected by the brush, E, to the lap, L. When a current of about 0.5 ampere is applied a small arc appears at the contact of the diamond and lap. A description of the apparatus and a table of the cutting rates for different orientations is given in the *Journal of Research* of the National Bureau of Standards, Vol. **34,** p. 587, June, 1945. Reprints can be obtained from the Bureau or the Government Printing Office, Washington D. C.

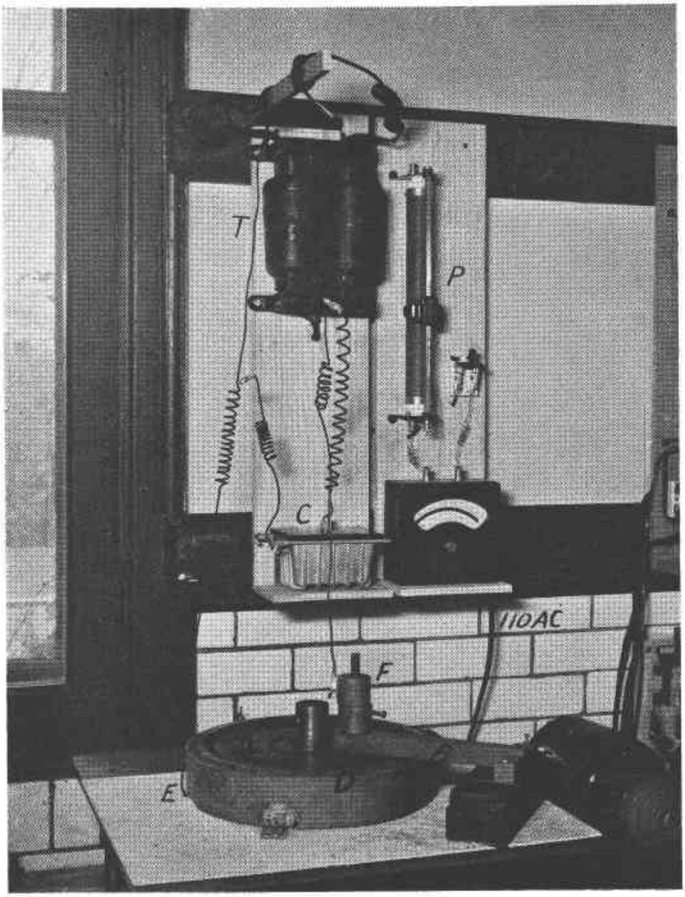

FIG. 4. Diamond lap with electric equipment and connections.

The electric arc has also been applied to the diamond saw. With the same arrangement shown above one lead is connected to the insulated dop, while the other lead is connected to the saw by means of a light phosphor-bronze brush. From published accounts, sawing could only be performed in certain directions parallel to either a cube or dodecahedron face. With the arc however, relatively rapid sawing can be done regard-less of the cutting direction. Saw cuts have been made with the periphery of the saw traveling parallel to the octahedron face.

(9) CONTROLLED ELECTROLYTIC DRILLING OF DIAMOND

WALTER B. EMERSON, *National Bureau of Standards, Washington, D. C.*

The purpose of project NRC-535 undertaken by the National Bureau of Standards in January, 1943, was to improve production of diamond wire-drawing dies .0004″ to .0015″ in diameter. It soon became apparent

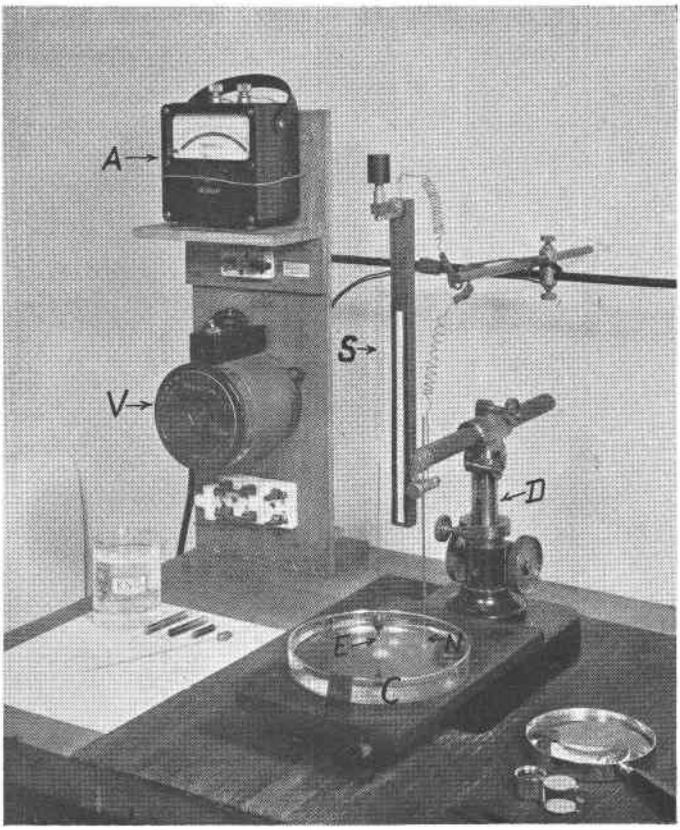

FIG. 1. Apparatus for electrolytic drilling.

that any appreciable decrease in production time would have to come from improved methods for drilling the secondary cone. This operation required from 75 to 125 hours for dies .001″ or less in diameter when performed on existing machines.

The electrolytic method described in this paper for drilling diamond makes use of the Wehnelt[1] electrolytic interrupter for the production of high frequency oscillations. Reference to Wehnelt's work is made by Starling[2] in his discussion of high frequency oscillations. Dawihl and Fritsch,[3] using this electrolytic method to obtain high frequencies, produced hemi-spherical holes about 0.30 mm. in diameter and 0.25 mm. deep in the surface of diamonds with sulfuric acid as the electrolyte. Some of the early experiments with electrolytic drilling at the National Bureau of Standards gave conical holes, .002″–.003″ deep, having small diameters. As a result of further extensive investigation, secondary cones .005″–.006″ deep are now drilled electrolytically in about one hour, with the equipment shown in Fig. 1. This consists of the following parts:

Electrodes, *E* and *N*: 70% Pt.–30% Ir wire, .020″ diameter.
Helical Spring Suspension, *S*: and holder for the drilling electrode.
Device, *D*: for raising, lowering, and rotating the drilling electrode, *E*.
Variac, *V*: 0-135V output.
Ammeter, *A*: 0–1 or 0–2 ampere range.
Glass Container, *C*: for the electrolyte.

Electrode *E* is electrically connected through spring *S* to one output terminal of variac *V*; electrode *N* is connected through ammeter *A* to the other output terminal of the variac.

Factors that affect drilling include (*a*) composition and shape of the electrode, (*b*) composition and concentration of the electrolyte, (*c*) load on the drilling electrode, (*d*) applied potential, (*e*) current, and (*f*) electrical characteristics of the circuit.

From tests of 40 electrolytes including acids, bases and salts, potassium nitrate (KNO_3) was found to be the most satisfactory for drilling secondary cones. Most electrolytes give cones having contour *A*, Fig. 2, in contrast to the more desirable shape for small die cones, *B*, produced with KNO_3. Sodium chloride (NaCl) gives a shallow, funnel-shaped hole, *C*, that has useful applications in making electrolytically drilled dies.

In preparing dies for electrolytic drilling the primary cone should terminate .005″–.006″ from the back surface of a "flat-back" die or from the spherical surface of a "spherical-back" die. NaCl is used for the first drilling of the secondary cone. This gives a shallow, wide-angle cone that blends nicely with the primary cone and places the apex exactly on the axis. The second drilling is made with a solution of KNO_3 which produces a long, small-angle secondary cone having a fair surface polish. The procedure for drilling the secondary cone is as follows:

[1] Wehnelt, A., *Elektrotechn. Zeitschr.*, **20**, 76 (1899).
[2] Starling, Sydney G., *Electricity and Magnetism*, 2nd Edition (**1916**), p. 445.
[3] *Zat. Ver. Deut. Ing.*, **85**, no. 11, 265–268 (Mar. 15, 1941).

Drilling with NaCl.

The drilling electrode is ground with 10°–12° taper to a .002″–.003″ diameter tip. The diamond, previously cemented on a glass pillar in the container, is placed beneath and in line with the axis of the electrode. The electrode is first lowered until it contacts the bottom of the primary cone and is then lowered an additional 3 mm., giving a pressure of about

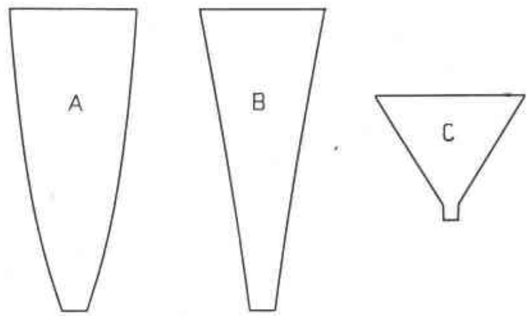

FIG. 2. Contour of cones with different electrolytes: *A*, with several electrolytes; *B*, with KNO_3; *C*, with NaCl.

0.2 gm. on the diamond. A 5 per cent by weight aqueous solution of NaCl is then poured into the container until the die is immersed sufficiently (about 2 mm.) to give 0.6 ampere when 90 volts are applied to the circuit. The non-drilling electrode should dip about 7 mm. beneath the surface of the liquid. Drilling with 90 volts potential is continued for 30 minutes.

Drilling with KNO_3.

The procedure for the second drilling operation is similar to the preceding one. The electrolyte in this case is a 10 per cent by weight aqueous solution of KNO_3 and the tip diameter of the drilling electrode is .0010″–.0015″. Voltage and current values are 90 volts and 0.6 ampere respectively. An occasional rotation of the electrode during the drilling tends to improve the contour of the cone.

If the initial distance to be drilled does not exceed .006″, the die will be pierced with a 40–45 minute drilling, giving a smooth-bore cone having a diameter of .0005″–.0006″ at its orifice. If the distance to be drilled is greater than .006″, an additional 40 minute drilling may be required. By controlling the weight applied to the drilling electrode, cones having diameters from .0006″ to .0015″ are produced by this method, Fig. 3 shows a .0007″ diameter cone drilled by the above procedure.

Countersinking the orifice.

The sharp edge formed where the secondary cone meets the back surface is given a slight countersink or chamfer to prevent damage by chipping when wire is drawn through the die. This is accomplished by inverting the die beneath the electrode and then drilling with a 5 per cent solution of NaCl. The electrode for this operation is ground with 30° taper to a fine tip which is inserted in the orifice. Sufficient countersink or relief is obtained in 5 minutes using 70 volts and 0.5 ampere.

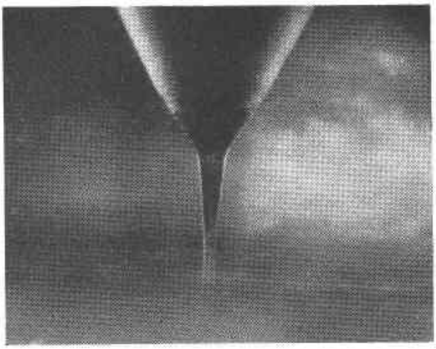

FIG. 3. Electrolytically drilled secondary cone. ×73.

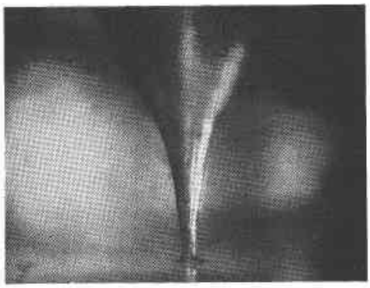

FIG. 4. A well-formed and well-finished .001″ die. ×73.

The cone surfaces of electrolytically drilled cones are usually quite smooth and round and give fair performance in drawing wire. It has been found, however, that die life is materially increased if the secondary cone and bearing are given a high mechanical polish. Fig. 4 shows a die having an excellent primary cone, secondary cone, bearing, countersink and finish.

In conclusion it can be stated that the conditions for drilling are not critical:—excellent results are obtained by die makers after a few hours of instruction. The procedure is neither tedious nor confining and one person can operate several drilling units. Wire-drawing tests indicate that these electrolytically drilled dies are equal or superior to those drilled mechanically.

(10) DEVELOPMENTS AND TRENDS IN THE USE OF INDUSTRIAL DIAMONDS

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Ten years ago the important uses of industrial diamonds were in core drilling bits and in tools for dressing grinding wheels. In the previous fifty years, only one important change took place in the industry, the replacing of carbonado by bort diamond in core bits. In most tools, the virgin crystals were mounted in metal in random orientation in the condition in which they were found when mined. Only a few thousand carats were used annually in a processed or fabricated form. These were used chiefly as wire dies, although some few were used as cutting tools. Industrial diamonds were a by-product of gem diamond mining, and the demand did not equal the supply. Hence, large stocks of industrial diamonds had accumulated, and fortunately, too, because the allied powers were able to draw upon them to meet the increased war-time demands.

Today the potential consumption of industrial diamonds far exceeds the ability to produce. In those mines in which large quantities of the lower qualities of diamonds are produced, gem diamonds now are a by-product of industrial diamond mining, and this may bring significant changes in the marketing and control of gem diamonds. This change in the industrial diamond position has been due to the war-time development of the impregnated diamond grinding wheel. By processing a hitherto worthless variety of diamond, an abrasive diamond grit has been produced. During the last year of hostilities, approximately nine million carats of bort diamonds were crushed and sized for introduction into impregnated wheels in this country alone. A number of concerns have experimented with the use of diamond grits in the manufacture of core drilling bits and the adaptation of the larger grit sizes to dressing tools. Such developments would be in keeping with the trend of the last few years towards the use of more and smaller diamonds in core bits and the use of several small diamonds instead of a single crystal in dressing tools.

The processing of diamond calls for the application of crystallographic principles and a knowledge of the properties of a *single crystal*, as distinguished from multicrystalline substances such as metals, alloys, and ceramic products. Such a knowledge is essential in the manufacture of abrasive diamond grit because the rupture of the crystal is dominated by its perfect cleavage. The efficient production of a uniform sized grit, free from elongated splinters and thin plates, cannot be attained without an understanding of the role of cleavage.

Although the production of diamond grit has overshadowed, in terms of carats used, other recent developments, war-time needs made it necessary to produce large numbers of sharp pointed diamonds for the contour shaping of the face of grinding wheels. This was especially true for the small diamonds known as *thread dressers* used in shaping thread grinders. Formerly selected diamond crystals with natural sharp points were used but the supply was inadequate and it was necessary to process or lap such points. While many of these points were produced by mechanically bruting or wearing down the surfaces, a more efficient method is to utilize the methods of the gem diamond cutter.

While the diamond cutter uses empirical methods for arriving at the proper directions for cutting and polishing flat surfaces, it is possible to establish crystallographic principles by which the most efficient direction of lapping any given surface upon the diamond can be found. Those directions in which the diamond will readily take a high polish are often called the "polishing grains."

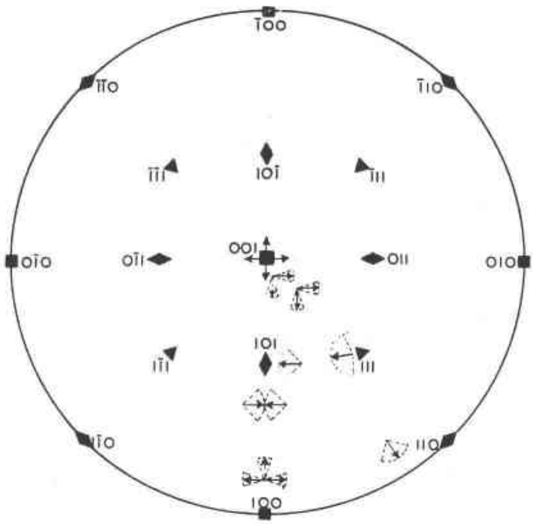

FIG. 1.

There are four polishing grains associated with each possible cube face and two with each dodecahedron, making a total of forty-eight. The diamond cutter refers to these as the four-point and two-point polishing grains, respectively. Because of the symmetry of the diamond, the polishing directions for a facet upon any part of the surface of a diamond may be deduced from those shown in projection in Fig. 1. The direction in which the lap should move across the surface is indicated by the arrows. The allowable deviation from the most efficient polishing direction is represented by sectors of circles. The rate of polishing decreases rapidly as the limiting directions are reached. The following rules will establish the polishing direction or directions at any point upon the surface of the diamond:

The polishing direction is always normal to the zone of the nearest cube and dodecahedron faces.

If the facet lies nearer the cube face, the polishing direction is away from that zone.

If the facet lies nearer the dodecahedron face, the polishing direction is towards that zone.

If the facet lies nearer to the cube face, there will be a second and inferior polishing direction. It will be normal to and directed away from the zone of the cube face and the second nearest dodecahedron.

While it is desirable to utilize the softer directions of the crystal in producing the tool, it is equally desirable to use the hard direction when the tool is put into use. The advantages to be derived from the proper crystallographic orientation of the working surface of the tool have been presented earlier on this program. Because hardness is a vector property, the reverse direction along a soft or polishing direction will be a hard or resistant direction. There are also on every flat surface some directions which are always resistant, irrespective of the sense along which one moves.

One often sees the statement that the cube face is softer than the dodecahedron, or vice versa. Such statements are meaningless, because there are hard and soft directions on both of these surfaces. It is, however, generally recognized that the soft direction of the dodecahedron face is softer than the soft direction of the cube face. Likewise, because there is no polishing direction on an octahedral surface, it is recognized as the hardest surface on a diamond crystal. There is insufficient data available to allow one to draw any conclusions with respect to the comparative resistance of the hard direction of the cube face to that of the dodecahedron, or the comparative hardness in various directions across the octahedron.

The wider recognition of the principles outlined above should lead to a greater use of shaped diamond tools. The necessity in the past of paying the high wages of the gem diamond cutter to perform the simpler operations of tool forming has handicapped their use. The gem cutter, too, is unfamiliar with the fundamentals of tool design. The full utilization of the diamond as a cutting tool must await the time when the tool designer understands the principles of shaping and using the diamond.

The position of shaped diamond tools and the larger diamond wire drawing dies is not as favorable as it was three years ago. These tools require the finer qualities of industrial diamonds, and the price of the rough diamonds rose during war-time above the ceiling prices of the finished tools. It is hoped that with the return of more normal conditions, shaped diamond tools may find their place in the precision cutting of the non-ferrous metals and plastics.

In a few short years the introduction of scientific and technical knowledge has placed the industrial diamond on a sounder footing. We no longer attempt to mechanically drill fine diamond dies with a diamond powder whose coarser particles are larger than the hole we wish to drill. This state of affairs had hardly been rectified by the development of suitable powder before the drilling was being done electrically without its use.

It is an interesting observation that no significant developments in the diamond industry came from within the industry itself. The pre-war status of that industry was one in which the use of the rudimentary tools of science, such as the microscope, was unknown. It was in such an atmosphere that governmental controls and policies were inaugurated in the early days of the war and established on unsound technical grounds. Less than two years ago, an official ruling of the Diamond Section of the War Production Board released the finer qualities of industrial diamonds for cutting into gem-stones on the grounds that they were non-acceptable and undesirable for industrial purposes. The fact that these diamonds, imported from Great Britain at industrial prices, would bring two to three times the import price on the gem market may have had a bearing on this ruling.

The troubles that beset the industrial diamond trade during the war years are perhaps those that are to be expected in an adolescent industry. What the future holds in store for the industry will depend to a great extent upon the availability and the prices of the various grades of industrial stones. For the immediate future, we face the prospect of a shortage in raw material. It must be remembered, however, that this shortage is not due to a falling off of supply, but to a many-fold increase in demand which has arisen through the development of a sounder diamond technology.