SYMPOSIUM ON DIAMONDS*

(1) INTRODUCTORY STATEMENT

EDWARD H. KRAUS, *University of Michigan, Ann Arbor, Michigan.*

Mineralogists have always been interested in the use of the diamond for gem purposes. They have also known of the use of carbonado and boart in diamond drill bits. Relatively little attention, however, has been given by them to the very extensive use of the diamond at present in industry as a whole. The great speeding up of the defense programs in this country and Great Britain, and especially the interruption of the supply of wire drawing dies, formerly produced in the low countries and France, have created many difficult problems. Efforts were accordingly made to supply these deficiencies and also to accelerate the production of diamond-set tools and diamond-bonded wheels which are so vital in precision machining of metallic and other parts. In attempting to solve some of these problems manufacturers have quite naturally sought the advice of mineralogists. Their stock of the necessary technical information is quite limited due to the fact that only recently have a few mineralogists endeavored to correlate the practice of industry with our knowledge of the various physical and structural properties of the diamond. It was therefore thought advisable to arrange a symposium on diamonds to be conducted at the time of the meetings of the Mineralogical Society of America in Boston.

The program of the symposium included seven papers by persons especially competent in the fields assigned to them. The symposium attracted an interested group and provoked much discussion. Because of the large amount of valuable information contained in the papers, it was deemed desirable that they should be published together, and, as far as feasible, substantially as presented.

The paper on the production and supply of diamonds by Ball indicated the changes that have taken place in diamond production and that there is increased production in the alluvial fields especially in the Belgian Congo. Ball raised the question as to whether there are significant differences in the properties of the diamonds formed in the pre-Cambrian and those in the Cretaceous diamond pipes of South Africa. The present situation in the gem cutting industry was discussed in detail by Kaplan. The rapidly changing economic conditions naturally exert a great influence on the evaluation of gem diamonds.

The methods used in the production of diamond wire-drawing dies,

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especially those of exceedingly small diameter, called superfine dies, as described by Herz, are most interesting. Indeed, it is a revelation to the professional mineralogist that it is possible to pierce a diamond and produce a hole with a diameter of only 0.0003″ which conforms precisely to specifications. The efforts made by the federal government through the Office of Production Management to speed up the manufacture of wire-drawing dies in this country were described by Shayne, who reported that very material and satisfactory progress is being made to supply the need for some of the diamond dies formerly obtained from abroad.

Problems involved in the use of diamonds as tools for machining purposes were reviewed in considerable detail by Slawson, who stressed the need of more adequate scientific information concerning the properties and structural strength of the diamond on the part of the designer and the cutter of these tools. The progress made in this country in the production of bonded diamond wheels was reviewed by Klein. The type of diamond powder which has been found to be satisfactory for this purpose and the uses of diamond bonded wheels were described. The various properties which are important in the selection of diamonds, especially for industrial uses, were discussed by Berman, who advocated the close cooperation of mineralogists in an endeavor to determine satisfactory evaluation criteria.

It should be noted that this was the first symposium on diamonds dealing with many of their uses, that is, as a gem and in industry, that has been held. In view of the interest taken in the symposium and the valuable information which has been gathered, it is hoped that a similar program may be arranged for the next annual meeting of the Society.

As chairman of the symposium, I desire to express my sincere appreciation for the enthusiastic response and cooperation of those who were invited to participate in the symposium, and to the officers of the Society for making provision for the session. Our thanks are also due to Mr. Harvey B. Wallace, President of the Wheel Trueing Tool Company of Detroit, and to the Norton Company of Worcester, Massachusetts, whose financial support has made the publication of the papers possible.

(2) DIAMOND PRODUCTION

Sydney H. Ball, *New York, N. Y.*

The diamond occurs as a mineralogic curiosity in a large number of places on every one of the continents, but its commercial occurrences are few. The first discoveries were made in India, perhaps 800 to 600 B.C., and India was the dominant producer until the rich Brazilian fields supplanted it late in the second decade of the 18th century. Brazil, in turn, lost the lead to South Africa about 65 years ago. Since, then, the story of production has been mainly an African one. Prior to 1909, the Union of South Africa was, from a practical standpoint, the only producer, but since the latter year diamond production has undergone one of its major cyclical changes. From 1907 to 1930, important alluvial diamond fields were successively found in the Belgian Congo, South-West Africa, Angola, Gold Coast and Sierra Leone. These virgin fields are, on the average, rich and have low operating costs, and their production has grown with astounding rapidity.

South Africa held the lead, as to value produced, up to 1936, but now its pipe mines are shut down, due to economic factors within the industry, and its alluvial production is slowly decreasing.

Production today is, by weight, about 14,000,000 carats (slightly over three short tons), worth some $35,000,000, as opposed to an average of 7,200,000 carats, worth about $75,000,000 for the four years 1927 to 1930. The change is mainly due to the large boart production of a single Belgian Congo company, Beceka, which in the past two years, by weight, has accounted for over one-half of the world's production. As a result of this shift in production and the shutting down of the pipe mines, the weight of fine cuttable material produced today is but 60% of that of a dozen years ago, cuttable goods making up about 55% of the 1927 production and but 16% of that of 1940.

If the war continues, the 1942 production will be less than that of 1941, since the larger producers of today are situated far from sources of supply and some of them must soon become short of certain essentials. Indeed, a year or two hence may well see some of them shut down through lack of supplies.

At present the Belgian Congo is the largest producer accounting for 75% of the world's production by weight and 25% by value. It is followed by Angola and Sierra Leone, the Gold Coast and Brazil, and the alluvial fields of the Union of South Africa. The British Empire produces about 25% by weight and somewhat less than 50% by value of the total. Brazil in the recent past has increased is production appreciably, the major portion of which is now purchased by the United States Government. British Guiana and Venezuela add their pittance. The Western hemisphere, however, by weight, produces but three per cent of the world's production, and by value, something less than 10%.

This change in production is not only geographic; it is also one of the geologic age of the rocks which are the source of the diamond. The best known diamond occurrences, to the layman and scientist alike, are the South African kimberlite pipes, intrusives of Cretaceous age. While the Union of South Africa pipes, those of Kimberley and that of the Premier

Mine near Pretoria, are most frequently mentioned, similar intrusives occur in South-West Africa, Rhodesia, southeastern Belgian Congo and Tanganyika Territory. The diamond content of the kimberlite of these other countries is, so far as we know, however, non-commercial. In passing, it may be stated that the Arkansas kimberlite intrusives near Murfreesboro are also of Cretaceous age. The alluvial diamond deposits of the Union of South Africa, South-West Africa and Tanganyika Territory are derived, in large part at least, from the erosion of kimberlite pipes.

Some of you will remember that an occasional diamond—usually green in color—is recovered with the gold of certain of the Witwatersrand gold mines. These diamonds occur as pebbles in a pre-Cambrian rock. The Belgian Congo diamonds are known to occur as pebbles in Jura-Triassic rocks and at least one stone was washed from a sheared basic igneous rock, a member of the pre-Cambrian basement, below the flat-lying Jura-Triassic rocks. While it must be admitted that possibly a native helper of the geologist who found the stone, knowing what his boss wanted to find, salted him, the evidence is fairly conclusive that the Kasai diamonds are derived from pre-Cambrian rocks. Further, N. R. Junner reports that the precious content of the Gold Coast alluvial deposits is derived from pre-Cambrian rocks. Indeed, diamonds have been recovered from the clean-up of the Ashanti-Adowsena gold mine, the ore bodies of which occur in the Tarkwaian quartzites of the Banket series of pre-Cambrian age. The important Sierra Leone alluvial deposits and those of the French African colonies likewise are, with little doubt, derived from pre-Cambrian rocks and the Gwelo Forest, Rhodesia, deposits may be.

Thirty years ago practically all diamonds produced came directly or indirectly from Cretaceous pipes. In 1940, due to the limited scale of pipe operatious, 96% by weight, and 72% by value of the African production was obtained from gravel deposits from pre-Cambrian rocks.

This change in production is also one of mining methods; and probably never before has a mining industry, after fifty years of dominant lode mining, become mainly an alluvial mining industry. The switch is one from a few large up-to-date units (the Premier Mine before the first World War was the largest tonnage mine in the world) to a large number of relatively small plants, most of which are well run. The condition seems atavistic, but there it is!

The lesser amount of cuttable and the greater amount of industrial diamonds produced today coincides with a change in the consumption due to the remarkable increase in the use of industrial diamonds; eightfold in the past 25 years. This year the United States alone will consume over 3,000,000 carats of industrial stones. Now over 75% of the world's rough diamond sales, by weight, and one-third by value, are of industrial stones. Today, in part due to the world war, managers are learning the necessity of the use of industrial diamonds in factories, and artisans by the thousands are being trained in their use. We can confidently look forward to further increases in the future; and ten years hence, don't be surprised to see underground drifts being drilled with diamond drills and not by percussion drills.

While war has increased the use of industrial diamonds, it has also somewhat restricted the market for gem stones. The United States, Canada, South America, and the East are buying more than their normal quotas of gem stones, but the war has practically stopped sales elsewhere. Further, the destruction of the cutting industries of the low countries has brought about a distinct shortage in the supply of small cut for mountings and no too abundant supply of large fine cut.

At present industrial diamonds, except in the case of Beceka and the carbonado alluvial deposits of Bahia, are by-products of gem mining. In the future, if the price of industrials continues its rise, more deposits may find industrials their dominant product.

You may be interested as to guesses regarding reserves. The pipe mines have blocked out reserves of the order of some five years' mining at normal rates, and the alluvial fields of some ten years. The reserves to be later blocked out may equal another ten years. In short, it is believed that the total reserves of diamonds are of the order of those of lead and zinc and much less than those of copper.

In closing, may I add that the three tons of diamonds require some 70,000 men to produce them, of whom 8,000 are Europeans: each man labors a year to produce 1.4 ounces of diamonds: and in the gem mines the production is but 0.425 ounces per man year. About 40,000,000 units of gravel are mined and milled to produce one unit of diamond. It is always a marvel to me how the mills are able to seek out that one-forty millionth.

(3) CUTTING OF GEM DIAMONDS

LAZARE KAPLAN, *New York, N. Y.*

Before the invasion of the low countries, our source of supply of polished diamonds was Belgium, Holland, and Germany, where approximately 95% of the world's supply of polished diamonds was produced. We, here, had the choice of either making our purchases by personally traveling to Belgium and Holland, or placing our order with a buying representative there.

To illustrate the vast difference between the amount of diamonds cut in these three countries and the United States, in the period preceding the invasion: there were about 40,000 diamond polishers in Holland, Belgium, and Germany (and about 1,000 in France, England, and the Transvaal), as compared with about 250 diamond polishers in the United States.

The following table will serve to illustrate the large quantities of unset cut diamonds which the United States imported from the years 1936 through 1940:*

Year	*Carats*	*Dollars*
1940	321,499	$22,009,943
1939	488,154	27,417,273
1938	330,925	17,016,842
1937	517,677	29,860,396
1936	445,610	22,707,703

Cutting in Europe was geared for quantity production and probably about 75% of the men worked on small stones ranging from 10 to the carat down to the smallest sizes. There were large institutions in Belgium (similar to schools) which did not actually manufacture their own merchandise but took in piece-work on a very large scale. A similar arrangement was operating under government control in Germany, showing the desire of the German government to encourage the diamond-cutting industry there. The German manufacturers did not cut their own merchandise but contracted to cut rough stones supplied by Dutch and Belgian merchants which they produced on a piece-work basis. Thus, the German cutters had no merchandise for sale. When necessary, the German government even granted subsidies to cutters to enable the industry to reduce its labor costs to a level that would induce the Dutch and Belgian merchants to send their work to Germany instead of doing the cutting in their own countries. The principal article cut in Germany was single cuts. (A single cut is a small round diamond of eighteen facets: one table, eight facets on top, eight facets on bottom, and one culet.) In Belgium, the system of homework was practiced, which the government tried to abolish and did succeed in reducing.

With the attack of the Germans on Belgium and Holland, the source of supply of polished diamonds officially or apparently ceased. Refugees began to arrive in the United States in great numbers, bringing with them large stocks of polished diamonds from Europe. Yet, notwithstanding the stoppage of cutting in Europe, we find large quantities of polished diamonds being imported from various countries into the United States. These came into the United States via round-about routes through France, Portugal, and the South and Central American countries. Thus, the shortage that was expected at the time of the invasion was less than anticipated.

* From "The Diamond Industry (from 1936 to 1940)"—by Sydney H. Ball.

To explain these importations, one must take into consideration the fact that for some years diamonds had been sent to this country and placed in a Bonded Warehouse, which meant that these diamonds had not actually been entered as importations nor had duty been paid. This system of entering diamonds in a Bonded Warehouse was greatly facilitated by the U. S. Exhibition Act which permitted diamonds to be exhibited here, pending sale or return, under the custody of the Warehouse, without payment of duty. Duty was only paid upon actual entry of merchandise. By chance, the New York World's Fair prevented a very large and valuable stock of both rough and polished diamonds from falling into the hands of the invaders, since many large European firms (including the Diamond Trading Company, Ltd. of London) had exhibitions at the Fair of merchandise entered here under the Exhibition Act and which had not as yet been returned to Europe when the invasion took place.

Thus, at the outbreak of the war in Europe, there were many diamonds in the Bonded Warehouse pending the time when the owner wished to make the formal entry, and pay the duty. Since then, these diamonds have been taken out of the Warehouse and considered as importations, so that figures of importations do not show an accurate picture of what actually came from Europe since the war. From Customs Reports we find that the United States imported from Belgium in the month of September, 1941, a total of 12,079 carats of polished diamonds, of which 8,321 carats actually came from stocks in the Bonded Warehouse. Thus, in reality, 3,758 carats were transferred from Belgium to the United States in that month. And, if we try to break down that 3,758 carats, we find that some of it may have been brought over by refugees.

The refugees claim that the diamonds they bring with them are from their old stocks in Europe. However, it seems reasonable to believe that these stocks would have been exhausted by this time. It appears more likely that the emigrant is seeking to conceal the fact that there are diamonds being cut now in Germany and in German-controlled countries which the emigrant purchases and brings with him to this country via round-about routes.

Until recently, cutting in the United States was mainly quality production. The work was superior and the "art" of cutting diamonds was practised with the main emphasis placed upon the quality of the work produced. However, with the advent of the newcomers, the European methods of quantity production are being introduced here.

Most of the American diamond cutting up until 1939 had been done in New York City where the majority of the 250 cutters were employed. Now, however, cutting has spread to many points outside of this city, such as New Jersey and Pennsylvania. Instead of the original 250 workers we now find about 1,000 good mechanics and about 800 apprentices in this country today. This increase is mainly due to the recently-arrived Europeans who are very enterprising. Many of them opened up diamond-cutting shops here. Others entered the employ of American cutters who now found it necessary to increase their staffs to meet the great demands being made upon American cutting. In addition to the new shops and the new European emigrant workers, the system of apprentices is becoming popular here. As a matter of fact, one refugee induced the town of Hazelton, Pa., to build a factory for diamond cutting without cost to himself, where local boys are taught to cut single cuts.

In Europe, before the invasion, diamond cutters earned between $5 and $15 a week. During the same period in this country, diamond cutters earned between $50 and $75 a week. However, the American cutters were all fine mechanics and quality-workers. The best of the European workers came here to benefit by the higher wage scale. Since the invasion, however, a man producing the equivalent of the European who made $5 to $15 is today making from $100 to $250 a week here for a 35 hour week. (In Europe there was a 40 hour week). The reasons for this tremendous increase in wages are:

(1) The American standard of living and the American diamond cutting wage scale have always been higher, as shown by the fact that we were paying from $50 to $75 a week before the war.

(2) Cessation of European cutting placed a great demand on the American manufacturers and thus created a great demand for cutters.

(3) Shortage of trained cutters here caused manufacturers to outbid each other for workers. Added to this, the demand of the newly established shops made the shortage more acute.

(4) Union policy and union standards.

The union calls itself the "Diamond Workers Protective Union of America" and it tries to be "protective" to its members in every sense of the word. It did not allow any apprentices to enter the industry in the past thirty years and followed the idea that the fewer the workers, the higher the wages and the steadier the work. Through this short-sighted policy, the industry was almost choked, and we find that the average age of the union member in 1939 was about 57 years.

Because of the new shops that were being established outside of the union and the acute demand of the shops for diamond cutters, the union felt it was losing control of the situation and finally decided to change its policy and admit new members and apprentices.

Today, there are 650 full-fledged members of the union who are expert workers, which is an increase of 250 in one year. The emigrant workers account to a great extent for this increase. There are also 400 apprentices in the union today, all of whom are new members since last year.

After the union passes upon an apprentice, it places him with a manufacturer. As an apprentice, he receives the starting wage of $3.00 per week and advances to $32.00 a week in three years. As the first part of the apprenticeship wage is below the Federal Minimum Wage provisions, this is done with the special consent of the Department of Labor in Washington, as the government recognizes the period of training for diamond cutting to be three years. The apprentice wage scale follows:

$3.00 per week for the first three months.
Increase of $1 per week each month for the next 29 months.
At the 32nd month, he receives $32 weekly, which continues through the 36th month.

After his apprenticeship is completed, the apprentice is given a trial period and his future salary is based upon his production. There are also some shops employing non-union labor and we figure that there are about 750 workers in these shops, of which about 400 are apprentices.

As we can see, the tremendous increase in the cost of labor played a very important part in the increase of prices of diamonds. In addition to this great advance in wages, the cost of materials, machinery, rent, and incidentals, all of which have always been considerably higher than in Europe, have increased as well. The Diamond Trading Company, Ltd. of London made a number of raises in the price of rough diamonds amounting to a total increase of about 25% since the invasion of Holland and Belgium. All of these factors can account for the increase of diamond prices.

However, large stones have and always will be profitable to cut in the United States as long as rough material is permitted to enter the United States duty free, and polished diamonds are subject to a 10% duty when imported. Consequently, the American cutter is immediately protected by an advantage of 10% which serves the same purpose as a subsidy. However, on smaller stones from $\frac{1}{4}$ of a carat down to the smallest sizes, the cost of American labor was and is so high per carat that the 10% advantage was not sufficient to enable the cutter to meet European competition.

In Europe, before the war, the cost of production of a single cut diamond was about 15¢ a stone. Here, however, the cost of production of the same stone is about $2.00. Thus small stones have so pyramided in price today that the demand for them is reduced. Jewelry manufacturers are cooperating very sensibly by eliminating the use of small stones from designs as much as possible. Otherwise, small diamonds would probably be much higher than they are.

Therefore, a very unusual situation exists today. Small diamonds from about 20 to the carat and smaller are at a premium at present. Whereas ordinarily, these stones would cost much less than the medium sizes (from $\frac{1}{5}$ of a carat to $\frac{1}{2}$ of a carat), today they have equalized or surpassed the price per carat of the medium size diamonds. Therefore, persons buying the medium sizes today are receiving much better value. In diamonds above ½ carat, the price increases have been even less, in proportion. Thus, in buying a diamond today, persons purchasing the larger sizes (from ½ carat and larger) are receiving the best possible value.

In view of the facts presented we naturally wonder what is likely to happen when conditions return to normal. Will the American manufacturers of small stones be able to compete with the European manufacturers under normal conditions? In view of the wage situation, it seems very unlikely. Then, too, it is interesting to recall that after the first World War, the Belgian government reduced taxes in order to bring the diamond industry back to Belgium. I would not be surprised if governments such as Belgium and Holland would make similar arrangements after this war to encourage diamond cutting, particularly in the smaller sizes. However, as far as larger sizes are concerned, we feel confident that the United States cutters will always be able to continue to increase and to improve their production. Industries in the United States have always expanded and progressed with the times and we feel certain that the diamond industry will not be an exception. Today, the diamond industry is being called upon to be of service to this country in producing shaped diamonds for tools which are so vital for war materials. As a matter of fact, in our factory in Puerto Rico, we have already begun to cut special shaped industrial diamonds for these tools and are looking forward to increase our service to our country.

(4) DIAMONDS IN THE WIRE DRAWING INDUSTRY

PAUL L. HERZ, *New York, N. Y.*

Diamonds are used extensively in the drawing of wire in sizes from 0.080″ in diameter (the size of a knitting needle) down to the finest made, 0.0003″. The wire is drawn through a tapered hole drilled into the diamond. Because diamond is the hardest known material and because it will take a high polish, smooth wire can be produced at high drawing speeds.

Up to fifty years ago steel draw plates or ruby or sapphire dies were used for drawing fine wire and it was necessary to draw the wire slowly. Because the dies wore rapidly, increasing the size of the hole, it was difficult to produce accurately gauged wire. In later years tungsten, molybdenum, and boron carbide dies have competed with diamond dies. Diamonds, however, enjoy an exclusive field for the harder and tougher wire materials such as chrome-nickel resistance wire, brass and phosphor bronze wire, and high carbon steel wire. Diamond is also used for drawing electrolytic copper wire from the smallest sizes up to diameters approaching 0.080″. In addition, diamond is indispensable wherever precision of size and perfect roundness are essential considerations. Gold, silver, and platinum wire for ornaments and, in general, all wire which is to be woven into metallic cloth is drawn through diamond dies.

There is a borderline field in which diamond encounters stiff competition with the ever improving sintered carbide dies, for example, the larger diameters of copper wire, or the medium size common steel wire. Here the choice of die material is governed by economical and practical considerations. The larger the diameter of the wire the larger must be the diamond, and the economical limit is reached when the cost of the stone is excessive. From the practical standpoint the drawing force increases sharply with the increase in the diameter of the wire. A kink in a fine or soft wire will straighten itself out when passing through the die but a thick tough wire will crack the diamond under similar conditions.

About fifteen years ago, wire drawing engineers thought that the newly developed carbide dies would replace diamond dies for the drawing of copper wire. Subsequently the diamond dies were improved principally by using smaller high grade diamonds instead of a large poor quality stones, and the diamond soon regained its supremacy in the copper wire industry.

There are no statistics available giving the quantity of diamonds used in the manufacture of dies. As a producer of dies, I have made a continuous effort to collect information on the manufacturing activities of die makers in every country and on the production of wire in various plants throughout the world. These data were corrected from year to year up to 1939, and I estimate that in normal times the consumption varies between 175,000 and 225,000 stones weighing from 50,000 to 60,000 carats. The manufacturing and maintenance (resizing) of these dies required the crushing into powder of between 100,000 and 110,000 carats of low grade diamonds.

The question has been raised as to the possibility of new materials being produced which will supersede diamonds in the wire drawing industry. It has been hoped that a new material might be developed which combined an equal molecular cohesion (hardness) with a superior resiliency. In the field of small size wire in which the use of diamond dies is now confined additional resilience is not necessary. There seems to be no reason for assuming that a material of equal hardness, which is the greatest asset of a die material, can be developed. I entertain little hope for a new synthetic material to match the close-packed, tenaceous, and fine grained structure of the diamond. I believe that diamond has a brilliant future in the die industry because the normal trend of the industry is towards harder and tougher wire as well as higher drawing speeds.

In the diamond die industry dies with openings between 0.010″ and 0.001″ are referred to as *double naught* dies and those of smaller sizes as *triple naught*. These small dies are especially difficult to manufacture.

The drilling is done by means of a steel needle charged with diamond powder mixed with oil which grinds a tapered hole in the diamond. The diamond must undergo some processing before being drilled. First, two parallel flats are ground upon the stone. Then a deep entrance cone is cut into one of the flats and the stone is ready for drilling.

A steel needle is inserted into the hollow chuck of a horizontal drilling machine, Fig. 1, and secured with shellac. An alcohol flame keeps the shellac plastic while the chuck revolves and the needle is then centered by touch. The centering operation must be so synchronized with the hardening of the shellac that the needle is perfectly centered and its tip revolves without whipping when the shellac has become hard. The needle is then ground to the required taper by means of a portable grinder.

The diamond is then attached to the holder which is free to move back and forth while it rests upon rollers. The cement is allowed to harden after the entrance cone of the diamond has been brought into alignment with the axis of the needle. The drilling is accomplished by oscillating the diamond against the rapidly rotating needle. During the process the operator will have to recharge the needle with diamond dust and regrind it as it wears and also reshape it to suit the pattern of the required profile.

When the hole has been drilled to about $\frac{3}{4}$ of its depth it is centered upon a spotting machine, Fig. 2, for counter drilling. The chuck plate which is removable is inverted and a conical indentation is ground upon the other side of the diamond so as to meet the hole previously drilled in the stone. This is a delicate task for the operation is done blind and the back cone must be exactly in the axis of the drilling and entrance cone. When an opening has been made through the stone it is ready for polishing.

In the polishing machine, Fig. 3, the diamond, as well as the needle, revolves. The stone is on the chuck and the needle is on the holder which plunges back and forth in the drilled hole. The purpose of this is to bring the die to size and give the drawing canal a high polish.

There are many different types of polishing machines. Some use a wire and a longer stroke instead of a needle. Another is vertical with the stone revolving horizontally and the in- and out- stroke of the needle is combined with a side rocker motion which rounds off and polishes the entrance as well as the outlet of the die.

A vertical drilling machine is likewise in use especially for drilling the

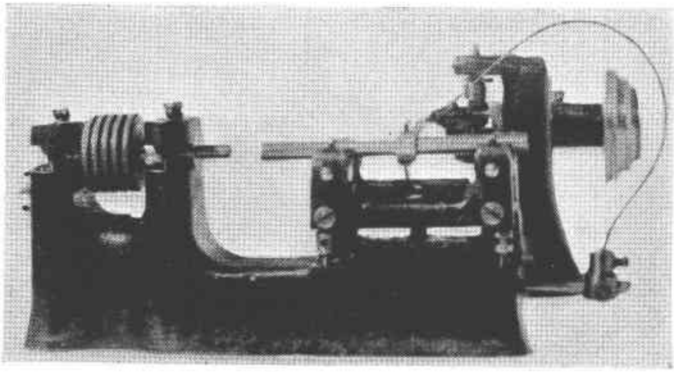

FIG. 1

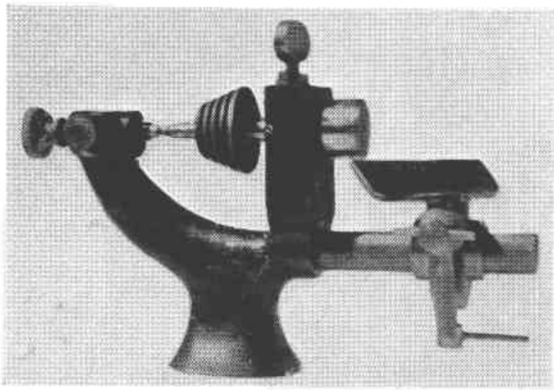

FIG. 2

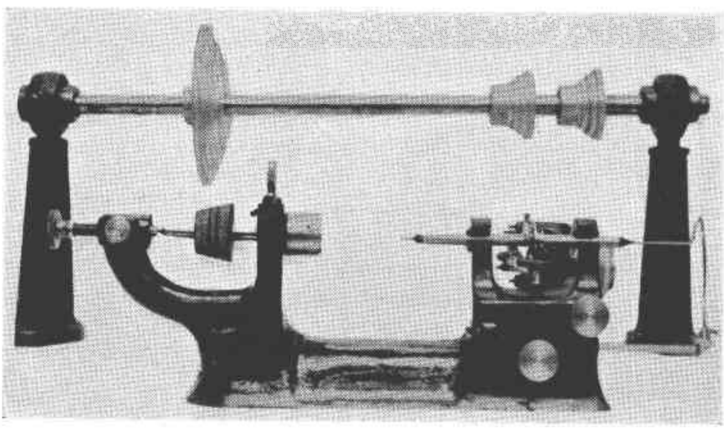

FIG. 3

larger size dies. The needle for larger dies may be sturdier and may oscillate more violently so that a large hole may be drilled as rapidly as the medium sized ones. With the very small dies the needle is no longer rigid, and the difficulties increase immeasurably so that the working skill and time required are much greater.

What are known as capillary dies range from 0.0012″ down to as low as 0.0003″ in diameter. Hitherto all capillary dies were imported into this country because the high labor costs made their manufacture in this country unprofitable, notwithstanding a 30% protective tariff. Yet we now need fine capillary dies for the making of many essential defense items.

Capillary dies must be drilled with a needle so fine that it no longer has any rigidity at the tip. On the ordinary drilling machine, Fig. 1, the diamond may be stuck and centered onto the holder with the drilling needle itself. With dies of capillary size it is impossible to center anything of any weight with such a fine needle. No matter how small the diamond may be, its weight is considerable. In order to overcome the difficulty of aligning the stone in the axis of drilling with the needle, the stone is no longer cemented onto the holder but is simply stuck with oil or vaseline so that it can float freely and center itself.

It takes many years to train skilled labor for this work. Few qualify because it takes special aptitudes to become a successful fine die driller. Good eyesight, calm nerves, the faculty of concentrating on and judging small distances and, particularly, a fine sense of touch without which you cannot center a needle or a stone properly. When the drilling needle is not centered to perfection and thus whips at the end, the time of drilling mounts rapidly and the hole drilled is neither round nor as small as you set out to make it. In other words consummate skill is required to drill a triple naught die and anything short of that skill produces defective double naught dies instead. It takes a skilled man an average of 130 to 200 hours to produce a capillary die and he cannot guarantee when he starts that he will turn out, let us say a 0.00042″ die. He can only say that he will start simultaneously drilling four or five stones, striving for 0.00038″ in the hope of getting one or more 0.00042″ in size.

(5) DIAMOND DIES IN THE NATIONAL DEFENSE PROGRAM

ALEXANDER SHAYNE, *New York, N. Y.*

In October of 1940, the Advisory Commission to the Council of National Defense, in the pursuit of its general policy of providing the United States with an adequate and steady flow of vital and strategic materials, made an extensive survey of the diamond die industry in this country, and found that with the exception of the limited output of a group of three Frenchmen resident here, no dies below 0.004″ were manufactured here, but that all such fine dies were imported. It was found, moreover, that the capacities of the manufacturers of these large sizes were limited and considerably below the demand then existing and far under the expected future requirements.

In view of the cutting off of imports from Europe, and in view of the fact that the diamond die was a particularly important factor in the drawing of wire destined for the manufacture of very many products vital to national defense, the Advisory Commission embarked upon a program of collaboration with the existing diamond die manufacturers in a concerted effort for the expansion of their facilities and for the acquisition of the intricate and difficult art of drilling the smaller-sized dies.

Considerable difficulties of a technical and time-consuming nature were presented in the transplanting of such an industry to the United States—an industry which had been slowly and painstakingly developed in Europe over a period of generations. Hence the newly-created Office of Production Management set up several avenues for the purpose of ensuring to the wire drawers of the United States uninterrupted sources of supply for the dies they required. We enlisted the aid of the British Diamond Die Controller, and through his close and valuable cooperation, it has happened that at no time have our wire drawers experienced any severe shortage of the necessary dies. By very close cooperation with our American diamond die makers, their production began to incraese as to large-sized dies, and before many months had passed, six concerns which had never before drilled dies below 0.004″ were in actual production of 0.001″ dies. Today, these six manufacturers are producing, in small quantities, dies below 0.0008″! In one instance in particular, a perfect die below 0.0004″ was achieved. Most of the diamond die concerns succeeded in drilling dies down to 0.001″ without any financial aid on the part of the government.

OPM took upon itself the task of gathering all available information and studying the technological processes of the art of drilling fine dies, and thereupon disseminated it among those manufacturers who were eager to acquire the knowledge necessary for the manufacture of these dies. This active participation of OPM in the solution of the problem has been one of the chief factors contributing to the present output of fine dies, which, although limited as to quantity, approximate in quality the dies previously imported and sought after by the wire drawers. The wholehearted willingness of the diamond die manufacturers to risk their time, their money and their effort in the long-drawn-out experimentation also contributed substantially. Most of the firms which have proved ability to produce dies below 0.0015″ have now received, or are about to receive, financial aid from the government for the expansion of their present facilities and for the expenditures entailed in the training of new personnel. This last step is expected to accelerate production of fine dies and quickly bring it to the level of our total demands, which have increased considerably within the past several months and threaten to increase still further. As a matter of fact, the total consumption of fine dies between 0.0004″ and 0.002″ inclusive is presently at the rate of over 600 per month, and is expected to reach well over 1,000 by February, 1942.

The major problems facing OPM and the diamond die manufacturers in the clarifying of the requirements for the production of fine dies were:

(1) the selection of personnel with definite aptitudes;

(2) the grinding of the needle to proper shape and size;

(3) selection of proper diamond powder for drilling;

(4) mounting of the stone for drilling;

(5) amplitude and intensity for the reciprocating action of the member carrying the stone to be drilled;

(6) ability to observe by means of optics the drilling operation of the stone while in progress; and other practical considerations, such as speeds of the needle, prevention of vibration, etc.

The British Diamond Die Controller had produced a drilling machine embodying the solution of practically all of the requirements just mentioned, and OPM succeeded in arranging for the bringing to this country of a model machine together with the pertinent drawings and technical data concerning its use and operation. The principle of this machine has been discussed on several occasions with the group of manufacturers engaged in drilling fine dies; the machine has been exhibited to them, and considerable guidance has been furnished as to how the principles incorporated in the machine can be adapted to the existing horizontal-type machine in use here. Several copies of the new-type machine are presently being manufactured and will no doubt be in operation before this paper is read. Only last week, under the auspices of OPM, these new machines were set up in a demonstration model shop for the benefit of those diamond die makers who have succeeded in drilling dies below 0.002″ and who are judged capable of utilizing the new machines to the fullest extent.

Moreover, in attempting to determine the desirable speed of the needle in the drilling operation, speeds were used from 4000 RPM up to over 200,000 RPM, and it was ascertained from these experiments that approximately 6,000 RPM is the most practical and desirable speed.

Some manufacturers have succeeded in developing a practically automatic machine for drilling dies down to 0.002″ in mass production, and these machines are being used at the present time. The training of operators for these machines is a matter of only a few weeks.

At the instance of OPM, a mineral oil has been developed and perfected which has been found superior to the olive oil formerly employed, and it is now being used by many in the industry with very satisfactory results.

For the time being, consideration has not been given to either the type of stone selected for drilling, or the direction of the drill hole in reference to the crystallographic axes.

One of the most difficult problems in drilling dies is the back-piercing operation. The larger the die, the simpler the operation. For extremely fine dies, however, the back-piercing process is a difficult one. Usually, when the die is drilled from the entrance end, after the stone has been drilled to approximately two-thirds of its depth, the drilling of the remaining third is accomplished from the opposite end. The British Diamond Die Controller has developed for this operation a special device based upon optics and other mechanical contrivances, which enables the operator to center the die with great precision so that the axis of the back-piercing is coincident with the axis of the portion already drilled. This machine, too, has been made available in this country, and promises to be equally important.

The new technique of drilling triple-0 dies now at the disposal of our diamond die makers promises to obviate still another formidable handicap—that is, the training of new personnel. This has been considerably simplified, and it is our belief that properly selected operators can be trained to become skilled and expert within three months, as opposed to the many years of experience required by the European method.

The program described will definitely assure a more than adequate supply of manufacturing facilities and trained personnel for the satisfaction of the needs of American wire drawers, and will render this country independent of any outside source of supply.

It may be of some interest to present some of the data which has been obtained through the studies and experimentation so far conducted.

(1) The needle for dies below 0.002″ must be approximately 2 microns smaller than the die to be drilled. The drilling needle is made of the ordinary needle rod, and receives the same heat treatment as the ordinary sewing-needle.

(2) If the pressure or impact-force to be exerted by the tip of the needle is not to exceed 75,000 pounds per square inch of projected area, then for a 0.002″ needle a pressure up to 3.8 ounces should be applied. For a 0.0003″ needle, the pressure should not exceed 0.083 ounce.

(3) It was observed that for a needle approximately 0.0005″ in diameter, the wearing away of its length was 0.0015″ per hour, while the drilling of the diamond stone progressed at the rate of 0.0001″ per hour.

(4) (a) The natural frequency of vibration of the entire system must be below the operating speed of the spindle.

(b) With a needle approximately 0.020″ in diameter, having a freely exposed length of 1 inch, the natural frequency of vibration of the needle will be about 30,000 RPM.

(c) If the tip of the needle is 0.0003″ and the included angle is at least 10 to 12 degrees, the natural frequency of vibration of the tip will be considerably higher than that of the main body of the needle.

(d) The needle which was successfully run up to 200,000 RPM (by means of a small air-turbine) was 0.016″ in diameter, was exposed $\frac{5}{16}$ of an inch in length, and held in a babbitt bearing.

(5) With the conventional French-type horizontal drilling machines, out of every 100 dies to be drilled to 0.0004″ size, only 3 per cent are obtained of the proper size, while the balance go in increasing percentages up to 0.002″. With the microscope attached to the drilling machine produced by the British Diamond Die Controller, the operator is not only enabled to shape the needle to the proper size and then watch the progress of the drilling itself, but he is also equipped with means of making accurate measurements of the shape and diameter of the hole being drilled, since there is a scale on the eye-piece divided into spaces equalling 0.0004″. In this manner about 80 per cent of the dies are drilled to proper size.

(6) The diamond for fine dies is usually about $\frac{1}{5}$ of a carat, having a total height of 0.06″. The top and bottom are ground parallel. On the side a window is ground for observation purposes. The preliminary drilling is done on a machine designed to take large impacts; the fine drilling is done on the British machine mentioned previously. To obviate the necessity of centering the stone in absolute line with the needle, the stone is held by a lubricant (vaseline) between the stone and the surface to which it is attached. Proper grading of diamond powder is most essential and particles under 3 millimicrons should not be used, since they have no cutting properties.

(6) DIAMOND SET TOOLS

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In previous papers (1) presented before this Society the variation in hardness in the diamond with direction has been discussed. Because of this variation in hardness it is possible to cut and polish diamond crystals with diamond powder as the abrasive. It is also possible with the aid of another diamond to make a slit in the surface of the diamond into which the edge of a cleaving iron is inserted to cleave the stone. However, the direction of least hardness within a diamond is so much superior to the hardness of any other known substance that the question of the absolute hardness is dismissed for the purpose of this paper with the statement,—*because of its superior hardness diamonds possess the ability to readily cut all other known substances.*

It is proposed further to limit this discussion to shaped diamond tools whose contour conforms to specifications. These tools are formed from single crystals of the better grades of industrial stones. They are commonly used in two ways. First, to cut a predetermined contour into the material being worked; second, to cut a contour into the face of a grinding wheel which in turn is used to grind into the material a shape which is identical to the shape of the diamond tool.

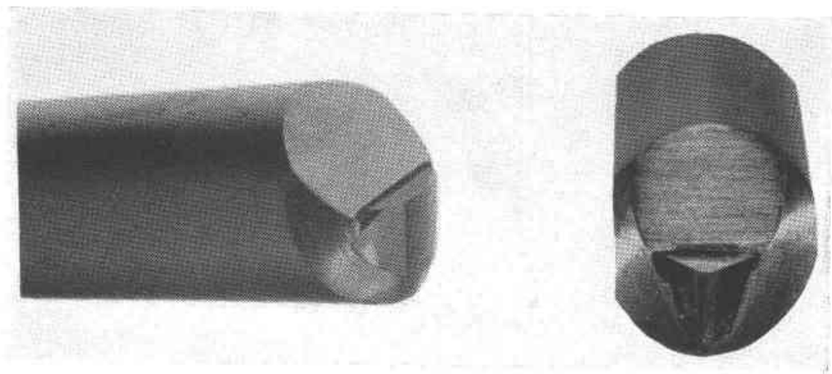

Fig. 1

The second method has been expanded into one in which a diamond point, following a templet, moves across the face of a grinding wheel and cuts into the face of the wheel a contour which is identical to that of the templet. The grinding wheel is then used to transfer the reverse of the same contour to the object.

In shaping a diamond crystal to conform to the specifications of the tool designer a knowledge of the variation in hardness with direction is necessary. Not only is a knowledge of the direction of least hardness necessary, but also the sense of that direction. In the cutting of gem diamonds certain empirical methods have been formulated which experience has shown to be the best direction for cutting facets. Because these facets are symmetrically disposed and have standard angular relationships to each other there are only a few fundamental cutting directions that must be known.

Although most diamond cutters use empirical methods in cutting gem stones, they are also familiar with the "grain." In the sense in which it is used by diamond cutters "grain" does not refer to the internal characteristics of the stone but to certain external growth markings upon natural crystal faces. The favorable direction of cutting is perpendicular to these markings. In most instances the cutter will know, too, the sense of this direction, but if not, it can readily be determined by trial and error. There is also, in many instances, a choice between two favorable directions one of which is markedly superior to the other.

Unlike gem diamonds the shapes of diamond tools are not limited to a few standard forms. Special operations call for tools with not only flat surfaces at certain definite angles, but also curved surfaces with specific radii of curvature (Fig. 1). A more thorough and fundamental knowledge of the variation of hardness with crystallographic direction is needed to shape diamond tools than to cut gem diamonds. One highly trained man can, however, direct the work of cutters who have the requisite amount of mechanical skill.

But of even more importance is the fact that this knowledge of hardness must be supplemented by a knowledge of the other physical characteristics. It is only possible to take full advantage of the superior hardness of the diamond and utilize its cutting qualities *when the cutting edge is so disposed that the diamond is least apt to rupture under strain.*

The ability of the diamond to resist rupture has been termed "structural strength." The structural strength of a non-crystalline substance is dependent upon its resistance to fracture alone, but in crystalline material gliding, parting, and cleavage may also play an important role.

The apparent fracture surfaces which occasionally appear upon diamond crystals are found, upon microscopic examination, to consist of a series of step-like cleavages. All evidence seems to indicate that fracture, as the term is used on quartz, does not occur on the diamond.

Nor is there any evidence of gliding in the diamond and the parting that may accompany it. The twinning that is observed can be referred to growth rather than gliding planes. Williams (2) has, however, interpreted polysynthetic twinning as being due to gliding although he describes simple contact twins as growth phenomena.

Growth twinning, following the spinel law, is very common upon the diamond. From the French glass industry the word "macle" meaning stirred (molten hard and soft glasses stirred together) has been taken and applied to diamond twins. When thin twinning lamellae are present, the cutters speak of them as "knots." These knots may be wedge-like portions within the stone which extend completely through the stone, starting at one side and wedging out in the interior, or exist as "islands" within the stone. Flattened stones are more likely to show twinning, with the twinning plane parallel to the flat sides. Rarely is the contact a true plane, but is more apt to be irregular. Sutton (3) refers to the vacillating character of the composition plane.

Because of the vacillating character of the composition plane there is no tendency for parting to take place between the two halves of the twin. In cleaving a twinned crystal the break proceeds regularly through the first member, but upon meeting the twinning plane will rupture the other member along one, or generally more than one, of the cleavage directions of the second.

The diamond possess an excellent octahedral cleavage and all evidence seems to indicate that breakage in industrial tools takes place along this cleavage. The dodecahedral cleavage is so much more difficult that it occurs only under exceptional circumstances.

The octahedral cleavage is perfect. In comparison with other minerals it is difficult. Our conceptions of the ease or difficulty of cleavage in minerals have been developed by working with large specimens. On the basis of comparable size of crystals, the cleavage in diamond is difficult. In cleaving the diamond it is first necessary to prepare a specially shaped groove to serve as a starting point and the process of cleaving consists of driving a metal wedge into this groove exactly parallel to the plane of cleavage.

In the opinion of some diamond cutters octahedral crystals cleave more readily than dodecahedral ones. They state that the more readily a diamond cleaves the more perfect will be the resulting surface. If we accept Buerger's concept of *lineage structure*, we should expect this, though the development of lineages within the diamond is less pronounced than in other crystals. Variations in crystal habit indicate differences in conditions under which crystallization takes place, and it might be concluded that variations in cleavability will be shown in diamonds from different sources. This affords an explanation of the preference which exists in the industrial diamond industry for Brazilian stones which more commonly show the dodecahedral habit than those from other localities. The evidence is incomplete and in any case such variations are not as important in shaping diamond tools as the proper crystallographic orientation of the stone so that rupture will be least apt to take place.

A proper design for a diamond tool should not only give the dimensional specifications, but should also give the orientation of the crystallographic directions of the diamond with respect to the cutting surface of the tool. This relationship between the crystallographic directions and the working surfaces of a tool has been discussed in a previous paper (4).

A basic consideration in cutting a gem diamond is obtaining the maximum weight in the finished stone. Most diamond crystals are distorted and the orientation of the cut stone is determined by taking into consideration the shape of the rough crystal. The strong tendency to carry this same policy over into the cutting of diamond tools and the reluctance to sacrifice weight for proper orientation accounts for some of the poorest diamond tools. The failure of the tools is then blamed upon the diamond rather than upon improper orientation. If the cutter has available a large inventory of rough stones from which to select a crystal for a specified tool, he can combine proper orientation with a minimum loss of weight.

The force applied at the cutting edge of a tool is only one of the factors that can cause failure. Strain will develop from differential temperatures which give rise to unequal expansion within the crystal, while the tool is in use. The high thermal conductivity and the low coefficient of thermal expansion of the diamond tend to minimize this factor. The following table gives interesting data at ordinary temperatures. No data are available for the temperature ranges at which cutting tools operate.

	Thermal Conductivity	*Thermal Expansion (linear)* per $^\circ$ C$\times 10^{-4}$
Diamond	0.35	0.009
Steel	0.14	0.110
Silver	1.00	0.188
Glass	0.002	0.090

Experimental evidence indicates that the diamond is but slightly affected by sudden or extreme temperature changes. Single crystals may be heated repeatedly to the highest temperature of the blast lamp and dropped directly into water. Crystals with incipient cracks may, in general, be subjected to the same treatment without breaking. Diamonds have been mixed with thermite which was then ignited. The diamond becomes imbedded in the metallic iron and seems none the worse for the treatment.

There is evidence that indicates that the wear which is shown by some diamond tools is the result of inversion to graphite. Diamond is the unstable modification of carbon at all temperatures above normal, under moderate pressures. At 900°–1000° C. the rate of inversion to graphite becomes perceptible. Under high pressure the diamond is the stable form. The greater the speed of cutting, and consequent higher pressure, the better a diamond tool holds its cutting edge.

In cutting material with a low thermal conductivity which is not ductile, as for example bonded silicates, the diamond may wear and develop a polished "flat" on the cutting edge of the tool. In such an operation the heat becomes excessive and the pressure on the cutting edge is not continuously uniform but oscillating. It is suggested that this wear may be due to the inversion of the diamond to graphite.

Although there has been a great increase in the use of shaped diamond tools in the past ten years there are still many industrial processes to which the use of diamonds might be efficiently and profitably adapted. The development of these new uses has been greatly retarded by a lack of knowledge of the physical properties of this very interesting mineral.

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(7) BONDED DIAMOND WHEELS

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Introduction

It is the purpose of this paper to describe a new and economically important development in the use of diamonds, viz., as the cutting constituent of bonded bodies employed in the finishing of tools composed of cemented tungsten and tantalum carbides. These hard materials known by such trade names as Carboloy, Widia, Firthite, and so forth, consist of the carbides in fine granular form bonded with a metal, such as cobalt. The mixtures are molded into shapes at high pressures and sintered in metallurgical furnaces. The furnaces must be carefully controlled with respect to the time-temperature cycle and the atmosphere obtaining in the furnace.

Cutting tools made of cemented carbides for shaping metals have proven so much superior to the tools currently in use that the demand for them in industry has grown to a phenomenal extent. It is the forming, shaping and re-sharpening of cemented carbide tools that made the development of bonded diamond wheels necessary.

It is true that wheels made with silicon carbide grain have been functioning, and are continuing to function, in certain types of application in this field. Despite their lower initial cost as compared with diamond wheels they possess certain disabilities which limit their use. Primarily, the disability of silicon carbide wheels arises from the fact that unless they are extremely free and sharp cutting they tend to produce cracking or checking of the cemented carbide being ground. To avoid this condition it is necessary to use wheels which wear rapidly and this in turn makes it difficult to maintain accurate dimensions of the carbide tool under "constant feed" conditions of grinding.

The growth in the manufacture of diamond wheels is shown by the following tabulation of relative figures. In this tabulation the production for the year 1936 is taken to be 1.

1936	1	1938	2	1940	5
1937	2	1939	3	1941	19

Manufacture of Diamond Wheels

Briefly the manufacture of diamond wheels proceeds as follows:

The diamond, which is crushing bort and mainly of Belgian Congo source, is purchased in the form of particles varying from approximately 1 to 5 carats each. The material is first fractured through a small jaw crusher, then further reduced in particle size in a steel ball mill using steel balls. The latter operation also serves to produce the desired shape of particle, viz., essentially wedge type with sharp edges and corners.

Sizing is done in a closed sieving system shielded from dust loss. This operation is not continuous since it is carried out on charges of definite weight. The grain sizes produced and used in diamond wheels vary from relatively coarse to quite fine particles, each grit number of which is accurately controlled as to uniformity.

The bonds used for diamond wheels are of two distinctly different types, viz., resinoid and powdered metal.

It must be stated that the wheels consist of centers, or preforms, made of metal or a resinoid molding composition and containing no diamond. The "diamond containing" material is present in the form of thin zones varying in thickness from $\frac{1}{8}$ to $\frac{1}{64}''$ for metal bonded and $\frac{1}{8}$ to $\frac{1}{32}''$ for resinoid. This zone is positioned either at the face (periphery) of the preform or at the side of the preform. The shape of the wheel and the use to which it is to be put governs the position of the bonded diamond zone with respect to the preform.

For each wheel the necessary weighed amount of diamond and bond is carefully mixed together and positioned in a heavy steel mold around the preform. The mold is then pressed to the desired pressure and the wheel removed by stripping off the mold. The wheel is then baked under controlled conditions to harden the resinoid bond properly, or to sinter and completely coalesce the metal bond.

Many sizes and shapes of wheels are made most of which fall into three classifications, viz., straight wheels, cut-off wheels and cup wheels.

Straight wheels are made up to 20″ in diameter.
Cut-off wheels are made up to 8″ in diameter.
Cup wheels are made up to 14″ in diameter.

Of perhaps singular interest to the mineralogist is the fact that the diamond used in all these products is substantially Belgian Congo bort, notwithstanding the fact that industrial diamond experts have declared it to be soft, weak and very inferior to mined South African bort and to Brazilian bort. Of course, their appraisal was probably justified inasmuch as they were considering bort in the relatively coarse lump form for such purposes as the trueing of grinding wheels, as wire drawing dies and for rock drilling heads. However, it was also claimed by some that the fine flours of Belgian Congo bort were useless in lapping and shaping industrial diamonds as well.

Our study of borts from the various sources led to the conclusion that the weakness of Belgian Congo variety was due to cracks, flaws, and other structural conditions which should be practically eliminated when the pieces as bought were crushed down to the desired relatively fine sizes. On this basis and to avoid paying premium prices for the other varieties, we standardized on bort consisting substantially of the Belgian Congo variety for wheel use.

Subsequently, carefully conducted laboratory tests on grinding cemented carbide with resinoid bonded wheels and with metal bonded wheels containing diamond grain from each of the sources verified and justified our conclusion. Recently we have been informed by two of the most important companies engaged in preparing diamond for industrial uses that they can and are successfully using Belgian Congo powders interchangeably with those of the other sources for shaping industrial diamonds.

Uses of Diamond Wheels

As stated previously the chief use for bonded diamond wheels is in grinding cemented carbide tools. In offhand grinding, using cup wheels, the metal bonded type is recommended for sharpening single point tools, for reconditioning excessively dulled or chipped single point tools, for grinding new "milled and brazed" tools and for grinding chip breakers. Cutting-off wheels are employed for cutting sintered carbide blanks to desired lengths, cutting rough semi-sintered blanks to desired shapes and sizes, and for salvaging chipped tools by cutting off the damaged portion of the carbide tip.

The metal-bonded type gives extremely low rate of wear. It is recommended for offhand grinding of tools where a liberal amount of pressure is used, where the carbide tips present sharp and narrow contacts which might prove destructive to the resinoid bonded type. Because of its harder and more heat resistant bond, the metal bonded wheel resists grooving or rounding of the corners to an exceptional degree. For the same diamond grit size a smoother finish and generally a keener cutting edge is produced with the metal bonded wheel than with a resinoid bonded wheel.

Diamond resinoid wheels are particularly suited for use in plants where carbide tipped tools are ground in large quantities, or on a production basis because its extremely fast cutting action provides the necessary rapid stock removal. They are also particularly suited to fixed feed, precision grinding operations such as cylindrical, surfacing, internal and cutter grinding.

While the first cost of the diamond wheel is necessarily high, appreciable savings in time and ultimate grinding costs result because it is very fast cutting and has an extremely low rate of wear as compared with silicon carbide abrasive wheels.

Additional savings in grinding time are possible with diamond wheels on multibladed tools such as milling cutters, broaches, and inserted tooth saws because of their ability to hold their size, i.e., progressive feeds can be applied to all inserts without leaving inaccuracies due to wheel wear. On tools of this class using silicon carbide wheels, the wheel wear is enough so that each blade or tooth after grinding must be checked separately for size.

Finally, because of the freer and cooler cutting action of diamond wheels the risk of checking or cracking the carbide tip is eliminated and this permits the production and commercial finishing of new, harder, and more sensitive grades of cemented carbides.

As may be expected from the development of such a novel product there has been much interest in possible applications to grinding of other materials and notable progress has been made. For instance, metal bonded diamond wheels are being used commercially for forming the special porcelain insulators of spark plugs.

Both metal and resinoid diamond wheels are being employed for slicing quartz plates used in piezo electric radio wave length controls. It is of interest to record that with a precision surface grinder using fixed feed, quartz plates 0.015″ thick are being cut from one inch square pieces maintaining parallelism between faces within less than 0.001″. The time per cut is less than 1 minute.

Metal bonded diamond laps of definite curvatures are being used commercially for rough grinding of opthalmic and instrument lenses. Lens edging is also being done with metal bonded wheels.

Also, consideration must be given to the use of diamond bonded wheels in the field of mineralogy and geology. At the meeting of petrographers engaged on industrial problems which was held at the National Bureau of Standards in May 1940, there was some discussion of the application of these wheels for cutting off specimens of hard minerals, rocks, and manufactured products as a preliminary step in thin sectioning and in the preparation of surfaces for mineralographic studies. At that time serious limitations were indicated and to a large extent these limitations exist today.

Briefly, the situation may be summarized as follows: in general, the constant pressure machines used by lapidaries and by mineralogical and geological laboratories for slicing work are not in very good condition from the standpoint of the precision required with diamond cut-off wheels. When mounted on such machines the wheels do not run true, they tend to wobble and are subjected to side grinding. Since they are relatively weak against cross bending stresses, breakage frequently occurs.

Precision grinding machines, on the other hand, are almost invariably of the fixed feed type and are of rugged construction. If a diamond cut-off wheel be mounted on such a machine, e.g. a tool and cutter or a surfacing machine, and if it be applied to the specimen using fixed feed with an increment of feed small enough to eliminate an excessive pressure, it is possible to use such a wheel with safety, precision, and with a good cutting rate on hard minerals. In our laboratories specimens of fused alumina abrasive, alumina boules for watch jewels, and boron carbide are regularly being cut off into thin plates with ease.

(8) EVALUATION CRITERIA

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The problem of the proper selection of a diamond for a specific purpose is indeed an important one for there is a large spread between the least and most valuable stones. An adequate evaluation of an industrial diamond must rest on an examination of its physical characteristics, for these determine its effective life. The most probable factors of importance are:

1. Hardness
2. Cleavage
3. Twinning
4. Flaws
5. Habit
6. Inclusions
7. Thermal properties
8. Color
9. Inversion to graphite
10. Aggregation of crystals other than twinning

These are not given here necessarily in the order of their importance because the order of importance may vary depending on the particular use.

Hardness is a crystal property. Different directions in a crystal may vary in hardness, but all crystals of the same substance should have the same hardness, provided there is no change in the chemical composition and there is no aggregation effect which conceals the true hardness. When certain diamonds are called *soft*, the term is erroneously used to describe lack of *strength*, or lack of *cohesiveness* of a crystal aggregate. According to Klein diamond dust made from inferior Congo crushing bort is just as effective as any other diamond dust. This evidence is substantiated by others in the diamond industry, and it lends strong support to the idea that diamond from whatever locality is about the same in hardness. The evidence also points to the conclusion that whatever strength or toughness properties are peculiar to certain diamonds are due not to inherent properties of the crystal, but to some other factor such as a lineage structure in the sense of Buerger's usage, or a larger scale aggregation. This will be dealt with in more detail later.

Cleavage is perhaps the best understood of all the physical characteristics of a diamond. Slawson has explained how to orient a crystal so that the cleavages will be least likely to develop. A visible cleavage plane within a stone is an obvious defect which diminishes the value of that stone for most purposes. But the failure and wear of all industrial diamonds probably comes about by successive cleavages of small particles and we must consider the effect on cleavage of other characteristics of the diamond.

The twin plane corresponds with the cleavage plane, and it may be a parting plane and, as such, a possible source of weakness. According to Slawson twinning is probably not caused by gliding.

Flaws are usually the loci of weaknesses in a stone. They may be irregular feather-like separations or negative crystal cavities, or incipient cleavages only partially developed. Small negative crystal cavities are not necessarily weakness areas of the stone. Since most industrial diamonds are flawed to some extent, one must examine the stones for the characteristics of the flaw, or its coincidence with cleavage directions, or the amount of strain caused by the flaw.

Inclusions are without doubt a locus of strain in a diamond. Few crystals containing inclusions fail to show strain phenomena around the inclusion when examined in polarized light. While it is true that a diamond may be mounted in a tool with the inclusion away from the working part of the diamond, yet the stone, if it has to be reset, will not perform so well when the inclusion is near the working part of the stone. When the strained part of an inclusion is bared, the stone is more likely to break because of the strain. Flaws and inclusions cannot be tolerated in dies, if they are close to the hole.

The color of a diamond crystal is said to have some effect on its suitability as an industrial tool. Many dark gray to black stones are excellent stones, but a defect might easily be masked by the opacity. Some of the dark colored diamonds are the result of a great many inclusions of graphite, or other material, and these too might be disadvantageous. But it is difficult to see how evenly distributed color, in itself, could lessen the toughness of a stone, and I doubt whether such color could be considered a disadvantage.

Many diamonds, on close inspection, are seen to be made up of subparallel aggregates of crystals; that is, the external planes, or cleavages, when examined, show deviations from a single plane. These deviations are sometimes a matter of less than a degree on such crystals as the Jaggerfontain or Brazil diamonds, or many degrees as in some of the so-called knotted stones. In the Brazil ballas the deviations are continuous and radial, producing the familiar rounded aggregate. Many Belgian Congo diamonds show a large deviation of many small units so that a granular effect is produced. There is some reason to believe that not only do we have these easily visible deviations from perfect development of the diamond crystal, but we also have to deal with microscopic failure of alignment, in the manner proposed by Buerger for other crystalline substances. The diamond is not peculiar in this respect—I believe most crystals larger than a few millimeters show more or less of the effect of subparallel growth.

This characteristic has a large influence on the strength of a stone and on its ability to withstand cleavage. Slawson states that the more readily a diamond cleaves, the more perfect is its cleavage surface. While such stones as the Brazil ballas and knotted stones cannot be used as shaped tools, they nevertheless are used as wheel dressing and trueing tools and are an important part of the total of diamonds used in industry.

For use as unshaped stones, we conclude that the so-called ballas is the best because of its heterogeneous orientation, which prevents any thoroughgoing cleavage from developing. For a similar reason, knotted stones or those showing obvious aggregation of a few individual crystals are also preferred. But this is not a universal rule, for certain diamond crystals, such as some Belgian Congos, show marked deviations from parallelism, but the units are small and granular and pull away from each other.

We have, thus far, enumerated certain characteristics which are advantageous or otherwise. Our criteria of selection must rest largely on the examination of stones in view of these characteristics, and in view of the uses to which the stones are put. In choosing a diamond for a shaped tool, an inclusion in one corner, which will be buried in the tool, is probably not serious and does not detract materially from the value of the stone. However, if the stone is to be reset, the inclusion may be detrimental. For diamond dies we must have freedom from flaws in the vicinity of the hole. For drills, a diamond must be tough and take heavy overall usage, so that the ballas or knotted stone is called for. A bearing must resist pressure and a stone without serious flaws and a single crystal must be used. Crushing bort can be the cheapest kind of available material without seriously detracting from its usefulness. For the dressing and trueing of grinding wheels a stone like the ballas is to be sought, or one having increased strength through subparallel aggregation.

It is, of course, impossible to get flawless and inclusion-free diamonds of just the right shape and size. These go to the higher priced gem uses. But we can grade the stones and choose the best available for the job, with these criteria in mind.

How is this grading accomplished? Many of you in this audience have handled diamonds so long that you have an intuitive knowledge of the good and bad stones, and their grading is a simple and easy matter. I have on a number of occasions consulted with members of a large local industrial diamond concern in an effort to learn what constitutes a good industrial diamond. The principal reason given by experts for choosing a good stone is that it is good because other similar stones have so proved. For some of us who are inexperienced (and it apparently takes a great deal of experience to pick stones on sight) there may be objective methods of approach.

Examination of flaws can be made with a polarizing microscope. The extent of the strain and the incipient cleavages can be seen under low magnifications. Inclusions can likewise be quickly examined in this way.

The determination of the degree of subparallelism can be most quickly accomplished by the use of a simple reflecting goniometer. A parallel light beam reflected from a cleavage surface or a crystal face will show the extent of the deviation. Usually, however, a qualitative estimate of the subparallelism can be obtained by observation under a binocular microscope. More elaborate techniques are available, such as x-ray Laue diffraction patterns, but these are too time-consuming for general use, although they may be profitable when larger stones are to be examined.

Stones of more brilliance than usual are generally considered tougher. This brilliance may be the result of subparallelism on a microscopic scale, but this needs a careful investigation for verification.

Many of the points discussed may seem obvious and rather academic to the expert in these matters, but it must be remembered that some of those who are now asked to pass on the qualities of stones cannot fall back on long experience as a guide, and, as time goes on, others also will be asked to help in the selection of the ever-increasing quantities of diamond used in industry.