DIAMOND AND GEM STONE INDUSTRIAL PRODUCTION

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by

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INTRODUCTION

The increasing use in industry of the harder natural and synthetic substances involves greater need for knowledge of the methods and machinery by which these materials are brought to their final shape.

It is well known that hardness (a specific property of solid material which has hitherto escaped a scientific definition) increases the difficulties of machining; on the other hand, a hard component maintains its given form, even when subjected to stress and continuous use, compensating for the great difficulties and the care necessary for proper shaping. The high cost of both the raw material and its machining lead to the production of very small components, the dimensions of which have to be kept to close tolerances. Eyeglasses and microscopes are therefore indispensable equipment.

In the methods of production used there are two main difficulties. These are the intrinsic hardness of the raw material and the necessity of machining to close limits. Both of these have to be considered in the light of economic results. As a matter of fact, all operations in the shaping of very hard materials are lengthy, although modern machinery can shorten productive and non-productive times considerably. The use of semi and fully automatic machines has been restricted to a few examples, but other methods, such as the simultaneous machining of several stones, or the operation and supervision of several machines by a single operator, exist, by which production can be increased.

It is the idea of the author and publisher to bring before the public a general survey of modern methods of machining, i.e. splitting, cleaving, bruting, grinding and polishing, of flat and curved surfaces including holes. Nearly every book dealing with gem stones contains a chapter on cutting and polishing these substances, but even then the matter is sparse. In the present book all available experience has been carefully sifted and systematically arranged, and the author hopes to have made some small contribution to a more systematic and scientific treatment of the art of cutting and polishing hard materials. The expert in this field must not expect his knowledge and experience to be widely enlarged by the description of revolutionary methods and new equipment; but he will find some methods and ideas mentioned which will help him in his daily work and avoid costly experiments.

Most methods for machining diamonds and other gem stones have not changed for a long time, passing from one generation to another. They have proved to be of great assistance in machining synthetic materials produced during recent years, which to-day are of great importance. Based on these considerations, besides the minerals, diamond, sapphire (corundum), and agate, considered as those applied to commerce and industry, there have also been included in the appropriate places the newer synthetic materials of great hardness, boron carbide, silicon carbide, and aluminium oxide, and the metal carbides such as tungsten carbide, titanium carbide, and the sintered products produced from them. It is hoped that these remarks will increase the usefulness of this book for those engaged on production.

The material in this book is based to a large extent on the traditions of craftsmanship. The full application of modern technique (electric motor, infinitely variable speed regulation, high spindle speeds, interchangeable manufacture, modern gauging methods and measuring instruments) has been made in this field only during recent years, and experiments are still in progress. Unfortunately, some of them are still considered secret and are not for publication.

Only recently, scientific investigations have been commenced on the relative value of abrasives, the nature of polishing action, surface roughness, and so forth, and whenever possible reference has been made to these results. Some of the results are in close conformity to what the craftsman has already found. It would be helpful if such research could be carried out on a larger scale in order to help the industry in the adoption of improved working conditions.

When collecting the material for this book the author decided to deal with the special branches of the industry, such as diamond cutting and grinding, polishing of semi-precious gems, and the manufacture of watch and pivot bearings. To avoid repetition, the basic operations have been dealt with first, and then, in another part, some idea of the organization of the special industry has been given. Nevertheless, each chapter has been made as self-contained and independent as possible.

The author thanks numerous British and continental firms as well as experts for their advice, in particular the publisher, Mr. Arthur Tremayne, for his active part in suggesting this publication as well as his great care in preparing the book.

PAUL GRODZINSKI

PUBLISHER'S NOTE

Arthur Scott wrote in 1889: "*Nearly two hundred years ago Englishmen were the first diamond cutters in the world, and the trade was nearly all carried out in London. At the present time, old English-cut diamonds will always fetch a very high price as the cutting is still so much valued.*"

It is appropriate to quote this historical statement and to emphasize the fact that the present work makes its appearance at a time when efforts are being made to revive the British industry of diamond and gem stone cutting.

Recent attempts to establish the industry in Great Britain, notably in the 'eighties and during and immediately after the 1914–1918 war, failed for various reasons, principally because the almost total lack of authentic technical literature meant that only empirical methods of production were followed. Traditional tool design and handicraft may maintain an industry which is existing and prosperous, but technique, founded on a scientific structure, is required for the rapid establishment of a skilled industry in entirely new surroundings.

Diamond and Gem Stone Industrial Production aims at bringing progressive ideas to those concerned by carefully sifting and presenting both the old and new methods of production. Only with a technique and equipment constantly developed and improved will it be possible to compete in the world market. In modern industry the degree of mechanization has proved to be decisive.

The general lines of research and development initiated in this book will be followed in the *Industrial Diamond Review*, a monthly journal with which the author is connected in a consultative capacity.

I

GENERAL METHODS

CHAPTER I

TECHNOLOGY OF MACHINING METHODS

In the first part of this book the basic methods for machining harder materials and for obtaining a high surface finish on them will be described in the order of their application; the exact description of the various operations for one complete production will be given in a second part.

The basis of all these machining methods is to have a material which is harder or at least as hard as the material to be machined. Distinction must be made between three principal methods:

(*a*) The use of one or more stones which cut by means of their sharp edges and their structure, other substances which may be of lower, or sometimes of equal, hardness.

(*b*) Loose powder of a crushed substance exerting a grinding and also a polishing action by being partly held and partly loose in a softer material.

(*c*) Powder of a crushed substance is embedded (hammered or sintered) in a relatively soft material, so that the exposed sharp edges can exert a grinding and polishing action.

In the case of the various industrial applications of the diamond and other hard abrasives, use is made of the same principles, but the description of these do not come within the scope of this book.

The action under (*a*) can be considered as a chip-producing or cutting action, as in addition to very fine chips, larger particles are also broken away. Examples of this are the drilling of holes in softer stones, such as in agate and sapphire by means of diamonds, and the bruting of diamonds and the preparation of diamonds for cleaving.

The most frequent application is that referred to under (*b*), using a "loose" powder for grinding and polishing purposes. The material for embedding abrasive grains, such as metal and in some cases even wood or leather, serve only as the bearer of the grain and are selected according to the particular purpose. For piercing and polishing of holes, steel and wooden needles are used, whereas for grinding and polishing of flat surfaces lapping discs of cast iron or steel respectively softer metals are employed.

With reference to (*c*), the grinding effect can be smaller or even larger than in the case of method (*b*). In any case a higher economy in the use of abrasive material would be obtained if all abrasives embedded in the base material could be utilized; this is seldom the case, so that, generally, the operation with bound grain is considered to be more expensive. No final conclusions can be drawn as some of these methods, for instance, grinding arbors for engraving, grinding and lapping wheels of special form for lapping hard metals and special sawing discs, have only been recently introduced.

When considering the problems of machining very hard materials, the following influencing factors have to be taken into consideration.

(1) Very high grinding speeds and perhaps somewhat lower polishing speeds;

(2) Comparatively slow relative or auxiliary movements for changing the direction of attack;

(3) A certain elastic and constant pressure;

(4) Selection of the size of grinding and polishing grain;

(5) Lubrication of the grinding surfaces; and

(6) Type of "bearer" material for "loose" and "bound" grain.

As far as (1) and (2) are concerned, Table 1 gives a short review of the usual grinding and auxiliary speeds when machining diamonds and gem stones. As will be seen, relatively great variations exist in the usual values. This may result from differences between newer and older values and to the equipment used and its condition. By the application of modern methods in the support of shafts as well as by damping and suppression of vibrations, it may be considered possible to apply higher speeds. In several

TABLE 1—COMPARISON OF USUAL WORKING SPEEDS

	Effective Diameter,* inches	Main Movement		Auxiliary Movement		Notes
		R.P.M.	S.F.P.M.	R.P.M.	Ratio Main to Auxiliary Movement	
DIAMOND						
Sawing	2⅜–2¾	2,500–4,500	1,800–3,250	—	—	Phosphor-bronze disc prepared with diamond dust
Bruting surfaces	(⅛)*	800–1,000	80–100	—	—	Working diamond
Bruting holes	(0·04)	2,000–3,000	20–30	—	—	Working diamond
Bruting with reciprocating movement	—	40–100	—	15–20	2·5–6·5	Working diamond
Piercing with reciprocating movement	(0·02)	7,000–8,000	35–40	500	14–16	Steel needle provided with diamond dust
Grinding surfaces	8–10	2,200–2,500	4,500–6,500	—	—	Cast-iron surface prepared with diamond dust and olive oil
Polishing surfaces	10–12	2,200–2,500	5,500–7,500	—	—	
Polishing holes with reciprocating movement	(0·02)	2,000	10	400–500†	4–5	Steel needle provided with diamond dust
Polishing holes with reciprocating movement and oscillation	(0·02)	2,000–3,000	10–15	500 and 500†	4–6	
GEM STONES (MOHS'S hardness above No. 8)						
Sawing—Mud-saw	8–12	300–450	625–1,425	—	—	Steel blade, lubricated by mixture of water and silicon carbide
Sawing—Diamond-saw	8	2,900–3,800	5,800–7,600	—	—	Diamond dust bound in metal
Grinding—Preparing	12–24	300–500	800–3,000	—	—	Silicon carbide vitrified wheel
Sanding	8	1,000	2,000	—	—	Wheels with abrasive paper or cloth
Polishing	10	1,000	2,600	—	—	Bronze disc } Prepared with diamond dust
Lapping	10	> 1,000	> 2,600	—	—	Tin-zinc alloy }

* The values in parentheses are rough estimates and introduced for comparison purposes.

† Oscillations per minute.

instances, however, it has been found that better results are obtainable with lower speeds. An open question is the problem of polishing action, whether a higher or a lower speed would be the more amenable. As a matter of fact, lower speeds are used for polishing holes than for drilling them.

So-called relative or auxiliary movements are necessary to obtain high-grade surfaces in which all traces of the abrasive substance are avoided. For the more accurate surfaces, for instance, plane surfaces are obtained when the direction of attack is changed. In the case of the diamond, special directions (cutting grain) exist in its surface in which the action of the abrasive is higher. Usually, the diamond cutter adjusts the crystal to the surface of the grinding wheel in the best cutting direction, an operation which requires high skill and experience, particularly in the case of stones of complicated crystal structure. It is a new idea to change continually by auxiliary motions the direction of attack, so that diamonds can be cut satisfactorily without special consideration of the direction of the grain.* This problem will be discussed more extensively in the paragraph dealing with cutting and polishing.

With reference to (3), a main point in these machining operations is the distinct pressure which has to be exerted between the stone and the cutting tool. If this pressure is exceeded, the stone may be damaged or the tool attacked by the stone; this happens particularly in the case of diamond grinding, where the grinding and lapping wheel becomes scored. Thin diamond sawing blades can collapse, and the stone will be torn out of its holder. If too small a pressure is exerted then, eventually, vibrations start; on the other hand, too high a pressure can cause the same phenomenon. In the case of vibrations—small jumps at regular intervals—the contact between stone and disc is momentarily removed so that the cutting and grinding action stops.

Therefore, in nearly all cases of machining hard materials, the pressure between stone and abrasive substance is exerted

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* A special reciprocating lapping movement is applied in finishing diamond facets, see p. 92 and in lapping hardmetal tips, see p. 220.

by means of a weight (grinding and polishing of diamonds, sawing), spring pressure (piercing), or elastic hand pressure (bruting, drilling, grinding, polishing, and sawing of gem stones). There exist only a few instances where a mechanical feed by a feed screw is applied; a machine operated feed, as in the case of the machining of metals, has not yet come to the knowledge of the writer.

Too high a pressure will also cause an excessive heat. This is dangerous for diamonds held either by cement or soldered, and in the case of mechanical clamping the convection of heat owing to the small contact between stone and holding metal causes difficulties. Therefore, when the diamonds become too hot they are frequently dipped into water. Industrial stones of more vigorous structure can be dipped directly into water, but this is not advisable for stones of gem quality which must be dipped slowly and carefully. In the usual range, a steady increase of abrasive action can be expected by increasing the pressure. This is shown in the tests of Kruel (Fig. 3) and Drache (p. 32), to which reference is made later on.

FIG. 1.—Increase in the size of facets during cutting
(A) Initial stage
(A′) Increase in the size of facet and therefore reduction of the applied specific pressure

It is interesting to note that in the case of grinding facets from a circular or ball-shaped stone, the exposed surface increases (Fig. 1); therefore the specific pressure, a constant weight assumed, will be reduced during the grinding operation. In some U.S.A. patents special devices are described which are claimed to provide an equal specific pressure in spite of the increasing size of the facets.

In factor (4), the selection of the size of grinding and polishing grain, the size of abrasive grains determines the abrasive effect and the surface quality of the finished component. For real abrasive action, i.e. for removing a distinct layer of material as well as for cutting the material by sawing, diamond grains and other abrasive substances with grit sizes nos. 80 to 120 are recommended. For finishing and polishing finer grits up to nos. 400 and 600 are used (see further, p. 122). The applied grains should be nearly uniform in size to avoid scratches. In the case of grinding with "loose" grain the size of the latter must be adapted to the size of the pores in the holding material.

Abrasive action is greatly influenced by what is called the hardness of the crystal. The expression "hardness," when used by lapidaries and gem cutters, means that one stone is more difficult to cut than another with the usual appliances and speeds. These workers have evolved a fine feeling for any difference in the "hardness" of their customary materials, but this is only a subjective method; any variations in the size of grain, the preparation of the wheel or bond, the rotation speed, etc., will influence the abrasive action and therefore the "hardness."

The extent of hardness (from the point of view of resistance to abrasion) has frequently been investigated by determining the loss of material when exposed to the grinding action of a distinct abrasive material. In this way the well-known comparison figures of Rosival have been determined (Table 2, p. 29). These figures, however, are of only theoretical interest.

The diamond is not only the hardest known substance, but has also the highest abrasive action. This has recently been expressed by A. J. Schroeder, dealing with the lapping process of metals: "Lapping abrasives should have an adequate 'biting.' Diamond dust does not break up, nor blend even after heavy service, and is therefore the best of all abrasives." The diamond is succeeded by the recently developed boron carbide, which has a similarly high abrasive action; this substance is now sometimes used together with diamond or silicon-carbide powder.

Recently a series of tests with regard to the abrasive action of different substances have been carried out under more practical conditions. The results may be extremely useful

TABLE 2

COMPARISON OF HARDNESS VALUES

Relative values of hardness (corundum 1,000)

Table partly according to Landolt-Börnstein

	Mohs (about 1820)	Franz (1850)	Pfaff (1874)	Auerbach (1891–96)	Rosival (1892)	Jaggar (1897)	Knoop (1939)	Ridgway (1933–34) (Scratch Hardness)	Ridgway (1933–34) (Wear Resistance
Gypsum	2	—	14	12	0·3	0·04	19·5	—	—
Rock-salt	2	—	20	20	2·0	—	—	—	—
Calcite	3	13·5	23	80	5·6	0·26	82·7	—	—
Fluorite	4	54	56	96	6·4	0·75	100	—	—
Apatite	5	235	141	197	8·0	1·23	220–263	—	57
Feldspar (moonstone)	6	392	310	210	59	25	300	339	131
Quartz	7	667	390	268	175	40	434–483	472	171
Topaz	8	843	705	456	194	152	766	523	160
Corundum	9	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
Diamond	10	—	—	2,170	140,000*	Greater than 1,000	4,890–5,180	—	—

* According to later investigations 90,000.

for practical work, in spite of the fact that they reveal nothing new to the expert. The main point is that the abrasive action of a distinct substance can only be considered in connection with the material to be ground. Tests have been carried out under the same conditions in which drawing dies are polished. This process includes, of course, the enlargement of holes. The Pohenkra machine (Figs. 140 and 141) has been employed in these tests, the stone rotating at 400 R.P.M.; the needle being stationary. In plates of about $\frac{1}{8}$ inch (3 mm.) thickness holes of 0·08 mm. in diameter, enlarged to 0·12 mm. at the top, have been polished with a steel needle. The grain size of the abrasive powder used (Table 3) was between 0·01 to 0·22 mm., and was kept between these limits by a special separation method.

Each abrasive substance has been tested on five different holes, and on each hole successively four enlargements were measured. The average value of twenty different tests should be considered as reliable. Table 3 shows an extract of the results in which the abrasive action of the diamond on a diamond drawing die, a hard metal drawing die, a hole in a synthetic ruby, and a plane surface on a synthetic ruby was set equal to one hundred. The three other hardest abrasive substances—boron carbide, crystalline boron, and silicon carbide—show on diamond surfaces only about $\frac{1}{200}$ of the action which the diamond performed. This would mean that for obtaining the same results with regard to grinding action, expressed by the removed material, the operation time has to be extended two hundred times. When grinding materials of less hardness, such as hard metal alloys or synthetic gem stones like ruby, the abrasive action is much increased without competing with the diamond. Boron carbide shows in these cases improved qualities, compared with the hitherto unmatched silicon carbides; its abrasive action is, according to the given table, about three to four times that of silicon carbide. Therefore, it may prove to be quite a reliable abrasive substance for the grinding of hard metal, in particular of hard metal drawing dies.

TABLE 3

COMPARISON OF THE ABRASIVE ACTION OF VARIOUS GRINDING MATERIALS*

Abrasive Material	Diamond Drawing Die Hole	Hard Metal Drawing Die Hole	Synthetic Ruby Hole	Synthetic Ruby, Plane Surface	Glass
Diamond grain	100	100	100	100	—
Boron carbide (B_4C)	0·5 (0·6)	60	66	70	—
Crystallized boron	0·5 (0·2)	48	—	—	-
Silicon carbide	0·5	22	17	—	100
Aluminium oxide	—	4	—	—	66

* W. Dawihl, K. Schroeter and M. Stockmayer, *Zeitschrift d. Vereins deutsch. Ingen.*, vol. 80 (1936), no. 33, p. 1001 further, W. Dawihl and O. Fritsch, *Schleif-und Poliertechnik*, 1937, no. 1, and 1938, no. 9.

TABLE 4

RESULTS OF THE GRINDING ACTION OF DIFFERENT GRINDING WHEELS

(Removed material for a speed of 3,000 r.p.m. test time one minute)

	Enamel of Tooth, Pressure, 50 gr.		Enamel of Tooth, Pressure, 100 gr.		Ivory, Pressure, 100 gr.	
	Sq. cm.	Per cent	Sq. cm.	Per cent	Sq. cm.	Per cent
Diamond impregnated wheel* ..	0·035	100	0·061	100	0·0958	100
Grinding wheel†	0·0086	24·5	0·0176	29	0·0286	30
Grinding wheel‡	0·0116	33·2	0·0214	35	0·0056	58·5

* Diamond bound by a special electro-plating process. † Assumed to be aluminium oxide.
‡ Assumed to be silicon carbide.

Further interesting comparison tests with diamond grains (not powder) bound by an electro-plating process are due to W. Drache. They show similar relations between diamond, aluminium oxide, and silicon-carbide wheels when grinding enamel of tooth and ivory (materials only of Mohs' hardness no. $2\frac{1}{2}$). The results of these tests are shown in Table 4. They indicate that aluminium oxide wheels have only a quarter to one-third of the action of diamond wheels, whereas the action of silicon-carbide wheels is between one-third to about two-thirds that of diamond wheels. The given figures also show clearly the influence of the pressure between tool and work piece. In the case of doubled pressure, the action of the diamond wheel was increased by 75 per cent, that of the aluminium-oxide wheel by 105 per cent, and that of the silicon-carbide wheel by 84 per cent; this means that the grinding action was nearly proportional to the applied pressure, a fact also shown by some of the tests by Kruel.

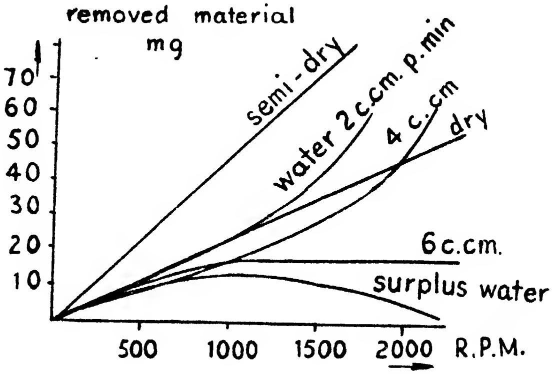

FIG. 2.—Influence of the cutting speed and type of lubrication on the abrasive power of discs into which diamond dust is rolled (according to Kruel)

On the question of the lubrication of the grinding surfaces (5), diamond dust is usually mixed with a pure fine olive oil to a paste. Other abrasive materials, such as silicon carbide, are only mixed with water, and in the case of sawing, a small amount of clay for increasing the consistency is added. Wheels in which diamond is bound are used either dry, wetted, or in a wet state. It has not yet been decided in practice which method is the best, and tests made by Kruel indicate the complicated nature of this process. Fig. 2 shows the amount of abraded material in relation to the speed of rotation and the applied amount of lubrication fluid (water).

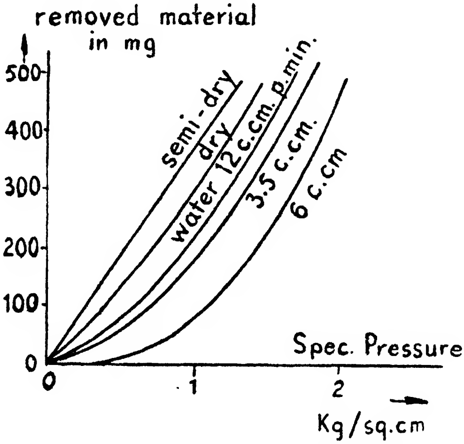

FIG. 3.—Influence of specific pressure and type of lubrication on the abrasive power of discs into which diamond dust is rolled (according to Kruel)

This indicates that with an increasing amount of water the abrasive action is reduced, and that in the case of water in excess of a distinct speed the abrasive action drops and is even reduced to nearly zero. There remains the open question of whether this may not be caused or at least influenced by vibrations. The abrasive action with a water supply of 6 c.cm. (0·36 cub. inch) remains constant over a long speed range. The highest values are obtained when the wheels are provided with a little moisture, giving at a speed of 1,000 R.P.M. 100 per cent more action, and 1,500 R.P.M. about 65 per cent more, than in the case of cutting dry. Fig.3 shows the abrasive action in relation to specific pressure. Here again in the wetted state a higher abrasive action has been obtained than in the dry or fully wet state. The curves for distinct water supply are of parabolic shape, indicating a higher abrasive action with increased pressure. This fact is not in conformity with the usual experience of grinding action actually being reduced in the case of too high a specific pressure.

On the question of (6), the type of "bearer" material for "loose" and "bound" grain, the abrasive action in the case of both types is very much influenced by the material used to hold and retain the abrasive, in spite of the fact that it does not participate in the grinding action. In the case of loose grain, the size of surface pores must be adapted to the size and shape of grains. The material must neither be too soft nor too tough and hard. If it is too soft, it wears down quickly, and if it is too tough eventually it will not expose the grains satisfactorily. Therefore, for cutting and polishing diamonds a relatively porous cast iron has been found to give the best results, whereas for the grinding and polishing of softer stones, laps of copper, bronze, tin, zinc, or even lead are used. The abrasive substances are emery, aluminium oxide, silicon-carbide, boron carbide, or diamond,

With regard to diamond grain bound in a bearing material, the usual vitrified bond used for grinding wheels, with aluminium oxide or silicon carbide as abrasives, has not yet been used in practice for diamond grain; a resinoid heat bond, a binding in metals by hammering or sintering, on the other hand, has proved satisfactory. No clear opinion as to the most suitable binding metal exists, and while some experts recommend relatively soft metals, such as copper, cobalt and iron, others recommend sintered carbides with only a little binding metal. It is stated in the latter case that these metals possess a holding power for the diamond grain which corresponds to its abrasive action. The hardness and resistance to wear of the metal is said to prevent the binding metal becoming plastic during working, and therefore the abrasive grain will not be covered by the smearing metal. Special hardmetal alloys have been evolved for this purpose

Table 5

ABRASIVE ACTION OF DIAMOND EMBEDDED IN DIFFERENT MATERIALS*

(*According to Kruel*)

Diamond grain embedded in—	Abrasive Action			Tensile Strength		Brinell Hardness	
	Mg.	Ratio	$\sqrt{\text{Ratio}}$	kg./sq. mm.	Ratio	kg./sq. mm.	Ratio
Aluminium	20	1	1	9	1	30	1
Copper	90	4·5	2·1	24	2·7	40–50	1·3–1·6
Cast iron	250	12·5	3·5	20	2·2	190	6
Steel St. 37	400	20·0	4·5	37–45	4–5	100–125	3·3–4
Steel St. 70	1,000	50·0	7·0	75	8	210	7

* Comparison ratios, tensile strength and Brinell Hardness added by the author.

which are even suitable for producing a high polish on hard surfaces.

Kruel found in the case of diamond grains embedded by hammering in steel surfaces that the abrasive action did not remain constant, but was reduced according to an exponential law. But by changing the position of the still embedded diamonds by scratching, so that new sharp edges were exposed, it was possible to increase to more than double value the abrasive action. He obtained his best results with a material of considerable hardness but enough toughness to detain the diamond grain. He stated that discs of a high-grade steel provided the best results (Table 5).

Interesting microscopic investigations on copper grinding wheels in which diamond dust has been embedded by a rolling process have been carried out by E. Klüppelberg.[1] They have a short durability and high diamond losses. The following conclusions on the action of these wheels could be drawn:

To ensure economical grinding, wheels of this kind must be absolutely smooth and further roughed by means of a tool producing ridges in the surface, the size of which has to correspond to that of the applied diamond grains. With progressive use of the disc, the condition of the effective grinding surface, and therefore its economy, changes, as:

(*a*) the single grains of the abrasive adjust themselves with one face parallel to the surface of the disc; this is usually a surface produced by splitting action;

(*b*) the surface layer of the disc is changed during the grinding process.

Both phenomena require the abrasive grain to be fixed in a hard and tough metal. Owing to the grinding pressure all grains which are not sufficiently strongly fixed are removed from the disc; these are both the smallest and the largest

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[1] E. Klüppelberg, *Metallschleifscheiben mit eingewalztem Diamantkorn und die Aenderung ihrer Schleiffläche durch den Schleifvorgang, Mitteilung aus der Fachschule für Diamant-, Edelstein- und Goldschmiedeberufe, Idar-Oberstein Werkstatt und Betrieb,* no. 23/24, pp. 300–304, 1939.

particles of the usual diamond powders. Therefore, and also in the case of bound grain, by rolling (or hammering), an abrasive of nearly uniform grit size is demanded, besides a uniformly roughed surface.

DIFFERENCES BETWEEN WORKING METHODS

As already pointed out, only three different technological methods can be distinguished in the machining of hard materials, i.e. (*a*) hard materials firmly embedded or held, (*b*) "loose" powder, and (*c*) "bound" powder. While the tools have to be adapted in their shape, purpose, and speed to the special process, the principles remain the same. Thus sawing is really a grinding operation, only that the abrasive powder is placed on the edge of a thin disc, whereas in the case of grinding and polishing, the abrasive substance is placed on the face of a disc.

The names of different processes are usually no indication of their technological principle. For instance, under the term of "cutting" of diamonds and other gem stones, grinding by loose abrasive grain is sometimes meant, and sometimes the bruting carried out by another diamond. Cutting and polishing (lapping) are carried out in the case of the diamond on the same wheel and the same machine, while it is generally understood that in the case of polishing, only the appearance of the surface has to be improved. In die production, polishing machines are utilized to enlarge the holes. It may be objected that these differences are insignificant, but, by using expressions which are not clear, it is difficult to understand the basic principles.

In the trade a great difference is made between diamond cutters working exclusively in diamonds and lapidaries working on other stones of less hardness. This distinct division will not be strictly continued in the subsequent paragraphs of this book as the working methods are very much related, while several methods will be mentioned which are outside the range of both these industries.

CHAPTER II

DIVIDING OF DIAMONDS AND GEM STONES

THE division of stones is necessary for several reasons. Large stones have to be divided into smaller ones before further machining. In order to obtain distinct shapes and forms some parts of the stones and flaws as well as inclusions must be removed. Differentiation must be made between the methods of:

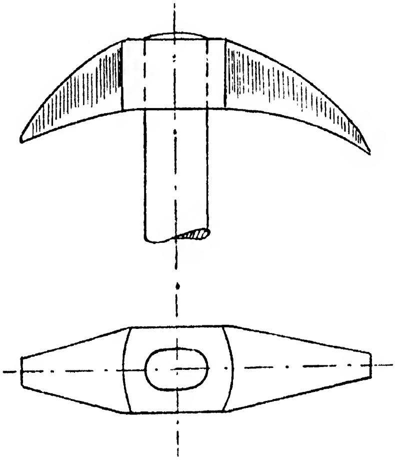

FIG. 4.—Shape of a chipping hammer for semi-precious stones

(*a*) chipping, splitting, and breaking;
(*b*) cleaving;
(*c*) sawing.

Small projecting parts and flaws can eventually be ground away, but for larger portions this would mean a long job.

(*a*) Neither chipping, splitting, nor breaking are used for stones of higher value, in spite of the fact that chipping or splitting sometimes occur accidentally in the machining or handling. Semi-precious stones and amorphous substances frequently obtain their rough shapes by the chipping and breaking process. A piece of agate, for instance, with bad spots, cracks, and so forth, is at first chipped into suitable pieces by means of a special hammer (Fig. 4). Great skill is necessary to divide the stones correctly. The carbon (carbonado) or black diamond, the amorphous variety of the diamond which is found in relatively large sizes, is frequently broken by a steel die in hand-operated presses (Fig. 5), in order to be suitable for use as an industrial diamond.[1] These split carbons are sometimes preferred to natural stones, as they have better working edges.

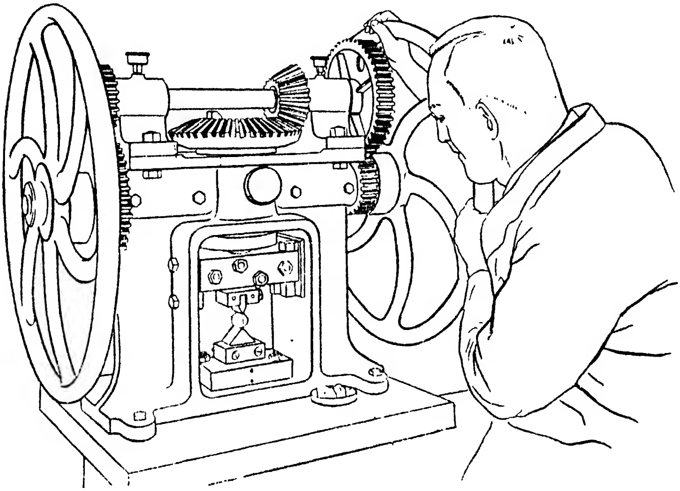

FIG. 5.—Breaking of carbons in a special hand-operated press; similar presses are used for other gems

Crushing diamonds and other hard materials into small sizes to make them suitable for grinding and lapping can be considered as another method in this range; the methods applied will be treated in the paragraph on diamond dust.

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[1] The same principle is also applied for breaking softer stones, as in the production of mineralogical specimens. Pliers of soft iron, so-called nippers, are occasionally applied to break off the edges of semi-precious stones, they are extensively used for preparing glass lenses.

(*b*) The process of cleaving is only applicable to crystalline substances with distinct cleavage planes, equal to the most perfect crystalline and machined surfaces.[1] From the crystals used for ornamental and industrial purposes, the diamond is in possession of this special property, and use can be made of it for dividing purposes.

The diamond octahedrons, which can be assumed to be the basic crystalline formation, can be cleaved parallel to all octahedron surfaces, i.e. in four directions; this fact is shown diagrammatically in Fig. 6. Sutton has detected another cleavage direction on diamonds which has hitherto not been used in practice. In the case of a diamond cube, the cleavage planes are parallel to the inscribed octahedron, i.e. the cleavage planes truncate the edges of the cube. In the case of a rhombic dodecahedron the cleavage planes are so situated that they go through the three four-pointed corners and truncate the three-pointed corners.

Cleaving diamonds seems to have been an art understood

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[1] The nature of cleavage planes is extensively described by Tutton in his book on Crystallography (1922), page 527: "From the foregoing it will have become clear that cleavage is not a mere tendency to fracture with production of two more or less plane fracture-surfaces, one on each of the two separated fragments, and along an approximately definite direction.

"Cleavage is much more than this, namely, the facility for splitting along an absolutely true plane, having an orientation within the crystal definitely fixed to one or two minutes of arc, and which definite direction is identical with that of an important face of low indices, very often a primary one, to within the same minute limit of accuracy as natural faces exhibit when grown undisturbed; and the plane surfaces of fracture are endowed with the same high degree of natural polish as the best formed faces, and afford equally sharp and brilliant images of the signal-slit of the goniometer. . . .

"Moreover, compared with the facility for splitting along the cleavage plane or planes, the crystal usually offers relatively enormous resistance to fracture along any other direction, and when it does occur the fracture is very irregular, and indeed is very frequently stepped or zig-zaged, the steps or zig-zags being composed of an alternation of irregular unreflective bits of crystal surface and of little true planes, having the direction of the nearest cleavage plane characteristic of the crystalline substance. . . ."

by the old Indians, but it disappeared, although it was described by De Boot in his well-known book about 1609. It was introduced again by Dr. Wollaston. Before cleaving, the diamond is carefully inspected to find the cleavage "grain," a work which requires high skill and experience. A fine ridge or groove is then rubbed into the stone at the place of the intended cleaving by means of a sharp diamond chip (Fig. 7). After the stone has been cemented[1] firmly to the end of a suitable support, a blunted steel knife

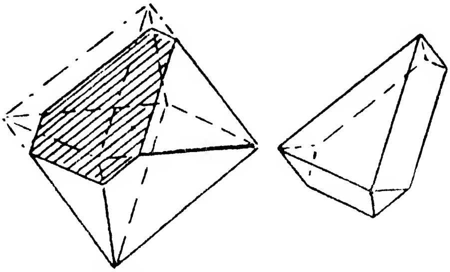

FIG. 6.—Cleavage of a diamond octahedron

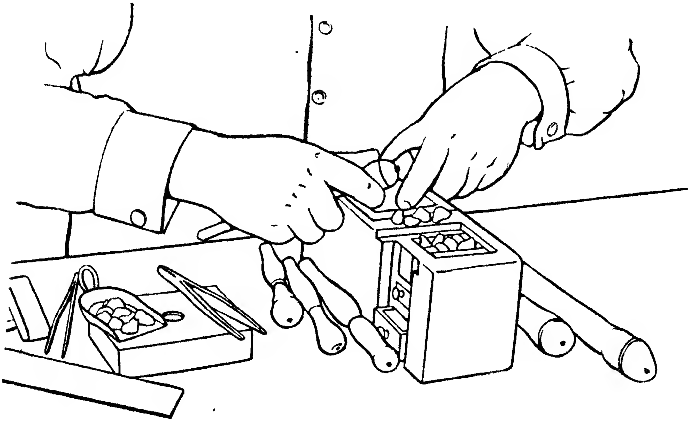

FIG. 7.—Rubbing the fine ridge into a diamond before cleaving

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[1] The composition of some usual kinds of cements will be given in the appendix, p. 244.

or blade is placed into the ridge (Fig. 8). Usually for support, a wooden stick with a thicker end is placed in a hole of the working table. For scratching purposes a diamond with a

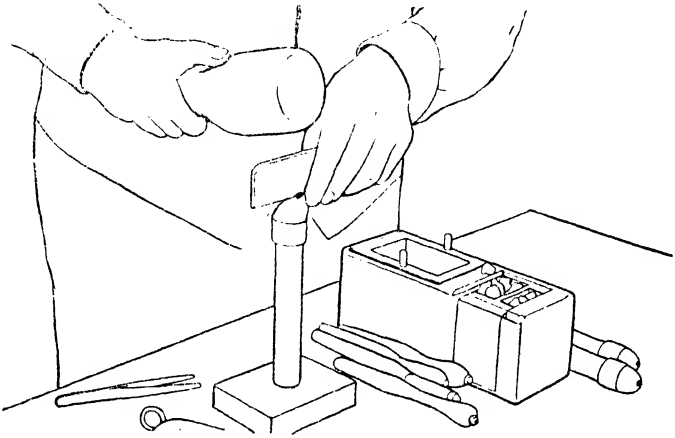

FIG. 8.—Cleaving of a diamond

sharp edge is necessary, and this process can be used to remove sharp edges to be more amenable for use. The diamond dust generated by scratching is carefully collected in a receptacle below the working hands.

Besides a good knowledge of the crystal structure a steady hand is necessary to effect a perfect cleaving, otherwise the whole stone may become shattered. Cleaving is usually applied to produce several diamonds from one crystal without loss. For the production of brilliants and roses, cleaving serves to remove spots and flaws, so that more favourable or smaller pieces are obtained. It can only be decided from moment to moment how the cleaving can be carried out in the most suitable and economic way. In this branch there are experts at work; it was, for instance, usual

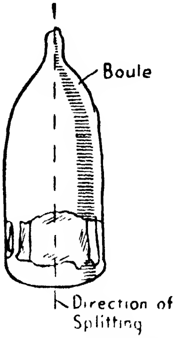

FIG. 9.—Splitting of a boule of synthetic sapphire

to send stones for cleaving to Amsterdam, where a small group were resident.[1] The best account on this subject with clear drawings will be found in the book of W. Fr. Eppler, *Der Diamant und seine Bearbeitung*, Leipzig, 1933.

The "boules" of synthetic sapphires and rubies as produced by the Verneuil process are first split along a twin plane (Fig. 9). Usually no great care is used to find the crystallographic orientations, and Krauss is of the opinion that a better consideration of it may bring greater economy.

(*c*) SAWING

The sawing of hard materials is an old process, but only lately has the speed of this operation been increased by using extremely thin sawing blades rotating at a high speed. The sawing process is to-day employed for removing spots and small inclusions as well as for dividing stones to obtain smaller sizes. The cleaved "boules" of sapphires are usually sawn by parallel cuts into smaller plates (Fig. 10); the same applies to agate. In the case of the diamond the larger stones are usually sawn; in fact, this process has superseded cleaving with its inevitable risks. The sawing of diamonds can only be performed in certain directions which do not coincide particularly with those of cleaving. These sawing directions are parallel to the faces of the cube inscribed to the octahedron (Figs. 11 and 12); one direction vertical to the main axis gives square sections; directions

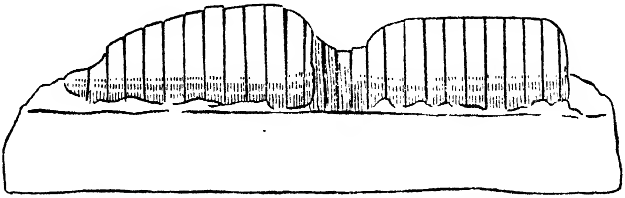

FIG. 10.—Boule of synthetic sapphire sawn into plates by parallel cuts

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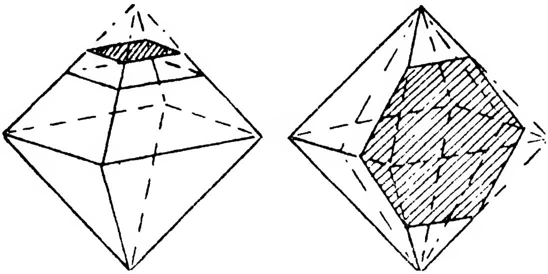
[1] One suggestion is to clamp the diamond in a special holder and split it mechanically (U.S.A. patent no. 1096849, J. F. Lindberg), but it is not known if this device has proved successful.

vertical to the first mentioned produce hexagonal sections. It is almost impossible to saw the diamond in other directions even if they differ a few degrees from the original axis. The special directions in which the diamond can be sawn are called "sawing grain."



Figs 11 and 12.—Sawing of a diamond octahedron; one direction gives a square section (Fig. 11), another section a hexagonal cross section (Fig. 12)

In the case of medium-sized diamonds, the sawing process is successfully used to produce from one diamond octahedron two brilliants. In the older process (Fig. 13A), a large part of the diamond has to be removed by bruting (see next paragraph), in the new method (Fig. 13B), by the combined

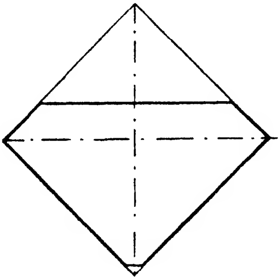


Fig. 13A

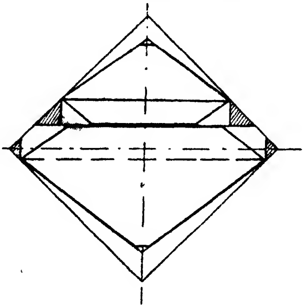


Fig. 13B

Fig. 13A.—Older process of cutting a brilliant without sawing

Fig. 13B.—New method of sawing a diamond whereby one small and one large brilliant is obtained application of sawing and bruting, a larger part of the crystal can be utilized. Former losses, including those during the grinding and polishing process, amounted to over 50 per cent of the weight of the raw stone; by the combined process (Fig. 13B) losses are reduced to about 45 per cent. The sawing planes are determined by experts and marked by ink, and according to this the operator has to adjust the diamond in his machine.

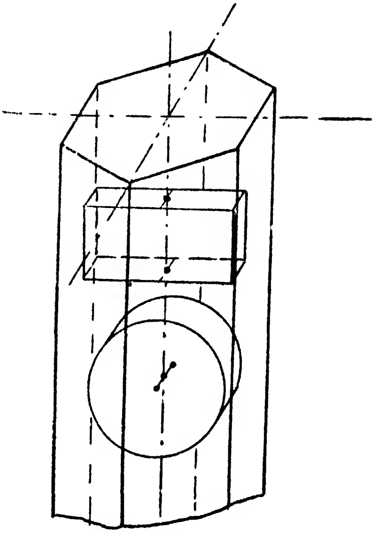


FIG. 14.—Position of piezo-electric plates and discs in a quartz-crystal

Piezo-electric crystals have to be cut out of the rough crystal, quartz, or tourmaline, in a definite direction giving the best possible effects. Fig. 14 shows the usual arrangement of plates and discs in the case of quartz, with the piezo-electric axis vertical to the optical axis. The plane of plate coincides with the optical axis. In the case of tourmaline, which is also used for these purposes, the piezo-electric axis coincides with the optical axis. Therefore, piezo-electric plates of tourmaline are so arranged that the plane of plate is vertical to the optical axis. Great care has to be applied in selecting good specimens of these minerals owing to the frequent occurrence of twinning, the effect of which is an opposite polarity at adjacent points of the same face.

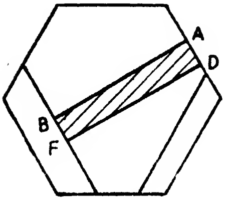


FIG. 15.—Cutting out a plate from a quartz-crystal

Best results in cutting out the plates are obtained by using steel saws charged with diamond dust. The mud-saw principle, however, with a steel or brass disc and an abrasive mixture containing fine silicon carbide powder mixed with water and some glycerine is also utilized (see p. 50). After sawing, the specimens are examined in polarized light to discover any portions of the plate which show twinning. The plates are cut from the prism in a direction perpendicular to any two of the parallel faces of the hexagon (Fig. 15). The use of a thin steel wire stretched in a hack-saw frame to draw the line along which it is desired to cut the crystal is recommended; the cutting is done with moistened silicon carbide powder. Discs are usually cut out with thin walled metal tubes, the edges of which are provided with diamond dust (see p. 111).

SAWING OF DIAMONDS

For sawing diamonds, a thin disc (about 0·0025 to 0·007 inch (0·06 to 0·15 mm.) thickness) of a special phosphor bronze with a diameter of 2⅜ to 2¾ inches (60–70 mm.) (Fig. 16) rotates with a speed of 4,500 revolutions per minute. Sometimes lower and sometimes higher speeds are mentioned in writings on this subject, but it is safe to assume that the usual circumferential speeds with which these discs should run are between 1,800 to 3,250 feet per minute.

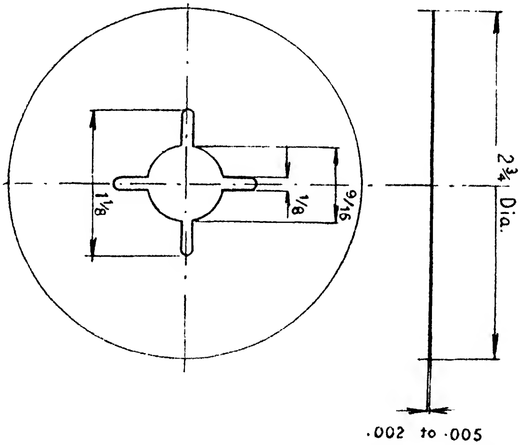


Fig. 16.—Diamond-sawing blade of heat-treated phosphor bronze

The diamond-sawing machines (Fig. 18) have been improved during the last years, and now have a small, neat appearance. The diamond is fixed in a metal holder, adjustable in every way, either by cement or by the pressure of V-shaped holders and kept in position by screws. The adjustable holder is placed at the end of a swinging holder loaded during operation by an adjustable weight. To prevent the arm dropping in the case of an accident, a stop is provided which, where a larger number of machines is involved, is automatically adjusted during running. These devices prevent damage to the sawing disc, and eventually to the operators if the diamond becomes lost. The arbor supporting the disc has hardened conical points running in hardwood centres lubricated by grease. For reversing the direction of rotation the arbor is lifted, the belt twisted, and the arbor replaced again. Sideways fine adjustment is effected by a screw mechanism, the diamond holder being provided with female thread, similar to the arrangement in Fig. 26, but the nut-member is split and after adjustment clamped to prevent any shifting.

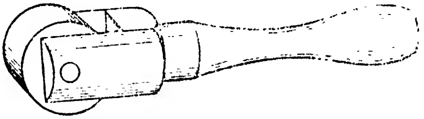


FIG. 17.—Steel roller for preparing diamond saws

The sawing disc is clamped rigidly between two relatively thick metal flanges, so that only a ring face of about ½ inch wide is exposed; therefore, the maximum cutting depth is about ⅜ inch, but by rotating the stone, materials up to ¾ inch in thickness can be cut. The thin disc is prepared at its outer periphery by diamond dust. First the edge is roughened and then a fine diamond powder mixed with olive oil is applied. In small factories, simple steel rollers (Fig. 17) are used, but in larger factories there are special machines for sawing. Such a machine (in German, the *Puderbank*) consists of a rotating cylinder against which the sawing blade is pressed by an adjustable weight. The cylinder (representing only an enlarged form of the small steel roller, Fig. 17) is provided with a mixture of diamond dust and oil, and, besides its rotation, performs a small axial reciprocating movement in order to prevent the sawing blade cutting into the cylinder. Several discs can be prepared simultaneously. The time for preparing a blade in such a machine is between 5 to 7 minutes.

This preparation causes the external edge of the disc to become a little thicker than the disc itself, thus avoiding wedging during cutting. During the operation the disc has periodically to be provided with some new diamond dust mixed with oil. The sawing of a one carat stone is said to require about one day, after which the disc has to be prepared again. With one sawing disc, up to six stones, each weighing about one carat, can be sawn. The full utilization of the sawing blades, however, is not considered satisfactory, as the circumferential speed of the saw is reduced and therefore the sawing capacity becomes less with smaller disc diameter.

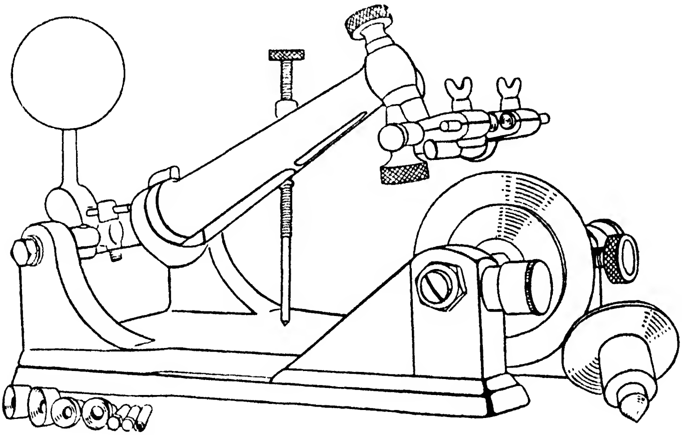


Fig. 18.—Diamond-sawing machine

In the diamond industry the most popular diamond-sawing machine is that shown in Fig. 18. But other machines of this kind similar, for instance, to the machines used for sawing gem stones and glass seem to be applicable for sawing diamonds. Fig. 19 shows a view of the diamond cross-cutting machine of G. Armeny (U.S.A. patent no. 697230, patented April 8, 1902). Here the diamond, held in a suitable holder, is fed against the sawing disc by a horizontal saddle under the load of a weight. The diamond is placed somewhat above the axis of the wheel and inclined. The saddle can be adjusted in three directions; the handwheel seen from the front performs the sidewise adjustment.

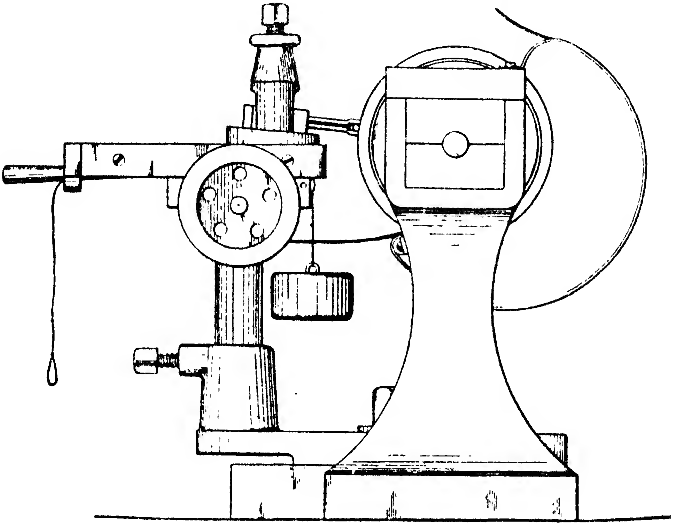


FIG. 19.—Improved diamond-sawing machine

SAWING OF GEM STONES

In spite of the fact that for sawing gem stones similar machines to those for sawing diamonds are used, the method is more primitive and robust. The blades are of greater thickness, and a simple saddle or tool rest is satisfactory, and sometimes the stone may even be held in the hand. The sawing blades, for one reason or another, do not run with such high speeds.

There are four different kinds of sawing blades making for different sawing operations. These are:

(*a*) Metal sawing discs provided with loose abrasive grains (so-called "mud" saws).

(*b*) Metal sawing discs charged with fine abrasive grains (abrasive grain hammered into the edge of disc).

(*c*) Resinoid bound disc impregnated with abrasive grain (so-called cut-off saws).

(*d*) Diamond grains bound in sintered metals.

(*a*) "MUD" SAW

"Mud" saw blades, usually between 8 to 12 inches (200–300 mm.) in diameter, and sometimes even more, are of steel (Armco or automobile fender steel) or copper. Small-sized discs are made of no. 18 to 21 Imperial Standard Gauge. They should run only at 300 to 450 R.P.M., resulting in circumferential speeds of 600 to 1,425 feet per minute, as higher speeds obviously tend to throw the mud mixture from the blade, thus reducing the cutting action. The abradant used is usually water and abrasive grain, or a mixture of light oil, clay flour and abrasive grain. The clay flour serves to give the mud the higher consistency, so that it sticks better to the metal. The mixture should have the consistency of ordinary cream, and be kept in a metal receptacle. The disc should be shielded against the splashing of the mixture for safety reasons. The recommended abrasive is silicon-carbide no. 120; the cutting rate can be increased materially if 10 per cent of no. 120 boron carbide is added. The disc should be mounted between two strong flanges of equal diameter so that only a ring of the sawing blade is exposed, a little more than corresponds to the depth of cut required.

Smaller stones are sometimes held in the hand, resting on a flat table against the saw; this procedure cannot be recommended owing to the risk to the operator. The stone should be held in a holder or clamp which can be placed on the steady rest as mentioned above. Commercially available devices can be used, but frequently simple methods are employed which will be described in a following paragraph. "Mud" saws should be operated with small pressure, in particular when starting the operation, but when a small slot has been made the pressure may be increased. If correctly handled with regard to speed and adjustment of pressure the saw wears down evenly. Speeds too high or too slow will tend to develop "flats."

(*b*) CHARGED METAL SAWS

Charged metal blades are prepared in a way similar to the saws used for diamonds, and are said to be four times thicker than the "mud" saws. As a rule diamond dust is used for preparation; the whole process is cleaner, although it increases the operating costs.

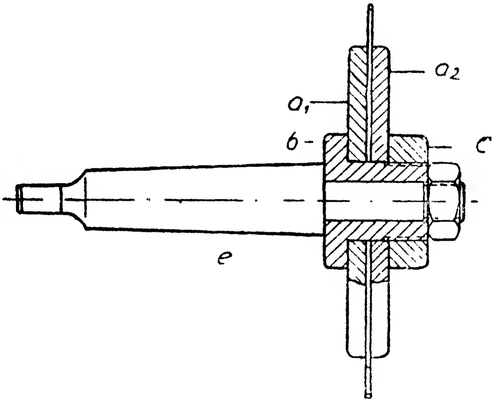


FIG. 20.—Mounting of a metal saw charged with diamond dust

The sawing blades have the same thickness as those used for "mud" saws, but generally with smaller diameters—up to 8 inches; besides steel sheet, hard rolled copper or phosphor bronze is sometimes used. Jewellers on occasion employ tinned sheet iron cut out of metal cigarette boxes, and turn these to round discs about 2 inches in diameter.

The necessary notching and charging is done while the disc is still mounted on the arbor. The disc must run absolutely true, thus the arbor hole must be of correct size and the periphery dead true; hand-made blades should be trued in a lathe for both inner diameter and periphery. The saws should run through a receptacle filled with a mixture of kerosene or equal parts of kerosene and crankcase oil. The speed is also in this case about 300 to 450 R.P.M., resulting in a circumferential speed of 600 to 1,425 feet per minute.

Fig. 20 shows the mounting of such a sawing blade of about 4 inches (100 mm.) diameter. The arbor is provided with a Morse taper, no. 2, and a cylindrical shank which allows the withdrawal of the disc mounted between flanges. The sawing disc is clamped between the metal flanges a_1 and a_2 and pressed by a nut *c* against collar *b*. The sawing disc of 4 inches (100 mm.) diameter, and of about 0·024 inch (0·6 mm.) thickness, prepared with hammered-in diamond and rotating at 3,750 feet per minute (3,800 R.P.M.), is said to have a cutting capacity of 0·06 square inch (40 sq. mm.) per minute. The total capacity until re-preparation or renewal of the disc is necessary is said to be about 4·7 square inches (3,000 sq. mm.).

In the following paragraphs some methods for preparing these discs as applied in different quarters will be described.

According to W. T. Baxter and the Gem Cutting Laboratory of Mineralogists (America), the disc is placed on an arbor and so controlled by holding a sharp piece of quartz or agate and shaving the disc, if necessary, that it fits snugly and runs true. With a knife blade or with an old hack-saw blade sharpened like a wood chisel, and a small hammer, the periphery of the disc is notched at intervals of about $\frac{1}{16}$ inch to a depth of about $\frac{1}{32}$ inch. Diamond dust of no. 120 grain size is mixed with a blob of vaseline about the size of a pea. The paste is applied to the notches with a toothpick and worked into them with the fingertips. For a wheel of 8-inch diameter about one carat of diamond dust is necessary. A small ball-peen hammer is used to close the notches by tapping lightly on the periphery of the blade. The taps must be delivered with equal force, and they will embed the diamond in the notches. A case-hardened, grooved roller (Fig. 21) is then used to roll the edge of the saw with the disc rotating under power. Instead of the roller, the smooth side of a piece of quartz or agate can be used, but neither is so satisfactory.

For adjusting the disc, W. T. Baxter suggests that wobbling sideways can be corrected by "massaging" the side of the saw with a flat 2-inch width of hardwood when the saw is in motion. The operation must be started near the arbor and should be moved towards the periphery.

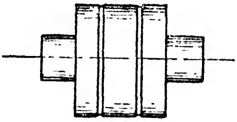


FIG. 21.—Roller with grooves for charging diamond saws

The T.C.M. Manufacturing Company applies the following method to their hard-metal sawing machine. The thin copper disc is at first dressed by means of a steel or hardmetal cutter (Fig. 22), so that it runs absolutely true. Diamond dust mixed with oil is smeared on a steel roller, and this is fed against the disc which is slowly rotated by hand. The disc is then alternatively driven by the motor and stopped again. During the time of slowing down of speed the roller is fed in a direction vertical to the disc. After this method has been repeated three times, the motor is allowed to run with full speed, and the roller is fed for two to three seconds against the wheel; then the roller is withdrawn, and this preparation is repeated for three minutes after the roller has been provided with diamond again. A rag soaked in

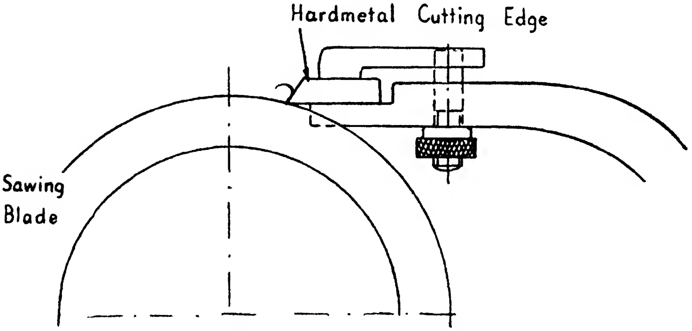


FIG. 22.—Method for truing the sawing disc

water is placed between cover and disc to clean the disc and to prevent vibrations.

The optical industry distinguishes between the methods of flat preparation (usually carried out in the workshops) and deep preparation (carried out by special firms). Flat preparation is applied to thin discs of 0·02 to 0·03 inch (0·5 to 0·8 mm.) thickness, and an impregnation depth up to 0·02 inch (0·5 mm.). The deep preparation is used for discs of 0·04 inch (1 mm.) and more thickness; the periphery takes notches of 0·12 to 0·16 inch (3 to 4 mm.) depth in which the diamond dust prepared with oil becomes embedded. It is obvious that the same sawing discs are useful for cutting gem stones and diamonds.

(*c*) CUT-OFF SAWS

There are two different kinds of cut-off saws on the market: for softer minerals, with a hardness of no. 7 or less on Mohs' scale, silicon-carbide cut-off wheels are recommended; for harder materials, above no. 8 Mohs' hardness diamond impregnated resinoid saws are suggested. Silicon-carbide cut-off saws are supplied 6 and 8 inches in diameter; thickness: $\frac{1}{16}$ inch (1·58 mm.) and $\frac{3}{32}$ inch (2·38 mm.), 10 and 12 inches diameters thick: $\frac{1}{16}$ inch (1·58 mm.) $\frac{3}{32}$ inch (2·38 mm.), and $\frac{1}{8}$ inch (3·18 mm.). They are supplied as resinoid and rubber bound, and should be operated with circumferential speeds of 6,000 feet per minute (necessary speeds 2,000 to 4,000 R.P.M.). These wheels have proved to be highly efficient for some uses, but they must be well shielded to protect the operator in case of breakage through improper use.

The diamond charged cut-off saw can be considered without doubt as the most efficient evolved up till now for the cutting of hard materials. The initial price is relatively high, but they are fast cutting and last for a long time. Diamond impregnated cut-off saws are produced in the following sizes, preferably with a grit no. 100.

	Thickness	
3 inches diameter ..	0·030 inch	0·762 mm.
4 inches diameter ..	0·035 inch	0·889 mm.
6 inches diameter ..	0·040 inch	1·041 mm.

These wheels may even run dry and can be put to considerable abuse without the risk of damage. According to W. T. Baxter, sapphire, for instance, can be fed directly into the saw. It is said that such a saw cuts stones with the same speed and ease as wood is cut by a high-speed steel saw. Owing to the high speed applied little friction heat is generated.

(*d*) DIAMONDS BOUND IN METALS

The latest invention for cutting hard materials is the sawing blade provided by diamond grains bound in sintered metals.[1] As other abrasives, with the exception of boron carbide, will not produce the necessary cutting action, only diamond impregnated wheels of this special type are known at the moment. In the case of diamond grains bound in metals by the electro-plating process usual thicknesses are 0·016 inch (0·4 mm.). Recommended speeds are 6,000 to 8,000 R.P.M.; thus for a diameter of 4 inches, peripheral speeds of 5,800 to 7,600 feet per minute result.

SAWING OF GEM STONES: MACHINES

In these pages a few sawing machines and attachments will be described. They have been evolved for different purposes which are mentioned, and include machines for cutting glass, sawing off crystals, sawing of hardmetal tips, and so forth.

In nearly all these cases the material to be cut is pressed against the sawing disc by means of a weight. In some cases the stone swings over the top of the wheel, but when the stone is placed at a lesser height it should be placed at least ¼ inch or ½ inch above the centre of the wheel axis.

The machine (Fig. 23) is used in the optical industry, but absolutely the same models are used for dividing gem

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[1] See *Industrial Diamond Review*, No. 4, 1941, p. 25.

stones. The sawing disc consists of a hammered and adjusted tin plate or a double polished steel sheet of 0·020 to 0·04 inch (0·5 to 1 mm.) thickness, and up to 16 inches in diameter. It is driven by a ½ to ¾ h.p. motor, and rotates at 400 to 500 R.P.M., resulting in a peripheral speed of 1,700 to 2,100 feet per minute. The piece to be worked is held in a clamping block and pressed against the disc by a rope and weight to control pressure and feed. The lower side of the sawing disc dips into a receptacle filled with kerosene or soda solution. When the cut has reached the middle of the stone the clamping device is swung round and the cut started from the opposite side. In this manner it is possible to cut blocks up to 12 inches thickness with a

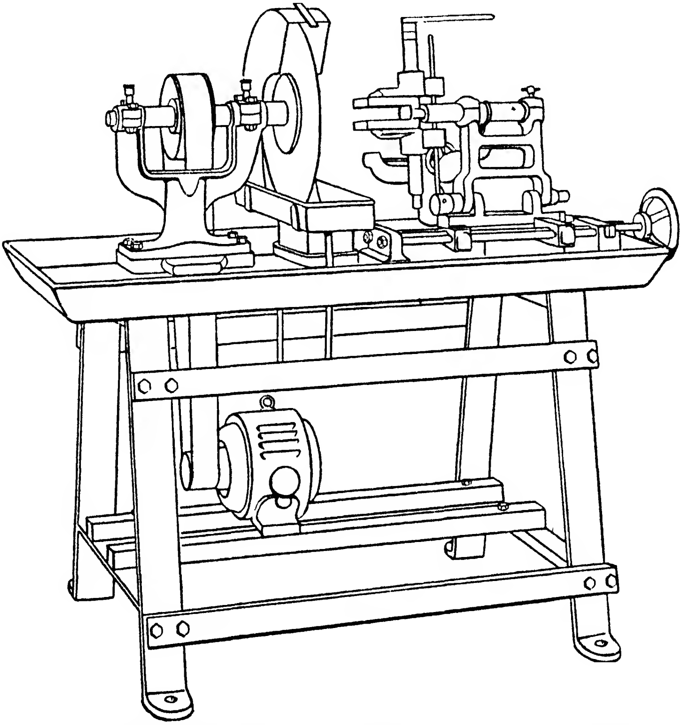

FIG. 23.—Sawing machine used mainly in the optical industry

diamond sawing disc of only 16 inches diameter. The stone-holding support can be adjusted by the spindle on the right-hand side so that exactly parallel cuts can be carried out. Sometimes, to make parallel cuts, sawing machines with multiple blades are used. The width of the cut of the diamond prepared saws is 0·04 to 0·05 inch (1·0 to 1·3 mm.). In glass, the cutting depth of 0·06 to 0·08 inch per minute is achieved; therefore for harder materials smaller feeds will be obtainable.

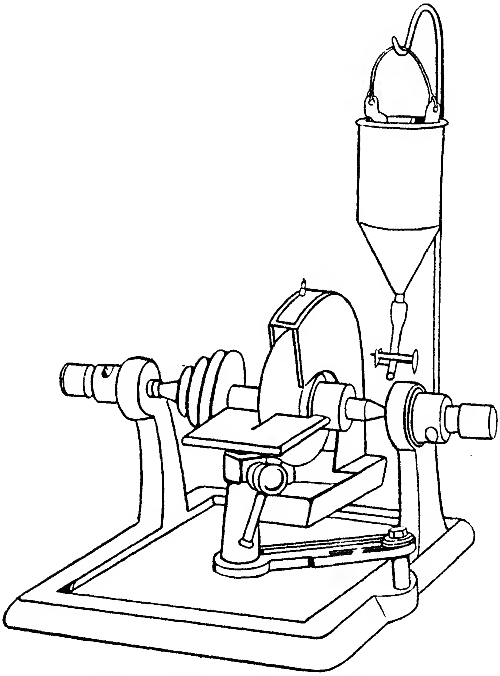

Fig. 24.—Small sawing machine for gem stones and hardmetal tips

Fig. 24 shows a small machine evolved for sawing gem stones and hard metals, manufactured by W. Kruel. The spindle is provided with two conical centres, and runs in hardwood bearings similar to the sawing machines used for diamonds. This ensures a vibration-free running under the high speed of 2,000 R.P.M. Another point in favour of this machine is that the assembly as well as the dismantling of the spindle is facilitated. The disc of 4 inches diameter is made of copper or steel sheet of 0·016 to 0·02 inch thickness. The stone or the hard metal piece rests on an adjustable table. Cross-sections up to ½ square inch (3 sq. cm.) can be cut. In one case a cross-section of 0·1 square inch sintered carbide (brand "Titanit") was cut in fifty seconds.

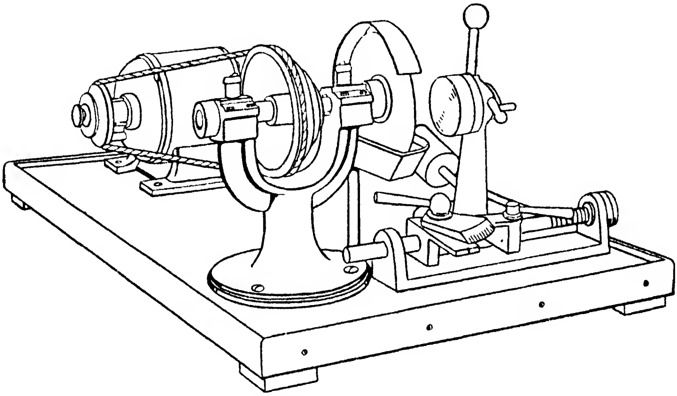

FIG. 25.—Crystal sawing machine

Fig. 25 shows a small machine mainly used for sawing exactly arranged surfaces or planes on crystals. The crystal to be sawn is cemented to the small plane, which by means of two quadrants can be adjusted into planes, one vertical to the other. The whole support is loaded by an adjustable weight, and can swivel round an axis parallel to that of the

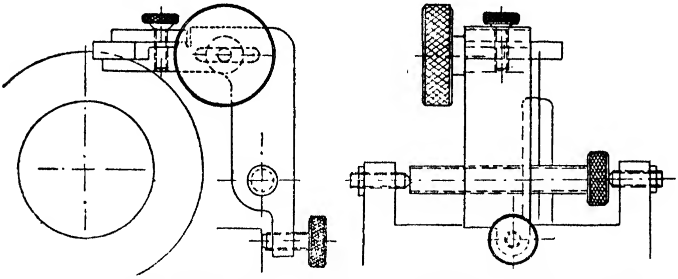

FIG. 26.—Principle of the T.C.M. hardmetal cutting machine

grinding wheel. The rest is also adjustable in a direction parallel to the axis of the sawing spindle; in order to obtain exactly parallel cuts at an equal distance a micrometer screw is applied. The machine is driven by a small motor of $\frac{1}{16}$ h.p., which drives the three-step pulley by a round leather belt.

Fig. 26 shows the principle of the simple sawing device evolved by the T.C.M. Manufacturing Company. The sawing disc consists of copper, and is adjusted in the usual way. The stone to be sawn is clamped in a holder, the swinging axle of which is formed by a fine thread screw held between the centres of fixed clamping screws. These centres allow a swinging movement with a minimum of friction, ensuring that the swinging movement is not carried out by the thread of the arbor. The thread serves only for adjustment in a sideways direction; this is performed by turning the knurled head of the screw. The clamping screw at the lower end of the holder limits the swinging movement. The necessary pressure is exerted by an adjustable weight. This device has proved to be quite successful in the sawing of hardmetal tips, and great savings can be obtained by it. Fig. 27 shows the shape of such tips cut out from the rectangular blocks shown in dotted lines.

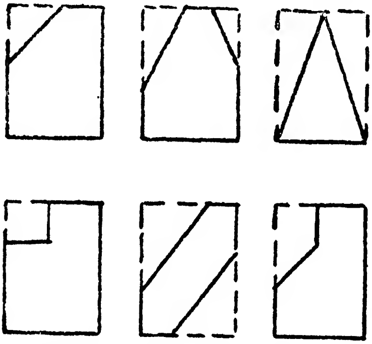

FIG. 27.—Cut hardmetal tips

Fig. 28 illustrates a hand-made device for sawing gem stones. For the support an ordinary hinge is used, one end being fixed to the work bench, the other serving as a small chuck for holding the stone. The device can be manipulated by hand pressure, but the use of a weight attached to the lever may also be considered.

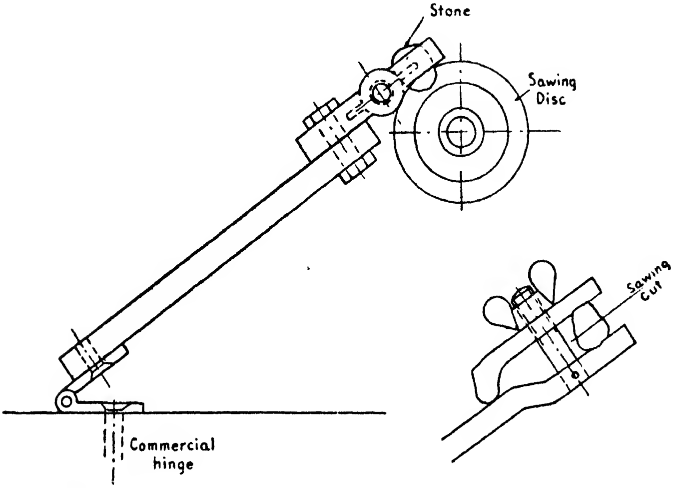

Fig. 28.—Auxiliary equipment for sawing gem stones

Small sawing machines of the kind described have found increased application during recent years, owing to the necessity of sawing tips of sintered carbides and other hard materials. Other machining methods, such as grinding, etc., would lead to a considerable loss in material.

CHAPTER III

BRUTING

The process known as bruting can be considered as a kind of chip-producing method distinguished from the abrasive action of nearly all other processes applied to the shaping of hard materials; owing to this it has proved to be much quicker. Bruting is applied for removing the corners and edges of the natural stones to give them a pear-like shape (Fig. 29) before being cut and polished as brilliants ; to form the "girdle" of brilliants after the main facets have been cut; and to machine the flats used as tables (Fig. 30), and necessary for drawing dies (Fig. 31). It serves further for centring purposes on diamond dies and for opening holes on the opposite side. Special shapes of industrial diamonds, such as cones and balls, are pre-shaped by the bruting process.

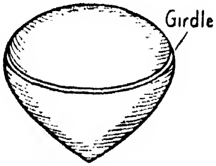

Fig. 29

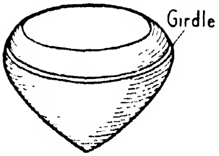

Fig. 30

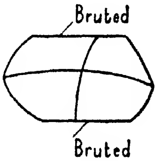

Fig. 31

Fig. 29.—Diamond shaped to a pear-like form used as rough form for the brilliant cut

Fig. 30.—Flat shapes on diamonds produced by bruting; the flats are later on used as tables for brilliants

Fig. 31.—Flat shapes on drawing dies produced by the bruting process (these faces may also be generated by grinding, see p. 171)

In the old method, two sticks, to which the diamonds to be bruted are fixed by a cement, are used. One diamond is rubbed against the other over a small receptacle or wooden trough, into which splinters and fragments fall directly.

In these operations great pressure must be exerted by the hands.[1] As a protection, but without hindering himself, the bruter wears leather gloves over the pressing fingers. That the fingers suffer under this continual work is inevitable.

For fifty years or longer bruting machines (Fig. 32), which in appearance are similar to the small lathes used for wood working, have been available. The spindle is placed in two plain bearings and a thrust bearing[2] and is usually driven by a three-step pulley from a high-speed motor (generally about 1,400 R.P.M.), resulting in spindle speeds of about 800 to 1,000 R.P.M. The spindle supports the special chuck with a brass holder (Fig. 33) to which the diamond is cemented. The design of such a chuck is shown in Fig. 34. Between the face plate of the lathe and another plate connected with the former by three screw bolts, a plate with open holes is mounted which can just slide in a plane vertical to the axis. With this plate, a cover-ring is connected which encloses the whole component and supports the brass dop. When

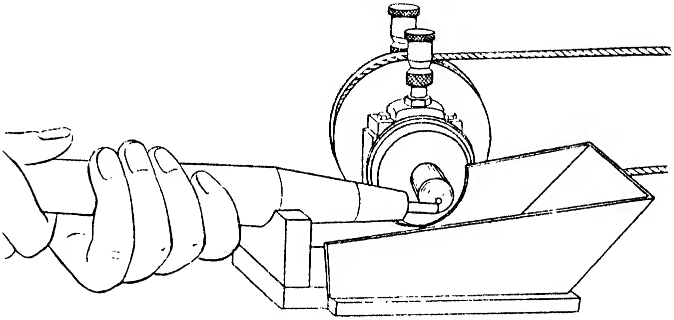

FIG. 32.—Operation on a bruting machine

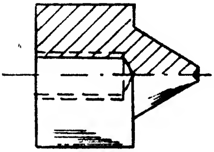

FIG. 33.—Dop for holding the diamond

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[1] The equipment used for this operation is the same as shown in Fig. 7.

[2] For these purposes head stocks of ordinary wood or metal turning lathes have been used with good result, equipped with the special eccentric chuck shown in Fig. 34, sometimes small adaptions are necessary.

tapping with the end of the holding stick or with a mallet against the projecting ring the stone can be eccentrically adjusted; this serves to remove special spots and flaws on the stone. By tapping against the opposite side the chuck is brought back into its original position.

The working diamond is mounted in a similar dop and screwed on a stick so that it can be easily exchanged with the diamond placed on the chuck. The stick is nearly two feet long, and the projecting steel rod on the end is pressed under the arm. The stick is conducted by a primitive turnable support or T-rest, resembling those used on wood-turner lathes, with the difference that clamping for adjusting the rest is performed by a single lever. Exactly below the working diamond, a sheet-metal container provided with metal gauze is placed to catch falling fragments and dust. Great care and skill are necessary to obtain best results. No excessive pressure should be applied, and over-heating the

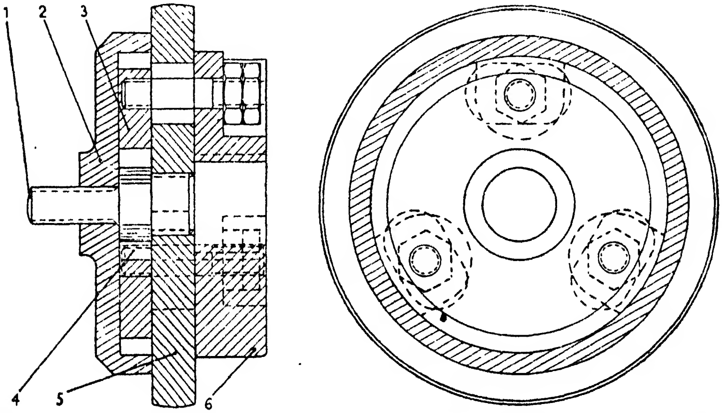

Fig. 34.—Special eccentric chuck for holding the diamond supporting chucks

(1) Thread for holding the dop (Fig. 33), the stud is connected with the floating plate (5)
(2) Coverplate, also connected with the floating plate (5)
(3) Plate, rigidly connected by three studs (4) with face plate (6) screwed on the spindle of the machine

stone should be avoided. For this work girls have proved to be most suitable.

It was already possible to mechanize the bruting process with regard to plane surfaces vertical to the axis of the crystal, but as far as the writer knows these machines have hitherto been in use only for the production of drawing dies, i.e. industrial diamonds. They could also be used with advantage for the bruting of the table and collet of brilliants. In these machines (Fig. 35) one diamond is fixed on a plate and rotates with the usual speed, whereas the other diamond is attached to a plate mounted on a sliding saddle performing a reciprocating movement in front of the other stone.

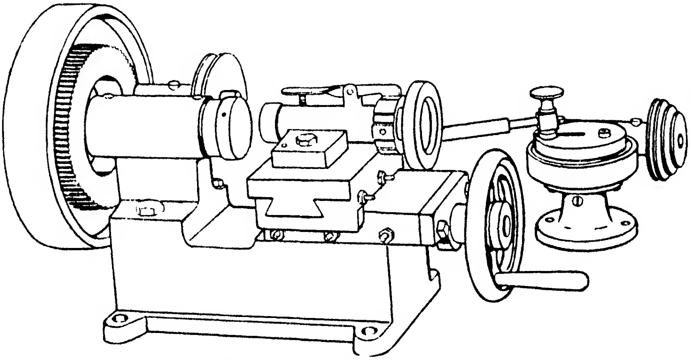

FIG. 35.—Bruting machine with reciprocating movement

Instead of the single rotating stone several stones may be fixed on the rotating plate. In one special machine of this kind it is said that the main plate rotates with a speed of from 40 to 100 R.P.M., whereas the reciprocating movement is performed with a speed of about fifteen to twenty oscillations per minute. A very fine feed adjustment in axial direction seems to be necessary to ensure that the stones are brought gently together. The feed operation is usually carried out by hand. The plate which performs the reciprocating movement can be fixed by a simple indexing device in different positions.

The bruting process is further applied for centring stones in which holes are to be drilled. For this purpose smaller machines corresponding in their construction to small lathes (Fig. 36) are generally used. A small saddle for supporting the working stick is arranged in front of the chuck. The saddle can be fixed in the desired position by means of a handle. These machines run at a speed of 2,000 to 3,000 R.P.M., i.e. with nearly three to four times the speed used in machines for bruting ornamental diamonds. For the bruting of sapphires and rubies, similar machines are employed, but they operate at a very much higher speed, i.e. 8,000 to 10,000 R.P.M. This may be due to the greater softness of the stone material, but the working tool is also in this case a sharp diamond edge.

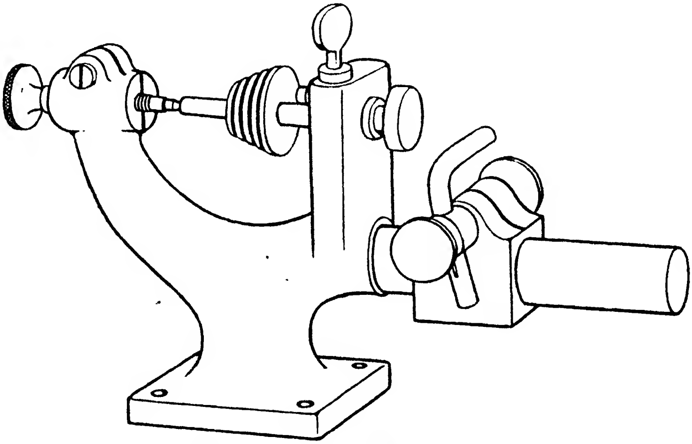

FIG. 36.—Centring machine used for diamond dies

An improved type of bruting machine is shown in Fig. 37. Here the diamond is held between two rotating spindles so that cementing of the diamond in the dop is avoided. The left-hand spindle head, the tool rest, as well as the eccentrically adjusted chuck are the same as those shown in Fig. 32, only the spindle head on the right-hand side is added. This is without eccentric chuck, and driven from a lay shaft from the main counter shaft. The spindle head is situated on a slide in the same direction as the spindle axis, and it can be moved by a hand lever; the two spindle heads are probably pressed together by a strong spring. Both spindles are hollow, and support a chuck for clamping a brass wire conducted through the spindles. One end of the wire is adapted to the shape of the stone, whereas the other is cut straight to abut on a flat face of the stone. In this machine usually diamonds which have been sawn are bruted. It is claimed that this machine can produce 100 per cent more and better stones.

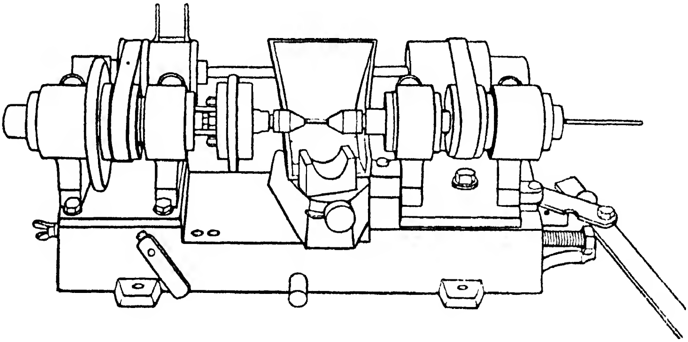

FIG. 37.—Double spindle bruting machine

Bruting is always performed by means of another diamond, serving as a cutting tool. This cutting diamond is used later on for the same process, but frequently macles (twins), which are said to be more vigorous, are employed. The bruting process produces crystals with a relatively rough surface which has to be improved by cutting and polishing.

CHAPTER IV

CUTTING AND POLISHING

CUTTING and polishing are the two most important processes for the finishing of ornamental and industrial stones. Whereas in the case of ornamental stones the art of cutting and polishing consists in providing the stone with regularly distributed, equal-sized facets (brilliants and roses), or with a curved surface (cabochon cut), in industrial diamonds distinct dimensions, in particular distinct angles, have to be provided.

USUAL DIAMOND SCAIFES AND THEIR DRIVE

The usual means for cutting and polishing diamonds is the diamond grinding wheel or scaife.[1] The wheel (Fig. 38) con-

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[1] Some explanation of the expressions which will occur frequently in the text is necessary. The word "scaife" (skaive, skif) used for the flat diamond grinding wheel with vertical spindle, is another term for "disc." In old Norse, the word is *skifa*, German *Scheibe*, Dutch *Schyf*. The word "lap," used for discs for polishing gems or metals, sometimes occurs in connection with lapidary. But this does not appear to be correct, and the derivation of the word from the old English *lappa* and the German *Lappen*, meaning a soft rug, seems to be more plausible. The whole diamond grinding machine is called a "mill" (French: meule. German: Muehle). The word "polish" means to generate a smooth and glossy surface by friction and has the same origin as the French *polir* and the German *polieren*. Bruting is a forced roughing or cutting, in the sense this word is used in the machining of other substances. "Bruting" may come from Old Saxon "brytan" with the meaning of breaking. The "cutting" used in the diamond trade generally denotes grinding and polishing, whence the name diamond cutter for the diamond grinder and polisher. The name "dop" is not found in many English dictionaries: in *Webster's New International Dictionary*, and *The Century Dictionary*, the derivation is given as being from the Dutch and Middle Low German Dop or Doppe, meaning a shell, husk or cover. *Lloyd's Encyclopaedic Dictionary*, 1895, explains "dop" as contracted from "do up." The "tang" which holds the dop designates a kind of handle or holder (in German *Zange*). Between grinding and polishing an intermediate operation called "sanding," from the use of sand-paper or "glazing," is applied in the production of softer stones.

sists of a cast-iron disc of about 1 inch thickness and about 10 to 12 inches in diameter; it rotates on a vertical axis formed by a steel spindle of about 23 inches in length and about 1¼ inches in diameter. Two conical centres are provided on the ends of the spindle. These conical points, usually hardened, run directly in blocks of hardwood (pock-wood, *lignum vitae*), lubricated by tallow or another consistent grease; one bearing is above, the other below, the grinding wheels. The position of the bearings demands a special design of the stand which was formerly made of wood, but now of cast iron. The Dutch model consists of two brackets united by traverses. The continental form (Figs. 39 and 40), and perhaps also the American form, consists only of one cast-iron bracket directly supporting the holders for the wooden bearing sticks. The wooden block, usually a square stick of 1¼ inches in width and about

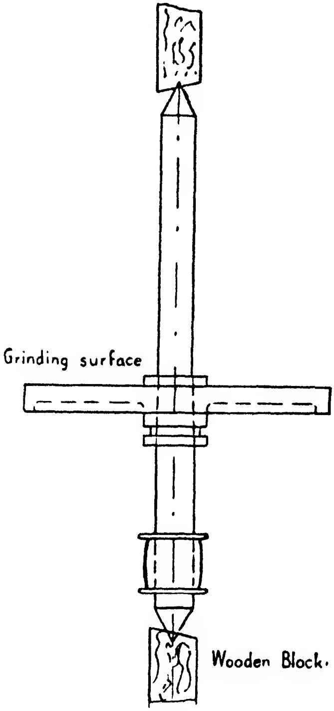

FIG. 38.—Construction of a usual cast-iron scaife with spindle and wooden bearings

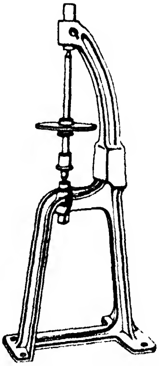

FIG. 39.—Modern cast-iron stand with scaife in position but without working bench

12 inches in length, is held in the bracket by means of a clamping screw with a tommy-bar head.[1]

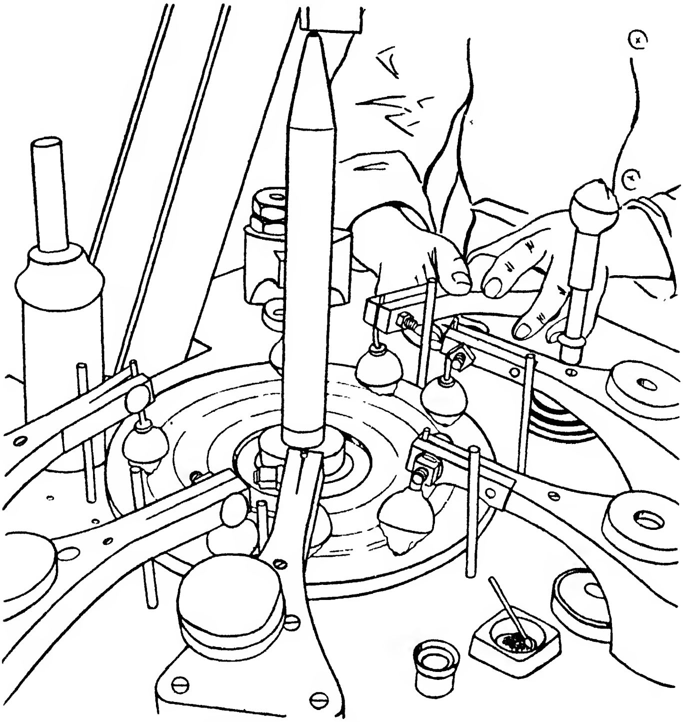

FIG. 40.—Scaife with 7 solder dops placed around it

It may be said that the horizontal revolving wheel is not

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[1] It is a general rule among diamond cutters, that the benches or mills have to be so arranged that the cutter sits with his back to the window, and the light comes over his shoulders. It is said that this is necessary, in spite of the fact that often the daylight is insufficient for the work, owing to the long distance from the windows. The author recommends the arrangement of benches along the window so that working under daylight conditions is facilitated. He is convinced that the above-mentioned arrangement is only due to the old system of power generation and transmission, i.e. a big flywheel operated by a crank and swinging lever in the form of a gate in the back of the room. With modern systems of group or individual motor drive these considerations have lost their value.

a necessity for diamond cutting and polishing as is sometimes assumed. The stand is provided with a wooden table with a hole in the centre for the spindle. The disc runs nearly in the plane of the working table. As it runs with a high speed, it must be properly balanced, and for this purpose a ring with a rectangular groove is provided below the disc (Fig. 38). In this, lead blocks are placed to balance the wheel correctly. Owing to the large distance of about 23 inches between the points, a fine adjustment is easily performed by slightly displacing the centre points. A readjustment is also necessary if the conical hole in the wooden block serving as pivot bearing has increased too much in size; then the end of the wooden block is partly sawn off and the spindle point replaced into the hole or on a new centre.[1]

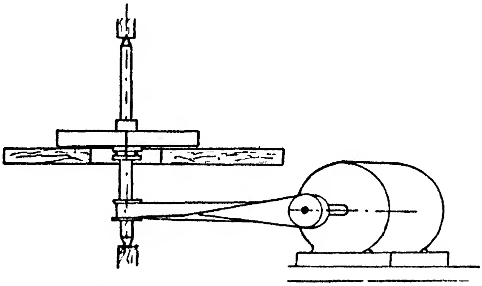

FIG. 41.—Usual drive for scaifes by means of an electric motor with horizontal axis, resulting in a half-twist of the driving belt

The lower end of the spindle supports a belt pulley of about 2 inches in diameter and about 2 inches in length provided with flanges. Usually, the spindles are driven from a horizontal counter shaft, but individual motor drive by means of electric motors of ½ to ¾ h.p. and about 1,500 R.P.M. has come into being to avoid energy losses through idle running machinery. As the axis of counter shaft or motors, usually placed on elevated benches (Fig. 41), is in a horizontal direction, whereas the axis of the driven pulley is vertical, the high speed running belt has to perform a half twist. This causes friction, in

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[1] The wooden sticks are cut oblique, the longer side opposed to the direction of belt pull, to reduce the wear and tear coming from this source.

particular in the case of short centres. A better idea is to place the motor vertically on a stand and to allow a sidewise adjustment for the belt length (Fig. 42). This permits the use of endless belts, either flat or V-belts. In the latter case multiple ones may also be used. These endless belts eliminate the necessity of belt joints and the unavoidable shocks caused thereby.

The speed of the scaife is usually between 2,200 and 2,500 R.P.M., resulting in a circumferential speed of 4,500 to 6,500 feet per minute in the real cutting zone. In the outer zones of the disc utilized for polishing, a circumferential speed up to 7,500 feet per minute is obtained.

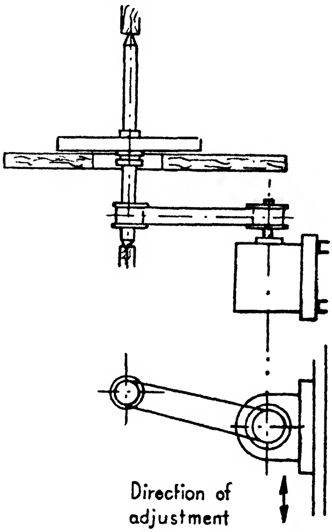

FIG. 42.—Motor arrangement with vertical spindle, avoiding the twisting of the belt; in this case endless V-belts can also be used

Diamonds are cut and polished, almost without exception, on cast-iron wheels composed of a special porous iron of considerable hardness.[1] The size of the pores must be adapted to the size of the diamond dust. These pores must retain the sharp diamond grain, but if too high a pressure is exerted, they may become blunted and should be freed to take another position on the wheel. This is only a rough explanation, as conclusive investigations with regard to the nature of this process are lacking. The composition and the manufacture of the scaifes is a secret of the manufacturer. It is known that only a few products work satisfactorily, i.e. produce a good grinding action and wear slowly. The disc is cast round the spindle of about $1\frac{1}{4}$ inches to $1\frac{1}{2}$ inches

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[1] Tests on a well-known continental product revealed a Brinell hardness of about 260 kg./sq. mm.

in diameter or is fitted by a cone. Cast-iron laps prepared with diamond dust and similar to the discs mentioned are also used for finish grinding a number of other hard materials, such as hard metals. Other gem stones are usually cut and polished on discs of softer material (see this paragraph, p. 96).

PREPARING AND RE-CONDITIONING THE SCAIFES

The grinding surface must be absolutely plane and true with regard to the axis. Usually, the discs fitted by a cone to the spindle are turned or ground with fixed spindles on the centres. For this purpose lathes of suitable size, with a centre height of more than 6 inches and centre length 25 inches, are used. The turning or grinding is best carried out between dead centres; the centre points should be shaped according to Fig. 43, and exactly running revolving centres with a point of similar shape are recommended.

The re-conditioning of the grinding face is generally performed by a fine silicon-carbide powder in water, the mixture being poured between the surface of the cast-iron disc and that of a thick lead disc. In this operation only the external surface of the disc which has been glazed during operation is removed; therefore this method is far more economical

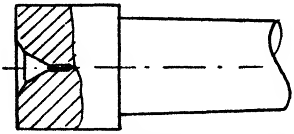

FIG. 43.—Centre for the reception of scaifes in lathes

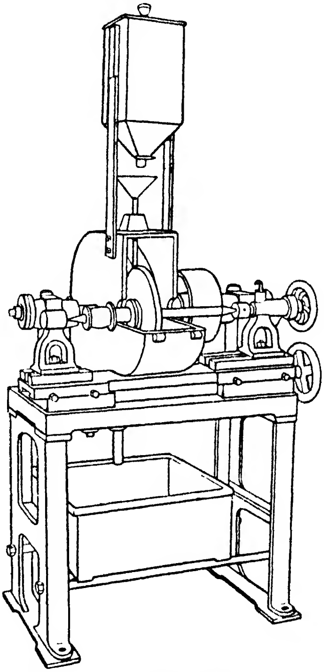

FIG. 44.—Machine for the preparing of scaifes (*Schmirgelbank*)

than turning or grinding which should only be carried out on new discs, or when they are absolutely out of alignment.

This special grinding operation is performed on a machine (Fig. 44) called "emery bench" (*Schmirgelbank*). The scaife is placed in a horizontal position of the spindle between two centres which are placed in brackets. These are mounted on a slide which can be shifted in the direction of the spindle axis by the handwheel shown on the right-hand side. Behind the spindle another spindle is arranged supporting the lead disc, which is of a somewhat larger diameter than the scaife. This wheel is relatively slowly driven by a motor or a transmission shaft. By means of the feed screw both wheels are gently pressed together, and a continuous stream of water and fine grit silicon-carbide powder is conducted to the space between both wheels. In this process part of the abrasive powder becomes embedded in the surface of the soft lead wheel and obtains the necessary hold. It thus exerts a certain grinding action on the cast-iron surface, even if this is glazed by pressed-in diamond dust. It may be mentioned that this kind of wheel is used for cutting sapphires (see p. 96). This action takes the surface layer from the cast-iron wheel and produces a fresh, clean and porous surface. The wheels are protected against splashing by special guards, leaving only a small space open for the

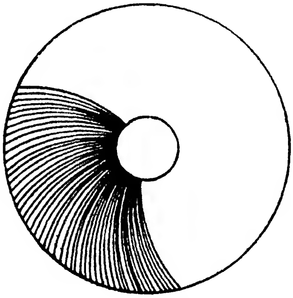

FIG. 45.—By means of a sharp silicon-carbide stick fine ridges are caused in the surface of the cast-iron wheel called "scoring" or "striping"; recently this operation has been carried out by machinery

supervision of the grinding process. Despite this, the machine causes considerable splashing of the grinding mixture during operation, so that it should be placed in an enclosed space. The grinding mixture may be recovered.

After this treatment the scaife is placed with the spindle in a vertical position in a vice (or it can be placed in its correct position on the working bench). The wheel is now slightly scored or scratched by a file-like silicon-carbide stick, and numerous fine radial ridges or grooves (Fig. 45) are generated.[1] In these ridges fine diamond dust mixed with olive oil is embedded, and sometimes pressed in by a hand roller. The diamond dust, the grain size of which has to be adapted to the size of the pores in the wheel surface, sticks sufficiently to the wheel to perform the grinding action.

If the grinding action of the wheel becomes too slow, the addition of some drops of olive oil will re-shift the diamond dust on the wheel and bring it into a new position. If this method is not effective enough, a small amount of new diamond powder may be added. The diamond powder consumption per diamond cutter (brilliants) is usually given as three carats per week. When considering this figure, it must, however, be observed that the diamond to be cut loses weight during cutting in the form of diamond dust which becomes useful for further grinding. Therefore, it can be safely assumed that the real consumption of diamond powder in grinding is about double this figure.

The correct abrasive mixture is obtained by mixing ten to twelve drops of pure olive oil with one carat of diamond powder; for smaller stones a greater amount of oil is required, resulting in a paste of lower viscosity. To ensure perfect mixing of oil with diamond dust with exclusion of clods a so-called "grinding" device is used, consisting of a receptacle with a nearly hemispherical cavity of about 2 in.

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[1] This operation is called in Dutch "scueden" and the operator has the name "skivenscueder." The former word is closely related to the English scud or scuff, meaning skim along and walk with dragging feet, the etymology being dubious. In England this operation is also called "striping."

radius into which a correspondingly formed pestle fits. Oil and diamond dust is placed between both and subjected to a "grinding" movement, resulting in a perfect mixing.

DOPS AND DIAMOND HOLDING APPLIANCES

The diamond to be cut is usually fixed by means of solder in a tulip-shaped bowl of brass or copper of about 1¾ inches diameter (Fig. 46), provided with a short stalk of copper wire about $\frac{3}{16}$ inch in diameter. The solder, usually an alloy of one part of tin to two parts of lead, melts at about 420 deg. F. (215 deg. C.). It is worked into a cone, the diamond nearly fully embedded at its apex. This leaves free only that portion of the stone which has to be cut; all other surfaces can hardly be recognized, making it extremely difficult to find the right position when definite angles are required. If another facet of the diamond has to be cut, it has to be taken out and soldered again in another position. This causes long interruptions in the work of cutting and polishing; if the diamond has not obtained the correct position, this procedure has to be repeated.

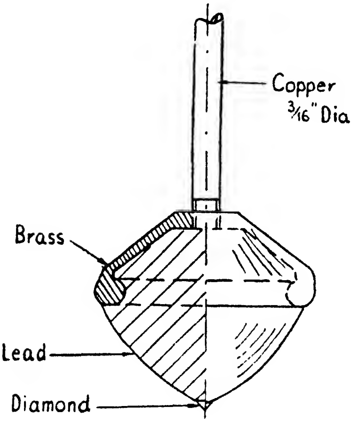

FIG. 46.—Usual solder dop

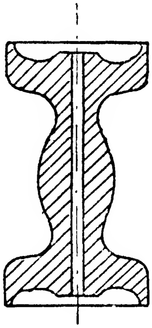

FIG. 47.—Special wooden holder for cooling down and transporting solder dops; the device can be used from both sides

In larger factories of the diamond industry, soldering is performed by special setters; usually one setter is provided for ten cutters. These men are accustomed to model the solder while it is still plastic with the thumb; and the thumb tips of these men become insensitive against extreme heat. The soldering is performed over a special gas-burner on which the dop is placed with the stalk pointing downwards. After the soldering, the dop is put in a special holder (Fig. 47) for cooling down, and by means of this holder the dops are brought to the diamond cutters and polishers.

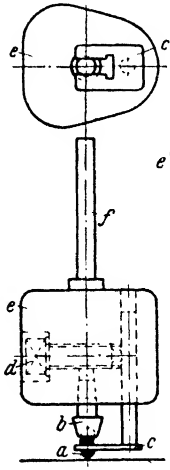

FIG. 48.—Mechanical dop for grinding the table

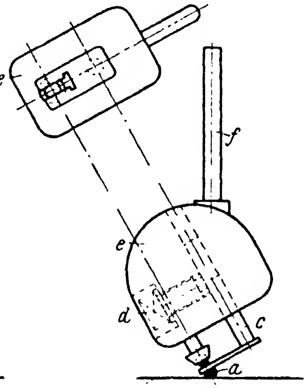

FIG. 49.—Mechanical dop for grinding side-facets

(*a*) diamond
(*b*) small dop for placing the diamond
(*c*) holding finger
(*d*) clamping screw
(*e*) body of dop
(*f*) stalk for fixing the dop in the tang

During the past forty years so-called mechanical dops (Figs. 48 and 49) have been invented in which the diamond is held mechanically. The diamond can be fixed at once in the required position, but various kinds of mechanical dops are needed for the different faceting operations. Therefore, a great variety in the design of mechanical dops exists, and no ideal system has yet been found.

Figs. 48 and 49 explain only the main principle without attempting to show a perfect design. There is a certain risk that the diamond may break owing to the clamping force if the screws are tightened too much; on the other hand, the diamond may be lost if the clamping pressure is not enough, or if the screw mechanism becomes loose during operation. Fig. 50 shows a more recent design with two adjustable fingers performing a swinging movement over the stone; therefore this dop is applicable for various sizes of stones.

The mechanical dop has brought a great improvement in the art of brilliant cutting, but for cutting industrial diamonds the old solder dop is still in favour. The reason is that the industrial diamond has sharp edges and acute facet angles which would cause the stone to break when clamped with the usual mechanical dops evolved for brilliants. But if care is used in developing mechanical dops for industrial diamonds, this problem also seems to be solvable. Fig. 51 shows a mechanical dop for holding the nearly cylindrical stones for diamond dies by which the stone becomes centred in relation to the axis of the dop.

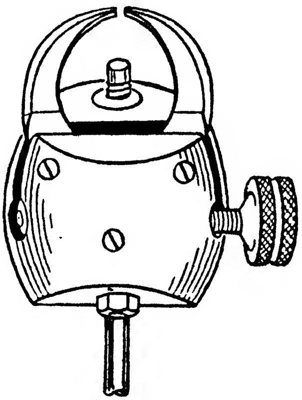

FIG. 50—Modern dop with two holding fingers and one centre height-adjustable support; the actual cup-shape diamond holder similar to *b* in Fig. 48 is not shown

The dop, either solder or mechanical, is clamped by means of a copper rod[1] of about 2 inches in length to the front end of the tang; this is performed by a latch and a clamping screw (Fig. 40). By bending or twisting the copper rod by hand the surface to be cut is brought into the correct position in relation to the surface of the scaife. Also in the surface plane, a further adjustment has to be made to cut the diamond in a direction vertical to its grain.

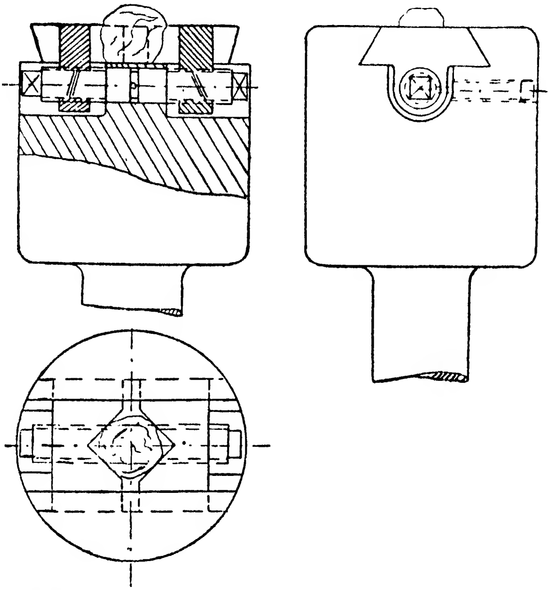

FIG. 51.—Mechanical dop for holding nearly cylindrical stones such as used for making drawing dies

The tang consists of a wooden base of about 3 inches in height, with a steel-plated top of about 8 to 10 inches in length. It has two wooden legs at the rear and a wire rod placed in a horizontal direction. These two wooden legs

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[1] The copper stalk is made of a special resistant material which can be subjected to severe bending in every direction; this is of importance for if the copper stalk breaks owing to excessive strain or fatigue serious consequences might follow.

rest on the wooden table, whereas the diamond, forming a third point, rests on the scaife, thus giving an ideal three-point support. The tang is usually placed in a direction radial to the scaife, and to maintain its position towards the rotating wheel adjustable pins are placed in the table or on a separate adjustable holder. The rearwards pin is placed against the horizontal wire mentioned above (Fig. 52). This arrangement prevents any change of position of the tang owing to the drag of the scaife and unavoidable vibrations of the machinery. Fig. 52 shows also the ordinary arrangement of these stops with regard to the direction of the rotation of the wheel. Lead plates weighing about 2 lb. and more are placed at the front or rear of the legs of the tang as well as on top of its flat surface to exert the correct cutting pressure. To avoid shifting the lead weights, pieces of rubber sheet

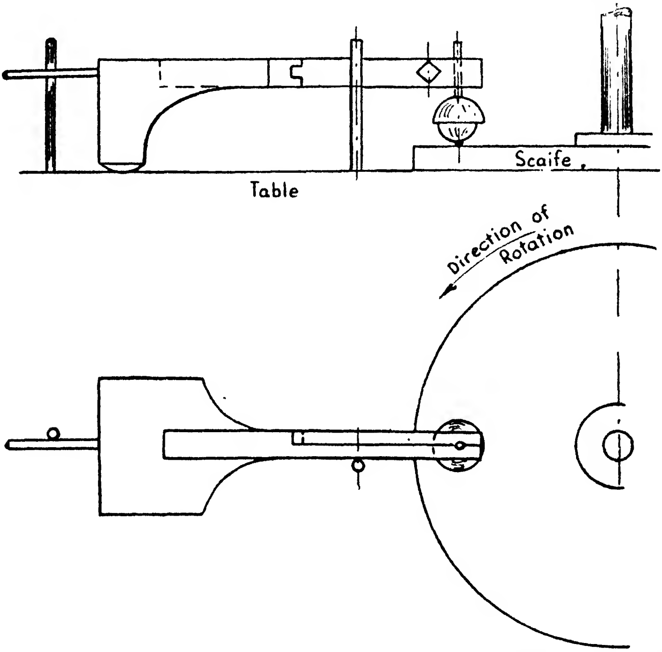

Fig. 52.—Arrangement of the usual diamond cutters tang on the wheel, inclusive stops

or linoleum are placed below them; a better method is to fix the weights by means of pins or commercial toolmakers' clamps. According to the position of the weights the actual load on the diamond can be increased or reduced (Fig. 53). It is quite obvious that with the same weight the highest pressure can be exerted if it is placed just above the dop.

The tang has several advantages which should not be overlooked even if some improvements are discussed. The advantages are: (*a*) pressure by weight, adjustable in wide limits; (*b*) adjusting the dop on every place; (*c*) no special adjustment necessary; and (*d*) by lifting the tang an easy inspection of the diamond is possible, and when replaced on the table the tang assumes a stable position. The main disadvantage is that no exact angles can be secured, and that this appliance is not useful for repetition work. There seems to be ample space for improvements of the simple dop-tang combination, and as a matter of fact numerous patents for improvements have been granted in various countries.

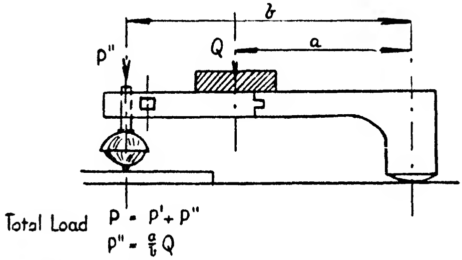

FIG. 53.—Influence of the change in position of weights on a tang

Q = weight of lead plate
P′ = weight of tang concentrated on the diamond
P′′ = additional weight on diamond by means of the lead plate

Bending the copper-wire dop stalk is not an efficient method for adjusting the diamond in relation to the grinding surface. As early as about 1600 the suggestion was made by De Boot to attach an adjustable quadrant[1] between tang

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[1] It is similar to the equipment shown in Fig. 65.

and dop. De Boot claimed that this was his invention, but even to-day the commercial dops are without it. If a quadrant is provided between tang and dop, then it is possible to obtain definite angles on the stone by a correct adjustment of the quadrant. The top surface of the tang must be parallel to the surface of the scaife, and to ensure this, two small spirit levels, one placed at 90 degrees to the other (Fig. 54) must be fixed on top of the tang; further, the tang should have legs adjustable in height similar to those used on instruments. In this way differences in the height of the surface of the scaife and the distance between the surface of the diamond and the top of the tang can be equalized. This, however, can also be carried out by a special adjustment between dop and tang.

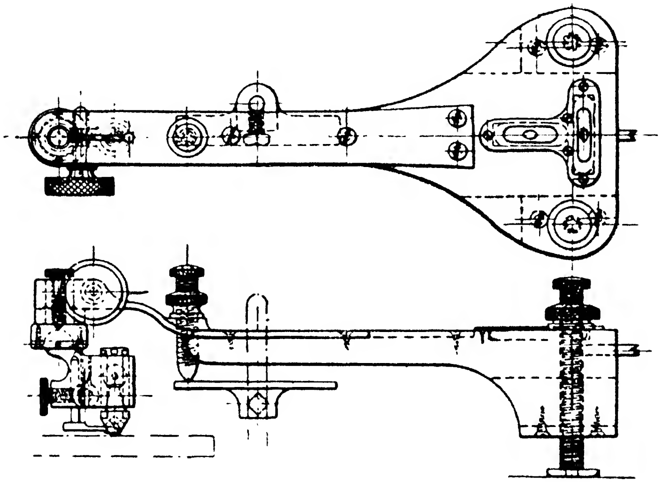
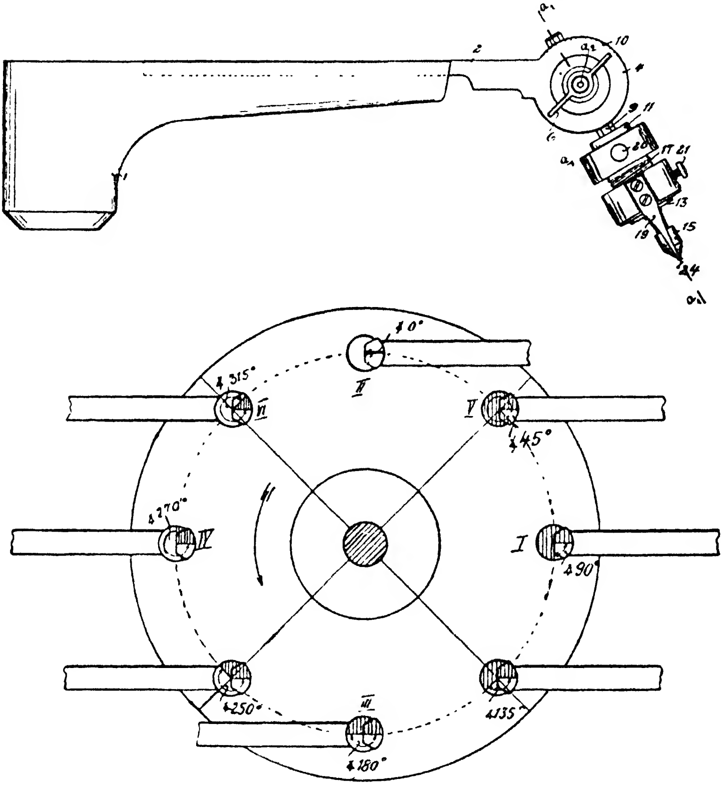


Fig. 54.—Tang allowing the adjustment of angles (E. Soetens)

In such a case the bendable copper stalk has to be dispensed with and replaced by a rigid metal holder, permitting controlled height adjustment and controlled turning in every direction. The latter is necesssary to effect a change in the direction of the grain. For cutting brilliants and other gem stones, indexing devices for changing the position of facets round the axis are of advantage.

Fig. 54 shows the mechanical dop of E. Soetens (U.S.A. patent no. 1103698, Appl. date June 13, 1913). The diamond to be cut is placed in a holder and held by an adjustable finger. The whole dop can be adjusted in any angle by means of a ball fixed by a clamping screw. The top of the tang is split for the reception of the ball holder and can be clamped by a screw. In order to prevent the grinding of too large facets an adjustable screw is



Figs. 55 and 56.—Angle adjusting tang according to Becker and the adjustment of eight tangs on the scaife provided which presses against a table to stop the grinding action. The legs of the tang are provided with adjustable screws, and two spirit levels are placed one rectangular to the other so that the horizontal position of the tang can be controlled.

Fig. 55 shows the design of a special dop and tang for brilliants according to H. E. Becker. The tang appears similar to the ordinary construction. The axis of the diamond holder ($a_1 a_1$) can be rotated on the horizontal axis (a_2), and clamped in every angle direction indicated by the graduations (10). The clamping is performed by the wing screw (6). The shaft ($a_1 a_1$) is of octagonal cross-section to allow the cutting of the eight main facets round the girdle; but instead of this another protractor or index ring may be arranged which is held in the required position by an index under spring pressure. The diamond is placed on top of a little dop and held in this place by two small fingers, so that nearly all the upper part remains free. Together with this instrument it is suggested that the tangs should not be placed radially, as is usual, but in a parallel direction on the table. In this case not only can more tangs be placed on the surface of the same scaife, i.e. eight instead of four or five, but also all desired directions can be obtained (Fig. 56). In this case, however, the upper spindle bearing, preferably has to be eliminated, as will be explained in another paragraph.

NUMBER OF DOPS AND DIAMETER OF SCAIFE

In the *Encyclopaedia of Diderot et D'Alembert* (about 1759) a scaife of about 13 inches diameter with only two tangs, placed on opposite sides, is mentioned. In far older literature only one tang is shown, which is the practice for brillianteering, i.e. making the last small facets for the brilliant and in the grinding of gem stones. Verwoort recommends four dops or tangs for the cross-work and two tangs for brillianteering. It will depend, of course, on the size of stone, and therefore of that of the facet, whether it is more economical to operate more tangs on the same machine. It is the usual practice to work with up to six tangs, while even eight tangs are sometimes recommended. Fig. 40 shows the cutting of industrial diamonds; in this special case seven tangs are used.

The size of scaifes to-day is eleven to twelve inches, nearly the same as those used in older times. It has been suggested that the diameter of the scaife should be increased up to 36 inches in diameter. Such a scaife could run at a lower speed, i.e only 1,000 R.P.M., to obtain the same circumferential speed as usual, providing eventually working places for about four polishers. The writer is of the opinion that this is an economical arrangement, as to-day power transmission problems do not represent such difficulties as in olden times.

IMPROVEMENTS IN DIAMOND CUTTING EQUIPMENT

The pivot bearings for the scaifes consisting of pock-wood bearings can be considered as a great technical success for the Middle Ages, when they were first introduced. No other primitive design could have provided a smooth running drive for high speeds and produced such a minimum of friction and wear. The length of distance between the bearings gives, as already mentioned, the possibility of good balancing. There is no doubt that this solution has up till now proved satisfactory, and is also applied for other purposes, as for small sawing machines, compass bearings, and bearings in electric meters. Notwithstanding the application of pivot points of high-speed steel or hard metal, and of lubricated bearings, there has been little advance on this construction.

There is, however, a definite demand for horizontal lapping wheels without a through-going spindle. This would mean the omission of the upper bearing and bracket so that the spindle would have to be guided in bearings below the disc. Fig. 57 shows a cross-section of the interesting spindle design of Whitehead, used extensively in America. The spindle is supported in two long bearings, readjustable by conical sleeves. Good provision is made for lubrication. The disadvantage of this design is that the driving pulley places strain on the spindle. Therefore a distinct improvement would be made if the spindle running into plane bearings was completely relieved from any stress set up by the belt. There exists, for instance, the possibility of driving the spindle from a co-axially arranged motor by means of a flexible coupling. In this case, rigid and long plain bearings similar to those in the Whitehead design would be suitable.

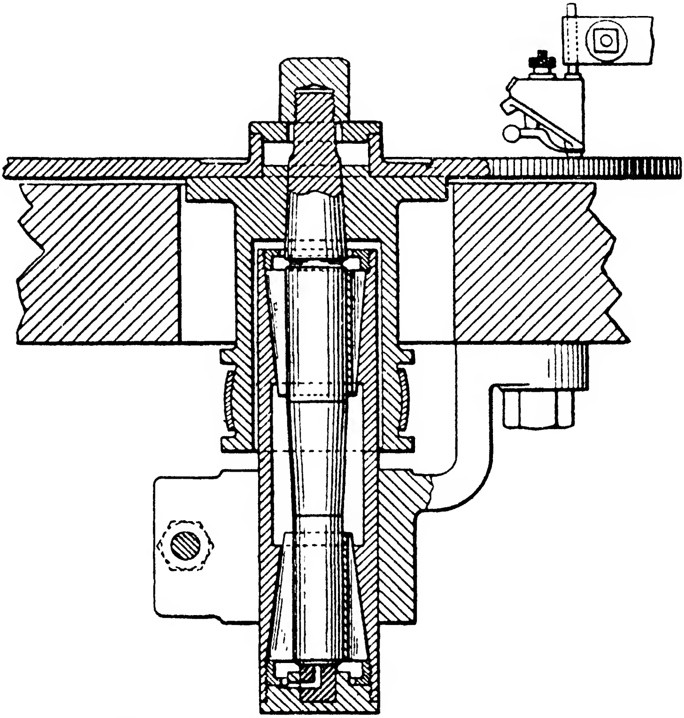


FIG. 57.—Design of Whitehead for a scaife supported in two plain bearings below the table

A further big improvement would be the introduction of scaifes with variable speeds, so that the cutter could adjust the speed to the requirements of the special stones he is machining. In the polishing machines for glass lenses a speed adjustment is nearly always present; W. T. Baxter publishes the sketch of a lapping wheel supported below the table and operated by a primitive variable friction drive (Fig. 58), so that the speed of the table can be changed in the ratio 1 : 3. As numerous variable speed units, mainly based on the V-belt or friction principle, are now on the market and are reliable, the incorporation of such devices would enable conversion of already existing installations.

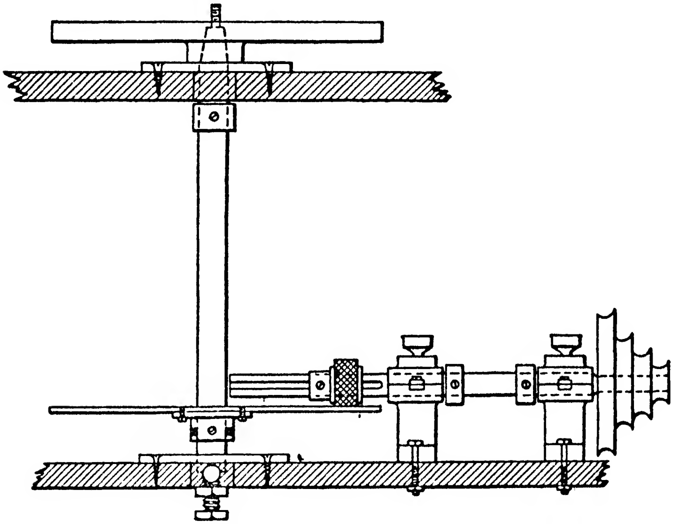


FIG. 58.—Variable speed drive for a horizontal lapping wheel according to W. T. Baxter

A universal application of these units is hindered by their relatively high price, while simple devices, such as that of Fig. 58, may not prove satisfactory when continually applied. The incorporation of variable speed units combined directly with the driving motors does not involve technical difficulties, and their use, in spite of the cost, may be strongly recommended, at least for experimental purposes.

A particular advantage of the replacement of the upper bearing would be that the cutter would have an absolutely free table and could place his tangs in any direction. Special, perhaps semi-automatic, appliances could be placed on top of the table without interfering with the upper part of the spindle. A further advantage would be the easier exchange of grinding discs. The replacement of the usual wooden tables by rigid cast-iron ones with machined top would be an improvement. These tables are more suitable for accurate work as is required for industrial diamonds and for placing special appliances as referred to above.

DIAMOND CUTTING AND POLISHING

The grinding (cutting) process in the case of the diamond is more difficult than for any other material, not only because it has to be ground by its own powder, but because it has to be cut according to its grain, to speak in the language of the diamond cutter. Only in this case can a certain grinding action be expected. A diamond not placed according to its grain on the scaife would not cut even over long periods, the disc may become scored and damaged, and if too high a pressure is applied the stone may also be broken.

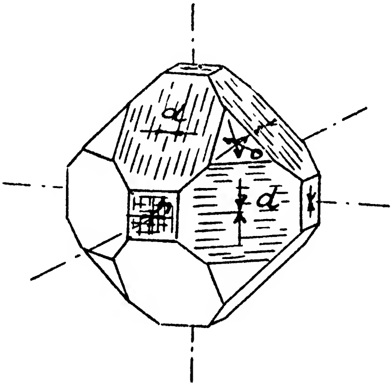


FIG. 59.—Schematic crystal showing the various cutting directions on the diamond; cube faces: *b*, rhombic dodecahedron faces: *d*, octahedron faces: *o*

Fig. 59 shows a schematic crystal limited by triangles, squares and hexagons, which can be considered as the combination of a cube, octahedron and rhombic dodecahedron. The surfaces contain grain markings and arrows representing the cutting directions vertically to the direction of grain. The cube faces have four different cutting directions, the rhombic dodecahedron faces only two and the octahedron faces three; one sees that these directions are always vertically to the edges.

To explain the principle of cutting more in detail, Fig. 60 shows a diamond octahedron, the basic structure of the cubic

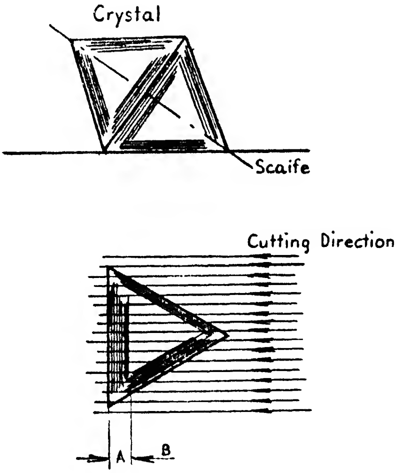


Fig. 60.—Cutting a triangular facet of a diamond octahedron

crystal system, placed with one of its triangular surfaces on the scaife, but it should be observed that the stone has to be somewhat lifted against the plane of the scaife in order to effect a grinding action. The grain of the diamond runs parallel to the edges of the octahedron (Fig. 60). The main rule in cutting diamonds is that the cutting direction or direction of attack of the grinding wheel must always be perpendicular to the direction of the grain. With the extension of one facet to be ground it is impossible to avoid the extension of the cutting system beyond the range of one grain, i.e. it goes over to neighbour grain zones.

One side of a diamond octahedron is placed on the grinding disc and in the upper part of the illustration only the triangle and the direction of its grain are shown. If a facet has to be cut of a greater width than A and extends into the zone B, there is already an interference with the grain running at 60 degrees and 120 degrees in the original direction. From the moment these other grain zones have been reached the grinding process is slowed down, as the crystal is no longer attacked in a direction perpendicular to the grain. These special conditions on the surfaces (and of course in the body) of diamond crystals have led to the opinion that in the same diamond surface different hardnesses are present. Professor K. Schlossmacher carried out research work on this question in the school of arts in Idar (Germany). The results suggested that every part of the triangle, cut according to a given rule, required the same production time. These tests are not, however, conclusive. Kraus and Slawson have further developed a theory brought forward some years ago by some continental scientists, that the apparent difficulties in cutting diamonds are due to intrinsic hardness differences in the crystal structure, just contrary to the opinion expressed by K. Schlossmacher. Based on the well-established physical theory of the atomic spacing they represent the following data:

TABLE 6

PHYSICAL DIFFERENCES IN DIAMOND CRYSTALS

(according to Kraus and Slawson)

Relative No. of bonds per atom per unit areas D^2		Hardness	Solution Effects
Octahedron (wide)	$4/3 \sqrt{3} = 1$		
Octahedron (close)	$4 \sqrt{3} = 3$	$4 \sqrt{3} = 1{\cdot}73$	$4 \sqrt{3} = 1{\cdot}73$
Rhombic dodecahedron	$2 \sqrt{2} = 1{\cdot}22$	$4 \sqrt{2} = 1{\cdot}41$	$4 \sqrt{3} = 1{\cdot}41$
Cube	$4 = 1{\cdot}73$	$4 = 1$	$4 = 1$

From this it would follow that the cube faces are the softest and the octahedron faces the hardest. In spite of the fact that diamond cutters also take this view, the writer is of the opinion that this could only be proved by scientific investigations.

Simple as this general rule is, its application involves several difficulties A large number of stones are bruted before grinding, so that the direction of the grain is more difficult to ascertain. Most of the stones are macles (twins), it is difficult to find the grain, and even in one surface several grains may be present. After a certain amount of grinding when the stone has lost its original form, it is nearly impossible to find the grain by control and observation alone. In these cases a trial method has to be applied by changing the position of the stone towards the wheel; this is easily effected in the usual equipment by bending the copper stalk or other adjusting devices. The real cutting of the stone is observed by a special sound. If this is not present the cutter knows that the stone "does not run."

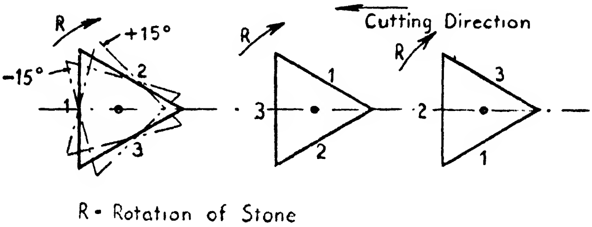


FIG. 61.—Cutting direction for a triangular facet

The difficulties in finding the grain, in particular in the case of macles and the longer time taken in production, has led to the idea of avoiding cutting according to the grain by (*a*) an automatic equipment to change the grain; and (*b*) application of higher cutting speeds, so that the diamond can also be cut against the grain. With regard to (*a*) the automatic change of grain seems to be only of advantage in the case of finishing operations. Assuming a stone rotates on its centre, so that the direction of grain is changed continually, then only three times in one revolution are the correct cutting directions present (Fig. 61).

Assuming that nearly the same effect will still be obtained for angles which differ from the correct angle of 90 degrees by 15 degrees to each side, i.e. instead of 90 degrees, a range between 75 to 115 degrees is present, then there is a total angle range of 3.2.15 = 90 out of 360 degrees, i.e. only for a quarter revolution will the maximum grinding action be obtained. This means that the automatic grinding would be about ¼ slower than when grinding according to the grain. The slowing down of the speed of cutting in the finishing process is a well-known fact, and is also desired when working to very close limits as often required for industrial diamonds. There is, however, the possibility of finding out the "real" grain by a mechanical device, for in many cases it can hardly be found by observation. This would mean that the grain could be changed mechanically when the real grain had been found by a special device. After this had been attained the stone would be run in the correct position.

These remarks refer only to the cutting of facets, in the case of curved surfaces, such as balls and cones, several grains are always present along the surface, and therefore devices which change grain automatically seem to represent the only means of obtaining correctly shaped bodies.

With regard to (*b*) several attempts have been made to increase the cutting speed to obtain better abrasive effects, but hitherto no general conclusions can be drawn.

There exist two further rules for cutting plane surfaces, i.e. facets, which are not so important as that already discussed. The second rule says that the direction of attack of the grinding wheel must be from the centre of the triangle and not from the edge (see Fig. 60). These two rules determine the direction of rotation of the grinding wheel, and therefore the position of the stone in relation to the surface of the disc. In the case of simple octahedrons, the grinding direction of the opposite side of the octahedron is in the opposite direction to the former, whereas in the case of macles, both faces have the same cutting direction. A third main rule says that at all those places where several grain directions cross, the direction with the major grain should be selected.

In the case of brilliant cutting more definite rules have to be observed, and the usual classification is given in the appropriate paragraph.

It is of great importance that the diamond cutter controls the stone completely before starting, and that he has a clear idea of the grain of the stone, even if this cannot be observed owing to the facets that already have been cut. In the case of bruted stones much depends on the experience and skill of the bruter. The correct placing of the stone towards the wheel requires great skill and a safe hand. Besides this, in the case of many diamonds on one scaife, each diamond has to be cut on another diameter of the wheel, so that the generated rings do not interfere.[1]

GRINDING OF GEM STONES

Grinding and polishing of diamonds is carried out on the same kind of disc, only using different diameters and thus slight variations in speed. In the grinding of gem stones, however, each operation involves different kinds of disc, which are usually made of softer substances. Frequently between grinding and polishing, another operation called "sanding" or "glazing" is included.

In nearly all books and technical articles dealing with grinding and polishing of gem stones, illustrations and descriptions show old picturesque mills, with a man lying in a prone position before big sandstones driven by water-wheels. Two men work from opposite sides on each big grinding wheel with a horizontal axis. This unhealthy

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[1] This does not refer to the last operation in which the diamond is moved across the scaife surface by hand to remove grinding traces caused by grinding on a special track. In Dutch and Flemish this is called "afzoeten," in French "mouvementer," perhaps a dialect for "mouver." The Dutch word may come from the Latin "sutus," meaning the form of a seam, therefore "afzoeten" means removing a seam. By this movement wear of the scaife is avoided. Similar movements are applied in lapping sintered carbides (see p. 220) and other metals.

practice is no longer carried out commercially, but exists for the delight of visitors. New methods have been introduced resulting in a much quicker production. The big sandstones have been replaced by modern vitrified grinding wheels, using as abrasive silicon carbide, which has proved to be suitable for stone materials with a hardness below no. 8 on Mohs' scale.

For roughing purposes, grit sizes of nos. 80, 100 and 120 are recommended, and for finishing purposes grit sizes nos. 120 and 180. If the use of the same wheel is preferred for both roughing and finishing operations, a grit size of no. 120 is preferable. The wheels used for grinding gem stones are of medium hardness or grade. In general, soft wheels are used on the harder gems and vice versa. Too hard a wheel may glaze and refuse to cut. Table 7 gives some suggestions for the selection of wheels according to the Norton scale.

Table 7

GRADE OF GRINDING WHEEL ACCORDING TO THE NORTON SCALE

Operation	Soft	Medium	
	K	L	M
Roughing	—	Over no. 7*	Below no. 7
Finishing	Over no. 7	Below no. 7 and for all-round work	

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* The numbers refer to the Mohs' hardness of gem stones (see Table 2, p. 29).

Most of the grinding on these wheels is done off hand, i.e. by holding the stone by hand against the periphery of the wheel (Fig. 62). It is advisable to use a steady rest for the forearm and elbow, enabling the operator to hold the work against the wheel without the bouncing effect which would cause the wheel to wear unevenly. A generous supply of running water is necessary to prevent cracking or splitting of the stone through excessive generation of heat. Plenty of water keeps the wheel surface flushed and clean for fast work. The wheel should be shielded thoroughly against splashing, and the water supply controllable by a valve. In the water pan a sponge should be placed to touch the wheel, and the pan provided with a drain to remove the sludge periodically.

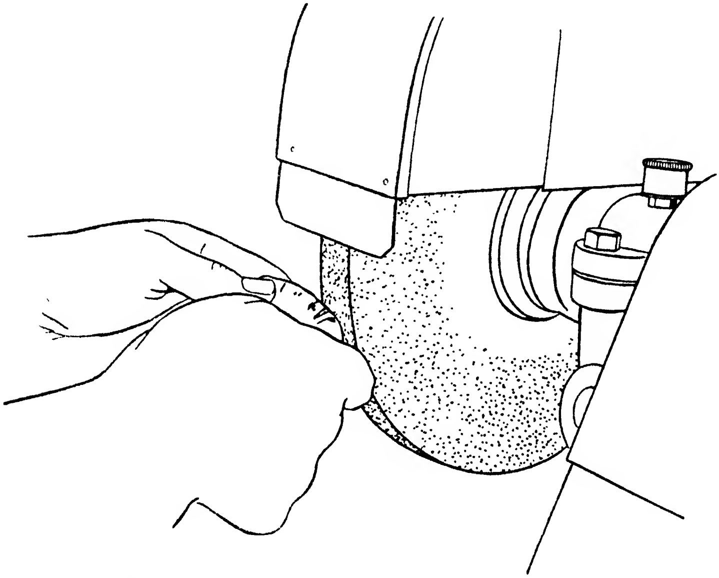

FIG. 62.—Roughing a gem stone on the periphery of a silicon-carbide grinding wheel

If the wheel shows a bouncing action in operation it must be trued by the usual means (silicon-carbide stick, rough diamond, wheel-dressing tool). The dressing tool should be placed on the machine rest and slowly guided across the face. Most work is done on the periphery, giving faster cutting action, but the sides of the wheels are used for the production of flat surfaces on the gem stones.

SANDING OR GLAZING

In the preparation of gem stones of no. 9 Mohs' hardness and below, a special grinding operation is included between the usual grinding, lapping and finishing operations. This has been given the name of "sanding," as special abrasive papers or cloths are used. This operation removes any deep scratches which have been left by the grinding wheels. It is usually only applied for finishing cabochons and large flat or convex surfaces.

Sanding discs consist of wooden or cast-iron wheels of about 1 inch in thickness and 8 or 10 inches in diameter. On these discs a good grade of abrasive paper or cloth is mounted. They are folded over the edge of the wheel and held in place by a metal hoop. Another method is to provide the grinding side with a felt cloth, such as from an old billiard table, and cement it to the curved surface of the wheel (Fig. 63). The felt can also be held by a rubber band or metal hoop. It is coated with a silicon-carbide powder of no. 220 grit size, and to ensure rigid attachment the back of the felt is slightly damped with water prior to placing in position. This avoids any risk of wrinkles. The surface of the cloth is coated with silicate of soda (waterglass), and the abrasive grain is immediately dusted on to the surface; excessive grit is taken off before the mixture dries.

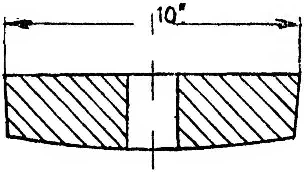

FIG. 63.—Sanding wheel (wood or cast iron)

"Sanding" is performed dry, otherwise special papers or cloths must be used. The wheel has to operate with a circumferential speed of about 2,600 feet per minute, i.e. for a wheel diameter of 8 inches and 10 inches, speeds of 1,250 to 1,000 R.P.M. are necessary. The sanding discs are mounted against the face plate of the polishing stands. The fixing nuts usually fit into a sunk hole of the wheel so that they do not project, and leave the wheel face free for operation. The grit size of the paper is usually no. 220 or no. 240, but to remove final scratches grit sizes of no. 320 and no. 400 are recommended.

LAPPING AND POLISHING OF GEM STONES

Faceting, lapping and polishing of gem stones is performed on metal wheels 10 inches to 12 inches in diameter, which rotate in a horizontal plane. They are called laps. The loose abrasive diamond grain used in diamond cutting would heat the stones too much and cause discoloration. Therefore, the following two principles are applied:

(*a*) "mud" lapping: a mixture of abrasive grit (usually silicon carbide) and water is fed on to the wheel surface; and

(*b*) diamond dust is rolled or hammered into the surface of the soft metal wheel, which allows continuous water cooling without too much loss in diamond powder.

It seems possible to use for these purposes wheels into which diamond powder is bound in a non-metallic or metallic sintered mass, as thereby water lubrication is possible. But these wheels, developed mainly for grinding and lapping hard metal tools, are not suitable for the usual gem-cutting machines. The diameter of 10 inches to 12 inches is too big and would need expensive wheels, but the special machines developed for hardmetal tipped tools are perhaps useful for this purpose.

Nearly all metals are used for "mud" lapping, beginning with cast iron, bronze, copper, tin, pewter, lead, etc. Lead, pewter, and tin are the most common. The old rule was to apply softer laps for softer stones (see, for instance, *Encyclopaedia* of Diderot and Alembert, 1757, Holtzapffel (about 1847), Emanuel (1867). For instance, for stones up to a hardness of no. 8 on Mohs' scale wood, lead and tin, whereas according to recent literature (Schlossmacher, 1932) even lead and tin-zinc prepared with silicon carbide are used for stones as hard as sapphires.

For gem stones of no. 7 Mohs' hardness or below, no. 120 silicon-carbide for roughing, and nos. 400 to 600 for finishing are recommended. For gem stones of no. 8 Mohs' hardness and harder, no. 120 silicon carbide for roughing and nos. 400 to 600 boron carbide for finishing are the best.

An operating speed of 250 feet per minute is needed for facet cutting of minerals of no. 7 Mohs' hardness or below, and a speed of 800 feet per minute for harder materials. These recommendations result in rotating speeds of 100 R.P.M. in the first and 300 R.P.M. in the second case for a wheel diameter of 10 inches.

TABLE 8

SPECIAL POLISHING METHODS FOR GEM STONES

Agate: Polished on beech-wood rollers formed according to the contour shape of work piece (18 to 20 inches in diameter, length up to 40 inches; speed about 200 to 400 R.P.M.). Tripoli with water on periphery side of tin-alloy wheels of 8 to 12 inches in diameter, rotating at 200 to 400 R.P.M.

Jadeite: Silicon-carbide wheels or pure tin discs prepared with aluminium oxide, lubricated with water mixed with vinegar.

Lazurite and Turquoise: Beech-wood rollers prepared with aluminium oxide or leather, felt or cork discs.

Malachite: Beech-wood rollers and softer leather, felt or cork discs prepared with aluminium oxide.

Opal-matrix: Leather disc flexibly held in a frame and prepared with aluminium oxide or tripoli.

For (*b*), bronze and copper discs are chiefly applied, but it seems possible to use other soft metals. After the wheel surface has been smoothly turned, it is somewhat roughened by a special tool and then provided with fine diamond dust by a hammering or rolling process. Investigations concerning these wheels, which are extensively used for grinding corundums, tourmaline and beryl, have recently been made by E. Klueppelberg, to which reference is made on p. 36.

Schlossmacher reports that for the finish grinding of corundum, bronze discs with a rotating speed of 1,000 R.P.M. with hammered or rolled-in diamond dust are used. They are continually lubricated with water. These wheels generate absolutely plane facets and very sharp edges. The diamond preparation has to be renewed after some weeks' continual use.

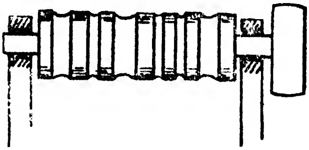

FIG. 64.—Wooden roller with special profiles for polishing curved gem stones; similar grooves are sometimes cut into the plain discs

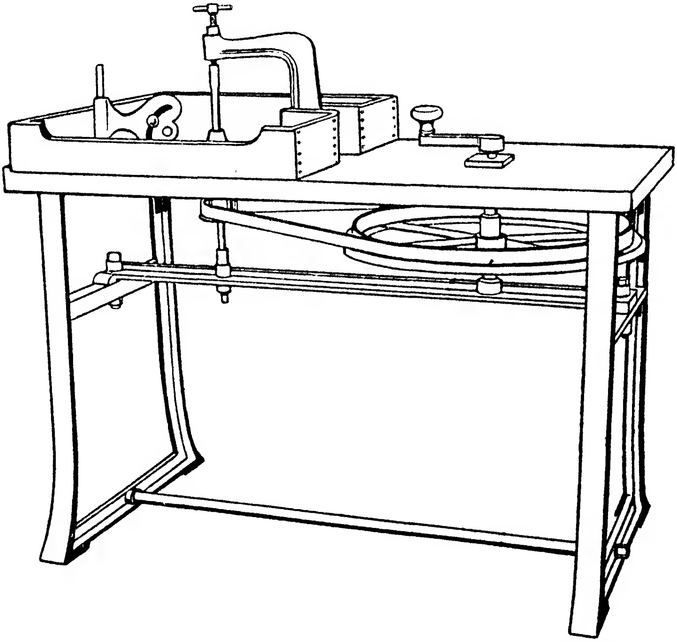

FIG. 65.—Old equipment of the lapidary. The lap (not visible) rotates in a horizontal plane; the vertical axis is held in wooden bearings; the wheel is rotated by the crank (the right-hand side). The stick supporting the stone is fixed to a "quadrant" seen on the left-hand side

In the final operation performed on all gem stones, even the faintest trace of scratches left by preceding operations must be removed to give "lustre." Cabochons are polished after sanding on a leather or hard felt buff (6 inches in diameter, 1 inch thick, 500 R.P.M.). The abrasive paste consists of no. 600 aluminium oxide mixed with water. The paste should be applied frequently and with great pressure. Final buffing to obtain a mirror-like glossy finish on pewter discs of different composition, and pure tin discs, as well as those of copper and bronze are used, the metal is obtained by a mixture of E-111 aluminium oxide, followed by levigated aluminium oxide, or tripoli, or rouge. Best results are obtained with circumferential speeds of 5,000 to 6,000 feet per minute, resulting in rotating speeds of 3,000 to 3,800 R.P.M. per wheel of 6 inches diameter and 1,600 to 1,900 R.P.M. for a wheel of 12 inches diameter.

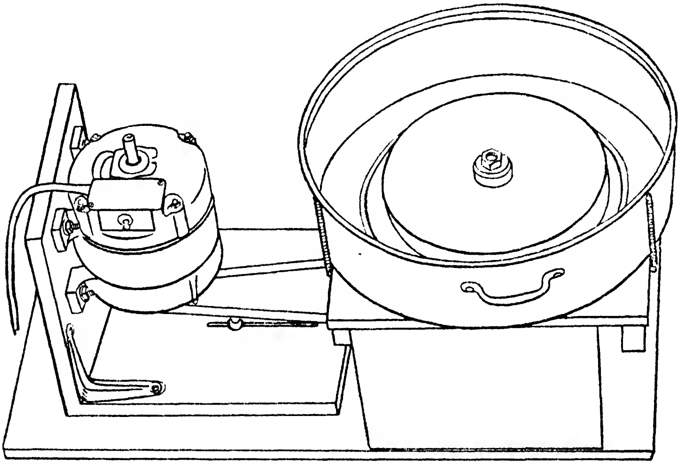

FIG. 66.—Modern lapidary equipment

Polishing operations are frequently carried out on wooden rollers, preferably beech, in the periphery of which the approximate contour of the stone has been worked (Fig. 64). Table 8 contains a survey of some polishing methods in which these rollers are applied. In the Swiss watch-bearing industry, special methods for the mass production of jewels have been developed, and will be described in a subsequent chapter.

On the continent metal laps are also used for these operations. For corundum, diamond dust is mixed in olive oil on a tin-zinc wheel rotating at over 1,000 R.P.M., and the paste applied by means of a leather pad; there is no continuous lubrication. Other, i.e. softer, gem stones are polished on pewter discs of different composition; and pure tin discs, as well as those of copper and bronze are used, the metal chosen according to the cohesion of the mineral to be polished. The wheels have frequently to be turned plane. The usual polishing substances, lubricated with water, such as tripoli, ruby, etc., are used, and in the case of peridot and garnet dissolved sulphuric acid is applied. Highest polish is obtained when the polishing agent just begins to dry.

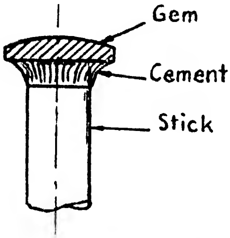

FIG. 67.—Gem stone fixed by cement to the end of a stick

In the older equipment, which is in use even to-day (Fig. 65), the "lap" is driven by a belt from a crank-wheel operated by one hand, while the other hand of the operator holds the stick supporting the stone.[1] The spindle is similar to that of the scaife, provided with two centres placed in wooden bearings. Fig. 66 shows a more modern equipment driven by a small motor in a vertical arrangement. The upper bearing is omitted. The main wheel is usually fitted by a cone, and it is possible to place other metal discs on top of it. In gem cutting, it is important that abrasives of different grit size should not be mixed, otherwise scratches are caused by the larger grains. Instead of thoroughly clean-

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[1] In different countries a varied practice in the arrangement of the "jamb-peg" seems to exist. According to Fig. 65, apparently in German practice, it is on the left-hand side of the worker. Figs. 68, 69 and 70 show a position to the right-hand side. In the first case the crank has to be operated with the right hand. In the case of motor-driven "mills" the peg will be found on the right-hand side of the operator

ing the disc, which involves delay, other discs of about no. 16 gauge (1·6 mm.) are placed on top of the main disc for operations which require another metal or grit size. The lap is surrounded by a big wooden or sheet-metal pan to prevent splashing the abrasive paste (see Figs. 65 and 66).

Gem stones which are softer than diamonds can be cut and polished by application of hand pressure, and therefore the equipment is simpler than in the case of diamonds. The stone is cemented on the top of a wooden stick (Fig. 67), the other end of which is placed against a so-called "jamb-peg"[1] (Fig. 68). In its original form this device consists of a wooden board with numerous conical holes, and is fixed by a vertical or somewhat inclined stem in a hole in the working table. By placing the conical end of the stick in different holes the angle of facets can be changed. The jamb-peg can be turned round its axis, providing a great variety of possible positions of the stick. The stick is always held in the hand,

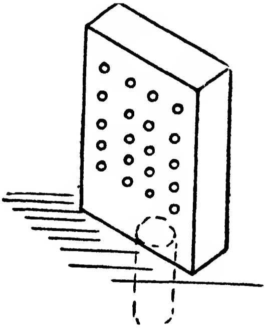

FIG. 68.—Old shape of the "jamb-peg"

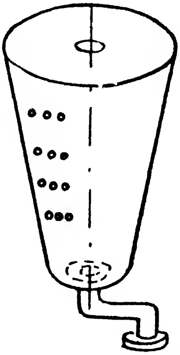

FIG. 69.—Improved form of "jamb-peg"

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[1] In old literature the designation "jim-peg" is found. However, jamb-peg seems to be more appropriate (derivation from *gamba* (Low Latin Italian and Spanish meaning leg, French: *jambe*). Jamb is an expression used in carpentry in relation to doors.

which exerts the necessary cutting pressure, so that the grinding action can be stopped at any moment and the result controlled by turning the stick. Fig. 69 shows a somewhat improved principle of a jamb-peg, consisting of a forged crank and a conical body of wood with holes for fixing the stick. In Fig. 65 the "quadrant" is shown.

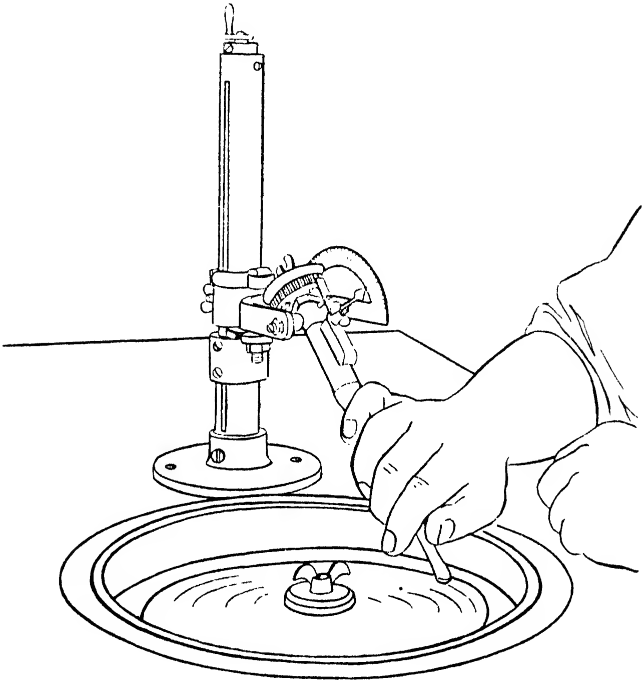

Fig. 70.—Modern equipment for cutting gem stones with facet-cutting attachment

Fig. 70 shows a more modern equipment, used in America, consisting of a vertical metal tube fixed on the table, the inside of which supports a screw mechanism. This tube guides a slide which can be lifted and lowered by means of the screw handle on the top. The slide supports a fork end with protractor into which the stone holder is fixed. This consists of a chuck for the stone and an indexing device, which allows the facets to be adjusted at distinct angles to the axis of the stone, and arranged round the main axis. It seems to fulfil all requirements, and by a single lifting movement the stone can be controlled and replaced in its original position where any alterations would be indicated by the quadrant of the protractor.

GRINDING SPECIAL PLATES AND DISCS OF MINERALS

There are certain difficulties in the manufacture of piezo-electric minerals to obtain their peculiar effects. The plates and discs should have a uniform thickness to very close limits. Usually grinding by hand on a stationary glass plate is applied, as in the preparation of crystallographical specimens, but the methods in their mechanization are more like those of the verifying process (see p. 157). According to A. Hinderlich, the preliminary grinding is carried out on a polishing plate with moist silicon-carbide powder; for the final grinding putty powder (tin oxide) is used, and rouge and water applied for very small alterations.

The method of grinding and polishing is described by Hinderlich as follows: "Upon a sheet of clean flat glass is placed some thin paste of abrasive mixed with water. The fingertips are firmly placed upon the polished side of the quartz so as not to scratch it with loose abrasive. The quartz crystal is swept over an area of at least 30 square inches of glass with gentle pressure to allow a supply of abrasive to come underneath, alternating with heavy pressure to perform the actual grinding. The fingertips are placed on the ground surfaces and not on the edges. After a few movements the fingers are lifted, the quartz rotated 45 degrees, and the fingers are put down again in order that all parts of the quartz may receive an equal amount of grinding. This method has proved quite successful for crystals above 1 mm. thick, but thinner ones are sufficiently flexible for trouble to occur unless great care is taken." The progress of the grinding has to be watched frequently, and sometimes the mineral has to be placed in actual working conditions to determine the exact frequency.

Optical flats of transparent quartz are ground and polished on cast-iron discs prepared with diamond dust, the sawn stone faces are fixed on discs by means of pitch.[1] Polishing is carried out by a series of lapping processes, the number of which depends on the degree of fineness required. Different grades of diamond dust are applied; in the last operations rouge is used, and for extreme accuracy pitch-discs prepared with diamond dust are applied. These operations are carried out on the same type of machine as is used for polishing optical lenses. The stone-carrying discs rotate on a vertical axis (with variable speed from 29 to 100 R.P.M.), the lapping disc performs a sidewards swinging movement. Lapping time is about eight hours, and high accuracy with regard to thickness and evenness of surface is obtained.

GRINDING AND POLISHING OF CRYSTALLOGRAPHIC SPECIMENS

Grinding and polishing of crystallographic specimens, usually materials of varying hardness, are carried out by means of different abrasives on matt glass plates (see p. 103). The specimen is moved by the fingertips or some simple attachments for this purpose are used. Fig. 71, for instance, shows a device for parallel-grinding by Wuelfing. It consists of a tripod with three adjustable screws, a_1, a_2, and a_3, in the centre of which a slotted tube is fitted. The specimen *p* to be ground is cemented to a cylindrical holder which is fixed in the slotted tube by means of a pin *t*. The height of the screws can be adjusted exactly by the measuring wedge *k*, provided on its upper side with a rule. The device is then placed on the glass plate *q*. More elaborate devices of this kind, for instance, equipped with spirit levels, are known. An improved instrument of this kind was manufactured by Jas. Swift & Co., London.

Fig. 72 shows a polishing machine for metallurgical specimens by Messrs. Cooke, Troughton and Simms, which can be usefully applied for polishing softer types of stones. The vertical shaft of the polishing disc is driven through a

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[1] *Engineering*, 15th November, 1940, p. 385.

worm and wormwheel and an endless woven belt by a $\frac{1}{8}$ h.p. motor. The disc can be driven with three speeds, 137·5, 275, and 412·5 R.P.M. The shaft rotates on shielded ball bearings, whereas worm and wormwheel run in an oil-bath. The disc is surrounded by a splash guard with overflow pipe a drain tap. A detachable guard ring serves simultaneously as support for the hand when hand polishing is applied. A height-adjustable water drip tank can be swivelled in any desired position. The specimen is propelled across the disc surface by means of a polishing head. It is fixed to an arm, pivoted on a cast-iron pillar which in turn acts as a fulcrum. A weight at the other end of the arm can be adjusted to vary the pressure applied to the specimen. The polishing head is driven by a cord belt from a pulley at the lower end of the vertical shaft, allowing 100, 200 or 300 R.P.M. The throw of the polishing head is variable. The specimen is cemented by suitable means to the mounting disc. In service the specimen follows the trace of the polishing

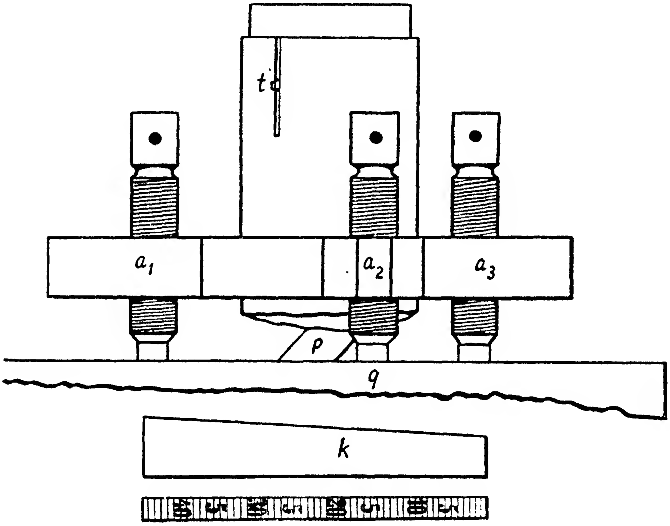

FIG. 71.—Device designed by Wuelfing for the production of a parallel surface on crystals

head, and also automatically rotates about the point of contact between the specimen and the polishing head.

The machine can also be obtained without the special rotating polishing head. The advantage of this device, is, however, that there is less likelihood of the surface of the specimen undergoing a change due to excessive friction, further a perfectly flat surface is obtained.

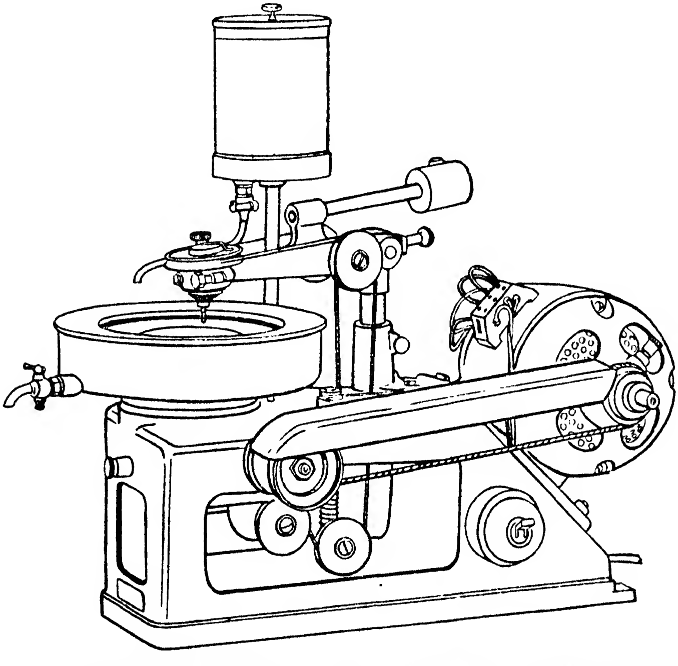

FIG. 72.—Automatic polishing machine by Messrs. Cooke, Troughton and Simms, London

Apparatus for crystallographic specimens with rotating grinding discs has been invented. By far the most ingenious of these machines is that developed by Tutton, and represents a goniometer in which the crystal is cut immediately under observation. Therefore all errors resulting from separate grinding and control are avoided.

CHAPTER V

DRILLING AND BORING OF HOLES

DRILLING of holes in gem stones, even in the hard substance diamond, is an old art, and was cultivated by the old Indians who in this way ruined quite valuable stones. It may be assumed that originally holes were drilled to utilize the stones as bracelets and necklaces. To-day holed stones, in particular those with very small holes, are useful for industrial purposes, as for drawing dies and watch bearings.

The following special drilling tools are employed for producing holes in hard materials:

(*a*) Steel needles with diamond paste for small holes up to 0·0004 inch (equal to $\frac{1}{100}$ mm., i.e. the thickness of the point of an ordinary sewing needle). These tools are also useful for deep holes.

(*b*) Sharp diamond points used for holes between $\frac{1}{32}$ to $\frac{1}{8}$ inch in diameter (0·5 to 3 mm.), and up to $\frac{1}{8}$ inch in length.

(*c*) Tubes with smooth edges for diameters up to $\frac{3}{16}$ inch in diameter (5 mm.); the edge is provided with a paste of fine abrasive powder.

(*d*) Tubes with slightly notched ends prepared with abrasive powder for diameters above $\frac{3}{16}$ inch (5 mm.).

With reference to (*a*) for obtaining a good effect, a sensitive automatic reciprocating movement is necessary (see pp. 160 and 172). Otherwise, insufficient diamond dust is brought between orifice and needle, and the delicate needle point is liable to rapid wear. Very high speeds have to be applied to obtain a grinding effect, as the speed in the centre is nearly zero.

As regards (*b*), (*c*), and (*d*), these operations are carried out only with a rotating movement of the drilling tool and a sensitive hand pressure; it is frequently necessary to lift the tool out of the hole to remove swarf and make the abrasive grains free. The sharp diamond points (Fig. 73), if correctly manufactured, have proved to have a high durability. In a special method of drilling holes in gems two small diamond splinters (carbons) are set in the end of a steel holder (see p. 109). In the two methods (*c*) and (*d*), only a small ring-shaped groove is ground out of the full material, so that no extended cutting work has to be performed. In the case of larger sizes the remaining circular disc can eventually be utilized for other purposes. The tubes under (*c*) are provided with diamond dust, boron carbide, or silicon-carbide of a grit size no. 320, and mixed with water or oil. In the method under (*d*) coarser grains are used, with a grit size of about no. 120. Besides steel, copper and brass are utilized for the tube.

FIG. 73.—Drill with diamond point

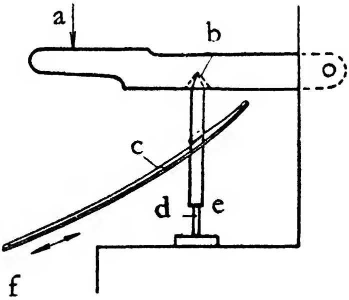

FIG. 74.—Old equipment for drilling stones. (*a*) Pressure with left arm, (*b*) thrust bearing, (*c*) bow, (*d*) drill, (*e*) support of stone to be drilled, (*f*) right hand of operator moving the bow.

The drilling of a relatively deep hole with closed base, as sometimes demanded, presents a difficult problem. In this case tube drills are used, but the core cannot be broken off when the tool is removed. The work is therefore begun with a tube of small diameter, and subsequently tubes of larger diameter are applied, allowing the remaining thin walled partitions to be broken off.

Amongst lapidaries, old-fashioned methods for drilling and boring stones are still in existence. The stone-boring apparatus (Fig. 74), the origin of which can be traced back to the Neolithic age, consists of a swinging holder attached over the working table so that its front end can be placed under the arm-pit and a special vertical spindle, operated by a bow, is placed between the lever and the working bench. The upper bearing for the drilling spindle frequently consists of an agate plate with several conical holes. The drilling spindle is of wood, about ½ inch thick and 4 to 5 inches long, with an inserted steel wire. The upper end is conical and fits into the agate hole, and the lower end has a small hole into which two small sharpened diamond splinters are set. According to a German source, small carbons are used which are rubbed on a diamond crystal (bort) in the shape of a beech nut. After the diamond has been placed in the metal the latter is peened round it. By filing so much metal is removed that the point of the diamond becomes visible. The tool is then tried on a glass plate until the diamond can drill free, an operation which later is perfected by filing.

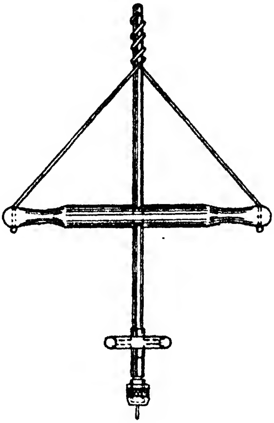

FIG. 75.—Drill used by jewellers for the drilling of fine holes

It is said that a master of this art must not only know how to operate the drill, but he must be in a position to produce his own.

Round the spindle a string is wound, the ends of which are attached to a bow. The gem stone to be drilled is either cemented on to an iron plate or clamped by suitable means. The lever is pressed under the left arm-pit, the left arm is placed on the table, and the left hand eventually guides the drill spindle when the operation has started. The drilling is carried out by a kind of sensitive reciprocating movement of the bow.

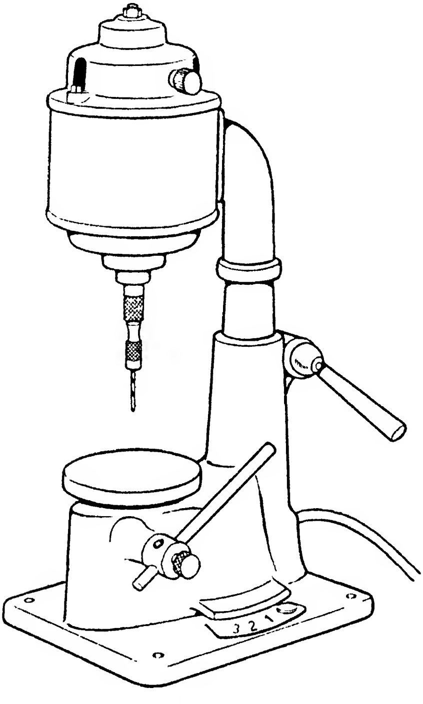

Fig. 76.—Modern drilling machine with stationary motor and movable plate

In the jewellery trade, another kind of old-fashioned drill appliance is introduced, known as *treuil*, French for rotating-arbor. It consists of a spindle and a double-armed lever (Fig. 75), which can be moved up and down. Between the ends of this lever and the top of the spindle two cords are attached which are wound round the spindle. When holding the lever between two fingers and moving the hand up and down the spindle is set in high-speed rotation. A needle provided with diamond dust is placed in a little chuck at the end of the spindle which performs the drilling operation. With this, pressure and feed can be sensitively controlled by the hand of the operator. The correct handling of this tool requires great skill; it is, for instance, applied in the

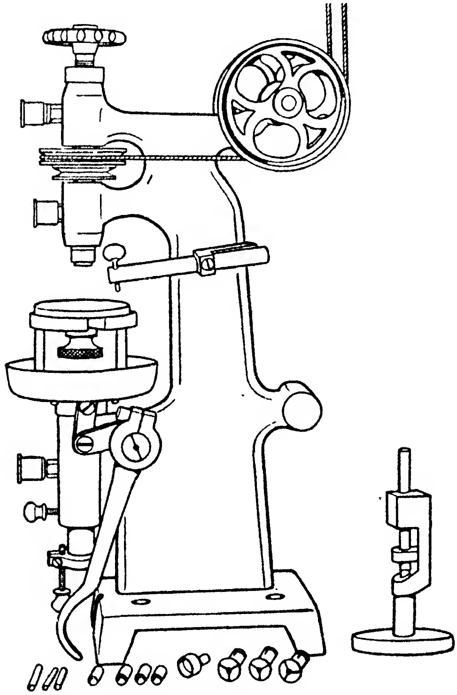

Fig. 77.—Swiss machine for the boring out of jewels from plates by means of tubes

drilling of pearls, as the drilling through the shell must be watched carefully.

In the modern industry use is made of high-speed electric drilling machines which have needles or tubes provided with diamond dust mixed with oil. In these machines (Fig. 76) the table supporting the stone is fed against the drilling tool. This principle has proved to be more sensitive than feeding the boring or drilling spindle against the stationary work-piece as is usual in hand-operated drill presses.

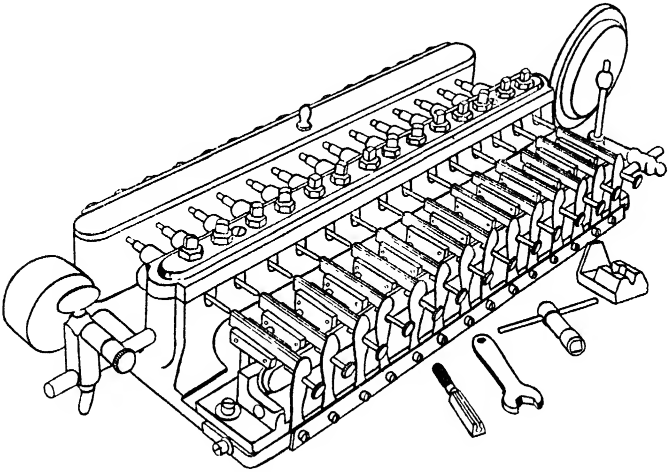

FIG. 78.—Multiple drilling machine for fine holes

Fig. 77 shows a machine used for cutting out the small circular plates necessary for watch bearings. The method is similar to that applied in the boring of glass. The boring tubes, provided on the edge with diamond dust, are held in collets. The plate to be cut rests on a small table, and is cemented to it. A hand lever allows the table to be fed against the tube rotating at high speed. The movement is limited by adjustable stops. In front of the machine different sizes of tubes (usually between 0·04 to 0·8 inch) and collets are shown, together with a device for inserting diamond grain in the edges of tubes. The machine will cut out approximately one hundred rubies per hour, and stones which have to be bored can be centred in the same operation by placing a sharp diamond point in the centre of the boring tube.

Fig. 78 shows a battery of fourteen small drill units used for watch bearings and similar stones. Usually ten to eighteen units are combined in one machine, and driven by a single belt arranged in serpentine form over the pulleys. Owing to the high speed of the small shafts (about 28,000 R.P.M.), they are supported at their rear end on leather, while the shaft rests in a special metal causing the least friction. The stones are held by cement on small slides which are reciprocated in the same way as the drill spindles. The feed pressure is generated by means of a soft spring. With the same drill of thin steel wire about ten stones can be drilled; after this, the end is cut off and the drill centred again. One operator can supervise a stone-drilling battery producing fifty rubies or 100 garnets per hour.

In the manufacture of diamond and hardmetal dies, other methods are in use by which, in addition to the high-speed rotating movement, a mechanical reciprocating movement is exerted by a cam under the pressure of a soft spring. As the machines evolved for this purpose are used exclusively in the manufacture of dies, methods and processes will be described in their special place.

CHAPTER VI

CARVING AND ENGRAVING

The engraving of precious stones to produce cameos and intaglios and sometimes of diamonds is performed by rotating tools which can be classified as follows:

(*a*) Small grinding wheels of various shapes provided with diamond dust on their periphery.

(*b*) Small grinding wheels of various shapes in the surface of which diamond dust or another hard abrasive is embedded.

(*c*) Small vitrified grinding wheels of various shapes using silicon-carbide as the abrasive.

(*d*) Small diamond points with a chisel edge or small conical diamonds.

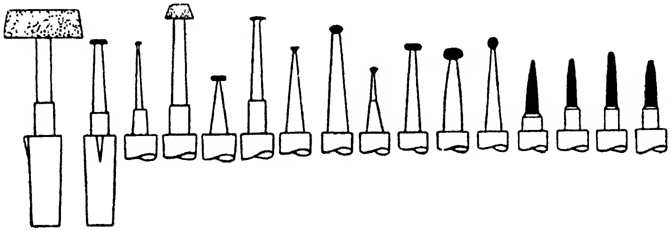

Fig. 79.—Various forms of engraving tools with conical shafts

Special tool forms (so-called *zeiger*) are used for engraving purposes in (*a*), (*b*), and (*c*). Fig. 79 gives the usual shapes, the diameters ranging from fractions of an inch to about two inches. The preparation of these tools is described elsewhere. Frequently now, small vitrified grinding wheels containing silicon-carbide with a grit size of about no. 80 are used. These small grinding wheels are usually equipped with cylindrical shafts, but their shape is similar to those shown in Fig. 79.

With reference to (*d*) the use of diamond points for engraving purposes, even in the very hard substance diamond seems to be old. It can be assumed that in these earlier applications only rough stones of suitable shape were used, perhaps only rough shaped by means of another working diamond (see p. 62). The application of ground diamond points for these operations is a more recent development. The diamond points (Fig. 80) are cut in a manner similar to the hardened steel chisels used for engraving metals. Recommended speeds for these tools are up to 30,000 R.P.M. Small diamond points, only rough-shaped but with a sharp point, are on the market, and they are not only suitable for marking and engraving metal, but also for the engraving of gem stones.

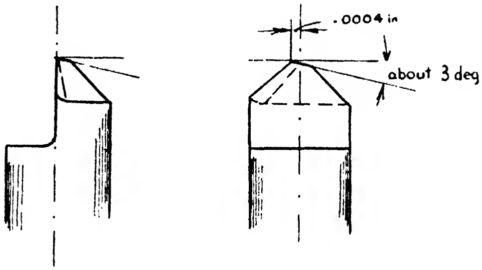

FIG. 80.—Shape of a special diamond point for engraving purposes; setting and size of the diamond point not taken into consideration

All these tools have to operate at a very high speed. Formerly, the tools were probably rotated by hand-operated drills (such as shown in Fig. 74). The earliest data are a reconstruction of a drilling device by Forrer, and the illustration on a tombstone of a Greek lapidary. But in the Middle Ages benches with a small horizontal spindle driven by a foot-operated lever, similar to the equipment used till now, were known. Perhaps the oldest illustration of such a machine is found in the *Staendebuch* (book of professions) by Jost Ammann, a Swiss, published in 1568. Fig. 81 shows a more modern lapidaries' bench, operated according to the same principle. The horizontal spindle runs in two bearings, between which the driving pulley is arranged. The speed is usually 1,000 to 4,000 R.P.M., easily obtainable with the treadle-drive or by means of an electric motor. The tools are easily exchangeable. The stone to be worked is conducted against the tool by the hands of the artisan, whose elbow is placed on small bolsters on the working table.

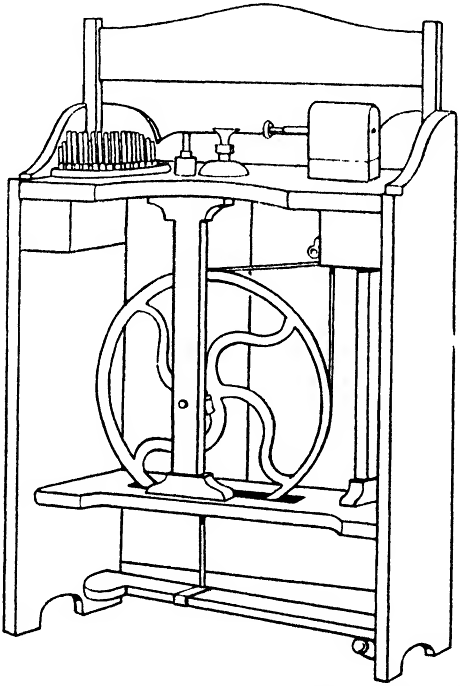

FIG. 81.—Bench with treadle drive for engraving

In modern workshops a fractional horse-power motor with precise and accurate ball bearings is used, and the spindle is equipped with a quick actuating universal chuck holding the tools. Usual speeds are 10,000 R.P.M. and more. In all these cases the stone is held in the hand and brought to the high-speed rotating tool. Only recently this method has been reversed by using a motor-driven flexible shaft, the hand-piece of which is receiving the tool. This makes a great difference in the working methods, as here the stone is stationary and the tool is guided by hand. The small hand motors now used extensively for similar work are too large for this fine work, and hand-pieces driven by flexible shafts are preferred.

Fig. 82 shows a stationary machine; the shaft of the fractional h.p. motor supports a special chuck for taking a grinding or polishing tool on one side, whereas the other side supports a special belt-driven device for propelling a flexible shaft equipped with a hand-piece. This device permits a universal turning of the flexible shaft. In this way both methods are combined in a single machine. The base of the motor contains a switch for three different motor speeds.

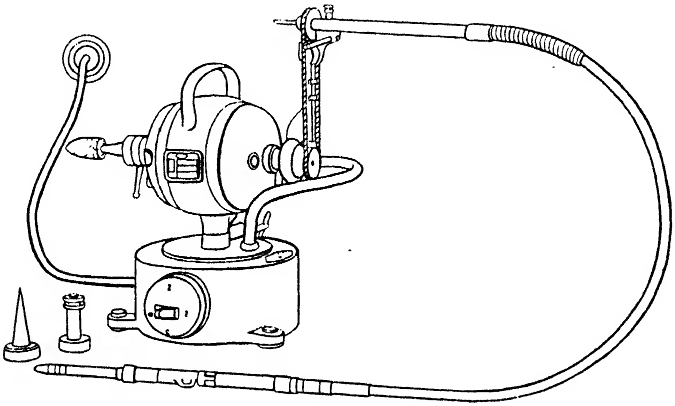

Fig. 82.—Modern equipment with stationary motor adjustable for three speeds; one end of the spindle supports the engraving tool in a chuck, the other end drives the flexible shaft

Fig. 83 shows the correct grasping of a hand-piece holding an engraving tool. The hand-piece is driven by a small flexible shaft from a hand motor fixed on a suitable stand. In the background various grinding tools can be seen. This picture is a good illustration of the point that even the modern hand motors, small in size, are too big for using on fine work. Even smaller hand motors, however, may be available in the near future.

With regard to the equipment shown in Figs. 82 and 83, the original use of these small motors, flexible shafts and hand-pieces was in dentistry. As a matter of fact, the shape of the small tools is very similar.

For smoothing or semi-polishing carved or engraved gems, points or discs of steel, copper, wood, leather, or horn fibre, and small strong hair-brushes are used. The ends of these tools are pasted with no. 600 silicon-carbide or boron carbide and a heavy machine oil. For high lustre a polishing paste, such as levigated alumina, tin oxide, tripoli or rouge, is recommended.

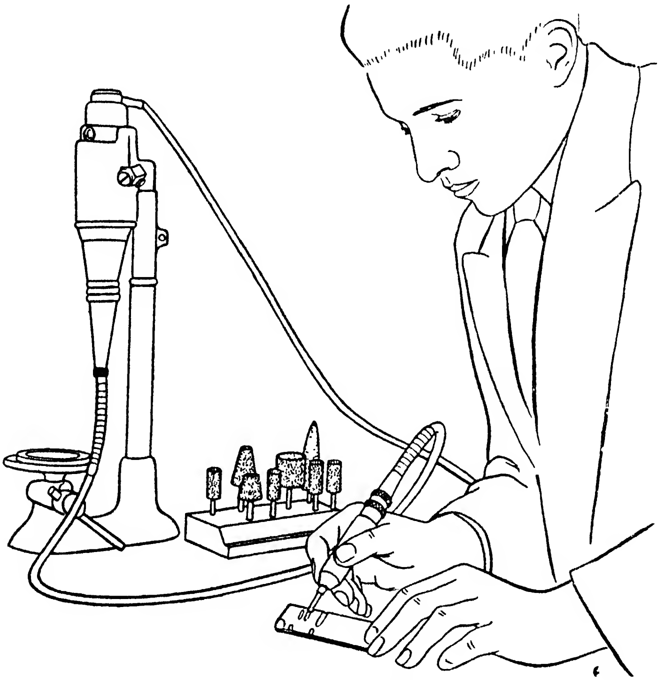

FIG. 83.—Engraving by using the hand-piece of a flexible shaft driven by a small hand motor, made stationary by a special stand

Agate and chalcedony are the materials chiefly engraved producing good effects owing to their striated structure. Diamonds are seldom engraved in spite of the fact that there are frequent allusions to them in literature and some interesting examples were shown at the Brussels World Exhibition. The Middle Ages produced engraved diamonds, while from the Orient came the most famous example, the diamond known as the Shah. The work of the engraver calls for great skill; besides technical prowess, he has to have a steady hand and a keen eye, accompanied by true artistic talent and a long schooling.

CHAPTER VII

DIAMOND POWDER

DIAMOND powder, originally waste matter from cleaving and bruting processes, was used only for grinding and polishing the diamonds. Now it is considered as the best abrasive material because of its great hardness and sharp corners (see the results of tests on p. 31). Owing to the large consumption of it, several industries set up special machinery[1] for crushing the diamonds besides the usual hand-operated mortars.

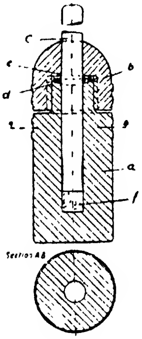

FIG. 84.—Standard model of diamond mortar
a, mortar body *b*, screw cap
c, pestle *d*, hemispherical washer
e, flat washer *f*, diamonds to be crushed

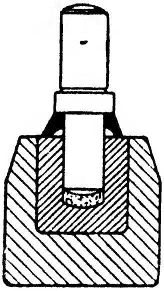

FIG. 85.—Small model of diamond mortar

For crushing smaller amounts, steel mortars are used in which a steel plunger with a good rounded end is applied. To avoid any loss of the costly powder, the inner part of the mortar is fully protected by a shell-like cover (Fig. 84). For even smaller quantities, more primitive mortars, such as shown in Fig. 85, are used, in which a rubber ring serves for

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[1] See, for instance, *Machinery* (London), vol. 57, no. 1480, p. 561.

sealing purposes. To crush the inserted diamond material, the steel shaft of the mortar is heavily struck with a wooden or bakelite hammer.

For a larger production of diamond dust several methods similar to those used in the production of other abrasives have been applied, but satisfactory results have only been obtained with appliances in which the powder is produced by a blow-like action. It has been established, even in the case of other abrasive materials, that grains of a better form and with sharper corners are obtained than by the application of milling and rolling equipment. There are machines for crushing diamond powder which can handle up to five hundred carats in one charge. To make use of the powder for cutting and polishing purposes the crushed material, still consisting of grains of various sizes, must be cleaned and graded. For this process, sieving or screening[1] and washing methods are employed. For many purposes sieving through several fine-mesh wire-gauze screens is quite satisfactory, but for polishing only very fine washed-out diamond powder, usually below a grit size of 0·002 inch (0·05 mm.), should be used.

TABLE 9

Grades of Diamond Dust According to "Machinery's Handbook"

No. 1.	10 minutes	No. 4.	2 hours
No. 2.	30 minutes	No. 5.	10 hours
No. 3.	1 hour	No. 6.	Until oil is clear

A common washing method, according to *Machinery's Handbook*, is to mix the crushed diamonds thoroughly with a high-grade olive oil. This mixture is allowed to stand five minutes, and then the oil is poured into another receptacle. The coarser sediment which is left is removed and labelled no. 0. The oil poured from no. 0 is again stirred and allowed to stand ten minutes, after which it is poured into another receptacle and the sediment remaining is labelled no. 1. This operation is repeated until practically

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[1] See automatic machine, Fig. 125, which can also used for sieving purposes.

all the dust has been recovered from the oil, and the time that the oil is allowed to stand is increased progressively in order to allow a longer time of precipitation for the smaller particles.

Table 10

COMPARISON OF GRIT SIZES AND MESH SIZES*

Imperial Standard†	A.S.T.M.‡	Dutch Standard N. 380§	Number per cm. linear	Number of Holes per sq. cm.	Clear Space,	
					mm.‖	in.
—	325	—	130	16,900	0·040¶	0·0016
300	270	0·05	110	12,100	0·053¶	0·0021
—	230	0·06	100	10,000	0·060	0·0024
240	—	—	90	8,100	0·066¶	0·0026
200	200	0·075	80	6,400	0·075	0·003
170	170	0·09	70	4,900	0·090	0·0035
150	140	1·05	60	3,600	0·100	0·004
120	120	1·25	50	2,500	0·12	0·0047
100	100	0·150	40	1,600	0·15	0·006
85	80	0·175	35	1,225	0·177¶	0·007
72	70	0·210	30	900	0·2	0·008
60	60	0·250	24	576	0·25	0·01
52	50	0·300	20	400	0·3	0·012
44	45	0·350	18	324	0·34¶	0·013
—	—	—	16	256	0·4	0·016
36	40	0·420	14	196	0·43¶	0·017
30	35	0·5§	12	144	0·5	0·02

* For finer sizes see Table 11.

† British Standards Institution, B.S.S. 410-1931.

‡ American Society for Testing Materials, 1926.

§ The Dutch Standard Sieves are designated according to the clear space in mm.; above 0·5 mm. holed sieve sheets are prescribed.

‖ According to the German Standard Specification D.I.N. 1171, March 1934, with the exception of sizes marked ¶.

No. 0 grade is known as ungraded or coarse dust; it is usually washed in benzine and recrushed.

Besides washing and grading in oil, grading takes place in alcohol and water, resulting in finer and more uniform powder owing to the lower viscosity of these fluids. Water

TABLE 11

FINER GRIT SIZES (SO-CALLED FLOUR SIZES)

Norton no.	Number per cm. linear	No.*	Approximate size, mm.
280	100–120	—	0·053
320	130	3	0·040
400	150	4	0·030
500	200	5	0·025
600	250	—	0·025

* According to Table 9.

TABLE 12

GRIT SIZES AND APPLICATION OF DIAMOND DUST

No.†	Approximate Corresponding Grit Size no.	Designation	Grit Size, mm.	Application
0	Larger than 85	Coarse	Grit of different sizes above 0·18	Coarse grinding, drilling, sawing, engraving
1	85–120	Medium	0·12–0·17	Pre-grinding, enlarging of large die holes
2	120–200	Fine	0·08–0·12	Finishing and for small die holes
3	200–300	Fine-fine	0·05–0·08	Fine grinding
4	300–400	Extra-fine	0·03–0·05	Pre-polishing, lapping
5	∞–500	Extra-fine-fine	0·0–0·025	Finish polishing
6*	∞–2,500	Superfine	0–0·005	Mirror-finish

* A continental diamond dust manufacturer offers a fine diamond dust even with maximum grit sizes of 0·003 mm., 0·0015 mm., and 0·0005 mm. for finest polishing purposes.

† These nos. are not the same as given in Table 9.

is also the cheapest medium. The usual process is to screen the diamond dust first and to apply the washing process later on for the higher grades.[1] High-grade diamond dust, particularly for polishing and lapping, should be of nearly uniform grain size, to avoid scratching and scoring. If the diamond dust is not crushed and graded in the worker's own workshop care must be taken that only a good quality is bought. For high-grade work the diamond dust should also be clean before use, see page 243. Hitherto, there have been no standard designations for diamond dust. Frequently the mesh and grain sizes as applied for other abrasives are used, but special numbers are given by different manufacturers which have no relation to another.

In Table 10 the grit sizes obtained with sieve gauzes are given; below grit sizes of 0·05 mm. the sifting must be performed by washing processes (hydraulic separation). The smaller grit sizes that have been calculated are given in Table 11, and compared with the ordinary numbers. Table 12 also gives some more specified data with regard to diamond dust and its applications. As to the other abrasive materials, such as aluminium oxide, silicon carbide and boron carbide, it is referred to in other technical literature.

It has proved to be of advantage in special cases to mix diamond dust with powders of lower hardness, such as boron carbide, tungsten carbide, silicon carbide to obtain good lapping and polishing effects.

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[1] Mr. W. F. G. Kerley, Lydbrook, Glos., submitted to the author the following recipe for the production of fine diamond dust, used for diamond die drilling. After having passed a sieve of no. 200 mesh the diamond grain is washed in olive oil for the following periods:

no. 1	3 min.	no. 4	2 hours
no. 2	10 min.	no. 5	5 hours
no. 3	20 min.	no. 6	24 hours

CHAPTER VIII

DIAMOND DUST IMPREGNATED TOOLS

A NEW and extended field of application was opened not long ago by processes in which diamond dust is mixed with other materials of lower hardness to form resistant bodies. The origin of these processes may be the idea of utilizing an inferior and cheaper raw material (a large part of diamond production consists of crushing bort and small diamonds), and to bring it into a shape with characteristics similar to complete diamond crystals or the crypto-crystalline formation of Carbonado. In spite of the fact that it will hardly be possible to obtain the same results with composite materials as with crystals, improved tool materials may be developed with superior characteristics to those hitherto in use. Such composite tools have already been successfully employed in the case of boring crowns, truing tools for grinding wheels, and grinding and lapping wheels, while their application to drawing dies, and even as metal-cutting tools, has been suggested. These far-reaching ideas are only in the course of development, but already several practical results have been obtained.

Table 13 contains a summary of the methods which have been tried out to bind diamond dust in other substances. With regard to the action of these tools, besides the holding material (its strength, toughness, hardness, and in particular at elevated temperature), much depends on the diamond concentration, i.e. the amount of diamond grain contained in the binding mass. Figures of diamond concentration that have been given vary considerably. Usual concentrations are below 30 and range to 10 per cent and even less. High concentrations may prove to be less effective as the surrounding matrix loses its grip on the single grain before

TABLE 13

PRODUCTION METHODS OF DIAMOND-BONDED GRINDING AND CUTTING TOOLS

Type of Production	Matrix	Temperature and Pressure	Examples
Diamond grain embedded in solid metal	Heavy Metal	Cold	
	Light Metal	Heated and tempered after embedding	G.P. 591879 and G.P. 659019
Diamond grain embedded in a fluid or plastic substance	Molten Metal	High	G.P. 236739
	Amalgam	Low	
	Electro-plating	Low	G.P. 4024
Diamond grain mixed with powdered substances and cemented in by application of heat and pressure	Metal Powder	High temperature, high pressure	B.P. 367871, U.S.A.P. 625463, G.P. 583630, Bel.P. 416751, *Jl. Chem. Met. Min. S.A.*, Feb. 1938, p. 365
	Hard Metal Powder	High temperature, high pressure	B.P. 349732, B.P. 436430, B.P. 533627, U.S.A.P. 1895534, G.P. 590707, G.P. 611800, G.P. 622823, G.P. 627862, U.S.A.P. 2074038
	Resin Powder	Relatively low temperature, not harmful to the diamond	S.P. 170525, F.P. 803212, U.S.A.P. 2150886 (metal and resin powder)
	Ceramic Powder		U.S.A.P. 2174453

ABBREVIATIONS

G.P.	German Patent.	Bel.P.	Belgian Patent.	S.P.	Swiss Patent.
B.P.	British Patent.	F.P.	French Patent.	U.S.A.P.	U.S.A. Patent.

the abrasive power of the latter has been fully utilized; therefore, the higher concentration becomes uneconomical. A diamond concentration not less than 50 per cent of the total mass is employed in tools made according to the Neven process.[1] It is understood that this mass contains special binding materials.

A manufacturer of phenol-resin bound diamond wheels offers three different concentrations: C, high concentration; B, medium concentration 50 per cent of C; A, low concentration 25 per cent of C. The A concentration is recommended for off-hand, side grinding, whereas tool and cutter grinding is best done on wheels of the C concentration. For milling cutters, B concentration is recommended, except for dry grinding for which C concentration is said to be more efficient. The latter is always recommended for peripheral grinding operations.

It is generally not very economical to use wheels fully prepared with diamond dust. In the case of a superficial embedding and the electro-plating process, diamond dust provides only very thin surface coatings. The thickness of the diamond preparation in phenol-resin bonded wheels varies between $\frac{1}{32}$ inch in seven steps of $\frac{1}{32}$ inch to $\frac{1}{4}$ inch (0·8 to 6·35 mm. in seven steps), but wheels with diamond preparation up to the arbor are also supplied. Small grinding wheels usually contain a diamond preparation up to the arbor.

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[1] *Machinery* (London), vol. 57, no. 1480, p. 561.

II

SPECIAL MANUFACTURING METHODS

CHAPTER IX

THE MANUFACTURE OF DIAMONDS AND GEM STONES FOR ORNAMENTAL PURPOSES

THIS book would be incomplete if some short notes were not given on this subject. The cutting and polishing of diamonds and other gem stones for industrial purposes would not have developed so much if the methods and this equipment, improved during many years, had not been available. Cutting and polishing of diamonds for ornamental purposes is dealt with in nearly all books on precious stones, and the reader who is specially interested in this subject, in particular in the various shapes of these stones, will find assistance in these books.

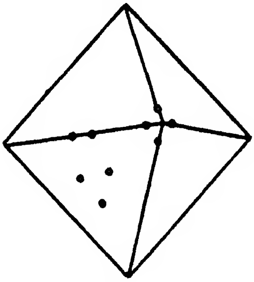

FIG. 86.—Situation of the so-called points on a diamond octahedron

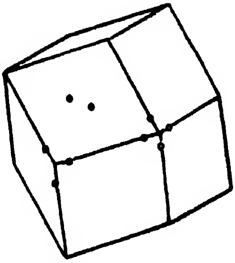

FIG. 87.—Situation of the so-called points on a diamond rhombic dodecahedron

DIAMONDS—BRILLIANTS

To produce diamonds for ornamental purposes the following main operations are necessary:

(*a*) Cleaving or sawing, to bring the natural stone into a more regular form, in particular to an octahedron shape.

(*b*) Bruting, to bring the stone into a pear-like shape.

(*c*) Cutting and polishing (faceting operations).

The methods applied and the equipment necessary for these operations have been already described in foregoing paragraphs.

For the production of brilliants according to the practice followed in Holland and Belgium, three different kinds of manufacture are distinguished by the different structure of the rough stones which obviously cannot be brought into a generally applicable system. These methods of forming the stone are of great importance for both the bruting and

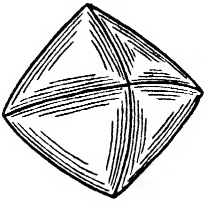
Fig. 88A

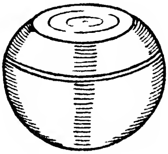
Fig. 88B

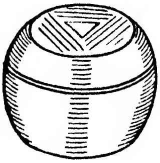
Fig. 89

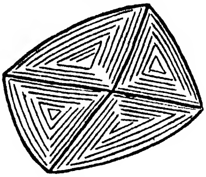
Fig. 90A

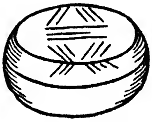
Fig. 90B

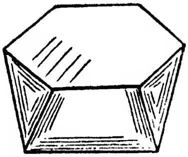
Fig. 91A

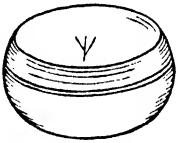
Fig. 91B

Methods of bruting rough stones
Fig. 88.—Four-point. A, rough stone; B, bruted
Fig. 89.—Three-point, bruted
Fig. 90.—Two point. A, rough stone; B, bruted
Fig. 91.—Sawn diamond (bruted as two-point). A, rough stone, B, bruted

the following cutting processes. The differences lie in the arrangement of the table with regard to the crystal structure of the diamond. Stones can be cut as: (A) Four point; (B) Three point; (C) Two point.

Fig. 86 shows the situation of these points on an octahedron, and Fig. 87 on a rhombic dodecahedron. The positions of the tables and the bruted stones are shown in Figs. 88 to 91. Fig. 91A shows a sawn stone resulting in a hexagonal table and bruting according to two point.

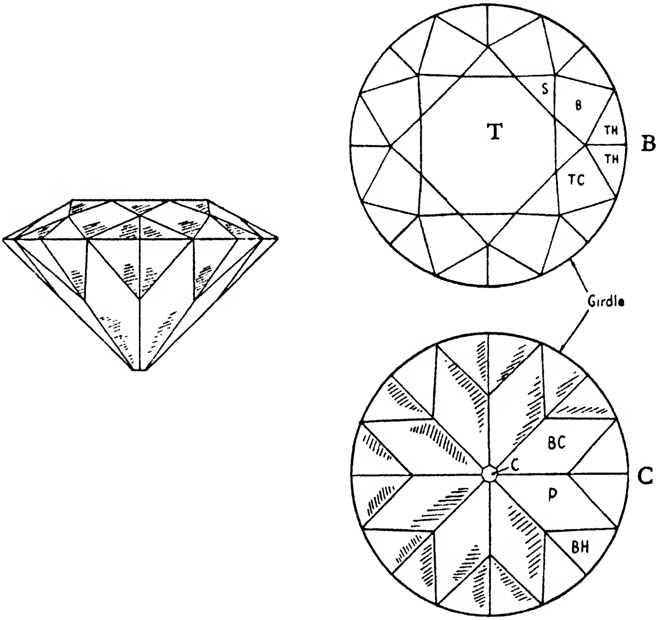

Fig. 92.—Brilliant cut, A, B, and C
A, side view; B, top view; C, bottom view

The shape of the finished brilliant is shown in Fig. 92. It consists of a total of fifty-eight facets which have special names. They include one table T (octagon), eight star facets S (triangle), four bezel or top main facets B (four-sided), four top corner facets TC (four-sided), sixteen top half or break facets TH (triangle), sixteen bottom half or break facets BH (triangle), four bottom corner facets BC (four-sided), four pavilion or bottom main facets P (four-sided), and one collet C. Another surface of the brilliant, and the only one which remains rough, is the surface of the large diameter, the so-called girdle. Fig. 93 shows a cross-section and the main designations of the brilliant.

Cutting (grinding) of the brilliant is divided into three groups, and individual craftsmen exist who are trained in these special groups, in spite of the fact that usually one cutter is trained to finish the whole stone. The groups are:

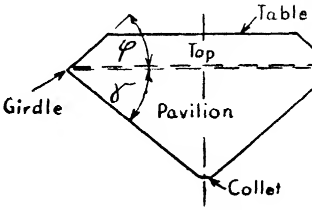

FIG. 93.—Main designations for the brilliant cut inclusive angles (see Tables 14 and 15, pp. 137 and 138).
Instead of "Top" the designation "Bizet" is also usual

(1) Cross work (Fig. 94).
(2) Octagon work (Fig. 95).
(3) Brillianteering (Fig. 96).

The table is the largest facet, and the cutting of the brilliant starts on it; the next facet, the smallest, is the collet just opposite the table; on modern stones it is very small and sometimes omitted. After these two facets have been cut, one of the big side facets is placed on the stone to be followed by the cutting of the opposite facet; the cutting of the corner facets then starts; these operations are performed on both the top and bottom of the stones. This work, the "cross work," is the most important, as it gives the correct width and thickness to the stone. The aim is to make the finished stone as large as possible, therefore the table should not be made too large in proportion to the stone. But both

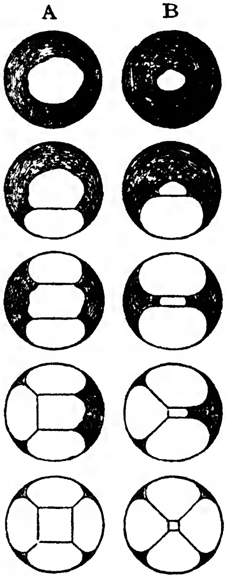

FIG. 94.—Cross work. A, top; B, bottom
Operation starts on the top side

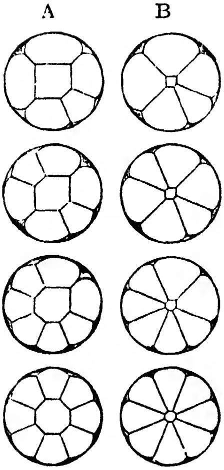

FIG. 95.—Octagon work.
A, top; B, bottom

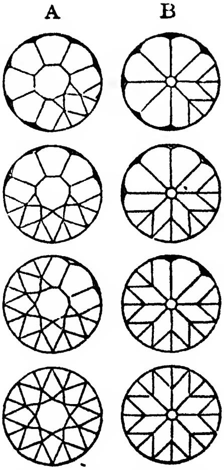

FIG. 96.—Brillianteering.
A, top; B, bottom

Operation starts on the top side

the size of the table and the size of the collet are reduced during the cross work and during further faceting.

In the octagon work (Fig. 95) the so-called four main facets are started by truncating the edges so that the square table is converted into an octagon shape. Also in this case one works from one facet to the opposite one. There are four main facets in the top and bottom part of the stone.

The last operation is the "brillianteering" (Fig. 96). This is carried out in such a way that the corners of the table octagon are again truncated, thus replacing this octagon by another of somewhat reduced size; in effect, four facets are intersecting in each corner of the new octagon. The lower part of the edges going out from the original octagon are also truncated, resulting in two girdle facets; the same operations are performed in the bottom part.

During the last few years, investigations have been carried out on scientific lines to improve the brilliancy and reflecting power of the diamond and of other gem stones, making use of the law of total reflection and the refractive index. These investigations led to "ideal" forms of diamonds and gem stones, but these ideal values cannot be applied exactly in practice as it is impossible to keep the theoretically correct angle. Further obvious differences in the angles exist between the sides and edges of facets. These considerations have led to the establishment of rules for practical stone cutting, also taking into account the thickness of the girdle. Table 14 gives the main data for the ideal form of brilliants, and Table 15 gives the practical forms according to a recent publication of Dr. W. Fr. Eppler. The last word in this connection has not yet been spoken. Some experts disagree with Dr. Eppler, but so far he has displayed the most knowledge and experience in this respect.

There exist a few modifications of the brilliant cut for smaller stones and several fancy shapes, with the intention of keeping as much material in the finished stones as possible. For example, there is the "double brilliant" (or Lisbon) cut and the "half brilliant" (or old English or single cut). These are some of the forms for fancy shapes (the approximate

TABLE 14
IDEAL BRILLIANT FORMS OF TRANSPARENT MINERALS

Mineral	Refractive Index *n*	Limit Angle of Total Reflexion	Height of—		Total Height		Table Diameter		Angles‖ of Main Facets		Angle of Table-Facets
			Upper Part	Lower Part	Without Girdle	With 2 per cent for Girdle	Without Table-Facets	With Table-Facets‡	ϕ Upper Part	γ Lower Part	
		Deg.	Per cent¶	Per cent	Per cent	Per cent	Per cent	Per cent	Deg.	Deg.	Deg.
Diamond* ..	2·42	24·5	19	40	59	61	56	—	41·1	38·5	—
Zircon* ..	1·95	30·9	22·0	40·7	62·7	64·7	59·0	—	47·0	38·8	—
Corundum*	1·77	34·5	24·0	40·9	64·9	66·9	60·0	—	50·2	38·9	—
Spinel* ..	1·73	35·4	24·6	41·0	65·6	67·6	60·5	—	51·0	39·0	—
Topaz* ..	1·63	37·8	26	41·1	67·1	69·1	61·0	—	53·0	39·1	—
Tourmaline†	1·62	38·1	27·3	40·7	68·0	70·0	59	—	53·1	39·1	(29·50)
Beryl†§ ..	1·59	39·0	27·9	40·7	68·6	70·6	59·4	—	54·0	39·1	(29·10)
Emerald ..	1·58	39·3	28·1	41·1	69·2	71·2	56·6	47·8	52·3	39·4	(29·0)
Aquamarine†	1·57	39·6	28·1	41·6	69·7	71·7	53·1	41·8	50·1	39·8	(27·6)
Rock crystal	1·54	40·5	27·5	42·9	70·4	72·4	44·2	15·8	44·5	40·6	(24·1)

* Values according to S. Roesch.

† Values according to W. Fr. Eppler.

‡ For minerals with *n* smaller than 1·59, to avoid losses in brilliancy.

§ Morganite (pink).

‖ See Fig. 93.

¶ The width at the girdle being taken as 100.

TABLE 15

PRACTICAL FORMS OF BRILLIANTS (DIAMONDS)*

Kind of Cut	Thickness of Girdle in Percentage of Diameter	Angle‡ of Main Facets		Height of—		Total Height—		Table Diameter in Percentage of Girdle Diameter	Height Relation of Upper to Lower Part	
		φ Upper Part	γ Lower Part	Lower Part	Upper Part	Without Girdle	With Girdle		Without Girdle	With Girdle
	Per cent	Deg.	Deg.	Per cent §	Per cent	Per cent	Per cent	Per cent		
Ideal	0·8	41·1	38·7	40·0	19·2	59·2	—	56·1	1 : 2·1	—
No. I†	1·4	35·6	38·6	39·9	16	55·9	57·3	55·3	1 : 2·5	1 : 2·4
No. II†	1·5	33·1	40·1	42·1	14	56·1	57·6	57·1	1 : 3·0	1 : 2·9
No. III†	6·3	32·8	41·7	44·6	10	54·6	60·9	69·0	1 : 4·5	1 : 3·6

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* According to Eppler and Klueppelberg: *Der praktische Brillantschliff des Diamanten, Deutsche Goldschmiedezeitung*, no. 25, 1939.

† No. I. Fine cut for small brilliants (loss in brilliancy, 10 per cent).
No. II. Fine cut for large brilliants (loss in brilliancy, 5 per cent).
No. III. Cut with consideration of the weight for small brilliants (lower loss in brilliancy than nos. I and II).

‡ See Fig. 93.

§ The width at the girdle being taken as 100.

shape given in brackets): Baguette (oblong), cut corner triangle (triangle, with the corner edges of the small base truncated), hexagon (hexagon with two long sides), key stone (trapezoid), kite (rhombic shaped with two long sides), half-moon, lozenge, marquise or navette (oval with two points), pentagon or bullet (rectangular base with point), square, trapeze and triangle, pear-shaped or pendoloque. Small fragments resulting from cleaving and sawing larger stones are also cut for use as roses. They are called melee ($\frac{1}{8}$ to $\frac{1}{16}$ carat size) and small melee (as small as $\frac{1}{400}$ carat size).

Several times an attempt has been made to mechanize brilliant production. The symmetrical construction of the brilliant seems to lend itself to a more mechanical procedure, by application, for instance, of indexing devices to obtain the various facets round the central axis and a special inclination to adjust the side angles.[1] In the case of brilliants made of imitation stones, in particular of glass and haematite, which are required in large quantities for cheap imitations, special machinery has been set up, as in Pforzheim, Germany, and Gablonz, formerly Czechoslovakia. With regard to diamonds, it is only known that semi-automatic machinery has been made in the U.S.A. and several patents exist.

Kraus and Slawson refer in their textbook on *Gems and Gem Materials* to the fact that semi-automatic machines for the polishing of diamonds (i.e. brilliants) have been devised and they show an illustration of such an equipment which was already contained in the two first editions (1925 and 1931) of this book. It is mentioned that this represents the Stern-Coleman machine and *was* (the italics are ours!) used in the establishment of Messrs. Stern Brothers and Co., New York. It has ingenious mechanical devices consisting of a micrometer gauge and a degree finder in combination with a tripping device. The angles and planes to be polished on the diamond are predetermined and the machine is set by the operator. When the desired depth is attained and the angle of the stone is polished, the tripping device automatically

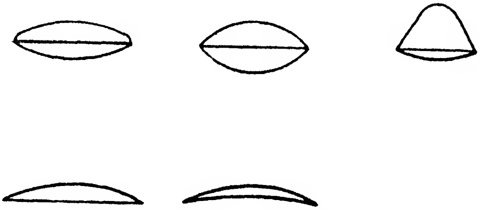
[1] See pp. 98, 102 and 141.

removes the stone from the polishing disc. One attendant can operate several machines at a time and it is claimed that the highest technical skill is no longer required.

Besides the skill necessary to place a diamond in the correct position towards the wheel, the diamond cutter must have a keen eye for the size of the minute facets. It is said that a large number of cut stones have not got accurately sized and distributed facets, but these fine differences in set stones will not become evident to the layman.

GEM STONES

Whereas in the cutting of gem stones no special requirements as to the crystal structure are set, the lapidary has to consider the crystal directions from an optical point of view to find out the directions giving best colour (dichroism).



Figs. 97 and 98.—Cabochon cut

These stones are quite often given the same shapes as diamonds as a result of their colour and different reflective power from which other angles result (Tables 14 and 15). Frequently the stones are given in place of a facet cut, a stepped cut with a big table and one or more rows of facets placed parallel to table and girdle. The oldest known method of stone polishing, the cabochon cut, is often also applied. The old shapes of cutting survive in the shape of double or convex cabochon, lentil cut, high cabochon, simple, plain or single cabochon, hollow or concave-convex cabochon (Figs. 97 and 98). This refers to the shape of cross-section, for the outline of these stones can be circular, elliptical or oval.

These stones are mostly fashioned by hand by using a template to obtain an equal or special curvature, although some shapes could be machined by special machinery, such as that used for the grinding of glass lenses in the optical industry, or by the application of grinding wheels with corresponding grooves in the rim. Actually these stones are not in such demand that the cost for greater mechanization would be justified.

The gem stones cut in brilliant form lend themselves more to a mechanized production than other forms and harder substances, such as the diamond, which has to be cut with regard to its grain structure. Besides the equipment shown in Fig. 70 (p. 102), a Swiss machine is of interest. Here the laps rotate in a vertical plane. The machine (Fig. 99) for grinding and polishing of gem stones to the shape of brilliants has two parallel, horizontal shafts from which one supports a copper wheel for grinding, the other a tin wheel for polishing. The wheels rotate with a speed of 1,300 to 1,500 R.P.M. giving, on the outer periphery of a wheel 3 inches in diameter, peripheral speeds of about

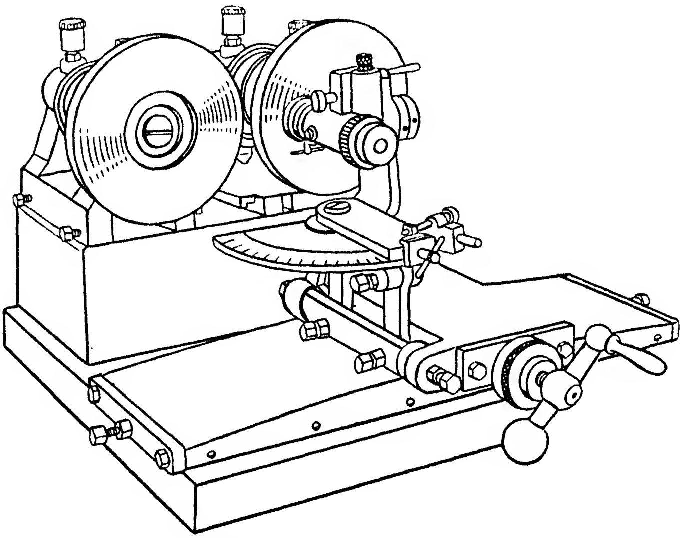


FIG. 99.—Swiss machine for accurate facet cutting on gem stones

1,000 to 1,200 feet per minute. In front of the wheels the stone holder and an adjusting device with quadrants in horizontal and vertical plane, as well as a transverse and longitudinal slide, are arranged.

CHAPTER X

THE MANUFACTURE OF WATCH AND PIVOT BEARINGS

As watch and pivot bearings are wanted in large quantities, their manufacture has been mechanized for a longer time; the manufacturing centres are in Switzerland and the French Jura.

SHAPES AND SIZES OF JEWEL STONES

The size of jewel stones for watch and pivot bearings is very small, and there exists a great variety of shapes and sizes. Only recently has standardization been attempted. Figs. 100 and 101 show the three main shapes of stones used

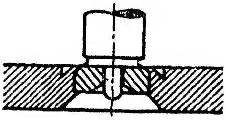


FIG. 100.—Holed stone such as used in watches

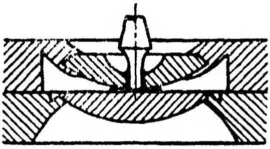


FIG. 101.—Holed stone and end stone, used for instance for the balance of watches

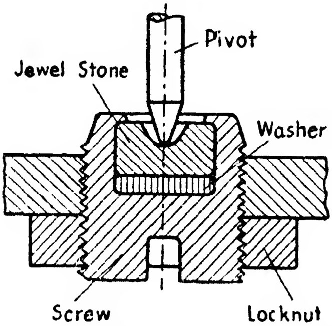
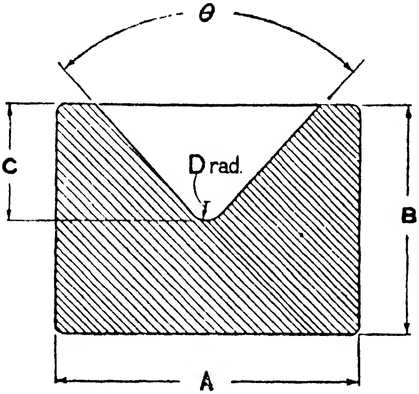


FIG. 102.—Cup-stone, used for compasses and pivot bearings

in watches, i.e. holed or ring stone (Fig. 100), drop-like stone with hole and end stone (Fig. 101). The illustrations show the mounting and the position of the shaft. Fig. 102 shows a pivot bearing, such as is used in instruments. The usual range of size of watch bearings, as produced in the Swiss watch-bearing industry, is given in Table 16.



FIGS. 103 to 106.—B.S.S. Instrument jewels
FIG. 103.—V-Jewel (see Table 17)

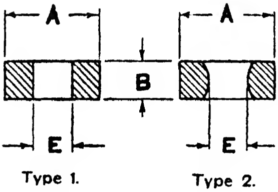


FIG. 104.—Ring stones (see Table 18)

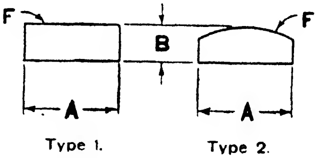


FIG. 105.—End stones (see Table 19)

Recently a British Standards Specification for the dimensions of instrument jewels was issued (B.S.I. no. 904—1940).[1] This specification excludes jewels for watches

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[1] Abstracted by permission from British Standard Specification no. 904—1940, official copies of which can be obtained from the British Standards Institution, 28 Victoria Street, London, S.W.1, price 2s. post free.

TABLE 16

USUAL SIZES OF WATCH JEWELS

	Outer Diameter No.*	Hole Diameter No.†
Glass garnet (*Spiegel-granat, glace grenat*) ..	7–20	8–10
Glass, ruby (*Spiegel-rubin, glace rubis*) ..	7–20	8–17
Ruby for the balance (*Balancier-rubin*)‡ ..	7–20	8–17
Droplike-stone-garnet (*Tropfenförmiger-Stein, goutte*)	11–25	14–36
Droplike-stone-ruby	11–25	14–36
Centre-stone-garnet (*Zentrum-stein*) ..	15–30	50–100
Centre-stone-ruby (*Zentrum-stein*)	15–30	50–100

* In $\frac{1}{10}$ mm. † In $\frac{1}{100}$ mm.

‡ See Figs. 100 and 101.

TABLE 17

V JEWELS (See Fig. 103)

Diameter A	Thickness* B	Depth of Recess C	Included Angle of Recess Cone θ	Radius at Base of Recess D
mm.	mm.	mm.		mm.
$1^{+0}_{-0\cdot04}$	$0\cdot75^{+0}_{-0\cdot04}$	0·4 ± 0·05	75° ± 5°	0·04 ± 0·02 0·08 ± 0·02
$1\cdot25^{+0}_{-0\cdot04}$	$1^{+0}_{-0\cdot04}$	0·5 ± 0·05	80° ± 5°	0·04 ± 0·02 0·08 ± 0·02 0·12 ± 0·02
$2^{+0}_{-0\cdot04}$	$1\cdot5^{+0}_{-0\cdot04}$	0·75 ± 0·05	85° ± 5°	0·04 ± 0·02 0·08 ± 0·02 0·12 ± 0·02

The eccentricity of the axis of the cone shall not exceed 0·005 mm.

* The thickness of sliding jewels shall be as given in Table 16, or, alternatively, shall be 1¼ times the diameter. If this greater thickness is required it should be definitely specified by the purchaser as, normally, manufacturers will supply jewels of the thicknesses given in the table.

TABLE 18

RING STONES

(See Fig. 104)

Diameter A	Thickness B	Bore E
mm.	mm.	mm.
$1{\cdot}25^{-0}_{-0{\cdot}015}$	$0{\cdot}4^{-0}_{-0{\cdot}04}$	$0{\cdot}3^{-0}_{-0{\cdot}005}$
$1{\cdot}25^{-0}_{-0{\cdot}015}$	$0{\cdot}5^{-0}_{-0{\cdot}04}$	$0{\cdot}5^{-0}_{-0{\cdot}005}$
$2{\cdot}0^{-0}_{-0{\cdot}02}$	$0{\cdot}75^{-0}_{-0{\cdot}04}$	$0{\cdot}75^{-0}_{-0{\cdot}005}$
$2{\cdot}25^{-0}_{-0{\cdot}02}$	$1{\cdot}0^{-0}_{-0{\cdot}04}$	$1{\cdot}0^{-0}_{-0{\cdot}005}$

The eccentricity of the axis of the hole shall not exceed 0·005 mm.

TABLE 19

END STONES

(See Fig. 105)

Diameter A	Thickness B
mm.	mm.
$1{\cdot}25^{-0}_{-0{\cdot}02}$	$0{\cdot}25^{-0}_{-0{\cdot}04}$
$1{\cdot}25^{-0}_{-0{\cdot}02}$	$0{\cdot}5^{-0}_{-0{\cdot}04}$

and clocks and cup jewels for integrating meters, but it seems that work with regard to these jewels is in progress.

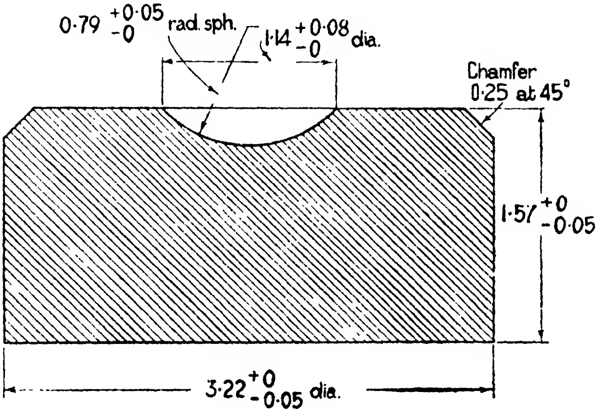

Fig. 106a

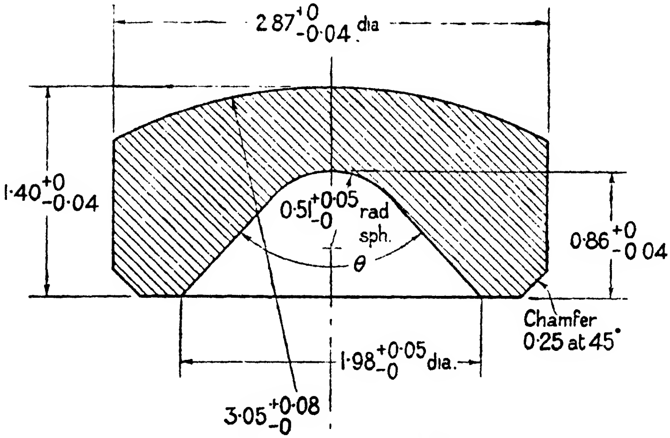

Fig. 106b

The standard mentioned comprises three sizes of **V**-jewels (Fig. 103 and Table 17), four sizes of ring stones (Fig. 104 and

Table 18), with cylindrical hole and a hole with rounded chamfer (in the latter case the form is arranged between purchaser and manufacturer), two sizes of end stones (Fig. 105 and Table 19), either flat or curved, and three different sizes of compass jewels (Fig. 106A, B, C). The appendix contains remarks as to the inspection of jewels. The given tolerances are, in relation to the small size of these jewels, not very exacting, and the finish required shall be subject to agreement between purchaser and manufacturer.

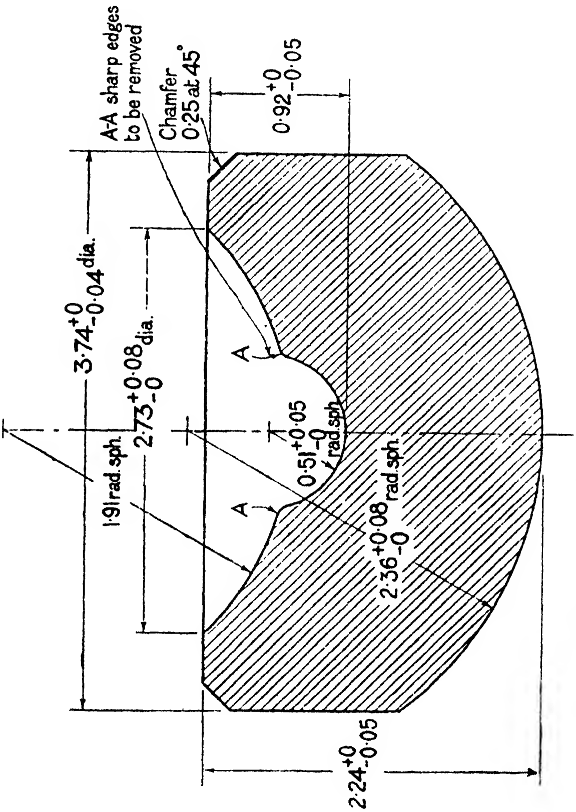

FIG. 106C.—Figs. 106A, B, and C, compass jewels; all dimensions in mm.

Besides natural and synthetic sapphires, rubies, garnets and diamonds are used. Owing to the difficulties in machining these hard materials, the costs for the numerous operations (see Table 20) remain high despite machinery to speed up production. The finished product costs about two hundred to four hundred times as much as the rough material. On the other hand, this justifies the application of even expensive raw materials such as diamonds.

Table 20 gives an example of the different manufacturing processes applied for the production of a holed stone with curved surface. The main operations and special appliances (as far as they are not described in Section 1) will be treated in the following.

DIVIDING

Before machining, natural as well as synthetic stones have to be divided by cleaving or sawing. Besides the equipment described in Section 1, special machines are used in the watch industry. Figs. 107 and 108 show a sawing machine differing from others of this kind by the fact that the sawing is carried out by a mechanical feed. The machine can take several sawing blades on the same arbor, so that in one cut several plates can be separated. The stone is clamped into

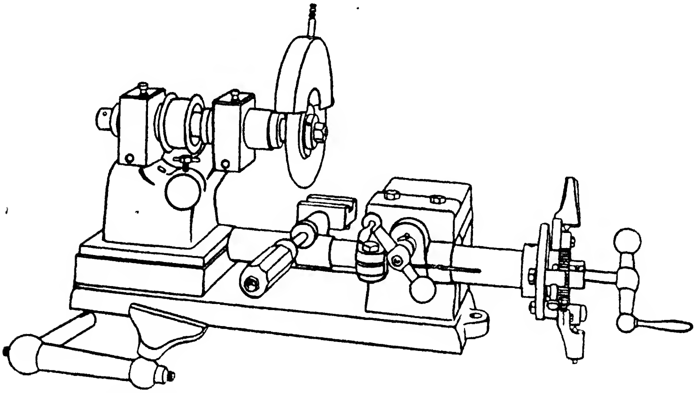

FIG. 107.—Sawing machine used for cutting rough stones into small plates of equal thickness; at the left-hand side toolrest for truing the disc

TABLE 20

SCHEDULE FOR THE PRODUCTION OF A CURVED AND HOLED STONE (*LOCHSTEIN*)

No.	Operation	Machine	Tool	Special Device
		I. PREPARING		
1	Washing	In diluted sulphuric acid		
2	Sorting	—	—	—
2	Sieving	—	—	—
		II. ROUGHING (*Préparage, Ebauchage*)		
1	Sawing (dividing)	Sawing machine (Fig. 107)	Diamond prepared disc	Loaded by weight
2	Turning or trepanning	Turning lathe (Fig. 109)	Diamond cutting edge	Off-hand
		Special drilling machine (Fig. 77)	Tube, edge prepared with diamond dust	—
3	Grinding of surfaces	Grinding and polishing machine (Fig. 110)	Disc prepared with diamond dust	Cemented to holders or wheels
4	Inspection	—	—	—
5	Sieving for thickness	Off-hand or special machine (Fig. 125)	—	Automatic
6	New-setting and cementing	—	—	—
7	Grinding to required thickness (verifying)	Hand-operated machine (Fig. 116)	Disc prepared with diamond dust	Off-hand
		Special machine (Fig. 114)	Disc prepared with diamond dust	Automatic
8	Drilling	Special drilling machine, one or multiple spindles (Figs. 78 and 120)	Needle with diamond paste	Automatic

III. Finishing (*Finissage*)

1	Drilling	See under II, 8	See under II, 8	See under II, 8
2	Enlarging of holes (*grandir*)	Special machine (Fig. 121)	Wire with diamond paste	—
3	Turning of the external diameter	Turning lathe (Fig. 109)	Diamond cutting edge	Off-hand
4	Turning of the oil cavity ..	Turning lathe (Fig. 109)	Diamond cutting edge or diamond lap	Off-hand
5	Polishing of oil cavity ..	Turning lathe (Fig. 109)	Wood, ebonite or fibre-needle with diamond dust	Off-hand
6	Polishing of curvature ..	Turning lathe (Fig. 109)	—	Off-hand
7	Washing	—	In alcohol	(For removing cement)
8	Resetting on other surface	—	—	—
9	Grinding to correct thickness	Grinding machine (Fig. 114)	Disc prepared with diamond dust	—
10	Polishing of surfaces ..	Grinding machine (Fig. 118)	Polishing disc	—
11	Rounding the hole edge ..	Turning lathe or special machine	Sharp copper point	Off-hand
13	Polishing of the edge (*olivier*)	Special machine	Copper needle with diamond dust	—
14	Inspection of shape ..	Optical equipment (Fig. 124)	—	—
15	Sorting or sieving ..	Special machines (Fig. 126)	—	Automatic

a small vice placed on a feeding device of high accuracy by means of a ratchet. In the clamping of the stone exactly parallel cuts can be carried out.

BRUTING

The next operation is to make circular discs out of the sawn plates. Diamonds and other hard precious stones are machined on bruting machines or small lathes (Fig. 109), having a considerably higher speed, i.e. 8,000 to 10,000 R.P.M. Softer stones are machined on silicon-carbide grinding wheels with horizontal spindles. In the case of small lathes, the stone to be machined is cemented to a plate fixed on the rotating spindle. The lathes are equipped with an adjustable T-rest serving as abutment for the working

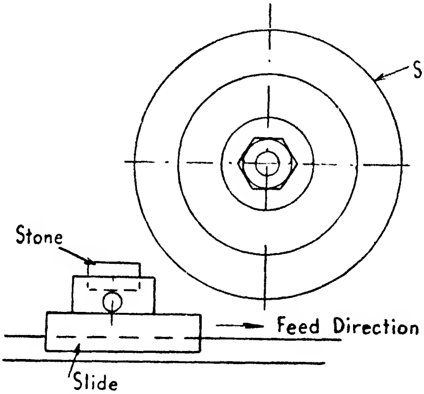

FIG. 108.—Principle of the sawing operation in machine, Fig. 107

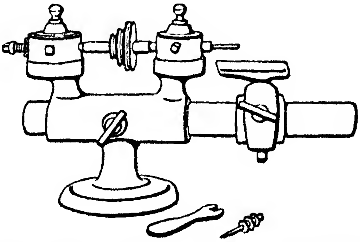

FIG. 109.—Small lathe used in manufacturing jewel stones

diamond which is cemented to a holder operated by hand. Usually, these machines are not equipped with the sheet-metal containers for catching the diamond dust in the case of bruting the diamond.

As a substitute for these processes, which require skilled craftsmen, the trepanning process has been introduced in the industry. By means of small copper or steel tubes prepared on their edge with diamond dust, circular discs are cut out. Such a machine (Fig. 77) has a capacity of about one hundred rubies per hour.

GRINDING AND POLISHING

The main production method is grinding and polishing the flat and circular surfaces, including drilling and subsequent enlargement of holes, production of curved shapes, and so forth. In the watch-bearing industry, in contrast to the cutting of diamonds and gem stones, grinding and polishing machines with a horizontal shaft and, therefore, discs rotating in a vertical plane,[1] are preferred. In this case the operation can be better observed during running of the machine, and

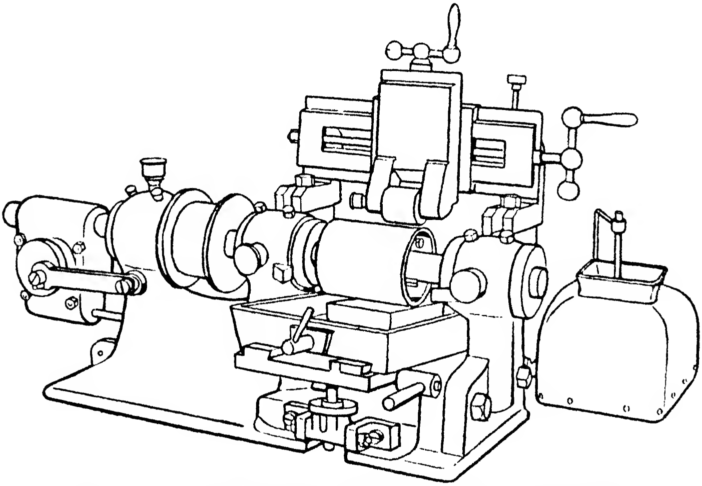

FIG. 110.—Flat grinding machine with roller and plate

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[1] See, for instance, Figs. 99, 113, 114, 115, 117 and 118.

the adjustment for the grinding of facets seems to be more simple. It is said that the grinding capacity of such a machine is larger, but the disc rotating in a horizontal plane has the advantage of the abrasive not being so liable to fall from the wheel.

Fig. 110 shows the machine for grinding the sawn stones and is of rigid construction. The main steel roller, ¾ inch in diameter and 4 inches long, performs, in addition to its rotating movement, a small reciprocating movement by a mechanism seen on the left-hand side of the machine. It consists of a worm connected with the shaft, a worm-wheel, and a crank drive connected with the base of the machine.

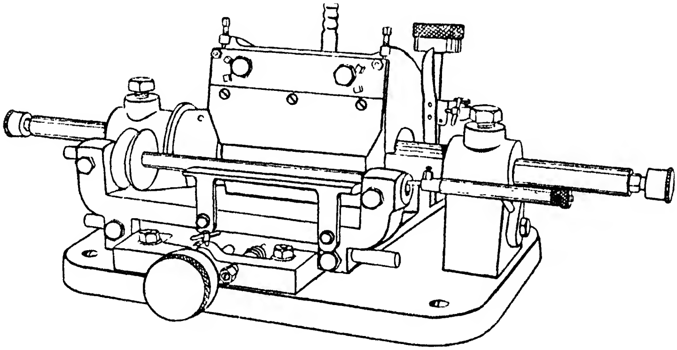

FIG. 111.—Machine for producing round stones

The stones are cemented to a table, the axis of which can swing with regard to the base, and is raised or lowered at the front end to adjust it towards the periphery of the roller. Above the main roller a small roller for charging the former is placed, situated on a compound rest. It can be detached, and the machine is covered during operation by the hood seen at the side.

Finishing of the outer diameter of the stones is now performed on special machines based on the principle of the centreless grinder. They consist of one main grinding wheel and a feed or control wheel, between which the stone is held in a special holding and feeding device. Fig. 111 shows the machine, but the construction of the holding device is not quite clear. This operation starts with a silicon-carbide grinding wheel, and is continued on a grinding wheel charged with diamond dust for giving the stones the exact diameter.

Fig. 112 shows a machine for charging the grinding wheel. It is strongly built, with the pillar blocks on ball bearings (double-row type) so that it can sustain a considerable strain. The movement of the back roller is directed by a mechanism with worm and worm-wheel similar to that shown in Fig. 110. The front roller can approach the grinding wheel to be charged by a winch. The grinding wheel is placed on a mobile stand.

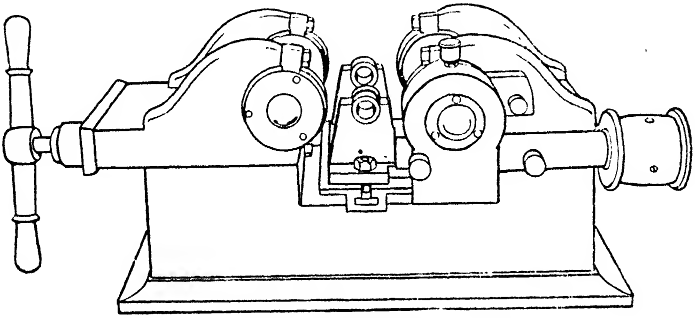

FIG. 112.—Charging machine for Fig. 111

A larger number of smaller stones which have to be ground to a flat shape are cemented to a rotating plate (Fig. 113). Whereas the stone-supporting plate rotates only at 300 to 500 R.P.M. (circumferential speed about 300 to 800 feet per minute for a diameter of 4 to 6 inches), the grinding wheel, with a diameter of 10 inches, rotates at 1,200 to 1,500 R.P.M. (3,000 to 3,500 feet per minute). The stone-supporting plate is reciprocated by hand across the surface of the grinding wheel, but for a fine adjustment of the thickness of the stone a feed screw is provided operated by a handwheel on the right-hand side of the machine. The machines are so constructed that the stone-supporting disc can be easily turned away without removing the wheel from the spindle. In one design the motion of the stone-supporting wheel is performed by a slide (straight-line motion), but in other models a swinging lever is used (Fig. 113). The capacity per hour of the machine is said to be 1,500 rubies or 3,000 garnets. A micrometer feed corrects any wear of the grinding wheel.

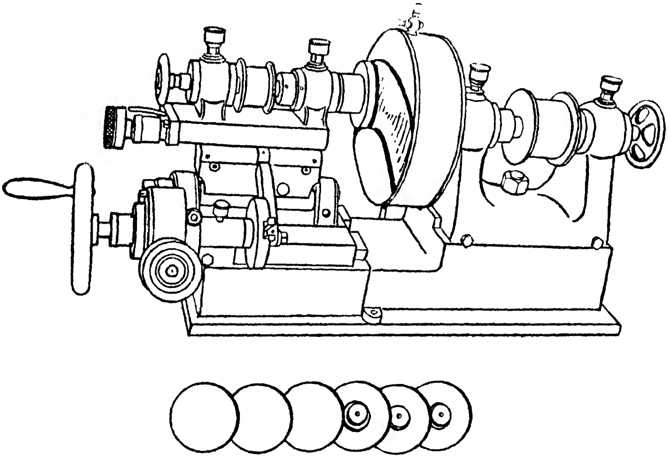

FIG. 113.—Flat grinding machine; the stones are fixed to a plate, a diamond-impregnated disc with rotating and oscillating movement serving as a tool

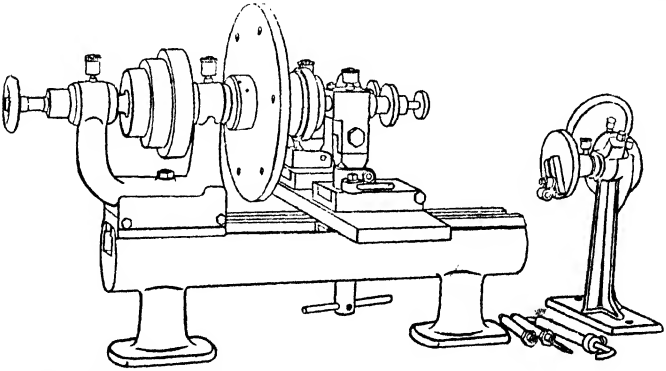

FIG. 114.—Flat grinding machine for exact thicknesses (verifying machine)

For the production of parallel surfaces having an accurate distance, necessary for flat stones of a certain width, the stones are cemented with their ground surface to special discs and machined on the free surface (Fig. 114). The slide supporting the stone-carrying disc has a fine adjustment up to $\frac{1}{100}$ mm. (0·0004 inch) axial direction, so that taking into consideration the thickness of the cementing film an accurate thickness of the stones may be obtained. Assistance in this direction is given by steel discs of the desired thickness which are made blue on their free side and fixed to the wheel. If these control-discs are touched by the grinding wheel, the white steel appears and the operator knows that he has to stop the machine. Fig. 115 is a stronger model of the machine shown in Fig. 114. This has an attachment

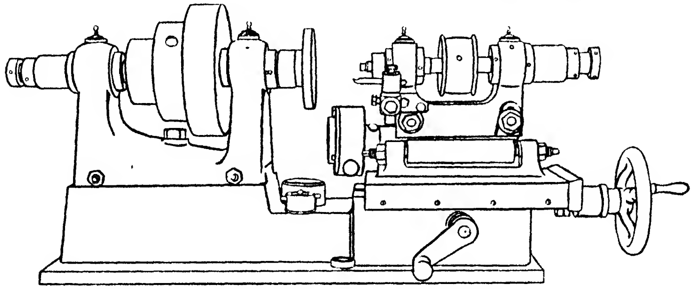

FIG. 115.—Stronger model of a verifying machine

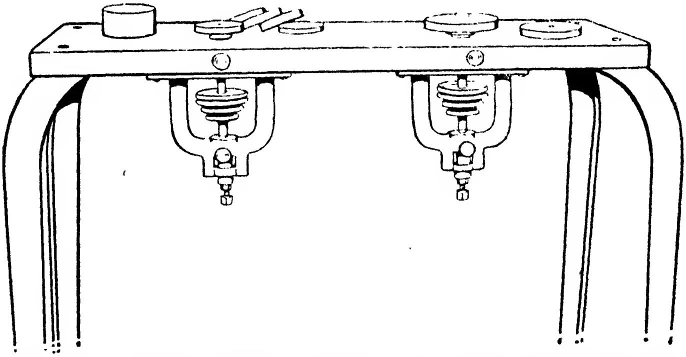

FIG. 116.—Hand-verifying machine for single-piece production

at the saddle supporting a steel for turning the outside diameter of the stone. The exact thickness of the stones is also obtained on simple machines with vertical shafts in which the same principle is applied in single piece production (Fig. 116); the rate of production is about three thousand stones per day.

In individual production the stones are finish polished on the small lathes. For this purpose a small arbor of horn or an alloy of tin and lead, shaped according to the surface or the curvature of the stone is used. This arbor or lap is provided with fine diamond dust and gently moved across the stone with a swinging movement. In mass production, plane surfaces, curvatures, and cavities are machined on special polishing machines (Fig. 117), as far as they are not combined with grinding machines (Fig. 118). For plane surfaces, as well as metal discs, wooden discs (pear-tree, maple, etc.) are employed, while for polishing curved stones, tambico and silk fibre brushes are used. In this case the stone-supporting discs are placed on slides. The operations are performed with considerably reduced speeds; the polishing wheel rotates at 400 R.P.M., whereas the stone-supporting disc rotates only at 30 to 50 R.P.M. In the case of brush polishing, the single

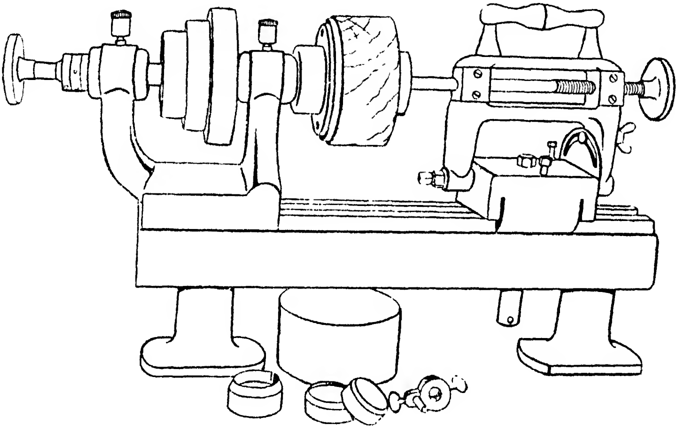

FIG. 117.—Stone polishing machine

stones obtain a somewhat larger distance than is usual in the case of polishing by wooden discs.

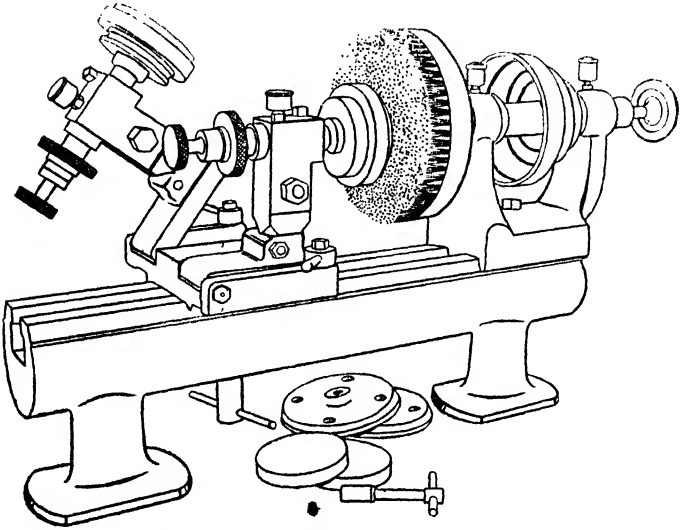

FIG. 118.—Special polishing machine

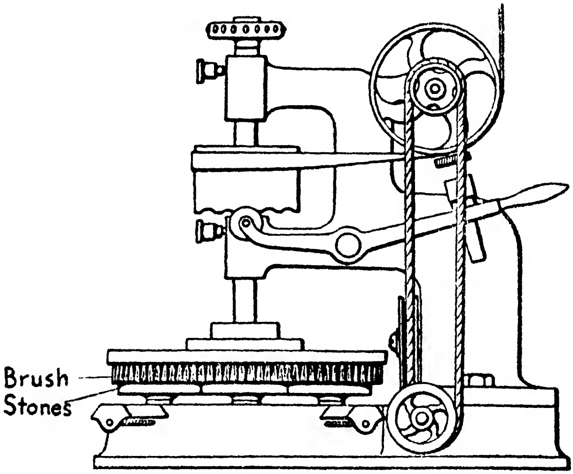

FIG. 119.—Brush polishing machine with vertical spindle

The distances between the stones and actual holes are filled by a cement.

A new type of polishing machine has a vertical shaft with a big brush wheel fixed at the lower end (Fig. 119). The driving disc is provided with axially arranged holes, against which a roller on a swinging lever under the load of a weight is pressed. Therefore, during one rotation of the spindle it is lifted about twelve times. The stones to be polished are cemented to smaller wheels which rotate and simultaneously carry out small reciprocating movements. The advantage of this machine is that abrasive powder, in particular diamond powder, is used economically. The machine produces about four hundred stones per hour.

DRILLING AND BORING

The old methods of drilling and boring have already been described in Section 1. In mass production, special drilling machines are used, in which the pressure is generated by springs and the piercing needle performs small reciprocating movements. In addition to the drilling machine with fourteen spindles shown in Fig. 78 on p. 112, Fig. 120 shows a drilling machine with twenty-four spindles driven by a single belt placed in a serpentine manner between the spindles.

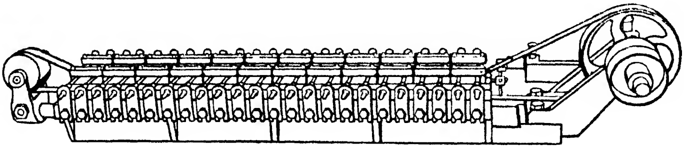

FIG. 120.—Multiple drilling machine driven by an endless belt (see also Fig. 78, p. 112)

The holes have now to be enlarged to the required diameter. Formerly small lathes (see Fig. 109) were used for this purpose, with the stone centred and cemented in the hollow spindle. Then a hardened steel needle provided with olive oil and diamond dust was introduced in the hole and reciprocated until it could be easily moved. After the diameter had been obtained with a minus tolerance of $\frac{1}{100}$ to $\frac{1}{200}$ mm., the hole was polished by means of a copper lap. The highest polishing effect is obtained by needles of pear-tree wood or fibre.

Several years ago the so-called Grandir machines were produced for enlarging drilled holes, operating on a similar principle to that applied in polishing and enlarging diamond and hardmetal drawing dies. In the first method, only one stone can be machined at a time; with the second method (Fig. 121), about two hundred to three hundred stones are worked on simultaneously. The stones are placed one against the other and clamped together. A steel wire, prepared with diamond dust, is placed through the hole, and reciprocated mechanically, thus enlarging it. During this operation the stones are put on to bars forming an angle; the length of bar is usually about 5 inches, but shorter and longer machines are supplied. The machine contains an accurate device for centring the stones. Recently semi-automatic machines of this kind have been developed. From a photograph it appears as if the stone-holding frame is, in these cases, reciprocated automatically by a crank drive.

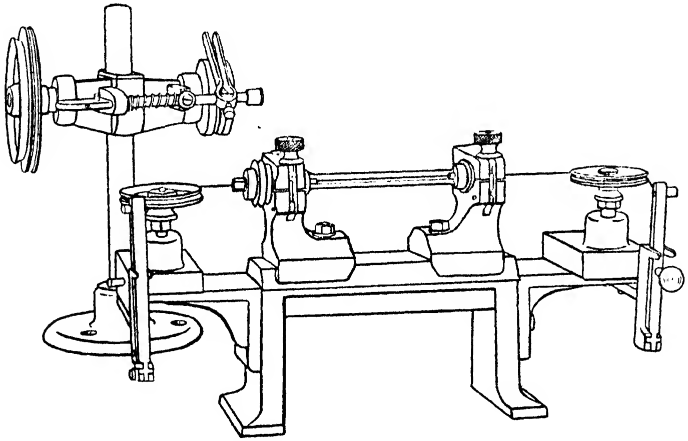

FIG. 121.—Grandir machine for the enlargement of multiple holes

SPECIAL METHODS

Various processes still have to be completed before the stone is finished. The edges of the holes, for instance, have to be broken. This process is called "olivieren," and requires special skill. The operation is carried out on small turning lathes.

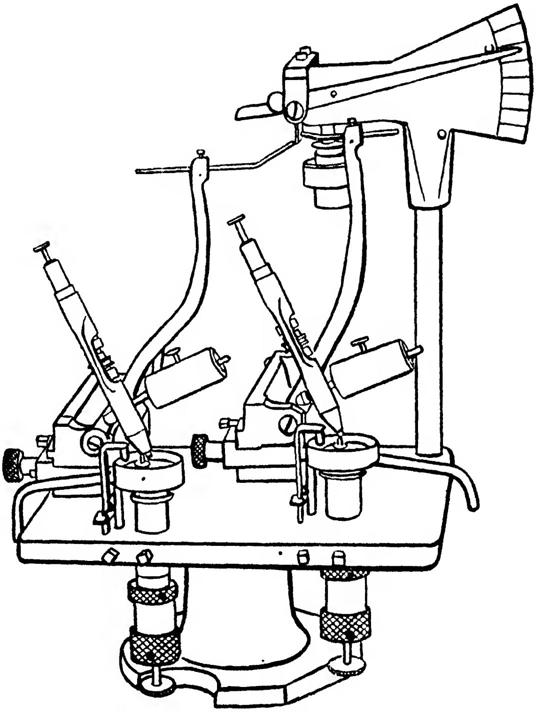

FIG. 122.—Machine for grinding conical cavities. The stone rotates on a vertical axis, whereas the tool (copper lap) is held under an inclined axis in a high-speed rotating quill

A further important operation is the production of the conical cavities for pivot bearings and compass stones (cup jewels). Fig. 122 shows an automatic machine[1] for mass production, equipped with a copper lap prepared with diamond dust. It gives an exact indication of the angle to

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[1] This machine is fully described in German Patent no. 253960. Similar methods are contained in German Patents nos. 319643, 460111, and described by R. J. Bray, Pivots and Caps in Compasses (Compass Department, Admiralty) 1917, and V. Stott, *Collected Researches, National Physical Laboratory*, 1931, vol. 24.

be polished, and is said to produce one hundred to two hundred and twenty oil cavities per hour.

The convex part of the end stones and the balance jewels is made by a grinding machine in which centrifugal action is used to generate these forms (Fig. 123). The main spindle is equipped with a cross-bar supporting one axle on each end. The cross-bar rotates with the speed of the spindle, but the two axles are driven from the main spindle by a chain and sprocket wheel, thus having their own relative movement of at least two rotations for each one of the spindle. The circular side faces of the rotating boxes consist of crown-like grinding wheels. The centrifugal pressure forces the stones against the rim of the grinding wheels and they thus obtain their curved form.

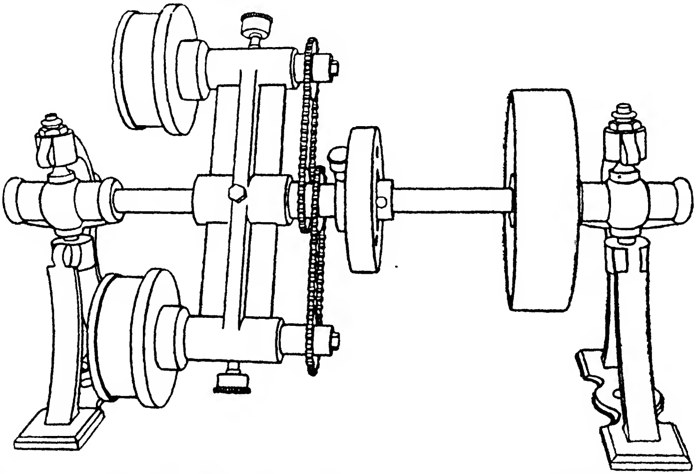

FIG. 123.—Special grinding machine using the centrifugal principle for producing the convex part of the jewels

CONTROL AND SORTING

The control and measurement of the finished stone is usually carried out under the microscope, or by a special contour projector. In the latter case the shape of the stone is compared with an enlarged drawing of it (Fig. 124). The roundness of the hollow cone in stones for pivot bearings can be controlled by rotating the stone on its axis. As the photograph shows, the transparency of the stone is of great advantage as the contour of the cone, the most important part, becomes clearly visible.

The control of the small radius at the bottom of V- and cup jewels is of great importance; an optical inspection method by means of a special microscope was recently described by F. E. J. Ockenden.[1] When applying optical methods for the inspection of the inside shape of transparent stones, these have to be immersed in a fluid having a refractive index closely approximating to that of the used material; for instance, corundum, refractive index 1·760 to 1·769, in methylene iodide, refractive index 1·742.

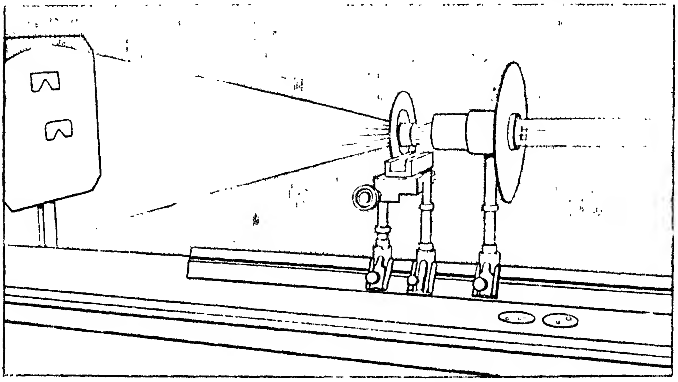

FIG. 124.—Contour projector for the control of stones

Owing to their small size, these stones are usually controlled by sieves or sieve sheets with holes between 0·7 to 3·0 mm. (nos. 7 to 30). These sieves progress in steps of 0·1 and 0·05 mm. and five sieve plates are provided in one receptacle. For the range of 0·7 to 3·0 mm. twenty-four receptacles with a total of one hundred and twenty sieves are necessary to sift stones according to $\frac{1}{10}$ mm. size. To obtain a finer sifting to $\frac{1}{20}$ mm. size another set of sieves is arranged which contains forty-seven sieve receptacles with a total of two hundred and thirty-five sieves.

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[1] *Journal of Scientific Instruments*, 16 (1939), p. 228, and *Collected Researches*, *N.P.L.*, 24 (1931), p. 1

Recently, the procedure of hand sifting has been mechanized by placing the receptacles on an inclined arbor (Fig. 125); the extended spaces between the receptacles are shown in this illustration, and usually twenty-four can be placed on the arbor. The latter is inclined at about 60 degrees and driven by a small motor from the triple pulley on the left

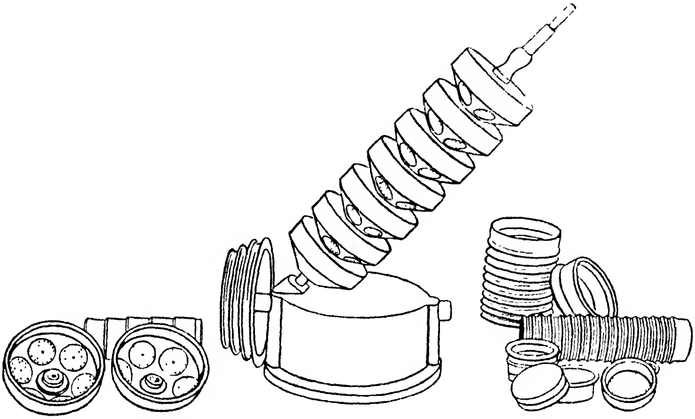

FIG. 125.—Small sifting machine for stones together with a number of small sieves

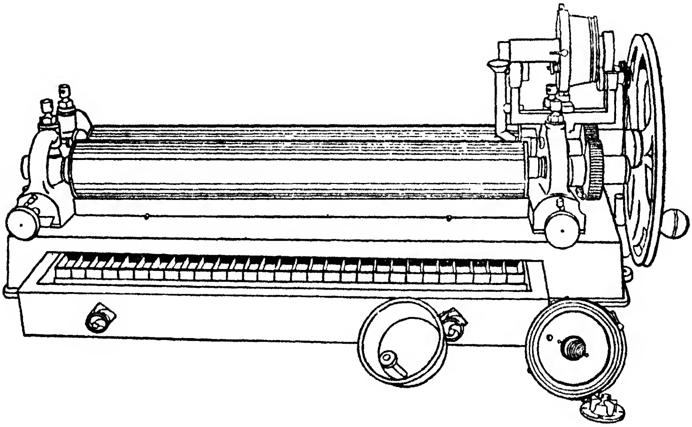

FIG. 126.—Measuring and sorting machine with roller

hand side. The receptacles receive at each revolution five strong blows in axial direction by means of a cam device. The stones are thus prevented from sticking in the holes. A fractional h.p. motor can drive up to six of these machines. As five different sized sieves are provided in each receptacle, it is necessary for a sorter to discover the finer differences.

Fig. 126 shows a machine for measuring and sorting the discs of different thicknesses. The stones fall from one container between two cylindrical and rotating rollers, the centre distance between which is adjusted by a micrometer screw so that their axes are not exactly parallel. By this inclination the stones are transported along the length of the rollers and fall according to their thickness through the slot between the rollers in sorting receptacles placed below. The measuring accuracy is said to be to $\frac{1}{100}$ mm. The machine can be driven by hand or motor, and is adjustable for various thicknesses.

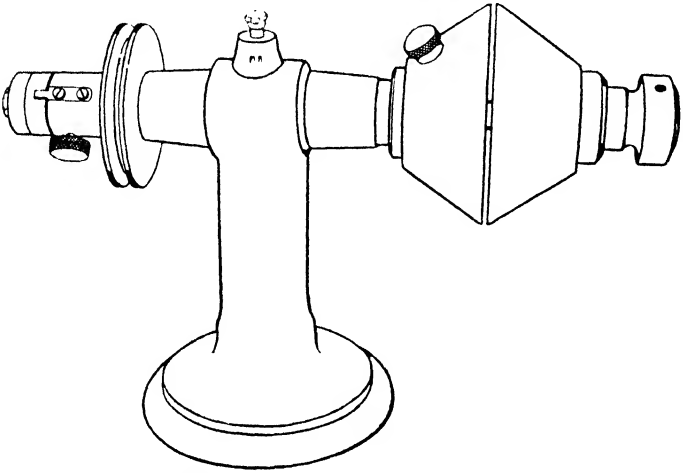

FIG. 127.—Measuring and sorting machine with bells

Fig. 127 shows another machine for determining the thickness of stones and operates by two bells placed with their open ends together, by which a slot of variating thickness round the circumference is formed. When rotating the bells, the stones will leave the interior at different places according to their thickness.

MANUFACTURING PROBLEMS

There exist large differences in the durability and wear of gem stones used for watch and pivot bearings, depending on the methods applied in the manufacture as well as on the rough material employed. Professor W. T. Gordon[1] recently mentioned that extensive research work has demonstrated that the cracking of bearings in corundum is due to the crystal structure of this material which parts in planes parallel to certain crystal planes. When producing the cups for the pivot bearings the angle between main crystal axis and axis of pin should lie between 45 to 48 degrees or 60 to 90 degrees (Fig. 128). In these cases the tendency to crack could be reduced to a minimum. Further small surface cracks or "riffs" in the polished jewel surface are said to be caused by certain methods of polishing.[2] These cracks are obviously caused by internal strains in the stone, and may appear at any time whether the bearing is in service or not. For pivot bearings with vertical shafts, riffs within the load-supporting areas are undesirable; with rolling contact, i.e. in the case of balls, they are said to have no effect.

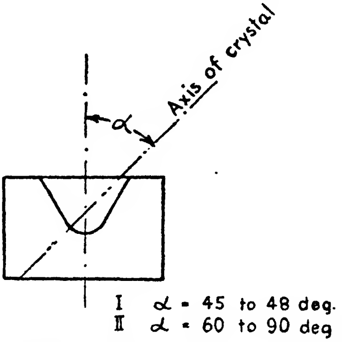

FIG. 128.—Correct situation of the conical hole of jewel stones with regard to the parting planes

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[1] *Chemistry and Industry*, April 1, 1938.

[2] *The Machinist*, vol. 78, 1934, p. 400 E.

CHAPTER XI

MANUFACTURE OF DIAMOND AND HARDMETAL DIES

THE dies through which fine wires of nearly every ductile material are drawn, must be of resistant and strong material so that the effect of wear remains negligible. Hitherto, only the diamond has proved to be suitable for wires of less than 0·04 inch (1 mm.) diameter, although above this range hardmetal dies, with the exception of wires with very close tolerances, are quite suitable; in the latter case the diamond die is again indispensable.

During the last decades, distinct kinds of machines for piercing and polishing of diamond and hardmetal drawing plates have been evolved, partially, fully, or semi-automatic. Outside the limited circle of producer and consumer they are not very well known. For a satisfactory machine of this kind the following demands are set, and are usually met by the equipment of reliable firms:

(1) Production of an exact hole to ensure the creation of many fine stones, i.e. those with smallest diameter, as these are highly appreciated owing to their difficult production. As supplementary stones, they are the key to economical wire manufacture.

(2) Production of exact, well-defined, as well as prescribed, shapes of drawing ducts, influenced by the material of the drawing die, the material to be drawn and the kind of drawing machine.

(3) Satisfactory mirror finish of the drawing duct, especially the drawing cone; this is of decisive effect on the durability of the die and the quality of the drawn wire.

The production of diamond dies has to be started from the solid crystal, whereas in the case of hardmetal dies preformed blanks can be utilized. The machining process of diamond dies at each step is shown in Figs. 129, 130, and 131, according to information given by Osram Kom-Gesellschaft, of Berlin. These operations are described in the following pages.

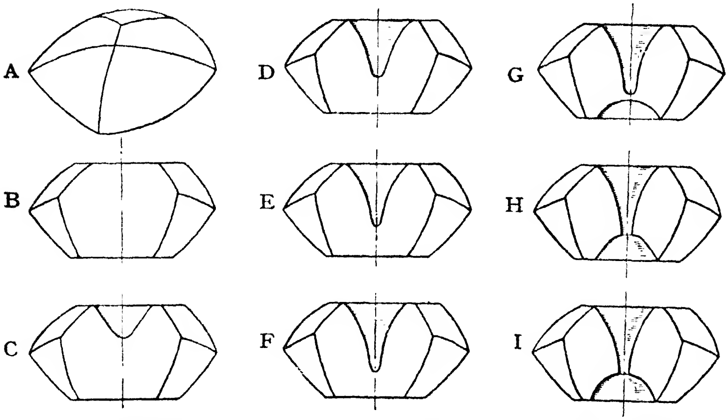

FIG. 129.—Machining operations of a diamond die (by courtesy of Osram GmbH)

A. Natural stone (before beginning the cutting operations the stone is carefully tested with regard to inclusions, stresses and cracks)
B. Two plane surfaces and two facets (windows) are cut on the diamond
C. Centring and rough turning of the hole
D. Rough boring
E. Boring to medium depth
F. Finish bored (see microphotograph, Fig. 130)
G. Turning from the reverse side
H. Both holes are united (see microphotograph, Fig. 131)
I. Polished (after the polishing the stone is tested again and mounted)

PREPARATION OF STONES

The raw stones are carefully selected and tested[1] with regard to inclusions, and further carefully cleaned. The raw stone is then provided with two parallel facets on opposite sides. This operation is performed on a small bruting machine,

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[1] Among these tests a control under polarized light should be included; for more details see *Industrial Diamond Review*, no. 7, 1941.

similar to a planing machine, or on a small grinding machine (scaife). The bruting or turning machine (called in this branch centring and polishing lathe, Fig. 36) corresponds to those used in the diamond industry (see Fig. 32, p. 62), but usually smaller machines, without the eccentric chuck and operating at higher speeds, are used. On it, by a hand-operated diamond tool, two small plane surfaces are provided

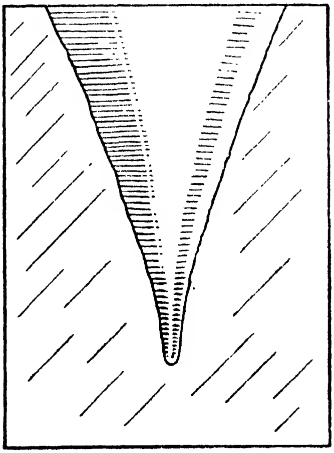

FIG. 130.—Reproduced from a Microphotograph of the bored stone (corresponding to operation Fig. 129 F)

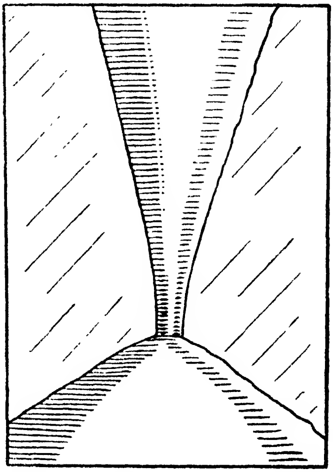

FIG. 131.—Reproduced from a Microphotograph of the polished bore (operation Fig. 129) H

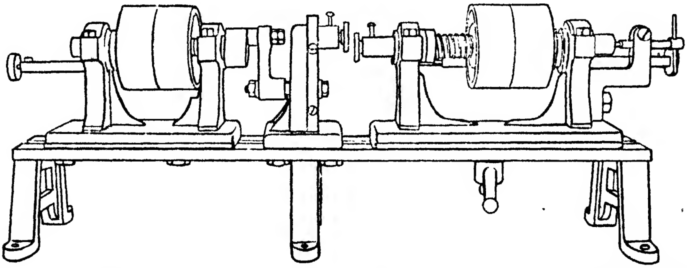

FIG. 132.—Small shaping machine with rotating and reciprocating movement for diamond dies (see also Fig. 35)

on the diamond, in which later on the entrance and exit orifice are machined. These same operations are performed nearly automatically on a kind of planing machine (see also Fig. 35, p. 64), in which two diamonds are operating under a distinct pressure. One stone is rotating, the other performs a planing movement, i.e. a reciprocating movement parallel to the rotating planes; a very fine axial adjustment is necessary, otherwise the stone is easily chipped. Before the drilling operation starts, it is usual to provide the stone with another pair of facets parallel to the axis of the drawing duct, through which it is possible to observe its shape during the time the stone is unmounted (Fig. 129B). This fact is a special advantage of the diamond, as well as of rubies and sapphires, for the drawing duct in sintered hardmetals and other opaque materials can only be observed and controlled through the hole itself.

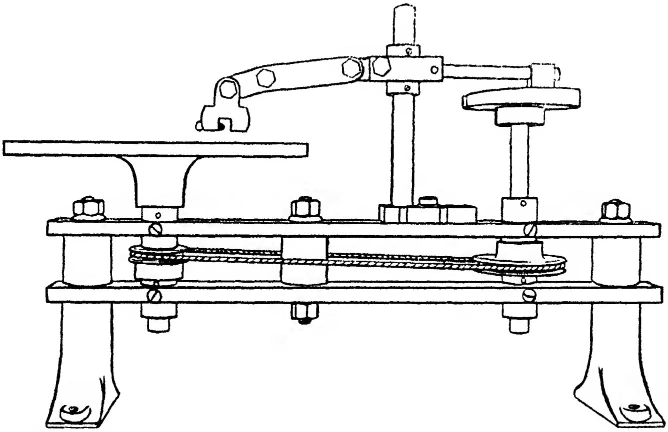

FIG. 133.—Small "scaife" for the planing of diamond dies

The stones are fitted in mechanical dops (see Fig. 51, p. 78) or chucks and ground on the scaife, i.e. a metallic disc rotating with high speed and provided on its surface with diamond dust to provide the stones with additional facets. For this purpose the usual machines (see p. 68) are used. Fig. 133 shows a small machine for this purpose, in which the stone is periodically lifted. This has the advantage of the new diamond dust coming between stone and disc, so that the grinding operation is accelerated. In certain cases the facets mentioned above are worked on these machines. The flattened stone, i.e. the stone provided with facets, is now brought again to the bruting machine (Fig. 134) and centred by a diamond point or pre-bored. Thus a small cavity is generated on that zone of the stone where later on the entrance cone of the drawing duct is situated.

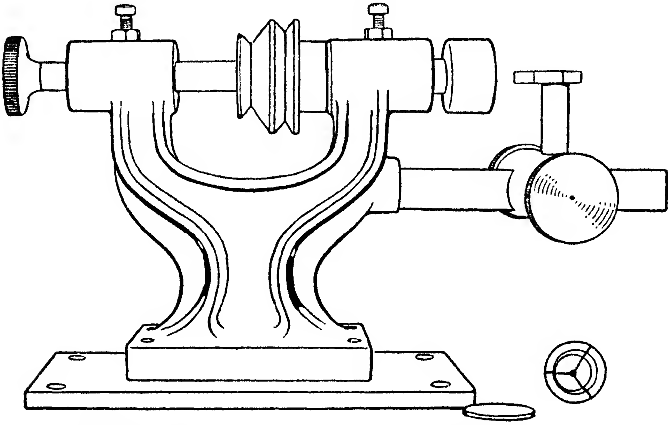

FIG. 134.—Small turning lathe for the preparation of diamond dies similar to Fig. 36. When in use this machine has to be provided with a receptacle for the catching of the diamond dust produced (see Fig. 32)

THE DRILLING PROCESS

For drilling, illustrated in Figs. 129D–F and Fig. 130, machines based on nearly the same idea are utilized. The stone, mounted on a stationary or revolving disc, is moved by an oscillating motion against a thin steel needle rotating at a high speed. The steel needle is provided with fine diamond dust, mixed with a fine-grade oil. The needles for drilling and later for polishing serve only as the holders for the grinding and polishing material. By the rotating movement (about 7,000 to 8,000 R.P.M.) and the blow-like reciprocating action (about five hundred oscillations per minute), a new portion of sharp diamond grain is always brought into the small clearance between needle point and die hole. This explains the drilling effect of the steel needle in the hard diamond or hardmetal die. The grinding action is further reduced in this case because the rotating speed of the needle point, in spite of a high number of revolutions per minute, is nearly zero. As a result, the depth of hole is only slowly increased.

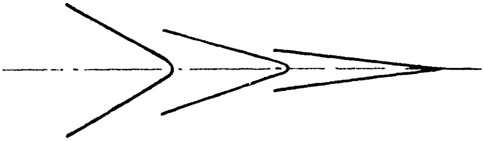

FIG. 135.—Shape of drilling needles; with increased depth more acute needle points are used

Due to the wear-resistance of the diamond, drilling a hole in it can take days, but no better grinding medium has so far been found. Recently boron carbide was shown to represent a relatively reliable grinding medium for hard metal dies. Corresponding to the shape of the conical hole which reduces its main diameter when coming to greater depths, the needles are replaced after some time in operation by a finer and thinner one with reduced cone angle (Fig. 135). Needles[1] are usually ground by a hand-operated mechanism (Fig. 136) driven by a small woven belt from the

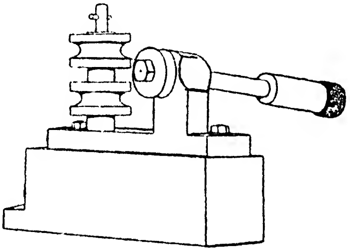

FIG. 136.—Small hand-grinding machine for grinding needles in the drilling machine

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[1] Needles of hardened steel, preferably commercial sewing needles or Stubb's wire.

drilling machine.[1] Thus it is possible to grind and re-grind the needles in their real working position, and so avoid an additional centring operation. With finer needles utilized, the stone to be drilled is conveyed to machines in which the stone-support performs smaller and smaller reciprocating movements. When starting the hole the machine performs a stroke of several millimetres, but this is reduced on succeeding machines until when the hole attains a depth of about 0·03 mm. it is almost invisible to the naked eye.

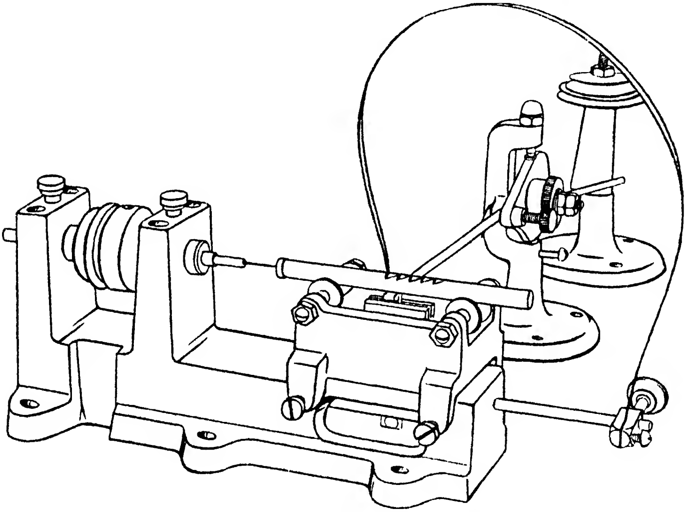

FIG. 137.—Horizontal one-spindle drilling machine

When the hole is about two-thirds of the stone thickness, the stone is taken from the drilling machine and carefully centred on the bruting machine on its opposite side (Fig. 134). This operation is performed by a diamond point, and the cavity is so produced that between the orifices of both sides only a very thin intermediate wall remains (Figs. 129G and 130). The art of drilling is to make the hole as small as possible, as this influences the final diameter of the die. Fig. 137 shows a drilling machine with the needle operating in a horizontal direction.

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[1] In France called "bistrique."

Machines of the vertical type have the advantages of economy of space, the possibility of applying multiple spindles, and of good visibility from the side of the operator. Further, in these cases a reduced diamond grain consumption is claimed. In these machines usually both die and needle rotate in opposite directions; the needle has usually about double the speed of the stone.[1]

For producing very fine holes the process is sometimes reversed, i.e. the needle is fixed in the reciprocating holder and the stone cemented to the face plate of the rotating spindle. There exist also horizontal machines in which both die and needle rotate.

Larger dies of sintered carbides are already sintered to the approximate shape. They are bored to exact dimensions on internal grinding machines. According to Popendicker the high-speed grinding wheel is replaced by a diamond-tipped tool. This seems to be an exceptional case, as diamond-tipped tools are usually only applied for soft materials.

POLISHING

The drilled hole is finished on the polishing machine with regard to both size and shape (Figs. 129 and 131). Polishing operations in individual cases, as opposed to mass production, are performed on the bruting machines described above. Machines of various kinds, based on different operating principles, have been developed. According to the nature of the polishing medium, one can distinguish between the two basic methods:

1. Polishing by a (rigid) steel needle, similar to those used in the boring operations.
2. Polishing by a steel wire or rope.

As regards method 1, the different requirements of the drilling and the polishing needle must be borne in mind. In drilling, only the diameter of the needle is of importance, but for polishing, shape and guiding direction have great

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[1] An improved machine with all spindles relieved from belt strain besides other improvements according to Prov. Patent Specification no. 3247—1941, L. Nussbaum and P. Grodzinski.

influence, as the drawing duct must obtain a distinct shape. This is achieved not merely because the needle performs a reciprocating movement, but also by its distinct sidewise movements. It has to describe a curved path, various points of its length building the envelope of the finished form. Owing to this the abrasive action is distributed over different parts of the needle. Polishing speed is usually lower than that of drilling or piercing; the stone-supporting spindles rotate in this case at about 2,000 to 3,000 R.P.M.; it must, however, be considered that the diameters are on the average considerably larger.

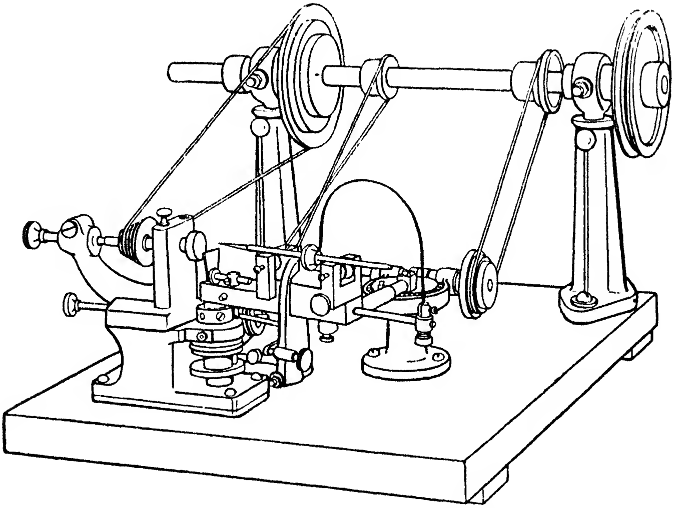

FIG. 138.—Single-spindle polishing machine with rotating die; similar machines are also equipped with rotating needle holders

Besides universal machines which can be used for drilling and polishing, machines for the last operation have been developed. Fig. 138 shows a polishing machine of a horizontal type in which the swinging movement is obtained by an eccentric. More in use to-day are vertical machines with multiple spindles possessing the same advantages mentioned in connection with drilling machines.

Fig. 139 shows the operation of a single spindle of the

Soldixa polishing machine (German patent no. 416806). The needle holder (8) is supported in two bearings (6) and (7).

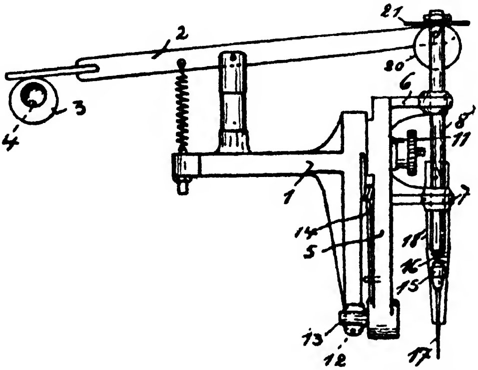

FIG. 139.—Unit of vertical polishing machine, model Soldixa

Each needle can be adjusted at any angle in relation to the axis of the hole, so that the same machine can be utilized

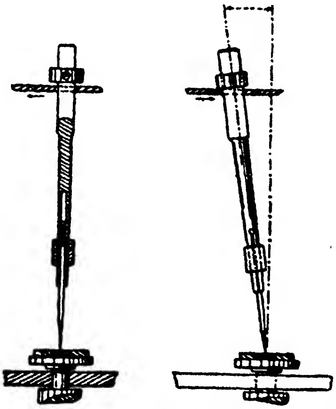

FIG. 140.—Needle movements in Pohenkra polishing machine

for the machining of various shapes and drawing angles. Polishing pressure can be adjusted over a wide range by spring pressure (spring 16 between needle holder and needle) acting against the needle-holder point. This machine also allows the re-polishing of drawing dies which have been damaged but have only a short guiding length. Each needle is lifted separately by an eccentric (4) and lifting lever (2) as well as an adjustable disc (20). Any non-positive movement of the needle is avoided by the double guiding of the needle holder.

In the Pohenkra polishing machine (Fig. 140, German patents nos. 226062 and 527000) a vertically hanging needle holder of light metal alloy is used, a collar of which is resting on the needle bar. This produces a reciprocating movement causing the needle to move under weight or spring pressure along the shape of the drawing duct and presses in any zone with nearly the same pressure. It is therefore claimed that this method corrects unsymmetrical or eccentric holes. Recently, the guiding prisms on the machine have been improved, corresponding better now to the kinematical principles (Fig. 141). The die is rotating in a die holder. The

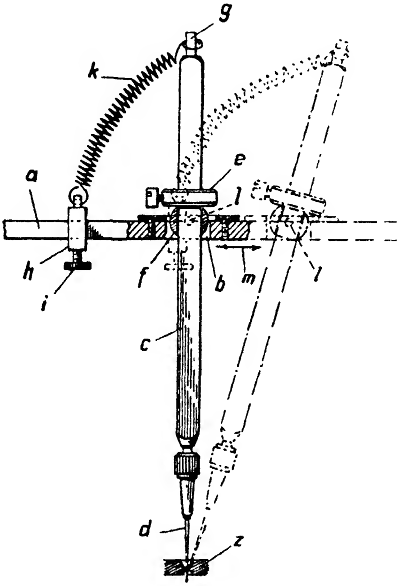

Fig. 141.—Improved model of Pohenkra machine

provision of the needle bar, with sidewards slots to allow easy removal of the bar for inspection, is a further improvement.

In the Haga polishing machine (Fig. 142, German patent no. 396870) the needle bar (*b*) performs a vertical reciprocating movement, driven by crank mechanism. The cranks on both sides of the machine frame are coupled by a layshaft and spur-gears. The needle holders (*g*) are situated in sidewise adjustable abutments (*c*) on the needle bar (*b*). When the abutment (*c*) is situated directly above the drawing hole, the needle holder only performs a vertical lifting movement (shown by the needle holder on the right-hand side), whereas in the case of a sidewise adjustment (shown by the needle holder on the left-hand side) a motion at a distinct angle is caused. Fig. 142 clearly shows the frame, the mounting, and the drive of the drawing dies.

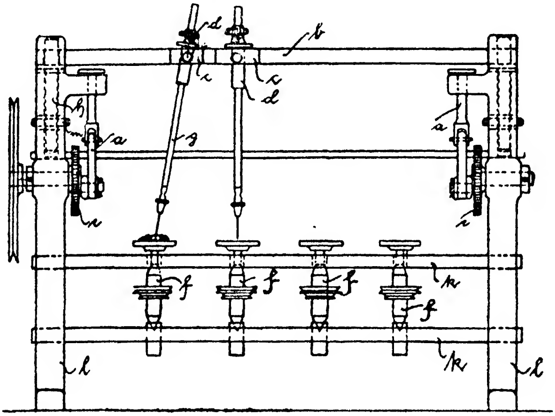

FIG. 142.—Principle of Haga polishing machine

In the machine for polishing fine holes up to 0·01 mm. in diameter (Fig. 143), any irregular wear of the polishing needle, caused by working in horizontal direction or under its own weight, is carefully and ingeniously excluded. The influence of the weight of the needle holder and needle is excluded by rotating them on their own axis. The axis of the needle is also somewhat inclined, so that the needle holder falls into the hole under the influence of the weight-component acting in direction of the axis. Owing to this very small and controlled load, breaking the needle point, in many cases only about $\frac{1}{1000}$ mm. thick, is avoided.

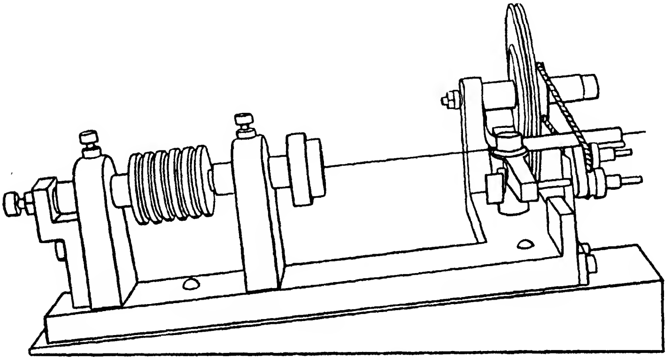

FIG. 143.—Polishing machine with rotating die and rotating needle. Machine somewhat inclined

Fig. 144 shows a polishing machine for large holes in which conical shapes of any shape and diameter can be treated. This machine allows the use of the polishing needle in a straight line direction, but adjusted to any desired angle or in a swinging movement. In the latter case the sidewise pressure can be arbitrarily adjusted by a spring.

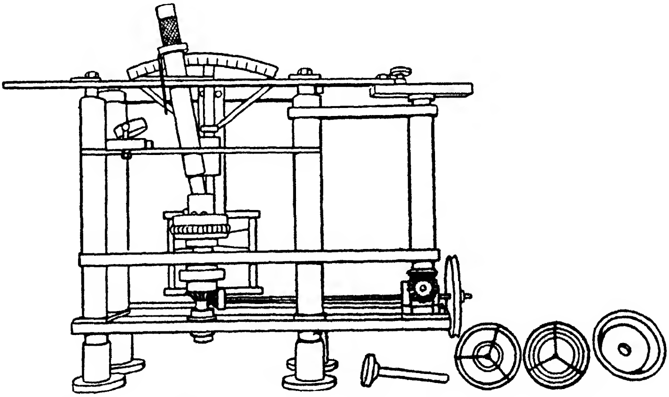

FIG. 144.—Adjustable polishing machine for large holes

The needle point is subjected to considerable wear during polishing. The re-grinding or re-polishing process of the needle should, however, not be performed in the machine by a simple auxiliary device (see Fig. 136); a needle-grinding apparatus should be provided, an example of which is shown in Fig. 145. The proper use of such a machine assures the needle obtaining the desired angle.[1]

With reference to the method under 2, Fig. 146 shows a machine operating according to the "rope" method. Polishing is effected in such a way that the wire rope acting as the polishing tool is conducted through the die opening and during the rotation of the die rubs and grinds on its walls. By a high-speed rotation of the die, the formation of ridges is carefully avoided. Further, these machines are equipped with devices to press the wire or rope to the external zones

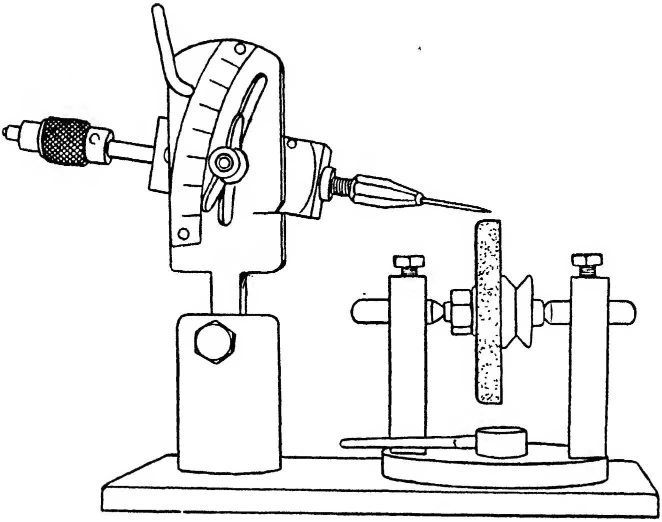

FIG. 145.—Special grinding apparatus for polishing needles

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[1] Very fine needle points are obtained by etching in acids or by an electrolytical process; the same principle being applied for pointing wires for the introduction in very small die holes.

of die with increased pressure, in order to obtain a well-rounded orifice and shape.

In the Bsteh polishing machine, which is of the vertical type, the wire under spring tension performs a reciprocating movement in the rotating die. To ensure uniform wear of the wire and also a uniform grinding and polishing action the active parts of the wire are exchanged after each operating stroke. This is effected by a combined screw and ratchet drive.

In the Haddow polishing machine (Fig. 147), also vertically arranged, the wire has a slightly bigger diameter than that of the die. When the wire is introduced it is pointed, and when drawn through the die its diameter is reduced. This method of drawing or reducing action is performed in such a way that the drawing and polishing wire coming from a spool is reduced in diameter, but is simultaneously provided on the entrance side with some polishing and grinding medium, so that during the drawing action a polishing action is exerted on the hole. By swivelling the rotating die holder the entrance and exit cones can also be polished.

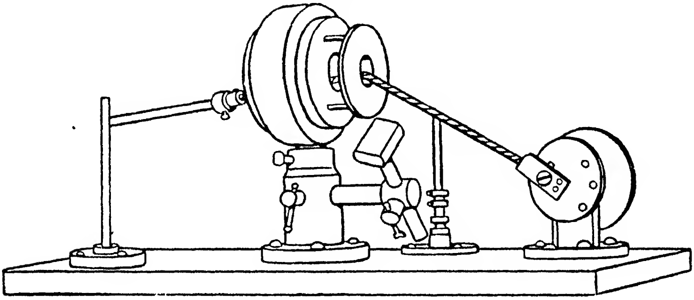

FIG. 146.—Rope-polishing machine, for large holes, horizontal arrangement

This method resembles very much those utilized for running-in bearings. The machine operates as follows: Pulley (34) drives both the rotating die holder (32) as well as the eccentric (28). This lifts the swinging lever (14), supporting on its free end roll (22). By means of the tension bar (27) and swinging arm (15) a parallel linkage is formed, so that the swinging arms held in ball bearings are uniformly lifted and lowered. The polishing wire, coming from the spool through the die, is elastically suspended on the lower swinging arm, giving an automatic adjustment for wear.

GENERAL REMARKS

Important as the application of carefully designed and built machines for economic production of effective and durable drawing dies may be, it must be supplemented by the application of a selected raw material, and suitable equipment for the production of diamond dust, machines for re-grinding needles, equipment for cleaning the dies, as well as instruments for the control and measurement of hole diameters and angles.[1] For the control of the small die holes

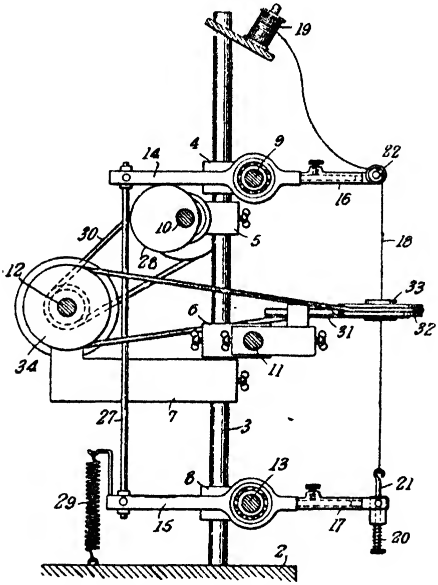

FIG. 147.—Scheme of the Haddow polishing machine, utilizing a kind of burnishing action

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[1] Modern methods of die inspection with regard to diameter and angle control are discussed in *Industrial Diamond Review*, no. 2, Jan. 1941

progressive workshops are utilizing more and more optical means, such as tool room microscopes and contour projectors (Fig. 124). Without these means the most perfect machine cannot produce holes corresponding to the requirements of to-day. Well illuminated and clean shops equipped with rigid and vibration-free working tables and machine supports are necessary.

As the production of diamond dies is a lengthy operation, drilling a fine hole sometimes requiring a week, it is desirable to mechanize production as much as possible. Semi-automatic machines have been installed in which, if a predetermined depth has been obtained, a trigging device stops the machine; the machine that has halted is indicated by a special light signal, thus attracting the operator's attention. In large workshops of this kind most of the operations are carried out by girl operators. One girl controls the operation of twenty little drilling and polishing machines. These are arranged in a long row; the girls sit on chairs, rolling on slides, so that they can quickly reach any machine with the least physical effort (a brake is provided to bring the rolling chair to a quick rest and secure it in the stationary position). The necessary microscope is also placed on rails, and can be quickly focused on the needle to observe whether it has still the correct shape.

CHAPTER XII

INDUSTRIAL DIAMONDS

For industrial purposes, diamonds are used which are much "harder" (in the sense of a greater resistance to abrasion) than the jewel or ornamental stones. If the grinding action on diamonds is proved to be too small, these crystals are rejected by the brilliant cutters. Originally, all crystals, including those of poor water, were reserved for ornamental purposes, but now, owing to the large demand for industrial stones, those of gem quality but of considerable hardness are reserved for this purpose.

Industrially used diamonds fall into two categories:

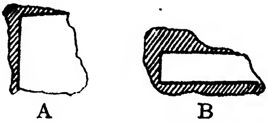


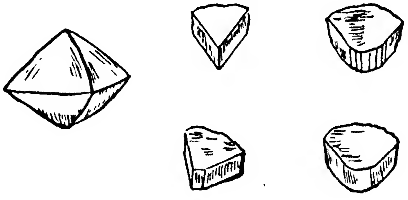
Fig. 148.—A and B. Cutting industrial diamonds according to the shape of the rough stone is not a satisfactory method

Rough stones, sometimes diamond splinters for fine work set in suitable diamond holders; and

Cut and polished stones for machining metals and non-metallic substances, recording points, hardness indenters, etc.

While the former stones need no machining and are eventually broken or cleaved, the latter are usually polished on those surfaces which perform the actual working and cutting. Special methods are known in which the diamonds are cut and polished on all surfaces, making much better hold possible by cold setting methods (see p. 201).

It is, perhaps, possible to use diamond crystals which are shaped by nature in the form desired, or can be cleaved or sawn into such a shape. In Figs. 148A and B is indicated how diamond shapes are obtainable with a very small loss of weight. Later on, from the cut and polished diamond, one cannot find out how it has been generated. However, a product manufactured according to Figs. 148A and B will have a much shorter life, and will splinter prematurely under the great stress imposed on the edges.



A B

Fig. 149.—A and B. Examples of correctly cut stones

A. Rough stone. B. Satisfactory cutting edges produced from the stone A

To obtain satisfactory industrial diamonds, that is to have a highly resistant cutting edge, cutting and grinding must be performed with regard to the crystal structure. Therefore high-grade diamond tools are cut out to the shape of solid stones of high quality. In Fig. 149A and B some examples are shown for the perfect shaping of industrial diamonds from rough stones. A diamond produced according to these principles does not only show a larger durability, but can be frequently re-lapped. The correct method in cutting industrial diamonds results in a loss of weight of the rough stone of between $\frac{1}{3}$ to $\frac{2}{3}$ of its original. An estimate of the cutting time is already difficult in the

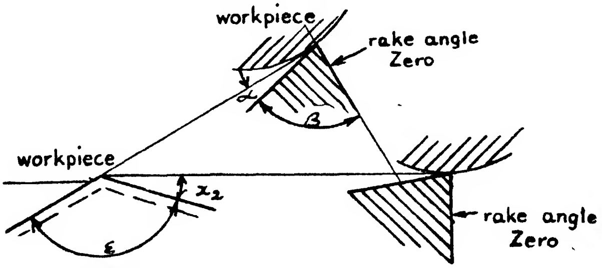


Fig. 150.—Cutting edge of a diamond tool for cutting metals

case of the relatively soft ornamental stones, but it is impossible in the case of the "hard" industrial diamonds.

The cutting edge of diamond tools (Fig. 150) for machining metals is made as strong as possible. For instance, the point angles are made in excess of 90 degrees, but, unfortunately, the cutting angle must be made somewhat below this. In order not to reduce this angle too much, the rake angle of the tool is usually made zero so that the rake surface assumes in the finished tool a horizontal position. This means not only an easier cutting, but also a facilitated setting. In this way the remainder, resulting from the difference 90 degrees minus cutting angle, is used for the clearance angle. Very small clearance angles result sometimes in a polishing action to the cut material. By adjusting the cutting edge somewhat above centre height, small rake angles are obtainable on account of a reduction of the clearance angle. The point angle of tools is usually made in excess of 90 degrees, usual values are 120 to 140 degrees, resulting in a very much stronger diamond point.

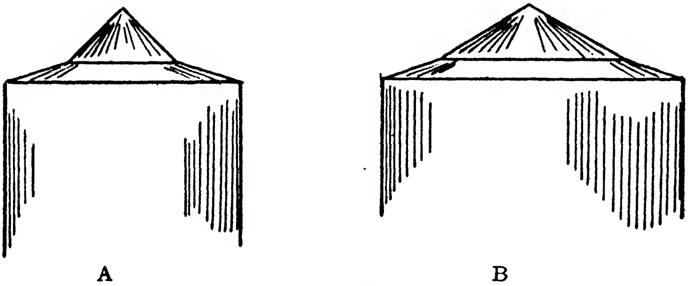


FIG. 151.—A and B. A 90-deg. cone angle has proved to be too weak for diamonds, therefore more obtuse angles B are preferred in cases where high stress and strain is imposed

Cones of 90 degrees included angle when tried out have proved definitely weak (Figs. 151A and B). Cones, therefore, of 120 degrees, and if possible even larger, such as the Vickers pyramid of 136 degrees side angle, are preferred for hardness testing points. Frequently, however, the angle of the point cannot be arbitrarily selected. This is the case of truing tools for thread grinding wheels where the point angle of thread has to be made either 55 or 60 degrees.

In the case of diamonds, and of cones and other shapes, the production of exactly prescribed angles between facets makes considerable difficulties. In crystallographic literature it is said that ground angles can be kept within an accuracy of 0·5 degree = 30 minutes. This is quite in agreement with the German standards draft for hardness tests according to the Vickers method, where an angle tolerance of ± 20 minutes is suggested. V. Weingraeber states, in an article on the possible errors of Vickers' tests, that at the time of writing (1938) the commercially available diamonds showed that this tolerance was exceeded even by degrees. He evolved a formula of the relative error which is caused by inaccurate angles, and a correction factor by which the hardness numbers obtained have to be multiplied to obtain accurate results. These relations are represented in the diagram Fig. 152.[1]

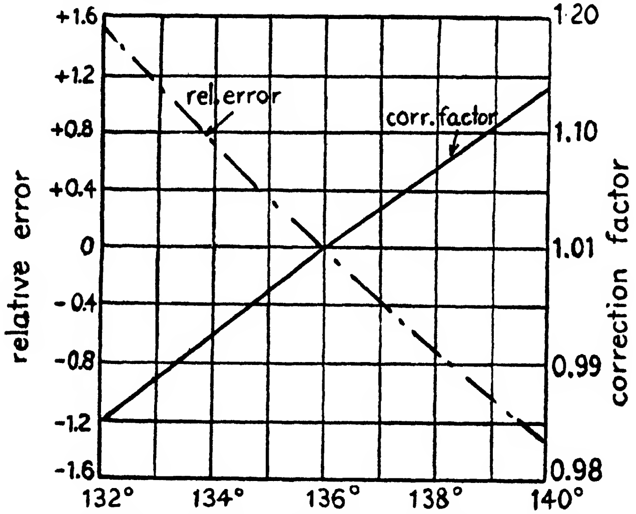


FIG. 152.—Influence of angle variations on the results of hardness tests

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[1] The question of how accurate the production of the points for hardness tests can be is of great practical importance. The German expert,

The stone has not only to obtain the required shape by the cutting process, but it must have an absolutely smooth surface and keen and sharp cutting edges. In particular, cutting edges have to be smooth even in the case of a 200-fold magnification. These keen and sharp edges which remain sharp even under continual use, as well as the polished surfaces giving the least friction to the flow of material, represent the advantages of the cut and polished diamond tools. As the cutting edges are usually of minute size they are checked by optical means, usually profile microscopes and contour projectors. If small defects are visible the whole cutting process has to be repeated.

In order to generate convex surfaces, or those provided with a radius, the position of the crystal with respect to the grinding wheel has to be changed continuously. If an attempt was made to obtain a radius merely by a swivelling motion of the diamond towards the grinding wheel, traces of grinding action would only be shown on those places which corresponded by chance to the direction of grain. To produce industrial diamonds, in addition to the usual equipment described in the first part of this book, machinery is applied for the automatic perfection of different shapes and forms, in particular cones with ball-shaped points, balls, etc. As this special equipment remains the secret of the workshops which have evolved it and no patents have been issued, it is not possible to indicate their main principles. Re-grinding and re-lapping of diamond tools should not be attempted, unless the equipment of the diamond tool manufacturer is

von Weingraeber, is of the opinion that a diamond (Vickers) pyramid can be produced to very close tolerance, and that only on the point differences might occur of fractions of $\frac{1}{1000}$ mm. In contrast to this, a Swedish expert, Jernkontoret, of Stockholm, states that the intersection of the four facets in one point of the pyramid is difficult to obtain and he therefore believes that cones with sharp points are the most suitable for hardness indenters. Diamond cones with rounded point, as are used in the Rockwell test, need not have a very high dimensional accuracy as they are adjusted according to control plates (see V. Weingraeber, *Werkstattstechnik und Werksleiter*, 1937, p. 384, 1938, p. 361, and P. E. Wretblad, *Werkstattstechnik und Werksleiter*, 1938, p. 264).

available. For re-polishing, the diamond has to be taken out, a point favouring cold-setting methods, and has to be reset again.

CALCULATIONS FOR CUTTING

Usually the edge angles of the bodies to be produced are given in drawings, but for cutting, the face angles must be known. This enables the cutter to determine the angles in relation to the surface of the grinding wheel. The basic relations between the edge angles and the face angles are not available to the diamond cutters, and if the edge angles only are given he has to use hit-and-miss methods which often result in incorrect angles. It is, however, very simple to calculate the face angles by using basic knowledge of spherical trigonometry, but even without this, it is possible to make such calculations, as will be shown in the following two examples. The method of drawing is quite applicable, but the accuracy is not high enough, and the results obtained should always be checked by a numerical calculation.

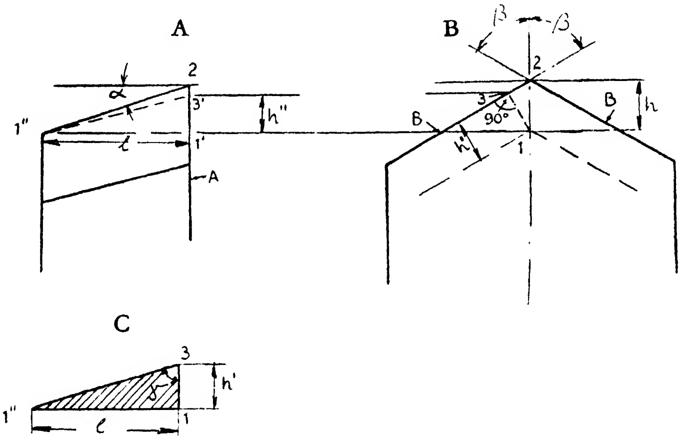

FIG. 153.—Determining the face angles on a chisel edge point

As an example, the face angles of a chisel edge (Fig. 153) should be determined by elementary methods. In the drawing only the angles α and β are given. The surface A and the two inclined surfaces B have to be cut. It is obvious that the cutter can only find the correct intersection of the two faces B by trial-and-error methods. The two angles do not give the shape completely, but it is understood that the included angle 2β should be maintained throughout the whole point. The face angle which has to be determined is γ; it is obtained if an angle protractor is placed from point 1 on face A vertically to the edge with surface B and

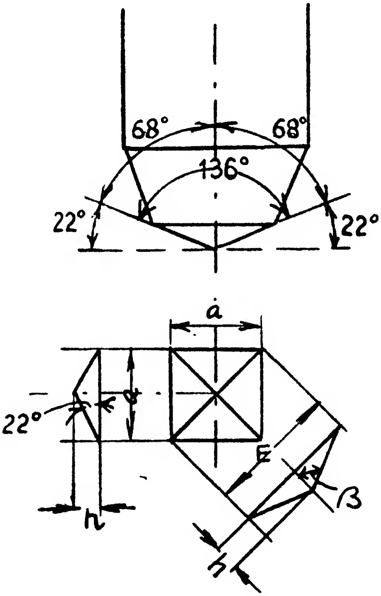

FIG. 154.—Determining the edge angles on a Vickers pyramid

the slope of that surface measured. If it is obtained, the distance is assumed to be $12 = h$ for $13 = h' = h \sin \beta$, and from the true size triangle $\tan \gamma = l/h' = l/h \,.\, \sin \beta$; further $\tan \alpha = h/l$, thus $\tan \gamma = \dfrac{1}{\sin \beta \,.\, \tan \alpha}$; for instance, for $\beta = 60°$; $\sin \beta = 0{\cdot}866$; $\alpha = 10°$, $\tan \alpha = 0{\cdot}17633$, then $\tan \gamma = \dfrac{1}{0{\cdot}866 \,.\, 0{\cdot}1763} = 6{\cdot}56$; $\gamma = 81° \, 20'$.

In the case of the Vickers point for hardness testing (Fig.

154) just the reverse problem arises. Here the face angle is given as 136 degrees, but for measuring the point with optical means edge angles are recommended, giving simultaneous control so that the face angles are kept between close tolerances. If E is the length of the diagonal and a the side length, then the relation exists $E = a\sqrt{2}$. The height of the body is h, and owing to the face angle the relation $h = \frac{a}{2} . \tan 22^\circ$ exists. The half-edge angle β is then given by $\tan \beta = E/2h = \frac{E}{a . \tan 22^\circ} = \frac{\sqrt{2}}{\tan 22^\circ} = \frac{1{,}414}{0{,}404} = 3{,}5003.$ Thus $\beta = 74^\circ\ 4'$ and $2\ \beta = 148^\circ\ 8'$.

CONTROL

Careful control of all diamonds used for industrial purposes in rough or shaped (polished) form is essential. Diamonds having even minute cracks should be excluded as under the strain of working conditions they will tend to break. Besides this control under a powerful lens or microscope, tests under polarised light[1] are strongly recommended, as hereby any strain set up in the diamond is observed. Obviously this method can only be applied to unmounted stones, but there exist scientific methods to control strain in mounted stones.

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[1] See *Industrial Diamond Review*, no. 7, 1941.

CHAPTER XIII

SETTING INDUSTRIAL DIAMONDS

Besides quality and precision cutting, the type of setting is decisive for the quality of a diamond tool. The diamond should not only obtain a strong hold against all the forces acting on the cutting edge, but the setting should also be able to deduct heat from the diamond. The projecting part of the stone must have a special position in relation to the axis of the tool. To make the tool as strong as possible, it should only be composed of a few components. To allow the exchange of diamond-tipped tools, one or several diamonds are set in holders of standard shape,[1] such as cylinders, square discs with a cylindrical shaft, oblong shapes with V grooves,

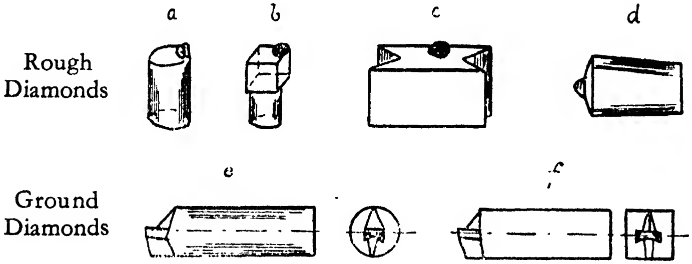

Fig. 155.—Standard shapes of tool bits, *a* to *d* usually rough diamonds, *e* and *f* usually ground diamonds, *a* and *b* discs for boring crowns, *c* disc for stone-sawing blades, *d* truing diamond for abrasive wheels, *e* and *f* cylindrical and prism socket for turning or boring tools

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[1] The idea of setting diamonds in an exchangeable bit of standard dimensions has proved to be of advantage in many ways, but there are some other fields in which this method appears advantageous, such as, for truing tools, metal turning diamonds, and so forth. Formerly only the bracing, casting, or cold-setting methods were available for this purpose, but now setting by sintering is possible, in particular with sintered carbides which have characteristics more related to the diamond than other metals.

etc. (Fig. 155), which are placed in the appropriate places in the main tool body either by mechanical clamping or by soldering. The advantage of this is that the set tool can be easily exchanged against another tool; some shapes, such as cylinders, allow the relative position of the point to be also changed.

A large number of methods for setting single and multiple diamonds in metals have been tried out, but no generally applied method has been found. The two main methods are setting under heat and setting under cold.[1]

SETTING UNDER HEAT

The embedding of diamonds in heated and molten metals up to temperatures of about 1,400 deg. C. (2,500 deg. F.), is possible with special precautions, but already at temperatures of 700 to 800 deg. C. (1,400 deg. F.) the diamond surface can be attacked to a certain degree. This is of no great matter in the case of rough diamonds, such as used for rock drilling and stone cutting, but it must be carefully avoided in the case of ground and polished diamonds, even if these surfaces are outside the embedding metal.[2]

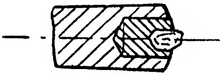

FIG. 156.—Setting a diamond by brazing

BRAZING

This method is generally adopted for holding diamond truing tools and small diamonds which are used as boring

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[1] Diamonds must be carefully cleaned before setting.

[2] Burned diamonds under the microscope show a series of triangular markings. To exclude these defects the necessary casting, brazing, and sintering operations have to be carried out in an inert atmosphere, so that any attack from free oxygen is excluded. Professor Robert E. Lyons, of the Chemistry Department of Indiana University, observed no change in a number of diamonds which were set by casting steel round them five different times. The explanation is obviously that during the heating operation no access to free oxygen was given, therefore the diamond was obviously protected by thin metallic films or those of non-conductive materials.

tools for metals, and as cutting points for gramophone records, etc. Some of these points and metal holders are so small that a mechanical holding by cold-setting methods seems hardly applicable.

In the case of brazing a diamond, the tool post (Fig. 156) receives a small hole somewhat larger than that of the diamond used. It is set in the hole and carefully secured with a hard solder. Table 21 shows the melting points of ordinary soldering metals and alloys; only the group of silver solders have melting points below 700 deg. C. (1,300 deg. F.), which are usually not considered safe for diamonds. Further, the brazing flux (borax) can be harmful to the diamond.

TABLE 21

MELTING POINTS OF USUAL SOLDERING AND CASTING METALS AND ALLOYS

	Deg. C.	Deg. F.
Cast steel	1,300–1,500	2,400–2,750
Monel metal	1,350	2,450
Beryllium-Copper	about 1,000	about 1,800
Copper	1,083	1,988
Brasses	890–950	1,634–1,742
Brazing spelters	850–950	1,562–1,742
Usual silver solders* ..	720–855	1,330–1,570
Special silver solders ..	630–695	1,166–1,283
Soft solders†	180–350	356–662

* See Table 22.

† Generally not suitable for diamond tools, but applied for temporary holding of diamonds during production.

Silver solders are, of course, somewhat more expensive than the usual brass spelters, but owing to their good properties, in particular their quick flowing, they should be more generally applied for this purpose. Table 22 shows the composition of standard silver solders and reveals that with increasing silver contents the melting point is reduced. There are also on the market several silver alloys with melting points between 630 deg. to 700 deg. C. (1,120 to 1,300 deg. F.) which seem to be suited in particular to diamond tools. Table 21 shows that between these alloys and the soft solders quite a large gap exists, but hitherto no suitable alloy in this range has been found. The soft solders, in spite of their favourably low melting point, are not suitable for diamond tools as they have unfavourable properties, such as low hardness and a high heat expansion.

TABLE 22

STANDARD SILVER SOLDERS

Designation	Composition			Melting Point	
	Copper	Zinc	Silver	Deg. C.	Deg. F.
	Per cent	Per cent	Per cent		
4	50	46	4	855	1,571
8	50	42	8	830	1,517
9	43	48	9	820	1,508
12	36	52	12	785	1,445
25	40	35	25	765	1,409
45	30	25	45	720	1,328

If insufficient care is exercised in the brazing of diamonds there is always a risk of the diamond loosening when stressed and heated during the operation. Therefore some combined methods have been tried out. The tool shaft receives a hole somewhat larger than the diamond to be inserted, and is then slotted (Fig. 157). The diamond is placed in the correct position, and the metal is carefully caulked round the diamond. The remaining slots and cavities are then filled by a solder.

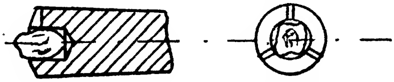

FIG. 157.—Rough diamond, caulked and brazed in

CASTING

A newly developed method of casting diamonds is in special alloys, such as brass, brass with small silver contents, and copper-nickel alloys, known as monel metal, etc.

Fig. 158A shows the mould for producing a dressing tool which contains three diamonds (Fig. 158B), according to B.P. no. 458195. The diamonds (*g*) are placed in recesses (*c*) in a body (*b*). They are held by wires (*d*) and screws (*e*). On top of this body a mould (*f*) for pouring the copper-nickel alloy is placed. The used wires (*d*) may be of the same alloy.

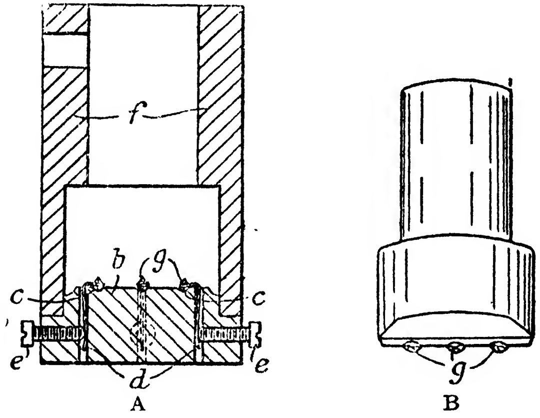

FIG. 158 A and B.—Casting metal around diamonds. A, construction of mould; B, finished diamond tool

When cool, the tool can be machined as shown in Fig. 158A. In a modification the body of the tool consists of steel, and the diamonds are located in recesses. The same method is applicable for single diamonds as well as multiple diamonds.

For larger numbers of small stones this method is not applicable. The diamond is held by vacuum in the mould with the advantage that the access of oxygen to the diamonds, and therefore eventual burning, is prevented. Fig. 159A (according to B.P. no. 476781) shows, for instance, a special mould and the resulting tool. The diamonds (D) to be inserted into the crown are placed on small holes (11*b*) made in a mica-ring (11). The holes are continued in a flange (7), which closes a vacuum chamber (2). During the time that the molten metal is filled in the mould (13) a vacuum is generated in

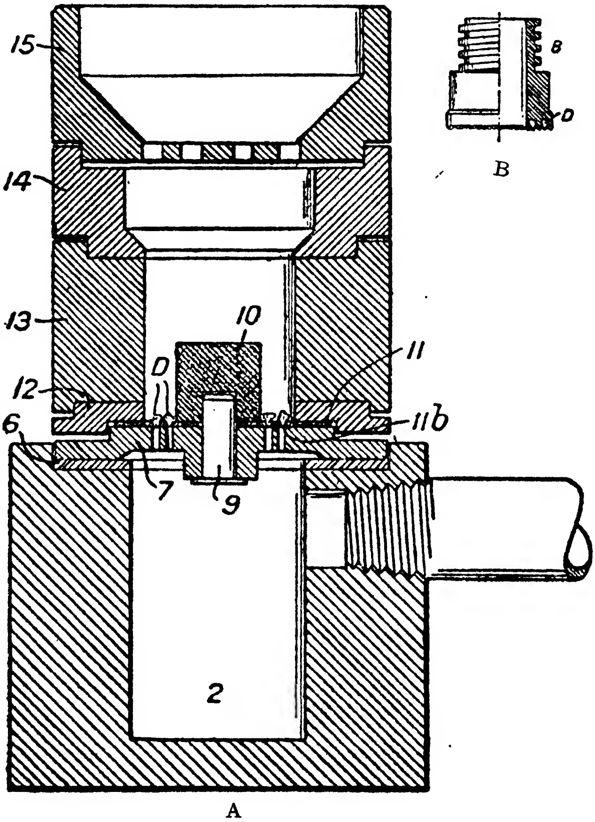

FIG. 159 A and B.—Casting metal under vacuum around diamonds. A, construction of the mould and vacuum supply; B, rock-drilling crown finished

chamber (2). Plate 7 has in the middle a pin (9) for centring the mica disc (11) and for the reception of a carbon core (10), which serves to produce the hole in the crown. Further. a gasket (6) is provided between flange (7) and cylinder, The mould is formed by cylinders (12) and (13), on which the funnel-shaped ring (14) is placed.

On top of this the cylinder (15), with holes at the bottom, is placed. Molten metal is poured into it, ensuring an equal distribution of the metal.

Provision can be made to provide the carbon core with holes so that diamonds can also be placed on the inner and outer side of the crown. Diamonds can be placed in this manner on the ends of tool holders. The method is also applicable to the production of diamond saws. The finished cast parts are cleaned with a sand blast to leave the diamonds projecting.

Brass and alloys of 95 per cent standard brass, together with 5 per cent fine silver, have proved to be satisfactory in the casting of diamond tools for truing grinding wheels. The melting point of brass alloys with more than 30 per cent tin is below 750 deg. C. (1,380 deg. F.). The copper-nickel alloys, known as "Monel" metal, appear to be of advantage for setting diamond tools, in spite of the fact that they are difficult to cast, and that the casting temperatures are relatively high. (Recommended pouring temperatures 1,540 deg. C. (2,800 deg. F.). Therefore special arrangements have to be made to cast under vacuum (see Fig. 159A). In the Monel metal (nickel 65 to 70 per cent, copper 26 to 30 per cent, iron up to 3·0 per cent, manganese up to 1·5 per cent, silicon up to 0·25 per cent, carbon up to 0·25 per cent) the best obtainable physical properties with regard to strength, such as hardness, toughness and resistance against corrosion, are combined in particular at elevated temperatures. This material can be used at very much higher temperatures than brass, i.e. up to 600 deg. C. (1,100 deg. F.), and the tensile and torsional strength begin to drop only after about 400 deg. C. (750 deg. F.).

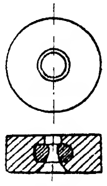

FIG. 160.—Diamond drawing die cast in brass

Diamond drawing dies are set usually in brass, and the molten brass is cast round the stone (Fig. 160). The metal ring is of great importance in securing the die against cracking caused by internal stresses due to the high pressure. The die must be exactly centred, and the side faces perpendicular; for this purpose simple devices (Fig. 161) are employed. The correct setting is of great importance as the stones are re-polished in the setting. The brass holders have usually a diameter of 1 inch or 1⅛ inch, and a thickness of $\frac{5}{32}$ inch to $\frac{9}{16}$ inch. A method in which cast steel is used for setting diamond dies has also been known for some thirty years, but special care must be taken that the stones are not burnt. It is reported that diamond dies are also set in Monel metal and beryllium-copper.[1]

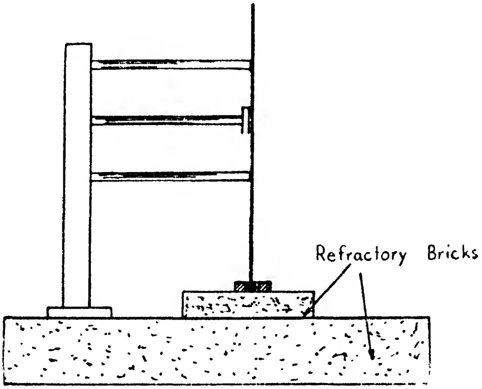

FIG. 161.—Holder for centring the die for the casting process

SINTERING

Sintering[2] of diamonds in a powdered metal is a more recent method made possible by the development of the powder metallurgy. This process is used to a large extent in binding diamond grain and dust, but it has not yet found widespread application for embedding diamonds of a somewhat larger size. Suitable metal powders for sintering diamonds are iron, copper, brass, cobalt and Monel metal, but hitherto no such application has appeared on the market.

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[1] The author has given a general review of the methods in setting and mounting drawing dies, see *The Wire Industry*, March 1941.

[2] See also p. 125.

The only product is the embedding of substantial diamonds in a matrix of sintered tungsten or tungsten carbide (Fig. 162). The manufacture of tools, such as those for truing, in which diamonds are embedded in sintered carbides, is similar to that of the usual hardmetal tools.

After the single diamond is fixed in the required position in a mould the matrix in powdered form is placed around the diamond. In the case of the diamond impregnated tool, the matrix, also in powdered form mixed with a corresponding large quantity of small diamond particles, is placed in the mould. Heat and pressure have to be applied in this case only for a short time so as not to be detrimental to the diamonds. The material, powder of tungsten carbide, or sometimes pure tungsten, is not melted, but only heated to a degree necessary to cement and harden the fine metal particles. As, during this process, only a superficial wetting of the surfaces of the binding material (usually cobalt) and metal carbides as well as those of the diamonds takes place, an adaptation to the exact contours and a permanent holding of the particles is ensured. In the case of larger diamonds, it is claimed that stone loss and breakage is eliminated.

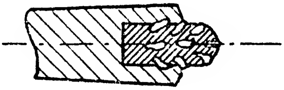

FIG. 162.—Diamond chips embedded in a tungsten or tungsten carbide matrix; tool used for truing purposes

The tools impregnated with numerous small diamonds (Fig. 162) are mainly used for finish-dressing. In a recently issued report it is stated that a diamond-impregnated hard metal dresser replaced a 3-carat diamond in the dry dressing of a 20 × 6 inches aluminium oxide wheel, and the costs per dressing were reduced from 21·5 cents to 3·5 cents.

COLD SETTING

The oldest method for setting diamonds has been to clamp the rough stone by caulking or mechanically. Whereas in the first case the diamond was held by the flexibility of the material, in the latter case clamps and tangs of various shapes adapted themselves to the roughness of the natural stone. These methods were satisfactory enough for earlier efforts at truing and cutting tools, etc., but they had to be abandoned with higher speeds and stresses. The main disadvantage is not only the mechanical hold, but also the few points of the stone which take an active part in the clamping, so that local stresses are generated in the stone and the deduction of heat from the diamond to the shaft is not good. This would eventually be the case if the shape of the rough diamond was fully or partly reproduced in the holding nuts and clamping chucks. One of these methods consists in hot pressing, and, recently, cold pressing of the diamond in a cap nut of mild steel.

The caulking of diamonds in soft steel is quite usual for inserting diamonds in truing tools, in boring crowns and

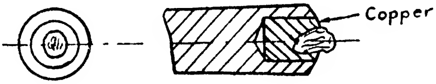

Fig. 163.—Caulking of rough diamond for truing tool

in discs or plates for stone cutting. Sometimes in the caulking process the slots are not braced with hard solder, and the edges are only hammered mechanically together. The tool shaft is provided with a hole large enough to insert the diamond, and the edges are then caulked round. This method requires, however, great skill in order not to endanger the diamond, and it cannot be considered as a routine method of setting diamonds. An approach in which the risk in caulking diamonds directly into steel is eliminated is shown in Fig. 163. Here the tool shaft is provided with a hole in which a piece of copper is placed. This receives another smaller hole for the reception of the diamond. The diamond is secured in its position by caulking. The method by which the shaft material of steel is placed near to the diamond is of special advantage for truing tools, as sparks indicate the point when the shaft material comes into contact with the grinding wheel, and the diamond has to be reset.

The caulking of rough diamonds by copper and tinfoils is used for fixing diamonds in the edges of boring crowns (Fig. 164). The arrows indicate the direction and intensity of the caulking blows.

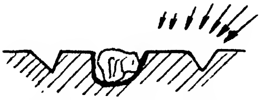

FIG. 164.—Caulking (peening) of a rough diamond for setting in a rock-drill crown

In more modern methods of cold setting the diamond is fully or partially ground and polished, even on the surfaces to be fixed. The first method of this kind, applied originally for holding the polished diamonds, for the finish turning of soft rubber and calender rolls, consisted of clamping the diamond into a recess of the tool shank, clamped by a cover plate. The diamond was polished flat on two sides, with facets on the front side and the rear remaining rough (Fig. 165). About fifteen years ago, owing to the introduction of the diamond for turning metals, somewhat more elaborate methods were developed, in which between cover plates and shanks a reception plate for the diamond was placed.

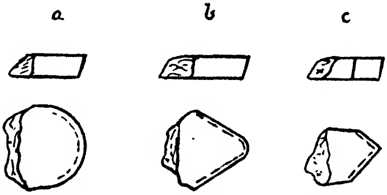

FIG. 165.—*a*, *b*, *c*. Different forms of calender diamonds

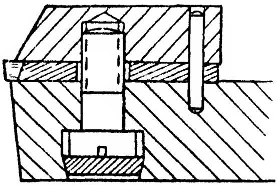

Fig. 166.—Cold set diamond by means of a cover plate

An improvement was to give the cover plate a small rocking movement on a pin or a ball to allow a distinct adaptation to the shape of the diamond (Fig. 166). The diamond was set either on a flat side or had only a point support. As these methods were not fully satisfactory, new experiments have been tried out. Fig. 167 shows a French design in which the diamond has a trapezoidal cross-section, and is pressed to the tool shank by means of two sideways arranged cover plates. This design has the advantage of the upper side of the stone being absolutely free, the flow of chip is not hindered, and the cutting operation can be observed without any obstruction. Formerly, diamond tools of this kind were produced by brazing the diamond in the tool holder.

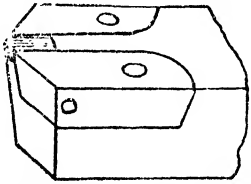

FIG. 167.—Cold set diamond without cover plate

In the methods for cold setting of turning and boring tools, invented by F. C. Jearum, use is made of diamonds of special shape lapped all over. The diamond is, for instance, wedge-shaped in both a vertical and horizontal direction; the vertical angle is 9 degrees included, whereas the side flanks slope to an included angle of 30 degrees (Fig. 168). For the shape of the diamond, a cavity is produced in the tool shank by means of die milling (Fig. 169). As the diamond is usually given no rake or top angle, it fits nearly close with the tool holder. After the diamond has been fitted into the

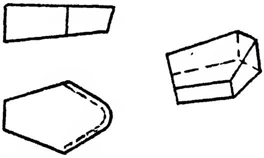

FIG. 168.—Wedge-shaped diamond polished all over

cavity of the lower member and enclosed by the upper half, the parts are held together by the encircling sleeve which is forced up the taper by the temporary nut. After this the assembled parts are secured by a transverse pin, which causes the halves to close tightly on the diamond surface at the front. When the threaded portion is cut off flush a small and handy tool is produced.

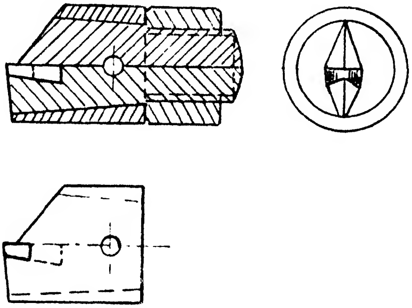

FIG. 169.—Patented method of setting the diamond (Fig. 168) in a tool holder

Another form for holding a diamond of the same shape is shown in Fig. 170A and B. Here two members form jointly the full diameter of the finished tool, but support a reverse shoulder at the rear to take a ring of triangular section, and axially split at one point; this ring, together with the parts, is incorporated in a screwed shank. When the parts are assembled the angular faces of the ring cause the members to contract, and so to clamp the diamond.

A B

FIG. 170 A and B.—Two other forms for setting diamond formed according to Fig. 168 in tool holders

It has been proposed by the same inventor that the shaped diamond should be given a truncated tetrahedral form

(Fig. 171). Here the upper and lower members are formed in one piece, the member having an inwardly tapering slot which is continued with the parallel portion. The member is formed to pass freely into the taper slot so that the diamond will fit closely into the same slot. Thus the diamond is jointly held between the four faces of the slots. With the diamond in position the half members are inserted into the encircling sleeve, and the screw is inserted to force the members home into the taper and so secure the diamond. The screw is long enough to end flush with the tool.

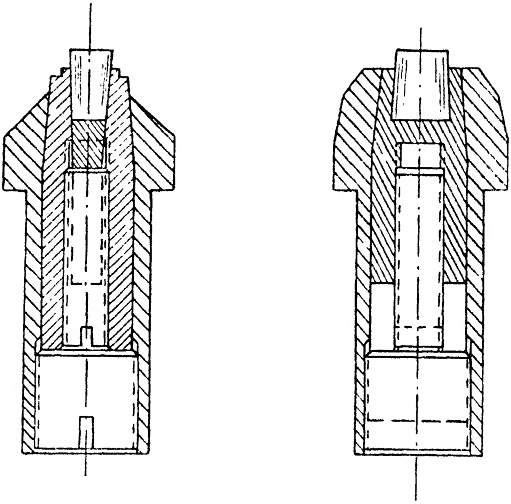

FIG. 171.—Cold setting of a diamond of truncated tetrahedral form

For a long time it has been recognized that the ideal form of support for a heavily stressed diamond tool would be a spherical or ball form, as any stress caused in the diamond by the clamping and during the operation would be equally taken off and distributed over a relatively great area. Further, the diamond is given an opportunity to adjust itself to the stress and strain. Formerly, the diamond was provided with a hemisphere of steel or sintered carbide cemented to the lower side of the diamond ground flat. This cementing is performed without the application of heat. Fig. 172 shows an example of this design. The diamond is clamped in the usual way by a clamping screw in the middle, while the rear end of the cover plate rocks on a pin with horizontal axis. According to this design, only half of the screw pressure acts on the diamond when the screw is fitted as usual in the middle between diamond and abutment. This method has proved to be advantageous for both turning and boring tools; however, it cannot be applied for tools of very small size.

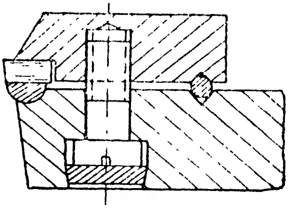

FIG. 172.—Diamond cut flat on the lower side and cemented by a cold process to a hardmetal hemisphere

A great improvement is the manufacture of diamonds integral with a ball-shape support (Fig. 173). The production of ball-shaped diamonds involves some problems. Compared with the cementing method as in Fig. 172, somewhat bigger diamonds have to be used, but, at the same time, the radius of hemisphere can be made larger, so that the centre of the hemisphere lies considerably above the cutting edge. Therefore, any rocking motion of the diamond has no great influence on the position of the cutting edge.

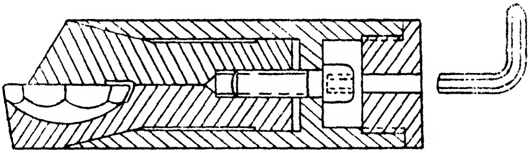

FIG. 173.—Diamond integral with a hemispherical support

Fig. 173 shows, as an example, a diamond tool with eight facets and a hemispherical support. As each facet can be brought into any position with regard to the surface of the work-piece, such a tool can replace numerous diamond tools where the diamond is held in a fixed position. The tool consists of a bush with a front end taper, into which the two halves of the collet-like holder fit. The lower side of the upper member is flat, whereas the lower member is die-sunk according to the radius of hemisphere. The diamond is $\frac{4}{10000}$ inch thicker than the distance between the two halves, so that when closed and the screw operated, the front ends are clamped together and the diamond held rigidly in position. When loosening the clamp, the diamond can be rotated into the desired position and re-clamped again; however, some skill is required in the handling of the tool.

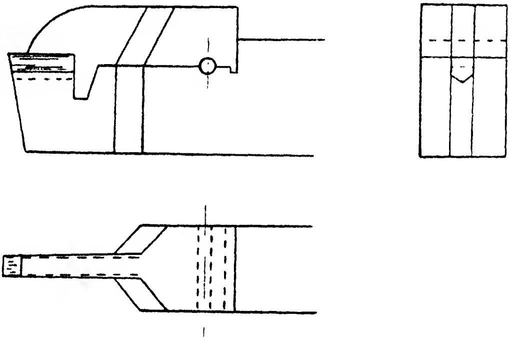

FIG. 174.—Design for a grooving and cut-off tool

Fig. 174 shows a grooving or cutting-off tool. These tools, owing to the small widths, require a special method of fixing. This has been achieved by fitting the cover plate into a wedge-shaped recess and giving the diamond a V-shaped lower side. The pressure during operation cannot pull out the diamond.

In the setting of hardness indenters, difficulties were experienced with the usual brazing method as the diamond was liable to loosen during use, and thus make the readings inaccurate (Fig. 175). In a new method, use is made of a diamond with a plane face ground vertical to its axis and resting on a hard metal block (Fig. 176). The steel holder is pressed over the diamond and the hard metal block by a cold-pressing method; the shape of the diamond on places which remain rough is thus reproduced in the steel, while, on the other hand, the diamond obtains absolutely rigid support. This more extensive method is justified in the case of these indenters which represent one of the most important components of hardness-testing equipment. The ideal form of support would be also in this case a hemispherical support, for instance similar to Fig. 173.

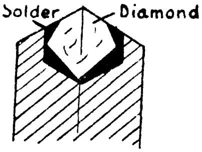

FIG. 175.—Old and unsatisfactory method of brazing a hardness indenter; the point sets eccentrically under strain

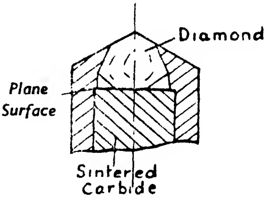

FIG. 176.—Improved form of hardness indenter placed on a sintered carbide block

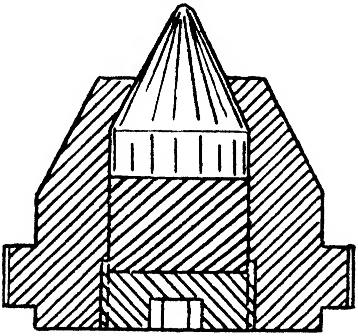

FIG. 177.—Conically shaped diamond for truing thread-grinding wheels, cold set in a special holder

Fig. 177 illustrates the cold setting of a diamond polished all over and provided with a conical point and a small rounding, a form which is used for truing thread-grinding wheels. The conical end of the diamond is placed in a special cap nut, the lower side is backed by a hardened steel plate or a block of sintered carbide, and the three parts assembled by a kind of grub screw. The whole component can easily be dismantled eventually for the re-grinding of the diamond.

The diamond in the cone tool illustrated in Fig. 177, which terminates in a radius at its apex, has been developed and applied to the "Matrix" patented multi-thread grinding device. In the form shown, as a pure cone with radius, it is covered by Registered Design no. 786364. In an alternative form, providing clearance by a combination of greater and lesser cone angles, the lesser being tangential to the radius, it is covered by Registered Design no. 837215, and British patent no. 533002, by the Coventry Gauge and Tool Co., Ltd., of Coventry.

These design registrations and patent apply to the protruding shape of the cone, and not to the type of mounting.

CHAPTER XIV

GRINDING AND LAPPING OF SINTERED CARBIDES

SINTERED carbides are of similar hardness to corundum and other synthetic abrasives, and, therefore, similar methods must be applied for bringing them into final shape as required in the manufacture of gem stones.

At first, cast-iron wheels prepared with diamond dust were used in the lapping of hard metal tips, corresponding to that method applied in cutting diamonds. This lapping proved to be one of the most successful methods of increasing the durability of cutting edges.

In grinding and lapping of sintered carbide tips, there are four separate operations:

(1) Grinding the tool shaft (usually bright mild steel) by a coarse aluminium-oxide wheel; the operation is performed on the periphery of the wheel.

(2) Pre-grinding the sintered carbide tip by a special silicon-carbide wheel of coarse grit; operation performed on the periphery of the wheel.

(3) Finish grinding of the sintered carbide tip by a special silicon-carbide wheel of fine grit, or by a coarse diamond dust prepared wheel; operation usually performed on the side of the wheel (cup wheel).

(4) Lapping of a small land on the cutting edge by a fine-grit diamond wheel; operation performed on the side of the wheel (cup wheel).

Occasionally operation (4) can be dispensed with. This is sometimes done for economical reasons, but it has been proved repeatedly that the tool life of many cutting tools is extended by about 50 per cent if polished or lapped tool edges are used. They provide a better flow of chips and reduce the wear of the cutting edge.

Operations (1) and (2) are usually carried out on a combined machine, for instance, a grinding-wheel stand with a bar rest and grinding wheels on either side, i.e. on one side an aluminium-oxide wheel, and on the other a silicon-carbide wheel. The two finishing operations (3 and 4) are then carried out also on a combined machine. This arrangement has proved to be of special advantage. If the edges of the tools are only slightly blunted, it is only necessary to carry out the two last operations (3 and 4). These tools should only be used until slightly blunted or broken out, so that the re-sharpening can be carried out in a minimum of time and without any considerable loss of the costly sintered carbide and of the expensive diamond wheel; otherwise, reconditioning of the tip has to start from the first operations (1 and 2).

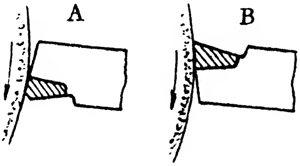

FIG. 178 A and B.—Correct (B) and incorrect (A) way of grinding sintered carbide tips

The *pre-grinding* operations (1 and 2) can be carried out on conventional lines, only care must be taken not to heat the tool tip, and to grind the tool from the top to the bottom as shown in Fig. 178. No great pressure should be applied, as small pressure gives a favourable grinding effect. To reduce the effect of hollow grinding (Fig. 179) when using the periphery of the wheel, a grinding wheel with a diameter of not less than 8 inch should be used. Table 23 gives some recommendations with regard to the selection of grinding wheels according to the shaft cross-section of tools.

For these reasons usually diamond wheels of 5-inch to 6-inch diameter are recommended, for which speeds up to 3,000 R.P.M. are usual.

Some kinds of sintered carbides, i.e. the tougher alloys with titanium contents, can be ground in the dry state on soft wheels, but in the case of larger tips grinding under ample water supply is recommended to avoid heat cracks. which later on may lead to the cutting edge breaking out,

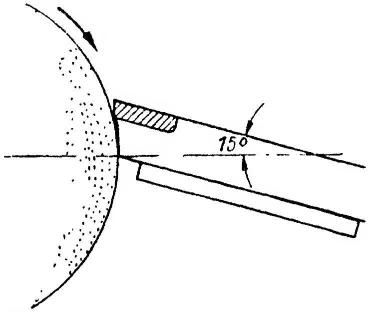

Fig. 179.—Effect of hollow grinding when using the periphery of wheel

If small tips are ground dry, the tip should not be cooled even for a moment. The cooling water should come from the tap in ample supply and without pressure. It should be clear so that the grinding operation can be observed. A drop-like supply is dangerous, as heating of the tip cannot be avoided, and the tip becomes momentarily and locally cooled.

Table 23

RECOMMENDED WHEEL SIZES TO AVOID HOLLOW GRINDING

Shaft Cross-Section of the Tool	Grinding Wheel Diameter	Width of Grinding Wheel
Sq. in.	in.	in.
Above 7	16–20	2⅜–3¼
3–7	12–16	1⅝–2⅜
Up to 3	8–12	1¼–1⅝

For the two finish-grinding operations (3 and 4) the use of cup wheels, i.e. grinding on the face of the wheel, is strongly recommended (Fig. 180). Plane surfaces are thus generated, the diameter of the wheel in this case having no influence. To reduce the cost of diamond prepared wheels, small diameters up to 3 inches are sometimes recommended which, however, must run at a relatively high speed up to 7,500 R.P.M. which is avoided with larger wheel diameters.

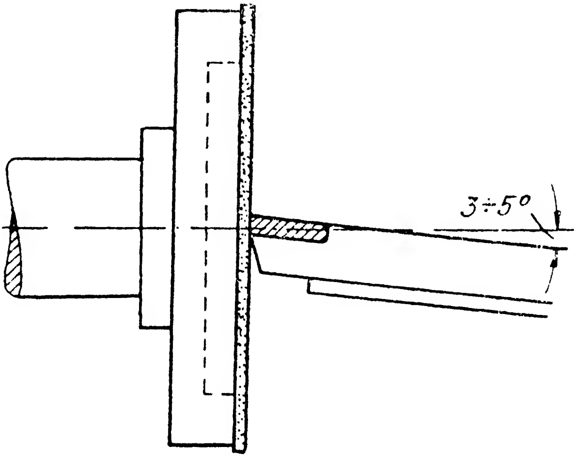

FIG. 180.—Grinding on the flat surface or rim of the wheel

In the *final lapping* operation (4) only a small land should be produced on the tool edge, i.e. that part which actually comes in contact with the material to be cut. By application of this method, illustrated in Fig. 181, no large amount of metal has to be removed, the expensive diamond wheels are saved and reconditioning time is reduced.

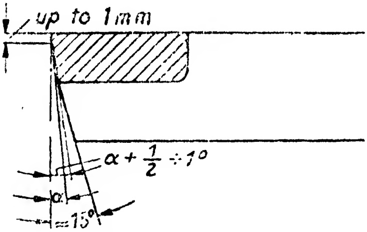

FIG. 181.—Finish grinding, or lapping a small land

With regard to cleaning and lubrication of these wheels, no standard method has hitherto been developed. All three possibilities, dry, half-dry and wet grinding, are recommended. While all diamond wheels can be used in a dry state, the half-dry method seems to be the most satisfactory. In this case a small felt pad is lightly pressed against the wheel face by a flat spring. The felt is kept moist with water, soda water, pure paraffin or benzine from a drip-feed. In the case of a bakelite wheel, a 2 per cent water-oil emulsion should be used. This prevents clogging of the wheel, which, owing to its fine nature, occurs easily. Occasional rubbing of the wheel with a wet, white pumice stone will help to keep the surface free from traces of steel and other impurities. It is a good plan to do this at the commencement of each working shift.

In these final operations the tool should only be pressed lightly against the wheel as the diamond grains have a high free-cutting power. An excessive pressure would cause "smearing" of the wheel and produce overheating likely to ruin the tool tip. On the other hand, the wheel surface can be scored, and there is no possibility of reconditioning the wheel surface in the machine. Scored and uneven bakelite bound wheels can be reconditioned on a flat steel or glass surface by means of fine abrasive powder.

Various kinds of diamond wheels for grinding and lapping hard metal tip tools are in use, and their main characteristics will be discussed.

CAST-IRON DISCS PROVIDED WITH LOOSE DIAMOND GRAIN

These are the same wheels as are used for cutting diamonds. A distinction is made between coarse prepared wheels for lapping and polishing of hard metal surfaces and fine prepared wheels for polishing cutting and knife edges, and points. These wheels are used dry or only in the half-wet state. They should only be applied when the hard metal surface has been already finish-ground on a diamond impregnated wheel.

They are highly efficient and inexpensive, but are not in standard use. They have to be carefully prepared and reprepared with diamond dust, which is a disadvantage, whereas the impregnated type of wheel is always ready for immediate use. These facts have led many workshops to standardize the impregnated wheels.

The re-preparation of such a wheel can be carried out in several ways, as by dry application of diamond dust mixed with a small amount of lard. To obtain a suitable paste, some drops of benzine or trichloraethylene are added. The amount of diamond dust which sticks on the fingertips when dipping the glass tube containing the diamond dust, i.e. about one-twentieth carat, suffices for preparing a wheel of suitable size. The diamond dust is brought to the stationary wheel by the rotating movement of the fingertip. Then the motor is started, and by using a bar of hard metal the diamond dust is pressed into the porous surface of the wheel.

If only matt surfaces are generated, it is unnecessary to re-prepare the wheel from the beginning. The surface is only wetted with a few drops of paraffin oil and rubbed with a rag, and remnants of hard metal dust are removed and the grains rearranged in a new position. Re-preparation is only necessary after the grinding of thirty to fifty tools. When correctly applied, one carat of diamond dust is sufficient for five hundred tools of medium size. The finer the grit, the more economical is the use of loose diamond dust. The polishing of hard metal tips by these wheels is dealt with in a separate paragraph.

METAL WHEELS IN WHICH DIAMOND DUST IS PRESSED

Diamond dust is pressed into the surface of metal wheels, consisting of aluminium, brass or steel, by roughing the surface by a special rolling process. The dust is pressed into the pores of the material and held in a fixed position by the flexibility of the metal. As the depth of the diamond preparation is very low, the wheels lose their abrasive action in the case of uneven wear. This is also promoted by an uneven distribution of the grain, varying surface roughness, etc. Parts of the wheel which have lost their diamond preparation, heat the hard metal surfaces considerably, and can cause grinding cracks. Recently, improved wheels of this kind have been developed with a depth of diamond impregnation up to $\frac{5}{64}$ inch (2 mm.). These wheels are still in the experimental stage, and no definite opinion of them can be formed.

WHEELS IN WHICH DIAMOND IS BOUND IN PHENOL RESIN

Diamonds bound in phenol resin can be recommended, particularly for off-hand grinding. They are soft and flexible, corresponding to the used material, and retain even after long use their keen abrasive action. Clogging of the wheel surface can be prevented by using a wet pumice stone (see above), and one-sided wear can be reconditioned on a flat steel or glass surface by applying fine abrasive powders mixed with oil, and performing circular movements. Before the wheels are used, they are placed in pure, light mineral oil for some hours. Their durability is said to increase by using oil as a lubricant. Oil impregnated wheels should run before use until no further oil is thrown.

In comparison to wheels in which diamond dust is bound in metal, these wheels can be used with fine grit sizes. Owing to the good abrasive action and their economy, they are useful for finish-grinding of even larger surfaces, for instance, in the case of off-hand grinding of woodworking milling tools and for tools with fine cutting edges and small cutting angles of 25 to 40 degrees. In many cases these wheels are more useful than wheels bound with metal, as in the latter case vibrations of the hand and the grinding wheel easily break out the edges of the cutting tool.

DIAMOND DUST BOUND IN SINTERED METAL WHEELS

As binding material, powders of iron, bronze, copper or cobalt are used. Owing to their hardness, these wheels suffer the least wear on their edges, and no one-sided wear is observed. According to their hardness they can only be cleaned and re-dressed by means of pumice stone, silicon-carbon stick, or silicon-carbide dust placed on a rough cast-iron disc. In contrast to phenol-resin wheels, oil as lubricant is not satisfactory for this type, which is used for obtaining the highest precision on cutting edges and other surfaces, such as on measuring instruments. Small cup wheels are developed for grinding the cutting faces on brooches and for external and internal grinding.

DIAMOND DUST BOUND IN SINTERED CARBIDES

It is a well-known fact that the harder the binding material the longer is the abrasive action of the single grains; this is particularly true as regards diamond grain. In the case of these wheels, a high diamond concentration has proved to be necessary to avoid too high a wear and too great blunting of the single grain. The abrasive material can be less thick than in other cases. These wheels have proved to be satisfactory for short operations demanding hard abrasive action, as in the case of fine profile threads. They must run absolutely true on the grinding spindle (the maximum permissible inaccuracy is 0·0004 to 0·0008 inch (0·01 to 0·02 mm.), otherwise the abrasive coating is worn off unevenly. A true concentric running can only be expected on new machines, or those with adjustable bearings, and in the case of an exactly mounted disc.

Table 24 gives the recommended grinding speeds in addition to general characteristics of the wheels. There is a wide range so that existing machines may be easily used. Grinding speeds on one wheel vary with the thickness of the rim, and particularly in the case of cast-iron lapping wheels. A general rule is the finer the grit the lower the speed, the coarser the grit the higher the speed. For fine grinding, sometimes very low speeds are recommended, i.e. 600 to 2,400 feet per minute, whereas for pre-grinding, in preparation for the polishing process, speeds between 2,400 and 4,000 are recommended. Lower speeds should be selected for semi-automatic machines, in particular when grinding titanium containing alloys. The American expert St. Clair recommends for both rough grinding with silicon-carbide wheels and finish-grinding with resinoid bound silicon carbide of no. 300 to 400 grit size, speeds between 1,600 and 2,600 feet per minute, but not higher. Lower speeds are also useful for larger surfaces, as heating of the metal is reduced and the grain is not blunted so quickly. With increased diamond concentration the speed can also be increased. Dry grinding should be carried out with lower speeds than that when water or oil lubrication are applied. The composition of the sintered carbides have also their effect, those with high cobalt contents being very much softer, and lend themselves to higher grinding speeds. On the other hand, the wheel surfaces must be more frequently

Table 24

GENERAL RECOMMENDATIONS FOR GRINDING AND POLISHING WHEELS FOR SINTERED CARBIDES

Kind of Wheel	Composition	Grit-size	Speed§
			S.F.P.M.
Roughing:—			
Silicon-carbide vitrified	SiC (N)*	60	5,000
Medium:—			
Silicon-carbide vitrified	SiC (O)*	80	5,000
Finishing:—			
Silicon-carbide vitrified	SiC (P)* (K)†	120	5,000
Cast iron	Porous cast iron		1,000–4,000
Phenol-resin bond:—			
Roughing		100, 180*	3,000–6,500‡
Finishing		100, 180, 240*	
Ultra-finishing ..		180, 240, 400*	
Lapping		400*	
Sintered metal (bronze)		about 100	3,000–6,000
Sintered hard metal:—			
Roughing		120	About 6,00c
Medium		230	
Finishing		500	

* According to Carborundum Co.

† According to Norton Co.

‡ A good average value is 5,000 F.P.M., but some experts advocate even lower speeds between 1,600 to 2,600 F.P.M.

§ With regard to the lubrication of wheels, see text, p. 215.

cleaned. Titanium containing sintered carbides demand lower speeds as already pointed out.

On grinding and lapping machines for hard metal tips the following points must be met:

Highly precise bearings with a minimum of clearance; adjustable plane bearings are specially recommended;

The tool must be able to move across the wheel face to avoid one-sided wear (mechanical lapping movement) and

Fine and exact adjustment for clearance and right-angles.

Some machines of this kind have an adjustment for compound angles and a radius device for sharpening round-nosed and thread-cutting tools. In order to utilize fully the wheel face, a hand-operated device for moving the tool edge across the wheel is provided. To grind and lap both left- and right-hand tools on the same wheel, reversible motors are used.

HIGH GLOSSY FINISH ON HARD METALS

To obtain a high glossy finish on hard metals, besides cast-iron discs, those of plastic materials, wood, felt, or the like can be used as bearing materials for the abrasive powders. Glossy surfaces can be obtained very quickly by means of felt discs. There are three cases:

(1) Highly precise surfaces, which are lapped and polished to limits of 0·002 inch (1/200 mm.). After the finish-lapping by a phenol-resin bound wheel, lapping with a cast-iron wheel and a fine diamond grain of 0·0005 mm. maximum grit size should be applied. The lapping paste must be prepared with lard on a glass plate, thoroughly mixed and uniformly placed on the cast-iron disc. A speed of 800 to 2,200 feet per minute on a relatively coarse cast-iron wheel is recommended, but larger surfaces should be polished on fine cast-iron discs.

(2) Surfaces without high dimensional precision, on which fine diamond grain of 0·0005 mm. grit size on wood or felt discs is used. A convex-shaped wooden wheel whose rim is covered by a felt ring is a usual device. This ring is uniformly provided with pure olive oil and diamond dust; the

polishing is performed in a few seconds. Hollow-ground tools are polished in this way by hardwood polishing tools.

(3) Metallographic polishing. Various kinds of felt discs with fine diamond grain up to 0·0005 mm. are used. Besides diamond dust, boron carbide and mixtures of tungsten carbide powder are employed. The grinding dust of sintered carbides tends to smear owing to the cobalt contents, therefore care should be taken to clean the lapping wheels periodically.

SPECIAL OPERATIONS

Lapping and polishing sintered carbide tips is of advantage in the case of *tools with multiple teeth*, in particular, milling cutters (Fig. 182). Absolute uniformity of teeth with regard to angles, diameters and plane operation is obtained. In these cases, the ordinary vitrified grinding wheels wear quickly, so that a frequent resetting and truing of the wheels is necessary. In the diamond wheel, however, every tooth is of equal width and diameter, and therefore supports the

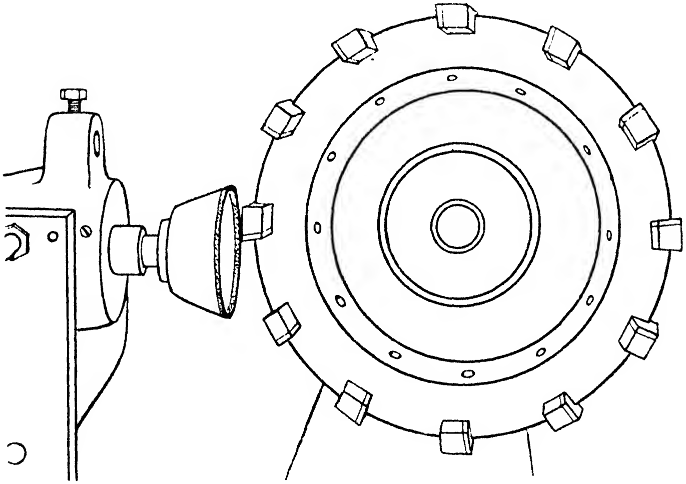

FIG. 182.—Grinding the teeth of a milling cutter on a diamond-impregnated wheel (metal bond)

same load when in service; this results in uniform stress and reduced tool wear.

Hand-operated lapping stones consist of small holders, the front part of which is prepared with diamond dust, either bakelite, sintered metal or hardmetal. With the aid of these tools, the cutting edges of slightly blunted hard metal tip tools are reconditioned. Various forms of these tools are on the market, and they are recommended particularly for fully and semi-automatic machines.

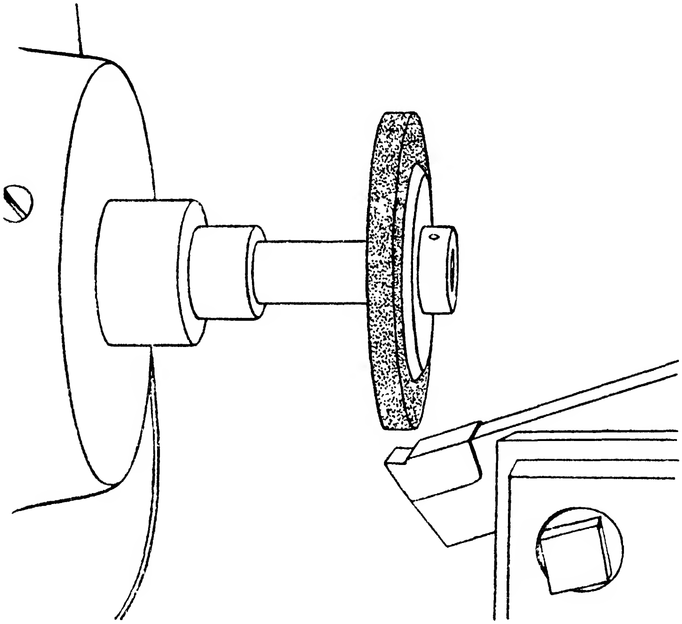

FIG. 183.—Cutting chip-breaking grooves by means of a diamond prepared wheel

A further important operation is the production of chip-breaking grooves in sintered carbide tool tips. These grooves on the front end of cutting tools serve to break the chips, as the long curly ones produced by these high-speed materials are extremely difficult to remove, and endanger the operators. The grooves can be cut by special wheels, either resinoid or metal bound, with a relatively coarse diamond preparation. Usual data for these resinoid heat-bound wheels are: 4 to 6 inches diameter, $\frac{1}{8}$ inch to $\frac{3}{8}$ inch thick, diamond preparation of no. 100 grit, and $\frac{1}{16}$ inch deep. Fig. 183 shows how this operation is performed. If the grooves are arranged at distinct angles and with a distinct curvature, they also serve to control the size of the curl produced.

For sawing hardmetal tips similar sawing blades and similar machines are used, as for the sawing of gem stones. Some of this equipment is already referred to on pp. 53 to 59.

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APPENDIX I

TECHNICALLY USED HARD MATERIALS

(The following abbreviations will be used throughout this tabulated list: C.C. = chemical composition; C.S. = crystal system; H. = Mohs' hardness; S.G. = specific gravity; R.I. = refractive index.)

BORON CARBIDE

C.C. = boron carbide (B_4C) according to American patent 1897214, but other varieties also known. Harder than silicon carbide. Composition of the commercial product: B_4C: 97 per cent, traces of free graphite, free boron and borides 2·0 per cent, iron 0·4 per cent, aluminium 0·2 per cent, silicon 0·3 per cent, calcium and magnesium 0·1 per cent. Used in cast condition as wear-resistant nozzles, and as a high grade abrasive material.

CORUNDUM

C.C. = oxide of aluminium (alumina) (Al_2O_3); C.S. = hexagonal (trigonal), ruby in six-sided prisms and sapphire in twelve-sided bi-pyramids. Sapphire crystals often barrel-shaped. Varieties: red = ruby, blue = sapphire, yellow, green, purple and colourless stones termed sapphire, with the colour as prefix. Emery is an impure form of corundum used as an abrasive. H. = 9, but rubies are in general slightly softer than sapphires. Cleavage is not apparent, but there is a "false cleavage" known as *parting*, and due to secondary twinning. S.G. = 4·00 (3·95 to 4·05). The lustre is vitreous, and the refraction double. R.I. = 1·76 to 1·77, with a bi-refringence of 0·008. Dichroism is strong in ruby and blue sapphire and most fancy sapphires, except the yellow. The whitish sheen seen in some rubies and sapphires is known as "silk." It is due to the presence of vast numbers of microscopically small canals reflecting the light.

Synthetic corundum for abrasive purposes contains, besides aluminium oxide (low-grade qualities from 60 to 80 per cent, usually between 90 to 95 per cent, but for the fine grades up to 99·0 to 99·5 per cent), ferric oxide, silicon oxide and titanium oxide. C.S. = hexagonal; cleavage, less than natural corundum, colour red to white, fracture conchoidal—granular; H. = greater than 9, great toughness; several qualities with differing alumina contents and according to different manufacturing methods.

Synthetic sapphire and rubies are produced by a special process (Verneuil), in which "boules" or "birnes" are generated. The boule of pear shape with a stalk attached to the lower side consists of a crystallized mass. There is one line of weakness due to a twin-plane causing the boule to split in two pieces vertically from top to bottom. Same physical and optical properties as natural stones. Extended use in the production of watch and pivot bearings, as well as in jewellery. The needle-like inclusions of natural corundum are absent in these products. The structural differences allow discrimination between the natural and synthetic gems.

"White" sapphires are obtained by using pure alumina, but all colours are now commercially obtainable; for instance, "red" rubies are obtained by addition to the alumina of about 2·5 per cent of chromic oxide, while for sapphires the oxides of titanium and iron are used; other oxides for other colours.

DIAMOND

C.C. = carbon (C); C.S. = cubic; common forms: octahedron (8 sides), dodecahedron (12 sides), trisoctahedron (24 sides), hexoctahedron (48 sides), and rarely cubes (6 sides). Faces are often distorted and curved, and some crystals are almost spherical. "Spinel twin" crystals are common and flattened twins are termed "macles." The varieties are (*a*) "Gem" variety: colourless and pale shades of pink, blue, yellow, green and brown. (*b*) Bort: minutely crystalline grey to black crystals, useless as gems, but powdered for use in cutting and polishing. A more detailed summarization of the qualities (*a*) and (*b*) is given in Table 25. Term also used for small off-coloured and flawed crystals used for industrial purposes. (*c*) Carbon, carbonardo, or black diamond; crypto-crystalline material composed of diamond, graphite, and amorphous carbon, generally used for industrial pur-

TABLE 25

CLASSIFICATION OF DIAMONDS

Designation	Kind	Subdivision	Use*
Goods (crystals)	Regular crystals	Pure white, spotted brown, flat shaped	Mainly for ornamental purposes
Irregulars ..	Irregular shapes with broken parts		Mainly for ornamental purposes, but have to be dealt with by the cleaver
Cleavage ..	Irregular shapes with impurities	Pure, spotted brown, cleavage	
Coated stones ..	Regular and irregular shapes, not transparent		
Macles	Twinning or two and more stones, flat stones		Mainly for ornamental purposes. Different possibilities for cutting
Rejection ..	Stones rejected for ornamental purposes		Industrial use
Bort	Imperfect crystallized stones	Dark brown, grey and black	Industrial use

* Owing to the big demand for industrial stones to-day, those stones which are mentioned as being used mainly for ornamental purposes are also used for industrial purposes.

TABLE

APPLICATIONS OF THE DIAMOND AND

Machining Operations			Metals			Non-Metallic	
			Soft and Light Metals	Steel Hardened	Hard Metal Alloys	Rubber, Hard Rubber	Synthetic Resins
Chip producing	Rough	Sawing ..	—	—	—	b	b
		Turning ..	b	a, b	b	b	b
		Boring ..	b	a, b	b	b	b
		Milling ..	b	—	b	b	b
		Shaping ..	b	—	—	b	b
	Fine	Scratching ..	b	a	b	b	b
		Filing ..	b	b	b	b	b
		Engraving ..	b	b	—	b	b
		Writing ..	b	—	b	b	b
	Superfine*	Grinding ..	c	c	c	—	—
		Finishing ..	b	b	c	b	b
		Polishing ..	b	c	c	b	b
Cold-working†		Drawing,‡ Injecting ..	b	b	b	—	—
		Cutting (glass)	—	—	—	—	—

Machining operations with diamonds: a, with natural edges;

* As superfine abrasive substances in powder form numerous other minerals are used, if the hardness of the work-piece is lower than that of the diamond, such materials as, for instance—

Corundum, emery
Garnet
Tripoli (SiO_2)
Haematite (Fe_2O_3)

26

OTHER HARD MINERALS AS WORKING TOOLS

Materials		Minerals			Ceramic and Synthetic Products				
Hard Paper	Enamelled Metal	Rocks, Stones	Coal	Precious Stones, Semi-Precious Stones, Diamonds	Porcelain, Earthenware,	Glass	Artificial Stones, Bricks, Fire-Bricks	Artificial Coal	Grinding Wheels
b	—	a	a, b	c	c	c	a	b, c	—
b	b	a	a, b	b	a, b, c	a, b	a, b	b	a
b	b, c	a	a, b	c	a, b, c	b, c	a, b	b	a, b, c
b	—	a	—	—	—	b, c	a, b	b	a, c
b	—	a	—	—	—	—	—	b	a
b	b	b	b	b	b	a, b	a	b	a
b	b	b	b	b	b	b	—	b	—
b	b	b	b	b	b	b	a	b	a
b	b	b	b	b	b	a, b	b	b	a
—	—	c	b	c	c	c	c	c	a, b, c
b	—	—	b	b	b	—	—	b	a
b	—	—	b	c	c	—	—	—	—
—	—	—	—	—	—	—	—	—	—
—	—	—	—	—	—	a b	—	—	—

b, with cut edges; c, powder form; —, hitherto not proved.

and the synthetic abrasives—

Aluminium-oxide
Silicon carbide
Boron carbide.

See further, p. 239.

† For the press-polishing of gold, silver and aluminium polishing stones of agate, red jasper (impure form of compact quartz), or haematite (Fe_2O_3) are used.

‡ In some cases, in particular for precious metals such as gold, silver and gilt and silvered wires, corundum in the form of sapphire and ruby used for drawing dies.

poses, e.g. rock drill crowns. Hardness greater than crystals; specific gravity less. (*d*) Ballas (also named Bort-Ballas), intermediate type between carbons and crystalline diamonds. Radial stalk-like formation of diamond crystals, or irregular growths of multiple crystals. Great durability.

H. = 10. Perhaps slight variation in direction, octahedral face the hardest and cube face the softest (critical discussion, see p. 89). Reported variation in hardness of crystals from different localities may be solely due to the existence of twinning. Cleavage = octahedral and strong. S.G. = 3·52, and is very constant through the purity of the crystals (the impure bort and carbons may be as low as 3·15). The lustre of diamond is adamantine, and the refraction single. Sometimes anomalous double refraction may be observed which is due to strain. R.I. = 2·42. The dispersion is very strong, and is exceeded only by sphene, demantoid garnet, cassiterite and blende. This property is responsible for the display of colour known as "fire," so well seen in diamond. Under ultra-violet light diamonds fluoresce, usually sky blue or violet, but yellow and brown fluorescence colours have been observed. Diamonds also phosphoresce; are transparent to X-rays, while yellow and colourless diamonds, after long and intimate contact with radium salts, assume a green or greenish-blue colour, and attain a degree of radio-activity. Positively electrified by friction; a non-conductor of electricity. The diamond burns in oxygen between 800 to 900 deg. C. (1,500 to 1,650 deg. F.), in powder form it can be burnt on a platinum sheet by a Bunsen-burner. In inert gas, such as hydrogen and nitrogen, it can be heated to temperatures well over 1,000 deg. C. (1,850 deg. F.) and can, for instance, be placed in molten iron and in heated metal powders if the reaction period is very short. For highly stressed diamonds any heat treatment should be avoided, if possible. Used extensively as gem stones and for numerous industrial purposes (Tables 26 and 27).

Table 27

INDUSTRIAL APPLICATIONS OF DIAMONDS AND OTHER HARD MINERALS*

Application		Diamond	Corundum		Quartz		Garnet
			Natural	Synthetic	Crystals†	Cryptocrystalline‡	
As Bearings	Knife edges § ..		+	+		+	
	Cylindrical‖ ..		+	+		+	+
	End stones¶ ..	+	+	+			+
	Cup (pivot)**	+	+	+			
As wear resistant materials	Plates†† ..	+					
	Hemispheres††	+					
	Nozzles for oil	+					
	Mortars and pestles ..					+	
Gramophone records	Cutting points	+	+	+			
	Reproducing points ..	+	+	+			
In scientific instruments†	Hardness-testers‡‡ ..	+					
	Scratching records§§ ..	+					
	Surface testers .	+	+				
	Optical lenses‖‖	+			+		

* Application of tools, see Table 26.

† Quartz (and also tourmaline) has found extensive application in scientific instruments, such as piezo-electric oscillators, pressure-indicators, quartz-clocks, wave-filters, microphones, etc., owing to the so-called piezo-electric effect; it is used further as insulation substance in electric apparatus, in particular electric motors.

‡ Such as agate and chalcedony, see page 236.

§ For instance, used in balances (non-corrosive and wear resistant).

‖ For instance, used in watches, balances, water meters, etc.

¶ For instance, used in watches, etc.

** For instance, used in electric meters, compasses, etc.

†† In measuring instruments for determining the size of work, sometimes during the machining operation.

‡‡ For making scratch tests (rough stones), and polished stones for sclerometers and micro-sclerometers; indentation tests (polished points: cones with sharp point, cones with rounded point, pyramids (square and elongated), and hemispheres; machinability tests (various shapes).

§§ Scratching of glass and celluloid or steel, enlargement of the records under the microscope.

‖‖ Of high refraction power and small size. Quartz is also sometimes used for this purpose and for optical flats, having a greater hardness than

GARNET

Name applied to a group of gem stones which crystallize in the cubic system with ball-like habit (dodecahedra and trapezohedra), and which have a definite relation between their chemical compositions. All consist of a double silicate in which one of the metals may be calcium, iron, magnesium, or manganese, while the other may be aluminium, iron or chromium.

H. = 6½ to 7½; S.G. = 3·55 to 4·20; R.I. = 1·74 to 1·89. Some of blood red and deep red colour. Industrially used for watch stones, but now mostly replaced by other minerals.

QUARTZ.

Two varieties, the crystalline and the crypto-crystalline. C.C. = oxide of silicon (silica) (SiO_2).

Crystalline type.—C.S. = hexagonal (trigonal), prismatic habit. Varieties: colourless (rock crystal), brown (smoky quartz), white (milky quartz), yellow to reddish-brown (cairngorm), yellow (citrine), purple (amethyst), pink (rose quartz), green (prase), green chatoyant (cat's eye), yellow chatoyant (tiger's eye), blue (siderite), brown, yellow, red, or green, with spangles of mica (aventurine), colourless with acicular inclusions (rutilated quartz or Venus' hair stone). H. = 7; S.G. = 2·65. Lustre is vitreous and refraction double, while the dichroism is weak. R.I. = 1·54 to 1·55.

Crypto-crystalline type.—Never occurs as crystals, always composed of a mass of minute crystalline fibres. Chalcedony is the term used for this type of quartz, variety names being given to the different colours, viz. cornelian, translucent flesh-red; sard, brownish-red; chrysoprase, translucent apple-green; bloodstone, dark green with scattered spots of red jasper; agates and onyx are banded varieties, and jasper is an impure variety. H. = 7; S.G. = 2·58 to 2·64 (slightly lower than crystalline quartz); R.I. = 1·53 to 1·54 (likewise slightly lower). Chalcedony is somewhat porous, and, therefore, can be stained in various colours.

SILICON CARBIDE[1]

C.C. = S.C.; C.S. = rhombic hexagonal, colourless transparent crystals; impurities of graphite and silicon give a black colour to the trade product. (American) silicon carbide, green (German and Norwegian), or blue. Other impurities are ferric oxide, alumina and alkali. Pure silicon carbide is said to be non-conductive for electric current, commercial product loses electric conductivity by cooking in a solution of caustic potash. At 2,200 deg. C. (4,000 deg. F.) dissociation of C and Si. Resistant against acids and relatively resistant up to the highest temperatures against oxygen (atmospheric oxygen); slowly burning in the blowpipe under large oxygen supply; sensitive against attacks of melting alkalis and their carbonates. Besides used as

TABLE 28

PHYSICAL PROPERTIES OF SINTERED CARBIDES

	Special Alloy for the Machining of—			
	Cast Iron, Brass, Light Metals	Wood	Steel	Steel
Approximate compositions: (remainder tungsten)				
Carbon, per cent.. ..	6	5·4	7	8
Cobalt, per cent	6	11	5·5	5·5
Titanium	—	—	7	12
Specific gravity	14·7	14	12·3	11·1
Approximate Brinell hardness, kg./sq. mm. ..	1,800	1,500	1,800	1,800
Thermal conductivity, cal./cm. sec. ° C.	0·19	0·16	0·14	0·09
Average heat expansion between 20 to 800 deg. C.	$5\cdot10^{-6}$	$55\cdot10^{-6}$	$6\cdot10^{-6}$	$6\cdot10^{-6}$
Electric resistance, Ω sq. mm. per m.	0·2	0·28	0·29	0·43

---

[1] The commercial grade is generally known under the proprietary name of "Carborundum" (see p. 242).

abrasive materials, also used for electric resistances and as a refractory material. Only one commercial quality.

H. = 9 to 10; S.G. = 3·2.

SINTERED CARBIDES

They consist of tungsten carbide and/or titanium carbide, with a soft metal, usually cobalt, as binder. Used extensively as cutting material, for wear-resistant plates, for drawing dies, and recently, for the embedding of diamond grain and dust as grinding, polishing and lapping bodies, or for holding diamonds for truing and boring purposes. Table 28 contains composition and physical properties of usual sintered carbides.

TITANIUM CARBIDE

Titanium S.G. = 4·5, melting point 1,800 deg. C. (3,270 deg. F.). Mainly used for sintered carbides.

TOURMALINE

C.C. = a complex boro-silicate of aluminium; C.S. = hexagonal (trigonal), with prismatic habit. The crystals are roughly triangular in section capped with pyramids. The opposite ends of the crystal have different terminations (*hemimorphism*), and they are deeply striated along their length. Varieties = red (rubellite), blue (indicolite), yellow, brown, green, violet-red; H. = 7¼; S.G. = 3·08; R.I. = 1·62 to 1·65; the lustre is vitreous and the refraction double. Dichroism is strong.

TUNGSTEN CARBIDE

Tungsten S.G. = 19·2, melting point 3,370 deg. C. (6,100 deg. F.), considered as the highest melting point of metals. Tungsten carbide reduced by mixing pure tungsten with carbon in the stochiometric ratio and heating to high temperatures. High hardness (H. above 9), but very brittle. Cast bodies not found suitable, but used in powdered form as abrasive, and as basic material in the production of sintered carbides, also for embedding diamond grain.

APPENDIX II

GRINDING, POLISHING AND LAPPING AGENTS

In the following notes brief particulars are given on the principal grinding, polishing and lapping agents mentioned in connection with the different processes described in this book. For more details the work of V. L. Eardley Wilmot, *Abrasives*, 4 vols., 1927, may be recommended.

Of greatest importance to the result is accurate grading of the polishing and lapping materials. A single oversize grain might ruin the already produced surface. Commercial products are sometimes lacking in accurate grading, and for very stringent conditions levigating methods are recommended. It is possible to standardize in distinct polishing agents, for instance, at the present time some foreign materials are difficult to obtain, but for the purpose of this book it was necessary to consider nearly all the generally used materials.

Aluminium Oxide (see pp. 229 and 242).

Boron Carbide (see p. 229).

Natural Corundum (see p. 229), practically pure oxide of aluminium, coloured by traces of metal oxides. Ordinary corundum in opaque, unclean crystals and grains, and as precious corundum; good cleavage. Contains in aluminium oxide 90 to 95 per cent. A polishing medium of higher degree than emery found in North and South America, Africa and India.

Synthetic Corundum (see p. 230).

Crocus (*crocus martis*) is the hardest iron oxide (iron peroxide); the grains are sharp and harsh. American quality is said to be harder than the English, but the latter produces finer finish. The substance is harder than lime, and equal to soft silica.

Diamond (see p. 230).

Diatomite should not be confused with tripoli; it represents a softer silica composed of minute plant skeletons or diatoms. It is sometimes known as "fossil tripoli."

Emery consists of an intimate mixture of granular corundum, magnetite with some haematite. Grecian or Naxos emery has a high percentage of alumina (about 65 per cent), grains are very hard and sharp; no detrimental physical and chemical changes under heat. Turkish emery (from Asia Minor) contains 25 per cent iron oxide and is slightly softer than the Naxos product. The grain breaks down under pressure, so that new cutting edges are constantly present; it is best suited for polishing purposes. The American emery (New York State and Virginia) contains 45 per cent of iron oxide and is the softest of the three.

Garnet (see p. 236) is used mainly in the production of mirror glass.

Kaolin or porcelain earth is a water-containing silicate of alumina, a product of the disintegration of different rocks. Levigated kaolin is used as polishing agent.

Lime: Vienna lime is unhydrated Dolomite containing a high percentage of magnesia (oxides of calcium and magnesia), cuts faster than crocus which it has almost entirely replaced.

Manganese dioxide, the use of this powder should be avoided, as it causes black dirt which is difficult to remove from the pores of the skin.

Pumice is a highly cellular, glassy volcanic rock or lava, usually of a certain acid variety: liparites; same composition as normal rhyolites found in vicinity of volcanoes, and forms porous blocks of a white or light grey colour; floats on water. It contains impurities such as feldspar and hornblende (tendency to scratch). Good quality pumice has the following composition: Silica 65 to 75 per cent, Alumina 12 to 15 per cent, Soda 4 to 5 per cent, Potash 4 to 5 per cent, and small percentages of other minerals.

Pumicite or Volcanic Dust is a natural glass or silicate atomized by volcanic explosions. It is a finely divided powder of a white to grey or yellowish colour, composed of small sharp angular fragments of highly siliceous, volcanic glass. Composition similar to pumice; a good grade contains, for instance, silica in form of silicates, also free silica 70 per cent, alumina 13 to 15 per cent, low in iron contents.

Putty Powder. Best grade contains 85 to 90 per cent tin oxide, remainder consists of lead oxides. Lead gives the "body" of the substance. It is said to have more filling than abrasive action; the filling with slight abrasion imparts the high polish. Low grades of putty powder (over 50 per cent of lead oxide) were extensively used for glass polishing. Use declined owing to poisonous nature of lead.

Quartz (see p. 236), an oxide of silica (SiO_2), transparent or opaque, white or coloured by dissolved metal oxides. Used as abrasive in the form of quartz sand and quartz flour for grinding pastes and sand-paper.

Rottenstone, is a residual product from the weathering and decaying of siliceous, argillaceous limestone, the calcium carbonate and other impurities having leaked out, leaving a siliceous skeleton. Soft, friable, very fine textured earthy mass of light grey to brownish or olive grey colour. Sometimes (according to Eardley Wilmot) erroneously claimed as tripoli, but it is more impure and less siliceous than Missouri tripoli. Varies considerably in chemical composition, for instance: Silica 80 to 85 per cent, Alumina 4 to 15 per cent, Carbon 5 to 10 per cent, Iron Oxide (FeO_2) 5 to 10 per cent and small amounts of lime.

Rouge, iron oxide produced by the same process as *crocus* is softer, hardness however increases with darkness. Green rouge is a chromium oxide. It must be absolutely free from impurities, such as other metallic oxides, sulphur, etc.

Sandstone, a sedimentary rock, which consists of quartz grains cemented by calcareous or siliceous minerals. Sandstones are frequently non-uniform in grain size and hardness and now very seldom used.

Silicon Carbide (see p. 237).

Tripoli, natural Tripoli is very fine grained silica (Missouri and Oklahoma), and different from Diatomite and amorphous silica.

The powders mentioned are given under their usual technical names, but frequently fancy names are added or given such as "jeweller's rouge," "red stuff," etc. Still more frequent are proprietary names with no indication of the composition of the compound, sometimes found also in scientific literature; such names make it also extremely difficult to trace the producer, therefore in the following some of these products are compiled; the special methods in their manufacture consist besides their pure representation in levigation and washing processes applied:

Name of Compound	*Composition*	*Manufacturer*
Carborundum	Silicon Carbide	Carborundum Co. of America, Niagara Falls, U.S.A.[1]
Crystolon	Silicon Carbide	Norton Co., Worcester, Mass., U.S.A.[2]
Sira	Aluminium Oxide	United Kingdom Optical Co., Mill Hill, London.
Durosol	Probably Aluminium Oxide	
Diamantine	Aluminium Oxide (no diamond contents)	
Aloxite	Aluminium Oxide	Carborundum Co. of America, Niagara Falls, U.S.A.[1]
Alundum	Aluminium Oxide	Norton Co., Worcester, Mass., U.S.A.[2]
Carbometal	Special Carbide	Cardimond Industrial Diamonds, London, W.1.
Norbide	Boron Carbide	Norton Co., Worcester, Mass., U.S.A.[2]

[1] In England: Carborundum Co. Ltd., Trafford Park, Manchester.

[2] In England: Norton Grinding Wheel Co., Welwyn Garden City.

CLEANING DIAMONDS

After the stones have been cemented, they must be freed from the remainder of the cement. As one of the main materials of the usual cement is shellac, this is easily performed by rubbing the stones with linen dipped in alcohol, which dissolves shellac.

The cut and polished stones have to be carefully cleaned from any dust, dirt, and oil; this is necessary for stones for technical purposes, as well as for jewel stones. Dust and dirt accumulate on rough and bruted surfaces, in particular, in the case of brilliants and roses, on the girdle which remains a rough surface. They cannot be removed merely by rubbing and cleaning with alcohol.

Formerly, for cleaning finished stones either aqua-regia, a mixture of two-thirds concentrated hydrochloric acid and one-third smoking nitric acid, or aqua-fortis, consisting of two-thirds sulphuric acid and one-third nitric acid, was applied. To-day, frequently for the first cleaning, cooking in a strong solution of potassium hydroxide is a method favoured, but which, in any case, must be followed by a second cooking. The stones are placed in a small glass and sulphuric acid poured over them. The glass is placed on an asbestos plate over a Bunsen-burner, carefully warmed, a portion of nitric acid added. As thus a considerable amount of nitric oxide highly active *in statu nascendi* is freed, the stones are absolutely free from dirt. The nitrate acid vapours are most unhealthy, and the first glass has to be covered by a second glass with perforated bottom, which is filled with chalk to neutralize the escaping vapours. The stones remain "cooking" for about half an hour in the solution, then they are taken out, rinsed in water, and dried by means of a linen rag or leather.

Softer gem stones are cleaned in sulphuric acid mixed with water. Diamond dust applied for high-grade polishing and lapping purposes should also be cooked in aqua-regia to remove all particles of foreign materials, including all metals.

CEMENTS FOR GEMSTONES

Cements melting at medium temperatures are used extensively in the manufacture of diamonds and gemstones for the temporary fixing of stones to holders, dops, plates, etc. The cement should only melt at an elevated temperature of about 130 to 140 deg. F. (60 to 70 deg. C.), according to the special requirements, and become firm at the room temperature. It should therefore be possible to knead and press the cement by hand, after it has been removed from the flame. The cement should only be brought a very short time near the flame (gas flame) in order not to burn it, which will impair considerably its sticking power. The commercial qualities have perhaps somewhat changed compositions, as given below; these recipes are taken from well-known mineralogical textbooks.

Sealing wax (German: *Siegellack*), consisting of shellac and rosin, smelted in turpentine, is used for fixing hard crystals and minerals during sawing and grinding, in particular for specimens for micro-investigation.

Cleaver-cement and Cutter-cement as used in the production of diamonds are special compounds, probably mixtures of sealing wax and rosin.

Wax-cement (German: *Wachskitt*) consists of a mixture of rosin (colophony) and a thick fluid wax; pure beeswax is recommended. The ratio of rosin to wax varies considerably; for instance, according to Schneiderhöhn 2 to 1, Rosenbusch 3 to 1, Schlossmacher 4 to 1.

The rosin is heated, and the wax is thrown into the fluid mass, in which it becomes dissolved when properly stirred up. Heating in a porcelain bowl placed in a water bath is recommended. Cooking time from one to two hours, until a thick fluid mass results (until it becomes stringy).

Remnants of the cement sticking to minerals can be removed by means of turpentine oil.

Canada balsam is used for the cementing of preparations, and for the fixing of covering glasses. Two different kinds, according to Schneiderhöhn, are used:

(*a*) For the cementing of the holder for objects a thick fluid balsam which melts at about 175 to 200 deg. F. (80 to 90 deg. C.).

(*b*) For the cementing of the cover-glass with the ground mineral surface, a cement which is not so tough, and melts at about 120 deg. F. (50 deg. C.) is recommended.

The cement under (*a*) is obtained by cooking the balsam in a porcelain bowl, eventually placed in a water bath. The cement should be preserved in a small glass bottle provided with a ground-in stopper. It should always be kept filled.

Commercial sealing wax. Its use is objectionable, according to M. N. Short (*Econ. Geol.*, 1926, p. 648), owing to considerable admixture of filler which tends to break loose during polishing, causing scratches. He recommends a special sealing wax containing 120 gram flaked shellac, 60 gram rosin, 60 c.cm. turpentine. The ingredients are placed in a "granite ware "saucepan, set on an electric hot-plate or Bunsen-burner, heated until vigorous bubbling, stirring from time to time, but not too hot on surface. When mounting, the brass tubes or plates have to be heated, as the sealing wax has higher shrinkage.

Pitch, used extensively for holding glass and optical quartz. Table 29 gives some data with regard to melting and softening points.

Sulphur, in molten condition applied for embedding metallographic specimens. The following method is suggested: Brass ring, eventually flattened on smooth steel plate, filled ⅛ to ¼ deep with mercury. Specimen is pushed through and brought in contact with steel plate. Molten sulphur poured over mercury and allowed to solidify; no material is dragged when polishing.

METALLIC SOLDERS AND EMBEDDING MATERIALS

Common solder, extensively used for holding diamonds during cutting, usual composition one part of tin to two parts of lead (see p. 75). This alloy attains, when solidifying, a pasty condition well below 230 deg. C. With higher tin contents the temperature at which the pasty condition occurs is reduced, reducing simultaneously the temperature range during which the material remains in the plastic condition; smaller tin contents increase the range, but adversely increase also the temperature.

Woods and similar metals. Alloys of bismuth, lead, tin and cadmium have very low melting points, for instance Woods metal (50 per cent Bismuth, 25 per cent Lead, 12·5 per cent Tin and 12·5 per cent Cadmium) melts at 60 deg. C. Recently a number of low-melting alloys have been produced with melting points between 100 to 200 deg. C., known under the name "Cerromatrix."

SYNTHETIC RESINS

Synthetic resins of the thermosetting and the thermoplastic types have recently found interesting application for embedding crystals and metallographical specimens, owing to their special properties. Some of these materials are transparent, thus allowing the position of the stone to be observed in the setting, a principle which would be extremely useful in cutting and polishing of gemstones. The application of these materials require a special heating and pressing equipment, and the removing of the material may not be so easy (see *Metals Handbook*, 1939 ed., pp. 170–175, for further information).

COLD-MOUNTING MEDIA

In spite of the fact that these are not in general use, it may be useful to apply them in special cases.

Portland cement, ordinary composition, tends to shrink and crack. It is not hard enough unless seven days old, but becomes too hard in two weeks; proved generally unsatisfactory. The same applies to cement and sand, cement and lime, cement and talc.

Plaster of Paris, used extensively by sculptors and jewellers.

Stone-Wood. Magnesia-cement used extensively for floors and recently for metal-forming dies.

Lumnite cement, according to M. N. Short (loc. cit.), consisting of 15 gram Lumnite cement, 2 grams Plaster of Paris, 9 c.cm.

water, just enough to mix a paste. Components placed in saucepan, stirred and water added until of uniform consistency. Formed against a glass plate with thin coating of vaseline or graphite. First set three hours, after which glass plate is submerged in water. Taken out after 24 hours, ready for final grinding and polishing.

TABLE 29

GENERAL PROPERTIES OF WAXES AND PITCHES

Material	Softening Point deg. C.	Melting Point deg. C.	Solidus Point deg. C.	Spec. Gravity
Beeswax		62–66	60–63	0·959–0·967
Carnaubawax		83–93	80–87	0·990–0·999
Shellac		78–80		
Pitch, soft	35–60	50–70		1·250–1·265
medium	50–80	70–90		1·265–1·285
hard	80–115	90–140		7·285–1·330
Colophony (Rosin)	60–80	100–140		1·07 –1·09
Sulphur	96			1·96

CLEANING GEMSTONES

To remove traces of cement, dirt and oil from gemstones other than diamonds boil in an aqueous solution of sodium hydroxide (NaOH), followed by quick drying and rinsing in commercial alcohol. Alternative methods are washing in benzine, trichlorethylene, carbon-tetrachloride, petrol or diluted sulphuric acid, followed by rinsing in commercial alcohol (not coloured methylated spirit).

APPENDIX III

Table 30

USEFUL CONVERSION FACTORS

To convert	*Multiply by*
Inches to centimetres	2·5400
Yards to metres	0·9144
Feet to metres	0·3048
Miles to kilometres	1·6093
Square inches to square centimetres	6·4516
Square feet to square metres	0·0929
Square yards to square metres	0·8361
Square miles to acres	640·0000
Circular mils[1] to square inches	0·78540 × 10^{-6}
Cubic inches to cubic centimetres	0·16387
Cubic feet to cubic metres	0·028318
Cubic yards to cubic metres	0·764555
Gallons to litres	4·5474
Metric carats to grammes	0·200
Grains (Troy) to grains	1·000
Grains (Troy) to grammes	0·0648
Ounces (Troy) to grammes	31·104
Ounces (Troy) to carats	155·52
Ounces (Avoir.) to grammes	28·35
Old English carats to grammes	0·20535
Old English carats to grains (Troy)	3·17
Graens (German) to metric carats	0·25
Old Dutch carats to grammes (see Table 31)	0·205
Pounds to kilograms	0·45359
Tons to kilograms	1016·05
Short tons to tons	0·893
Pounds per foot to kilograms per metre	1·4881
Pounds per mile to kilograms per kilometre	0·28186
Pounds per square inch to kilograms per square millimetre	0·0007031
Tons per square inch to kilograms per square millimetre	1·5749
Pounds per square foot to kilograms per square metre	4·88
Feet head of water to pounds per square inch	0·432
Atmospheres to pounds per square inch	14·73
Miles per hour to feet per second	1·4667
Miles per hour to metres per second	0·44703
Horse-power to foot-pounds per minute	33·000
Horse-power to kilowatts	0·746

---

[1] One mil = 1/1000 in.

Table 30 (*continued*)

USEFUL CONVERSION FACTORS

To convert	*Multiply by*
Horse-power to gramme-metres per second	76·040
Horse-power to force de cheval	1·014
Kilowatt-hours (B.T.U.) to foot-pounds	2·654200
Kilowatt-hours to horse-power hours	1·340
Foot-pounds to joules (watt-seconds)	1·356
Foot-pounds to gramme-calories	0·324
Gramme-calories to British Thermal Units	0·00397
British Thermal Units to therms	10^{-5}
Radians to degrees	57·296
Common logarithms to Napierian logarithms	2·3026

Water weighs 10 lb. per gallon, 62·3 lb. per cubic foot, 0·036 lb. per cubic inch.

Ice weighs 57 lb. per cubic foot, 0·033 lb. per cubic inch.

Degrees Centigrade C. to Degrees Fahrenheit.........(1·8) C. + 32

Table 31

CONVERSION OF DUTCH (OLD) TO METRIC CARATS

Dutch	Metric Carat	Milligram
⅛	0·128	25·526
¼	0·256	51·248
⅜	0·384	76·872
½	0·512	102·496
⅝	0·640	128·112
¾	0·768	153·744
⅞	0·896	179·368
1	1·025	205·000
2	2·05	470·000
3	3·075	615·000
4	4·100	820·000
5	5·125	1,025·000
6	6·150	1,230·000
7	7·175	1,435·000
8	8·200	1,640·000
9	9·225	1,845·000
10	10·250	2,050·000

1 Dutch carat = 205 milligrams. 1 Metric carat = 200 milligrams.

TABLE 32.—REVOLUTIONS PER MINUTE (R.P.M.) FOR VARIOUS DIAMETERS TO GIVE PERIPHERAL SPEED IN FEET PER MINUTE (S.F.P.M.)

Example 1. Wheel diameter 7 in., 4,000 ft. per min. prescribed; from table: 2·183 R.P.M.
Example 2. Wheel diameter 1 in., 1,650 ft. per min. prescribed; from table for: 1,000 ft. per min. 3·820
600 ft. per min. 2·292
50 ft. per min. 0·191
R.P.M. 6·303

Diameter of Wheels		Peripherical Speed								
		1,000 S.F.P.M.	2,000 S.F.P.M.	3,000 S.F.P.M.	4,000 S.F.P.M.	5,000 S.F.P.M.	6,000 S.F.P.M.	7,000 S.F.P.M.	8,000 S.F.P.M.	9,000 S.F.P.M.
in.	mm.	R.P.M.	R.P.M.	R.P.M.	R.P.M.	R.P.M.	R.P.M.	R.P.M.	R.P.M.	R.P.M.
$\frac{1}{16}$	1·58	61·116	122·232	183·344	244·464	305·568	355·688	427·792	488·928	550·038
$\frac{1}{8}$	3·2	30·558	61·116	91·672	122·232	152·784	183·344	213·896	244·464	275·016
$\frac{1}{4}$	6·3	15·279	30·558	45·836	61·116	76·392	91·672	106·948	122·232	137·508
$\frac{1}{2}$	12·7	7·640	15·279	22·918	30·558	38·196	45·836	53·474	61·116	68·754
1	25·4	3·820	7·639	11·459	15·279	19·098	22·918	26·737	30·558	34·377
2	50·8	1·910	3·820	5·729	7·639	9·549	11·459	13·368	15·278	17·188
3	76·2	1·273	2·547	3·820	5·093	6·366	7·639	8·913	10·186	11·459
4	101·6	955	1·910	2·864	3·820	4·775	5·729	6·685	7·640	8·595
5	127	764	1·528	2·292	3·056	3·820	4·584	5·348	6·112	6·876
6	152	637	1·273	1·910	2·546	3·183	3·820	4·456	5·092	5·729
7	178	546	1·091	1·637	2·183	2·728	3·274	3·820	4·366	4·911
8	203	477	955	1·432	1·910	2·387	2·865	3·342	3·820	4·297
10	254	382	764	1·146	1·528	1·910	2·292	2·674	3·056	3·438
12	305	318	637	955	1·273	1·591	1·910	2·228	2·546	2·864
14	356	273	545	818	1·091	1·364	1·637	1·910	2·182	2·455
16	406	239	477	776	955	1·194	1·432	1·672	1·910	2·149
18	457	212	424	637	849	1·061	1·273	1·485	1·698	1·910

INDEX

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