CHAPTER IX

Sawing, Grinding and Lapping

By W. L. BOND

9.1 Introduction

THERE are two general methods of cutting brittle materials: grinding and lapping. Grinding is familiar to us through the old grindstone and "emery wheel." Lapping, a less familiar term is derived from the Latin lapis, a stone. Hence, the very word lapping is peculiar to stone cutting. In the early stone cutting, sand, emery or other rock fragments were probably placed loosely on a plate over which the stone to be cut was slid by hand.

Since 500 B.C. fine gem engraving has been done in Europe and Asia, samples of this work being on exhibition in museums. It is believed that all gem engraving prior to 500 B.C. was done by scratching with a single splinter of sapphire glued to a stick and often worked with a bow to operate as a drill. The Greeks early discovered the cutting power of emery powder used loose on a plate, and thereafter their carvers not only made flat surfaces and curved ones but also made designs involving circular holes and crescents perhaps by trepanning with a hollow reed and emery. Facetted stones, however, were not made before the 14th Century A.D. Fig. 9.1 shows how diamonds were cut in 1823.

A great deal of the gem work of the world is still carried on with primitive tools. The jade workers of China still saw with a wire stretched on a frame somewhat like a bucksaw. Silicon carbide is used in place of emery, and slabs so cut are trepanned into bracelets and rings by the use of a piece of sheet metal wrapped almost completely around a wooden disc, the disc being oscillated by a strap connected to a foot treadle. The wire saw is still used in this country to cut slate, marble, Arkansas (whet) stone from the earth, sometimes a whole hill being literally sawed in two. The wire in this case is a three strand cable forming a continuous belt around pulleys and is fed with sand and water. Diamonds were sawed by means of a wire saw and diamond powder as early as 1744.

The emery wheel is also quite old, having been made in India for centuries by shellacking emery to the periphery of a wooden disc and turning the disc on a wooden axle by means of a hand crank. Wheels up to 30 inches in diameter were in use. Itinerant knife grinders carried smaller models about India as they plied their trade. The ancient Greeks sharpened their tools by rubbing them on stones and developed the sand stone grinding wheel quite early, the emery wheel not finding its way to them from India.

Before 1600, lenses were formed from glass by sliding the glass back and forth over a cast iron form with emery between the iron and glass.

The two terms lapping and grinding are used so loosely that there is some doubt as to which class some operations belong. However, by popular conception, a "grindstone" is made up of hard particles cemented together to form a porous mass. The ancient grindstone was a porous sandstone, that is, its particles were quartz. The modern abrasive wheel is silicon carbide or aluminum oxide grains cemented together with rubber, shellac, bakelite, porcelain, sodium silicate or any one of many possible cements.

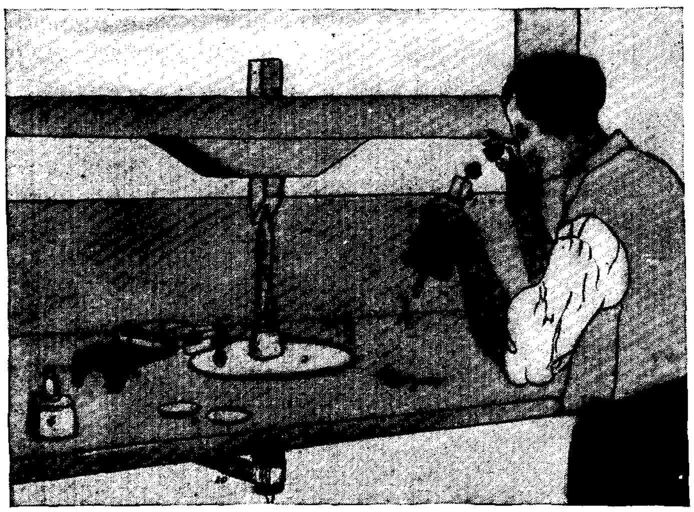

Fig. 9.1—Diamond grinding prior to 1823

9.2 The Grinding Process

If a hard stone with which we are scratching a softer one happens to have a sharp corner the scratch will be deep. The scratching removes material and if we keep scratching or scraping long enough we can remove any desired amount. If we had a great many of these scraping points arranged to function simultaneously, the removal of material would be greatly expedited. This is arranged in sand paper and emery cloth by gluing hard sharp grains to paper or cloth. In order to have exposed scraping surfaces the grains must project above the cement. In a "grindstone" if the stone is made of hard grains held together with a minimum of binder—so that the stone is porous because the interstices are not cement filled—as the stone wears away, there will always be projections to do the scraping. The stone must wear away fast enough to keep sharp edges at work.

The word "grinding" has several meanings, according to the dictionary. One meaning is that given above, and the word is so used in this chapter to define that process. A second and very much broader meaning found in the dictionary is to "operate" or "work," and in this respect may include the lapping process discussed below. The word grinding is used in a few places with this broader meaning.

9.3 The Lapping Process

If we rub two pieces of glass together with an abrasive between them, the conditions (after the glaze is removed) are those shown in Fig. 9.2. Here, as we move the upper plate to the left, we expect the sharp point of the particle to break a chip out of the upper plate as the particle rolls over be-

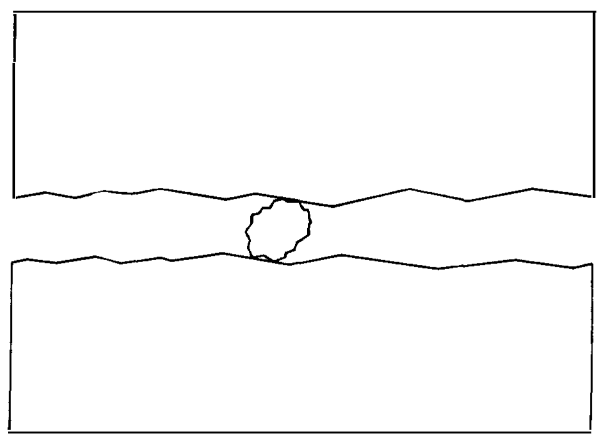

Fig. 9.2—Diagram to indicate the method by which particles of abrasives remove material in lapping

tween the plates. A moment later the particle may break a chip from the lower plate unless it has lost its point. If we grind glass on a metal plate the conditions are different because many particles will bury themselves in the metal and remain fixed until they are undercut and hence, freed or else until the loss of the exposed cutting edge makes the stress in the metal higher than in the glass and the particle is pulled out of its setting. We know this imbedding takes place because such a lap after a little use becomes "charged" so that even if all loose material is washed off the plate it will remove material from anything rubbed on it. Hence, even in lapping, the cutting action may be partially like that in the grinding process. That "grinding" is not the major factor is shown by the relatively slow cutting of a clean charged plate as compared with the same plate supplied with an adequate quantity of loose abrasive. It is also shown by the different texture of a surface produced by an abrasive when bonded as in an "emery" paper or a "whet stone" as compared to the texture produced by the same abrasive when used loose. At Wheeler Dam, during its construction, there was a machine for cutting out large cores of dolomite rock. The cutting was performed by $\frac{3}{32}$ inch steel shot rolling under the edge of a hollow steel cylinder 3 feet in diameter. The shot had no cutting edges at all, it was spherical. But since it was made of a very hard tough steel its crushing strength was such that it could easily be forced into the weaker dolomite pulverizing the region of penetration. In this case the shot did not bury itself in the steel cylinder because of the toughness and resiliency of the steel. These things—the charging of a metal plate and the cutting of dolomite with steel shot—show the mixed nature of the lapping process.

9.4 Abrasives

We all know that a hard stone will scratch a softer one. In fact, the Mohs scale of hardness is merely an arrangement of ten minerals, running from talc which can be scratched by any other mineral, to diamond which can be scratched by no other mineral. A table of Mohs hardness of some common materials is given here. The starred items are true by definition.

*Talc	1	Glass	$4\frac{1}{2}$–$6\frac{1}{2}$
Lead	$1\frac{1}{2}$	*Apatite	5
*Rocksalt	2	*Feldspar	6
Copper	$2\frac{1}{2}$–3	Garnet	$6\frac{1}{2}$–$7\frac{1}{2}$
*Calcite	3	*Quartz	7
Brass	3–4	Steel	$5\frac{1}{2}$–$8\frac{1}{2}$
Dolomite	$3\frac{1}{2}$–4	*Topaz	8
*Fluorite	4	*Corundum	9
Phosphor Bronze	4	Silicon Carbide	$9\frac{1}{2}$
Iron	4–5	*Diamond	10

Most of the abrasives used in industry are made chemically. Nature's product is of too variable a quality.

Abrasive grains should be hard and also tough. Furthermore, the shape should be favorable—long splinters and flat plates are undesirable for lapping not only because equidimensional particles are stronger, but also since long splinters and flat plates will not stand up and present a cutting edge to the work.

On coming from the mine or furnace, the crude abrasive is crushed, washed free of undesirable matter and separated by passing through a series of silk sieves of increasing fineness. The sieves are designated by the number of threads per inch and the series used by many American manufacturers is: 10, 12, 14, 16, 20, 24, 30, 36, 40, 46, 50, 54, 60, 70, 80, 90, 100, 120, 140, 160, 180, 200, 220. The material that passes through the 100 screen but does not pass through the 120 screen is called "100 grit." This grading is not perfect, in fact a rough rule is that size "N" abrasive is, on the average, of size $\frac{0.58}{N}$ inches across but contains particles ranging from $\frac{0.45}{N}$ to $\frac{0.75}{N}$ inches. This rule is a result of the measurement of many particles under a microscope. Smaller sizes still are present but in very small quantity. Since grit sizes are now generally stated in "micron" sizes we shall adopt as our "size rule:"

$$S_{av} = \frac{15000}{N}, \quad S_{max} = \frac{19000}{N} \quad \text{and} \quad S_{min} = \frac{11000}{N} \text{ microns}$$

Above size 220, abrasive grains are separated by "flotation" in water, the fine grits requiring many minutes to settle through a foot or so of water, the coarser grits but a few seconds. The sizes so separated are named to still obey the size rule given above. The size series runs: 240, 280, 320, 360, 400, 500, 600, and some suppliers extend the series in differing steps, as far as No. 3200.

Some suppliers list their abrasives by arbitrary catalogue numbers; for example, the American Optical Company's abrasives M302, M302½, M303, M303½, M304, M305, correspond to sizes No. 400, No. 600, No. 800, No. 1200, No. 1600, No. 3200, respectively.

Optical workers designate emeries by settling time. In one system, the emery is stirred up in a vessel a meter deep and 30 centimeters in diameter. After standing, say 10 minutes, the fluid is drawn off carefully and the emery settling subsequently is called ten minute emery.

If we apply the Stokes law to the settling of emery, assuming the particles to be spheres, we find the relation between settling time in minutes and S_{max} to be, for one meter vessel:

$$S_{max} = \frac{100}{\sqrt{T}} \text{ microns}$$

Because of convection currents in the settling vessel, and also because of Brownian movement, it is impossible to separate fine abrasives very uniformly. Twyman[1] gives a measure of imperfection of grading as $I = \frac{10\, S_{max} - S_{av}}{S_{av}}$. He says that if I is 4 or less the grading is good, if I is 10 or over, it is bad. We see by this rule that our size rule was derived for well graded abrasive since $I = 10\,\frac{1900 - 1500}{1500} = 2.7$. Sometimes emeries are sold as F, FF & FFF, 4F & XF. These correspond approximately to Nos. 240, 320 and 400, 500 and 600, respectively.

One of the most important abrasives is corundum, an aluminum oxide Al_2O_3. It occurs naturally, but the artificial product from the electric

[1] "Prism and Lens Making," F. Twyman, Robt. Maclehose & Co.

furnace is commercially the more important because of its purity, the natural corundum often being quite impure. Sapphire and ruby are really corundum with different impurities, but the word corundum generally refers to opaque material of no value as a gem. Sapphire is said to be slightly harder than ruby and both to be harder than corundum. This is doubtlessly due to their relative amounts of impurity. Artificial corundum is sold under such trade names as Alundum, Aloxite, etc. A product used for buffing and called "levigated alumina" seems to be too poorly separated as to size for fine finishing on hard laps.

One of the oldest abrasives is emery, an impure natural corundum. Emery is found as a more or less solid rock composed of corundum grains mixed with magnetite grains, hematitite, etc., in fact little more than half the material is corundum and even the corundum itself is impure and softer than pure corundum. The effective hardness as measured in terms of efficiency as an abrasive is about half that of pure corundum. It should be used only for finishing where a less harsh abrasive is desired.

Silicon carbide is entirely artificial, i.e., never found in nature. It is formed in the electric furnace as a result of heating a mixture of coke and sand. It is harder than corundum but apparently not as tough. Corundum is the better for cutting tough materials such as metals, the harder silicon carbide is the better for brittle materials. It is sold under the trade names of Carborundum, Crystolon, etc.

Garnet is used extensively as garnet paper for wood finishing. It has been used to some extent as a fine grinding powder as a substitute for fine emery. It is quite acceptable for glass work but is a little slow for quartz. It is mined then crushed, screened, etc., in preparation for the market. It can be made artificially but is abundant in nature.

Rouge is an oxide of iron, Fe_2O_3. Although found abundantly in nature, the material used as a polishing compound is made by roasting ferrous sulfate. The top layers of the crucible become red "rouge," the bottom layers become purple "crocus" used as a finishing agent for metals.

Also used for polishing quartz is chrome oxide, Cr_2O_3, sometimes called green rouge. It is made by burning ammonium dichromate or potassium dichromate and sulfur. Another finishing powder faster cutting than rouge is cerium oxide.

There are many abrasives used in the lapping art that are too soft to be used on quartz. Such abrasives are ground glass, crushed steel (sometimes called steel emery), flint, sand, pumice, Kieselguhr, tripoli, rotten stone, etc.

9.5 Lapping

In a study of the lapping process as applied to quartz, the cutting power of several lapping metals was investigated. The lap resistance to abrasion and the relative cutting speed of two sizes of abrasive were also studied. The results are shown graphically in Fig. 9.3.

Several things come out of this data. For one thing, the popular idea that soft metals wear very well under abrasive conditions is certainly not true since hardened tool steel wore about seven times as well as aluminum. Also, the harder the metals are the better they wear as evidenced by the fact that the resistance to abrasion of the four metals is in the same order

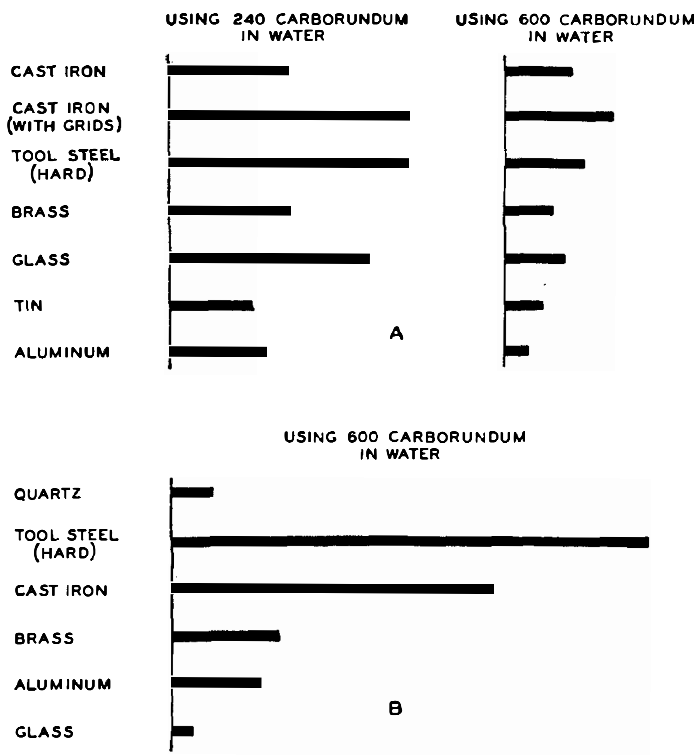

Fig. 9.3—Cutting speeds of abrasives on quartz with laps of various materials, A, and resistance to abrasion of lap materials, B

as their Moh hardness. But aluminum of hardness 2 wore $2\frac{1}{2}$ times as well as quartz. This is explained by the toughness of aluminum and brittleness of quartz. This is the grain of truth in the popular belief that soft materials resist abrasion better than hard ones do. The truth is that resilient materials resist abrasion better than brittle ones do.

Again the speed with which the lap will cut quartz is directly related to the hardness of the lap metal, as in general, the harder the metal the faster it cuts quartz. Somewhat surprising is the speed of cutting of a glass lap.

This could but mean that the major part of this cutting is of the steel shot type, since glass is so superior to the softer metals. It also explains the popularity of glass as a lapping plate where flatness is not of prime importance—glass resisted abrasion the most poorly of all. Hardened tool steel would seem to be the best choice of all, but steel warps so in hardening that this may not be practical. Cast iron, while not as fast a cutter as tool steel or even glass, resists abrasion so much better than glass that it is a very practical choice, particularly since it can readily be machined. In passing we remark that softer laps cut more slowly but produce a finer finish with the same size abrasive. A block tin lap will produce a smoother surface than will a cast iron lap and quartz can be polished with No. 180 Carborundum on a soft wood lap. Another finding is that silicon carbide cuts at a rate proportional to its particle size. Number 240 is $2\frac{1}{2}$ times as large as No. 600 and cuts approximately $2\frac{1}{2}$ times as fast since the average of the seven cutting speed ratios shown on Fig. 9.3 is 2.45. Some authors assume that the rate varies as the volume of the particle. This would require No. 240 to be 15 times as fast as No. 600—a conclusion incompatible with this data.

Another finding is that cutting grooves or grids in the cast iron lap increased its cutting speed. In passing between the work and the lap the silicon carbide is rapidly broken down so that only smaller material reaches the inner part of the work unless one contrives to feed in fresh silicon carbide in some other way than from the edges of the work. Grids accomplish this feeding in of abrasive nearer the center of the work. Also, since the grids are 90° V's they form ramps that help the large grains to get started. If we imagine sliding a box on a smooth floor covered with a thin sprinkling of coarse gravel, we can see how easily the box might work its way down to the floor with no gravel under it and henceforth, push the gravel out of the way. If there were a V groove in the floor, some of the gravel would be left on the V ramps on the side towards which the work was moving. Any that projects up a little above the level of the floor will now be funneled under the work piece.

This brings up another subject, coolants. If the abrasive is wet, it will stick better to the banks of the V. Also, a wet abrasive will be more likely to pass between the work and the lap instead of being brushed aside. This is because of the irregularities of work and lap acting like smaller V's. In this way we explain the observed fact that dry lapping doesn't cut fast even when the speed of motion is too slow to need cooling. This subject will be discussed later.

The analogy of the box on the floor is a reminder of a common error in lapping—that of using too thin a solution so that the block rests on the lap with only an occasional grain going under—and producing a bad scratch.

The block should always have many grains under it. This is assured if the mixture is of a creamy consistency; this can be accomplished by stirring just before applying—and it can't be done if the brush has to leave the abrasive through an inch or so of water that carries little or no abrasive.

We have noted that the abrasive is larger when it enters the cutting region than it is when it leaves. This tends to round off the entering edge of the work. Also the stream of abrasive has an eroding action so that the rounding off of the edges extends to a greater height than the grain size of the abrasive.

What are the relative merits of grinding versus lapping? We believe the answer is "Lapping is faster, grinding is more accurate." This isn't the popular notion, but we have defined lapping as done with loose abrasive, grinding with fixed abrasive. The most accurate "lapping" is done by charging the (metal) lap and cleaning off the loose abrasive. The cutting is then done with the imbedded abrasive. But we call this grinding because the abrasive is bonded. Hence—by our definitions—grinding can be more accurate since it doesn't have loose abrasive rounding off the corners, but lapping can be faster since fresh sharp abrasive is being supplied constantly.

In choosing an abrasive for fast cutting we would prefer the hardest, toughest, sharpest stuff, we could get. If the work is not especially hard an abrasive softer than the better abrasive might cut so little slower than the better one that the difference would be negligible. For example, in quartz cutting, silicon carbide cuts very nearly as fast as boron carbide which is a harder abrasive. For quartz cutting, silicon carbide is practically as fast—and a whole lot cheaper than boron carbide. But in cutting silicon carbide or boron carbide blocks, the boron carbide abrasive shows itself definitely superior to the silicon carbide abrasive.

We could carry this comparison on to diamond abrasive but diamond is so expensive that it is used almost entirely as fixed abrasive—the loose lapping method using so much more abrasive than the bonded method. Diamond at $2.00 per carat ($10.00 per gram = $4,500 per pound) as compared to silicon carbide at $0.15 to $0.60 per pound would have to be unusually effective to be adopted.

We now meet the question, How much harder is the diamond than silicon carbide or corundum? The steps in Moh's scale are not necessarily equal. In fact the late Dr. Kuntze of Tiffany's used to say that the step from 9 to 10 was larger than the step from 1 to 9. Diamond must be much harder because a single sharp point can be used to dress a corundum wheel for hours at a time—during which it has scraped over hundreds or thousands of miles of corundum. But if we use a corundum point on quartz it breaks down in a travel of inches.

Attempts to compare the hardness of diamond and corundum by the cutting rate on a third material give ratios that depend on the third material. In cutting wood with revolving grinding wheels the ratio would be 1 to 1. In cutting glass it might be 2 to 1; and in cutting silicon carbide it mght approach any given large number since the corundum practically won't cut the silicon carbide. The reason for the 1 to 1 ratio on soft work is that if each wheel fills its pores completely as it passes the work it can do no more. The only way to make this wheel cut faster is to have larger pores—that is larger grain size. All we can say then is that diamond is certainly much, much harder and stronger than any other abrasive.

9.6 Lapping Quartz

In practice, rough lapping of quartz is done on a cast iron plate revolving about a vertical axis, abrasive being painted on in a water or soap water solution. The lap must not revolve so fast that centrifugal force throws off the abrasive. If a large wheel is turned faster and faster a speed will be reached where abrasive will not stay on the wheel outside a certain distance from the center. The outer areas are then useless for lapping and the wheel should be slowed down till the whole surface can be used. The faster a lap can be driven up to this point the faster it will cut. As the centrifugal force on a particle of mass m going at a velocity v at a distance r from the center is $f = \frac{mv^2}{r}$ we see that

$$v = \sqrt{\frac{fr}{m}} \tag{1}$$

But v is $2\pi rN$, where N is the number of revolutions in unit time. Hence,

$$N = \frac{1}{2\pi}\sqrt{\frac{f}{mr}} \tag{2}$$

This tells us that a lap B four times as large as a lap A can be driven half as fast in revolutions per minute as seen from equation (2) but it will cut twice as fast as the lap A as shown by equation (1).

It is customary in rough lapping to use coarse abrasive to increase the cutting speed. To get fine finishes we must use fine abrasive. In lens grinding, the roughing might be done with No. 100 Carborundum. If No. 600 were used next it would take needlessly long to remove all the pits of the coarse grind so several intermediate steps of increasing fineness are used. A good rule is to double the number for each step, for example following the use of No. 120 we should use No. 240.

A corollary rule is to use each grade until all marks of the previous grade are removed. This usually means the removal of a layer of material equal to the average diameter of a particle of the previous size.

9.7 Muck Sawing

Muck sawing is really lapping with the edge of a thin disk so as to cut a deep groove in the crystal. The saw blade is commonly of steel and turning about a horizontal axis, its lower side dips into a suspension of carborundum and soap water. The soap helps the abrasive to stick to the blade so that it may be turned faster without losing its abrasive by centrifugal force. Bentonite clay also helps hold the abrasive. Since a saw is really a lap we see that the analysis of speeds holds for saws and that larger diameter discs can cut faster than smaller diameter discs.

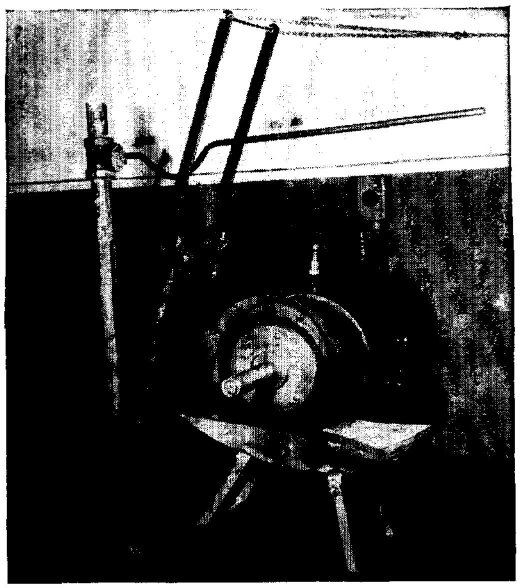

Fig. 9.4—Muck saw used in the early days of manufacture of crystal plates

Often the crystal is mounted on a pivoted arm and allowed to descend upon the saw by gravity, augmented or restrained by weights. The pivoted arm can be made to descend very truly with little friction. Slides such as used in milling machines are much more expensive and abrasive can get in the slides and ruin them. In Fig. 9.4 is shown a muck saw used in the Western Electric Company many years ago.

There is a tendency for vibrations to build up in the pivoted arm and wear the saw out of round. Fluid damping provided by a dash pot will damp out these vibrations and save the saw. Ordinarily this dash pot will increase the cutting rate right from the start. This is because any vibration of the arm lifts the crystal off the disc and when it is lifted it isn't cutting. The crystal then hammers down on the disc and smashes the abrasive grains, they being easily broken by impact. When the grains are smashed they are too fine to cut rapidly. If the pressure is hand applied the hand acts as quite an effective vibration damper.

Corresponding to the gridded lap we can hack serrations in the edge of the disc to increase the cutting rate, but the disc wears down so fast that the serrations would need to be recut so frequently that it is ordinarily not done.

Because of the erosion action, mentioned earlier, the saw cut is always a wedge or V shaped slot. Hence its surfaces are not parallel to the saw blade and slabs cut by this method are not as accurately oriented as could be desired. The angle between the walls of the cut is often as large as two degrees.

9.8 Diamond Sawing

To increase the accuracy of cut we now consider going to grinding methods instead of lapping. In grinding we can rotate the saw much faster than we could in lapping because centrifugal force does not throw off the grains—they are cemented down or imbedded. We can "charge" a steel or copper disc with abrasive by pressing the grains into the metal or trapping it in pockets in the metal, then saw with the disc revolving rapidly in a coolant. Such a saw charged with diamonds saws faster than the silicon carbide muck saw does, but if charged with silicon carbide the cutting rate is lower and the saw loses its charge almost at once. We can saw with a thin, rubber bonded silicon carbide wheel travelling at say 5000 surface feet per minute. The cutting rate is good but there is much heating and the thermal shock sends out cracks that spoil much of the quartz. The same sort of wheel made with diamond cuts much more smoothly and with much less heat. This is probably because the diamond particles hold their sharp edges while the silicon carbide grains loose their edges much more quickly so that much of the cutting is with dull edges with the consequent greater evolution of heat.

For several centuries gem cutters (or lapidaries) have made diamond saws by pressing crushed diamonds into the edge of a copper disc. The diamonds commonly purchased for this use are small (about 20 per carat) and unsuited for use as gems due to color, cracks, shape, etc. and cost about a dollar and a half per carat (a carat is $\frac{1}{5}$ gm.). The diamonds are crushed in a mortar, Fig. 9.5 by striking the plunger repeatedly with a hammer. Both the mortar and plunger are made of very hard steel and the plunger fits the mortar well enough that diamond particles do not fly out when the plunger is struck with a hammer. The diamond is crushed to about 100 mesh and mixed with a small amount of oil—the lapidaries use olive oil. A little of this paste is rubbed on the edge of the prepared disc and the disc edge is rolled firmly with a roller which forces the diamond into the metal.

The disc is prepared bybeing accuratly turned in a lathe, then the periphery is chopped with a heavy knife, making cuts about $\frac{1}{16}$-inch apart around the edge and $\frac{1}{16}$-inch deep, as shown in Fig. 9.6. The rolling makes the

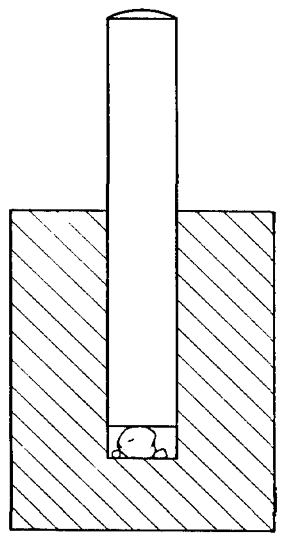

Fig. 9.5—A diamond mortar

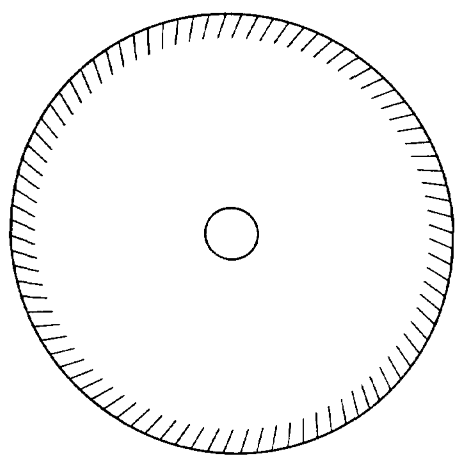

Fig. 9.6—Serrations in the edge of a disc to make a diamond saw

edge of the disc thicker than the saw center so that the saw does not rub except in the diamond charged region.

Saws made in a similar fashion are on the market. Also there is on the market a saw made by compressing metal powder and diamond dust at an elevated temperature—a "powder metallurgy" product. These are very brittle but if operated on a vibration free and true machine they will last long.

Diamond saws are run anywhere from 2500 to 5000 surface feet per minute. The coolant must never fail while cutting is in progress, as heating destroys the saw by loosening the diamonds.

In diamond sawing, the high speed for optimum cutting requires a more rigid machine than does the slow muck saw. The hammering mentioned

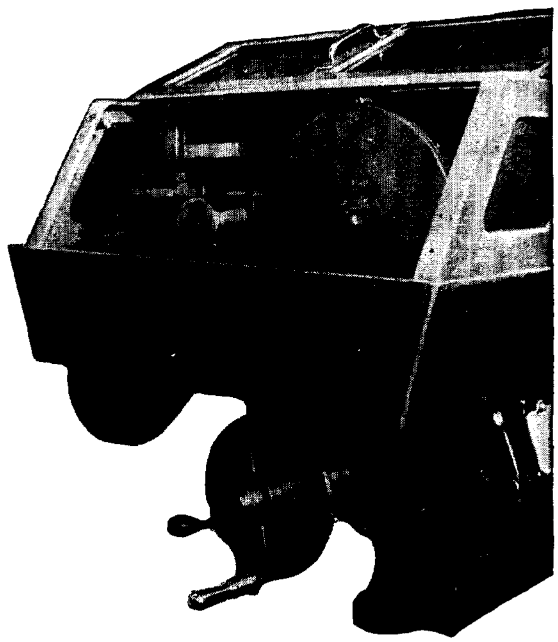

Fig. 9.7—A diamond saw machine made from a milling machine

under muck saws is even more serious—the discs must be very accurately round and centered or they will hammer. Since a muck pan is not needed it is common to hold the crystal and feed the saw into the crystal under a spray of coolant. A pivoted arm works more smoothly than a poor slide and is easier to construct, and is hence less likely to cause sudden strains on the saw and crystal. But, at the high speed the arm must be so stiff that it has no resonances near the frequency of the saw. If there are such resonances the resonating member will build up vibrations and hammer the saw. A poorly made arm may twist in the cut so that the saw binds and is subjected to stresses much larger than normal sawing stresses. A good milling machine or surface grinder can make an excellent sawing machine if used with a good diamond blade. Fig. 9.7 shows such a saw.

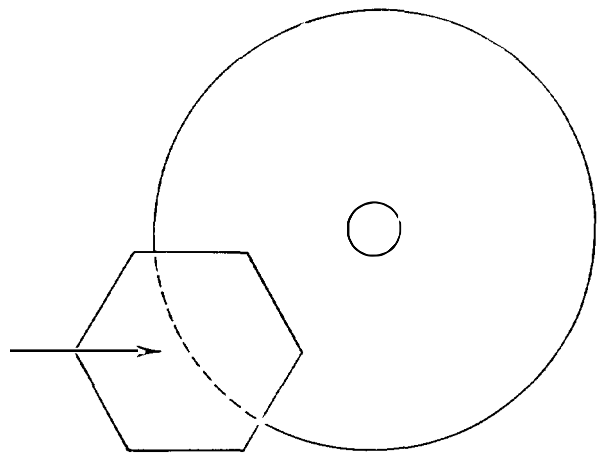

Fig. 9.8—Traverse cutting

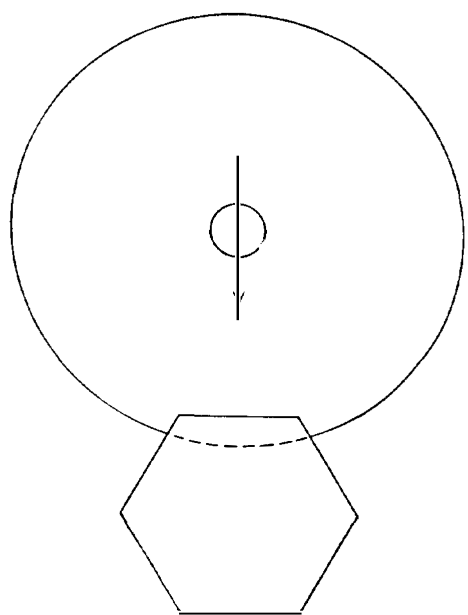

Fig. 9.9—Plunge cutting

There are several schools of thought as to the best way to feed the crystal into the saw. One school moves the crystal directly towards the axis of the saw saying that experience with thin metal slitting saws has shown this method to give the least saw deflection. This is plunge cutting. Another school slides the crystal repeatedly under the saw taking many successively deeper cuts, "tangentially" the argument being that the reduced angle of contact of saw to stone makes for less choking of the saw with quartz dust. It is quite common practice to cut "tangentially" but cut completely through the stone in one pass as in Fig. 9.8. Plunge cutting is illustrated in Fig. 9.9. This is generally a matter of convenience. Since a saw travelling at 4000 surface feet per minute and cutting 4 square inches per minute will have a layer of dust of thickness $\frac{4}{12 \times 4000} = .00008$ inch where the saw leaves the stone, saw choking does not seem to be a limiting factor for realizable cutting rates in quartz.

If the saw is entering a sloping crystal face it will deflect and not cut a slice of proper orientation. It is well when possible to avoid such sloping entries particularly in the case of final cuts which must be of high precision in orientation. If the saw enters normally but the crystal tapers so that one side of the saw continues to have more material to remove than has the other side the saw will deflect. Repeated action of this kind can leave one side of the saw less sharp than the other side so that the saw will deflect even in favorable situations. This can be compensated for by occasionally turning the saw around on its arbor.

9.9 Cutting Fluids

The subject of coolants is very important in both sawing and lapping. Plain water is quite effective but may require a rust inhibitor to preserve the steel parts of the machine. Washing soda and tri sodium phosphate have been used for this purpose. Both destroy paint very quickly. Kerosene is good from the rust standpoint but it attacks the skin of many people and the odor is objectionable. Soap water is extensively used in lapping but it can dry into a horny deposit that is difficult to remove. Another thing to consider in the choice of a coolant is the effect on the quartz. If the quartz is left with minute fissures there may be an objectionable aging effect. Kerosene seems to allow for faster cutting but makes worse fissures as indicated by the fact that more plates break in the sawing; also such plates age worse than those cut in water solutions.

9.10 Precision Lapping

When we said that grinding was more accurate than lapping, we left out two important factors of practice. A slow moving metal plate is not subject to vibration difficulties and the metal can be more accurately shaped than a porous stone can be. Also, a good iron plate will not wear out of true so rapidly as a cemented abrasive wheel. But the best accuracy is still attained when the metal plate is charged and then cleaned off, and moved slowly enough to avoid vibration. However, lapping is good enough for many very precise jobs, even with loose abrasives. But in order to be good, lapping must be done on a true plate. If we are trying to lap a surface flat the lap must be flat.

Let us consider the problem of producing a flat surface on a block of quartz using a true lap and holding the block by hand. If the existing surface is highly convex the block will rock about, grinding first here then there and we will have trouble producing a flat surface. However, if the

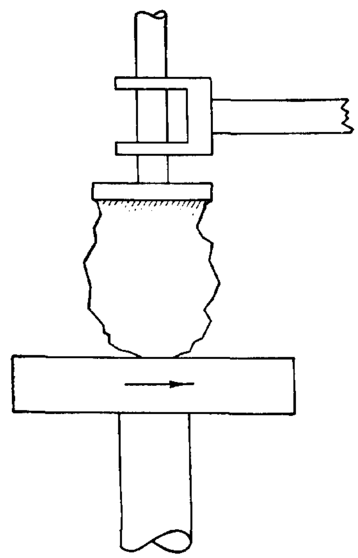

Fig. 9.10—Lapping a definite orientation

block is slightly concave this difficulty disappears. By conscious effort this rocking can be reduced till the surface eventually flattens out. In this case the quartz floats freely and can follow any flutter of the lap due to its plane not being perpendicular to its axis of rotation.

Even when the block and lap are perfectly flat, the revolving lap has a tendency to roll the block over. In Fig. 9.10 we see that the forces would tend to turn the block counter-clockwise. Also the large grains entering on the left side cause this side to cut faster. Hence for two reasons the block will tend to grind thinner on the left. If the block is very thin compared to its length in the direction of motion the turning effect becomes small, in which case it will bend and tend to grind excessively under the pressure points. If the block is reversed frequently the turning effect averages out. This all suggests that it requires some skill to do even these simple operations, particularly since the block must be constantly sweeping in and out from the center to the edge of the lap. This is so for two reasons. If the block stays at one distance from the center the abrasive will be quickly cleaned off this zone and no more cutting takes place. The second reason for sweeping is to distribute the wear over the whole lap so that no part wears away faster than other parts—we want the lap to stay flat. It is sometimes feasible to overcome these things that tend to round off the work piece by working on a slightly convex lap.

In trying to grind a second surface parallel to the first we find the thick corner by micrometer measurement, then press down nearer this corner as we attempt to get a flat surface by the previous method. Alternate grinding and measuring will, with enough skill, bring the surfaces to parallelness at the thickness desired.

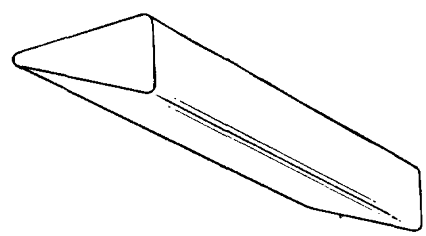

Fig. 9.11—A knife edge straight edge

We have mentioned keeping laps flat perhaps we should tell how we get them flat. The easiest test is by use of a precision "knife edge" straight edge. This straight edge Fig. 9.11 has a triangular cross section and an edge that is part of a small cylinder. In any way that it is held near the perpendicular to the surface it will present a straight edge to the surface. With a good light behind it, a gap of a few hundredths of a thousandth of an inch will appear as a thin gray line. Also, if the straight edge is moved slightly it will make a polish mark on the high spots and none on the low places. This test is of about the same sensitivity. The straight edge is made straight by grinding it on a flat lap so we have to start with a flat lap. How do we get the first flat lap?

If we grind two laps A and B together we can make them fit each other and we can tell where they fit by rubbing them together briefly, clean and dry. They will polish each other where they touch. If they polish uniformly they fit to a small fraction of a thousandth of an inch. If they fit any way we rotate them on each other, they might both be flat but again they might be spherical—one concave the other convex. If now we have also ground B to a third lap C and they fit they might also be spherical.

But if C also fits A all three must be flat, because if A is convex and B fits it B must be concave; if C fits B, C must be convex and convex C placed on convex A won't fit unless the convexities are negligibly small—that is all three are practically flat.

If we rub two of these plates together a few minutes at a time cleaning them carefully between times we will finally get a good polish so that the surface is a fair reflector. If an optically flat glass plate is placed on one of these polished laps and the pair viewed by monochromatic light a number of bands will be seen crossing the plates. They are interference fringes and if they are not perfectly straight the plates do not "fit." A straight line

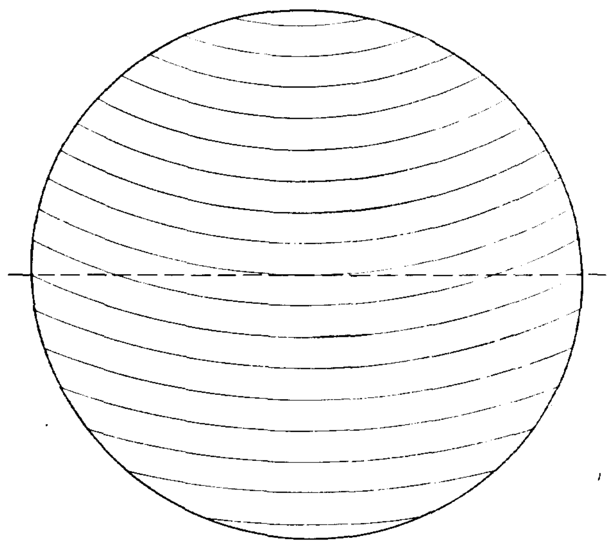

Fig. 9.12—Interference fringes observed in a test for lap flatness

laid on the fringes will show the degree of non-fit. As shown in Fig. 9.12 if n fringes cut the line the non-fit is of amount n fringes which is n half wave lengths of the light used. If green mercury light is used this would be $\frac{.00005461}{2}$ centimeters per fringe. In the figure this is 2 fringes. If we press the plates together at the lower edge of the figure, the fringes will likely shift and change shape. While the plates are so pressed together, if the fringes are concave upward as indicated in the figure, the lower lap is concave. If the fringes are convex upward, the lower lap is convex. If we grind two similar laps together, the top lap tends to become concave (because of the overhang), and the bottom, convex. We can take advantage of this to produce flats by placing the convex lap on top, while lapping.

The best stroke for such grinding is the star stroke, the motion being straight across, allowing an overhang of not over a sixth of the diameter, back and forth, slowly changing the direction of stroke and also turning the top lap on the bottom one so that the center of the top lap travels in a path like that shown in Fig. 9.13.

If we wish to cut a surface of a certain orientation on a crystal we could hold it by hand at the approximate orientation and lap it down till we get

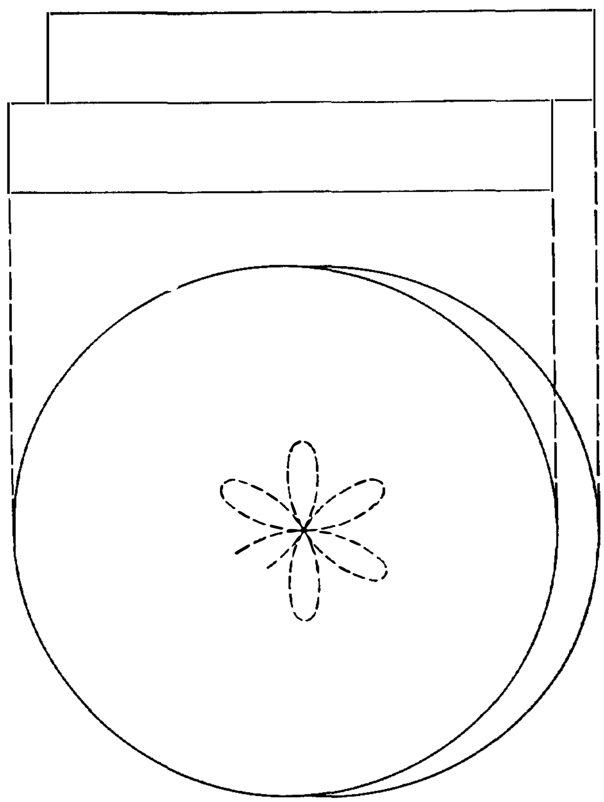

Fig. 9.13—The star stroke for flattening laps

a surface, then check its orientation and lap the piece, bearing down on one side or the other so as to correct the error. It is more economical, however to fix the crystal in some device to hold the orientation as the cutting occurs, such a device as shown in Fig. 9.10 for instance. It is not difficult to hold such a mechanism to an orientation accuracy of 5 minutes but the surface is not likely to be as flat as we could make it by the free floating method. It is not so flat because, if the lap flutters or vibrates or if any part of the holding mechanism has play or vibration the surface will become convex.

The convexity is objectionable long before it causes any objectionable orientation error as shown by Fig. 9.14. If the peak of this block is .001 centimeter high and the block is two centimeters across the block is objectionably out of flat but the two parts A and B differ from the desired orientation by only three and a half minutes. Consequently after being cut on a device like Fig. 9.10 we could improve the flatness without losing the orientation by grinding by a free floating method.

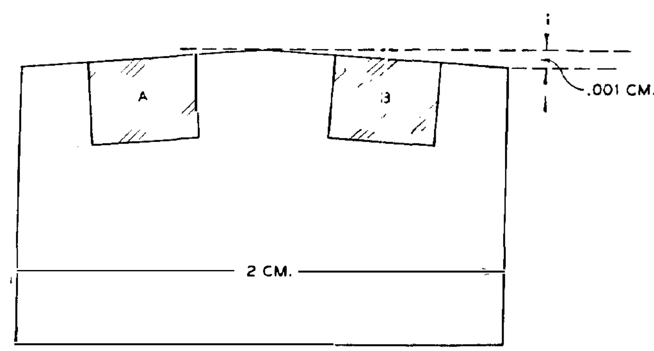

Fig. 9.14—Misorientations due to non-flatness

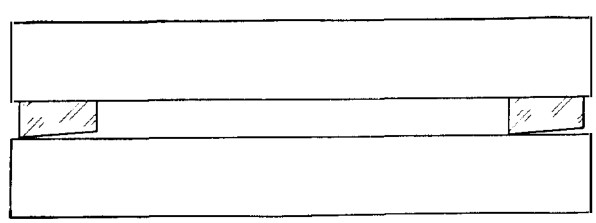

Fig. 9.15—Diagram to indicate that several (two shown) crystal plates being ground to have parallel faces will hold the laps parallel when the plates are of equal thickness, and both faces will approach parallelness and flatness when all plates approach equal thickness. When the number of plates is four or greater, and they are occasionally interchanged in position, the thinnest receives the least grinding, the thickest the most, resulting in all being eventually ground to the same thickness.

We mentioned grinding a second surface parallel to a first by skillful hand work. We can make the surfaces as parallel as the micrometer will read by using enough care. If two such blocks, made as nearly identical as possible, are placed on a large flat surface as in Fig. 9.15, a second flat plate laid on top could be used to improve the accuracy of parallelness by a little grinding.

This leads us to "nest" methods of lapping. The simplest nest method is the Western Electric system where a number of crystals are lapped between two ring laps, being pushed about between them by a "nest," the crystals being in holes in this nest which is a thin sheet of zinc or fibre. The top lap rests on the crystals and is restrained from moving off center or revolving by three links. A cross section is shown in Fig. 9.16. The nest

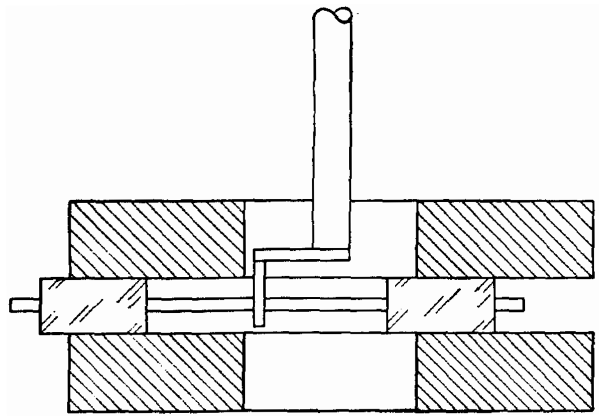

Fig. 9.16—The simplest nest lap can be operated on a vertical drill press. The two laps remain stationary while a nest (Figure 9.18) moves a number of plates around between the laps causing abrasion on both t●p and bottom sides of the plates.

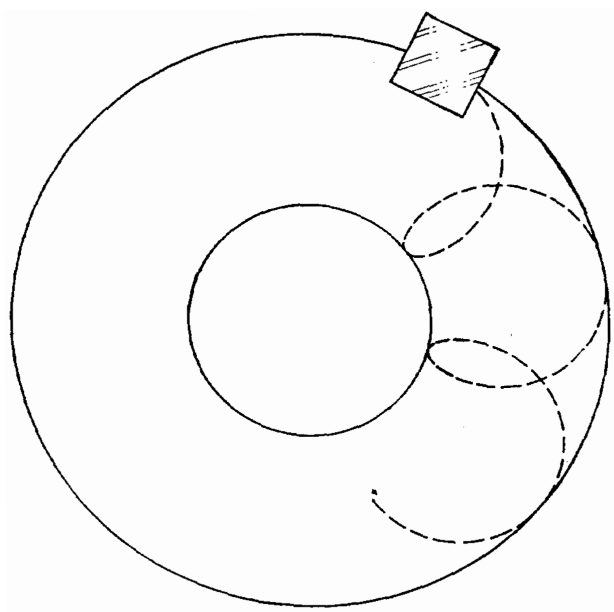

Fig. 9.17—Path of a plate over a lap in the drill press lap

is stirred around by a crank pin. This causes each crystal to move over the laps in a path like Fig. 9.17.

Let us assume that there are eight plates in the nest, Fig. 9.18 and that grinding has brought them down to fit between the laps perfectly. This fit is possible without all crystals being the same thickness. Let us assume that A is the thickest, E the thinnest, the others intermediate. If now A and E are interchanged and C and G are interchanged the laps will not touch the thinner plates, but will rest on A which is where E was, and on B and H, the next thickest blocks. The thickest blocks will now grind away faster than the thinner ones and when the laps finally rest on them equally, they will be much more nearly equal in thickness. If we continue

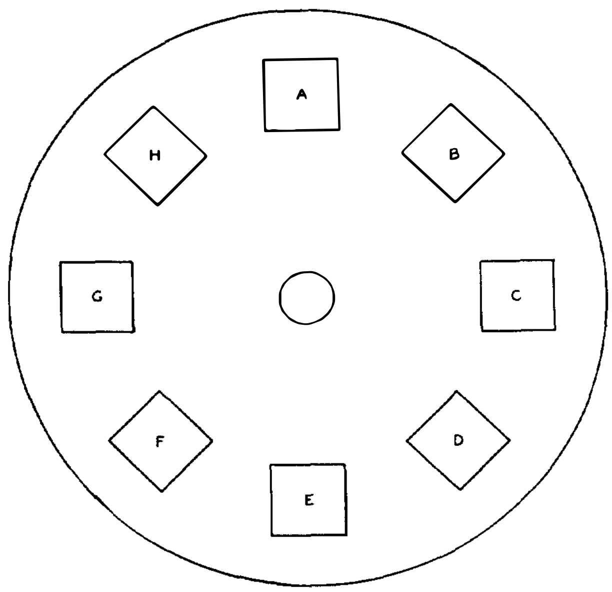

Fig. 9.18—A nest for crystal grinding

periodic grinding and "shuffling" the blocks will become very nearly the same and if the laps are very flat the plates will be accurately plane parallel.

The laps tend to wear out of true. The reason is apparent from Fig. 9.17. At the points where the crystal starts to reverse its travel to and from the center it pauses in this motion while traveling tangentially. In doing this it grinds too much from this zone and this zone tends to fall away below the general level of the lap surface. If the crystals travel in paths that are spirals of Archimedes the wear would be the same all over, but several plates in one rigid nest cannot all travel in spirals of Archimedes.

Having ground the major surfaces of a crystal we may have to edge grind to give an accurate rectangle or square. This can be done with large crystals with a device as shown in Fig. 9.19. If the guide edge is accurately square with the lap we will generate a right angle. A good method to generate right angles is that shown in Fig. 9.20. A steel block has all its angles 90°. The crystal or stack of crystals is clamped and cemented into a corner groove. The two exposed crystal edges are then ground parallel to the opposite steel block surfaces. This gives the crystals one good right angle. If the crystals are now remounted with this good corner in the groove and the other two edges are ground we will have four good right angles.

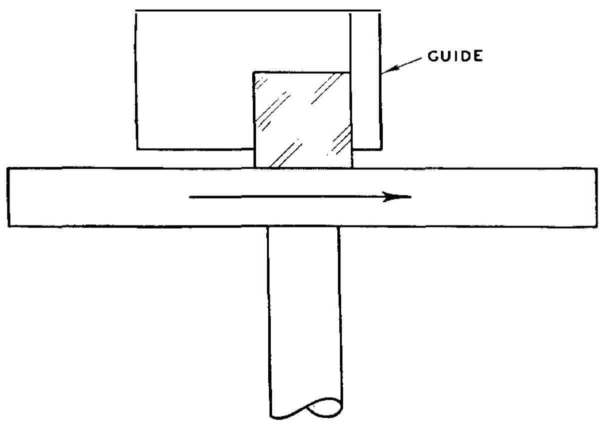

Fig. 9.19—Squaring a plate by means of a guide

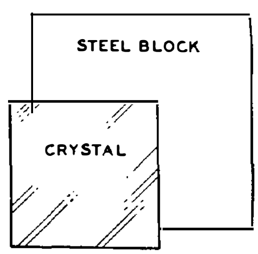

Fig. 9.20—Square steel block for generating squares

Probable Regions of Good Performance During Temperature Run from −55° to +90°C
Thickness of Crystal = .512 mm Capacity = 32 mmf BT Quartz

In all systems where we clamp the crystal over a revolving lap and allow it to descend to a fixed stop the erosion effect will cause the crystal to wear away for a long time after the crystal reaches the stop. The coarser the grain size the larger this effect.

Experiments on metal bonded diamond wheels show them to be much faster than silicon carbide lapping or grinding, and to have less heat cracks unless pushed too fast. If diamond machinery is built very rigidly and is very well balanced it should be able to do most of the jobs that carborundum now does. Diamond laps can be made very flat to compete with silicon carbide in the nest method, diamond edgers are used successfully and rough cutting is an easy task for diamonds. Since diamonds are faster and probably can be just as accurate, possibly more accurate because of the absence of the erosion effect, we believe that diamond grinding tools will replace carborundum lapping eventually.

9.11 Special Grinding and Lapping Machines

The Ultra-Lap, Fig. 9.21 has two revolving discs to one of which the work is secured. These plates not only revolve in opposite directions but

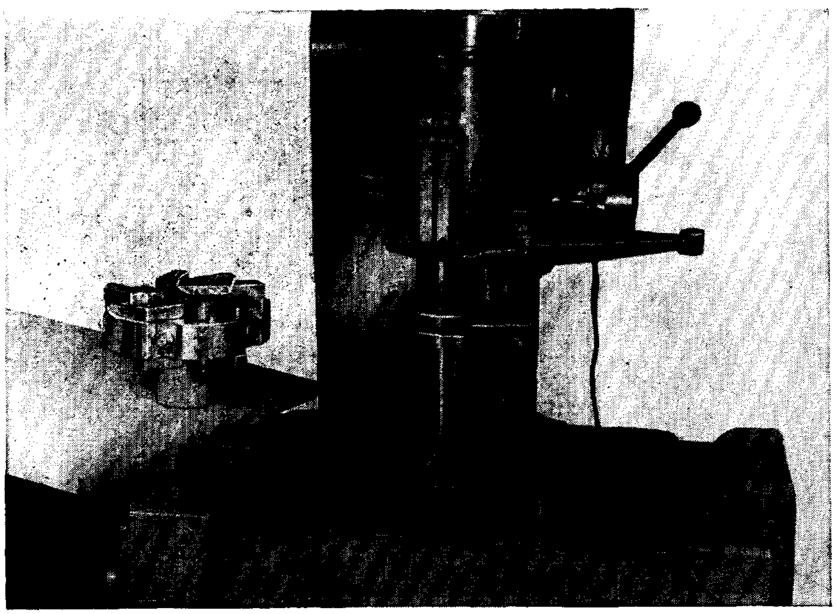

Fig. 9.21—The Ultra-Lap

the top one oscillates over the bottom one with a stroke adjustable as to amplitude and overhang. Although the machine is most often used with loose abrasive it also works well with a diamond wheel.

The Blanchard Grinder, Fig. 9.22, is a heavier machine, and more accurate than the Ultra-Lap. Here the work carrier turns slowly under a rapidly revolving cutting wheel about a center displaced enough from the axis of the cutting wheel that the grinding marks on the work cross at right angles. The work disc slides out from under the cutting wheel to facilitate loading and unloading.

This machine has very fine adjustments to control the depth of cut, and the degree of parallelness of the work axis and grinding wheel axis.

The Hunt-Hoffman Lap, Fig. 9.23, is a multiple nest lap. Since the nests act as planetary gears the crystals carried in them cover the lap surface

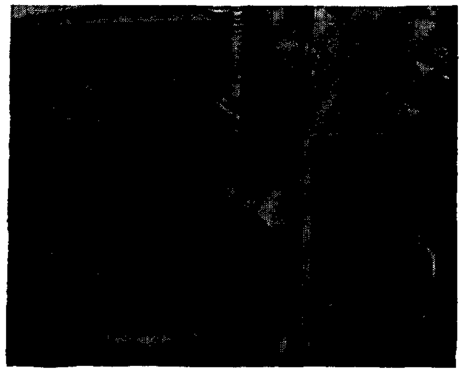

Fig. 9.22—The Blanchard Grinder

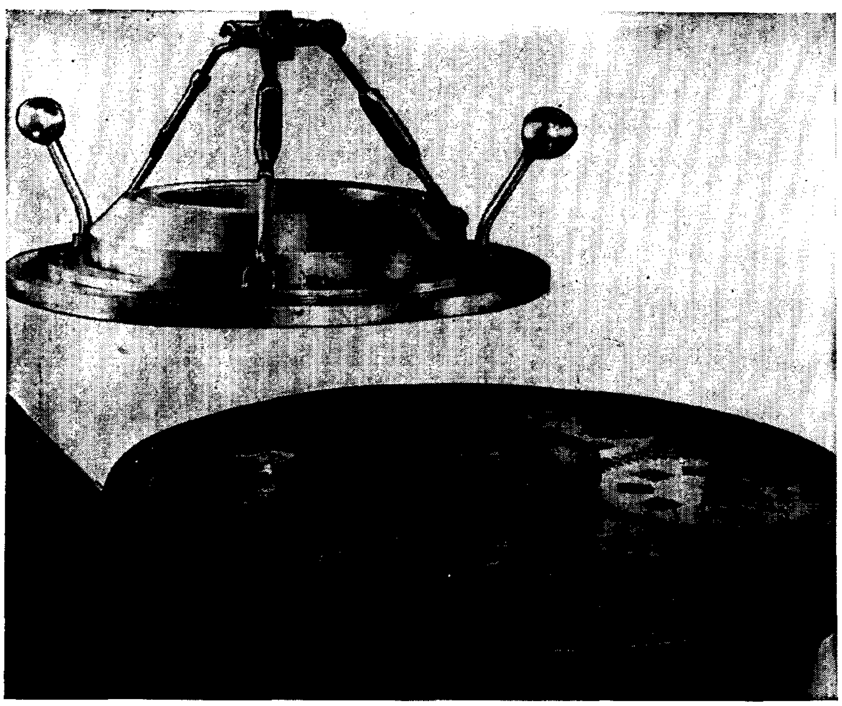

Fig. 9.23—The Hunt-Hoffman Lap

quite thoroughly. Also, a weakness of the simple drill press nest lap is avoided. In the simple drill press nest lap, square crystals in round holes were damaged at the corners. If square nest holes were used the same side of a crystal always pointed towards the center. This had a tendency to produce wedge shaped crystals unless the laps were kept in excellent condition—and this situation made it more difficult to keep the laps in good condition. It is said that the laps stay flat longer in the Hunt-Hoffman machine and that a lower degree of skill is required to produce a given degree of precision in the quartz plates.

In Fig. 9.24 is shown a machine used in the Western Electric Company. The crystals are carried in small discs carried in turn by the nest. This

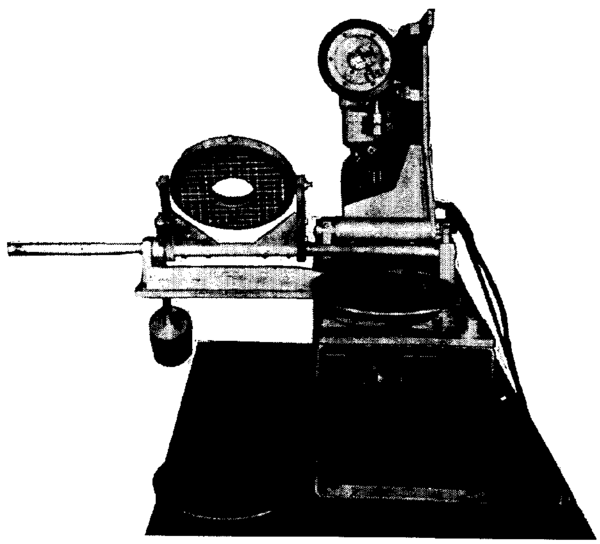

Fig. 9.24—An improved single nest lap in which the nest exercises two movements and the bottom lap rotates

allows the square crystal to be moved by forces along a whole edge instead of at a corner and at the same time to be free to rotate so as to present different edges to the lap center. The upper lap is supported by a gimbal. This allows counterbalancing to reduce the weight on the crystals. Also the nest is forced to rotate about its center as it sweeps around between the laps. The simple drill press lap left to chance this rotation about the nest center. As a result, when a thick crystal tried to enter a tight spot on the lap this crystal would resist, the nest would swing around this crystal and the very point that needed grinding most got none. The positive nest drive gets around this difficulty.