MODERN DIAMOND CUTTING AND POLISHING

By Akiva Caspi

This article examines the sophisticated techniques and equipment currently used to fashion a polished gem from a rough diamond. The basic manufacturing techniques—sawing, bruting, blocking, and polishing—are described with regard to the decisions that must be made to obtain the greatest value from a specific piece of rough. Over the last 25 years, the diamond-cutting industry worldwide has been revolutionized by sophisticated instruments for marking, laser sawing machines, laser kerfing machines, automatic bruting machines and laser bruting systems, automatic centering systems, and automatic polishing machines.

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Acknowledgments: The author thanks Dr. James E. Shigley of GIA Research for his dedication and assistance in the preparation of this article.

Gems & Gemology, *Vol. 33, No. 2, pp. 102–121*

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To many, a rough diamond looks like any transparent crystal or even a piece of broken glass. When cut as a faceted gemstone, however, it becomes a sparkling, shimmering object that is unique in appearance. Yet most of the people who are involved with gem diamonds—jewelers, gemologists, and the jewelry-buying public—are unfamiliar with many of the details involved in that transformation (figure 1).

The manufacturing of gem-quality diamonds has advanced more since 1980 than in the preceding 100 years. During the past two decades, a quiet revolution has taken place in much of the diamond-manufacturing industry. By adapting computer-imaging techniques, precision measurement systems, lasers, and other modern technological equipment, many manufacturers have improved their ability to cut gem diamonds in ways unimaginable only a few short years before. A significant result of this revolution is a diamond industry that is now better able to operate profitably. In addition, modern manufacturers can handle rough diamonds that would have been difficult, if not impossible, to cut by traditional manufacturing techniques.

This article has two purposes. The first is to describe this technological revolution by discussing the key steps in the manufacturing process and describing the recent technological improvements that have been made at each step. Although this article is based primarily on the author's experience in the Israeli diamond industry over the last 10 years, most of the advanced technology discussed can now be found in major manufacturing centers worldwide. The second purpose is to discuss the critical decisions that a manufacturer must make during the cutting process to obtain the maximum value from the finished stone.

BACKGROUND

The manufacture of a diamond into a faceted gemstone (figure 2) presents some very special challenges, including:

1. As the hardest known substance (10 on the Mohs

Figure 1. The cutting process is critical to the transformation of a diamond from a simple crystal to a brilliant faceted gem in a beautiful piece of jewelry. The faceted diamonds in these contemporary rings range from 1.04 ct for the smallest oval to 1.96 ct for the largest marquise. Courtesy of Hans D. Krieger, Idar-Oberstein, Germany; photo © Harold & Erica Van Pelt.

scale), diamond is also one of the most difficult gem materials to facet.

2. Although diamond is optically isotropic (i.e., it has only one refractive index), its hardness varies with crystallographic orientation, such that it can only be polished in certain crystallographic directions. These directions have traditionally been referred to as the "grain" (see, e.g., Vleeschdrager, 1986, p. 37).
3. The cutting process seeks to take advantage of the critical angle of total light reflection within the faceted diamond to achieve the maximum amount of light return through the crown facets. Diamond has a very high refractive index (2.42), and a mathematical basis for the shape and facet arrangement of the round brilliant cut was established early in this century by M. Tolkowsky (1919). Today, many other cutting styles are also used, including a variety of fancy cuts (see G. Tolkowsky, 1991).
4. The differences between the various color and clarity grades for faceted diamonds can be quite subtle, and very slight variations in cutting style and weight retention can result in significant differences in value.

All of these challenges must be addressed throughout the cutting process. Today, as it has for decades, gem diamond manufacturing involves the following basic steps:

1. Selecting (or sorting) the diamond rough. This includes examining each diamond for its potential color grade, clarity grade, and cutting style.
2. Marking the rough for manufacturing.

3. Cleaving and/or sawing the rough crystal.
4. Bruting the girdle.
5. Polishing the facets.

For large diamonds, some of these steps are repeated a number of times, for example: sawing→table polishing→ bruting→blocking (polishing four or eight facets)→[repolishing the table→ rebruting→ provisional polishing (8 facets)]→final table polishing→final bruting→ final polishing. This comes from a constant effort to improve the final appearance of the stone and the yield from the rough. The conventional means of manufacturing diamonds, and the various cutting styles used, have been described in several texts, including those of Bruton (1981), Watermeyer (1991, 1994), Ludel (1985), Vleeschdrager (1986), and Tillander (1995).

The goal in cutting a rough diamond is to maximize the market value of the faceted stone or stones produced from that piece of rough. This value is based on the well-known 4 Cs: Carat weight, Color, Clarity, and the less easily evaluated Cut. To illustrate, figure 3 shows where diamond manufacturing takes place on what can be thought of as an economic "conveyor belt." In this figure, the assumption is made that the final selling price of a cut diamond in a piece of jewelry is $100. Before the diamond is mined, it has no value ($0). When the original piece of rough is discovered in the mine, extracted from the host rock, and sorted, it has an estimated value of $26. The cut diamond is sold to the jewelry manufacturer for $30, and then to the retail jeweler for $50. Thus, in this example, one sees that the manufacturer's component is only $2, a very small percentage of the total retail value (but about 7% of the price of the loose diamond as it is sold to the trade). Typically, the actual profit would represent only about 0.5% of the value of the cut stone in a finished piece of jewelry—about 50 cents in this example.

As a second example of this same idea, assume that a 0.50 ct faceted diamond will sell at retail for $4,500 when set in a standard ring, that the rough diamond was sold to the manufacturer for about $1,170, and that after cutting its value was $1,260. The $90 window for the manufacturer must be enough to cover the cost of production, capital investment, risks (some diamonds are damaged during cutting), and profit. To ensure profit, therefore, the manufacturer has to be very efficient when he cuts the diamond. As will be illustrated later in this article, minor errors in diamond manufacturing can cause major losses in value.

In the mid-1980s, the Israel Diamond Institute was one of a few groups in the international diamond industry that made a conscious decision to pursue the use of sophisticated technology in the local manufacturing sector. The Israeli industry at that time was based largely on conventional methods. Earlier attempts to introduce automatic polishing machines had not been totally successful, because the manufacturers lacked not only the knowledge but also any understanding of the available technology.

Recognizing both that the Israeli diamond-manufacturing industry was very conservative and that the sophisticated techniques used in other industries could not readily be applied to the problems of cutting diamonds, the institute's engineer first analyzed the processes and established which areas would benefit most from technological innovations. Gradually, new manufacturing methods were introduced, including computer-aided evaluation of the rough crystals, lasers for precision sawing, automat-

Figure 2. Many decisions are required to turn a rough diamond like the macle on the left into a fine triangular brilliant-cut diamond like the stone on the far right. Courtesy of Kleinhaus, New York; photo © Harold & Erica Van Pelt.

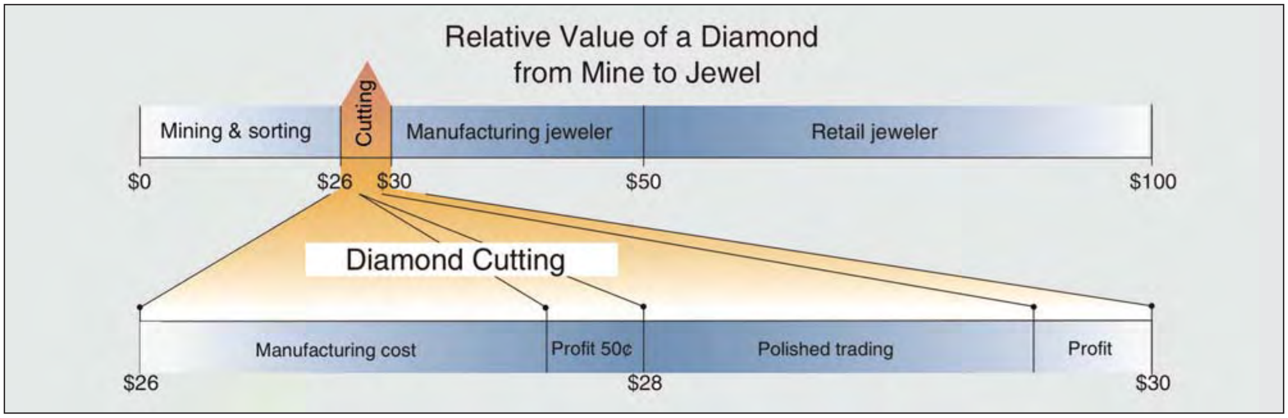


Figure 3. This economic "conveyor belt" illustrates the added value that a diamond attains as it passes through the manufacturing process from the mine to the retail jewelry store. Typically, within this conveyor belt, the diamond manufacturer's component is only a very small portion of the ultimate retail value, about 2%. Within this narrow range, all manufacturing costs must be included as well as some profit for the manufacturer.

ed bruting and polishing equipment, and computer imaging for more accurate measurement of the polished stones. These changes have resulted in significant improvements in the manufacturing process, and have been adopted throughout the Israeli industry and in other cutting centers such as India.

The introduction of new manufacturing technologies is ongoing, with much effort currently under way to educate other diamond manufacturers on how to use these technologies effectively in their own facilities. Since these efforts are still relatively new, few articles describing them have appeared in the trade press (see, e.g., Lawrence, 1996). At present, the best source of information is the proceedings volume published following the October 1991 International Technical Symposium sponsored by the De Beers Central Selling Organisation (CSO) in Tel Aviv, Israel (Cooke and Caspi, 1991). According to Lawrence (1991, p. 1–3) in this proceedings volume, there are many important benefits to using modern technology for diamond manufacturing:

1. Reduced manufacturing costs
2. Improved quality of the finished diamond
3. Increased efficiency, to compensate for the lower labor costs in other manufacturing centers
4. Better decision making regarding the manufacture of a particular piece of rough
5. Increased profits for the manufacturer

THE MANUFACTURING PROCESS

Sorting the Diamonds. Rough gem-quality diamonds are sorted in several ways. The main sorting categories are size, shape, color, and clarity. At the CSO, rough diamonds are sorted by hand and by machine into more than 5,000 categories (Stewart, 1991, p. 3–2). Most diamond manufacturers have far fewer categories, and they use one or more of a variety of sorting techniques, depending on the quantities they are handling and the typical sizes.

Size. All rough diamonds are sold by weight. However, large parcels of small rough diamonds normally are sorted first by sieving techniques (Bruton, 1981). That is, diamonds are passed through a series of sieve plates, each with holes of a given diameter. Smaller diamonds fall through the holes in the plate, while the larger ones remain trapped in the sieve. Several layers of sieve plates are stacked together, with decreasing hole diameters at each level downward. This enables the sorter to create packages of diamonds of approximately the same size prior to weighing. A scale is usually used to weigh the rough diamonds, although the CSO has some very sophisticated equipment for this purpose.

Shape. Rough diamond crystals occur in nature in different shapes. The diamond manufacturer traditionally describes these shapes using the following three general terms:

1. *Sawable*—rough diamonds, often octahedral or dodecahedral in shape, that will yield more total weight as polished stones if they are sawn or cleaved in two before being polished.
2. *Makeable*—rough diamonds that are polished as a single cut stone without first being sawn or cleaved. They usually require more work than

sawable rough and have a lower yield. Sometimes their grain structure cannot be determined easily. Both macles and "flats" would typically fall within this group.

3. *Cleavage*—irregularly shaped rough that requires special attention, as was the case with the original Cullinan rough diamond.

Sorting by shape enables the manufacturer to decide how best to cut the diamond and which manufacturing process to use.

Color. Color sorting (using a standard color-grading system) is done in natural daylight. In many diamonds, though, color is quite subtle. In addition, colors that result from atomic-level impurities or defects may be evenly or unevenly distributed within the rough crystal. Color can also result from the presence of a colored inclusion(s), or from staining (usually brown) by a foreign material within a surface-reaching fracture. Some diamond crystals have a surface coating or frosting that may be all or partially removed during cutting. Thus, the manufacturer must evaluate all these situations when considering how to cut a particular diamond to obtain the best color possible.

Clarity. Last, rough diamonds are sorted in terms of their potential clarity grade (again, according to a standard system). As with color grades, the better clarity grades are only distinguished by slight differences, such as in the number, visibility, position, and size of internal features (inclusions, fractures, etc.), as these features would appear in the final faceted stone. The uneven surface of the rough diamond often makes internal features difficult to see. The manufacturer must envision the shape and orientation of the stone within the rough crystal, and judge where these internal features may be located and how visible they will be, or whether any or all can be removed by cutting.

Figure 4. The most critical stage in diamond manufacturing, marking the diamond for sawing or cleaving, requires a complex decision-making process to optimize the value of the finished stones.

Marking the Rough Diamond. The decision as to whether or not to divide the diamond crystal is made by an individual called the *marker.* This is usually the most experienced person in the manufacturing company (very often the owner of the company), a specially trained employee, or even a subcontractor. This step is crucial because it represents *the major* decision on how to manufacture a given piece of diamond rough. As stated by Grochovsky (1991, p. 10–1), "the marking of a stone comes only after considerable evaluation, as any error made at this stage (of the manufacturing process) is irreversible."

To outsiders, marking appears to be a very simple process. The marker examines the rough diamond with a loupe and, frequently, measures the dimensions of the diamond with a gauge. He then marks a black line on the diamond crystal's surface (figure 4). In the next step of the manufacturing process, the crystal will be either sawn or cleaved along this line (Bruton, 1981, p. 235; Watermeyer, 1991, p. 22). In actuality, however, marking is really the most complicated step in diamond cutting (see Grochovsky, 1991, pp. 10–1 to 10–5). This is because the marker must optimize the value of the two finished stones. To understand the marker's decision in marking a particular crystal, we must again review the influence of each of the 4 Cs on the value of the cut diamond.

Carat Weight. When working with sawable rough, the marker must maximize the weight of the two finished diamonds. By examining the rough crystal with a loupe, the marker usually sees several alternatives. However, the marker must keep in mind the value information presented in figure 5 (although the individual prices are fictitious, the relative prices are based on pricing lists over several months in 1996). These two graphs illustrate the relative *price change* for cut diamonds as *carat weight increases* (while the color and clarity grades are kept con-

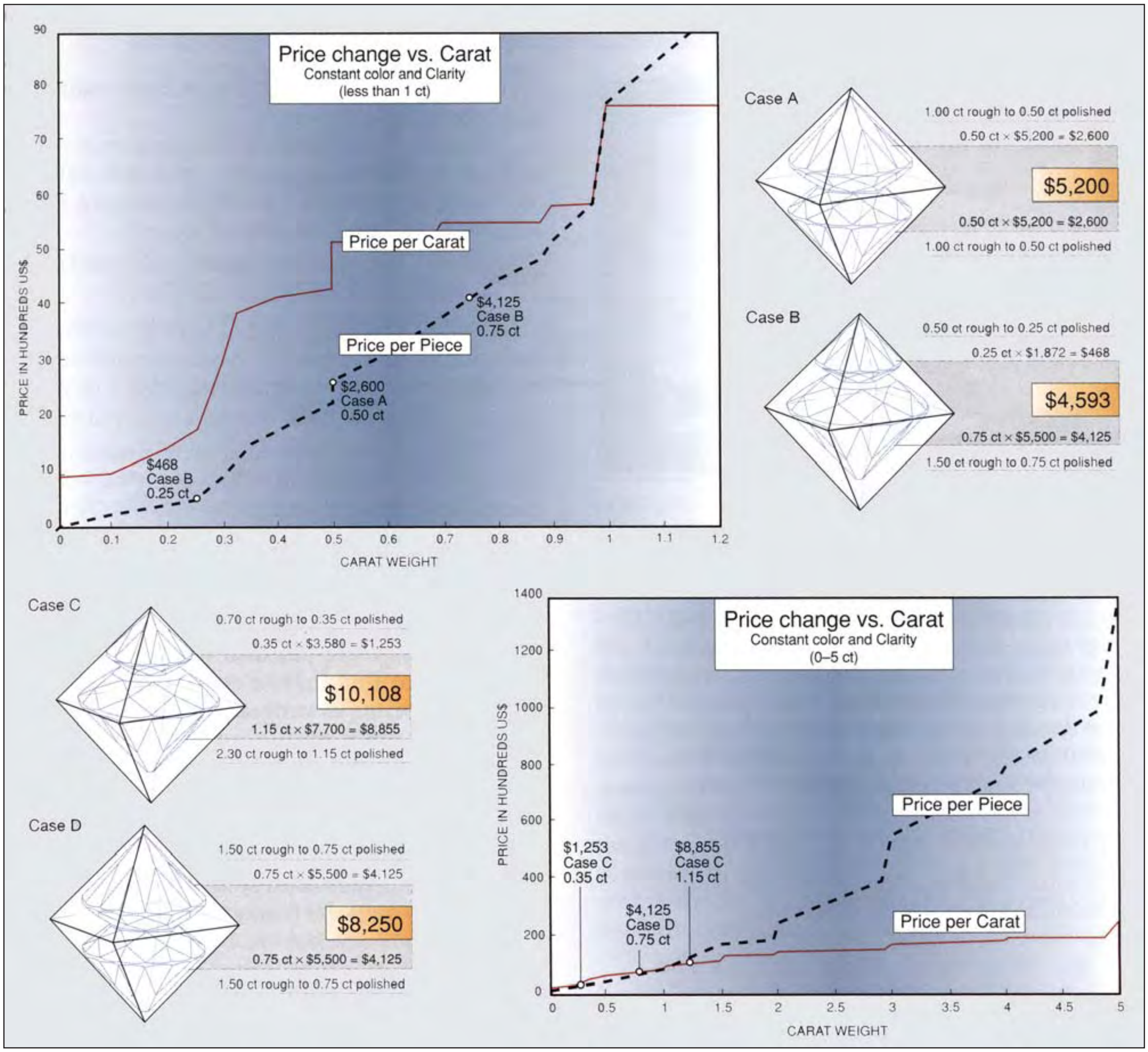


Figure 5. These graphs show the relative prices per carat and per piece for cut diamonds with weights primarily below (top) and above (bottom) approximately 1.00 ct. Note how the price differential increases significantly as carat weight increases (assuming other factors are identical; for the purpose of this illustration, the diamonds are all round brilliants and all have the same color and clarity grades). At certain key points (such as near 1.00, 2.00, and 3.00 ct), price jumps sharply. In the diamond-manufacturing process, the price per piece of the single stone—or total price for the two stones—cut from the original piece of rough is the crucial value to maximize. Even though case B will yield a 0.75 ct stone, case A provides the greater total value for the original piece of rough. However, the added value for the 1.15 ct stone that case C will yield makes it the better choice than the two equal-size stones in case D.

stant). In both graphs, one line represents the *price per carat* and the other represents the *price per piece* (found by multiplying the price per carat by the weight). In figure 5 (bottom), note the significant difference in these two prices as the carat weight increases. In both graphs, also note that the two lines are not smooth; at certain carat weights, the value jumps sharply (nearly vertical line segments). For example, from 0.98 ct to 1.02 ct, where the weight change is only about 4%, the price per piece may change by almost 35%. The marker is mainly interested in maximizing the total value for the two pieces cut from the original piece of rough.

To get a better idea of the alternative value

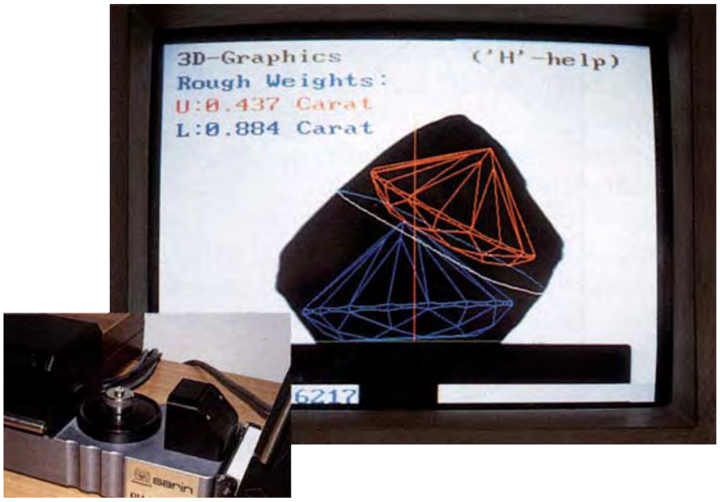


Figure 6. The marker uses the Sarin Dia-Expert system (here, with Dia-Mension hardware) to help identify the best position to mark a rough diamond for sawing or cleaving. The system consists of a sample stage, light source, and camera (inset), as well as a computer system. Within an image of the cross-section of the rough diamond that is depicted on the computer screen, the operator may ask the computer to superimpose computer-generated outlines of possible cut stones that could be manufactured from this particular piece of rough. In the option shown here, the solution is unusual, since the table facets of the two proposed cut stones are not adjacent to the sawing plane, which is the most common arrangement. Photo by James E. Shigley.

choices a marker has when examining a piece of rough, consider the case of a 2.00 ct well-formed octahedral crystal. Furthermore, assume an idealized situation where the two stones fashioned from this crystal will end up having the same color and clarity grades. The marker has many options available, but let us examine two (assuming here a 50% yield—that is, 50% of the original crystal is lost as powder or dust during the manufacturing process, so that the two final cut diamonds total 1.00 ct):

Option 1: To cut the crystal into two identical pieces that will yield two polished diamonds, each weighing 0.50 ct (case A in figure 5)

Option 2: To cut the crystal in such a way that it yields two polished stones of very different weights, 0.75 and 0.25 ct (case B in figure 5)

In this situation, it appears that the two 0.50 ct stones will yield the maximum total value (see again figure 5).

As another example, if the rough crystal weighs 3.00 ct, the marker again has to decide between similar options (assuming a 50% yield—or a total weight of 1.50 ct for the two cut stones):

Option 1: Two stones weighing 1.15 ct and 0.35 ct (case C)

Option 2: Two identical 0.75 ct stones (case D)

Referring again to figure 5, the first choice—that of manufacturing two diamonds that differ in weight (case C)—will yield the maximum total value.

Of course, real situations are not this simple. The weight, shape, potential color and clarity grades, and current situation in the retail marketplace all influence the very important decision of how to mark a particular rough diamond. The marker must take into consideration all of these factors.

To estimate the polished weight, the marker uses a special tool known as a Moe gauge. This measuring device is calibrated in Moes, units of measurement that are unique to the instrument. The weight of the final cut diamond can be estimated by cross-referencing Moes dimensions for diameter and total depth to a set of tables supplied with the instrument.

A new computer-based system has recently been introduced to help the marker (figure 6). Known as Dia-Expert and manufactured by Sarin, a Ramat-Gan company, this equipment is used as follows:

1. The marker sets the rough diamond on the system's sample stage.
2. He selects the faceting proportions to which he thinks the diamond should be cut.
3. If he chooses, he can define the quality of the cut stone in terms of color and clarity.
4. The system measures the geometric proportions of the rough crystal in a number of orientations, so that a detailed three-dimensional description or model of the crystal is then "known" to the computer.
5. The marker may ask the computer system certain questions, such as what the largest stone and the remainder will be, or what two cut stones will result if the rough diamond is sawn or cleaved along a defined line.
6. For each option, the system will show the potential shapes and sizes of the cut stones

TABLE 1. Sample information provided by the Sarin Dia-Expert system.[a]

Option	Stone	Weight	Cut quality	Price per carat	Stone's price	Total
A	1	1.12	Very good	$ 9,300	$ 10,416	$ 20,181
A	2	1.05	Very good	9,300	9,765	
B	1	1.82	Very good	10,700	19,474	$ 22,660
B	2	0.54	Very good	5,900	3,186	
C	1	1.67	Very good	10,700	17,869	$ 22,322
C	2	0.73	Very good	6,100	4,453	

[a] *For an assumed cutting style and color and clarity grades, the system has made three recommended options (labeled A, B, and C) for manufacturing cut stones from the sawn pieces of this crystal. "Cut quality" is defined by the operator, and "price per carat" is taken from a table in the system. With this information, the system calculates the two weights for each option. Thus, the operator can see the results for each of the three marking options.*

superimposed on an image of the rough (again, see figure 6). It also indicates the resulting weight of each cut stone and the total value of each option.

7. When the marker selects a particular option, the system in cooperation with the operator will physically place a black line on the rough crystal, along which the diamond will be sawn or cleaved.

Table 1 presents the type of information that the Dia-Expert system would produce. The system has suggested a particular cutting style and three possible options (here labeled A, B, and C) to manufacture two cut stones from a particular crystal. In each case, the "quality of cut" for the two future stones was selected as "very good," and the prices per carat were determined from another table (not shown, where the marker has made assumptions regarding the clarity and color grades of the two cut diamonds; the basis for the decision as to what quality of cut to specify is described below). Note that inclusions are *not* taken into consideration in this example, and the system operator might have to change the anticipated clarity grade if inclusions would affect any of the options. The Dia-Expert system gives the estimated weight and orientation of both cut stones within an outline of the rough crystal. Again, the price per piece of each cut stone is derived by multiplying its price per carat by its estimated weight. In this example, the system recommends option B, which gives the maximum value for the original piece of rough. Although use of this system reduces marker uncertainty in evaluating a rough diamond, the Dia-Expert does not replace the marker. At present, the system operator must still consider the presence of inclusions and fractures within the rough crystal that the Dia-Expert equipment cannot resolve.

Using the same relative prices as are given in figure 5, figure 7 demonstrates how sensitive the

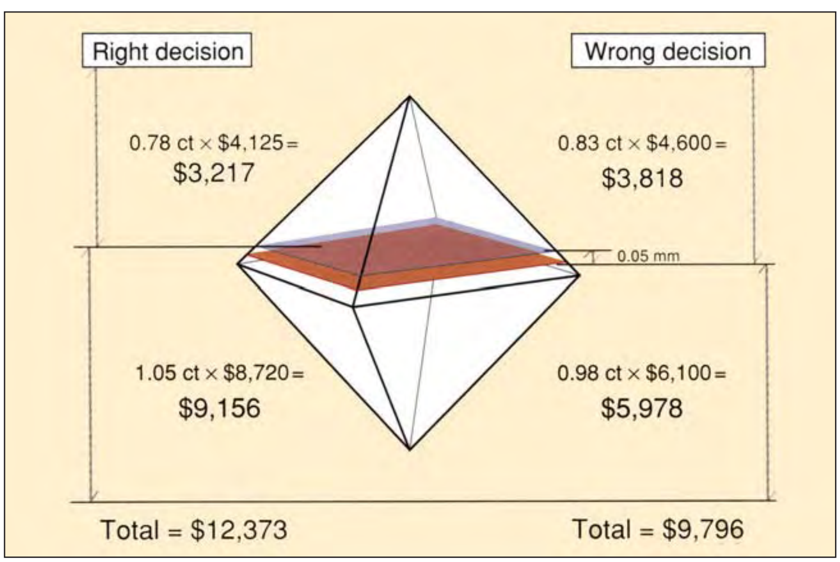


Figure 7. The marker must carefully evaluate where to place the marker line on the rough diamond so as to achieve the maximum yield from that piece of rough. As this illustration shows, even a small, 0.05 mm, change in the placement of this line can result in a major difference in the total price of the two final cut diamonds. To determine the price per piece, the final carat weight of each stone is multiplied by the price per carat (using the same relative prices as are given in figure 5).

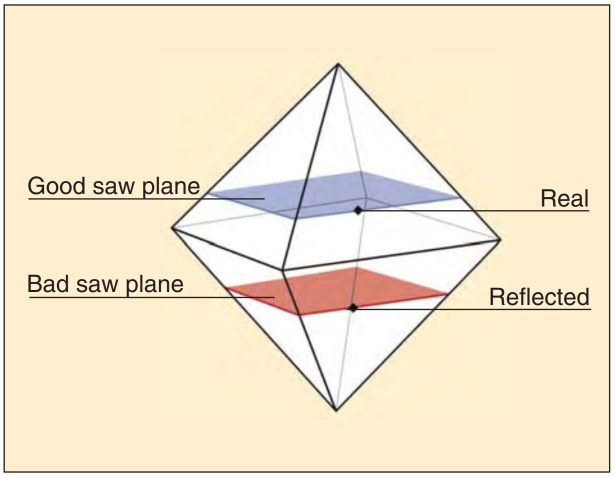


Figure 8. One of the greatest challenges facing the marker is the location of inclusions in the rough diamond and how to avoid or place them in the polished stone. This illustration shows the locations of a real inclusion in a diamond crystal and a reflection of this same inclusion produced by the refraction of light. The diamond could be sawn through either location, depending on where the marker line is placed. If the crystal was sawn through the imaginary "inclusion" (the reflection), the result would be a larger lower-clarity stone and a smaller higher-clarity stone. If the crystal was sawn through the real inclusion, however, it would yield two stones similar in weight to those in the first option, but both would be of higher clarity—and, therefore, would have a higher total value.

marker's decision is. In this representative example, a small inaccuracy of 0.05 mm in positioning the marker line would cause a major loss in value.

As noted earlier, a further challenge associated with marking a rough diamond is the crystal that has a coated or frosted surface, which may greatly limit the marker's ability to see the stone's internal characteristics. With such a stone, it may be necessary to polish one or more flat facets ("windows") for these observations.

Color. Estimation of the final color appearance is very important in the marker's decision whether to polish the diamond to good proportions (high color) or to poorer proportions (lower color grade but higher weight yield). As any of the major diamond price guides will show, the price of a cut diamond drops steadily from one color grade to the next until about "S." At the higher end of the scale ("D"–"G") especially, a drop in color by one grade can change the price by as much as 20%.

Clarity. Clarity is the most difficult feature to assess. The marker must determine not only the existence of an inclusion (which may be very small), but also its exact location within the future cut stone, since he has to decide whether or not to remove it during the cutting process. There often is a trade-off between achieving a smaller, inclusion-free stone and a larger stone that contains an inclusion. If the inclusion is to be left in, every effort must be made to position it within the stone so as to minimize its visibility and optical effect. A small mistake in locating an inclusion or other imperfection—and hence, in placing the marker line—can have disastrous consequences once the rough crystal is cleaved or sawn.

Because of light refraction within a diamond crystal, it is sometimes difficult to decide which inclusions are real and which are reflections (there may be more than one). Figure 8 illustrates such a situation. Let's assume that either option would produce two stones, one weighing 1.10 ct and the other, 0.90 ct. If the marker decides to saw the crystal along the "good" line (i.e., through the real inclusion), he will get two inclusion-free stones. But if he makes the wrong decision, and saws along the "bad" line (i.e., through the imaginary inclusion), the larger, 1.10 ct, stone from the top half will contain the real inclusion; only the 0.90 ct stone from the bottom half will be inclusion-free. Such a misjudgment could result in a significant financial loss, especially if the stone was of good color. Price differences between clarity grades can be substantial, especially for the higher grades (as much as 18% between IF and VVS grades).

Cut. Last, the marker must decide whether to fashion the rough as a round brilliant, into one of the well-known fancy shapes (i.e., marquise, oval, etc.), or into one of the newer cutting styles (see, e.g., Tolkowsky, 1991). The choice of shape will influence the overall appearance (i.e., brilliance, dispersion, etc.), face-up color, and visibility of inclusions (these features would also be influenced by the size of the faceted diamond).

The same faceting shape can be manufactured with different proportions (which define the geometric relationships between different parts of the cut diamond). Achieving better proportions usually results in a lower yield from a given piece of rough. Sometimes going from one set of proportions (an excellent cut) to another set (a fair cut) can increase the yield by as much as 15%, but the price per carat then decreases.

The main problem for the marker is that the above 4Cs are dependent on one another. Attempts to maximize the value from one factor must often be done at the expense of one or more of the others. If the marker wants to increase clarity, he may have to remove material and thus decrease the size (carat weight). Cutting for better proportions also means tighter tolerances, and thus less weight retention. Consequently, markers must stay constantly in touch with the current market demand for various sizes, shapes, proportions, and color and clarity grades of cut diamonds. This demand can change daily, seasonally, or according to the preferences of the different international markets.

Cost. To these 4Cs, we must add a fifth C: the *cost of production*. This C is used only by manufacturers. For example, depending on the marking, "sawable" stones can be turned into "makeable" ones (with no defined grain orientation), which often require more work to manufacture and thus are more expensive. Also, a fancy cut, as compared to a standard round brilliant, is more expensive to produce. Most manufacturers specialize in certain shapes, which their machines and labor handle most efficiently. A marker working for such a manufacturer will prefer his specialized shape to other alternatives if the difference in value is not significant. Last, laser sawing (see following discussion) is more expensive than mechanical sawing.

The main effect of this fifth C is seen in the geographic locations where diamonds are cut today. Smaller, less-expensive diamonds, where the value added by manufacturing is about 15%, are handled in the Far East—India, Thailand, China, and other countries (known as lower-cost centers, where the cost of a worker is about $30 to $200 per month). Larger, more expensive diamonds are cut in the United States, Antwerp, and Israel, where the added value is low (from 2% to 5%).

Crystal Grain. Before examining the actual manufacturing of the cut diamond, we must first understand how the *crystal grain* affects the cutting process (Bruton, 1981, p. 238; Watermeyer, 1991, p. 18).

Because of crystal grain (in this context, directional variations in hardness relative to crystallographic orientation), a mechanical operation (such as polishing) on a diamond often can take place only in certain directions. In some rough diamonds, these grain directions can be identified by the shape of the crystal, by certain surface features (such as trigons), or by the internal structure of the crystal. The experienced diamond manufacturer knows the effect of crystal grain on the cutting process. However, problems can arise when: (1) there are no surface or internal features that indicate grain orientation, (2) a crystal changes its orientation (referred to as being in a *twisted form*), and (3) one crystal is embedded in the main crystal (known as a *naat* or knot).

In each of these cases, the manufacturer may not be able to complete some mechanical operations successfully. This happens, for example, in sawing or when a facet is being polished and there is a *naat* present. Then, the diamond has to be polished in two different directions. A detailed description of diamond crystal grain and its features is found in Ludel (1985, Chapter 7).

Sawing the Rough Diamond. *Mechanical Sawing.* Diamonds are sawn today as they have been for many years (for further details, see Bruton, 1981; Ludel, 1985; Vleeschdrager, 1986; Grochovsky, 1991; and Watermeyer, 1991). In mechanical sawing, the rough diamond, held in a dop, is slowly lowered onto a high-speed (~10,000 revolutions per minute) revolving blade (figure 9). The pressure of

Figure 9. In this photo of a mechanical sawing operation, two machines are shown. The sawing machine controls the lowering of the crystal, attached to a dop, onto a thin copper blade that is revolving at a high speed. Photo by James E. Shigley.

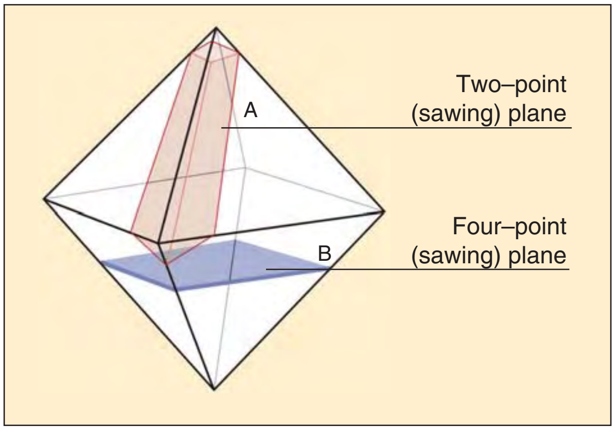


Figure 10. The sawing plane used for an octahedral diamond crystal is indicated by outline B. Mechanical sawing commonly takes place along such planes (ones parallel to cubic faces). This plane is also known as the "four point" plane, because the sawn surface has four equidistant corners. Outline A indicates another sawing plane, a two-point plane; such planes are parallel to dodecahedral crystal faces.

the diamond on the thin (about 0.06 mm) blade is controlled by a manually adjusted screw. The crystal is sawn along the direction indicated by the marker's line.

Sawing must be performed in certain orientations to the grain (figure 10), often called the two-point plane (parallel to a dodecahedral face) and the four-point plane (parallel to a cubic face). Planes can also be labeled by the number of places along the girdle where naturals can occur (see, e.g., Sevdermish and Mashiah, 1996, p. 718).

Recently, mechanical sawing has also benefited from new technology. The mechanical screw that lowers the diamond onto the sawing blade has been replaced by a computer-controlled system, attached to the traditional machine, that is able to sense the pressure of the diamond on the blade (figure 11). When the pressure drops below a predetermined limit, the system lowers the diamond further onto the blade and increases pressure on the stone. This system also prevents the diamond from moving downward beyond a predetermined speed, so that the blade does not penetrate the stone at an undesired plane. An experienced sawer usually can handle 20 to 30 machines at the same time.

Laser Sawing. Laser sawing, in which a laser replaces the metal blade to saw the diamond crystal (figure 12), was first introduced 20 years ago (see Cooper, 1991). The equipment consists of a YAG (yttrium aluminum garnet) laser with a computer-controlled sample holder and a lens that can focus the laser beam up or down. As figure 13 illustrates, in the special holder or cassette (which may hold several diamonds), the diamond can be moved in a two-dimensional, or X-Y, plane (i.e., side to side or back and forth) under the fixed position of the laser beam. Once the laser beam strikes the diamond, it heats that spot to a very high temperature, "burning" or vaporizing it. As the rough diamond moves beneath the laser beam, a narrow slice through the diamond is created.

Laser sawing has the following important advantages (see also Cooper, 1991; Davis, 1991; Prior, 1991):

Figure 11. Modern sawing machines, like this Dialit AS500, have a pressure controller. After setting the diamond in the machine, the operator sets the required pressure of the diamond on the blade and the maximum velocity in which the diamond will be sawn. The control system continuously checks and adjusts the pressure.

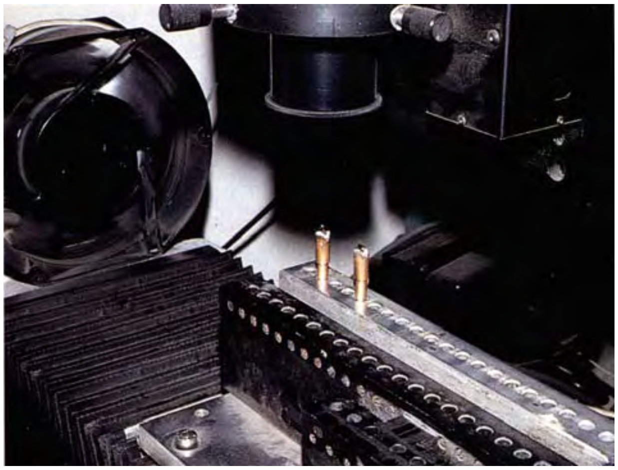


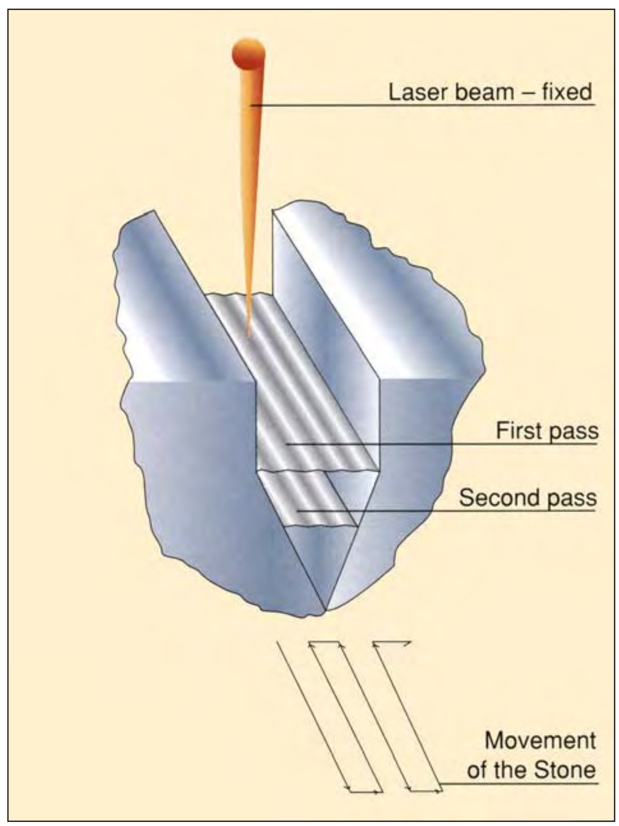
Figure 12. In this laser-sawing operation, a YAG laser is being used to saw two dark yellow diamond crystals. The laser beam is oriented vertically, and it strikes the upper surface of each crystal as the latter is moved back and forth by a motorized cassette. Photo by James E. Shigley.

1. The laser can saw a rough diamond in any crystallographic direction (you are not limited to the directions of cleaving or mechanical sawing). This permits greater accuracy, greater yield, and greater versatility in handling complex crystals that could not be sawn easily by mechanical means.
2. There is no contact of a tool (such as the sawing blade) with the diamond, which eliminates the expense of periodically replacing a worn-out tool.
3. There is the possibility of both greater and constant speed for sawing. For example, a 1.00 ct crystal can be laser sawn in about 20 minutes, as compared to about 120 minutes for mechanical sawing, without hindrance from any grain obstacle (such as a *naat*).
4. The weight loss is similar to that experienced with mechanical sawing.
5. The laser equipment can be operated continuously: As many as 30 rough diamonds can be lined up in a cassette and sawn one after another without any operator involvement after the computer has been programmed with the special parameters of each diamond (i.e., its height and other dimensions). This lowers labor costs.

However, the use of lasers for sawing diamonds also has several drawbacks vis à vis mechanical sawing. These include both (1) the greater expense of purchasing and maintaining laser equipment, and (2) the critical need for safety in operating the laser equipment.

These drawbacks can be overcome by one manufacturer specializing in the use of this technology, and offering it to a number of other manufacturers. However, because of the greater capital costs, currently this equipment is primarily used on those rough diamonds for which mechanical sawing is not possible. It is worth noting, though, that the author knows of one large-volume manufacturer in India who saws all of his diamonds by laser and currently has approximately 30 laser-sawing machines.

Figure 13. In laser sawing, a wide "path" (about 0.2 mm across) is made by moving the diamond back and forth beneath the fixed position of the laser beam. Then, the focal point of the laser beam is lowered and a second, narrower path (about 0.17 mm across) is formed. This process is repeated several more times, with the width of the path decreasing gradually to yield a V-shaped groove by the time the laser beam reaches the bottom edge of the rough diamond.



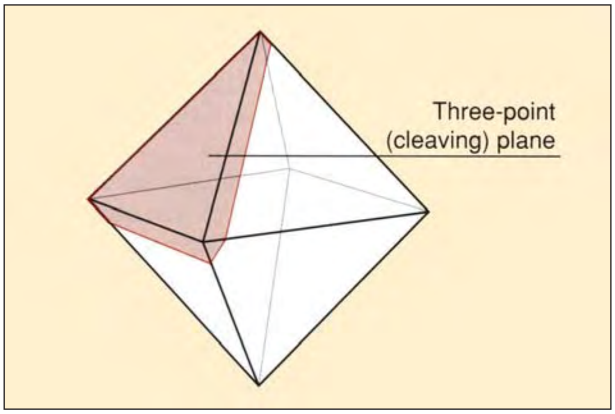


Figure 14. A diamond is cleaved along a different grain orientation than it is sawn. Compare, for example, the cleaving plane marked on this octahedral diamond crystal with the sawing planes marked on the illustration in figure 10. (Note that the cleaving plane is also known as the "three point" plane because of the three corners of the cleaved surface.)

Cleaving the Rough Diamond. Cleaving is the traditional method for dividing a rough diamond into two parts (see Bruton, 1981; Ludel, 1985; Vleeschdrager, 1986; Watermeyer, 1991). Cleaving is performed along a different grain orientation than sawing, as seen in figure 14 (compare with figure 10). The marker's decision to cleave rather than saw a diamond depends on the shape of the rough and the location of inclusions.

The cleaving process has two stages. The first is preparing the *kerf*—a small V-shaped groove carved into the diamond's surface along a specific direction. The laser kerf is the best, as it is a narrow, straight-sided groove that is squared off at the bottom. The second stage is splitting the rough diamond with a special knife. The cleaver taps on the shoulder of the blunt blade with a small hammer, and the diamond is divided instantaneously.

Kerfing. Traditionally, kerfing was a very fatiguing process that was done totally by hand. The cleaver first glued the diamond to a special rod and then used another diamond with a sharp edge to scratch the surface of the first diamond until a groove (the "kerf") was created. Preparing the kerf in this manner was an exacting occupation that required years of study. In addition, the procedure was very time-consuming.

Today, lasers have revolutionized kerfing (see Cukrowicz and Jacobs, 1991; Doshi, 1991). Modern kerfing is performed in the following steps:

1. The rough diamond is installed in a special dop.
2. The *setter* places 20 or more diamonds in a cassette so that the marker line on each is aligned and is at the same height (the same focus position for the laser beam).
3. The cassette is loaded into the laser system.
4. The cassette is moved along the marker's lines in a special pattern so that the laser creates the required kerf in each.

Once the kerf is prepared, the rough diamond is set in a plastic-like material. A thin metal blade is inserted into the kerf, and the shoulder of the blade is struck with a hammer. If the kerf has been positioned correctly, the diamond will split easily.

Laser kerfing has the following advantages over manual kerfing:

1. It can follow the marker line more precisely.
2. The kerf is narrower and shallower, which is all that is needed for cleaving,
3. Because laser kerfing is much faster than the traditional manual method, it is less expensive for manufacturers who handle large quantities of diamonds.
4. Productivity is high: One person using a laser system can kerf more rough diamonds than can 60 individuals using the manual method.

However, there are potential problems with laser safety and damage to the diamond. In addition, the marker still must identify the best cleaving direction by the morphology and surface characteristics of the rough diamond in order to place each kerf correctly.

Bruting. It is with this step that the diamond receives its basic shape (round, marquise, etc.; see Bruton, 1981; Ludel, 1985; Vleeschdrager, 1986; Watermeyer, 1991). Bruting is done by rotating one diamond against another diamond that may also be rotating or may be stationary in the hand of the *bruter* (figures 15 and 16). Thus, the two diamonds are progressively ground away by mutual abrasion. The bruter's task is two-fold: first, to fix the center of the diamond on the dop and, subsequently, to fix the diameter of the cut stone. As with previous steps in the manufacturing process, the bruter must answer one or more of the following questions to maximize the value of the final cut stone: (1) What should be the shape of the final stone? (2) What should be the faceting proportions? (3) What should be the position of the table facet within the piece of rough being worked? Depending on the shape and the proportions chosen, a wide range of price-per-carat values can be achieved from the same piece of rough.

For round diamonds, the size of the cut stone is determined during this critical stage. Yield is affected by two factors: the diameter to which the diamond is cut, and the center of symmetry around which the diamond is bruted. A minor mistake made in either of these factors because of excessive bruting can produce a significant loss in yield.

Traditional bruting uses a machine with a small motor that rotates at about 3,000 rpm. The diamond to be bruted is cemented onto a dop that is then inserted into a spindle (which will be rotated at high speed). Another diamond is cemented onto a second dop, which in turn is attached to the end of a long rod; this is used as the bruting diamond. The bruter holds this rod by hand and presses the bruting diamond against the spinning diamond so that abrasion takes place (figure 15). During the process, the bruter stops frequently to check the results. If it appears that the stone is not being bruted around the required axis of symmetry, the bruter taps on the spindle to change the axis of the bruted diamond slightly and thus align it properly.

In practice, the traditional mechanical bruting technique was an inexact science. It was based largely on trial and error: bruting, stopping, checking the position of the diamond, changing the center if necessary, and rebruting to achieve the desired

Figure 15. With a manual bruting machine, the diamond is glued to a dop that is set in the machine. In his hand, the bruter holds a stick with another dop to which a diamond has been glued. As the diamond in the machine is rotated, the other diamond is bruting it.

Figure 16. In this photo of an automated bruting machine built by Milano Industries in Israel, two diamonds are mounted for bruting to create a girdle surface on each by mutual abrasion. By viewing the screen, the operator can correctly position each stone and then monitor the progress of the bruting process. Photo courtesy of Milano Industries.

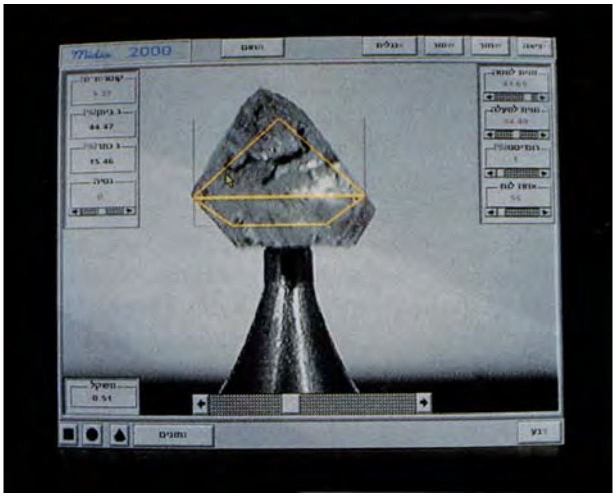


Figure 17. A manual centering system has two video cameras, so that the operator can view the piece of rough from the side and the top. By rotating the image of the rough diamond, the operator can center it on the dop before the glue holding the diamond is hardened. First, an outline of the future cut stone is superimposed on the outline of the crystal. Then, the diamond is centered so that the maximum diameter and maximum yield are achieved. The operator makes sure that the image of the cut stone will fit within the outline of the rough diamond. Photo by James E. Shigley.

shape. To this end, the bruter must also look for signs and marks on the bruted area (such as symmetrical naturals on opposite sides).

Toward the end of the 1980s, a new, fully automated approach to bruting was invented. A number of bruting machines are now in use (see Cooke, 1991a), but they are generally based on the same principle. With these new machines, the two stones are bruted simultaneously (figure 16). Each stone rotates around its own axis of symmetry and, in so doing, each brutes the other.

These new bruting machines operate with little or no supervision. The bruter need only install the diamonds in the machines, center the stones, and stop the bruting when one of the stones reaches its required diameter (in the newest equipment, this last function is performed by the machine). This stone is then replaced by another stone and the process is repeated. One person can operate up to 10 machines simultaneously.

Centering Systems. The introduction of automatic bruting machines has stimulated the use of other modern systems to help the manufacturer increase a diamond's yield. Before the stone is placed in a bruting machine, some manufacturers use a centering system to align the center of the future polished diamond (in the rough) with the center of the bruting machine. These centering systems were developed in two generations: manual and automatic.

A manual centering system has two video cameras for viewing the rough diamond from the side and from the top. A person referred to as the *centerer* glues the sawn or cleaved diamond onto a special dop. On the output screen, the centerer sees both the shape of the rough diamond and a superimposed graticule (image) of the future cut stone that can be adjusted to fit the size of the rough crystal (figure 17). The operator positions the image of the cut stone until it reaches its maximum size, just fitting within the piece of rough. Then, the dop is heated in an oven to harden the glue. After this, the dopped diamond is installed in the bruting machine, for which the axis of rotation has previously been properly centered. At that point, all three axes (i.e., the centering axes of the machine, the dop, and the future cut stone) are aligned.

Use of this manual system offers several advantages over centering while bruting in the machine (see Caspi, 1991):

1. The stone is centered according to the structure of the rough diamond.
2. The proportions of the cut stone can be made to match the manufacturer's requirements more closely than if the stone is not centered before bruting.
3. Most diamonds that have been centered can be bruted without requiring any adjustments to their position on the dop.
4. Both productivity and yield are increased, as a skilled operator can center many more stones in the same amount of time, and the operator of the machine does not waste the time required to center in the machine.

The latest development, the automatic centering system, does all the above procedures automatically (see figures 18 and 19). The system has one or two video cameras and special computer software, which enable it to do all of the following functions without the involvement of the operator:

1. Photograph the rough diamond from many angles and integrate this information into a three-dimensional image of the rough.

Figure 18. The Sarin automatic centering system (Dia-Center) consists of a sample chamber, light source, camera, computer, and monitor. On the right of the sample chamber (shown above) is the light source, and on the left is the camera. In front of the holder is the mechanical apparatus that moves the holder and centers the diamond. The camera measures the dimensions of the rough diamond, which is glued to a special dop, from a number of orientations. After the computer decides where the optimal center of the future cut stone will be, it moves the upper part of the dop so that the center of the diamond and the center of the bruting machine are co-axial. Photo by James E. Shigley.

2. Identify the largest diamond with the required proportions that can be cut from the particular piece of rough.
3. Move the holder to which the stone is glued so that the center of the optimal cut stone is co-axial with the centers of both the dop and the bruting machine. This process takes about 30 seconds per diamond.

The automatic system provides the best center position and requires no expertise on the part of the operator. Once the diamond is centered, the operator simply sets the holder in the bruting machine, watches the diamonds in the machine, and then stops the bruting procedure when a diamond reaches the diameter specified by the computer.

Laser Bruting. In 1992, a new, laser method of bruting emerged. The main advantage of this method, which is used primarily for fancy cuts, is that the shape is symmetrical and exactly as planned by the bruter or marker. In Israel, most fancy-shaped diamonds with rounded outlines—such as marquises, ovals, and pear shapes—are bruted by this method.

Polishing. This is the final stage in diamond cutting. The *polisher* uses a special tool called a tang (figure 20) to hold the diamond and polish it on a scaife, a special metal polishing wheel powered by an electric motor at speeds of up to 4000 rpm (for further details, see Bruton, 1981; Vleeschdrager, 1986; Watermeyer, 1991; Curtis, 1991; Schumacher, 1991; *GIA Diamond Dictionary*, 1993).

The Polishing Process. Round brilliant-cut stones are typically polished in the following sequence:

1. The table facet
2. The eight main facets on the pavilion
3. The eight main facets on the crown
4. The eight star facets on the upper crown
5. The 16 upper-girdle (top-half) facets on the crown
6. The 16 lower-girdle (bottom-half) facets on the pavilion

To achieve a good cut (which affects the final carat weight, as well as the color and clarity grades), the following features must be kept in mind (see Schumacher, 1991):

1. The symmetrical arrangement of the facets, facet junctions, and corners (i.e., the quality of the corresponding parts of a stone)
2. The quality of the facet surfaces, that is, their surface texture
3. The overall proportions, such as table size, crown angle, pavilion depth percentage, etc.
4. The girdle size

Figure 19. The automatic centering system also constructs a three-dimensional image of the rough diamond on which it superimposes an image of the future cut stone that gives the best possible fit. Photo by James E. Shigley.

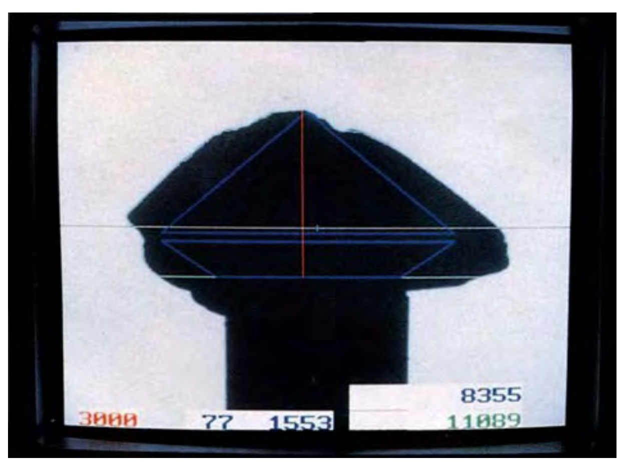


Figure 20. Polishers use a wide variety of tangs (shown here in the foreground and hanging on the central bars), depending on the facets being polished, the shape of the stone, and the like.

An important consideration when planning this process is the polishing direction. As with cleaving and sawing, polishing can only be performed in a certain direction for each facet. This direction is defined as the angle between the linear velocity direction of the polishing wheel and the grain (crystal) orientation of the particular facet. In most other directions, polishing will not occur (Watermeyer, 1991).

An experienced *polisher* identifies the polishing direction for each facet by recognizing certain features on the rough, such as trigons. In some diamonds, however, this direction cannot be determined from surface features, and the polisher has to

Figure 21. The Dialit GS7000 automated polishing machine (left) can polish the crown (excluding the stars) and pavilion facets on a stone. The control panel is on the left. The holder is set in the machine, with a few additional holders in the wooden cassette. The Dialit GSB800 automated blocking machine (right) can block eight facets on the crown or the pavilion. Photos courtesy of Dialit Ltd.

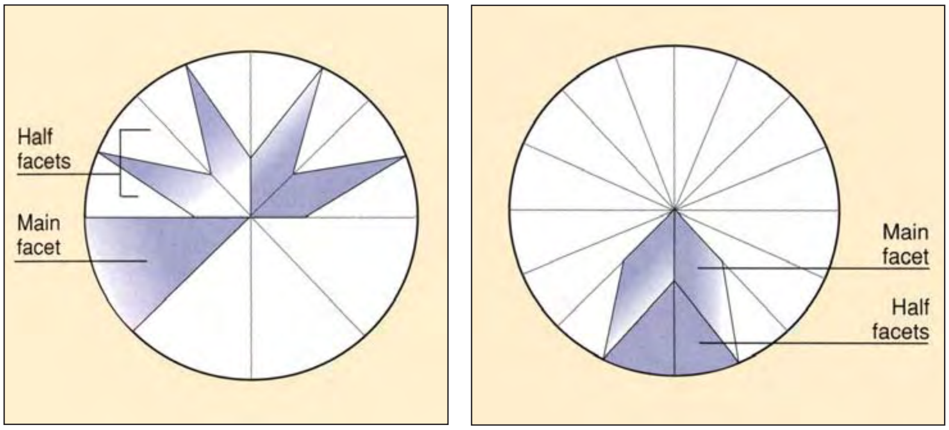


Figure 22. When polishing a diamond by manual methods (left), one first polishes the eight main pavilion facets, and then proceeds to the 16 lower-girdle (half) facets on the pavilion. With automated facet polishing (right), the reverse sequence is followed: the 16 lower-girdle (half) facets of the pavilion are polished first, followed by the eight main pavilion facets.

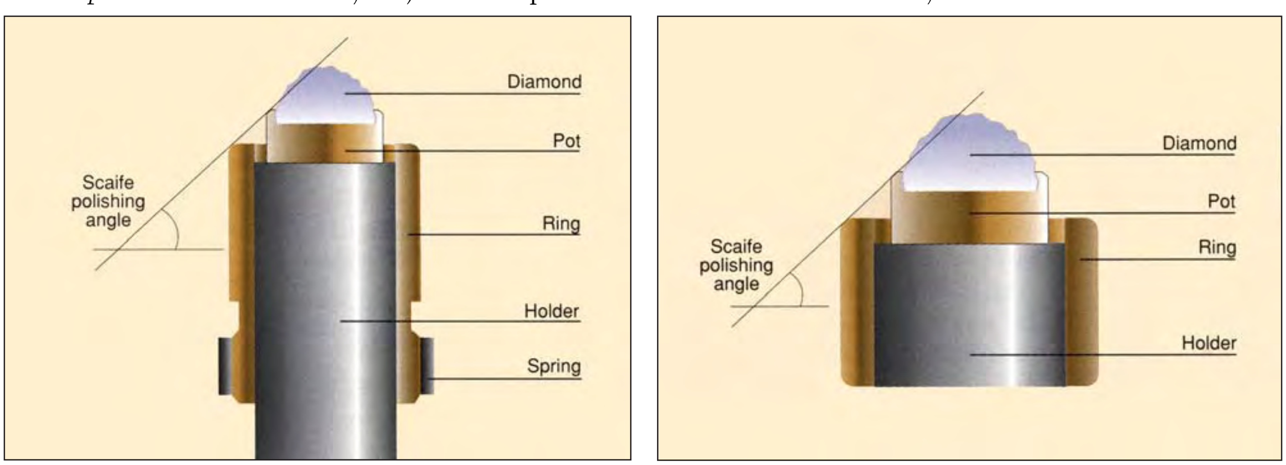
look for the direction of the grain (for details, see Ludel, 1985, Chapter 7, and Watermeyer, 1991). This requires simple trial-and-error (first attempting to polish the facet and then examining the stone to see if polishing has occurred).

For polishing, the diamond is held by a tang. Used for many years, tangs are still seen today even in the most advanced cutting factories. A wide variety of tangs are used, depending on the facet(s) being polished, the shape of the stone, and the like (again, see figure 20). Modern tangs look basically like the older versions, except for minor changes that help the polisher set the angle of the facets and divide the diamond into exactly eight or 16 sections.

Automatic Polishing Machines. Automatic polishing machines are essentially robots that manufacture round cut diamonds (figure 21). These machines initially appeared in the early 1970s. The first was the Piermatic, which was designed to handle regular four-point sawn goods (Bruton, 1981; Vleeschdrager, 1986; Cooke, 1991b). The basic difference between conventional hand polishing and automatic polishing is the order in which polishing takes place (figure 22). The automatic machine, by a single setting of a holder, can polish two different angles (i.e., eight main pavilion facets and 16 lower-girdle facets). The diamond is set in a special holder, which enables the system to sense when one facet is fully polished and then automatically change to the next facet. Using this equipment, a trained operator can polish 16 diamonds simultaneously.

The holder has two means to halt the further polishing of a facet (see figure 23). When either the

Figure 23. This diagram illustrates how a diamond is set in a holder (left, full holder; right, upper part) for automatic polishing. The angle for polishing the 16 lower-girdle facets is indicated. When the ring comes into physical contact with the scaife, and electrical contact is made, the computer automatically halts the polishing of that particular facet and moves on to the next. When the 16 half-facets are completed, the angle is lowered by approximately 1° and the eight main pavilion facets are polished. For this procedure, an electrical contact is made (and the computer moves to the next facet) when the pot *comes into contact with the scaife.*



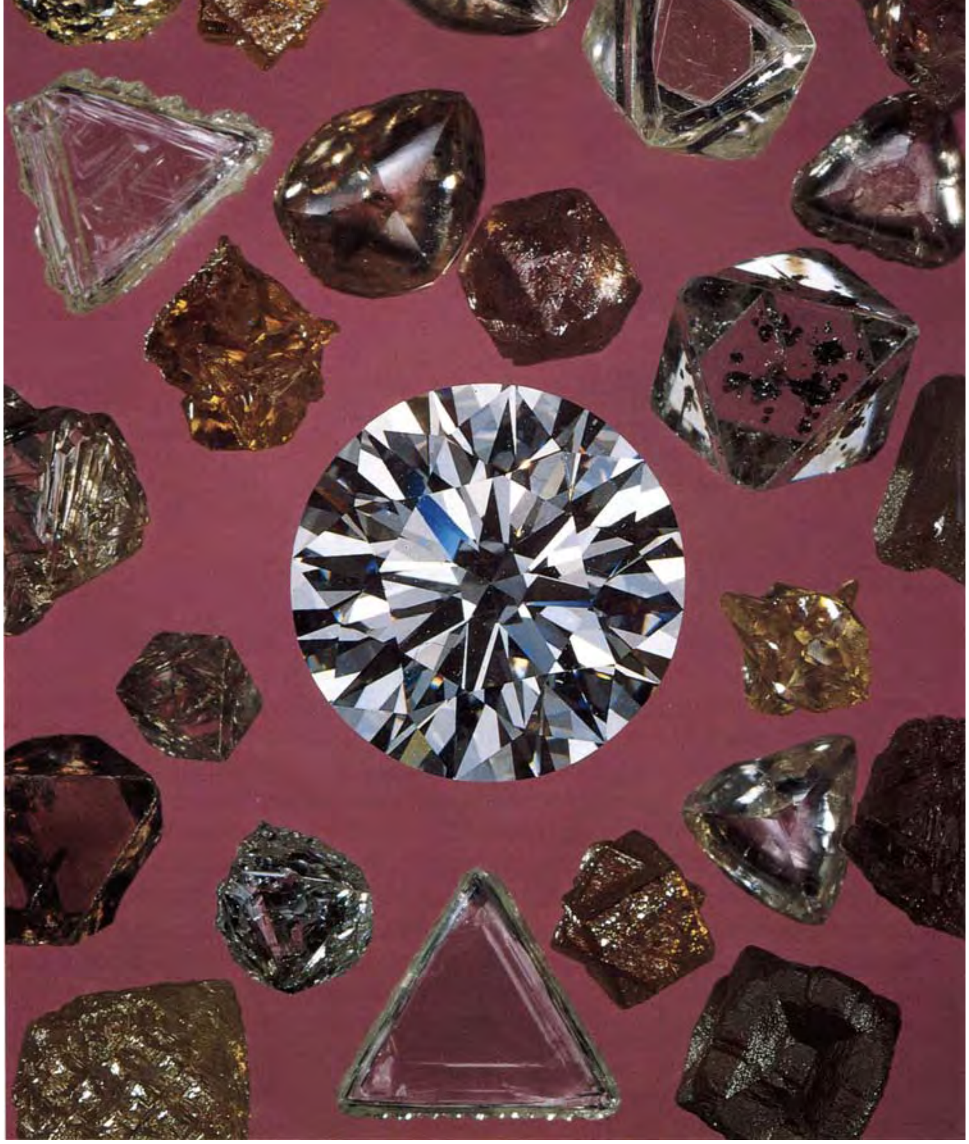


Figure 24. With the new technology and equipment available throughout the diamond-cutting process, modern diamond manufacturers can produce better-quality stones and higher yield from many different types of rough diamonds. Photo © Harold & Erica Van Pelt.

ring or the pot of the holder touches the scaife, an electrical contact is made, which tells the computer to halt the polishing process of a particular facet immediately and move on to the next facet.

To set the polishing angle, the *setter* places the diamond in a setting system. The operator finds the angle that matches the required proportions of the finished stone, and makes sure that it is contained within the rough. Then the ring is adjusted axially to coincide with the selected angle. The holder is set into the machine, and the machine polishes the diamond.

Two methods are used to handle the grain. In regular (four-point) sawn goods, the polishing direction of the 16 lower-girdle facets repeats itself every group of four facets. The machine, after polishing a facet, changes to the next polishing angle (the angles between the velocity vector of the scaife and the grain for the 16 lower-girdle facets are 90°, 150°, 210°, and 270°). The polishing direction of the eight main facets repeats itself every two facets (for these facets, the angles are 120° and 240°).

For diamonds other than four-point sawn goods, a new grain-seeking capability has been introduced into the automatic polishing machines (Cooke, 1991b; Caspi, 1991). The diamond is lowered to make gentle contact with the scaife, and the polishing rate is measured. A special sensor detects if polishing has taken place. If the facet is not oriented in the correct direction, the sensor indicates that the facet did not take the polish, at which point the machine will automatically change the facet orientation and re-measure until it finds the optimum polishing position. This grain-seeking capability enables the modern polishing machines to polish:

1. Makeables
2. *Naated* stones
3. Two- or three-point stones
4. Four-point stones that have been sawn off-grain

CONCLUSION

The revolution in diamond cutting started less than two decades ago, but already it has completely changed the diamond industry in several major cutting centers. With such advances as the decision support system for marking, laser kerfing, mechanical or laser sawing, automatic bruting machines, and automatic polishing machines, diamond manufacturers can obtain better-quality diamonds, with a higher yield per stone, in a more productive operation (figure 24). The main disadvantage of these modern systems is their cost: The capital investment required to start up a modern factory is usually 10 times more than that needed to set up a traditional factory. In most cases, however, the cost of producing an individual diamond with this technology has gone down, because one operator can operate several machines simultaneously and the cost of production is amortized over several diamonds.

Like other revolutions, this one has created some new jobs, but there are also situations where workers who could not adjust to the new technology have had to abandon the industry. It is interesting to note that the new cutting factories have better working conditions, because the machines perform better when operated in a cleaner, air-conditioned environment.

Today, diamond technology is most highly developed in Israel and Belgium, but there are very modern operations in South Africa and Russia. Such technology is rapidly spreading in other centers, such as India and China, as well.

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