THE GEMOLOGICAL PROPERTIES OF THE SUMITOMO GEM-QUALITY SYNTHETIC YELLOW DIAMONDS

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The distinctive gemological properties of the gem-quality synthetic yellow diamonds grown by Sumitomo Electric Industries are described. These synthetic diamonds, produced on a commercial basis, are grown as deep yellow single crystals in sizes up to 2 ct. The material is currently marketed for industrial applications only, in pieces up to about 0.40 ct. The synthetic diamonds can be distinguished by their ultraviolet fluorescence (inert to long-wave; greenish yellow or yellow to short-wave); their unusual graining, veining, and color zonation under magnification; and the absence of distinct absorption bands in their spectra.

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The first synthetic diamond crystals of a quality and size suitable for gem use were produced by the General Electric Company in 1970. These crystals were reported to range up to slightly more than 1 ct and to be colorless, yellow, or blue. Although the crystals were of very good gem quality, technical difficulties and high costs prevented the production of these synthetic diamonds from proceeding beyond an experimental stage. It has been widely believed in the jewelry trade since then that such problems would render the commercial production of gem-quality synthetic diamonds economically impractical for some time. Even so, the success of the G.E. scientists in growing gem diamonds in the laboratory prompted some initial concerns within the jewelry industry.

The situation has now changed. In April 1985, Sumitomo Electric Industries of Itami, Japan, announced that they had accomplished the large-scale production of synthetic diamond in the form of gem-quality single crystals (figures 1 and 2). In that report, the synthetic diamonds are described as yellow crystals in sizes up to 1.2 ct (about 6 mm in maximum dimension). More recent information supplied by Sumitomo representatives indicates that they are now producing crystals up to 2 ct (about 8 mm in maximum dimension). Technical product information published by Sumitomo characterizes these synthetic diamonds as being particularly well suited for industrial uses because of their high thermal conductivity, high fracture strength, and relative absence of inclusions. The principal market for these synthetic crystals is for use in precision cutting tools and for heat sinks in electronic equipment. The reported commercial production of synthetic diamonds by Sumitomo indicates that they are able to grow the crystals at a rate sufficient to sustain the needs of an industrial market. This means that we are no longer dealing with an experimental laboratory product but rather with a gem-quality synthetic diamond that is being manufactured on a large-scale and routine basis. Thus, the

Figure 1. Three synthetic yellow diamond crystals manufactured by Sumitomo Electric Industries along with four of the synthetic yellow diamonds that we had faceted. The crystals (left to right) weigh 1.05, 0.63, and 1.07 ct, and measure 5.5, 4.7, and 5.3 mm in maximum dimension. The crystals can be described as distorted octahedral shapes that are modified by large cube crystal faces on the top and bottom and by smaller dodecahedral crystal faces around the edges. The four faceted stones were cut from the rectangular pieces of synthetic diamond (the form in which it is currently sold for use as heat sinks) in such a fashion as to retain maximum weight. The faceted stones weigh between 0.16 and 0.24 ct, and measure between 3.48 to 3.84 mm in maximum dimension. Photo © Tino Hammid.

time is at hand when we may see synthetic gem diamonds coming to light in the jewelry trade.

Representatives of Sumitomo state that their company has no current interest in expanding the sale of gem-quality synthetic diamonds for use in jewelry. At present their entire production of single-crystal synthetic diamonds can be absorbed by their industrial market. However, because of the future implications of this new diamond synthesis technology, and because of the possible directions that developments in this area may take in the next few years, the GIA Research Department has carried out a careful examination of this material to document its gemological properties and means of identification. This article reports the results of our testing by both standard gemological methods and more sophisticated laboratory techniques. As part of the study, we arranged with diamond cutters in New York and Los Angeles to have several pieces of the Sumitomo synthetic diamond faceted. Some general information is presented on the cutting and polishing behavior of the material. The results of our study indicate that the Sumitomo synthetic diamonds exhibit some distinctive features that easily enable them to be separated from natural diamonds by conventional gemological techniques.

BACKGROUND

Some three decades have gone by since the successful synthesis of diamonds was first publicized. The recognized creation of diamonds in the laboratory was achieved in 1955 by scientists at the General Electric Company (Bundy et al., 1955). Since then the synthesis of industrial diamonds has been carried out on a very large scale using several

Figure 2. This close-up view of a Sumitomo synthetic diamond crystal illustrates the appearance of the crystal, the arrangement of the crystal faces, and the nature of the outer surface of the crystal. The crystal weighs 1.07 ct. Photo by John Koivula.

different crystal growth techniques. Synthetic industrial diamonds are currently produced in a number of countries, including South Africa, the Soviet Union, and Ireland, for a wide range of applications. Nassau (1980) and Davies (1984) both review the history of diamond synthesis.

As mentioned above, synthetic diamonds in cuttable-size, gem-quality crystals were first produced by G.E. in small numbers in the early 1970s. The gemological properties of these synthetic gem diamonds have been documented by Crowningshield (1971) and by Koivula and Fryer (1984). The unusual magnetic properties of G.E. synthetic diamonds, first noted by B. W. Anderson (Webster, 1970) and later discussed by Koivula and Fryer, were further investigated by Rossman and Kirschvink (1984). On the basis of the work of these various researchers, the G.E. synthetic diamonds were found to exhibit distinctive gemological properties such as fluorescence, phosphorescence, lack of strain and graining, and the presence of metallic inclusions that would allow them to be recognized using conventional gemological testing methods. The very limited experimental production of these gem-quality diamonds by G.E., however, meant that there was little if any chance that one of these synthetic diamonds would appear in the jewelry market.

SYNTHETIC DIAMOND PRODUCTION BY SUMITOMO

With the recent announcement by Sumitomo, the possibility that gem-quality synthetic diamonds will be seen in the jewelry trade now takes on new importance. According to the information provided by Sumitomo representatives, they have succeeded in mass producing single-crystal synthetic diamonds of consistently high quality for various industrial applications. The crystals are grown at high temperatures and pressures by a flux method using a metal alloy solvent. Small diamond seed crystals are used to start the growth process. The synthetic diamond crystals are transparent, largely free of inclusions and defects, and range up to 2 ct. These synthetic diamonds not only compare very favorably in mechanical properties (such as fracture strength) and thermal conductivity with the best grade of natural industrial diamonds, but they also have the additional important characteristic of possessing very consistent physical properties from one crystal to the next. This is particularly significant for industrial uses. Such uniformity is rarely found in any given selection of natural diamonds. The synthetic diamonds produced thus far contain a controlled amount of nitrogen (reported to be 30 to 60 parts per million), and are thus yellow in color. Although the company representatives state that they are able to vary the color in the crystals from near-colorless to deep yellow, the only material currently being sold is deep yellow. A brief description of the Sumitomo synthetic diamonds and one use of them to develop high pressures is reported by Onodera et al. (1986).

Representatives of Sumitomo state that they are marketing the product for industrial applications in the form of sawn, laser-cut, partly polished, rectangular pieces in various sizes from 0.10 to 0.40 ct (approximately 3 × 1.5 × 1.5 mm to 4 × 4 × 2 mm). This size range is dictated by the industrial application, the production costs, and the yield obtainable from cutting one of the single crystals. It is in this rectangular form that the synthetic diamonds are sold for electrical heat sinks (their primary market) and for industrial and surgical cutting tools. The current price range is \$60 to \$145 per rectangular piece for sizes from 0.10 to 0.40 ct. Sumitomo does not sell, and does not at present have plans to sell, the uncut synthetic diamond crystals to anyone. Sumitomo representatives have also stated that the company is currently experimenting with the production of synthetic blue diamonds for use as semiconductors as well as synthetic colorless diamonds for industrial applications. Both the blue and the colorless synthetic diamonds have already been grown in the laboratory as single crystals, but they are not yet being produced on a commercial scale.

DESCRIPTION OF THE SUMITOMO SYNTHETIC YELLOW DIAMOND

To document the gemological properties of this new kind of synthetic diamond, we examined 20 of the rectangular pieces of the material as currently marketed by the Sumitomo company. The 20 pieces were produced from at least five different batches (as determined from batch numbers supplied with the pieces) grown over an unknown period of time, with 10 of the pieces coming from a single batch. Each piece has two large, polished, parallel surfaces with various smaller crystal faces around the edges (figure 3). The pieces range in size from 0.11 ct (approximately 3.0 × 1.6 × 1.4 mm) to 0.37 ct (3.7 × 3.6 × 1.7 mm), with the majority representing the larger sizes. All are of similar appearance and of high quality—transparent, free of any cleavages or other prominent inclusions—and an attractive deep yellow color. Even when taken from different growth batches, the synthetic diamonds as a group exhibit a virtually identical appearance and very uniform physical properties. Such consistency illustrates the degree of control of the diamond growth process that has been attained by Sumitomo.

In conjunction with the preparation of this article, the authors met with several Sumitomo representatives. They showed us various examples of their synthetic diamond production, including a very deep yellow round brilliant identified as weighing approximately 0.8 ct. They reported that this well-cut round brilliant was fashioned from a 1.7-ct rough crystal. A brief examination of the cut stone with the microscope revealed a cloud under the table, a step-like fracture under the girdle, and a rod-shaped grayish metallic piece of flux material near the culet. This cut stone is presently on exhibit at the Sumitomo company headquarters.

By special arrangement, we were also able to examine in greater detail three of the uncut single crystals of synthetic diamond. Sumitomo representatives state that the morphology of their synthetic diamond crystals can be varied to yield from cube to octahedral crystal shapes. A typical crystal is a distorted octahedron modified by cube and dodecahedral faces. Crystals with perfect octahedral shapes are reported to be difficult to grow.

Figure 3. This is one of the larger pieces of Sumitomo synthetic diamond that is currently marketed for industrial applications. The piece has been cut from a single crystal such as the ones shown in figure 1. It weighs 0.37 ct and measures 3.7 × 3.6 × 1.7 mm. The large front and back surfaces have been sawn and polished. Various cube, octahedral, dodecahedral, or crystal faces that are modifications thereof, occur along the edge. Magnified 12×; photomicrograph by John Koivula.

The crystals we examined are roughly equidimensional and are more regular in shape than most natural diamond crystals. They are covered by various cube, dodecahedral, and octahedral crystal faces (again, see figures 1 and 2). The dominant development of the cube faces relative to the other faces results in the equidimensional shape of these crystals, which apparently represents Sumitomo's standard product. On each crystal, the upper cube face is smooth, but the lower cube face is quite rough and bears the imprint of the small seed crystal. Depending on the type of industrial application, the rectangular pieces of synthetic diamond are cut from the crystals parallel to either the cube or dodecahedral directions.

Figures 2, 3, and 4 illustrate the appearance of the crystal faces on a crystal and on pieces of the Sumitomo synthetic diamond. Some pieces ex-

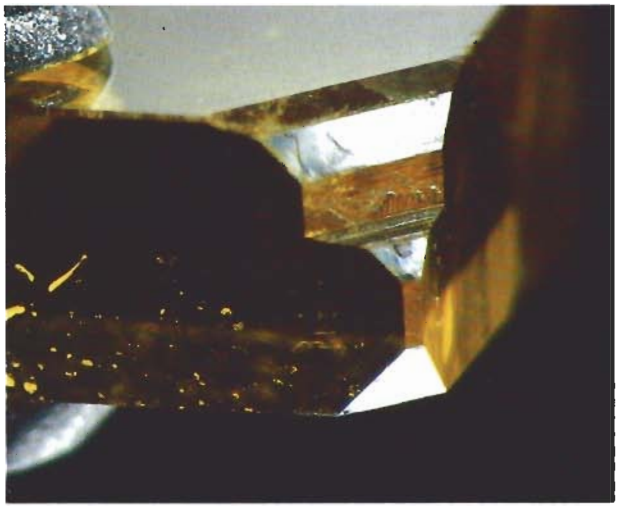


Figure 4. This edge of a piece of Sumitomo synthetic diamond shows the step-like appearance and arrangement of crystal faces. Magnified 25×; photomicrograph by John Koivula.

hibit only a few faces, whereas others show groupings of faces that are more complex. The uneven development of the crystal faces results in variations in their relative surface areas. The faces themselves are flat with no indication of curvature. The smoothness of the faces also varies greatly, from a polished appearance in some instances to very rough and irregular in others. Occasionally the pattern on a crystal face takes on a dendritic appearance, as in figure 5. Sumitomo reports that their synthetic crystals often have surfaces with dendritic growth patterns. However, some of the more irregular crystal surfaces have almost a frosted, melted, or coated look.

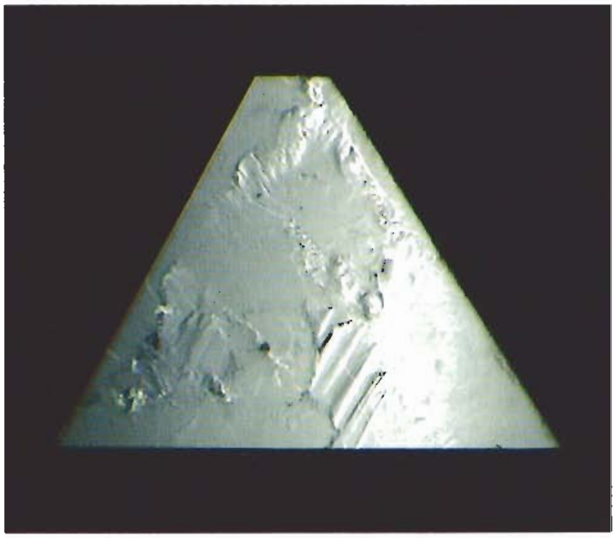
Figure 5. This close-up view of a crystal face on a Sumitomo synthetic diamond displays an irregular surface in the form of a dendritic pattern. The edge of this face has an unusual smooth border. Magnified 40×; photomicrograph by John Koivula.

We carefully examined all 20 pieces of synthetic diamond for the trigons or other growth features that are commonly observed on natural diamond crystals. Each of the synthetic diamonds exhibits various growth features, but in general these differ in appearance from the features on natural crystals. Figure 6 shows the unusual growth-related features that appear on an octahedral face of a Sumitomo synthetic diamond. Between adjacent crystal faces the edges are rather sharp, with no indication of the rounding that is often seen on natural diamond crystals. These differences in the shape and appearance of the synthetic diamond crystals as compared to natural crystals reflect differences in the conditions of growth rate, temperature, time, pressure, and chemical environment, and in depositional history.

DIAMOND TYPES

The discussion of the gemological properties of the Sumitomo synthetic diamond that follows requires a brief summary of what is known about the different types of diamond. It was recognized at an

Figure 6. An octahedral face of a Sumitomo synthetic diamond, seen here in reflected light, shows the unusual growth features on the diamond's surface. No trigons or other growth features seen on natural diamonds are present. Magnified 40×; photomicrograph by John Koivula.



early stage in diamond research that differences in the absorption of light and in other physical properties could be used to classify diamonds into general categories. The classification scheme proposed by Robertson et al. (1934), and since elaborated on by other workers, is generally accepted and is helpful in understanding the gemological properties of diamond. Although the system was initially founded on measurable physical properties, it became clear as research proceeded that the presence of small amounts of nitrogen and boron in diamonds were the major causes of the differences in properties. The classification scheme is based on the concentration levels of nitrogen and boron as well as on the state of aggregation of the nitrogen in a diamond. According to this scheme, all diamonds can be described as containing one or more of the following categories or types:

Type Ia: About 98% of natural gem diamonds are of this type, which is characterized by the presence of nitrogen in fairly substantial amounts (up to about 3000 parts per million, or 0.3%). The nitrogen is distributed in aggregates of a small number of atoms substituting for neighboring carbon atoms. Several kinds of nitrogen aggregates are recognized, leading to the designation of IaA and IaB subcategories. Diamonds in this category usually range from near-colorless to yellow, but they may also be brownish or grayish.

Type Ib: Diamonds of this type are very rare in nature (less than 1%), but all yellow synthetic diamonds are type Ib. They contain lower amounts of nitrogen (up to about 1000 parts per million). The nitrogen is dispersed through the crystal structure in the form of singly substituting atoms. Diamonds in this group are intrinsically yellow and usually have a deep color.

Type IIa: These diamonds are very rare in nature. They are believed to contain nitrogen but at concentration levels below that which can easily be detected with standard infrared techniques. These diamonds are usually near-colorless.

Type IIb: Diamonds in this category are extremely rare in nature, and are believed to contain greater amounts of boron than nitrogen. They exhibit electrical conductivity and are usually blue or gray in color, although on occasion they can be near-colorless.

Excellent reviews of diamond types and the related optical and physical properties can be found in Clark et al. (1979), Walker (1979), Field (1979), and Collins (1982).

Diamond types can be identified by infrared spectroscopy, even if two different types are present in the same stone (as is the case with most natural diamonds). As shown in figure 7, the various diamond types have different and distin-

Figure 7. These infrared spectra were recorded with GIA's NICOLET 60SX FTIR spectrometer for three diamonds: type IaA—a 0.36-ct light gray stone with parallel polished flat surfaces; type IaB—a 1.13-ct milky round brilliant faceted stone; type Ib—one of the rectangular pieces (0.37 ct) of Sumitomo synthetic diamond. As is evident from these spectra, the differing patterns of infrared absorption bands provide a way to distinguish diamond types.

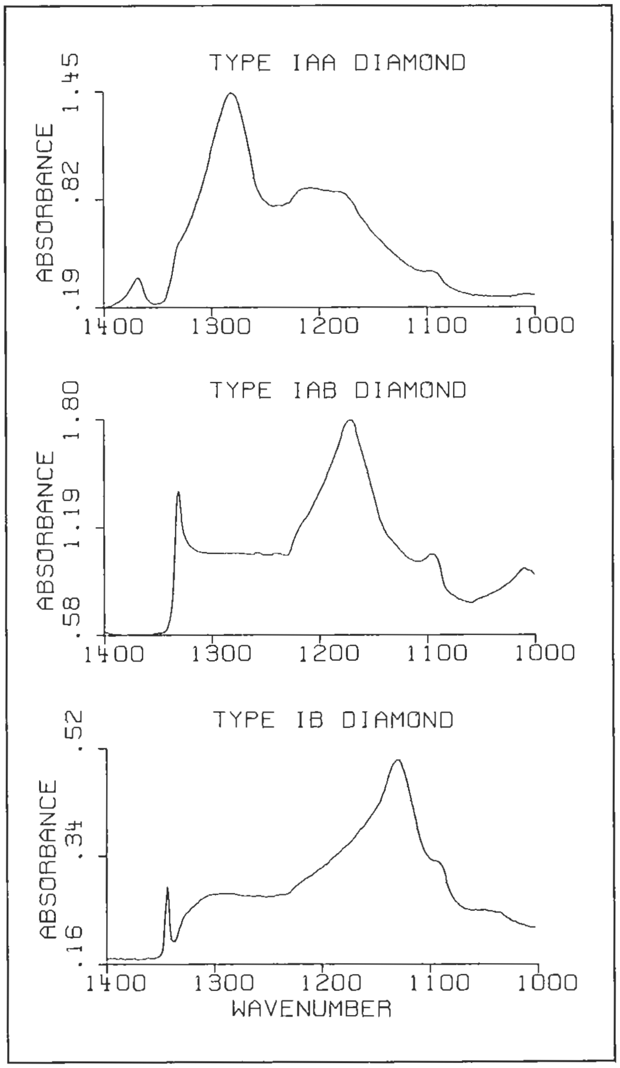


TABLE 1. Comparison of intense yellow natural and synthetic diamonds.

Properties	Natural		General Electric synthetic	Sumitomo synthetic
Type	Ia	Ib	Ib	Ib
Form of nitrogen and concentration level	Aggregated; usually 2000–3000 ppm	Dispersed; usually 100–1000 ppm	Dispersed; usually less than 100 ppm	Dispersed; usually less than 100 ppm
Abundance	Common—about 98% of all gem diamonds	Rare—about 1% of all gem diamonds	All yellow G.E. synthetic diamonds	All yellow Sumitomo synthetic diamonds
Size range of rough	Crystals up to several hundred carats known	Uncertain; crystals up to about 40 ct known	Crystals slightly more than 1 ct or smaller	Crystals about 2 ct or less
Key Identifying Features				
Ultraviolet fluorescence				
Long wave	None to intense; blue, green, yellow, or orange	Usually none, but occasionally orange	None	None
Short wave	Same colors as LWUV fluorescence but variable intensity	Same colors as LWUV fluorescence but variable intensity	None	Moderate to intense; yellow or greenish yellow
Phosphorescence to ultraviolet radiation	None to persistent; various colors	None to persistent; various colors	None	None
Fluorescence to X-rays	None to intense; various colors	None to intense; various colors	None	Weak to moderate intensity; bluish white
Optical absorption spectrum (hand spectroscope)	Usually one or more sharp absorption bands; variable intensity	No sharp bands	No sharp bands	No sharp bands
Additional Characteristics				
Color distribution	Uniform or zoned	Uniform or zoned	Obvious color zoning	Obvious color zoning in rough
Strain (with magnification)	None to obvious; various patterns	None to obvious; various patterns	None to weak strain around inclusions of flux	Cross-shaped pattern in rough
Graining (with magnification)	None to obvious; various types; sometimes colored	None to obvious; various types; sometimes colored	None	Cross-shaped or phantom patterns in rough; hourglass pattern in faceted stones
Inclusions	Crystals, mineral grains, cleavages, knots	Crystals, mineral grains, cleavages, knots	Flux, pinpoints, broom-like features	Vein-like colorless areas, black flux, white pinpoints in rough
Surface appearance of rough	Trigons and other surface growth markings	Trigons and other surface growth markings	Dendritic patterns sometimes present	Irregular or dendritic patterns
Reaction to magnet	No reaction	No reaction	Some attraction due to metallic flux inclusions	Some attraction due to metallic flux inclusions

guishable infrared spectra in the range between 1000 and 1400 wavenumbers (cm^{-1}). The lowermost spectrum in this figure is for one of the Sumitomo synthetic diamonds, which on the basis of its spectrum was determined to be a very pure type Ib. This is important because most natural type Ib diamonds are not a pure type Ib, but also have a small percentage of type Ia character that is easily recognizable in their infrared spectra.

On the basis of our examination using infrared spectroscopy, we can quickly substantiate the pure type Ib character of all the yellow Sumitomo synthetic diamonds. Therefore, the first thing to realize when considering the features that will help to identify these synthetic diamonds is that they represent a type of diamond that is extremely rare in nature. The Sumitomo synthetic diamonds do not correspond with the vast majority of yellow natural diamonds of similar color that are type Ia. The gemological properties discussed in the next section provide a means of identifying diamond types in general and the ways to recognize a Sumitomo synthetic diamond in particular.

RESULTS OF TESTING

During our study we examined three single crystals and 20 rectangular pieces of the Sumitomo synthetic yellow diamond. After examination, we had nine of the rectangular pieces faceted so that we could document the behavior of the material during cutting. In general, all samples of the Sumitomo synthetic diamond exhibit similar, if not identical, gemological properties. The properties discussed below apply to the crystals, the rectangular pieces, and also the faceted synthetic diamonds unless otherwise indicated. Table 1 compares key features of type Ia natural, type Ib natural, the G.E. type Ib synthetic, and the Sumitomo type Ib synthetic yellow diamonds as an aid in the following discussion.

Color. While we are aware that Sumitomo synthetic diamonds can be grown in various shades from near-colorless to deep yellow, all of the stones we examined are deep yellow, and this color is virtually identical from one sample to the next. As expected, the color of the stones became slightly more saturated in appearance after faceting. When compared to the fancy intense yellow master diamond at the Los Angeles Gem Trade Laboratory, the color of the synthetic diamond was much more saturated. When color graded, the faceted synthetic diamonds ranged from yellow to brownish yellow or orangy yellow. The color of some of these Sumitomo synthetic diamonds corresponds to that of the best natural-color yellow diamonds, which the trade frequently refers to as "canary."

Upon further examination, we found that the color of the synthetic diamonds is not distributed evenly within the material. All the pieces of partly polished rough synthetic diamond exhibit a deep yellow inner zone and a narrow near-colorless outer zone, as shown in figure 8. In addition, within the area of deep yellow color there sometimes is a more subtle variation in color intensity. This color zoning was observed to be much less obvious (and sometimes totally absent) in the Sumitomo synthetic diamonds that we had faceted.

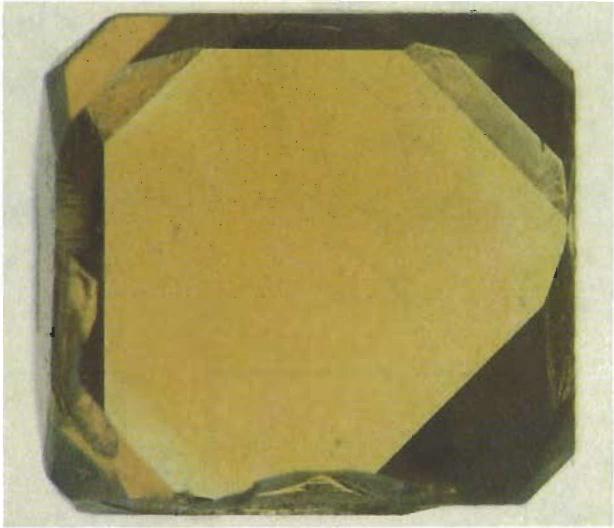


Figure 8. Color in a rectangular piece of the Sumitomo synthetic diamond is distributed such that the deep yellow central portion is rimmed by a narrow (1 mm wide) zone that is either colorless or very pale yellow. The straight line separating these two color zones is sharp and follows the outer shape of the crystal. The colorless zone appears to extend around the entire outer portion of the crystal. This color zoning may be less obvious in a faceted Sumitomo synthetic diamond. Magnified 18×; photomicrograph by John Koivula.

Spectroscopy. Because the Sumitomo synthetic diamonds are type Ib (as are the yellow G.E. synthetic diamonds), their spectra as seen with a hand spectroscope are very different from those seen in most type Ia natural yellow diamonds. The yellow coloration of diamond is due to the concentration of nitrogen and its presence in either a dispersed (type Ib) or an aggregated (type Ia) form. During the growth of most diamonds in the earth, which requires extended periods of time under high temperatures and pressures, some of the nitrogen atoms are able to migrate into clusters within the diamond crystal structure. This leads to the formation of a triangular arrangement of nitrogen atoms that is responsible for the N2, N3, and N4 groups of absorption bands. The N2 and part of the N3 groups are referred to as the "Cape lines" often observed in the ultraviolet and visible spectrum. Because synthetic diamonds are grown in a laboratory over a relatively short time and do not remain at high temperatures and pressures for long periods, there appears to be no opportunity for nitrogen atoms to migrate into groups. The nitrogen atoms thus remain dispersed, and the synthetic diamonds fall within the type Ib category.

Figure 9 illustrates the differences in nitrogen configuration and visible-range absorption spectra for yellow diamonds. The singly substituting nitrogen in a type Ib diamond (like the Sumitomo synthetics) produces a gradually increasing absorption of light toward the violet end of the spectrum. Using a Beck hand spectroscope at both room and cooled temperatures, we observed no sharp absorption bands in the Sumitomo synthetic diamonds, but only a gradual darkening of the

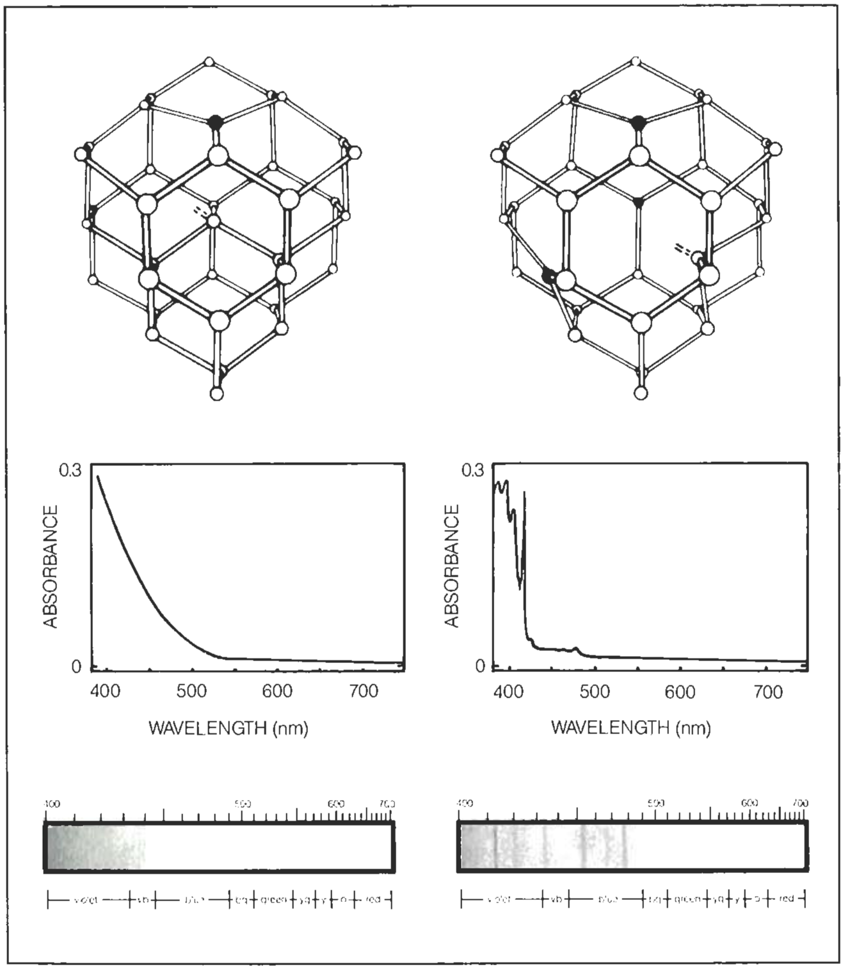


Figure 9. Comparison of yellow type Ib (left) and type Ia (right) diamonds. At top is a drawing of the diamond crystal structure (adapted from Bursill and Glaisher, 1985). Carbon atoms are depicted as open circles, while nitrogen atoms are shown as black circles. In a type Ib diamond, nitrogen substitutes for carbon in the form of single, dispersed atoms. In contrast, in a type Ia diamond, there are clusters of nitrogen atoms like the N3 center, shown at the upper right. In the middle section are absorption spectra for these two diamond types as obtained with an ultraviolet-visible spectrophotometer. Absorption of violet and blue light results in a yellow color. A type Ib diamond (e.g., a Sumitomo synthetic diamond) has an absorption curve that increases smoothly toward the violet end of the spectrum. In contrast, in a type Ia diamond there often are sharp absorption peaks, such as the "Cape" series, that can be seen with the hand spectroscope.

spectrum toward the violet end. These results were confirmed by spectra recorded at 60°Kelvin (−213°C) with a Pye-Unicam dual-beam ultraviolet-visible spectrophotometer. In contrast, in a type Ia diamond, the clusters of nitrogen atoms lead not only to an increasing absorption toward the violet end but also to the presence of superimposed sharp absorption bands. With a hand spectroscope, many near-colorless to yellow type Ia diamonds (the vast majority of natural diamonds) exhibit all or some portion of a series of absorption bands of varying intensity at 415, 423, 435, 452, 465, and 478 nm, which is known as the "Cape" series. Most other diamonds in this same color range exhibit other absorption bands (e.g., 503 nm). Thus, at present the observation of any one or more sharp absorption bands in the spectrum of a yellow diamond would immediately identify it as natural (although not necessarily naturally colored). However, the absence of absorption bands does not prove synthetic origin.

Ultraviolet Fluorescence. When exposed to ultraviolet radiation, natural yellow diamonds can either be inert or they can fluoresce in a range of colors. If they do fluoresce, natural yellow diamonds can appear blue, green, orange, yellow, or (rarely) red, when exposed to ultraviolet radiation, and the intensity of fluorescence is typically greater under a long-wave as opposed to a short-wave lamp. After such exposure, many natural yellow diamonds will also continue to glow or phosphoresce when the lamp is turned off.

The synthetic diamonds we examined respond quite differently when tested for ultraviolet fluorescence. When exposed to long-wave ultraviolet radiation (366.0 nm), the Sumitomo synthetic diamonds are inert; but when exposed to short-wave ultraviolet radiation (253.7 nm), they display a zoned moderate to strong yellow and green fluorescence (figure 10). The core of the crystal has a distinct green fluorescence. The fluorescence emission spectrum corresponding to the green

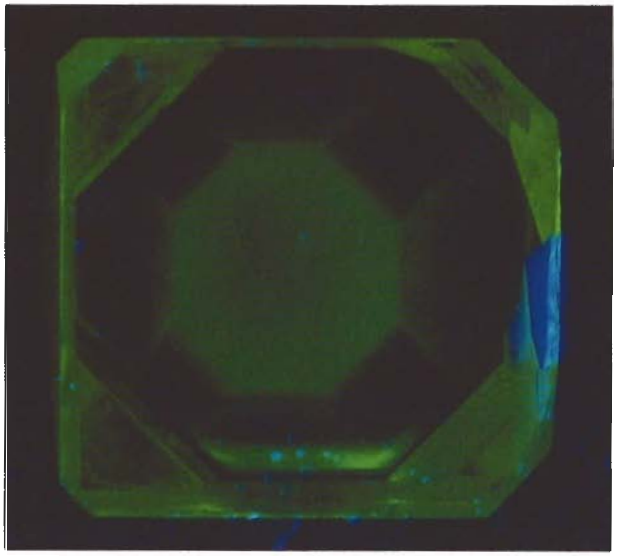


Figure 10. A Sumitomo synthetic diamond fluoresces yellowish green to yellow to short-wave ultraviolet radiation. The greenish fluorescence is often especially pronounced within the central portion of the diamond in the form of a phantom cloud. Four-hour exposure, 160 ASA film, magnified 20×; photomicrograph by John Koivula.

fluorescence seen with short-wave ultraviolet radiation is illustrated in figure 11. The same zoning of luminescence colors can be observed using cathodoluminescence. This kind of fluorescence response, whereby the stone is inert to long-wave ultraviolet radiation but fluoresces greenish yellow to short-wave ultraviolet radiation, has not been reported for natural yellow diamonds and provides an easy way to recognize the Sumitomo material. The small number of natural type Ib diamonds we have observed fluoresce orange to short-wave ultraviolet radiation. Interestingly, some other colors of the G.E. synthetic diamonds examined by Crowningshield (1971) showed a similar fluorescence behavior, but the yellow G.E. synthetic diamond he examined was inert to both long-wave and short-wave ultraviolet radiation. The Sumitomo synthetic diamonds were found to display no phosphorescence.

Fluorescence to X-rays. Many natural diamonds show a bluish white glow when exposed to X-rays. The Sumitomo synthetic diamonds were found to react in the same way when exposed to an X-ray fluorescence unit operating at 66 kV and 35 mA. Under these conditions, the synthetic diamonds all show a bluish white glow of variable intensity but no phosphorescence.

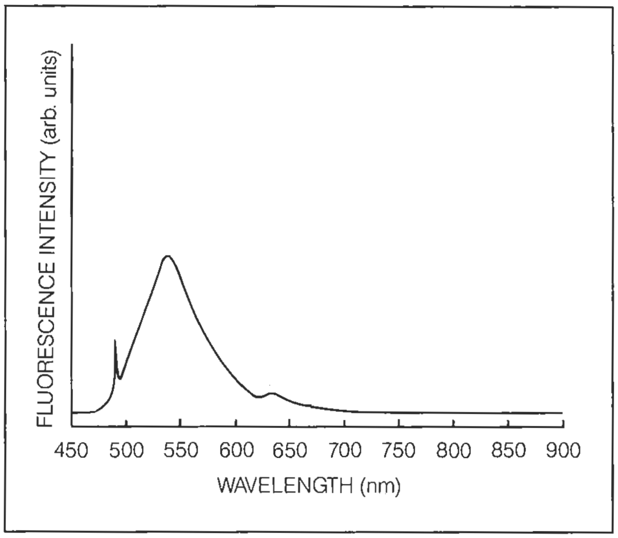


Figure 11. A Sumitomo yellow synthetic diamond produces this fluorescence emission spectrum when excited by a tunable laser. The broad emission peak centered at 540 nm is the green fluorescence of the core of the stone when exposed to short-wave ultraviolet radiation. This broad band and the sharp emission band at 496 nm are thought to be caused by the H4 center. Since the H4 center is related to nitrogen aggregation in the diamond crystal structure, the fluorescence spectrum shown here reveals some unexpected nitrogen aggregation in very minor amounts in the synthetic diamond, at levels apparently not detectable by infrared spectroscopy. Spectrum recorded by Dr. Stephen Rand at Hughes Research Laboratories, Malibu.

Electrical Conductivity. Each of the Sumitomo synthetic diamonds was tested for electrical conductivity with a standard conductometer; as expected, none showed conductive behavior.

Thermal Conductivity. As mentioned above, the Sumitomo synthetic diamonds are reported to have a high thermal conductivity. Using a standard GEM Duotester, which is designed to differentiate a diamond from a diamond simulant on the basis of thermal conductivity, we found that the Sumitomo synthetic diamond responds the same as does a natural diamond. Testing with this type of meter will not indicate that a diamond is synthetic.

Specific Gravity. The specific gravity of the Sumitomo synthetic diamonds was tested using the same heavy-liquid procedure devised by Koivula and Fryer (1984) when they examined the G.E. synthetic diamonds. A large, 16-ct, gemmy octahedral natural diamond, with a specific gravity of 3.51 calculated by careful hydrostatic measurements, was suspended in a specially prepared liquid of Clerici's solution mixed with distilled water. The synthetic diamonds were placed in this liquid one at a time, and each was observed to rise very slowly. The specific gravity of the Sumitomo synthetic diamonds was thus estimated to be 3.505 (±0.005) as compared to about 3.52 for many natural diamonds. The difference is not sufficient to enable one to distinguish a synthetic from a natural diamond based on this property.

Examination with the Microscope. All of the synthetic diamonds were carefully examined to document the nature of any inclusions and other microscopic features. With the microscope, two kinds of solid inclusions were observed in the rectangular pieces of synthetic diamond. Almost all of the synthetic diamonds contain the first kind—whitish, pinpoint-size or smaller inclusions randomly distributed within the material. The other, more prominent type of inclusion consists of opaque, black, metallic pieces of varying size of the metal alloy flux material used to grow the synthetic diamond crystals (figure 12). These flux inclusions, which do not look like any inclusions in natural diamonds, occur most commonly near the outer edges of the rectangular pieces of synthetic diamond. After faceting, neither of these two types of inclusions could be observed in the cut stones. In addition to the inclusions, some of the pieces of synthetic diamond contain small cleavages or fractures near their edges, but these are not common.

A less common but diagnostic inclusion observed with magnification in most of the synthetic diamond pieces consists of unusual, vein-like colorless areas (figure 13). The cause of this feature is not known, but the areas extend from the outer edge of the synthetic diamond inward for a distance of several tenths of a millimeter. Because of this location, however, these colorless veins were not present in the faceted synthetic diamonds. The vein-like areas appear to be randomly distributed among the crystal pieces, but usually only one or two occur in any one piece. When present, the colorless veins are parallel to the dodecahedral crystal faces. Features such as this have not been observed in natural diamonds.

Figure 12. A large, opaque, black inclusion of flux material can be seen near the edge of this piece of Sumitomo synthetic diamond. Magnified 50×; photomicrograph by John Koivula.

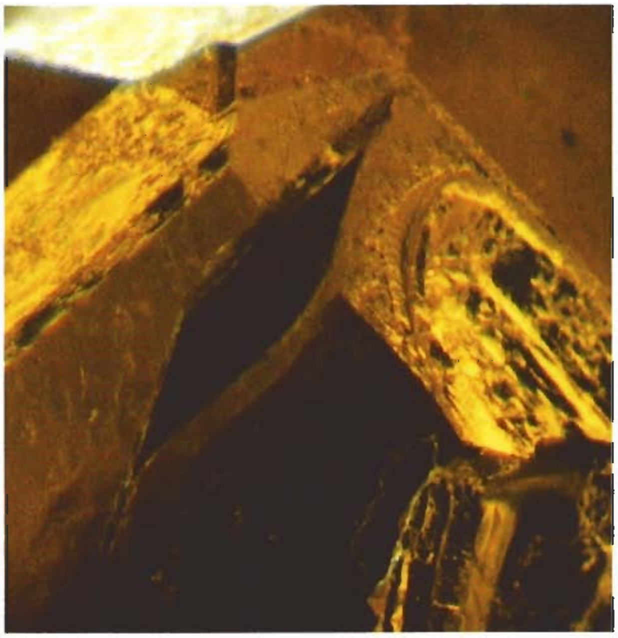
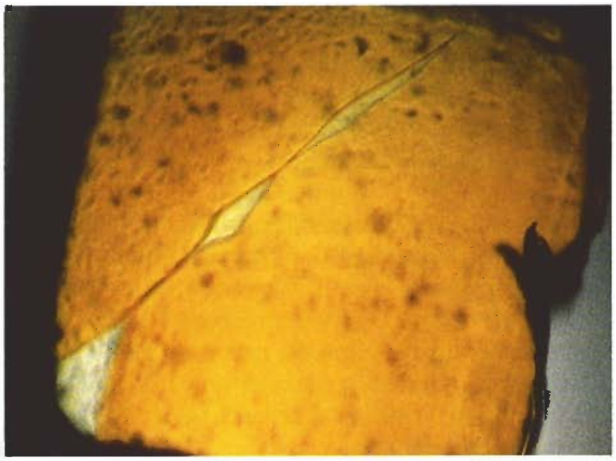


Figure 13. This vein-like colorless zone is a diagnostic feature in the Sumitomo synthetic diamonds we examined. Such a zone is associated with a prominent strain pattern observable in polarized light. Since these vein-like colorless zones are usually near the outer edge of a synthetic diamond crystal, they may be removed during cutting, and thus may not be seen in a faceted Sumitomo synthetic diamond. Magnified 50×; photomicrograph by John Koivula.



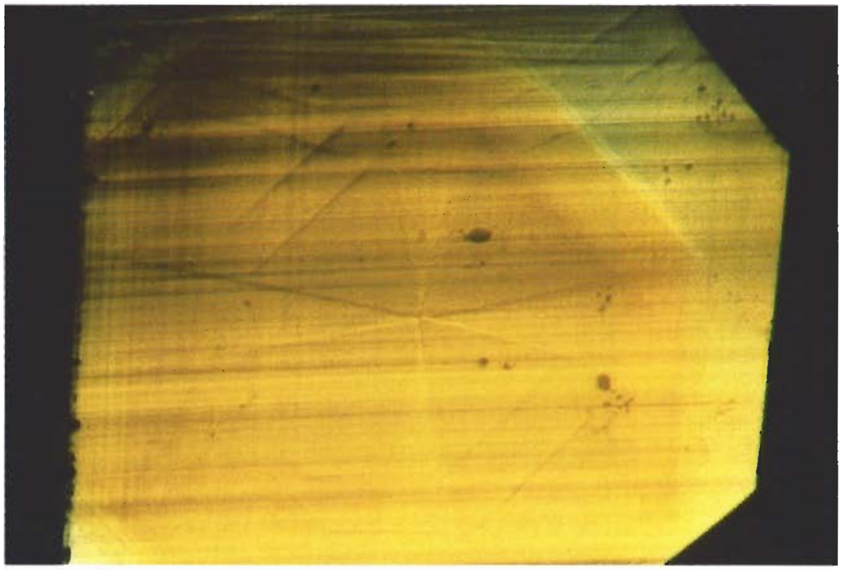


Figure 14. This view of a Sumitomo synthetic diamond illustrates the two prominent types of internal graining seen in this material as well as the distinct color zoning. Comprising one type are the sets of grain lines that parallel the outer shape of the crystal. Comprising the other type are the sets of grain lines that radiate outward from the center to form four wedge-shaped areas. These two types of internal graining were not seen in any of the faceted Sumitomo synthetic diamonds. Magnified 35×; photomicrograph by John Koivula.

In contrast to the scarcity of prominent inclusions, graining is especially evident in the Sumitomo synthetic diamonds. It was observed both internally (figure 14) and even on the surface (figure 15) on almost all pieces of the material. As evident in figure 14, two types of graining are present. The first type occurs as sets of lines seen internally and externally that appear to be parallel to the outer shape of the original diamond crystal. These grain lines provide a phantom "record" of the external shape during crystal growth of the diamond. The second type, seen only internally, occurs as sets of straight lines that radiate outward from the center of the crystal, forming four wedge- or V-shaped areas in the shape of an "iron cross."

Because graining was so prominent in the pieces of Sumitomo synthetic diamond, we were especially interested to see how it would appear in the stones we had faceted. Neither the grain lines that parallel the shape of the crystal nor those that form the wedge-shaped areas could be seen in the faceted stones. Rather, a different pattern of graining, in the form of an "hourglass" shape, was observed through the pavilion of all the faceted stones (figure 16). In addition, as seen in figure 17, some faint phantom grain lines were observed on the surfaces of all the faceted stones, similar in appearance to those seen externally on the pieces of synthetic diamond (figure 15).

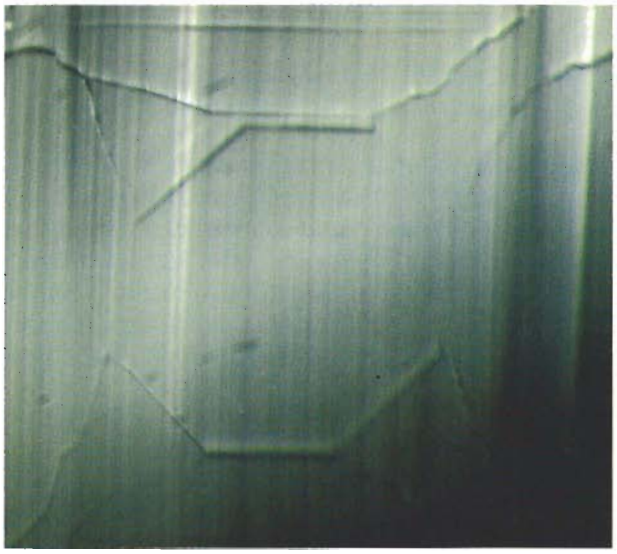


Figure 15. When the synthetic diamond shown in figure 14 is viewed using lighting by surface reflection, graining is evident on its exterior. This graining often persists after cutting on a polished outer surface. Magnified 35×; photomicrograph by John Koivula.

Reaction to Polarized Light. When examined with either a standard polariscope or a microscope equipped with polarizing filters, the Sumitomo synthetic diamonds exhibit a distinctive cross-shaped interference pattern (figure 18). This pattern varies slightly in appearance from one stone to the next, and is most evident when the rectangular pieces of synthetic diamond are viewed along a direction perpendicular to the two parallel polished sides. When the diamond is rotated to a direction perpendicular to the edge of a rectangular piece, the interference pattern cannot usually be seen. The four arms of the cross-shaped pattern either coincide with or are at a 45° angle to the directions of the radiating internal grain lines

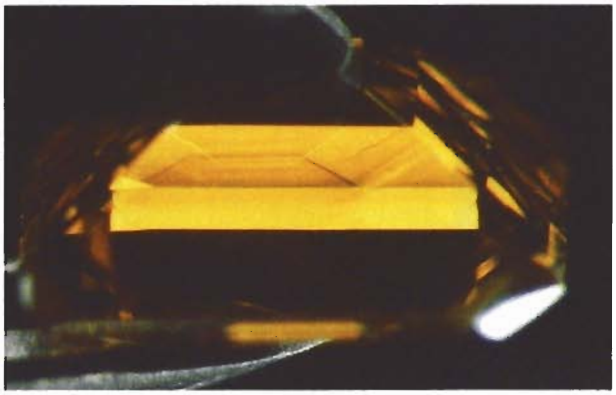


Figure 16. This type of hourglass-shaped internal graining pattern was visible in all eight of the emerald-cut synthetic Sumitomo diamonds. It was always observed in shadowed darkfield through the pavilion. No similar pattern was observed in any of the rough crystal sections. Magnified 35×; photomicrograph by John Koivula.

described earlier. This cross-shaped pattern could not be observed in the faceted synthetic diamonds.

Magnetism. Because, as reported by B. W. Anderson (Webster, 1970) and more recently by Koivula and Fryer (1984), some of the G.E. synthetic diamonds react to a magnet, the Sumitomo synthetic diamonds were tested in a similar manner. Each was attached to a string and then a magnet was positioned nearby. Only one of the Sumitomo synthetic diamonds was attracted to the magnet. An additional test was devised in which the synthetic diamonds were again suspended in the same mixture of water and Clerici's solution used for specific-gravity testing. When a magnet was brought close to the glass container holding this liquid and the suspended diamonds, two of the eight diamonds tested were observed to move through the liquid in the direction of the magnet. We suspect that this magnetic behavior is related to the occasional presence of metallic flux inclusions in the synthetic diamonds. Since the number of flux inclusions varies greatly from one diamond to the next, this could explain the observed difference in magnetic attraction.

Figure 18. Before faceting, the Sumitomo synthetic diamonds typically exhibit a cross-shaped interference pattern when examined with a polariscope or a polarizing microscope. Magnified 18×; photomicrograph by John Koivula.

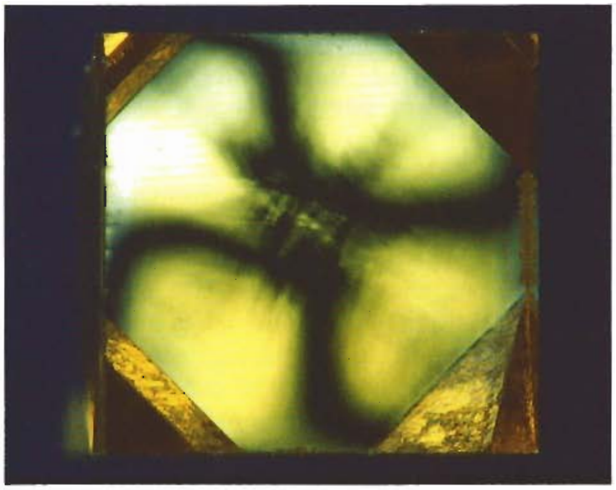


Figure 17. The surface grain lines shown here on one of the faceted stones reflect the external shape of the original Sumitomo synthetic diamond crystal. All of the faceted Sumitomo diamonds showed similar patterns on their tables. Oblique shadowed illumination, magnified 25×; photomicrograph by John Koivula.

FACETING BEHAVIOR

Because the Sumitomo synthetic diamonds are now available on a commercial basis, we were interested in documenting some aspects of how the material might behave during faceting. In particular, we wanted to learn how easily these synthetic diamonds could be polished and what their weight retention from the rough might be. We arranged with several diamond cutters in New York and Los Angeles to have nine of the rectangular pieces of Sumitomo synthetic diamond faceted (figure 19). These pieces varied from 0.34 to 0.39 ct, and from 3.55 × 3.54 × 1.63 mm to 4.00 × 3.76 × 1.62 mm. We arranged for one piece to be faceted as a round brilliant, which yielded a 0.08-ct stone

Figure 19. Four of the synthetic diamonds that we had faceted from the rectangular pieces of the material. The round single cut weighs 0.08 ct and measures 2.80 × 2.80 × 1.69 mm. The step-cut faceted pieces weigh between 0.16 and 0.24 ct and measure between 3.48 and 3.84 mm in maximum dimension. Photo © Tino Hammid.

measuring 2.80 × 2.80 × 1.69 mm. The weight retention after cutting was 22%, and the depth percentage was 60%. The remaining eight pieces were faceted in a square step cut. In these instances, we instructed the cutter to facet the synthetic diamonds so as to retain maximum weight while fashioning as attractive a stone as possible. These faceted synthetic diamonds range in weight from 0.16 to 0.24 ct. The largest of them measures 3.84 × 3.63 × 1.72 mm. The weight retention for these stones after cutting varied from 49% to 64%, and the depth percentage from 43% to 52%. Considering the cost of the pieces of synthetic diamond we used and the approximate cutting cost, the price per carat of this type of Sumitomo synthetic diamond would be equal to or slightly exceed the price of a natural diamond of similar hue and clarity.

If Sumitomo at some future time were to release the rough crystals themselves, the weight retention of a faceted stone would certainly be much higher than we obtained in faceting the rectangular pieces and might, therefore, be cost effective. The approximately 0.8-ct faceted round brilliant that we examined briefly was identified as having been cut from a 1.7-ct rough crystal. Because we had no information on how this round brilliant was cut from the rough, we were interested in estimating the weight of the round brilliants that could be cut from the three crystals that Sumitomo loaned us.

Because of the blocky shape of these crystals with their blunted top and bottom surfaces, we felt it would be impractical to try to saw them and to fashion more than one faceted stone from each. Thus, they could be considered much like a recutting project on an "old-style" faceted stone. In examining the three crystals, the GIA Proportionscope was used to verify sufficient thickness above and below the octahedral girdle plane for fashioning a Tolkowsky cut, which would yield the largest stone. Accordingly, a 62% depth was selected in our calculations to retain the greatest amount of weight. Note that this is in contrast to the standard practice of sawing natural octahedral rough and then cutting to slightly spread proportions to retain the greatest weight. By using the standard GIA weight-estimation formula (diameter^2 × depth × 0.0061), the 0.63-ct crystal would yield a 0.32-ct round brilliant with 51% weight recovery; the 1.07-ct crystal, a 0.45-ct stone with 42% recovery; and the 1.05-ct crystal, a 0.57-ct stone with 54% recovery.

After completing the faceting, the cutters had some interesting comments on the faceting behavior. An attempt was made to cleave and then saw one of the pieces of synthetic diamond. In doing so, the cutter noted no significant differences between this material and natural diamonds. One cutter observed that the facets on the synthetic diamonds had only one polishing direction. All of them reported that the synthetic diamonds polished easily and seemed to be less brittle than most natural diamonds. However, while some natural diamonds will polish more rapidly if downward pressure is applied to the dop, this was not the case for the synthetic diamonds. Rather, when pressure was applied to the dop, the synthetic diamond would rapidly take all of the diamond powder out of the wheel, which would then need to be refinished before further use.

The synthetic diamonds were free of knots or other defects that might have influenced the polishing. One cutter reported that the synthetic diamonds could be polished on just the coarser portion of his wheel, and did not require polishing on the finer portion as is typical for natural diamonds; this behavior is very unusual. While natural diamonds frequently become very hot during polishing, the synthetic diamonds did not get nearly as hot on the wheel, and they could be touched with the hand soon after being taken off of the wheel. We know that this tendency not to heat up is the result of the superior thermal conductivity of the Sumitomo synthetic diamonds, since they are produced for the very purpose of acting as heat sinks in electronic equipment. However, if the dop was pushed too hard, facets on the synthetic diamonds could be burned as they could on a natural stone, and they would then require repolishing. The cutters also noted that the synthetic diamonds turned a bright orange or brownish orange while they were placed on the wheel. Although some natural intense yellow diamonds will turn orange on the wheel, this color is not nearly as intense as the color displayed by the Sumitomo synthetic diamonds. Finally, we asked the cutters whether, if they had not been told that the stones were synthetic diamonds prior to faceting, they would have noticed some difference during faceting. They reported that they would have suspected that something was different about the diamonds.

We arranged to have only a small number of the Sumitomo synthetic diamonds faceted, and are unable to fully account for some of the observations reported above. Too, there were slight differences in the answers of different cutters to our questions. The cutter at the firm of Lazare Kaplan International, the same company that faceted some of the G.E. gem-quality synthetic diamonds in the early 1970s, did comment that the Sumitomo synthetic diamonds faceted like the G.E. stones.

MEANS OF IDENTIFICATION

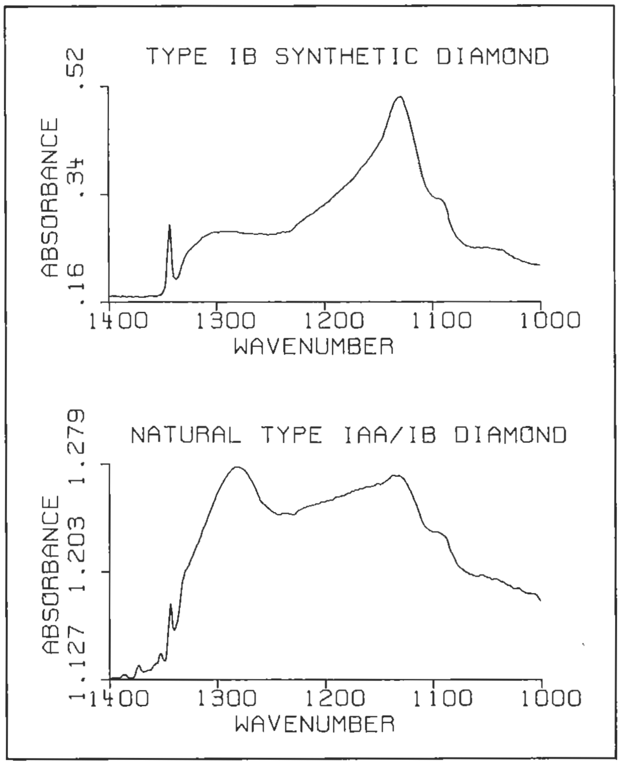
It is important to recognize that when Sumitomo synthetic yellow diamonds meant for industrial uses are faceted as gemstones, they correspond to the type Ib category of natural diamonds which is very rare. We have found that these synthetic diamonds can be distinguished very easily by the jeweler/gemologist using standard gemological techniques. The following diagnostic properties are based on our examination of the Sumitomo synthetic diamonds that we had faceted.

1. **Ultraviolet Fluorescence**
   In examining a small yellow diamond suspected of being synthetic, the most easily observed distinctive feature is the unusual ultraviolet fluorescence. Unlike natural yellow diamonds, these synthetic diamonds are inert to long-wave ultraviolet radiation but fluoresce a greenish yellow or yellow to short-wave ultraviolet radiation.
2. **Spectra**
   In conjunction with the unusual fluorescence behavior, the Sumitomo synthetic diamonds can be readily distinguished from most intense yellow type Ia natural diamonds by the presence of sharp absorption bands in the latter when viewed with a hand spectroscope. The observation of any sharp absorption bands in the violet

and blue portions of the spectrum is enough to confirm natural origin. However, the absence of any bands does not prove the stone is synthetic.

3. **Color**
   Presently the Sumitomo synthetic diamonds are only available commercially in a deep yellow color. At this time, an unknown diamond with a light yellow color is unlikely to be a Sumitomo synthetic diamond, but its spectrum and its reaction to ultraviolet radiation should be tested for the results described above.
4. **Size**
   At present, the precut Sumitomo material available for industrial purposes is quite small, and is likely to yield faceted stones of less than 0.24 ct. This situation may change in the future if the Sumitomo Company releases some of their larger crystals on the market. This possibility seems unlikely at this time according to their statements.

Figure 20. The infrared spectrum of a pure type Ib Sumitomo synthetic diamond is compared here with that of a natural type Ib diamond that has a small amount of type IaA character. The fact that natural type Ib diamonds invariably have some type IaA features in their infrared spectra provides a means of distinguishing them from type Ib synthetic diamonds, which lack these features.



5. **Magnification**
   Further confirmation that a stone in question is a Sumitomo synthetic diamond comes from observations with the microscope. The prominent internal graining, distinct color zoning, metallic flux inclusions, and unusual colorless areas that are present in the rectangular pieces of synthetic diamond may not be seen in faceted stones. Nor is the cross-shaped interference pattern likely to be seen. The two most distinct features seen with the microscope are the "hourglass"-shaped pattern of internal grain lines visible through the pavilion of all of the faceted stones and the surface grain lines on the table facets that phantom the shape of the original parent crystals.

A final verification of the natural or synthetic origin of a yellow diamond is provided by infrared spectroscopy. As shown in figure 20, the infrared spectrum of a natural Ib diamond invariably displays not only Ib-related features but also those due to type Ia nitrogen. The infrared spectra of the Sumitomo type Ib synthetic diamonds lack these Ia features. Therefore, it is our opinion that at the present time the identification of synthetic diamonds from Sumitomo can be made on the basis of standard gemological testing supported, if necessary, by examination with more advanced equipment.

CONCLUSION

The large-scale production of gem-quality synthetic diamonds by Sumitomo Electric Industries forces members of the jewelry industry to reconsider their views regarding the likelihood of such material appearing in the gem marketplace. After some initial concern in the early 1970s, the G.E. synthetic gem-quality diamonds were found to have identifiable gemological characteristics. Moreover, they were only produced in small numbers on an experimental basis at great cost. Since their appearance, the opinion that the commercial production of synthetic gem diamonds at a cost comparable to natural gem diamonds is economically impractical has been widely held and frequently reiterated. The advent of the Sumitomo synthetic gem-quality diamonds may change this situation, and we may see other companies following their lead in this area. However, because diamond-growth conditions in the laboratory are not equivalent to those in nature, the features exhibited by synthetic diamonds will differ from the features of natural diamonds. As new kinds of gem-quality synthetic diamonds are produced, a careful examination of them should continue to identify those characteristics by which they can be recognized. The Sumitomo synthetic diamonds can be readily distinguished by standard gemological tests, but to do so the jewelry industry will need to pay closer attention to documenting the gemological properties described here when working with small yellow diamonds of intense color.

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