# DIAMOND, INDUSTRIAL

### By Ronald F. Balazik

Although best known for its spectacular gem qualities, diamond also has unique properties that make it ideal for many industrial and research applications. In fact, as the hardest substance known (more than twice as hard as its best competitors<sup>1</sup>) diamond has been used for many centuries<sup>2</sup> as a grinding, drilling, cutting, and polishing tool (Spear and Dismuks, 1994). Today, industrialgrade diamond (i.e., diamond that does not meet gem-quality standards for color, clarity, size, or shape) continues to be used principally as an abrasive in many applications despite its initial cost (Boucher, 1997). Even though it is more expensive than competing abrasive materials, diamond has proven to be more cost effective in numerous industrial processes because it cuts faster and lasts longer than any rival. In addition to its utility as an abrasive, diamond has other exceptional properties (including chemical, electrical, optical, and thermal characteristics) that make it the best material available to industry for special lenses, heat sinks in electrical circuits, wire drawing, and many advanced technologies.

Both synthetic (i.e., manufactured) diamond and natural diamond have industrial uses. However, synthetic industrial diamond is superior to its natural diamond counterpart because it can be produced in unlimited quantities and, in many cases, its properties can be tailored for specific applications (Boucher, 1996). Consequently, manufactured diamond accounts for more than 90% of the industrial diamond used in the United States.

#### **Legislation and Government Programs**

The National Defense Stockpile (NDS), operated by the Department of Defense (DOD), contained the following categories of industrial diamond in 1997: industrial stone, crushing bort, and diamond dies. At yearend, the NDS had an inventory of 3.39 million carats of industrial stone (valued at \$89.6 million), 62,300 carats of crushing bort (\$326,000), and 25,500 pieces of diamond dies (\$255,000).

Congress has authorized the DOD to dispose of all NDS diamond dies and portions of the stockpiled stone and bort. Large quantities of NDS diamond stone and bort were sold in 1997; no stockpiled diamond dies were sold. Additional sales are planned by DOD for 1998. Further information concerning NDS diamond is available in the Prices section of this report.

#### Production

The U.S. Geological Survey (USGS) conducts an annual survey of domestic industrial diamond producers and U.S. firms that recover diamond wastes. Although most of these companies responded to the 1997 survey, a few significant firms withheld certain data that they deemed proprietary. Thus, only estimates of U.S. primary and secondary output are provided below.

As one of the world's leading producers of synthetic industrial diamond, the United States accounted for an estimated output of 125 million carats in 1997. Only two U.S. companies produced synthetic industrial diamond during the year—Du Pont Industrial Diamond Division, Gibbstown, NJ; and GE Superabrasives, Worthington, OH. General Electric (Fairfield, CT), which owns GE Abrasives and other diamond manufacturing plants abroad, is one of the world's largest producers of industrial diamond.

Six firms also manufactured polycrystalline diamond (PCD) from synthetic diamond grit and powder in 1997 (W. Born, National Research Company, oral commun., 1998). These companies were as follows: the Dennis Tool Co., Houston, TX; GE Superabrasives; Phoenix Crystal, Ann Arbor, MI; SII Megadiamond Industries Inc., Provo, UT; Tempo Technology Corp., Somerset, NJ; and U.S. Synthetic Corp., Orem, UT.

It is estimated that about 10 million carats of used industrial diamond were recycled in the United States during 1997. Most of this material was recovered by recycling firms from used drill bits, diamond tools, and other diamond-containing wastes. Additional diamond was recovered during the year from residues generated in the manufacture of PCD; most of this material was recovered by the manufacturers from within their production operations (W. Born, National Research Company, oral commun., 1998).

The recovery and sale of industrial diamond was the principal business of four U.S. companies in 1997—Industrial Diamond Laboratory Inc., Bronx, NY; Industrial Diamond Powders Co., Pittsburgh, PA; International Diamond Services Inc., Houston, TX; and National Research Company, Fraser, MI. In addition to these companies, other domestic firms may recover industrial diamond in smaller secondary operations.

A new diamond mine under development near Fort Collins, CO, since 1995 may prove to be the first notable domestic source of natural industrial diamond in the United States. The mine is the first commercial diamond mine in North America in almost a century (U.S. Geological Survey, 1998). Approximately two-thirds of the diamonds recovered at the mine have been graded as gem quality (Holmes, 1997); presumably, the remainder could be used for industrial purposes. However, further production may be delayed—the mine was closed and offered for sale late in 1997 (H. Coopersmith, The Colorado Diamond Company, oral commun. 1998).

#### Consumption

The United States remained the world's largest market for industrial diamond in 1997. Based on economic indicators such as production and trade data, it is estimated that U.S.

<sup>&</sup>lt;sup>1</sup>Cubic boron nitride and silicon nitride are the hardest rivals.

<sup>&</sup>lt;sup>2</sup>Diamond was used as a tool (for engraving) before 300 B.C.

23.2

consumption of industrial diamond rose to 284 million carats during the year. This growth primarily reflects expanded output in many domestic industries where diamond is used. The following U.S. industry sectors were the principal consumers of industrial diamond in 1997: construction, machinery manufacturing, mining services (drilling, etc.), stone cutting/polishing, and transportation systems (infrastructure and vehicles<sup>3</sup>); within these sectors stone cutting and highway building/repair together had the largest demand for industrial diamond (Industrial Diamond Review. The early history, accessed July 1, 1998, at URL http://www.idrmag.co.uk/history/ framed/text.htm). Research and high technology uses included heat sinks in electronic circuits, lenses for laser radiation equipment, and close-tolerance machining of ceramic parts for the aerospace industry.

Diamond tools have a myriad of industrial functions. Diamond drilling bits and reaming shells are used principally for mineral, oil, and gas exploration. Additional applications for diamond bits and reaming shells include foundation testing, masonry drilling, and inspecting concrete in various structures. The primary uses of point diamond tools are for dressing and truing grinding wheels and for cutting, machining, boring, and finishing; beveling glass for automobile windows also is an application. Cutting dimension stone and cutting/grooving concrete in highway reconditioning are the major uses of diamond saws; other applications include the cutting of composites and the forming of refractory shapes for furnace linings. Very fine diamond saws are used to slice brittle metals and crystals into thin wafers for electronic and electric devices. Diamond wire dies are essential for high-speed drawing of fine wire, especially from hard, high-strength metals and alloys. The primary uses of diamond grinding wheels include the sharpening and shaping of carbide machine tool tips, die grinding, plate glass edging, and optical grinding.

Two types of natural diamond are utilized by industry—diamond stone (generally larger than 60 mesh/800 microns) and diamond bort (smaller, fragmented material). Diamond stone is employed primarily in drilling bits and reaming shells used by mining companies and also is incorporated in single- or multiple-point diamond tools, diamond saws, diamond wheels, and diamond wire-drawing dies. Diamond bort is utilized for drilling bits and as a loose grain abrasive for polishing. Other tools that incorporate natural diamond include engraving points, glass cutters, bearings, and surgical instruments.

Synthetic diamond grit and powder are used in diamond grinding wheels, saws, impregnated bits and tools, and as loose abrasives compounds for polishing. Very large diamond grinding wheels can be as much as 1 meter in diameter.

Loose powders and compounds made of synthetic diamond for polishing are used primarily to finish optical surfaces, jewel bearings, gemstones, wiredrawing dies, cutting tools, and metallographic specimens. Hundreds of other products made from metals, ceramics, plastics, and glass also are finished with diamond powders and compounds.

The utilization of polycrystalline diamond shapes (PDS) and polycrystalline diamond compacts (PDC) continues to increase for

many of the applications cited above, including some of those that employ natural diamond. In particular, the use of PDS, PDC, and matrix set synthetic diamond grit for drilling bits and reaming shells has increased in recent years. Moreover, PDS and PDC are used in the manufacture of single- and multiple-point tools, and PDC is used in a majority of the diamond wire-drawing dies. The manufacturing of PCD for PDS and PDC now accounts for much of the diamond powder consumed in the United States (W. Born, National Research Company, oral commun., 1998).

#### Prices

Natural and synthetic industrial diamonds differ significantly in price (Boucher, 1997). Natural industrial diamond, which normally has a more limited range of values, varies in price from approximately 30 cents per carat for bort-size material to about \$7 to \$25 per carat for most stone. Synthetic industrial diamond has a much more diverse variety of prices that varies according to size, shape, crystallinity, and the absence or presence of metal coatings. In general, synthetic diamond for grinding and polishing varies from 30 cents per carat (as low as 10 cents per carat for low quality material) to \$1 per carat; strong and blocky material for sawing and drilling sells for \$3 to \$4 per carat. Large synthetic crystals with excellent structure for specific applications sell for several hundred dollars per carat.

In 1997, the DOD appraised the average per-carat market value of crushing bort and industrial stone in the NDS at \$5.21 and \$26.41, respectively. In certain cases, however, significantly higher assessments of industrial diamond in the stockpile have been made by those who bid on diamonds offered for sale during the year by the DOD; for example, some bidders at NDS disposal sales have paid almost \$100 per carat for stockpiled diamonds that they valued as gem-quality stones.

#### **Foreign Trade**

The United States leads the world in industrial diamond trade. In 1997, imports came from 27 countries, and exports-reexports went to 42 countries. Although the United States is a major producer of synthetic diamond, its growing domestic markets have become more reliant on foreign sources of industrial diamond in recent years. Moreover, U.S. markets for natural industrial diamond always have been dependent on imports and secondary recovery operations because domestic production of natural diamond was lacking. The Colorado diamond mine noted on page 2, however, may eventually reduce import reliance somewhat if mining resumes.

During 1997, U.S. imports of diamond powder, dust, and grit reached a record high of 254 million carats valued at \$109 million. Imports of industrial quality stones were 2.8 million carats valued at \$21 million. China and Russia grew more important as major sources of synthetic diamond for U.S. markets. (See tables 1 and 2.)

During 1997, the United States exported and reexported 129 million carats of industrial diamond powder, dust, and grit valued at \$104 million. Additionally, the United States exported and reexported about 3.6 million carats of industrial diamond stone valued at \$30 million. (*See tables 3 and 4.*)

 $<sup>^{3}</sup>$ One and a half carats of industrial diamond reportedly are consumed in the production of every American automobile.

#### World Review

Based on various reports (Boucher, 1997; Union Miniere, 1998), global demand for industrial diamond in 1997 was estimated to be well above 500 million carats valued between \$650 and \$800 million. The United States remained the world's largest single market for industrial diamond during the year as its industrial base continued to expand. World demand for industrial diamond in recent years had been growing at annual rates exceeding 10% (Boucher, 1997). However, the decline of several important Asian markets dampened demand for some products in 1997 (Ellis, 1998; Union Miniere, 1998).

More than 30 countries produced industrial diamond in 1997. (*See tables 5 and 6.*) Two-thirds of global output, however, was focused in just four countries: the United States, Ireland, Russia, and South Africa (Boucher, 1997).<sup>4</sup> Furthermore, at least 75% of world's synthetic output in 1997 was manufactured by only two companies: General Electric and De Beers (Boucher, 1997). The dominance of synthetic diamond was even more pronounced, accounting for an estimated 90% of global production and consumption.

#### Outlook

The United States will continue to be the world's largest market for industrial diamond well into the 21st century and will remain a significant producer and exporter of industrial diamond as well. Strength of U.S. demand will depend on the vitality of the Nation's industrial base and on how well the life cycle costeffectiveness of diamond compares with competing materials that initially are less expensive. Requirements for more precision machining and attempts to compensate for future increases in labor and energy costs also could spur demand.

The construction industry is likely to exhibit the most dramatic increase in U.S. demand for industrial diamond as the \$200 billion Federal Transportation Equity Act legislation of 1998 is implemented to improve the Nation's highway system.<sup>5</sup> Fulfillment of the Act will require significant quantities of saw-grade diamond for the repair and replacement of roads, bridges, and other components in the transportation infrastructure of the country.

As in the United States, world demand for industrial diamond will continue to grow during the next few years. Constant-dollar prices of synthetic diamond products, including chemical vapor deposition diamond films, will decline as production technologies become more cost effective and competition from low cost producers in China and Russia increases. Nevertheless, competing demand for diamond among certain consuming industries could induce short-term price increases for some products (W. Born, National Research Company, oral commun., 1998). Moreover, concentration of production among a limited number of major industrial diamond manufacturers could tend to limit price reductions.

PCD for abrasive tools and wear parts will continue to replace competing materials in many industrial applications by extending tool life, increasing product diversity, providing closer tolerances, and yielding lower parts cost (T. Corcoran, ANCO Industrial Diamond Corp., written commun., 1997). For example, PDC and PDS will continue to displace natural diamond stone and tungsten carbide products used in the drilling and tooling industries (W. Born, National Research Company, written commun., 1997).

Truing and dressing applications will remain a major domestic end-use for natural industrial diamond stone. The stone cannot be manufactured commercially. No shortage of the stone is anticipated, however, because new mines (for example, in Canada) and more producers selling in the rough diamond market will maintain ample supplies (T. Corcoran, ANCO Industrial Diamond Corp., written commun., 1997). More competition introduced by the additional sources may temper price increases as well.

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<sup>&</sup>lt;sup>4</sup>Some reports estimate that Ireland may be the largest producer, at least for certain major products.

<sup>&</sup>lt;sup>5</sup>The legislation (P.L. 105-178; enacted June 9, 1998) is titled, Transportation Equity Act for the 21<sup>st</sup> Century, and will fund road building/repair through 2003.

<sup>&</sup>lt;sup>6</sup>Prior to January 1996, published by the U.S. Bureau of Mines.

#### TABLE 1

#### U.S. IMPORTS FOR CONSUMPTION OF INDUSTRIAL DIAMOND STONES, BY COUNTRY 1/

	Nati	ural industria	l diamond sto	ones				
		(including g	glazers' and		Miners' diamond,			
		engraver's dia	amond unset)			natural and	l synthetic	
	(	7102.21.300	0 and .4000)	1	(7102.21.1010 and .1020)			
	199	6	1997 1996		96	1997		
Country	Quantity	Value 2/	Quantity	Value 2/	Quantity	Value 2/	Quantity	Value 2/
Belgium	206	1,200	238	1,320	276	735	308	3,700
China	47	80	12	15	(4/)	10		
Congo (Kinshasa) 3/	354	796	19	287	101	1,710	20	1,180
Ghana	181	1,000	252	1,910	87	577	130	682
India	7	119	46	47	(4/)	2	(4/)	7
Ireland	133	289	326	503	6	20	120	18
Japan	(4/)	17	6	136				
South Africa	(4/)	16	6	165	(4/)	85	2	243
Switzerland	6	20	2	20	201	417	357	840
United Kingdom	402	3,520	139	549	495	6,990	225	6,190
Other	342 r/	3,270 r/	551	3,200	14 r/	680 r/	28	443
Total	1,680	10,300	1,600	8,150	1,180	11,200	1,190	13,300

#### (Thousand carats and thousand dollars)

r/ Revised.

1/ Data are rounded to three significant digits; may not add to totals shown.

2/ Customs value.

3/ Formerly Zaire.

4/ Less than 1/2 unit.

Source: Bureau of the Census.

#### TABLE 2

#### U.S. IMPORTS FOR CONSUMPTION OF DIAMOND POWDER, DUST AND GRIT, BY COUNTRY 1/

	(Thousand carats and thousand dollars)							
	Diamond powder and dust							
		Syn	thetic	<u> </u>		Natural		
	(7	(7105.10.0020; .0030 and .0050)			(7105.10.0011 and .0015)			
	19	96	199	07	19	1996 1997		97
Country	Quantity	Value 2/	Quantity	Value 2/	Quantity	Value 2/	Quantity	Value 2/
Belgium	3,100	4,210	3,910	4,900	1,790	2,130	2,520	2,320
China	23,800	5,150	39,000	7,250	7,320	994	9,270	1,510
France	177	109	1,320	810	77	190	347	157
Germany	7,920	1,850	1,920	393	24	19	30	35
Ghana	190	181	269	203	328	396	296	197
Hong Kong	4,440	797	1,180	297	1,950	401	1,170	145
India	54	41	526	181	209	100	135	61
Ireland	112,000	61,400	108,000	63,200	2,390	1,300	2,450	1,400
Japan	4,240	2,240	5,620	2,790	2	6	12	13
Korea, Republic of	25,000	9,290	14,800	8,950	876	636	764	473
Russia	9,930	2,100	46,900	6,730	1,070	210	399	100
Switzerland	1,340	946	5,870	2,090	332	195	380	467
United Kingdom	5,500	1,970	2,810	2,590	433	333	766	391

2,110

235,000

618

101,000

7<u>71</u>

19,300

773

8,040

471 r/

7,370

583 r/

17,400

#### (Thousand carats and thousand dollars)

Total r/ Revised.

Other

 $1/\operatorname{Data}$  are rounded to three significant digits; may not add to totals shown.

1,230 r/

91,500

3,610 r/

201,000

2/ Customs value.

Source: Bureau of the Census.

#### TABLE 3

#### U.S. EXPORTS AND REEXPORTS OF INDUSTRIAL DIAMOND STONES, BY COUNTRY 1/

		Industrial unwork				
		(7102.21.	.0000)			
	199	6	199	97		
Country	Quantity	Value 2/	Quantity	Value 2/		
Belgium	1,650	14,500	1,840	15,300		
Canada	328	1,120	432	1,270		
Germany	50	394	83	655		
Hong Kong	55	572	93	746		
Ireland	73	325	20	200		
Israel	53	397	135	1,820		
Italy	17	39	13	71		
Japan	768	6,880	729	7,350		
Korea, Republic of	106	976	98	831		
Netherlands	25	246	16	88		
Switzerland	16	163	23	219		
United Kingdom	43	416	34	340		
Other	75 r/	544 r/	82	657		
Total	3,260	26,600	3,590	29,500		

#### (Thousand carats and thousand dollars)

r/ Revised.

 $1/\operatorname{Data}$  are rounded to three significant digits; may not add to totals shown.

2/ Customs value.

Source: Bureau of the Census.

TABLE 4

#### U.S. EXPORTS AND REEXPORTS OF INDUSTRIAL DIAMOND POWDER, DUST AND GRIT, BY COUNTRY 1/

#### (Thousand carats and thousand dollars)

		Diamond powder and dust						
		Synthe	tic		Natural			
		(7105.10.	0025)		(7105.10.1010)			
	1996		199	97	199	6	199	97
Country	Quantity	Value 2/	Quantity	Value 2/	Quantity	Value 2/	Quantity	Value 2/
Australia	625	1,290	679	1,290	34	69	11	28
Austria	1,260	962	1,380	821	194	72	112	126
Belgium	2,180	2,070	5,490	5,490	327	260	400	330
Brazil	1,480	1,010	1,860	1,240	96	79	5	3
Canada	2,990	6,280	3,910	7,200	49	112	125	306
China	1,280	497	1,590	1,190				
France	232	184	126	78	16	25	11	28
Germany	17,300	19,300	4,960	3,520	279	233	155	140
Hong Kong	7,700	3,620	4,130	3,280	163	139	348	92
India	4,130	2,310	9,500	3,810			28	30
Ireland	10,800	13,200	26,700	29,900	214	412	140	294
Israel	290	130	240	93	219	53	974	222
Italy	999	607	1,540	688	84	87	108	70
Japan	25,000	20,900	25,800	20,600	334	324	747	631
Korea, Republic of	12,300	9,000	11,000	7,850	143	268	77	34
Luxembourg	115	73	259	195	170	198	62	68
Macao	834	190	1,660	406			309	165
Malaysia	465	150	982	525	64	37	2	4
Mexico	193	131	294	259	169	145	194	138
Singapore	1,460	1,020	6,550	3,190	147	161	97	65
Switzerland	2,100	988	3,110	1,660	221	197	360	232
Taiwan	3,940	2,570	6,460	3,910	218	108	11	3
Thailand	450	376	533	335	12	34	127	104
United Kingdom	3,240	1,960	2,810	773	1,410	1,080	1,380	706
Other	1,870 r/	1,360 r/	1,250	1,310	27 r/	20 r/	97	177
Total	103,000	90,200	123,000	99,500	4,590	4,110	5,880	4,000

r/ Revised.

 $1/\operatorname{Data}$  are rounded to three significant digits; may not add to totals shown.

2/ Customs value.

Source: Bureau of the Census.

## TABLE 5 NATURAL DIAMOND: ESTIMATED WORLD PRODUCTION, BY TYPE AND COUNTRY $1/\,2/$

(Thousand carats)

Country	1993	1994	1995	1996	1997
Gemstones: 3/					
Angola	130	270	2,600 r/	2,250 r/	1,110
Australia	18,800	19,500	18,300	18,897 4/	18,100
Botswana	10,300	10,550 4/	11,500	12,700 r/	13,000
Brazil	- 1,000	300	676 r/4/	200 r/	300
Central African Republic		401 r/	400	350	400
China	230	230	230	230	230
Congo (Kinshasa) 5/	2,010	4,000	4,000	3,600 r/	2,500
Ghana	- 106 4/	118 4/	126	142 r/	140
Guinea	134	306	274	165	160
Liberia	- 60	40	60	60	60
Namibia	1,120	1,312 4/	1,382 4/	1,420 r/	1,500
Russia	- 8,000	8,500	9,000	9,250	9,550
Sierra Leone	- 90	155	113	162 4/	110
South Africa	4,600	5,050	5,070	4,280 r/	4,380
Venezuela	– 267 r/	380 r/	125 r/	105 r/	100
Zimbabwe	26	104	114	300 r/	350
Other		180 r/	183 r/	231 r/	235
Total	47,400 r/	51,400	54,200 r/	54,400 r/	52,200
Industrial:					
Angola	- 15	30	300	250 r/	124
Australia	23,000	23,800	22,400	23,096 4/	22,100
Botswana	4,420	5,000	5,300	5,000	5,000
Brazil	600	600	600	600	600
Central African Republic	125	131	130	120	100
China	850	850	900	900	900
Congo (Kinshasa) 5/	13,600	13,000	13,000	17,000 r/	12,500
Ghana		473 4/	505	573 r/	560
Guinea	- 33	75	91	40	40
Liberia	- 90	60	90	90	90
Russia	- 8,000	8,500	9,000	9,250	9,550
Sierra Leone	- 68	100	101	108	90
South Africa	5,700	5,800	5,880	5,670 r/	5,790
Venezuela		203 r/	66 r/	55 r/	50
Zimbabwe	- 18	69	90	137 r/	100
Other	– 117 r/	96 r/	127 r/	149 r/	151
Total	57,300 r/	58,800 r/	58,600	63,000 r/	57,700
Grand total	105,000	110,000	113,000	117,000	110,000

r/ Revised.

1/World totals and estimated data are rounded to three significant digits; may not add to totals shown.

2/ Table includes data available through May 27, 1998.

3/ Includes near-gem and cheap-gem qualities.

4/ Reported figure.5/ Formerly Zaire.

## TABLE 6 SYNTHETIC DIAMOND: ESTIMATED WORLD PRODUCTION, BY COUNTRY 1/2/

#### (Thousand carats)

96 1997	1996	199:	1994	1993	Country
00 25,000	25,000	25,00	3/ 25,000	30,000 3	Belarus
16,000	15,500	15,50	15,500	15,500	China
5,000	5,000	5,00	5,000	5,000	Czech Republic
3,500	3,000	3,00	3,500	3,500	France
50 750	750	1,00	1,000	1,000	Greece
60,000	60,000	60,00	65,000	65,000	Ireland
32,000	32,000	32,00	32,000	32,000	Japan
50 3/ 250	250 3/	25	3/ 271	98 3	Poland
5,000	5,000	5,00	5,000	5,000	Romania
80,000	80,000	80,00	80,000	80,000	Russia
5,000	5,000	5,00	5,000	5,000	Slovakia
60,000	60,000	60,00	3/ 60,000	60,000 3	South Africa
25,000	25,000	25,00	25,000	25,000	Sweden
8,000	8,000	8,00	3/ 8,000	10,000 3	Ukraine
00 125,000	114,000	115,00	104,000	103,000	United States
00 451,000	439,000	440,000	434,000	440,000	Total
00 00	8,0 114,0	8,000 115,000	3/ 8,000 104,000	10,000 3 103,000	Ukraine United States

r/ Revised.

1/World totals, U.S. data, and estimated data are rounded to three significant digits; may not add to totals shown.

2/ Table includes data available through May 27, 1998.

3/ Reported figure.