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Abrasives

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Abrasives include the substances, natural or artificial, that are used to grind, polish, abrade, scour, clean, or otherwise remove solid material, usually by rubbing action but also by impact (pressure blasting for example). They do not include abrasive tools, for instance, lathe tools and files—or polishing agents such as waxes, which act by filling pores.

Detergents and cleaners whose action is chemical rather than physical are omitted although some chemical-action polishes and cleaners may also contain solid abrasives, for example, many automobile and metal polishes.

General Considerations

The most important physical properties of materials that qualify them for use as abrasives are hardness, toughness (or brittleness), grain shape and size, character of fracture or cleavage, purity or uniformity. For making bonded abrasive products such as grinding wheels, additional important factors are stability under high heat and bonding characteristics of grain surfaces. The economic factors of cost and availability are always important.

No one single property is paramount for any use. For some uses extreme hardness and toughness are needed, as in diamonds for drill bits; for others, the factors of greatest importance are hardness and ability to break down slowly under use, to develop fresh cutting edges when grains become worn—for example: in garnet for sandpaper neither highly cleavable or friable grains nor extremely tough grains are wanted. For still other uses, great hardness is objectionable; for example, abrasives for dentifrices and for glass-cleaning soaps. For the most efficient use in the more critical applications, the different types of abrasives are rarely completely interchangeable; thus, while crushed quartz and garnet are both used in sandpaper, the papers are not at all interchangeable in their use applications.

In the last analysis, the choice of a high grade abrasive depends upon the quality and quantity of work done by the abrasive per unit of cost. Initial cost of an artificial abrasive may be much greater than that of a natural abrasive but the artificial abrasive may do so much better work than the natural one and do it so much faster that the ultimate cost will be less. It is for this reason that artificial abrasives have largely replaced natural abrasives.

Abrasive Value

Mineralogical hardness or "scratch" hardness as expressed in Mohs' scale is an important property in evaluating abrasive materials, but, as noted before, it is only one of several essential properties. The mineral hardness of pure crystal almandite garnet is about 7.5, but if the crystal is crossed by incipient fracture planes, or if it contains inclusions of other minerals, the apparent or useful hardness may be much lower. While the quartz grains in a sandstone have a hardness of 7, the bond holding the grains together may be so weak that the stone is valueless as a commercial abrasive. In artificially bonded wheels and stones, the hardness, strength, and character of the bond are fully as important as the hardness of the abrasive grains. Thus, in an overall consideration of abrasive hardness of loose abrasive grains, both "scratch" hardness and toughness must be considered. In naturally or artificially bonded abrasive stones, bond characteristics are a third factor, which is most important.

The problem of abrasive hardness is further complicated by the inadequacies of methods of testing hardness and of expressing relative values. The Mohs' scale is inadequate both because the methods of testing are very crude and

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because the intervals between steps in the scale are not uniform; thus there is far less difference between hardnesses of 6 and 7 than between 9 and 10. Numerous attempts have been made to remedy these deficiencies. Ridgway, Ballard, and Bailey (1933) proposed an extension of Mohs' scale to include artificially prepared substances. Knoop, Peters, and Emerson (1939) devised a diamond indentation method of measuring hardness, which gives reproducible results on a wide variety of materials and has the merit of giving definite numerical values over a wide range up to the hardness of the diamond.

Table 1, after Thibault and Nyquist (1947), shows relative hardnesses on the Knoop scale.

Another consideration, perhaps even more important than true hardness in appraising abrasive value, is toughness or friability. Very hard materials are not necessarily tough or resistant to fracture. Diamond is an excellent example of this. It is the hardest material known to man yet it can fracture easily under impact.

Several techniques for testing friability have been developed and are in widespread use in the quality control of abrasive grain. The basic operating principle common to all strength-of-grain tests is to impact a given sample of abrasive grain under a set of standardized conditions followed by measurement of the amount of breakdown. Naturally, the higher the survival the tougher the grain, other factors being equal.

FIG. 1—*Wig-L-Bug mill.*

A simple and inexpensive device for performing this test is an ordinary ball mill. A detailed description of this test is given in the "American Standard Procedure for Ball Mill

TABLE 1—Knoop Hardness Numbers Determined at 100-G Load (K_{100}) for Various Hard Substances. Random Crystal Orientation

Substance	Knoop No. 100-G Load, (K_{100})	
	Average	Range
Primary boron carbide ("Norbide")	2800	2670-2940
Molded boron carbide ("Norbide")	2760	2580-2900
Gray silicon carbide (Regular "Crystolon")	2460	2250-2680
Gray silicon carbide (Regular "Crystolon" [check])	2550	2320-2760
Green silicon carbide (Green "Crystolon")	2480	2230-2740
Green silicon carbide (Green "Crystolon" [check])	2480	2130-2620
Titanium carbide	2470	2350-2620
Tungsten titanium carbide	2190	2050-2320
Alpha-aluminum oxide ("38 Alundum")	2050	1860-2200
Alpha-aluminum oxide (synthetic boule)	1950	1680-2100
Primary (unbonded) tungsten carbide (WC)	1880	1570-2140
Cemented carbide ("Kennametal K6")	1800	1700-1940
Cemented carbide ("Kennametal KM")	1500	1390-1600
Cemented carbide ("Kennametal K12")	1410	1280-1500
Garnet (Barton Mines, New York)	1360	1240-1440
Topaz (Thomas Range, Utah)	1340	1240-1500
Synthetic blue spinel (Linde)	1270	1190-1460
Quartz	820	760-880
Hardened tool steel, Rockwell C-60.5	740	730-760

Source: Thibault and Nyquist, 1947.

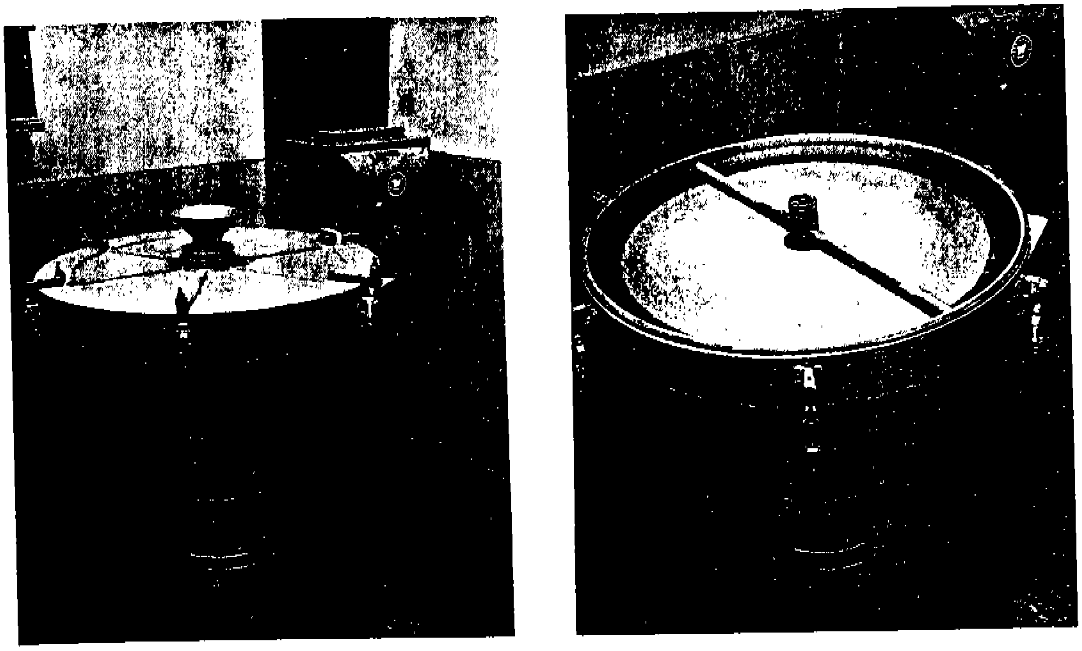


FIG. 2—*Strength-of-grain machine.*

Test for Friability of Abrasive Grain" (Anon., 1965).

The Wig-L-Bug Mill (Fig. 1) is also used for the testing of small samples. This feature makes it particularly attractive for testing the strength of diamond grain.

With this machine a small, closely sized weighed sample is placed in a capsule along with a milling sphere. The capsule and contents are vibrated vigorously for a given length of time. The sample is then removed (often by washing), rescreened, and the portion remaining on the screen is expressed as a percent survival. On a "Standard" sample, typical of the materials to be tested, it has been found best to adjust the running conditions so that approximately 50% breakdown is achieved.

Various other devices have been developed for impacting abrasive grain. A machine built and used by Norton Co. is one of these (Fig. 2). A distinct advantage that this machine has over the previously mentioned ones for ordinary abrasives is its capacity to test a relatively large sample 0.23 kg (½ lb). This machine ejects abrasive out of a rapidly whirling tube against the walls of the chamber. After striking the wall the grains accumulate in a collecting cylinder and are later screened to determine the percentage of surviving grain.

The grain shape is another fundamental physical property which must be considered in selecting the best abrasive for a particular application. Blocky and nearly equidimensional grains are called strong-shaped grains and are less friable than slivery or flakey ones which are considered weak-shaped grains. In grinding wheels strong-shaped grains are preferred in extra heavy duty applications involving high heat and pressure while weaker-shaped grains are selected for precision grinding to close tolerances and where high surface finishes are required. Strong- and weak-shaped grains, respectively, are illustrated in Figs. 3 and 4.

In modern abrasive technology close control of abrasive shape is necessary. The determination of the bulk density of an abrasive is a dependable indicator of shape inasmuch as bulk density is a function of shape. A sample of weak-shaped grain will not pack as efficiently and consequently will have a lower bulk density than the same abrasive but of a strong shape.

The following techniques are commonly used for the measurement of the bulk density (shape) of abrasive grain.

The "loose-pack-density test," as it is often called, is fully described in "American Standard Test for Bulk Density of Abrasive Grain" by the American Standards Assn. (Anon., 1964). The test apparatus is illustrated in Fig. 5. In performing this test, vibration is purposely avoided. In practice, the container is filled to overflowing and then carefully leveled with a

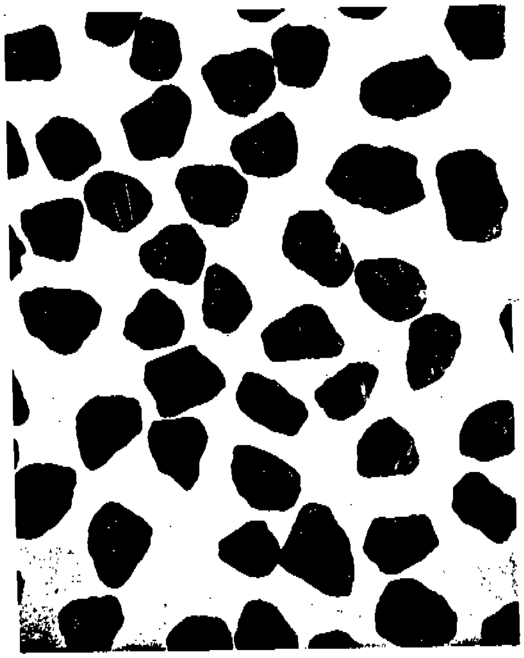


FIG. 3—*Strong-shaped abrasive grain.*

straight edge. Great care must be exercised so as to avoid any vibration. The weight of the grain filling the container is then obtained and the bulk density calculated using the traditional

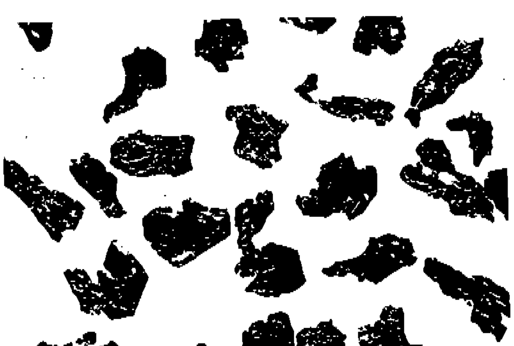


FIG. 4—*Weak-shaped abrasive grain.*

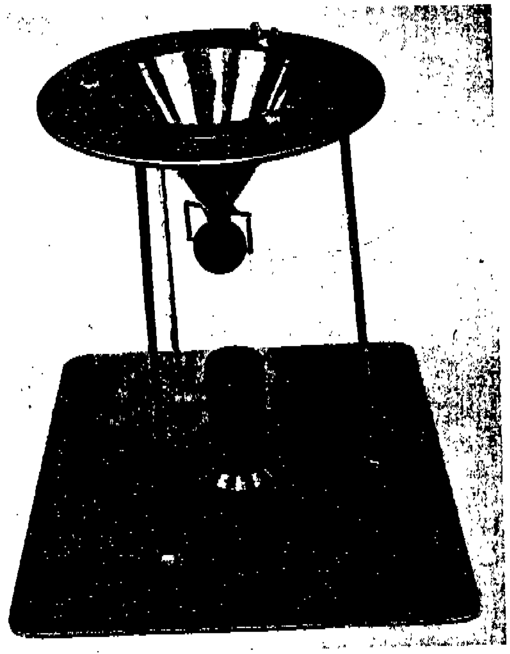


FIG. 5—*Loose-packed-density (LPD) apparatus.*

formula $D = W/V$ in which D is the bulk density of the sample in grams per cubic centimeter, W is the weight of the grain in grams, and V is the volume of the cylinder in cubic centimeters.

In the following test, however, controlled vibration is a necessary part of the determination. This second shape test is often referred to as "the weight per cubic foot" determination.

Fig. 6 shows equipment designed and built by Norton for the measurement of the weight per cubic foot of abrasive grain. In this test, as in the loose-pack-density test, it is absolutely essential that the sample to be tested be as closely sized and as free of dust and fines as possible, otherwise spurious results can be expected.

Before making a run with this equipment, the grain to be tested is placed in the hopper and a receiving container of suitable capacity is installed. A container with a capacity of 0.0035 m^3 (1/8 cu ft) is normally used but other containers—for example, 0.00088 to 0.00044 m^3 (1/32 or 1/64 cu ft)—may be used if the sample to be tested is small. To start a run, the motor is turned on and the storage hopper containing the sample is opened. When the motor starts, a gear-driven cam causes the collecting container to bump up and down, this being the controlled source of vibration, which causes

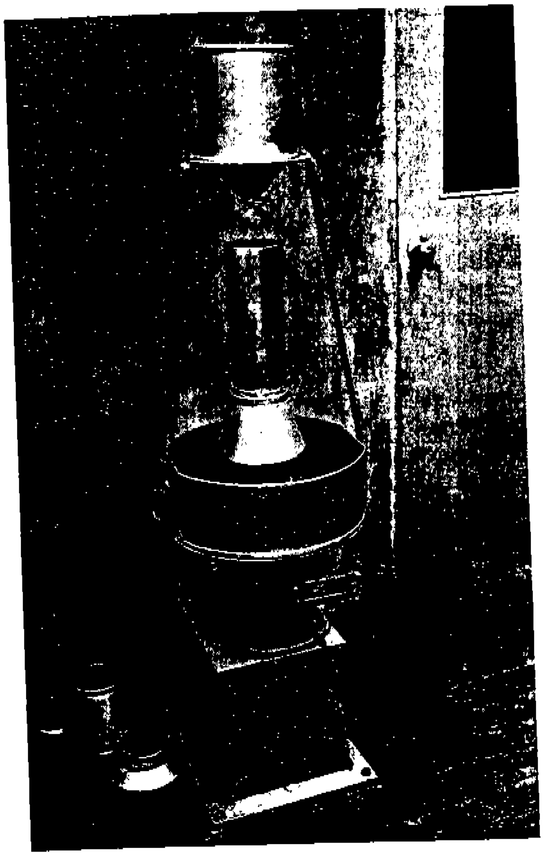


FIG. 6—*Weight-per-cubic-foot (WPCF) machine.*

settling or packing of the grains. Abrasive is allowed to flow continuously into the collecting container until it overflows and during the run more abrasive is added as needed to keep the container full-to-overflowing. The machine is so constructed as to collect any abrasive which overflows. Each bump cycle of the collecting cylinder is counted on an automatic counter. In practice the machine is run until a predetermined total number of bumps has been accumulated. At this point the motor is shut off and the excess abrasive removed by carefully drawing a straight edge across the top of the collecting cylinder. The grain is then weighed and expressed as "pounds-per-cubic foot."

Characteristics other than shape influence the strength of abrasive grains. The manufacture and processing of aluminous abrasives permit control of some of these important characteristics. For example, it has been clearly established by laboratory and field tests that, other factors being equal, the finer the crystal size of an abrasive the stronger that abrasive will be. The cooling history of a fused alumina melt is the dominant factor influencing the crystal size of the finished product. Perhaps at the cost of oversimplification it may be said that rapid cooling will result in fine crystal size and slow cooling will result in coarse crystals. As a frame of reference, a slow-cooled product might typically result in a product the crystal size of which would be in the order of 1500 m and a rapidly cooled product 400 m.

A rapid and inexpensive quality control check for crystal size is "the monocrystalline count." An immersion mount of the grit to be tested is prepared. Any convenient grit size can be used but 24-grit has been found by experience to be quite ideal. Each grain is then examined on the petrographic microscope to determine whether it is made up of a fragment of a single crystal or perhaps two or more crystals. The former grain is a monocrystalline grain while the latter is polycrystalline. A count is made of, say, 100 grains and that percentage which is found to be monocrystalline is by definition "the monocrystalline count." Generally speaking the higher the monocrystalline count the weaker the grain. It is theorized that a polycrystalline grain is less apt to disintegrate because a fracture upon starting through the grain might pass through one crystalline unit making up the grain but then be stopped or deflected upon encountering another crystalline unit not in crystallographic continuity with the first.

A secondary treatment which has been found to increase the strength of fused aluminum oxide abrasive grain is heat treatment or roasting. The theory is that the heated slag (impurities between crystals) softens and flows out onto the surface of the grain, cementing imperfections and healing incipient fractures.

Types of Abrasive Products

Loose Abrasive Grains: Abrasive grains are produced from a wide variety of materials, both for use as grains and for incorporation into other products. Thus abrasive grains are not only important products of themselves but are the starting point for making bonded shapes, coated abrasives, abrasive tools, polishes, cleaners, grinding pastes, and compounds.

For pressure blasting, in addition to silica sand, other natural mineral grains are used such as corundum, garnet, flint, and chert as well as manufactured products such as fused alumina, silicon carbide, and steel shot. All except the last have a hardness of 7 or more. Besides hardness the physical properties of toughness, grain shape, grain size, uniformity, and specific gravity are important. Grains should be tough, so that they will not disintegrate readily under impact. For some uses rounded grains are considered desirable, for others sharp cutting edges are favored. Uniformity of grain size and other physical properties is always desired. The higher the specific gravity, the greater the force of impact for grains of equal size. Each use has its own special requirements.

Common uses for pressure blasting are: cleaning stone and concrete, cleaning metal castings, preparing surfaces for painting, etching of glass, and plastics.

Loose grains of relatively coarse sizes are used for sawing stone, rough grinding plate glass, and surfacing stone. Materials used are quartz sand, garnet, corundum, emery, aluminum oxide, silicon carbide.

Grains of somewhat smaller sizes of the same materials are used for grinding lenses, rough polishing of building stone and plate glass, rough polishing of gems and ornamental stones, and dressing and polishing wood surfaces.

Fine-grained powders are used for polishing and lapping of a variety of materials including glass, building and decorative stone, metals, plastics, tile and artificial stone flooring, gems and semiprecious stones, and wood surfaces. The abrasive materials used are rouge, crocus, tin oxide, aluminum oxide, chromium oxide, cerium oxide, diamond dust, feldspar, garnet, rottenstone, pumice, diatomite, tripoli, ground silica, clay, whiting, zirconium oxide. Most automobile body cleaners and polishes contain diatomite. A familiar bathroom and kitchen scouring powder for glass and porcelain bodies uses feldspar or volcanic glass.

In one method for drilling small holes in glass, porcelain, gem stones, and similar materials, a brass tube is used, charged with diamond, corundum, emery, aluminum oxide, silicon carbide, or boron carbide dust in a vehicle of water, oil, or grease. Diamond-tipped drills are also used for this purpose.

Ground feldspar, fuller's earth, and other materials are used as nonskid dusting agents for oily floors. Emery, magnetite, and silicon carbide are cast into the treads of steps and ramps to increase "footing" and coarse or gritty slag and volcanic rocks are rolled into asphalt pavements to improve traction.

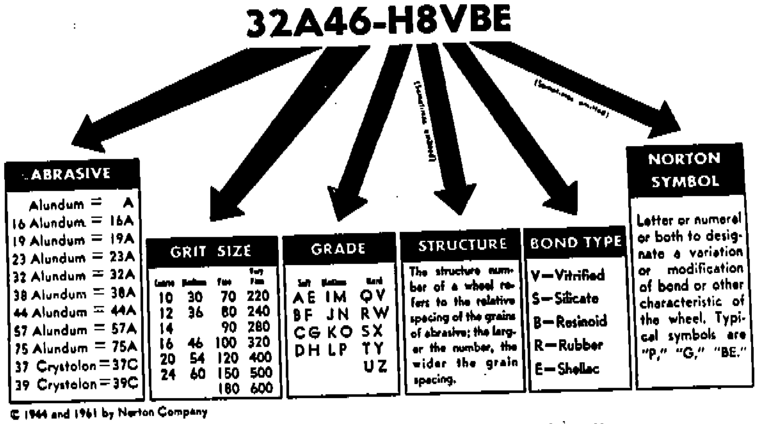
Bonded Abrasives: Abrasive grains, closely sized, are bonded and pressed or molded into a wide variety of bonded abrasives such as grinding wheels. Originally the abrasives in such products were corundum or emery but with the introduction of the electric-furnace abrasives, aluminum oxide, and silicon carbide, the use of the natural abrasives has very greatly declined. There are five main types of bonded abrasives, depending on the type of bond and method of manufacture: (1) Vitrified wheels with a clay-feldspar bond, which is vitrified in ceramic kilns. This bond type accounts for over 75% of the grinding wheels manufactured today. Because of their high rigidity and dimensional stability, vitrified bonded wheels are preferred for precision grinding operations. They are unaffected by water, acids, oils, and ordinary temperature variations. (2) Resinoid wheels with a hard synthetic resin bond. These are high speed wheels used in foundries, welding, and billet conditioning shops. They are also used in cutoff and thread grinding operations. (3) Rubber wheels, being bonded with natural or synthetic rubber, are somewhat elastic in nature. They are used for grinding ball races, most centerless feed wheels, and for portable snagging operations where finish is an important consideration. Rubber-bonded cutoff wheels can be made very thin. (4) Shellac wheels are used for producing high finishes on such items as camshafts and paper mill rolls. (5) Silicate bonds find application in operations where heat generated in grinding must be kept to a minimum. Silicate bonded wheels are mild acting and are used in grinding edge tools of all kinds.

Wheels are made that vary in at least five physical properties, aside from size and shape: (1) type of abrasive grain (aluminum oxide, silicon carbide, corundum, emery, diamond, etc.); (2) grit (size of abrasive grains, 8 to 1500-mesh); (3) grade (strength of bond, 18 to 20 grades); (4) structure (grain spacing, 10 to 12 spacings); (5) bond (vitrified, etc., five bond types).

Fig. 7 shows a wheel marking system which is widely used in the abrasive industry (Anon., 1970).

When all these variables are combined with an almost infinite number of sizes, shapes, and spindle diameters that are standard or can be had on special order, the complexity of the abrasive wheel business is apparent.

In addition to grinding wheels, bonded abrasives are made up into blocks, bricks, and sticks for sharpening and polishing stones such as oil stones, scythe stones, razor and cylinder



*Structure numbers are not always shown in the marking. However, such products may nevertheless be made to a definite structure.

FIG. 7—*Grinding wheel marking system.*

hones. Curved blocks and segments are made, which can be combined into large wheels such as pulpstones or used mounted or unmounted for grinding or polishing the interior or exterior of curved surfaces.

Rubber pencil and ink erasers contain abrasive grains and similar soft rubber wheels, sticks, and other forms, are made for finishing soft metals.

Coated Abrasives: Coated abrasives consist of sized abrasive grains cemented to paper or cloth backing. Originally "sandpaper" was perhaps coated with sand but today crushed quartz is used on silica-type paper because its grains have much sharper cutting edges. The use of crushed glass to surface "glass" paper is now obsolete. The principal abrasives used today for this purpose are crushed quartz, garnet, aluminum oxide, and silicon carbide. Most "emery" cloth today is coated with silicon carbide or aluminum oxide. "Flint" paper in the United States is coated with crushed quartz but true flint is used in Europe.

With the exception of sintered abrasives, all abrasive grains, natural or artificial, are made by graded crushing and close sizing. Crushing usually is done in rolls to avoid making extreme fines (for which there is little demand) with close screening between sets of two rolls each. Products are washed in classifiers to remove slimes, then are dried, passed through magnetic separators to remove iron-bearing material, and again very closely sized on screens. Such careful sizing is essential to prevent contamination of grades by coarser grains. The finest powders are sized by air or water flotation and sedimentation.

In earlier practice, grade numbers were more or less arbitrarily assigned to grain sizes and unfortunately the garnet, flint, and emery scales were all different. Artificial abrasives were given numbers based on bolting-cloth mesh designations, which roughly correspond with but are not exact equivalents of standard testing sieve meshes. Gradually garnet and "flint" paper grade numbers have come to include both the old and the new numbers.

TABLE 2—Size Grades for Abrasives

Modern Mesh Designation	Old Garnet Scale	Flint Scale	Emery Scale
400			
320			
280	8/0		
240	7/0*	5/0	
220	6/0	4/0	
		3/0	
180	5/0		3/0
150	4/0	2/0	2/0
120	3/0		1/0
		1/0	
100	2/0		
		1/2	1/2
80	1/0		1
		1	
60	1/2		1 1/2
50	1	1 1/2	2
		2	2 1/2
40	1 1/2		
		2 1/2	
36	2		3
30	2 1/2	3	
24	3	3 1/2	
	3 1/3†		

* Approximately 220-mesh Tyler.
† Approximately 20-mesh Tyler.

Table 2 shows the relationship between the different scale sizes.

The bond for coated abrasives may be either glue or a synthetic resin adhesive. The backing is either paper or cloth.

Garnet and "flint" papers and cloths are most widely used for wood, leather, hard rubber, plastics, felt, and rubbed paint and varnish finishes on metals. Abrasives coated with silicon carbide and aluminum oxide are used chiefly in the metal-working industries. To date, diamond has found but limited use in coated abrasives.

More detailed information on coated abrasives is contained in the section on garnet later in this chapter.

Grains and Powders For Soap, Cleaners, and Polishes: Many different materials, mostly natural but some manufactured, are used in making soaps, cleaners, and polishes.

Feldspar, pumice and pumicite, sand, ground quartz, tripoli, diatomaceous earth, clay, and wood flour are used in hand and scouring soaps. Often low price is the primary factor in the selection of the abrasive, in spite of extravagant claims by some manufacturers. The commercial success of a cleanser depends largely upon advertising and sales ability rather than on superiority over competitive products, provided a fairly good product is made. Occasionally the abrasive is a really important factor. A household cleanser should not contain quartz or any mineral of equal or greater hardness, as glasses and enamels are nearly all 6 or lower in hardness and are scratched by any grain of equal or greater hardness. The abrasive should not contain calcium carbonate, calcium sulfate, or other easily reactive lime compounds because lime reacts with most soaps to form insoluble substances, which are very difficult to remove from glass or enamel surfaces.

An ideal mineral abrasive for this use might be a mineral or rock between 3 and 5 in hardness occurring in abundance in easily mined deposits, close to rail transportation, and within a reasonable freight-haul distance of important markets. The material should be uniform in texture and physical properties and contain no impurities harder than 6 and no easily reactive impurities such as lime compounds.

The ultimate grain size of abrasives in this group depends upon the finished product. It ranges from extremely fine air-separated and water-floated particles in the micron sizes, much finer than 325-mesh, up to 100-mesh or even coarser for heavy-duty scouring soaps.

Classification

Abrasives * may be divided into two general classes, natural and manufactured. The former includes all rocks and minerals used for abrasive purposes without chemical or physical change other than crushing, shaping, or bonding into suitable forms. Manufactured or artificial abrasives are made either by heat or chemical action from metals or mineral raw materials.

Table 3 lists most of the important abrasives, classified as to inherent types and the forms in which they are used industrially.

For most types of use there are manufactured products that can be substituted for the natural products, usually at higher initial cost but with higher efficiency. This is not always true; for example, there is no satisfactory manufactured substitute for garnet for making coated abrasive paper and cloth. For some abrasives whose use is gradually lessening—for instance, chaser stones—the making of manufactured substitutes has not been economically attractive, but for even such a low-priced commodity as pressure blasting sand there are substitutes such as steel shot, fused aluminum oxide, and silicon carbide grains.

The decline in the use of most natural abrasives and their replacement by manufactured abrasives has not been a net loss to the mineral industry, however, for virtually all manufactured abrasives are made from mineral raw materials.

Natural Abrasives

Corundum and Emery: Corundum and emery have become of relatively little importance both from the standpoint of domestic production and consumption and on a worldwide basis. No corundum is mined today in the United States or Canada and there are only two relatively small producers of emery, both in the Peekskill, NY, area. At this locality, a spinel emery occurs in veins in an igneous complex of hornblende and olivine pyroxenite. It is associated with mica schist in rocks containing sillimanite, cordierite, garnet, and quartz. Most of the domestic emery is used in tumbling

* In this book separate chapters are devoted to diamonds, diatomite, tripoli, lightweight aggregates (including pumice), silica sand, and quartz. Hence in this chapter only brief reference will be made to these minerals.

Superior Hardness
Diamond H-10
Corundum H-9
Emery H-7 to 9
Garnet H-6.5 to
Staurolite H-7.0
Intermediate Harc
Silica Abrasives
Buhrstone
Chalcedony
Chert
Flint
Novaculite
Quartz
Quartzite
Sandstone
Silica sand
Other Rocks anc
Argillaceous li
Basalt
Feldspar
Granite
Mica schist
Perlite
Pumice and pu
Quartz conglo
Inferior Hardness
Apatite
Calcite
Chalk
Clay
Diatomite
Dolomite
Iron oxides
Limestone
Rottenstone
Siliceous shale
Silt
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Tripoli
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TABLE 3—Classification of Abrasives

Natural Abrasives

Superior Hardness (above 7 in Mohs' scale)
- Diamond H-10
- Corundum H-9
- Emery H-7 to 9
- Garnet H-6.5 to 7.5
- Staurolite H-7.0 to 7.5

Intermediate Hardness (H-5.5 to 7)
- Silica Abrasives
  - Buhrstone
  - Chalcedony
  - Chert
  - Flint
  - Novaculite
  - Quartz
  - Quartzite
  - Sandstone
  - Silica sand
- Other Rocks and Minerals
  - Argillaceous limestone
  - Basalt
  - Feldspar
  - Granite
  - Mica schist
  - Perlite
  - Pumice and pumicite
  - Quartz conglomerate

Inferior Hardness (H-under 5.5)
- Apatite
- Calcite
- Chalk
- Clay
- Diatomite
- Dolomite
- Iron oxides
- Limestone
- Rottenstone
- Siliceous shale
- Silt
- Talc
- Tripoli
- Whiting

Manufactured Abrasives

- Boron carbide
- Boron nitride
- Calcium carbonate (pptd.)
- Calcium phosphate
- Cerium oxide
- Chromium oxide
- Clay (hard burned)
- Diamond
- Fused alumina
- Glass
- Iron oxides
- Lampblack
- Lime
- Magnesia (pptd.)
- Manganese dioxide
- Periclase (artif.)
- Silicon carbide
- Tantalum carbide
- Tin oxide
- Titanium carbide
- Tungsten carbide
- Zirconium oxide
- Zirconium silicate

Metallic abrasives, including steel wool, steel shot, angular steel grit, brass wool, and copper wool

Porcelain blocks for mill liners and grinding pebbles

Types of Abrasive Products

- Abrasive grains and powders, loose
- Abrasive grains bonded into wheels, blocks, and special shapes
- Coated abrasives; grains bonded to paper and cloth
- Abrasive grains and powders; paste form; oil or water vehicles
- Abrasive grains and powders; brick and stick form; grease, glue, and wax binders
- Natural rocks shaped into grindstones, pulpstones, chaser stones, millstones, etc.
- Natural rocks shaped into sharpening stones, such as oil stones, whetstones, scythe stones, razor hones, etc.
- Natural stones shaped into rubbing and polishing stones such as holystones and pumice scouring blocks
- Natural stones shaped into blocks for tube-mill and pebble-mill liners
- Pebbles, natural and manufactured, for grinding mills

barrels and for various types of nonslip floors and stair treads. Production in recent years has come from two producers and has averaged about 9 kt/a (10,000 stpy) valued at about \$20 per ton.

Diamonds—Industrial: Diamonds are reviewed in detail in a separate chapter in the "Commodities" section; therefore only their uses as abrasives are outlined here.

In 1981 the total world production of natural industrial diamonds of all types was about 31,100,000 carats, with US imports of 21,600,000 valued at \$5.34 per carat.

There are three major types of natural industrial diamonds: (1) bort, which includes off-color, flawed, or broken fragments of diamonds unsuitable for gems, (2) carbonado, or black diamond, which is a very hard and extremely tough aggregate of very small diamond crystals, and (3) ballas, a very hard, tough, globular mass of diamond crystals radiating from a common center. Carbonadoes come only from Bahia, Brazil; ballas chiefly from Brazil but a few from South Africa. Bort comes from all diamond-producing centers. In addition, there is a considerable production of diamond dust and powder, waste from cutting gem diamonds. Artificial diamonds are discussed in Part 4, Commodities, "Diamonds."

The industrial diamond has become one of the most important and essential materials in modern industry. Diamond drilling, once used only for locating metallic ores, is now widely used also for exploring nonmetallic mineral deposits; for exploring geologic structures; for testing foundations for dams, buildings, and heavy machinery; for exploring internal condition in heavy concrete structures such as dams; for stope mining; explosive demolitions under special conditions; and other purposes.

Some of the most important uses are: diamond-drill bits for drilling rock and concrete; diamond dies for wire drawings; diamond-tipped tools for truing abrasive wheels and for turning and boring hard rubber, fiber, vulcanite, hard plastics, etc.; diamond-toothed (segmental) saws and rim-impregnated (continuous rim) saws for sawing stone, glass, quartz, metals, slicing expansion joints in concrete highways, etc.; wheels, both for grinding and for cutoff work, in which the working face consists of diamond grit bonded with a resinoid, metal, or ceramic product; diamond-tipped tools for cutting glass and for engraving gems; diamond powder for cutting gems. High-speed tool steels, cemented carbides, and other exceedingly hard, tough alloys can be cut and shaped efficiently with diamond tools, and diamond-tipped tools are essential for the rapid and accurate shaping, truing, and dressing of abrasive wheels.

A diamond wheel marking system (Fig. 8), analogous to that previously shown for ordinary grinding wheels, is used by the abrasives industry (Anon., 1970).

With diamond, as with ordinary abrasives such as aluminum oxide and silicon carbide, the previously mentioned properties of size, shape, and friability must be closely controlled so that diamond with the proper physical properties may be selected for a particular application.

Resinoid or vitrified bonded diamond wheels require a fairly friable, weak-shaped diamond abrasive grain; metal bonded wheels require a more durable, strong-shaped grain.

Akin to the weight-per-cubic foot apparatus (see page 15) used for the ordinary abrasives a similar device (Fig. 9) was designed and built by Norton Co. (Hight, 1971) to determine the bulk density of diamond abrasive samples. It consists of a sample collecting tube which will hold a 20-g sample, funnel, vibrator, rheostat, depth gage, and timer. The cardinal rule in any determination of this type is close reproducibility of conditions from one test to another.

Another shape test is a microscopic technique, developed at the Diamond Research Laboratory, Johannesburg. It is fast and inexpensive but is quite subjective. This method was further refined by Custers and Raal (1959).

In this method four shape categories are recognized. Shape No. 1 is a near-perfect cube or sphere while shape No. 4 is a thin flake or a needlelike grain. Shapes No. 2 and No. 3 are intermediate with No. 2 nearer No. 1 and No. 3 nearer No. 4. The arithmetic mean of 100 grains is determined and this becomes the "shape count" for that particular sample.

A common and inexpensive friability test for measuring the strength of diamond is the Wig-L-Bug friability test mentioned on page 13.

A friability test which is similar in principle but much more sophisticated as to controlled running conditions was devised by Belling and Dyer (1965) at the Diamond Research Laboratory, Johannesburg.

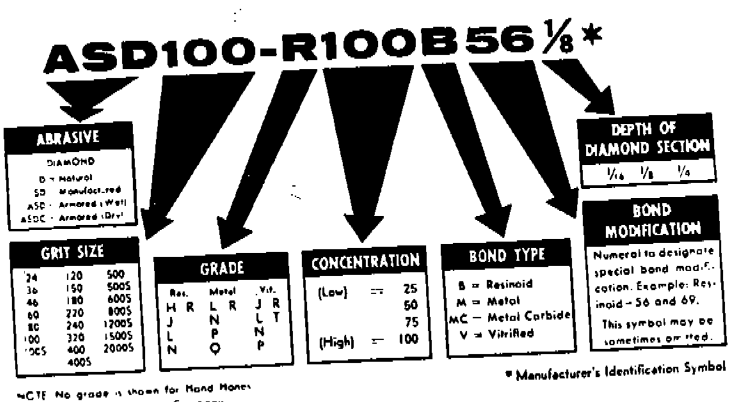

FIG. 8—*Diamond wheel marking system.*

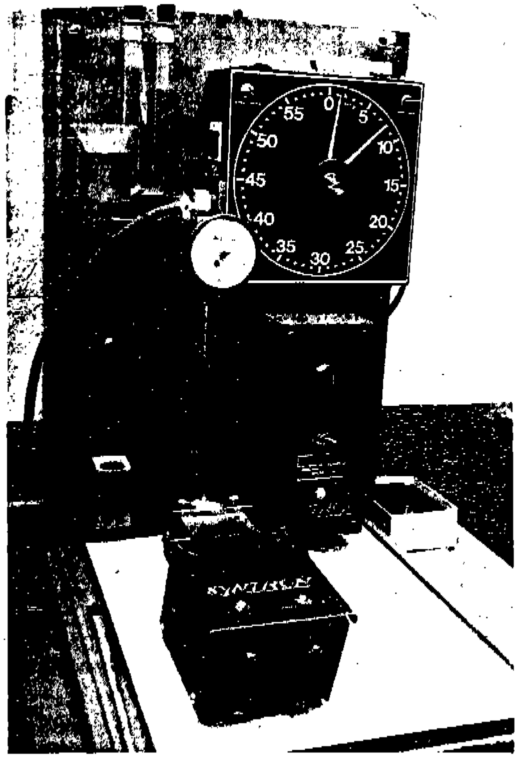

FIG. 9—*Tap-density apparatus.*

Garnet: † The name "garnet" is given to a group of iron-aluminum silicate minerals having similar physical properties, crystal forms, and general chemical formula.

Composition—In garnet, general formula $3RO \cdot R_2O_3 \cdot 3SiO_2$, the bivalent element may be calcium, magnesium, ferrous iron, or manganese, the trivalent element, aluminum, ferric iron, or chromium, rarely titanium; further, silicon is also replaced by titanium in some examples. There are three prominent groups and various subdivisions under each, many of these blending into each other. These are as follows:

1) Aluminum Garnet
   - A. Grossularite, calcium-aluminum garnet ($3CaO \cdot Al_2O_3 \cdot 3SiO_2$).
   - B. Pyrope, magnesium-aluminum garnet ($3MgO \cdot Al_2O_3 \cdot 3SiO_2$).
   - C. Almandite, iron-aluminum garnet ($3FeO \cdot Al_2O_3 \cdot 3SiO_2$).

† This portion of the chapter was originally prepared by H. H. Vogel, former Vice President of Barton Mines Corp. (now retired), and has been updated by Barton Mines Corp. staff.

   - D. Spessartite, manganese-aluminum garnet ($3MnO \cdot Al_2O_3 \cdot 3SiO_2$).

2) Iron Garnet
   - E. Andradite, calcium-iron garnet ($3CaO \cdot Fe_2O_3 \cdot 3SiO_2$).

3) Chromium Garnet
   - F. Uvarovite, calcium chromium garnet ($3CaO \cdot Cr_2O_3 \cdot 3SiO_2$).

Properties

Color—Colors vary greatly but generally are as follows:

Grossularite—white, pale green, or yellow.
Pyrope—deep red to black.
Almandite—deep red, brownish red to black.
Spessartite—brown to red.
Andradite—black, green, and yellow green.
Uvarovite—emerald green.

Hardness ranges from 6 (grossularite) to 7.5 (almandite); some almandite has a hardness of between 8.0 and 9.0.

Crystal System—Cubic, commonly as rhombic dodecahedrons or tetragonal trisoctahedrons, or in combination of the two.

Cleavage—Occasionally an indistinct dodecahedral cleavage is observed; some species of almandite possess a pronounced laminated structure, these are planes of weakness along which the mineral separates, this *parting* has no relation to the crystal form and is not a true cleavage.

Fracture—Garnets having a glassy structure usually have a marked conchoidal fracture but sometimes the mineral tends to break into thin flakes. In other varieties the fracture is sharp and uneven.

Index of Refraction—The index of refraction of the garnet group ranges from 1.735 to 1.94.

Tenacity—Aggregates of crystal composed of many small individuals are brittle and shatter readily. Massive garnet and well formed crystals are remarkably tough and shatter with difficulty.

Fusibility—Garnets having a high iron content, such as almandite, fuse at a temperature of about 1200°C. White garnets containing a considerable percentage of chromium are infusible.

Other Properties—Specific gravity of the garnet group ranges from 3.5 to 4.2; luster vitreous, resinous, or dull; transparent to opaque.

Production—Production of abrasive garnet in the United States, as published by US Bureau of Mines, is shown in Table 4.

Occurrence—Garnet commonly occurs as accessory minerals in a large variety of rocks,

TABLE 4—Production and Value of Garnet in the United States

Year	Short Tons*	Value, $
1973	22,772	2,380,000
1974	24,684	2,551,000
1975	17,204	2,092,000
1976	24,565	3,568,000
1977	20,022	3,136,000
1978	22,058	3,678,000
1979	23,303	4,335,000
1980	26,550	4,573,000
1981	27,850	4,300,000

Source: Adams, 1977; Baskin, 1979–1980; Smook, 1981.

*Metric equivalent: 1 st × 0.907 184 7 = t.

more particularly in gneisses and schists but also in contact metamorphic deposits, in crystalline limestones, pegmatites, and in serpentines. It occurs as gangue in ore veins formed at high temperatures. As most varieties of garnet are resistant to chemical and mechanical erosion, they tend to be concentrated in the sands of present-day or preexisting beaches, streams, or other alluvial deposits.

Deposits of garnet are found in many foreign countries and in nearly every state. An estimated 95% of the world's production of technical abrasive garnet comes from a small area in the Adirondack Mountains, New York State. Eighty percent of current usage of garnet is accounted for by United States industry.

The superior abrasive quality of Adirondack garnet currently being mined for technical applications is due to a combination of crystal properties including hardness (which is at the top of the garnet hardness range). This garnet, basically a combination of almandite and pyrope, exhibits incipient lamellar parting planes which break under pressure into sharp chisel-edged plates. When crushed to a very fine size it retains its natural sharp irregular grain shape. These features, particularly important in coated abrasives, are also desirable for other abrasive applications. Since Adirondack garnet occurs in large crystals a complete range of sizes results from the crushing and grinding operations necessary for liberating and separating the garnet from matrix minerals.

United States—In recent years garnet production in the United States has been confined almost exclusively to two states, New York and Idaho.

NEW YORK. Although there were at one time several technical abrasive-grade garnet producers in New York, present production is confined to one company, the Barton Mines Corp., Gore Mountain, near North Creek. This company supplies garnet to coated abrasive, glass, and metal lapping industries throughout much of the world. It has been in continuous operation since 1878 and, through technical advances enabling it to utilize leaner ores, has constantly proved new ore reserves. This mine is believed to be the country's second oldest continuous operating mine under one management and, geologically, is one of the world's most interesting ore deposits.

The almandite-bearing rock, which is an igneous-metamorphic rock of uncertain origin, lies at the surface and is quarried. The ore body is over 2 km (1¼ miles) long and ranges in width from 15.2 to 91.4 m (50 to 300 ft). The principal gangue minerals are hornblende and plagioclase feldspar which constitute from 40 to 80% of the rock. Less abundant minerals include hypersthene, magnetite, biotite, apatite, and pyrite. The garnet content of the ore body ranges from 20 to less than 5% and averages slightly less than 10%. The garnet occurs as crystals, mostly imperfectly developed, known locally as "pockets." These range in size from a fraction of an inch to more than a foot in diameter. Occasionally crystals up to 914 mm (36 in.) in diameter have been seen; however, their average size is less than 102 mm (4 in).

Nearly every crystal of garnet is surrounded by a rim of coarsely crystalline hornblende. The quarry faces present a striking appearance, showing crimson-red garnet crystals set in a coal black background. Specific gravity of the garnet averages about 3.95, while the hornblende ordinarily is 3.07 to 3.24, with some specimens of very dense hornblende having been found with a specific gravity as high as 3.40. The general matrix is diorite.

The ore is mined in benches about 12.2 m (40 ft) in height, hauled in trucks, and dumped into a crushing system designed for initial liberation of garnet particles and reduction of particle size to dimensions required for separating the garnet from gangue minerals and other impurities. Separation is accomplished through a combination of concentrating methods including heavy media, magnetic, flotation, screening, tabling, and air and water separation. Processes are interconnected and are continuous or semicontinuous until a concentrate of 98% minimum garnet content has been achieved for the various grade sizes.

Elsewhere in New York, garnet is produced as a byproduct of wollastonite mining at Willsboro by Interpace Corp. and is sold in graded form for sandblasting operations in the Northeast. This garnet occurs as loosely cemented fine crystals that appear to be remnants of weathering and water deposition within preexisting stream channels or along shorelines. Separation is made electromagnetically after crushing and drying of the wollastonite ore. Separation is not complete and varying amounts of wollastonite accompany the garnet in its packaged form.

IDAHO. The only other important producer of abrasive garnet is the Sunshine Mining Co.'s subsidiary, Idaho Garnet Abrasive Co., whose deposit is on Emerald Creek and whose plant is at the creek's mouth near Fernwood, Benewah County, Idaho. This company works an alluvial deposit of almandite garnet, derived from the erosion of soft mica schists in which the garnets have a maximum grain size of about 4.8 mm (3/16 in.).

The garnet bearing gravel is mined by dragline and the garnet is concentrated on jigs and tables. It is then crushed and screened into various sizes.

This garnet is used mainly for sandblasting and spark plug cleaning.

FOREIGN COUNTRIES—Garnet is or has been commercially mined in Madagascar, Japan, Argentina, India, and Tanzania. Garnet mining in Russia has been reported but details regarding mining are not known.

Preparation For Market—GRADING AND SIZING—Practically 100% of the garnet sold today is a sized and graded product. Sizings are governed by mining techniques and end use. They generally conform to standards established in cooperation with the National Bureau of Standards for quality criteria, standard methods of test, rating, certification so as to provide a uniform basis for fair competition. Grading standards for coated abrasive use and micron sizing for grades used in glass grinding and metal lapping have exceedingly close tolerances. Wheel grades, polishing grades, and sandblast grades each have different standards and much greater tolerances. Government specifications can be found in Product Standard PS8–67, Grading of Abrasive Grain on Coated Abrasive Products, and in Commercial Standard CS–271–65, Grading of Abrasive Grains for Grinding Wheels. Also there are innumerable special grades for tumbling and miscellaneous uses.

HEAT TREATMENT—Practically all garnet grain used today is heat treated as a processing function and not for the purpose of improving inherent abrasiveness. Impurities picked up during processing adhere to garnet particle surfaces and destroy cleanliness and capillarity needed in later processing to give adhesion for bonding. Early in the 1930s it was thought that "roasting" temperatures improved the hardness, toughness, and fracture of the garnet. In the late 1940s it was thought higher temperatures would further increase the abrasive quality. Temperatures approaching 1000°C were used for some products. In the early 1960s scientific investigation determined that too high a temperature could destroy the abrasive quality of garnet and that heat treating solely accomplished the cleansing of particle surfaces or at most it produced superficial heating of microscopic fractures on the grain surface. In the mid-1960s the coated abrasive industry accepted uniform color standards assuring cleanliness of the grain surface and presenting a color standard most closely approaching the natural red color of abrasive garnet. This degree of heat treatment is known as RT treatment.

TEST FOR ABRASIVE QUALITY OF GARNET—There is no exact method for testing the abrasive quality of garnet or any loose abrasive except by practical application. However, several rough tests and examinations serve to indicate their abrasive possibilities. The fracture, sharpness and shape of the grain, the character of the grain structure, and the determination of presence of inclusions of other minerals which would weaken the grain structure can be studied under the microscope. Hardness and toughness of grains can be determined roughly by placing a definite grade, such as #60, between two glass microscope slides and rubbing them together. The relative scratch hardness of the grains and the amount of breakdown can be indicated in this manner.

The US Bureau of Standards has developed an abrasive tester designed primarily for testing abrasive quality of corundum. This can be adapted for testing the abrasive quality of any loose abrasive grain. Loose abrasive grain is also tested on various production or laboratory machines for evaluating glass removal on flat plates. These data can be correlated with the anticipated performance of the material to be abraded as an evaluation of actual abrasive performance. In all these methods actual stock removal is determined either by weighing or measuring. In the coated abrasive industry, test belts are made and stock removal is measured on test blocks. These tests measure stock removal only, and are a valuable indicator when other important variables such as bond, backing, coating, flex, grit size, etc. are closely controlled.

In judging the abrasive quality of garnet as well as all other abrasives, stock removal, while important, is not the only factor in judging the value of an abrasive. Surface finish in most cases is perhaps a more important factor. An abrasive used on some materials can be too hard and cause deep scratches in the substructure which cannot be removed in subsequent operations. Also, if the abrasive does not have the proper grain shape or becomes dull in use and does not break down to yield new sharp cutting edges while in use, it will tend to burn or gouge the material being ground or surfaced, thus rendering it unusable in subsequent operations.

Uses And Markets—The major industrial uses of garnet are: manufacture of coated abrasive products; grinding and lapping of glass, metals, ceramics, plastics; and for sandblasting. There are also a number of miscellaneous uses.

Abrasive Papers and Cloth—Garnet-coated papers and cloths are used primarily for wood sanding but also for finishing of leather, hard rubber, plastics, glass, and the softer metals. Coated abrasives have been improved in recent years mainly by using resin bonds in place of glue bonds for certain applications. Also, electrostatic coating is now in general use. In this process an electrostatic charge causes the grains to imbed upright in the wet bond on the backing. In effect the sharp cutting edges of the grain are bonded perpendicular to the backing. It also causes the individual grain particles to be spaced more evenly due to individual grain repulsion.

Garnet paper and cloth products comprise approximately 10 to 11% of the total volume of coated abrasives produced for the past several years. This percentage has remained fairly constant notwithstanding the general growth of the economy and substitutions of abrasive papers and cloths for other grinding methods.

Glass Surfacing—During World War II when imported corundum became scarce for grinding of optical lenses the War Production Board searched for substitute abrasives. Garnet was the logical mineral, possessing desirable properties and availability, although it had never before been processed for this application. After development it fulfilled the critical need and by the time the war ended the desirable qualities of garnet were widely known, particularly because it decreased lens scratching to a considerable extent. Its use improved the quality and reduced rejections, both important factors in the economy of lens grinding. Garnet also produced a finish which reduced polishing time. These same properties which made garnet a competitive abrasive for this application continue to produce new markets in the glass, plastics, ceramics, and softer metals industries.

Loose Grains—A major nontechnical use of garnet in loose form is for sandblasting. Garnet has the advantage of having no free silica and hence cannot cause silicosis. It is heavier than quartz sand and, thus, grains of equal size deliver harder blows. Practically all production of Idaho garnet is sold to West Coast aircraft industries as a sandblast agent because of its price and location.

Gem Garnet—Some domestic garnet is marketed for cutting into semiprecious gems. The dollar value of this is small and unimportant. Ordinarily gem garnet is produced in parts of the world having low labor costs; there are numerous such sources of suitable quality garnet.

Miscellaneous Uses—In grain sizes garnet is used for the manufacture of grinding wheels, as tumbling media, for nonskid applications, and as filter media. In powder sizes it is made into lapping and buffing compounds.

Markets And Prices—The problems of the established producers of garnet are meeting costs of technological developments, maintenance, and increasing sales in the face of competition from other natural and manufactured abrasives. In general, every abrasive has an application in which it surpasses other abrasives. In most applications these qualifications overlap and it is in these overlapping fields where competition is keenest and is based on relative cost, considering grinding and finish abilities.

Garnet has kept its relative position in the expanding abrasive market and present producers have solved problems of maintaining necessary ore reserves through exploration and application of new mining technologies which permit economical use of leaner ores.

Although garnet is common in most states and countries throughout the world, most of it is of a quality that would be uncompetitive. However, there are potential new sources and much technical quality byproduct garnet available. Relatively large capital investment is required to produce garnet and this factor combined with the relatively small and specialized

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market discourages the opening of new deposits. Furthermore, the present market is adequately supplied by present producers.

Market prices of garnet grains and powders vary widely depending on garnet type, purity, particle size, grade control, shipping quantities, and packaging.

Silica: Silica sand and quartz are reviewed in detail elsewhere in the volume, so that only their abrasive use and applications are given here.

Silica Sand—Silica sand is extensively used for pressure blasting, for the initial grinding or surfacing of plate glass, and as a cutting medium for gang saws on stone.

For pressure blasting the main centers of production in the United States are Ottawa, IL, and Cape May, NJ. The Ottawa material occurs as a friable sandstone, which is broken down to its natural grain, washed, and screened. The grains are spherical in shape. The Cape May sand is subangular and uneven in shape but larger grain sizes are obtainable, more so than with the Ottawa sand.

In Canada, pressure blast sand is obtained from the decomposed rock containing friable quartz and china clay at Lac Remi, north of Montreal, Que.; from a similar type of material near Smoky Falls, north of Lake Nipissing, 40 km (25 miles) west of North Bay, Ont.; also from a friable quartzite at East Templeton, Que., a few miles northeast of Ottawa, Ont. The grain of the Canadian sands is sharp. The ranges of grain size are approximately: No. 1 between 20 and 35-mesh for light work; No. 2 between 10 and 28-mesh; No. 3 between 6 and 10, and No. 4 between 4 and 8-mesh. The last two are used for the heavy cast-iron work and steel work.

Pure, clean beach and river sands and Illinois sand are used for the preliminary or coarse surfacing of plate glass. The crushed sand is water-graded into a number of grades at the glass plants and fed to the surfacing machines. Approximately three tons of sand are required to surface one ton of plate glass.

Cutting sand, composed of sharp, solid quartz grains, is used as an abrasive for sawing stone. It is usually ungraded and about equivalent to a No. 1 pressure blasting sand.

Burnishing sand is a fine, rounded-grain silica sand of uniform size between 65 and 100-mesh, used in rolling down and burnishing gold decorations on porcelain.

Evans (1980) gives the following quantities and values for industrial sand sold or used by producers in the US: for grinding and polishing 190.5 kt (210,000 st) at $1,710,000 and for pressure blasting 1.7 Mt (1,868,000 st) at $13,645,000.

Although production figures are not available at this time, it should be noted that blast furnace slags have been processed and used as substitutes for pressure blasting sand. Increased use of such materials may be expected in the future because of the possible health and environmental advantages over silica products.

Quartz—Crushed and graded quartz is used for the abrasive backing of "flint" sandpapers. Almost any deposit of massive white quartz is suitable. Being the cheapest of all the abrasive-coated paper, it still is sold in fair amount, mainly in hardware stores and by small jobbers. It is made only in the form of paper, not as cloth. True chalk flint from England and France is extensively employed for this purpose in Europe and has better cutting qualities and longer life than ordinary quartz.

Powdered quartz and silt are sometimes used for scouring compounds and for the harsher metal polishes.

Sand and sandstone are also crushed and ground and used for abrasive purposes, as in hand soaps, scouring compounds, metal polishes, etc. In 1979, Tepordei (1978-1979) reported a sale for abrasive use of 366.5 kt (404,000 st) of ground sand valued at about $5 million.

Soft Siliceous Powder Abrasives: Many natural highly siliceous materials either occur as a powder or are used only in the powder form for mild abrasives. For the majority of these, use as an abrasive is of minor importance as compared with their principal applications. Among these, diatomite, pumice, and tripoli are reviewed elsewhere in this volume. Their abrasive uses are therefore given only briefly here.

DIATOMITE—Diatomite production in the United States comes primarily from California and Nevada with small outputs from Oregon and Arizona (Table 5).

The amount used for abrasives is insignificant in comparison with its other applications —most important of which are filtration, fillers and insulation. Its abrasive uses include metal (silver) polishes, dental powders and pastes, and occasionally it is used as a friction agent in the manufacture of matches.

PUMICE—Under the name of pumice are included lump pumice and pumicite or volcanic

TABLE 5—Diatomite Sold or Used by Producers in the United States

Year	Domestic Production (Sales), Short Tons*	Average Value Per Ton, $
1973	609,000	59.26
1974	664,000	76.31
1975	573,000	80.01
1976	631,000	87.08
1977	648,000	98.56
1978	651,000	111.26
1979	717,000	125.97
1980	689,000	146.02
1981	707,000	152.48

Source: Meisinger, 1982.
*Metric equivalent: 1 st × 0.907 184 7 = t.

dust, the natural powder. Lump pumice is used by manufacturers of furniture and musical instruments; for dressing the wood and metal surfaces; by silver platers for preparing their metal surfaces: by lithographers for cleaning stone surfaces; for rubbing down and polishing fine tools and instruments; by restaurants for scouring grills and cooking utensils, and for domestic and toilet uses, such as hand cleaners. Pumicite or ground pumice is mainly used as a cleanser, the thin, sharp, and striated grains being particularly suitable.

The use of pumice as an abrasive has declined greatly in the last decade; the largest drop was in pumice, mostly pumicite, used in cleaning and scouring compounds and in hand soaps. Abrasive use of pumice now accounts for less than 1% of total production. Minor uses for abrasive pumice are in polishing compounds; polishing powders for bone, celluloid, and hard rubber; for dental use; and in some rubber erasers.

The 1980 consumption of pumice for abrasive purposes was about 24 kt (27,000 st), with a value of $568,000.

The consumption of pumice for "other uses" which includes abrasive use has declined from approximately 907 kt (1,000,000 st) in 1955 to 492.6 kt (543,000) in 1980.

TRIPOLI, MICROCRYSTALLINE SILICA, AND ROTTENSTONE—The fine-grained, porous materials, tripoli, microcrystalline silica, and rottenstone, are known to the trade as "sift silicas."

Tripoli, which in the United States comes from southwest Missouri and northeast Oklahoma, is mainly used in the form of made-up tripoli grease bricks or tripoli compositions for buffing and polishing. The compound is applied to a rapidly revolving belt or canvas wheel and used for the finishing or buffing of metals, plated products, and so forth. It is used also to a small extent in the manufacture of some scouring and cleaning powders and soaps; for the rubbing down of painted surfaces, such as automobile bodies. A similar but finer-grained material occurring in the northwest corner of Arkansas, about 80 km (50 miles) southeast of the Missouri deposits, is used mainly for oil-well drilling mud.

Microcrystalline (sometimes erroneously termed "amorphous") silica, which comes mainly from southwestern Illinois but to some extent from Wayne County, TN, also is used for buffing and polishing compounds. These compounds are termed "silica" by the trade and are much in demand for white "coloring" operations on high-class work. Chemically precipitated amorphous silicas also are used in polishing and buffing compositions.

Both tripoli and microcrystalline silica have been mined from deposits at Harrisburg, northwestern Georgia.

Rottenstone, a fine-grained gray-buff siliceous-argillaceous limestone, comes from Antes Forte, Lycoming County, PA, and is used as a polish base, for instance, for automobile polishes.

The domestic production of tripoli, rottenstone, and amorphous silica for abrasive use in the past few years has ranged from 72.5 to 116 kt (80,000 to 128,000 stpy) with a crude value of about $6 per st. Processed tripoli has values which range from $60 to $80 per st.

Nonsiliceous Soft Abrasives: *Ground Feldspar* is extensively used in scouring and cleaning compounds and for a window cleaner.

Chalk (calcium carbonate) is a soft, compact, fine-grained, white limestone composed of the calcareous remains of small marine shells. A small amount of this chalk—mainly from England and France—known as "whiting" is used as a very mild abrasive for hand polishing of nickel, gold, silver or plated ware, buttons, and similar materials.

China Clay (kaolin) and some pipe clays have been used successfully in polishing powders. Pipe clay at one time was the standard polish for naval and military tunic buttons.

BATH BRICK, used for scouring steel utensils, is made from a very fine-grained, quartzose clay found along the banks of the Parrot River in England.

STAUROLITE, a complex iron aluminum silicate, has been commercially recovered from various river placer deposits in the southeastern US. DuPont operates a deposit in Clay County, FL. It is used mostly for pressure blasting.

Sharpening Stones: Hand-used sharpening stones include scythestones, whetstones, oil stones, water stones, razor hones, holystones, and rubbing stones. While, in general, stones made from bonded artificial abrasive grains have largely replaced these natural abrasives there is still some small production of oilstones and whetstones in Arkansas, whetstones in Indiana, and scythestones in New Hampshire. Arkansas novaculite stones are still preferred for sharpening fine-edged tools for surgeons, carvers, and engravers. It is claimed that these stones give a smoother and longer-lasting edge.

Natural abrasive stones are made from a wide variety of material, including sandstone, novaculite, mica schist, siliceous argillite, shale, slate, and pumice. The superior cutting quality of some of these stones is due to the inclusion of well disseminated fine-grained inclusions of garnet or other minerals of superior hardness.

Grinding Pebbles and Tube-Mill Linings: Tube-mills, conical-mills, and cylindrical batch mills are used more often than any others for the fine grinding of hard ores, minerals, paints, chemicals, ceramic bodies and glazes and enamels, portland cement clinker, and similar materials.

Most efficient grinding can be done in mills with iron or steel liners and iron or steel balls, slugs, or rods, but where contamination of the color or chemical purity of the product by metals and metal oxides must be avoided, the grinding surfaces consist of blocks or bricks for the mill linings and natural pebbles or artificially prepared balls.

These materials should (1) have high abrasive hardness; (2) have great toughness and freedom from flaws, which will result in breaking and chipping; (3) produce a white powder when abraded; and (4) contain no dark-colored metallic impurities such as iron or manganese. While most of the natural and artificial mill linings and pebbles have a specific gravity close to that of quartz (2.6), a greater density in pebbles has obvious advantages. The heavier the pebbles per unit of size, the greater are the impact and abrasive grinding forces. Thus, with heavy pebbles less mill volume is needed for a given pebble load (by weight), resulting in greater mill capacity; or with equal pebble volume, faster grinding can be done. Small balls grind finer than large ones (because of more surface area per pound), but with small pebbles the unit weight is low unless high-density pebbles or balls are used.

The most favored natural mill-lining material for most purposes is Belgian silex, which is a very hard, tough, more or less cellular quartzite resembling French buhrstone. This is imported in rectangular blocks more or less shaped to fit the curve of a mill. During World Wars I and II, when imports were cut off, and to a much lesser extent at other times, domestic substitutes have been used. These have consisted chiefly of quartzite from near Jasper, MN; Iron City, TN; and Baraboo, WI; and granites from Salisbury, Lilesville, and Faith, NC. Some of these materials are reported to give service equal to that of Belgian silex. Special hard, dense, porcelain blocks are used in some mills for grinding paint, ceramic, and chemical materials.

For grinding media, Danish flint pebbles, when available, have long been standard because of their superior hardness, toughness, and uniformity. These pebbles are found on the shores of Greenland but are marketed through Denmark. Other foreign sources of similar pebbles exist along the seacoasts of Belgium, France (between Havre and St. Valery-sur-Somme), Norway, and England. Seven sizes of Danish pebbles are marketed, ranging from 25.4 to 203 mm (1 to nearly 8 in).

Domestic substitutes for grinding media are natural pebbles of flint, quartz, and quartzite, as well as artificially rounded (by tumbling small blocks in rotating cylinders) pebbles made from quartzite, granite, chalcedonized rhyolite, and other rocks. During World War II, pebbles were shipped from Encinitas Beach, CA (true flint); from Jasper, MN (quartzite); from the Austin chalk beds in south-central Texas (true flint); from Salisbury and Faith, NC (granite); from Baraboo, WI (quartzite), and several other points in the United States. Extensive deposits of quartzite pebbles in southwestern Saskatchewan have been reported. Beach pebbles were reported non-uniform in hardness and requiring careful sorting.

Ceramic pebbles are made from very dense, tough porcelain, alumina, and sillimanite (mullite). A dense, heavy pebble is made from zircon, having a specific gravity of 3.7. For certain purposes blocks of ore are used as grinding media; thus nepheline syenite blocks are used instead of pebbles for grinding this material.

Table 6 shows production statistics for special silica-stone products.

TABLE 6—Special Silica-Stone Products Including Grinding Pebbles, Grinostones, Oilstones, Tube-Mill Liners, and Whetstones

	1975	1976	1977	1978	1979	1980	1981
Short tons*	2,953	2,696	2,200	2,175	2,094	2,131	1,978
Value (thousand $)	1,061	1,404	3,236	2,630	2,064	2,233	2,660

Source: Baskin, 1978–1979; Smook, 1982.
*Metric equivalent: 1 st × 0.907 184 7 = t.

Manufactured (Artificial) Abrasives

The discovery of the electric-furnace method for making silicon carbide by Edward G. Acheson in 1891 began the revolution in the high-grade abrasives industry. Prior to that time, all abrasives were natural minerals and rocks, except for minor chemically prepared materials such as rouge and Vienna lime. Today, as noted before, artificial abrasives, with a few notable exceptions such as diamond and garnet, dominate if not monopolize the field of high-grade abrasives.

Manufactured abrasives are essential to modern industry because they are not only superior to natural abrasives but they are also much more uniform in quality and their properties can be varied to meet differing needs. Modern high-speed streamlined production methods require very accurate, specialized tools with a degree of uniformity and dependability that cannot be met with natural abrasives.

Manufactured abrasives may be divided into three main groups: (1) electric furnace products, (2) chemical precipitates, with (3) several miscellaneous additions.

Table 7 (Baskin, 1978-1979) gives production statistics for certain types of artificial abrasives.

Electric-Furnace Abrasives: Electric-furnace abrasives include silicon carbide, aluminum oxide, and boron carbide. Tungsten carbide, tantalum, and titanium carbides are used in making cemented-carbide high-speed cutting tools but are not considered as abrasives in customary usage.

Silicon Carbide—Silicon carbide, with the chemical formula SiC, is commonly known by the trade names Carborundum, Crystolon, and Carbolon. It is made by fusing a mixture of high-grade silica sand and carbon in an electric furnace. The preferable form of carbon used today is petroleum coke, but anthracite and coke made from coal low in ash have been used. High iron and alumina in the ash are objectionable because they tend to assist in the formation of elemental graphite and metallic silicon during the reaction. High-ash carbons make impure grades of silicon carbides.

"Silicon carbide is made by charging a resistance type electric furnace with pure glass sand . . . finely ground petroleum coke, saw-

TABLE 7—Crude Artificial Abrasives Produced in the United States and Canada (Thousand St‡ and Thousand $)

Kind	1975	1976	1977	1978	1979	1980	1981
Silicon carbide*	134	159	192	182	196	170	159
Value	$31,842	$45,953	$53,814	$51,371	$62,702	$64,346	$70,941
Aluminum oxide (abrasive grade)*	141	191	185	142	225	193	199
Value	$28,368	$43,356	$48,819	$46,633	$67,511	$63,881	$67,253
Aluminum zirconium oxide	17	20	20	23	28	19	W
Value	$8,506	$11,383	$11,281	$14,668	$14,893	$8,438	W
Metallic abrasives†	236	250	243	204	264	235	247
Value	$72,864	$75,372	$72,740	$59,882	$84,918	$81,935	$90,471
Total	528	620	640	551	713	617	605
Value	$141,580	$176,064	$186,654	$172,554	$230,024	$218,600	$228,665

Source: Baskin, 1980; Smook, 1982.
*Figures include material used for refractories and other nonabrasive purposes.
†Shipments for US plants only.
W = Withheld.
‡Metric equivalent: 1 st × 0.907 184 7 = t.

Oilstones,

980	1981
131	1,978
233	2,660

gives produc- s of artificial

lectric-furnace de, aluminum ngsten carbide, s are used in -speed cutting s abrasives in

bide, with the only known by Crystolon, and g a mixture of n in an electric of carbon used anthracite and ash have been in the ash are to assist in the e and metallic gh-ash carbons carbides.

charging a re- with pure glass eum coke, saw-

nada

1980	1981
170	159
$64,346	$70,941
193	199
$63,881	$67,253
19	W
$8,438	W
235	247
$81,935	$90,471
617	605
218,600	$228,665

dust and common salt. The silicon of the sand combines with the coke, which is carbon, to form silicon carbide. The sawdust makes the mixture porous so that the carbon monoxide gas formed in the course of the chemical reaction can escape freely" (Heywood, 1942). The salt (sodium chloride) combines with the various impurities in the sand and coke to form chlorides, which can then be eliminated from the mix, by volatilization. The temperature at the core of the furnace is about 2200°C. If the temperature is too high, silicon carbide decomposes, the silica being volatilized and the carbon becoming graphitized. The time of a run is about 60 hr (36 hr heating and 24 hr cooling). At the end of the run the core consists of loosely knitted silicon carbide crystals surrounded by unreacted or partially reacted raw materials. The quality of the product depends largely on the raw materials used and the accuracy of control and operation of the furnace.

Several types of products are made in which the toughness of the grains is varied. A special surface treatment is given to grains for coated abrasives to increase adhesion of the glue.

The lump material from the furnace is crushed, first in jaw crushers then in rolls, hammer mills, or ball mills, passed through a magnetic separator to remove magnetic impurities, and then washed to remove dust. The grains are then dried and screened mechanically into 20 or more standard sizes, from 8 to 240-mesh. The finer flour sizes are made by air or water flotation and sedimentation.

Fused Aluminum Oxide: Aluminum oxide abrasives are made in electric-arc furnaces. Bauxite, the crude raw material, should have the following typical physical and chemical properties:

Typical Chemical Analysis

Al_2O_3	85.0% to 87.0%
TiO_2	3.0% to 4.5%
SiO_2	3.0% to 5.5%
Fe_2O_3	6.0% to 10.3%
L.O.I. plus combined water	1.0% to 2.0%

The ore as mined is crushed, then calcined in rotary kilns to remove both free and combined water. The calcined ore is mixed with iron borings (about 2%) and ground coke (about 3%) and charged into the furnace. The coke reduces the impurities which combine with the iron and sink to the bottom of the furnace.

At the end of the melting period, the charge is allowed to cool under controlled conditions to obtain desired texture. The finished, crystallized alumina consists of about 95% Al_2O_3, 3% TiO_2, 1.5 % SiO_2, and 0.5% Fe_2O_3. For certain purposes, Bayer-process alumina is used instead of calcined bauxite, making a product with about 99% Al_2O_3.

The cooled mass from the furnace is crushed, screened, and cleaned in about the way that silicon carbide is treated. Here also several types of grain are made, varying in toughness, type of fracture, glue adhesion, and other properties.

Two new heavy-duty abrasives have been developed recently. One is an electric furnace fusion product made up primarily of an intimately crystallized mixture of aluminum oxide and zirconia. Although other proportions have been successful, those containing approximately 25% and 40% zirconia, respectively, have found most widespread commercial application.

These fused alumina-zirconia abrasives are noted for their extreme durability and therefore are particularly well suited for foundry snagging and steel conditioning operations.

The other family of new abrasives is the sintered product. This differs drastically in method of manufacture from the more traditional fused product in that the raw materials are heated in kilns only to the sintering temperature (1200°C±) rather than being carried all the way to the fusion point (2000°C±). Although other basic starting materials have been used, bauxite with or without additives is formed while still in the green (unfired) state into predetermined sized and shaped granules by certain granulation techniques or by extrusion through an appropriately shaped orifice. The resultant presized and preshaped granules are then sintered to make the finished abrasive grain. Process steps, such as crushing, shaping, sizing, washing, and drying common to manufacturing fused products, are thus eliminated in making a sintered product.

Typical Screen Analysis

+1/2 mesh	4%
+3 mesh	11%
+14 mesh	42%
+65 mesh	24%
+100 mesh	6%
+200 mesh	9%
+200 mesh	4%

Boron Carbide: Boron carbide is an artificial abrasive introduced in 1934 by the Norton Co. under the name of Norbide. Its chemical formula is B_4C. Although considerably harder than silicon carbide it is far from the hardness of the diamond (see Table 1). It is made from boric oxide, B_2O_3, and carbon in the form of petroleum coke in a carbon resistance furnace at a temperature of about 2600°C. The finished product is crushed and ground to make a range of sizes of grains and powders. In grain form it is used for grinding and lapping operations for jobs previously possible only with diamond dust. Pulverized Norbide may be molded under very high heat and pressure to form extremely wear-resistant products such as pressure blast nozzle liners, thread guides, extrusion dies, and all types of extremely accurate plug, snap, and ring gages. It is not manufactured into bonded wheels or sharpening stones.

Boron Nitride: Boron nitride in cubic form is a new, manufactured abrasive discovered by General Electric Co. laboratories in 1957 and trademarked "Borazon."

It, unlike manufactured diamond, has no known counterpart in nature. It is made at temperatures and pressures comparable to those required for diamond manufacture. The thermal stability of cubic boron nitride exceeds that of diamond. It is stable at temperatures above 1371°C (2500°F) while diamond reverts to graphite at about 816°C (1500°F). The Knoop hardness (K_{100}) is 4700 which places it well above the ordinary abrasives but inferior to diamond (General Electric Co., 1970).

In resinoid bonded grinding wheels Borazon has been found to be effective in grinding hard and tough tool steels.

Tungsten Carbide: Tungsten carbide is classed as a cutting medium rather than as an abrasive. However, it could be argued that the action of the rock bit tipped with tungsten carbide on the end of the steel shank of a jackhammer is as much abrasive as it is cutting. Certainly the almost universal use of tungsten carbide tip on such bits has revolutionized drilling blastholes in mining and quarrying operations. Costs have been reduced because the penetration rate is increased, a smaller hole can be drilled permitting the use of sticks of dynamite with reduced diameter, giving more economical use of the explosive.

Mention has been made in an earlier paragraph of the use of steel impregnated with tungsten carbide in saw blades.

Manufactured Diamond: In February 1955, General Electric Co. announced that its laboratories had succeeded in producing diamond from carbonaceous material subjected to pressures of around 5.5 GPa (800,000 psi) at very high temperatures for prolonged periods. Crystals up to 1.6 mm (1/16 in.) long were made in 16 hr but smaller ones were produced in much shorter times. The press is capable of maintaining temperatures above 2760°C (5000°F) at pressures up to about 11 GPa (1.6 million psi). Costs were reported to be about twice that of comparable natural diamonds and sizes were small; nevertheless economical commercial production was anticipated. The diamonds so far made have not been of gem quality.

In October 1957, the company announced it had produced well over 100,000 carats and that by the end of the year a "substantial quantity" would be in industrial use. The company also stated that diamonds could now be made in a relatively few minutes and that their performance equals that of natural diamonds.

The use of manufactured diamond has steadily increased. In 1969, domestic production of manufactured industrial diamond amounted to approximately 13 million carats; by 1981 this quantity had soared to approximately 57.0 million carats.

Today there are several types of manufactured diamond on the market, of both domestic and foreign manufacture, each with unique characteristics which make them suitable for the specific end-use applications previously discussed under "Industrial Diamond (Natural)."

In resinoid bonded grinding wheels, the adherence of the bond to the abrasive seems to be improved if the diamond is metal-coated. Hence, metal-coated (nickel, copper) diamond is still another commercially available diamond type.

Metallic Abrasives: Metallic abrasives include crushed steel, steel shot, angular steel grit, steel wool, brass wool, and copper wool. The following description of the first three of these products is by Johnson and Schauble (1939):

> Crushed steel is made from high-carbon and crucible sheet steel specially treated to impart brittleness. It is then crushed to sizes ranging from 2 to 200-mesh. After screening, each batch is heat-treated and separated into 25 sizes ranging from 20 to 200-mesh. Sizes from 70-mesh upward are screened on silk bolting cloth, and the finer sizes in powder form are used in steel cement, various chemical compounds, and fireworks sparklers.
>
> Steel shot is merely chilled cast iron. Only raw materials of the highest grade, including selected scrap and charcoal iron, are used in its manufacture; these are melted in a cupola. During the casting period, the molten metal is separated into small spheri-

cal globules by directing high-pressure steam or heated compressed air against the stream of metal. The globules are blown into water and cooled. The shot, made brittle by the rapid cooling, is heat-treated to impart a temper of hardness and graded by mechanical means into 15 sizes that range from 4 to 90-mesh. Coarse material left on the 4-mesh screen is granulated by specially designed crushing equipment and in this form is known as angular steel grit. The crushed material is heat-treated to impart toughness and durability, then graded into 15 sizes ranging from 7 to 100-mesh. Steel shot and angular steel grit are used for many abrasive purposes.

Steel wool, made from both ordinary and stainless steel, in various finenesses, is used for finishing wood and soft metals such as aluminum and for scouring and cleaning. It is made in several types of machines by shaving or scraping continuously moving wire with a fixed serrated cutting tool. Brass and copper wool are used chiefly for household cleaning.

Chemical Precipitates: Chemical precipitates, mainly oxides, all have a very fine grain size and are used as final polishing agents.

Iron Oxides—ROUGE, a ferric oxide, has its largest use in the polishing of plate glass, but is also widely used in powder, paste, coated cloth, and stick form for polishing precious metals, stone, and other materials to give a final high luster.

CROCUS, similar to rouge in composition but a purplish red in color, is used in finishing cutlery and some brass work.

BLACK ROUGE, a precipitated black magnetic iron oxide, is used primarily in plate printing inks and in paints, but has small abrasive applications.

Other Precipitates—CHROMIUM OXIDE or "Green Rouge" is used chiefly for platinum and stainless steels.

TIN OXIDE is used largely for polishing glass and precious stones.

PUTTY POWDER is a mixture of tin oxide and oxalic acid, used for about the same purposes as tin oxide.

CERIUM OXIDE is a polishing agent for polishing glass and a substitute for tin oxide for some other uses.

MANGANESE DIOXIDE is reported as having limited abrasive use.

MAGNESIA in the soft precipitated form has been noted as a mild polishing powder. The hard-burned variety, artificial periclase, also has been used as an abrasive.

CALCIUM CARBONATE, precipitated, is a mild abrasive used in some dentifrices.

CALCIUM OXIDE OR LIME, under the names of Vienna lime or Sheffield lime, has important abrasive uses. This so-called Vienna lime (originally from Vienna, Austria), which is used on the American continent in grease-brick buffing composition, is obtained from certain beds of dolomite at Francis Creek and Manitowoc, WI. Vienna lime is made by calcining the dolomite and cleaning and grinding to a certain fineness. It is packed in carefully sealed containers. As soon as the lime becomes hydrated it ceases to function and also attacks the grease compositions. It is used for the buffing of brass, copper, bronze, steel, pearl, celluloid, and similar materials but its main use is for the coloring of nickel after plating, as it gives nickel a deep undersurface blue peculiar to the metal. Lime attacks aluminum, therefore it is not used on that metal.

The use of porcelain blocks and pebbles for grinding mills has been noted. This "porcelain" may consist largely of zirconium oxides or silicate, or of mullite converted from andalusite, kyanite or dumortierite.

Miscellaneous Manufactured Abrasives: *Glass*, crushed and screened, has been used for coated abrasives to make "glass" paper.

Lampblack, known as "satin rouge," finds some use for polishing celluloid and bone.

Clay, very hard burned and finely pulverized, has been reported as used as an abrasive for polishing metal.

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