ABRASIVES

1. Introduction

An abrasive is a substance used to abrade, smooth, or polish an object. If the object is soft, such as wood, then relatively soft abrasive materials may be used. Usually, however, abrasive connotes very hard substances ranging from naturally occuring sands to the hardest material known, diamond.

Abrasives were literally as old or older than the Egyptian pyramids; in ancient times, humans used a variety of materials to refine or polish surfaces. For example, the Chinese used corncob skins for polishing. Shark skin, with its dermal denticles known as placoid scales, naturally provided abrasive properties. Humans also harvested the most common and abundant minerals in the earth's crust, namely, the quartz family of minerals. The ancient Greeks called quartz "crystal" and this quartz took the form of sandstone, loose sand, and flint. This crystal material was used in the abrading of stone, wood, metal and grinding grains, and limestone. Additionally, the ancient Greeks developed the use of corundum (naturally occurring aluminum oxide) and garnet, which were superior to quartz. Other abrasive materials known were hematite, now known as Jeweler's rouge, in 325 BC by Theophratus (1). Diamond as a polishing material was referenced in India in 800 BC (2) and its exceptional hardness was referred to in ancient Hindu proverbs (3) and in the Bible (4).

During the Industrial Revolution of the 1800s, the development of abrasive articles went hand in hand with the metal-working industry. In early years, sandstone rocks were mined out of the earth and carved into grinding wheels. Flint and naturally occurring corundum were bonded to paper to form sandpaper. The abrasive grains used were primarily mined materials such as sandstone, quartz, naturally occurring corundum, and garnet. These minerals had significant amounts of impurities, including iron, silica, and silicates, which lowered their abrasive grain hardness and hindered their performance. During the late 1800s, and early 1900s, synthetically manufactured abrasive grains revolutionized the abrasive industry. The synthetic abrasives tended to be harder, tougher and purer than mined abrasive grains. Edward Acheson is credited with inventing synthesized silicon carbide in 1891 (5). Excluding diamond, silicon carbide was the hardest abrasive grain available for years to come. Even today, silicon carbide is produced under essentially the same process and furnace that Acheson invented. The silicon source (typically from very pure sand) and carbon source (usually graphite) are reacted at temperatures in excess of 2000°C to cause the reduction of silica by carbon.

Around the turn of the twentieth century, synthetically manufactured fused alumina was invented. In this process, alumina-based raw materials are heated above its melting point, typically ~2000°C, and subsequently cooled to form fused alumina. This basic process was originally patented by Werlein (6) in France in 1893 and by Hasslacher (7) in Germany in 1894. This process was further advanced by C. M. Hall through the addition of iron borings into the fusion melt to remove metallic impurities (8). The resulting aluminous abrasive grain was purer. A. C. Higgins then developed an improved furnace design that involved the use of a water-cooled shell container (9). This new furnace design used a solid, thin alumina coating on the furnace walls that prevented the molten alumina from attacking the steel furnace walls. This basic Higgins furnace design is still widely used today in manufacturing many fused alumina grains.

Over these multitude of centuries, abrasive articles were employed, quite simply, to change a surface. These abrasive articles relied on a broad range of technologies including ceramics, inorganic chemistry, paper, textiles, organic chemistry, polymer science, and related process technologies. During the past 150 years, as these technologies grew, so did the advancement of abrasive technologies to create abrasive articles with even higher efficiencies.

There are four major forms of abrasive articles. A bonded abrasive is a three-dimensional (3D) composite of abrasive grains dispersed in a bond system. This bond system may be organic (eg, resinoid wheels) glassy inorganic bond (vitrified wheels), or metallic. Bonded abrasives are commercially available in a wide variety of forms including wheels (most popular), stones, mounted points, saws, segments, and the like. Coated abrasives are generally described as a plurality of abrasive grains bonded to a backing. Nonwoven abrasives comprise a plurality of abrasive grains bonded into and onto a porous non-woven web substrate. Nonwoven and coated abrasives are also available in a wide variety of converted forms of belts, sheets, disks, cones, flap wheels, etc. Loose abrasive slurries comprise a plurality of abrasive grains dispersed in a liquid medium, such as water. Loose abrasive slurries are typically employed in polishing type applications where a very fine surface finish is desired.

These abrasive articles are used in a plethora of different refining processes including metal degating, grinding, shaping, cutting, deburring, finishing, sanding, cleaning, polishing, and planarizing. Today abrasive articles are employed in some aspect in most manufactured goods sold. The abrasive article may be used in the supporting equipment to make the manufactured good and/or the direct process to produce the manufactured good. For examples, resinoid grinding wheels are used to remove metal gates from castings, where cut rate is measured in mm^3/s. Coated abrasive belts grind away parting lines from a forged hand tool and consequently reshape the surface of the hand tool. Metal bonded saws are employed to cut through concrete in road construction. Nonwoven flap wheels debur the surface of metal components. Coated abrasive belts sand wood boards to a finished surface such that these wood boards are ready for staining. Nonwoven abrasives are popular for cleaning the surface of metal components including cooking utensils. Loose abrasive slurries are utilized in precision polishing, eg, in semiconductor planarization or polishing glass to optical clarity.

2. Properties of Abrasive Materials

2.1. Hardness. Table 1 lists the various scales of hardness used for abrasives. The earliest scale was developed by the German mineralogist Friedrich Mohs in 1820. It is based on the relative scratch hardness of one mineral compared to another ranging from talc, assigned a value of 1, to diamond, assigned a value of 10. Mohs' scale has two limitations; it is not linear

Table 1. **Scales of Hardness**

Material	CAS Registry Number	Mohs' scale	Ridgeway's[a] scale	Woodell's[b] scale	Knoop hardness[c] kN/m^2,[d]
talc	[14807-96-6]	1			
gypsum	[13397-24-5]	2			
calcite	[13397-26-7]	2			
fluorite	[7789-75-5]	4			
apatite	[1306-05-4]	5			
orthoclase	[12251-44-4]	6	6		
vitreous silica	[60676-86-0]		7		
quartz	[14808-60-7]	7	8	7	8
topaz	[1302-59-6]	8	9		13
garnet	[12178-41-5]		10		13
corundum	[1302-74-5]	9		9	20
fused ZrO_2	[1314-23-4]		11		11
fused Al_2O_3/ZrO_2[e]					16
fused Al_2O_3	[1344-28-1]		12		21
SiC	[409-21-2]		13	14	24
boron carbide	[13069-32-8]		14		27
cubic boron nitride	[10043-11-5]				46
diamond	[7782-41-3]	10	15	42.5	78

[a] Ref. 10.

[b] Ref. 11.

[c] At a 100-g load (K-100) average.

[d] To convert kN/m^2 to kgf/mm^2 divide by 0.00981.

[e] 39% ZrO_2 (NZ Alundum).

and, because most modern abrasives fall between 9 and 10, there is insufficient delineation. Ridgeway and co-workers (10) modified Mohs' scale by giving garnet a hardness value of 10 ($H = 10$) and making diamond 15. Woodell (11) extended the scale even further by using resistance to abrasion, where diamond equals 42.5. This method is dynamic and less affected by surface hardness variations than the other methods, which involve indentation.

Knoop developed an accepted method of measuring abrasive hardness using a diamond indenter of pyramidal shape and forcing it into the material to be evaluated with a fixed, often 100 g, load. The depth of penetration is then determined from the length and width of the indentation produced. Unlike Woodell's method, Knoop values are static and primarily measure resistance to plastic flow and surface deformation. Variables such as load, temperature, and environment, which affect determination of hardness by the Knoop procedure, have been examined in detail (12).

A linear relationship exists between the cohesive energy density of an abrasive (13) and the Woodell wear resistance values occurring between corundum ($H = 9$) and diamond ($H = 42.5$). The cohesive energy density is a measure of the lattice energy per unit volume.

2.2. Toughness. An abrasive's toughness is often measured and expressed as the degree of friability, the ability of an abrasive grit to withstand impact without cracking, spalling, or shattering. Toughness is often considered a measure of resistance to fracture and given the symbol K_c. This value is directly related to the load on an indenter required to initiate cracking and leads to a brittleness index defined as hardness/K_c (14).

A practical industry friability test (15) for abrasives involves careful sizing of subject grains to pass a given sieve size while being retained on the next finer screen. A unit weight of this grain is then ball-milled using a standard steel ball load for a given time. The percentage of milled grain retained on the original screen is a measure of toughness or lack of friability. Other methods of evaluating this property involve centrifugally impacting sized grits and then evaluating the debris (16).

2.3. Refractoriness (Melting Temperature). Instantaneous grinding temperatures may exceed exceptionally high temperatures at the interface between an abrasive and the workpiece being ground (17). Hence, melting temperature is an important property. Additionally, for alumina, silicon carbide, B_4C, and many other materials, hardness decreases rapidly with increasing temperature (18). Fortunately, ferrous metals also soften with increasing temperatures and do so even more rapidly than abrasives (19).

2.4. Chemical Reactivity. Any chemical interaction between abrasive grains and the material being abraded affects the abrasion. Endurance scratch tests made on polished glass and iron rolls using conical grains of aluminum oxide and silicon carbide (20) showed that silicon carbide produced a long scratch path on the glass roll and a short path on the steel roll. Exactly the opposite was true for aluminum oxide. These effects are explained by the reactivities of the two abrasives toward glass and steel. Silicon carbides resist attack by glass but readily dissolve in steel, whereas aluminum oxide may be attacked by glass and is relatively inert to steel. The advent of boron carbide, harder that either fused aluminum oxide or silicon carbide, brought grand hopes for its use in grinding wheels and belts. Boron carbide's ease of oxidation and its reactivity toward both metals and ceramics prevented wide commercialization.

2.5. Thermal Conductivity. Abrasive materials may transfer heat from the cutting tip of the grain to the bond posts, retaining the heat in a bonded wheel or coated belt. Fused zirconium oxide has a relatively low thermal conductivity compared to other abrasive materials. It also has a lower hardness than aluminum oxide, yet it performs quite well on hard-to-grind materials. This finding is attributed in part to the decreased heat flow from the grinding interface into the grain (whose hardness decreases as its temperature rises) and to the bond (subject to heat degradation).

2.6. Fracture. Fracture characteristics of abrasive materials are important, as well as the resulting grain shapes. Equiaxed grains are generally preferred for bonded abrasive products and sharp, acicular grains are typically preferred for coated abrasives. How the grains fracture in the grinding process determines the wear resistance and self-sharpening characteristics of the wheel or belt.

2.7. Microstructure. Crystal size, porosity, and minor phases play an important role in determining the fracture characteristics and toughness of an abrasive grain. As an example, an alumina sol–gel abrasive grain containing zirconia or a spinel as a minor phase promotes toughness for heavy-duty grinding applications, whereas the same composition without the minor phase is more friable and thus tends to be more suited for medium-duty grinding.

3. Abrasive Materials

3.1. Silicon Carbide. The first artificial abrasive was silicon carbide [409-21-2], SiC, which was produced by a process developed by Edward Acheson in 1891 (5). In this process, silicon carbide is produced from quartz sand and carbon in a large electric furnace in which the charge acts as the refractory container and thermal insulator for the ingot being formed. Reaction temperature range from 1800 to 2200°C, melting the quartz sand, which then reacts with the solid carbon to form crystalline silicon carbide. There are two basic types of silicon carbide: one is gray or black in color and the other is green. The green form is somewhat purer, slightly harder, but is more friable. It is particularly suited for the grinding of tungsten carbides; the black form is commonly used on cast iron, nonferrous metals, and nonmetallic materials. In 2000, the United States and Canada produced 45,000 metric tons of crude silicon carbide valued at $26,300,000.

3.2. Fused Aluminum Oxide. Fused aluminum oxide [1344-28-1] was the next manufactured abrasive to be produced (6,7). By 1900, the first commercially successful fused alumina of controlled friability was produced from bauxite [1318-16-7]. The Norton Company obtained the rights and patent in 1901 and constructed the first plant to produce this material on a commercial basis. In 1904 the Higgins furnace, which used a water-cooled steel shell instead of a refractory lining, was first used (9). A typical Higgins furnace is $\sim$ 2 m in diameter by 2 m in height, producing an ingot of $\sim$ 5.5 ton. The fusion and slow cooling of a mixture of bauxite, coke, and iron turnings gives a coarse crystalline product of about 95% alumina and 0.7% titania [13403-67-7], designated regular aluminum oxide. By adding more coke to the charge, greater reduction is obtained and the percentage of residual titania is reduced, producing a semifriable alumina (~97% alumina). As the name implies, this material is less tough than the regular alumina. After crushing, further heat treatment in rotary furnaces is used to alter the valence state and solubility of titania, producing an exsolved dispersed phase that affects the impact strength of the resulting product. Most aluminum oxide is now fused in tilting furnaces and poured into ingots of sizes suitable for the desired rate of cooling and resulting crystal size. Small ingots cool rapidly and produce microcrystalline alumina, which is tougher and stronger than regular.

Bayer alumina (see ALUMINUM COMPOUNDS), containing ~0.5% soda as its only significant impurity, is also the starting material for the production of fused white aluminum oxide abrasive. During the fusion process much of the soda is volatilized, producing small bubbles and fissures in the final product and giving a slightly less dense, much more friable abrasive than regular or semifriable aluminum oxide. This white abrasive is widely used in tool grinding as well as in other applications requiring cool cutting, self-sharpening, or a damage-free workpiece. Special pink or ruby variations of the white abrasive are produced by adding small amounts of chromium compounds to the melt. The chromium addition improves the suitability of white abrasive for tool and precision grinding.

In 2000, 90,000 tons of regular fused alumina and 10,000 tons of high purity fused alumina were produced in the United States and Canada, valued at U.S. $33 and 5.4 million, respectively (21).

3.3. Fused Alumina–Zirconia. The performance of fused alumina abrasives can be greatly improved for many grinding applications by the formation during the fusion process of a eutectic alloy with zirconium oxide [1314-23-4]. Extremely rapid cooling of the melt, achieved by casting into a bed of steel balls or between steel plates, is important to obtain optimum properties of this grain. Typical applications include the production of large resin-bonded snagging wheels for the heavy-duty conditioning of steel slabs and billets and for weld-bead removal in pipeline construction. This grain is also used extensively in coated abrasive applications, but cannot be used in vitrified bonded wheels because of thermal instability. There are two principal varieties of alumina–zirconia abrasives: a near eutectic combination of 40% ZrO_2 and 60% Al_2O_3, and a less costly 25% ZrO_2 and 75% Al_2O_3 (22, 23).

3.4. Sol-Gel Sintered Aluminum Oxide. Since the early 1980s, sol–gel technology has been used to improve the performance of aluminum oxide abrasives and has had a major impact on both the coated and bonded abrasive business. Sol–gel processing permits the microstructure of the aluminum oxide to be controlled to a much greater extent than is possible by the fusion process. Consequently, the sol–gel abrasives have a crystal size several orders of magnitude smaller than that of the fused abrasives and exhibit a corresponding increase in toughness (24).

In the sol–gel process, a colloidal dispersion or sol is first formed by dispersing synthetic boehmite (aluminum oxide monohydrate) [1344-28-1] in acidified water. There are two types of modifiers that may next be added to the sol that will subsequently permit densification of the abrasive to occur during the final sintering step. The first type of modifier is a water-soluble salt (preferably a nitrate) and during sintering these modifiers form a secondary metal oxide phase within the alpha alumina matrix. In some instances, the metal oxide modifiers react with alumina, eg, $MgAl_2O_4$ or $MgLaAl_{11}O_{19}$. Examples of common modifiers include magnesia, silica, zirconia, yttria, rare earth metal oxides, nickel oxide, and titania. The second type of modifier is a seed particle that is isostructural with alpha alumina such as alpha iron oxide, alpha chromic oxide, or alpha alumina itself (25). These seed particles function as a template to facilitate the transformation from a transitional alumina into alpha alumina or corundum, the hard abrasive form of aluminum oxide (26).

After the addition of modifiers, the sol is then dried to a soft, friable solid, which may then be easily crushed into the desired particle sizes. Alternatively, the sol may be partially dried into a gel state that may then be extruded into rods or other controlled shapes. The final step is to fire the particles at temperature ranging from 1200 to 1500°C (see Fig. 1).

The 3M Company commercialized the first sol–gel abrasive under the trade name Cubitron in 1981 (27). There are several types of sol–gel abrasive grains manufactured by 3M. Cubitron 321 grain (28) contains magnesium and certain rare earth oxides that form a distinct platelet phase. This platelet phase increases the toughness of the grain (29). Cubitron 321 grain is particularly suited for use in grinding wheels and coated abrasives under heavy duty grinding conditions and on stainless steel and exotic alloys. Another Cubitron (30) grain is seeded but does not contain the spinel phase. This grain is used in low to moderate pressure grinding of metal, paint, and wood.

Saint-Gobain abrasives also produces a sol–gel abrasive under the name Cerpass and SG (31). This grain uses alpha alumina seed crystals to produce a microstructure containing a submicron growth of alpha alumina. SG and Cerpass abrasive grains are used in both bonded and coated abrasive applications and is also produced in a rod form for use in specialized grinding wheels (32).

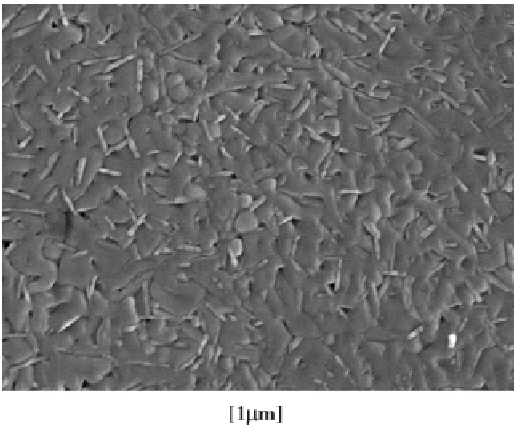

Fig. 1. SEM photomicrograph of polished and thermally etched section of Norton SG sol–gel alumina abrasive grain.

3.5. Diamond. Diamond [7782-40-3] is the hardest substance known with a Knoop hardness value of 78 – 80 kN/m^2 (8000 – 8200 kgf/m^2). The next hardest substance is cubic boron nitride with a Knoop value of 46 kN/m^2. The United States was the world's largest consumer of both natural and synthetic industrial diamond in 2000 with an estimated usage of 484 million carats (1 g = 5 carats). Of this amount, $>$ 90% was synthetic diamond (21).

Abrasive applications for industrial diamonds include their use in rock drilling, as tools for dressing and trueing abrasive wheels, in polishing and cutting operations (as a loose powder), and as abrasive grits in bonded wheels and coated abrasive products.

3.6. Cubic Boron Nitride. Cubic boron nitride [10043-11-5] or CBN, is a synthetic mineral not found in nature. It was first produced by the General Electric Company using the same equipment used for the production of synthetic diamond and is designated as "Borazon". CBN is nearly as hard as diamond, yet it does not perform as well in the usual diamond grinding applications such as abrading ceramics, rock, or cemented tungsten carbide. However, CBN is an extremely efficient abrasive for grinding steel (33). Although its cost is comparable to that of synthetic diamond, it successfully competes with the inexpensive fused aluminum oxide in grinding steel tools. CBN improves grinding wheel life by as much as 100 times over that of alumina, thus increasing productivity, reducing downtime for the wheel changes and dressing, and improving the quality of parts (34).

3.7. Boron Carbide. Boron carbide [12069-32-8], B_4C, is produced by the reaction of boron oxide and coke in an electric arc furnace (70% B_4C) or by that of carbon and boric anhydride in a carbon resistance furnace (80% B_4C) (see BORON COMPOUNDS; REFRACTORY BORON COMPOUNDS). It is primarily used as a loose abrasive for grinding and lapping hard metals, gems, and optics (35). Although B_4C is oxidation prone, the slow speed of lapping does not generate enough heat to oxidize the abrasive.

3.8. Metallic Abrasives. Metallic abrasives are most commonly used as a blast medium to clean or to improve the properties of metallic surfaces. Industries that utilize metallic abrasives include foundries, steel manufacturers, machine tool industries, and metal working plants. In 2000, ~269,000 metric tons of steel shot and cut wire shot were produced in the United States with an estimated value of $125 million (21).

3.9. Natural Abrasives. With the introduction of the first manufactured abrasives at the beginning of the twentieth century, the use of natural abrasives has steadily declined.

Diamond. Natural diamonds account for ~10% of the industrial market (21). The two types of natural diamonds used by industry include diamond stone (typically coarser than 60 mesh/800 μ) and diamond bort (smaller, fragmented pieces). Abrasive applications for industrial diamonds include their use in rock drilling, as tools for dressing and trueing abrasive wheels, in polishing and cutting operations (as a loose powder), and as abrasive grits in bonded wheels and coated abrasive products.

Garnet. Garnet [12178-41-5] is the name given to a group of silicate minerals possessing similar physical properties and crystal forms but differing in chemical composition. Seven species exist but the two most important are pyrope, a magnesium aluminum silicate, and almandine, an iron aluminum silicate. Industrial uses for garnet include the lapping, manufacturer of coated abrasives, hydrocutting, and the finishing of wood, leather, hard rubber, felt and plastics. In 2000, the domestic production of crude garnet was 60,200 tons with a value of >$7 million (21).

Silica. In the past, silica has found wide use as an abrasive, particularly as an inexpensive coated abrasive for woodworking. The term sandpaper is still used as a generic term for coated abrasives although the use of sand in coated abrasives has very little commercialize presence.

Tripoli. Tripoli [1317-95-9] is a fine grained, porous, decomposed siliceous rock produced mainly in Arkansas, Illinois, and Oklahoma. It is widely used for polishing and buffing metals, lacquer finishing, and plated products. Since Tripoli particles are rounded, not sharp, it has a mild abrasive action particularly suited for polishing. Tripoli is also used in toothpastes, in jewelry polishing, and as filler in paints, plastics, and rubber. Rottenstone and amorphous silica are similar to Tripoli and find the same uses. In 2000, the abrasive use of Tripoli in the United States totaled 73.3 million tons and was valued at ~ $3.8 million (21).

4. Sizing, Shaping, and Testing of Abrasive Grains

4.1. Sizing.

Manufactured abrasives are produced in a variety of sizes that range from a pea-sized grit of 4 (5.2 mm) to submicron diameters. It is almost impossible to produce an abrasive grit that will just pass through one sieve size yet be 100% retained on the next smaller sieve. Thus a standard range was adopted in the United States that specifies a screen size through which 99.9% of the grit must pass, maximum oversize, minimum on-size, maximum through-size, and fines. The original Bureau of Commerce size standards, although non-metric, have been internationally recognized. These standards have been updated by ANSI Standard B74.12-1982 in the United States (36) and by FEPA Standard 42-GB-1984 in Europe (37). Table 2 shows the average

Table 2. **Bonded Abrasive Grit Sizes**

Grit	Diameter, μ	Grit	Diameter, μ	Grit	Diameter, μ
4	5200	24	775	120	115
5	4500	30	650	150	95
6	3650	36	550	180	80
7	3050	40	460	220	69
8	2550	46	388	240	58
10	2150	54	328	280	48
12	1850	60	275	320	35
14	1550	70	230	400	23
16	1300	80	195	500	16
18	1100	90	165	600	8
20	925	100	138	1200	3

diameter of grit sizes ranging from 4 to 1200. Designations for the finest grit sizes vary in the United States, Europe, and Japan.

The permissible variation in the openings of U.S. standard test sieves varies from 15% for the coarser sizes to 60% for the range of 200–400 grit. To reduce this built-in error, the diamond industry has developed precision, electroformed test screens that are produced by a combination of photoengraving and electroplating. These screens, in which the accuracy and uniformity of aperture size can be tightly controlled, are too expensive for routine testing; they are used instead to calibrate standard wire sieves (38). The sizing of diamond abrasive grains is much tighter that that of other abrasives; details can be found in (39).

4.2. Shaping. Screening is a two-dimensional (2D) process and cannot give information about the shape of the abrasive particle. Desired shapes are obtained by controlling the method of crushing and by impacting or milling. Shape determinations are made optically and by measuring the loose-packed density of the abrasive particles; cubical-shaped particles pack more efficiently than acicular-shaped particles. In general, cubical particles are preferred for grinding wheels, whereas high aspect ratio acicular particles are preferred for coated abrasive belts and disks.

4.3. Testing. Chemical analyses are done on all manufactured abrasives, as well as physical tests such as sieve analysis, specific gravity, impact strength, and loose poured density (a rough measure of particle shape). Special abrasives such as sintered sol–gel aluminas require more sophisticated tests such as electron microscope measurement of alpha alumina crystal size, and indentation microhardness.

5. Coated Abrasives

5.1. Manufacture. In a broad sense, a coated abrasive is defined as a plurality of abrasive particles adhered to a substrate, commonly called a backing. There are several typical constructions in this coated abrasive family, namely, conventional coated abrasives, lapping film, and structured abrasives. A conventional coated abrasive comprises a backing with a first binder called a make coat; the make coat adheres the abrasive particles to the backing. It is generally preferred to orient the abrasive particles, such that the majority of abrasive particles are substantially perpendicular to the backing. Over and in between the abrasive particles is a second binder, called a size coat; the size coat reinforces the abrasive particles. There may optionally be a third coating, called a supersize coating applied over the size coating. This supersize coating typically comprises a grinding aid or antiloading additive. A second coated abrasive construction is commonly referred to as “lapping film”, where a plurality of abrasive particles are randomly dispersed in a binder. This abrasive particle/binder composite is applied over the front surface of the backing. Likewise, these products are typically employed in precision polishing applications, where previously loose abrasive slurries were used. Recently, a new coated abrasive construction has emerged, named a structured abrasive, which comprises a plurality of shaped abrasive composites are bonded to a backing.

5.2. Sizes. Coated abrasive articles are commercially in abrasive particle sizes ranging from grit sizes ANSI 16 (particle size of ~1180 μ) to finer than JIS 10,000 (particle size <0.5 μ). Likewise, coated abrasives come in a plethora of converted forms including belts, disks, sheets, rolls, flap wheels, and mop wheels. Coated abrasive belts may range in size from 1 to >200 cm width and lengths 5 to >500 cm. For example, 1 × 30-cm belts are employed in a portable tool to grind the inside corner of a sink. Larger belts, for example stroke sanding belts, are 15 wide × 450-cm long are employed in furniture markets. Coated abrasive discs come in sizes from 1 to >100 cm in diameter. The 1-cm coated abrasive disk may be employed to remove defects from a painted surface. Coated abrasives made with a vulcanized fiber backing are used in leveling welds on a surface. Lapping film in the form of a daisy shaped disc is used to polish ophthalmic surfaces.

5.3. Backings. There are several types of popular coated abrasive backings: paper, cloth, vulcanized fiber, polymeric film, and foam-like substrates. Paper backings are designated by their basis weight. The lightweight papers tend to be more flexible and are used in sheet and disk products. The heavier papers are stiffer and are typically used in belts, and disk products.

Fourdrinier paper is the most common type. This paper may be treated to seal the front surface, make the product waterproof, or modify some other physical property of the paper. During the 1920s a major advancement in coated abrasives was the invention and development of waterproof coated abrasives (40). This enabled operators to sand automobile painted surfaces wet to reduce the airborne dust. Eighty years later, waterproof paper backings are a mainstay in coated abrasives.

Another large volume backing is cloth. Cloth typically is much stronger than paper, while still being flexible. The majority of cloth is employed in coated abrasive belts, with a small percentage in disks and sheet rolls. The cloth may be woven or stitch bonded (41). Like paper, cloth backings are designated by their weights.

Typical, cloth fibers used are cotton, polyester, rayon, nylon, or combinations thereof. Rayon tends to be used when it is desired to have a flexible coated abrasive belt, eg, in polishing the contours of cast parts such as golf clubs and hand tools. Conversely, polyester and nylon fibers are commonly utilized in heavy-duty applications such as lumber planing and metal de-gating. Cotton fibers are versatile; cotton fibers are employed in a range of applications from general purpose belt grinding to coated abrasive disk sanding. The cloth is typically treated to seal the backing and modify the physical properties of the cloth. These treatments are either a thermoplastic or thermosetting resin, along with optional additives. Typical thermosetting polymers include: phenolics, epoxies, acrylates, aminoplast resins, urethane, latexes, melamine formaldehyde, and mixtures thereof. There are numerous cloth treatments; the cloth may be first saturated to fill in the intersices of the cloth. The cloth may contain one or more coating(s) over its front surface, knows as a presize or subsize coating. The presize coating may provide a smooth coating onto which the abrasive particles are coated. The cloth may contain a backing coat on the backside of the backing. The backsize coating may serve to protect the cloth fibers during abrading. These treatments seal the cloth, enhance the heat resistance of the cloth, and modify the cloth to the desired flexibility or stiffness. For example, in mold sanding of intricate furniture it is necessary to have a flexible cloth backing. Conversely, in lumber planning it is desired to have a stiff backing.

A third common backing is vulcanized fiber. This backing is essentially exclusively used in coated abrasive disks, ranging in size from 5 to 25 cm in diameter. These fiber disks are employed extensively to remove weld lines, deburring, shaping, and other metal fabrication operations. Fiber disks are commonly used in coarse grades, where metal removal and life tend to be more important than surface finish.

A fourth backing is polymeric film, such as polyester, polypropylene, and polyamide films; a popular film backing is a primed polyester film. Film backings have advantages in that they provide a very smooth front surface for coating abrasive particles and have a very uniform surface finish. Polymeric films are commonly employed in precision polishing with fine grade abrasive particles. In polishing applications, this backing uniformity and smooth surface may translate into a more consistent surface finish.

Another abrasive backing is a foam or other compressible backing. The abrasive particles may be coated directly onto the foam or laminated to a foam. The foam may be an open- or closed-cell polyurethane. The foam thickness may range from 0.2 to 20 mm. These foam backings are generally employed in hand sanding applications and some disk applications.

5.4. Resin Binders. In the majority of coated abrasive constructions, the binder is a thermosetting polymer. During manufacturing, a thermosetting resin is coated and exposed to an appropriate energy to initiate the curing of the resin into a cross-linked polymer. Examples of typical resins include resole phenolic, epoxy, acrylate, urea–formaldehyde, melamine formaldehyde, urethane, aminoplast resins having pendant alpha, beta unsaturated groups and mixtures thereof. For heavy duty coated abrasive applications, for many years, thermally cured resins such as phenolic resins, epoxy resins, urea–formaldehyde resins, and urethane resins were popular. Coated abrasive articles can use resins that are cured upon exposure to a radiation energy source such as electron beam or ultraviolet (uv) light, these resins include epoxy, acrylates, acrylated epoxies, acrylated urethanes, and mixtures thereof.

Phenolic resins are considered to be the workhorse of coated abrasives and widely used in heavy duty-to-medium duty grinding applications. Coated abrasive products utilizing phenolic based binders were first commercialized in the 1930s (42). There are two types of phenolic resins: resole and novolac. Resole phenolic have the ratio of formaldehyde to free phenol >1, where in novolac phenolics this ratio is <1. Resole phenolic resins are traditionally employed in coated and non-woven abrasives, whereas novolac phenolic resins are employed in bonded abrasives. Resole phenolic resins polymerize via a condensation mechanism. During phenolic polymerization, water is released. In the coated abrasive manufacturing, the oven temperatures are controlled such that not too much water is released in a short time so as to result in defects in the cross-linked phenolic binder. Resole phenolic resins are typically polymerized on temperatures $<175^\circ$C, usually $<125^\circ$C. Phenolic resins have excellent physical properties in regard to abrasive articles. They are relatively low cost, hard, heat resistant, and tough. One major drawback of phenolic resins is the processing. Phenolic resins, along with other thermally curable resins, use a festoon type oven to cure the resin into a cross-linked polymer. After coating, the abrasive web is hung on racks and transported through a large oven. It is common for this festoon cure to take anywhere from 30 to 300 min to advance the phenolic resin into a "B" stage type cure to the make and size coats. During this festoon cure, the coated web is carefully handled to maintain a good abrasive grain coating. After the festoon cure, the resulting product is wound into a jumbo to either be converted or further thermal cure.

In the medium to finer grades, other resins are commercially used including epoxy, urea–formaldehyde, plasticized phenolic, and urethane resins. These resins can be thermally cured using a festoon type oven. In some instances, the made and size coats have different polymer chemistries to achieve a desired abrasive characteristic.

In some light duty product, hyde glue is used for the make and/or size coat. Hyde glue is not a thermosetting polymer, but rather it is coated out of water and subsequently dried. These products cannot be used wet, only dry sanding conditions. Hyde glue binders are generally softer in comparison to thermosetting binders. The hyde glue-type binders are traditionally used in light duty sanding where a fine surface finish is desired.

Recently, radiation curable resins have emerged, the radiation energy source can be electron beam, uv light on visible light. These binder systems are rapidly cured in comparison to phenolic resins that are usually festoon cured. Likewise it is possible to blend a radiation curable binder with a thermally curable binder (43). There are two common types of uv light curable resins, cationically cured epoxy resins and free radically cured-based acrylate resins. In some instances, these resins may be mixed together or in the same molecule (44). For visible and uv light binders, a photoinitiator is added to the resin. Upon exposure to the light, the photoinitiator cleaves and generates a free radical, which initiates the polymerization process.

5.5. Additives to Binder Systems. The abrasive article binder system may further contain additives that modify the polymer physical properties polymer and/or positively affect the abrading performance of the resulting abrasive article. Examples of such additives including fillers, grinding aids, antiloading additives, coupling agents, dyes, pigments, wetting agents, plasticizers, and combinations thereof.

Fillers are commonly used in bonded and coated abrasives, especially in the coarse-to-medium grades. Fillers are particulate matter, generally softer and smaller in size than the abrasive particles. Fillers offer at least one of the following advantages, lower cost, change binder system friability, increase binder system toughness, hardness or, heat resistance. Fillers that tend to inorganic particulates have a particle size between 5 and 120 μ. Examples of popular fillers include metal carbonates (eg, calcium carbonate), silicates (eg, calcium metasilicate), silica (eg, glass beads, glass bubbles), graphite, carbon black, mica, and the like.

Grinding aids are another class of additives generally preferred in dry metal grinding applications. It is theorized that grinding aids will either (*1*) reduce the grinding temperature, (*2*) act as a lubricant, and/or (*3*) minimize the amount of metal chips from rewelding to the abrasive grains. Examples of popular grinding aids include metal halide salts (eg, potassium tetrafluoroborate, sodium aluminum fluoride), poly(vinyl chloride), iron pyrites, waxes, halogenated waxes, and phosphate salts (45). Typically, the grinding aid is included in the outermost layer of the abrasive article. In the case of bonded abrasives, the grinding aid may be incorporated into the abrasive particle and binder mix. In coated abrasives, the grinding aid is typically dispersed in a binder and incorporated into either the size or supersize coating.

Where grinding aids are generally preferred in dry metal grinding, antiloading materials are sometimes preferred in dry paint, wood sanding. During sanding of soft substrates, the debris removed can become lodged in between adjacent abrasive particles. This phenomena, known as "loading" may reduce the cutting ability and ultimately shorten the coated abrasive life. It is theorized that nonloading additives may either act as a lubricant, inhibit the debris from adhering to the abrasive article outer surface and/or the anti-loading material flakes off during abrading and take the debris along with it. Common examples of anti-loading materials include metal salts of fatty acids, graphite, mica, talc, and fluoro chemicals. The most popular materials are metal stearates such as lithium stearate, calcium stearate, and zinc stearates (46). These metal stearates are typically dispersed in a binder and applied as a supersize coating.

5.6. Coating. Regarding typical coated abrasive manufacturing, the backing is first coated with a make coat resin to the desired weight. Immediately afterward, the abrasive grains are either drop coated or electrostatically coated into the make coat resin. The electrostatic coating process tends to orient the abrasive grains. In some instances, there may two different abrasive grains coated. The first abrasive grain may be drop coated and the second abrasive grain electrostatically coated. Alternatively, both types of abrasive grains may be electrostatically coated simultaneously. Next the make coat resin is either dried or exposed to an energy source to at least partially cross-link the resin. Following this, a size coat resin is coated over the abrasive grains to the desired weight. Likewise, the size coat is either dried or exposed to an energy source to cross-link the resin. Similarly, if desired, a supersize coating is applied and solidified. After the binders are cured, the resulting coated abrasive may be flexed to break the thermosetting polymers in a controlled manner. This flexing process alters the flexibility and abrasive performance of the product.

5.7. Structured Abrasives. In recent years, a new coated abrasive construction has emerged, known as a structured abrasive. The structured abrasive comprises a plurality of shaped abrasive composites adhered to a backing; these shaped abrasive composites may be precisely or irregularly shaped (47). These shapes may be any geometric shape such as pyramidal, ridge-like, hemisphere, cube-like, and block-like (48). Structured abrasives offer flexibility in designing and optimizing the abrasive article in that both the composite shape, size, and density, along with the abrasive composite chemistry may be optimized to achieve superior performance. Structured abrasive products have gained acceptance in medium grinding to very fine polishing applications.

To make a structured abrasive article, a slurry is first prepared comprising a plurality of abrasive grains dispersed in a resin, along with optional additives. A production tool is generated comprising cavities having the desired shape, density, and size of abrasive composites. For precisely shaped abrasive composites, this abrasive slurry is coated onto the backing and the resulting construction is brought into contact with the production tool. The abrasive slurry flows into the cavities of a production tool. Next, an energy source, such as uv light, is transmitted through the production tool and into the resin. The resin is at least partially cross-linked and the resulting abrasive slurry is solidified to form a plurality of abrasive composites bonded to a backing (49). For nonprecisely shaped abrasive composites, the abrasive slurry is coated into the cavities of a production tool, such as a rotogravure roll. The backing is brought into contact with the abrasive slurry and the rotogravure roll imparts a pattern to the abrasive slurry. The abrasive slurry is removed and then exposed to an energy source to at least partially cure the resin to form the structured abrasive (50).

6. Lapping Papers and Films

6.1. Manufacture. Lapping papers and films differ from other coated abrasives in several regards. The products are made by casting a slurry of abrasive grain and binder on the backing. The slurries are usually not 100% solids, but are either aqueous or solvent based. In addition to the binders and the abrasive grain they also frequently contain modifying agents, such as dispersants, antistats, wetting agents, catalysts, etc.

The common binder classes employed are polyester resins, acrylates, epoxies, and phenolics, as well as blends of two or more resin classes. In most cases, the solvent is dried from the binder systems and cured. Some systems, however, merely dry the slurry leaving an uncured binder film to hold the abrasive grain to the backing. (The binder systems without solvent, of course, always require a cure.)

The abrasive grain is frequently described in microns, designating the mean particle size, rather than the ANSI, FEPA, or JIS grading systems employed with coarser coated products. The abrasive grains are almost invariably $<60\ \mu$, and most commonly $< 10\ \mu$ mean particle size. The abrasive grain types vary from very hard, such as diamond, to the conventional coated abrasive materials (ie, silicon carbide, fused alumina, sol–gel aluminas), to softer abrasive grains like ceria, rouge, etc. As with other forms of coated abrasives, the coated article may contain a single abrasive grain or a blend of abrasive grains.

The backings used for coated lapping products may be a paper or other nonwoven cloth, a woven cloth, or a polymeric film. Of these choices, polymeric films are by far the most common as the film provides a smooth uniform base, in turn allowing precise control of the roughness of the abrasive coating. The most common polymeric film used is poly(ethylene terephthalate). The thickness of the film varies with the end use application, but is most commonly between 0.5 and 3.0 mil ($\sim$12.5–75 μ).

The slurries may be coated onto the backing via a wide variety of coating techniques; common techniques are knife coating, knife over roll coating, gravure roll coating, three/four roll coating, and extrusion coating. The drying is accomplished with conventional forced air ovens. The rate of the drying, as well as the formulation, is frequently controlled in order to affect the presence or absence of Benard Cells, and hence the surface roughness in the dried product.

6.2. Applications.

The lapping products are used in a host of fine polishing applications. They are used in tape format for the polishing of large industrial calender and mill rolls, for the "buffing" of both floppy and rigid memory disks, for the contouring of magnetic heads, etc. Disks and sheets are used for the polishing of fiber optic connectors, metallurgical laboratory sample preparations, defect removal/polishing of glass, the fining of ophthalmic lenses, die polishing, etc. The specific application, of course, determines the thickness of the backing, the type and size of the abrasive grain, and the class of the binder system. Many applications, such as fiber optic polishing, are sequential and involve steps with two, three, or four progressively finer and less aggressive lapping products.

7. Nonwoven Abrasives

Nonwoven abrasives are unique forms of abrasives that find use in many aspects of material finishing and surface cleaning. This category of abrasives provides a different interaction with the workpiece than coated abrasives or grinding wheels, and are, therefore, commonly called surface conditioning abrasives. A great deal of study has gone into the cause/effect relationship of these abrasives with a surface. Much evidence exists suggesting that these articles generally provide compressive, rather than tensile stresses, on surfaces. Nonwoven abrasives also create a very clean surface that enhances long-term corrosion prevention and superior wetting properties for subsequent coating.

Nonwoven abrasives are so named because of the random fibrous matrix on which they are based. This matrix provides a sturdy backbone on which can be coated a variety of resins and minerals in such a way as to provide the desired surface finish for many diverse types of articles. These abrasives are available as disks, belts, pads, brushes or wheels, and can be adapted for use on many power tools as well as large industrial cleaning equipment.

As mentioned above, the compressive stresses are imparted by the interaction of the springy nonwoven matrix with the surface being worked upon. This spring-like action works as a tiny peening hammer on the surface. What this does is to relieve the tensile stresses induced by the actions of machining metals or heavy stock removal using grinding wheels or coated abrasives. Also, adsorbed surface contaminants, carbonaceous deposits, or surface segregated components are effectively removed using nonwoven abrasives. The very light surface abrasion removes undesirable surface contaminants or chemistry that may affect coating adhesion or corrosion resistance. This is useful when a very clean and uniformly wettable surface is desired prior to priming or similar processes. Actual stock removal is very minimal, but burrs and sharp corners are effectively removed and rounded by the spring action of the matrix. Effective removal of burrs and sharp edges is also desirable for long-term protection against fatigue failure and corrosion resistance.

7.1. Manufacture.

The first step in the manufacture of nonwoven abrasives is the creation of the carrier web. A mechanical carding, melt bonded, or air laid process in which crimped polymeric fibers are laid down on a carrier belt and passed through a variety of resin baths to give desired characteristics forms this web. The coated web is then passed through a drying oven to provide structural integrity. This web is commonly called “prebond”, as it does not have any abrasive added at this time. In some cases, an additional scrim layer may be mechanically bonded to provide even greater structural integrity.

In the second step, the “make coat” is applied, which can be a two-step resin/abrasive process or can be applied as a one-step resin/abrasive slurry. In the former, the prebond web is passed through a resin bath and the abrasive can be gravity applied or blown through the web using an air stream. In the latter process, the slurry can be roll coated or applied by spraying. Many of the webs that are produced by either of these two methods can then be converted into the usable forms listed above.

In order to create wheels, another resin coat, called the “size coat”, is added. In this case, a “make coated” web is passed through a resin bath and lightly oven cured to produce a tacky web. This web is then treated in one of two ways to make wheels. In one process, winding the size-coated web into a roll that is cured before wheels are sliced from it makes “convolute” wheels. These tightly wound rolls can have a variety of densities depending on the degree of conformity desired. In the second process, “unitized” wheels are cut from slabs that have been compacted and cured under pressure. Density is a function of the number of layers and resins used for a given thickness.

Ganging together nonwoven rings on a suitable core material makes large industrial “brushes”, 8–80 in. in width. Alternatively, long strips of nonwoven material can be gathered radially around a core to form “flap brushes”. These assemblies are compressed to form a brush. The resulting brush is then surface dressed and balanced before being put into service. They are used primarily for the surface cleaning of coiled metals in the removal of rust, carbon, and other surface contaminants.

7.2. Nonwoven Abrasives Sales.

Nonwoven abrasives were commercialized in the 1960s (51). Nonwoven abrasives have rapidly emerged into three major markets: consumer, commercial, and industrial markets.

8. Bonded Abrasives

Grinding wheels are by far the most important bonded abrasive product both in production volume and utility. They are produced in grit sizes ranging from 4, for steel mill snagging wheels, to 1200, for polishing the surface of rotogravure rolls. Wheel sizes vary in diameter from tiny mounted wheels for internal bore grinding to >1.8-m wheels for cutting-off steel billets. Bonded shapes other than wheels, such as segments, cylinders, blocks, and honing stones, are also widely used.

8.1. Marking System.

Grinding wheels and other bonded abrasive products are specified by a standard marking system that is used throughout most of the world. This system allows the user to recognize the type of abrasive, the size and shaping of the abrasive grit, and the relative among and type of bonding material. The individual symbols chosen by each manufacturer may vary, but the relative position for each item in the marking system is standard.

Grain Size. The surface finish, or degree of roughness, produced by a grinding wheel on the workpiece being ground is roughly proportional to the size of abrasive grains in the wheel (see the section Sizing and Table 2).

Grade. The grade, or grinding hardness, of a bonded abrasive product is determined by the bond content. It is represented alphabetically with A being the softest (least bond) and Z being the hardest (most bond).

Structure. The structure designation is a numeric indication of the relative volume of abrasive in a unit volume of wheel. A low number indicates a high volume of abrasive grain, thus the grains are closely packed. As the structure number increases there is less abrasive grain in the wheel, and the abrasive grains tend to be more widely spaced.

8.2. Bond Type. Most bonded abrasive products are produced with either a vitreous (glass or ceramic) or a resinoid (usually phenolic resin) bond. Bonding agents such as rubber, shellac, sodium silicate, magnesium oxychloride, or metal are used for special applications.

Vitrified (Glass or Ceramic) Bond. Vitrified wheels probably account for about one half of all conventional abrasive wheels. Vitrified bonds are formed from mixtures of clay, feldspar, and frit. The clays and feldspars are naturally occurring materials and the amounts of these materials are mainly determined by the nature of the wheel to be built, but also affected by the mineralogy and detailed chemistry of the clays and feldspars. The frit is synthetic glass and its composition is under better control. The bond mixtures soften and melt in the temperature range from 950 to 1400°C, with mixtures richer in clay melting at higher temperatures, those with more frit melting at lower temperatures.

It is possible to prepare bond mixtures with different viscosities, and hence different surface tensions at a given temperature, and so tailor the bond to the required structure of the final wheel. In particular, it becomes possible to help control the porosity in, and provide the strength to, the wheel by careful choice of bonding mix. Vitrified wheels may be compounded to include organic "spacer" materials. These organic materials are lost during the firing step and thus would not show up in the finished wheel. However, these organic materials can have a significant effect on the structure, properties, and grinding performance of the wheels.

Resin (Resinoid). The resinoid bond, originally called Bakelite, was named for its inventor, Leo Bakeland (see PHENOLIC RESINS). Bakeland's original patent was issued in 1909, but it was not until the 1920s that this type of bonding was perfected for use in abrasives. The resin consists basically of phenol and formaldehyde. It is a thermosetting polymer, with a combination of properties that make it particularly suitable for a number of grinding operations. It withstands heat better than rubber or shellac, and resists thermal and mechanical shock better than vitrified bonds. A drawback of resinoid bond is its susceptibility to degradation by water. Phenolic resins may be modified with other resin types to reduce brittleness and extend characteristics of toughness and strength.

Resin bonds commonly cure at temperatures in the range of 150–200°C, so there are no problems with grain reactivity, and fiberglass and metal reinforcements may be molded to make a much safer product for high speed or abusive applications. This low processing temperature also allows the use of inert fillers to strengthen the bonded product, or of “active” fillers to increase the efficiency of grinding. Active fillers, also known as grinding aids, include such materials as cryolite, pyrites, potassium fluoroborate, sodium and potassium chloride, zinc sulfide, antimony sulfide, and tin powder. Such materials, alone or in combination, aid grinding by acting as extreme pressure lubricants or as reactants for the metal being ground; this prevents rewelding of the chips being removed.

Resinoid-bonded wheels find wide use in heavy-duty snagging operations, where large amounts of metal are generally removed quickly; in cutting-off operations; in portable disk grinding (as for weld beads); in grinding of steel mill rolls; and in vertical spindle disk grinding.

Rubber. Both natural and synthetic rubber are used as bonding agents for abrasive wheels. Rubber-bond wheels are ideal for thin cut-off and slicing wheels and centerless grinding feed wheels. They are more flexible and more water- resistant than resinoid wheels. In manufacture, the abrasive grain is mixed with crude rubber, sulfur, and other ingredients for curing, then passed through calender rolls to produce a sheet of desired thickness. The wheels are stamped from this sheet and heated under pressure to vulcanize the rubber.

Shellac. Shellac wheels are limited to a few applications where extreme coolness of cut is required and wheel life is immaterial. They are produced by mixing shellac [9000-59-3] and abrasive grain in a heated mixer, then rolling or shaping to the desired configuration.

Magnesium Oxychloride. A mixture of abrasive grains, MgO, water, and $MgCl_2$, placed in an appropriate mold will cold-set to form a grinding wheel that is then cured for a long period of time in a moist atmosphere. This type of bond finds some use in disk grinding applications and cutlery grinding. These wheels have been largely replaced by soft-acting resinoid bonds.

9. Special Forms of Bonded Abrasives

There are many specialized forms and uses of bonded abrasives, a detailed discussion of which is found in reference (52).

9.1. Honing and Superfinishing.

Honing and superfinish stones are produced from large vitrified-bonded abrasive blocks that are diamond sawed to smaller rectangular pieces suitable for mounting in metal or plastic holders. Honing stones, used to true engine and hydraulic cylinders, can vary in grit size from 36 (0.55 mm) to 600 (8 μ); superfinish stones, used to polish the external diameters of machine and automotive parts, vary in grit size from 600 to 1200 (3 μ). Both types of stones are quite soft; steel ball indentation hardness and density are often used as quality control to measure grade.

9.2. Pulpstone Wheels.

Grinding wheels play an important role in the production of paper pulp. Massive pulpstone wheels are made from vitrified abrasive segments, bolted and cemented together around a reinforced concrete central body. They may be up to 1.8 m in diameter and have a breadth of 1.7 m. In operation, debarked wood logs are fed into a machine and forced against the rotating pulpstone, which shreds the wood into fibers under a torrent of water. The ground fibers are then screened and passed through subsequent operations to produce various types of paper.

9.3. Crush-Form Grinding. In crush-form grinding, a rotating, contoured crushing wheel is forced into the face of a revolving vitrified wheel, crushing the face to the exact contour needed on the metal object to be ground. The contoured wheel is then placed in production and when wear or dulling occurs, the face is again crushed to regain proper contour. Many parts formerly turned with metal-cutting tolls and then surface ground are now shaped and surface finished in one pass of a crush-formed wheel.

9.4. Creep Feed Wheels. Creep feed grinding is an abrasive machining process, characterized by the use of slow (creep) workpiece velocities and extremely large depths of cut that are hundreds or even thousands of times greater than those in regular grinding applications. With this process, it may be possible to grind complex profiles or deep slots in only a few or even a single pass. A shape is generated in the face of an open-structure vitrified wheel by diamond tooling or a crush form roller. The profiled wheel is fed into the part under a flood of coolant.

Creep feed wheels are manufactured by incorporating in the wheel mixture a substance that is burnt-off during the firing process to leave voids throughout the wheel structure. By this means, the level of porosity can be increased from 35% of wheel volume for a conventional wheel to ∼60% for some of creep feed wheels. This additional porosity is ideal for the creep feed process, as the voids can be saturated with coolant prior to entering the grinding zone so that a large volume of coolant can be taken into the grinding zone by the wheel. This is important since the contact arc is much longer than for reciprocating grinding. Also, as the feed rate is comparatively low the heat generated can easily build up in the work piece. This must not be allowed to happen, so the heat must be removed rapidly from the grinding zone and it is essential to have an efficient supply of coolant throughout the zone.

As well as making coolant application difficult, the long arc of contact also has the effect of promoting the formation of wear flats on the grinding grits. These wear flats give rise to rubbing forces between the wheel and work piece, and additional power is required to provide this rubbing energy. The size of the wear flats is dependent on the grade of the wheel. The softer the grade, the sooner the force on a grit will build up to a level that will either fracture the grit or remove it from the bond. Thus, a soft wheel will give a lower wear flat area, and hence lower rubbing energy than a hard wheel. It is thus usual to choose a wheel with a soft grade for creep feed grinding (53).

For significant improvements in grinding performance, soft grade wheels containing thermally conductive solid particles are utilized. In these grinding wheels, the thermally conductive particles are held by the vitreous matrix with a binding force (or strength) weaker than the strength of the bond between the abrasive grain and the vitreous matrix. Thus, the thermally conductive particles are generally more readily lost from the grinding wheel during the grinding of a work piece and act as heat sinks to conduct heat away from the grinding zone (interface between the grinding wheel and work piece during grinding).

When these thermally conductive particles are separated from the grinding wheel, they distribute and dissipate the heat in and from the grinding wheel to thereby assist in reducing and preventing the risk of a burn of the metal work piece and thermally induced breakdown of the grinding wheel (54).

10. Superabrasive Wheels

10.1. Diamond Wheels. Little natural diamond is used in grinding wheels today. Synthetic diamonds are manufactured in many versions that have been tailored for specific grinding applications and can be produced with excellent quality control. Diamonds with more perfect crystal structure are used in metal bonds for sawing stone and concrete and for grinding glass and ceramics. Diamonds for grinding of carbide are designed to be multicrystalline, giving the diamond the property of friability. These friable diamonds are used in resin bonds. To improve the retention of the diamond, the grains can be coated with metal, usually nickel. The metal adheres well to the grain, and the specially controlled rough surface of the coating adheres very well to the resin. This reduces pullout of the crystal from the matrix. Other metals (copper, silver) are used to improve the heat transfer properties of the wheel, keeping the resin cooler when heat of grinding is a concern.

In addition to resin and metal, vitrified bonds are also used. Resinoid wheels are hot pressed to zero porosity to maximize grain retention. Grit sizes range from 16 to 1800. Wheels are constructed with the diamond in a thin rim on the periphery of the wheel body, or core, which may be metal- or fiber-filled plastic, steel, aluminum, ceramic, or bronze. Intricate shapes are produced by electroplating a single layer of superabrasive on a shaped core.

The amount of superabrasive in the wheel rim is expressed as concentration. A wheel with 100 concentration contains 25% by volume of superabrasive crystal. Concentrations usually range from 50 to 200. As concentration is increased wheel cost increases, but tool life will increase and finish will improve.

Diamond wheels are not recommended for grinding ferrous materials. Under the temperature and pressure conditions of grinding, diamond (carbon) is chemically soluble in iron; thus diamond will wear excessively and be uneconomical.

10.2. Cubic Boron Nitride Wheels. Although CBN is only about two-thirds as hard as diamond, it is about twice as hard as aluminum oxide and silicon carbide abrasives. This property, plus its non-carbon chemistry and its high thermal conductivity, make it an excellent abrasive for steel. As with diamond, wheels are made using metal, resin, and vitrified bonds and as plated products. The porous nature of a vitrified bonded wheel makes it particularly suitable for automated, high production grinding; when trued, the vitrified wheel is ready to grind. It is not necessary to dress the wheel, ie, to remove some of the bond and expose the abrasive. Like diamond, most CBN used with resin bond is coated with metal to increase grain retention.

CBNs high thermal conductivity helps prevent heat buildup in the part. This reduces the chance of work-piece metallurgical damage, and may improve the quality of the ground surface by leaving it in a neutral or compressive state. When the surface is heated then cooled, as when grinding with aluminum oxide (a thermal insulator), it may be in tension, leading to cracking and failure.

11. Metal-Working Fluids

Metal-working fluids may be divided into four subclassifications: metal forming, metal removal, metal treating, and metal protecting fluids. In this discussion, the focal point will be on metal removal fluids, which are those products developed for use in applications, such as grinding and machining, where the material, typically metal, is removed to manufacture a part.

11.1. Types of Fluids. Metal removal fluids are generally categorized as one of four product types: (*1*) straight (neat) oils, (*2*) soluble oils, (*3*) semisynthetics, or (*4*) synthetics. The distinctive difference between each type is based mainly on two formulation features: the amount of petroleum oil in the concentrate and whether the concentrate is soluble in water. Straight oil as defined by Childers (55) is petroleum or vegetable oil used without dilution. Straight oils are often compounded with additives to enhance their lubrication and rust inhibition properties. Straight oils are used "neat" as supplied to the end user.

Soluble Oil. Soluble oil (or emulsifiable oil) is a combination of oil, emulsifiers, and other performance additives that are supplied as a concentrate to the end user. A soluble oil concentrate generally contains 60–90% oil. They are diluted with water, typically at a ratio of 1 part concentrate to 20 parts water or 5% (56). When mixed with water they have an opaque, milky appearance. They generally are considered as general purpose fluids, since they often have the capability to be used with both ferrous and nonferrous materials in a variety of applications.

Semi-Synthetic Fluids. These fluids have much lower oil content than soluble oils. The concentrate typically contains 2–30% (56) oil. When mixed with water, characteristically at a ratio of 1 part concentrate to 20 parts water or 5%, the blend will appear opaque to translucent. These fluids usually have lubricity sufficient for applications in the moderate-to-heavy-duty range (ie, centerless, internal, and creep feed grinding). Their wetting and cooling properties are better than soluble oils, which allow for faster speeds and feed rates.

Synthetic Fluids. These fluids contain no mineral oil. Most synthetic fluids have a transparent appearance when mixed with water. There are some synthetic fluids that are categorized as synthetic emulsions that contain no mineral oil, but appear as an opaque, milky emulsion when mixed with water. Synthetic fluids have the capability to work in applications ranging from light (ie, double disk, surface) to heavy duty (ie, creep feed, threading). Synthetic fluids generally are low foaming, clean, and have good cooling properties allowing for high speeds and feeds, high production rates, and good size control.

11.2. Functions of a Grinding Fluid. Grinding fluids provide two primary benefits, namely, cooling and lubrication.

Cooling. A tremendous amount of heat is produced in the metal removal process making it important to extract that heat away from the part and the wheel. Dissipating heat from the work piece eliminates temperature related damage to the part such as finish and part distortion. Removing heat from the grinding wheel extends wheel life while preventing burning and smoking. The metal removal fluid carries away most (96%) of the input energy with its contact to the work piece, chips, and grinding wheel. The input energy ends up in the fluid where it will be transferred to its surroundings by evaporation, convection, or in a forced manner, by a chiller. Methods for cooling metal-working fluid are discussed in detail by Smits (57).

Lubrication. Fluids are formulated to provide lubrication that reduces friction at the interface of the wheel and the part. The modes of lubrication are described as being physical, boundary, or chemical. Physical lubrication in metal removal fluid is provided by a thin film of a lubricating component. Examples of these components may be a mineral oil or a nonionic surfactant. Boundary lubrication occurs when a specially included component of the metal removal fluid attaches itself to the surface of the work piece. Boundary lubricants are polar additives such as animal fats and natural esters. Chemical lubrication occurs when a constituent of the fluid (ie, sulfur, chlorine, phosphorous) reacts with a metallic element of the work piece, resulting in improved tool life, better finishes, or both. These additives are known as extreme pressure (EP) additives.

In addition to the primary functions performed by a fluid as previously described, there are other functions required from a fluid. These include, providing corrosion protection for the work piece and the machine, assisting in the removal of chips or swarf (build up of fine metal and abrasive particles) at the wheel work piece interface (grinding zone), transporting chips and swarf away from the machine tool, and to lubricate the machine tool itself.

11.3. Application of Metal-Working Fluids. Understanding the application of metal removal fluids to the grind zone is an important aspect of the grinding process. Metal removal fluids are held in a fluid reservoir and pumped through the machine to a fluid nozzle, which directs the fluid to the grinding zone. Smits (57) describes the various nozzle types: Dribble, Acceleration Zone, Fire Hose, Jet, and Wrap Around. Smits (57) discusses how fluid flow rate, fluid speed entering the flow gap, fluid nozzle position, and grinding wheel contact with the work piece all influence the results of the grinding process. The fluid leaves the cut zone and flows back to the fluid reservoir where it should be filtered before being circulated back to the cut zone.

12. Summary

Abrasive articles and abrading processes are interwoven into a vast variety of manufactured goods produced today. Long-term sustained sales and sales growth in the abrasive industry will depend on many factors. Over the years, manufacturers through improvements in their production practices have reduced the inherent demand of abrasive articles. Near net manufacturing, eg, has reduced the amount of coarse grade abrasives needed for metal degating. Conversely, increased demand for finer and more consistent surface finishes has contributed to the growth of finer abrasive articles.

What does the future hold for abrasives with its strong dependence on other manufactured goods? Quite simply the abrasive's future may be intertwined with continued technology development in abrasive articles and abrading processes with the goal to lower the overall manufacturing cost. As becomes evident form this article, there are a variety of technologies affiliated with abrasives; these technologies include organic chemistry, polymer science, inorganic chemistry, glass chemistry, and ceramics and related process technologies.

Advances in abrasive technologies will most likely be achieved through advances in these related fundamental technologies. Thus, achieving higher abrasive efficiencies and correspondingly lower abrasive costs through technology development should inherently advance the abrasives industry.

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