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Modern Grinding Process Technology

Dr. Stuart C. Salmon

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The sponsoring editor for this book was Robert Hauserman, and the production supervisor was Suzanne W. Babeuf. It was set in Century Schoolbook by North Market Street Graphics.

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I dedicate this book to my father, Arthur Henry Salmon, who died in England on May 1, 1991. Along with my mother he was the driving force behind my entire life. He challenged me. There was always a better way. Nothing was ever good enough. It seemed, at times, that there was little that could please him; it was then he would encourage me. He always wanted the best. Dad, I tried my hardest and will keep on trying. I love you and I miss you.

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Preface

This book has been distilled from more than twenty years of both practical experience and academic research in production grinding processes and systems.

My first attempt at writing an up-to-date grinding manual came with Korber AG in Hamburg, Germany. At their request a text book was written mainly to promote their Schaudt cylindrical and Blohm surface grinding machine tool products and technology. The *Abrasive Machining Handbook* was produced by Korber AG and given free to its customers.

Know-how is the key to success. The *Abrasive Machining Handbook* provided insight into the latest grinding processes and gave confidence to an industry which was hanging on to the historical "trial and error" practices from a bygone time.

The Society of Manufacturing Engineers saw Dr. Robert Hahn retire from the lecture circuit and wanted to provide the United States industry with a Modern Grinding Technology Workshop encompassing the most modern grinding techniques. A course book was written for the workshop attendees drawing on the basic fundamentals to take the audience into the next generation of grinding process technology. The book underwent two iterations and forms the backbone of this text.

It is the aim of this book to be a reference guide providing both practical and theoretical understanding so that the reader can be confident in his or her approach to applying modern grinding technology to the manufacturing world of materials today and tomorrow.

I hope that you find the book useful and easy to read. Ultimately you will have to put the information to good use. There are exciting things happening in the world of abrasives: new processes, new tools, and more efficient methods. We can no longer keep on trying to do the same old things better. There is much to try to do and it all begins just a few pages from here.

Acknowledgments

In order to write a book such as this, there has to be a commitment to impart truth and confidence in a noncommercial way in a commercial world. The abrasives industry is entering exciting times. I am most grateful to the following companies for their assistance in this work, supplying photographs, graphics, and comments. Without them this book would be incomplete and without each other we have nothing. Thank you:

3M Company—St. Paul, Minnesota

6th Grinding Wheel Factory—Guizhou Province, China

Abrasive Engineering Society—Butler, Pennsylvania

American Ceramics Society—Westerville, Ohio

Brown & Sharpe—Providence, Rhode Island

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ELB—Babenhausen, Germany and Fort Lauderdale, Florida

GE Superabrasives—Worthington, Ohio

Hauni-Blohm—Hamburg, Germany and Richmond, Virginia

Jones and Shipman—Leicester, England and Atlanta, Georgia

K.W. Antriebstechnik GmbH—Mainaschaff, Germany and Charlotte, North Carolina

Maegerle—Uster, Switzerland and Schaumberg, Illinois

Master Chemical Corporation—Perrysburg, Ohio

Norton Company—Worcester, Massachusetts

Rolls-Royce Apprentice Training School—Derby, England

SBS—Portland, Oregon

Schaudt—Stuttgart, Germany and Dayton, Ohio

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Studer—Thun, Switzerland and Brookfield, Connecticut

Tyrolit—Schwaz, Austria and Newport News, Virginia

Ultimate Abrasive Systems—Atlanta, Georgia

Wendt GmbH—Meerbusch, Germany and Wendt Dunnington, Chester Springs, Pennsylvania

Winterthur Grinding Wheel Company—Winterthur, Switzerland and Worcester, Massachusetts

Last and by no means least, I extend a special thank you to my wife Sue, who, throughout the ordeal of compiling this book, writing and rewriting, late nights, early mornings, and cancelled weekends, complained little. In spite of all that stood in our way, you were my strongest source of encouragement to press on. On behalf of all those who benefit from this work, thank you.

Modern Grinding Process Technology

Chapter

1

An Introduction to Abrasives

Abrasives and the action of abrasion have been in progress since the beginning of time. Since then, the earth has taken on an ever-changing form due to the erosion of rocks and land mass. Some erosion is caused by the wind and some by the ocean. We will, however, discount human attempts to rearrange the planet. The wind may carry particles of dust and sand, and the ocean and water may carry rocks, pebbles, and boulders. The air and the water are the transporting media moving the harder particles across and against the softer land masses. These are abrasives at work, creating wonderful and amazing natural rock formations like the Grand Canyon, Natural Arch Bridge, and Watkins Glen. We might even consider the craters on the moon, caused by an abrasive action from the bombardment of meteoroids from outer space. In some cases the gentle erosion by the wind has created very picturesque features on our land; in other cases, the natural abrasive action has brought disaster in the form of erosion at the coastline, washing away entire communities at the water's edge. Such is the power of the abrasive action in nature and, as we shall learn through the course of this book, similarly so in industry.

Stone Age people were the first "Abrasive Engineers." They formed weapons and tools, shaping them by abrasion. From the natural stones and rocks found around them, prehistoric humans saw that it was not the hard stones that ground the best, but the softer, more fragile sandstones. This is a phenomenon that will develop in our understanding as we progress through the course. Abrasives, it seems, are almost an inherent part of our being. We use them in our everyday lives without even giving them a second thought.

1.1 Abrasives in Our Everyday Lives

Every morning when we brush our teeth we use abrasives. Most toothpastes contain a very mild abrasive like hydrated silica, which helps clean our teeth, abrading away deposited plaque. The shower stall, bathtub, and washbasin may well have been cleaned using household products containing silica or calcium carbonate, a milder abrasive. The metal utensils with which we eat have been finished using abrasives. The bicycle, motorcycle, or automobile we use to transport ourselves and the electronics and telecommunication equipment we use to do business would be very difficult to make, but for the proper use of abrasives. The foods we eat, flour and chocolate for example, all require the direct use of abrasives in their manufacture. The furniture in our homes was finished using abrasive processes and abrasive media. Surprising as it may seem, our lives depend almost totally on abrasives. Therefore, it would be sensible to understand their uses, as well as how to use them safely, economically, and efficiently.

All of us, at one time or another, have sharpened a pencil or a crayon on a rough stone, concrete, or brick surface. Inherently, we did not try to shape the brick or the stone with the pencil. The most basic principles of abrasives seem to be born in us. The abrasive grain must be aggressive and sharp. Moreover, the abrasive grain has to be harder than the material we wish to shape. Materials scientists are developing materials with hardness and wear resistance which pose a significant challenge to the manufacturing engineer. As materials science develops these new materials, so new abrasive products and processes have to be researched and developed. A whole new world of "Superabrasives" now exists, made from ultra-hard materials, some artificial and some naturally occurring, like diamonds, which are used to machine and fabricate the next generation of materials.

1.2 The History of Abrasives

Let us take a moment to look back and imagine the work of the first engineers. In particular, we will focus on the likes of James Watt and George Stevenson. They pioneered the era of the steam engine, the railroad engine, and of course the whole railroad and transportation system. To build a successful steam engine, precision engineering was a prerequisite. The valve gear and the engine piston bores and pistons had to have close sliding fits. Tolerancing was in its infancy and standards of limits and fits and interchangeability were a thing for the future. Each engine's piston and bore was machined individually and painstakingly formed to a shape which gave the required engine life and performance. The industrial revolution caused the engineering profession to rethink and adjust its mission. No longer was striving for

perfection the single purpose in an engineer's life. Of equal consideration and importance was the production of the commodity and the interchangeability of parts manufactured efficiently and economically. With Henry Ford came the motor car and mass production. Interchangeability and exacting engineering standards demand a tolerancing system of clearances and limits and fits of assembled components. Creating accurate fits requires very precise machining. Milling, broaching, and turning are generally not accurate enough for today's demands in precision. Grinding is an essential process not only for precise sizing and form accuracy, but also for producing the necessary working surface finish. From those early times of Watt, Stevenson, and Ford it was recognized that the demand for consistency and better control of size and surface finish were essential to the success and continuing improvements in engineering design and production. Abrasive engineering delivers that result. Surprisingly, abrasives have been under our noses since the beginning of time.

Over the course of this book we will concentrate on the use of abrasives and develop a practical understanding of their origins, their manufacture, their preparation, and the processes used in modern-day industry.

Abrasive machining has become the generic name given to the process of removing materials, both metals and nonmetals, by means of making very small chips or particulate produced by the cutting edges of abrasive particles. Abrasive papers (sandpaper, emery paper, etc.) first appeared on the streets of Paris, France in the late eighteenth century. The first known article describing the method of making coated abrasives appeared in 1808; calcinated and ground pumice were mixed together with a varnish and spread onto paper with a brush. Emery cloth was invented in England in 1831 (sand, powdered glass, or emery was mixed with glue and spread onto a cotton cloth). An American patent in 1835 covered a method for making coated abrasives by allowing steam to act on the reverse, uncoated, side of the paper to prevent curling. Sand was sprinkled from a sieve onto glue-coated paper that was carried by an endless belt. Prior to and during this time, naturally occurring elements such as sandstone and corundum were cut from solid rock to form the rounded shape of a grinding wheel to be used with newly developed mechanisms and machines.

The abrasive particle is a very hard material. It can only cut or abrade other materials which are softer than itself. By virtue of its shape and its hardness, the abrasive particle is able to penetrate the surface of the material being machined. Since ancient times, natural abrasives were plentiful and were used extensively to sharpen tools and weapons as we previously described. The sandstone wheels were not homogeneous and wore unevenly. Remember, the stone itself was soft, but it was the features of abrasive particle, its shape and its hardness, which allowed abrasion to take place. The inconsistencies in the natural stone, however, meant that the essentially manual machining process was most unpredictable and yielded less than satisfactory results. The need for consistency in an abrasive tool led to the manufacture of artificial abrasives which are more prevalent today. Natural abrasives still in use today are emery, diamond, and quartz sand. The emery and quartz are typically bonded to paper or cloth and form the familiar sandpaper and emery paper used in woodworking. Crocus rouge is still used in very fine polishing compounds, as well as diamond in the form of very fine dust. A common application for such polishing compounds is in metallography for the preparation of the flat surface of the specimen mount.

As the industrial revolution progressed, the need for stronger and more consistent grinding wheels grew. No longer were the unpredictable natural forces holding a sandstone together reliable, particularly as grinding wheel speeds became faster. As a first step, grinding wheels were manufactured by crushing the natural stones into grains and reforming them into grinding wheels using clays and resins to bond the abrasive grain together again. The resin wheels were baked to cure them and the clays were fired in a kiln just like porcelain and china is made today. Because the wheels were made from very small particles, they could be molded into a whole variety of shapes. The use of abrasives was forming into three distinct groups—bonded, coated, and free abrasives. Bonded abrasives are held together by a bonding agent to form a grinding wheel or stone. Coated abrasives are adhered to papers and cloths in the form of grinding belts. Free abrasives are suspended in a fluid medium for polishing or tumbling.

It was not until the nineteenth century that synthetic abrasives began to replace the natural abrasives of sandstone, crocus rouge, emery, corundum, and diamond. The natural abrasives which occurred due to the forces of nature contained many impurities and varied in quality. Synthetic abrasives, however, are pure, consistent, and can be carefully controlled. The most common artificial abrasives available today, in order of their popularity, are aluminum oxide, silicon carbide, cubic boron nitride (CBN), and synthetic diamond. Aluminum oxide and silicon carbide combined are used in over 90 percent of today's abrasive machining applications. Cubic boron nitride and synthetic diamond, termed "Superabrasives," form only a small part of the overall abrasive usage due to their cost and the very special considerations necessary for their successful and economical application. Nonetheless, the new "Superabrasives" are enjoying wider acceptance and are growing in their application. CBN is particularly popular in

the Pacific Rim nations. In fact, it is estimated that in the 1980s over 60 percent of all CBN produced was used in Japan.

Today, the abrasive grain is virtually all artificial and can be manufactured in a variety of different, carefully controlled shapes and sizes. The ability to make abrasive grain consistently to high levels of performance and accurate size provides the abrasive machining process with a wide range of success in a world of machining operations. Machining with abrasives may be carried out with extremely high precision. There are specialist groups of engineers and scientists dedicated to nano-precision (10^{-9}). Nano-precision signifies dimensional tolerancing within a nanometer (0.00000004 in). Nanometer precision furthers the science of achieving such levels of dimensional accuracy and also provides exceptionally high degrees of surface finish. Generally, for high precision work, the stock removal rate in abrasive machining is small due to the size of the abrasive particle being very small. Conversely, abrasive machining may also be used to remove large quantities of material in a very short time, generally to the detriment of surface finish and high precision. Yet, as we shall see, there are some abrasive processes which are exceptions to the rule. The world of abrasive machining covers both ends of the spectrum. Indeed, abrasive machining can achieve the highest qualities of surface finish better than any other machining process. Almost any shape or size of workpiece may be finished by abrasive machining. Surface grinders produce flat, angular, or contoured forms on a flat or contoured surface. Cylindrical grinders produce both internal and external cylindrical shapes, tapers, thread forms, and cam profiles. Recent developments in abrasives and abrasive processes have proven that the complete machining of a workpiece from a rough casting or forging can be achieved by grinding processes only. In most cases grinding achieves better results, both economically and in terms of surface integrity, without the need to premachine the workpiece by conventional milling, broaching, or turning processes. Abrasive machining has a most exciting future. Today it is the only process available which successfully and economically machines the most difficult superalloys. With the ever increasing number of ceramic materials in the marketplace, abrasive machining is assured a place in machining technology. There are few alternatives. One cannot technically mill, broach, or turn these very hard and brittle ceramics with any economical advantage. Grinding is both technically and economically the number one choice when one has to consider machining ceramics. As we look to the future, there is little doubt that abrasive machining is a most versatile process with a very prosperous future.

The abrasive particle is a cutting tool and a most important part of the abrasive machining system. Each abrasive type has different physical properties, as well as both practical and economic considerations. The objective of today's manufacturing world is to achieve the lowest piece part cost for the desired quality and quantity of those parts. Abrasive cost, tooling, and equipment cost are critical in this scenario. The cost of labor, however, is fast becoming less significant in the face of automation and the computer control of the process.

It is therefore important that we take an in-depth look at the major abrasives in use with today's industry so that we might develop an understanding and an approach to selecting the most suitable abrasive media and abrasive processes to achieve the lowest piece part cost for the appropriate level of part quality.

1.3 The World Market in Abrasives

Before analyzing the grain, its manufacture and its uses, we should appreciate the size of the world market in abrasives. Going into the 1990s the American sales of abrasive products was over $1 billion. The breakdown of this figure is roughly $650 million in coated abrasive products, $400 million in conventional wheels, and $120 million in superabrasives. The western world combined adds another $1.75 billion to the total annual abrasive products sold in the free world. It is an interesting statistic that about 30 percent of all machine tools are abrasives oriented. If the sales of abrasive machine tools and abrasive consumable products are combined for the United States, the total market is in excess of $2.5 billion annually. World trends show us that:

Europe and Scandinavia—They parallel the United States in dollar volume of abrasive sales. Along with Japan, Europe has pioneered much of the CBN application development, as well as leading the way in new creep-feed grinding technology and automated grinding systems. Most major abrasive companies and suppliers in Europe are firmly established in the United States. The reverse is also true for U.S. suppliers in Europe.

Canada—Canada is an appreciable user and supplier of abrasive products with particular strength in coated abrasives and wide belts for forestry applications.

Peoples Republic of China—China has a complete and self-supporting abrasives industry producing abrasives of all types, as well as a strong machine tool industry. China exports raw abrasive materials—aluminum oxide, silicon carbide, zirconia, CBN, and synthetic diamonds—to the rest of the world.

The Pacific Rim—Japan, Korea, and Taiwan have a potential market annually in excess of $350 million in abrasive products in the 1990s. Japan has produced some of the finest machine tools, specifically

designed with superabrasives in mind. The Pacific Rim nations are also among the world leaders in ceramic technologies, both in processing and their manufacture into consumer products. It is here, on the Pacific Rim, where we will witness the upsurge in the application of advanced abrasive machining technology into the 21st Century.

Australia, India, and the Far East—Much like Canada, coated abrasives for the forestry and woodworking industries take the lions' share of the estimated $425 million abrasives market. $175 million of that market is in bonded abrasives for precision grinding in areas like Malaysia, Indonesia, and the Philippines, where high technology manufacturing is increasing rapidly. India has an established precision grinding industry and conducts significant research and development in abrasive technology.

South America—Brazil has a completely independent and self-sufficient abrasives industry, and exports a large volume of abrasive

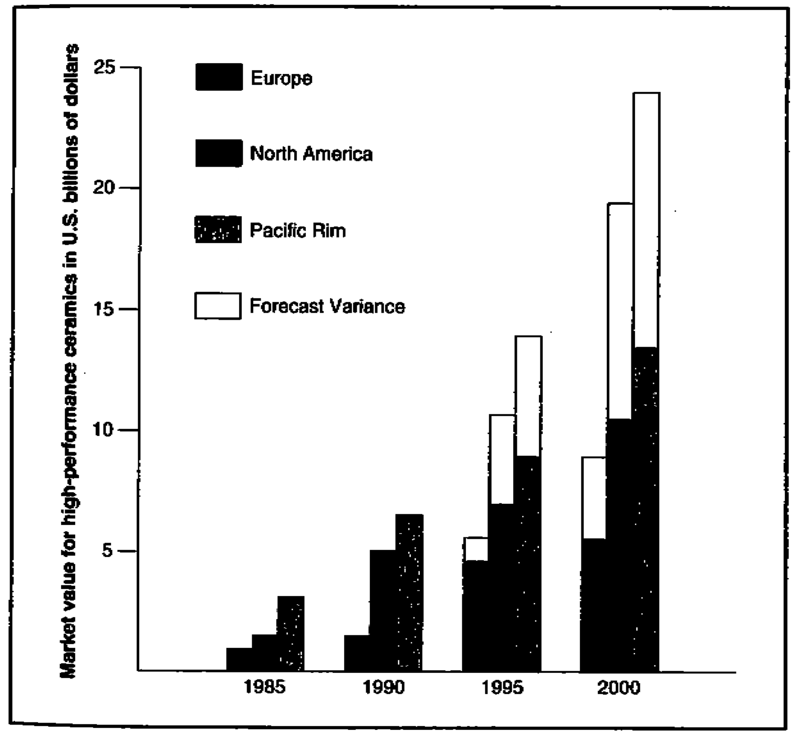


Figure 1.1 Market value of ceramics. (*Reference courtesy of Industrial Diamond Review—January 1991.*)

products to the rest of the world. Argentina has a growth rate in abrasives of 15 percent annually since 1983. Due to the very low cost of labor in the South American countries, much of the mundane machining tasks are being relocated there from North America, boosting the abrasives market in that region.

Eastern Bloc—The Eastern Bloc countries conduct much basic research and development in their universities and research institutes. Much of the equipment and machine tools used in the Eastern Bloc countries comes from Europe, as few highly sophisticated machine tools are built in these Eastern Bloc countries. This situation is changing, but very slowly. The pace of technological change is not keeping up with the sweeping political reforms of the late 1980s.

The ceramics industry is seen as the next frontier in abrasive machining with a market potential of phenomenal proportions (see Fig. 1.1).

Chapter

2

The Manufacture and Properties of Abrasives

2.1 Introduction

In 1944 the Grinding Wheel Manufacturers Association adopted a standard marking system to identify the characteristics of a grinding wheel. In 1958 the American Standards Association adopted a version of the standard. Grinding wheels which contain superabrasives, either CBN or diamond, and particularly those manufactured in Europe, tend to have a marking system which adheres more to the European *Federation Europeenne des Fabricants de Produits Abrasifs* (FEPA) standard (see Fig. 2.1). Throughout this chapter, reference will be made to the standard wheel designation symbols in line with the properties of the various abrasives and particularly the way in which a grinding wheel is manufactured.

There are four main types of synthetic abrasives: aluminum oxide, silicon carbide, Cubic Boron Nitride (CBN), and synthetic diamond. We will examine the procedures for manufacturing these abrasives and the properties of each of them.

2.2 Silicon Carbide

- Chemical formula—SiC.
- Standard wheel designation symbol C.

The first abrasive to be manufactured was silicon carbide (SiC). In 1891 Dr. Edward G. Acheson, working on the assumption that diamond is indeed a form of carbon, mixed together powdered coke and

Standard US grinding wheel designation.

Manufacturer's Prefix and abrasive type	Grain size	Hardness	Porosity	Bond type
38A	**60**	**K**	**2**	**V**
A - Aluminum Oxide C - Silicon Carbide B - Cubic Boron Nitride D - Diamond	Size in US Mesh. Coarse 16-36 Medium 46-80 Fine 90-220	Alphabetical A - Softest Z - Hardest	Dense 0-3 Medium 4-6 Open 7-9 Highly Porous 10+	V - Vitrified B - Resin R - Rubber M - Metal

European/US standard for superabrasive wheels.

Due to the influx of superabrasive wheels from Europe and Japan, the grading system has become mixed and will need some "detective work" to sort out. An example is as follows:

D126	**R**	**75**	**B**
FEPA standard Diamond 120/140 US mesh.	R Hardness	75 Concentration	B - Resin bond

FEPA equivalents:

FEPA	US Mesh
601	30-35
501	35-40
426	40-45
356	45-50
301	50-60
251	60-70
213	70-80
181	80-100
151	100-120
126	120-140
107	140-170
91	170-200
76	200-230
64	230-270
54	270-325
46	325-400

Figure 2.1 Standard wheel designations.

sand and fused the mixture in a crude electric arc furnace. He produced silicon carbide. Acheson thought that he had discovered a substance composed of carbon and corundum (a popular natural abrasive of the time). He named his substance Carborundum and later founded the Carborundum Company.

Silicon carbide is manufactured on an industrial scale today in a resistance arc furnace. The furnace is a refractory enclosure, typically 3 m (10 ft) high, 3 m (10 ft) wide and up to 12 m (40 ft) long with a carbon graphite electrode entering the furnace from either end. The mixture is made of 60 percent silica sand and 40 percent coke, along with a small amount of sawdust, to increase the porosity of the mix. Salt is also added as a catalyst to assist in the purification of the silicon carbide. The furnace is half filled with the mixture and a central core of granular carbon is laid down to connect the two carbon electrodes at either end of the furnace. The furnace is then completely filled. Some furnaces might contain as much as 90,000 kg (200,000 lb) of mix which could yield up to 11,000 kg (25,000 lb) of silicon carbide. A voltage of approximately 300 V is applied to the electrodes and the current allowed to pass for up to 36 hours, over which time the voltage drops to 200 V. During this time the furnace reaches temperatures over 2200°C (4000°F). The furnace is cooled after a soaking time at temperature and the side walls of the furnace are dismantled to expose the charge. The charge is then broken and crushed. The center core of graphite is usually saved to be reused. The center of the charge offers the most pure silicon carbide which is green in color, while the less pure abrasive is black. The need for large amounts of electrical power to energize the furnaces tends to make geographical location important to the producers. China and Scandinavia are large producers of silicon carbide due to the abundance of hydroelectric power as a natural resource. Indeed, the original Carborundum Company settled in Niagara Falls, New York, one of the United States' great hydroelectric power resources.

Silicon carbide (see Fig. 2.2) is especially suited to the machining of very hard materials, in particular tungsten carbide, cast iron, chilled iron, marble, and some ceramics, as well as the more reactive yet softer materials like titanium, aluminum, copper, and brass. Silicon carbide is very hard and has an aggressive shape which assists in penetrating the surface of softer materials like low tensile strength steels, aluminum and copper alloys, plastics, rubbers, and soft wood. The slightly impure black silicon carbide is well suited to very rough grinding and snagging operations, whereas the pure green silicon carbide is more friable and lends itself to cooler cutting and more precise grinding operations in very hard and heat sensitive materials.

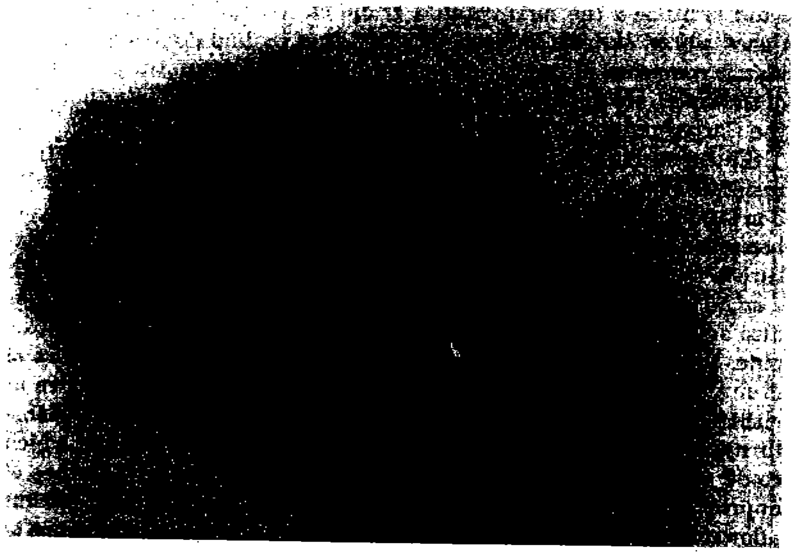


Figure 2.2 A piece of silicon carbide broken from the cooled charge.

2.3 Aluminum Oxide (Fused)

- Chemical formula—Al_2O_3.
- Standard wheel designation symbol A.

Around the same time as Acheson, in 1899, Charles B. Jacobs was performing similar experiments to produce pure and more uniform aluminum oxide in France.

The industrial manufacture of aluminum oxide requires a fusion process similar to that for silicon carbide. Bauxite, a naturally occurring clay-like substance, mined from large open-cast mines, is rich in hydrated aluminum oxide. Before processing, the hydrated aluminum oxide has to be calcinated to drive off any moisture. The bauxite is then mixed with ground coke and iron borings. The base of an open cylindrical pot furnace is covered with carbon bricks. The sides are left uncovered, however, and when in operation they are cooled by water jets. Once the furnace is half filled with the above mixture, two or three vertical electrodes are lowered into the furnace. A starter charge of metallurgical coke is placed between the electrodes and the mixture. The electric current is applied and the coke quickly glows to incandescence. The fusion process has begun. The intense heat, in the order of 2000°C (3700°F), melts the bauxite and reduces the impurities which settle to the bottom of the charge. As the fusion process continues,

more mixture is added until the furnace is full. The electrodes are raised and lowered to maintain the correct temperature automatically. This fusion process may last from 16 to 36 hours. Once complete, the furnace is left to cool for several days. The ingot is then emptied of its charge and the outer impure layer is stripped off. The center core of 99.9 percent pure aluminum oxide is broken up and crushed. Once crushed, the abrasive is washed and then screened for size. Pure aluminum oxide is white (see Fig. 2.3). Regular aluminum oxide is a special term given to impure aluminum oxide which is brown in color and typically 95 percent pure. The hardness and brittleness of the abrasive increases with purity. Aluminum oxide is the most commonly used abrasive and is used to machine a vast array of materials from the most difficult machine superalloys to high alloy steels and mild steels.

There are a number of techniques used to modify the properties of the aluminum oxide grain to adjust its friability, hardness, and bonding. The silicon treatment is one which improves the grain's adhesion to resin bonds as well as improving its water resistance. Ceramic coating also provides the grain with a superior surface for better mechanical bonding in a wheel matrix. Heat-treating the abrasive and quenching the grain can increase friability. Alloying elements also adjust the friability of the grain; zirconium is a common alloy used in this way. Compounds such as chromium oxide and vanadium oxide are also added. These oxides mod-

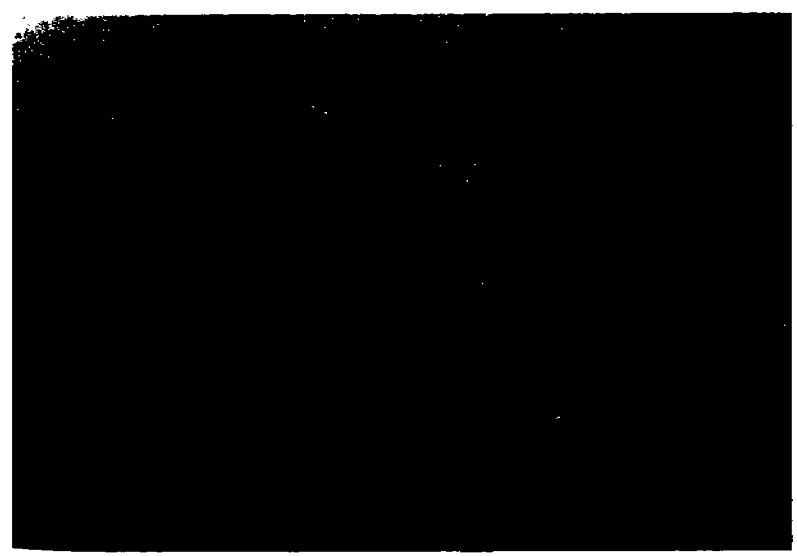


Figure 2.3 A piece of aluminum oxide broken from the cooled charge.

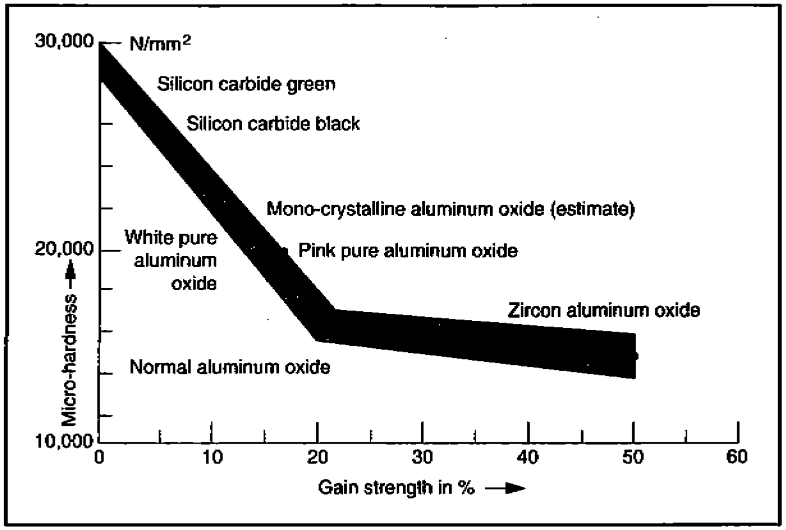


Figure 2.4 Properties of aluminum oxide and silicon carbide.

ify the toughness of the grain to a very small degree. However, it is said that the coloring effect, pink and blue-green, respectively, is used more as a marketing tool than for technical reasons (see Fig. 2.4).

Aluminum oxide is used in over 70 percent of the abrasive machining applications in the world. It is by far the most widely used of all abrasive media. The demand for large quantities of aluminum oxide has prompted more modern manufacturers of the grain to use a continuous fusion process. Here a furnace, similar to the one described above, is tipped every three to four hours. Depending on the property of the required grain, the molten aluminum oxide might be poured into large refractory molds and allowed to cool slowly to produce large crystal grains. Conversely, the molten aluminum oxide might be poured into water which will quench the compound and yield a very fine crystalline structure. Once cooled, the grain is further crushed and then washed prior to grading for size. The grain might then be postprocessed or coated prior to being combined with the bonding agent and formed into the shape of a grinding wheel.

2.4 Aluminum Oxide (Ceramic)

- Chemical formula—Al_2O_3.
- Standard wheel designation symbol SG.

Ceramic abrasive is the generic term which has been given to the aluminum oxide produced by the Sol-Gel process. There are apparently two types of such abrasive mineral on the market; "SG" (which stands for Seeded-Gel) manufactured by the Norton Company and "Cubitron" manufactured by the 3M Company. 3M has produced the Cubitron grain commercially since the late 1970s and used it exclusively in coated abrasive products. Norton launched their SG grain in vitrified bonded wheels in the late 1980s. Now both the SG and Cubitron grain is found in vitrified aluminum oxide products of the world's abrasive product manufacturers. The process used to manufacture the ceramic aluminum oxide grain produces a "solid" crystal of aluminum oxide with a great deal less friability than typically found in the fused aluminum oxide. However, the sharpness of the ceramic abrasive is much longer lasting than the traditional fused aluminum oxide. The Sol-Gel process is very much like growing crystals in a supersaturated solution and has the potential to allow the manufacturer to produce mineral grains to a given shape and aspect ratio, a feature never before found in an abrasive grain mineral. Perhaps one day we might find grinding wheels manufactured by orienting columnar grains so that their best cutting action and wear resistance is preferentially positioned for optimum performance. Presently, the Norton Company and others are combining the properties of the ceramic and fused aluminum oxide into vitrified grinding wheels for precision grinding. Pure SG wheels tended to produce high residual stresses in heat and crack sensitive materials so the pure SG wheels are generally used in rough grinding operations. The combination of the ceramic and the fused aluminum oxide tends to produce a wheel more suited to fine precision grinding (see Fig. 2.5). The wheel exhibits a high level of sharpness, an aggressive cutting action, good form holding, and long life. The properties of the SG grain are complemented by the friability of the fused aluminum oxide. The grade designation is typically written, for example, SG2 (20 percent alumina mix) SG5 (50 percent alumina mix). This is a very exciting technology in that a new, relatively low cost abrasive has inserted itself between the conventional abrasives and the very expensive superabrasives with measurable improvements in grinding by a factor of three to five times.

2.5 Cubic Boron Nitride (CBN)

- Standard wheel designation symbol B.

In 1950, the General Electric Company recognized the fact that there was an increasing need for a reliable source of diamond and went about the task of creating artificial diamonds. In 1954, GE had

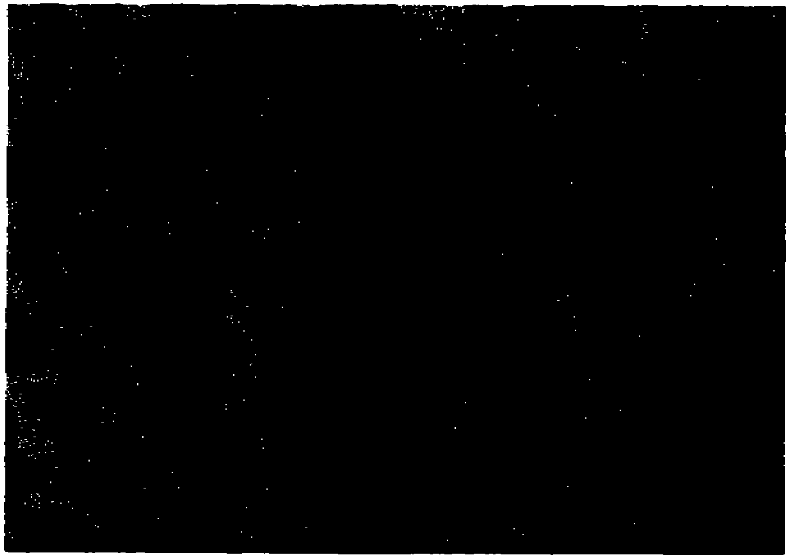


Figure 2.5 Seeded-Gel (SG) aluminum oxide on the left and fused aluminum oxide on the right. (*Photograph courtesy of Norton Company.*)

successfully manufactured a synthetic diamond in the laboratory, and by 1957 introduced commercially available synthetic industrial diamonds.

As a result of work carried out in the development of synthetic diamonds, the General Electric Company introduced a new abrasive to the industry in 1969 with the trade name Borazon, or cubic boron nitride (CBN) as it is more commonly known. CBN is an abrasive with a hardness greater than that of silicon carbide and yet not as hard as diamond. CBN has the ability to machine even the hardest of steels to very precise forms and finishes with a great deal less wear than aluminum oxide or silicon carbide. Moreover, CBN is chemically inert in the presence of carbon. Unlike diamond, which is carbon based and has an affinity for the carbon in steels, CBN can machine steels at very high stock removal rates and with superior surface finishes. CBN does however appear to react with water at high temperatures. Water vapor dissolves the protective boron oxide layer leaving the surface exposed to hydrolysis and leading to rapid wear and therefore a low G-ratio. G-ratio is the term which describes wheel wear. A high G-ratio is generally felt to be beneficial as the grinding wheel wears less than a grinding wheel with a low G-ratio. A G-ratio number of, say, 10 means that the grinding wheel machines 10 times as much material as is lost from the grinding wheel.

Peculiarly, the G-ratio number has never included the amount dressed from the grinding wheel in preparation. In order to enjoy the high G-ratios promised by the manufacturers of the new abrasive, it was necessary in the early days to use a straight oil cutting fluid, as opposed to the more accepted water-based cutting fluids. Today, water-based cutting fluids have improved immensely, such that the differences in G-ratio between oil and water when grinding with CBN are not nearly so pronounced.

There are two major suppliers of CBN abrasive: GE Superabrasives and DeBeers. Originally each company had its own trade name: Borazon, CBN, and Amborite, ABN, respectively. Both companies have since agreed to call what is essentially the same mineral, "CBN."

CBN is manufactured by a process which requires very high temperatures and pressures. It is synthesized in crystal form from hexagonal boron nitride which is commonly called "white graphite," derived from the pyrolysis of boron chloride-ammonia ($BCl_3{\cdot}NH_3$). The hexagonal boron nitride, composed of atoms of boron and nitrogen, is combined with a catalyst like metallic lithium in an environment in the range of 1650°C (3000°F), and pressures of up to 68,000 bar (1,000,000 psi). A black, opaque grain results. De Beers used lithium nitride as their catalyst and found that a yellow, translucent grain results, hence, their designation Amber Boron Nitride (ABN). The intense heat and pressure in the presence of the catalyst causes the nitrogen atom to donate an electron to a boron atom which then forms a chemical bond to the nitrogen atom and forms a very strong crystalline structure similar to that of diamond. The crystals are blocky in shape with noticeably sharp edges and corners. Until the mid-1970s CBN was manufactured in only two forms: Type I (GE) or ABN 300 (De Beers), uncoated and used in plated wheels, and Type II (GE) or ABN 360 (De Beers), consisting of 40 percent by weight uncoated and 60 percent nickel coated. The nickel coating provides increased bond strength for use in resin bonds (see Fig. 2.6).

The CBN referred to above has a grain structure which fractures along cleavage planes. The grain therefore wears until the force on the grain is sufficient to cause shearing of the cleavage plane to expose a sharper, keener cutting edge. This shearing force is very high due to the high hardness and toughness of the abrasive. Diamond truing is therefore the best method for forming or truing very fine detail in the grain on the periphery of a grinding wheel. Diamond has the hardness, and therefore the ability, to fashion the shape of the surface grains. The advent of reliable vitrified bond systems for superabrasives makes crush dressing practical, yet for the finest detail, diamond dressing systems are superior.

A new type of CBN grain structure has been developed by both GE Superabrasives and De Beers. The new grains are types 500, 510, 550,

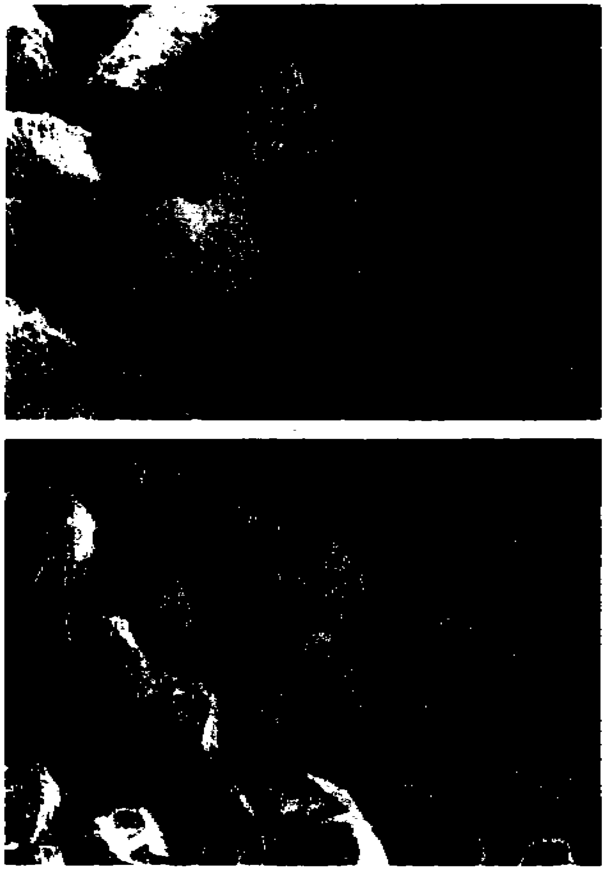


Figure 2.6 Nickel coated CBN 560 (top) with CBN 550, an uncoated abrasive (below). Both are 40/50 U.S. mesh. (*Photograph courtesy of GE Superabrasives.*)

560, and 570 CBN by GE and ABN 600, 610, and 660 by De Beers. This new structure is microcrystalline. The grains tends to be quite large, as large as FEPA B851 (20/30 U.S. mesh), and appear to sharpen themselves in-process by very fine crystallographic breakdown. This attritious wear mechanism therefore exposes an aggressive surface as opposed to a worn flat surface typical in monocrystal grain. CBN grinding wheels manufactured with the microcrystalline grains should be expected to require less truing and dressing.

Compared with aluminum oxide and silicon carbide, CBN has minimal wear and therefore stays sharper for a longer period of time

between dressing. An individual CBN grain will exhibit a life 100 times that of an aluminum oxide grain (see Fig. 2.7). Because of its inherent sharpness CBN tends to machine cooler, providing high surface integrity and superior surface finish. The cost of the abrasive is high; however, the benefits derived from the dramatically reduced amount of wheel dressing and the quality of the workpiece surface may be advantageous. It is important to appreciate that CBN requires a very rigid machine tool with the correct truing and dressing method employed. Machine tools designed along the more traditional lines of a grinding machine do not have the vibrational stability nor the high speed capability required for the economical use of CBN. CBN has been shown to perform more successfully with increased wheel speed, providing high stock removal rates and minimal wheel wear. High-speed grinding tests, using plated CBN wheels, have been carried out in excess of 300 ms^{-1} (60,000 sfm) and have shown longer wheel life and better quality workpiece surfaces. There are machines working in production in the United States using plated CBN wheels, running in excess of 150 ms^{-1} (30,000 sfm). At normal speeds there is one disadvantage with CBN in that it does not machine very soft or gummy materials easily. The plated grinding wheels clog and load up with the soft, sticky material. At ultrahigh speed however, it would appear that the chip formation changes and brittle fracture occurs in the softer materials, such that at high speed it would appear that both hard and soft materials will machine alike. The demands on the machine tool for dynamic stability under high-speed conditions are great. CBN, along with diamond, has been termed a "Superabrasive," so similarly it requires "super" machine tools which have been designed with the specific requirements of CBN and diamond abrasives in mind. The truing and dressing methods for these abrasives require high dynamic rigidity of the machine tool as well as the truing and dressing mechanism in order to cope with the inherent vibration experienced with superabrasives. Dynamic wheel balancing is essential.

2.6 Diamond

- Chemical formula—C.
- Standard wheel designation symbol D.

In the 1950s, both the General Electric Company in the United States and ASEA in Sweden independently discovered a synthesis process which created a crystalline diamond from graphite. In 1957, the General Electric Company announced that the commercial manu-

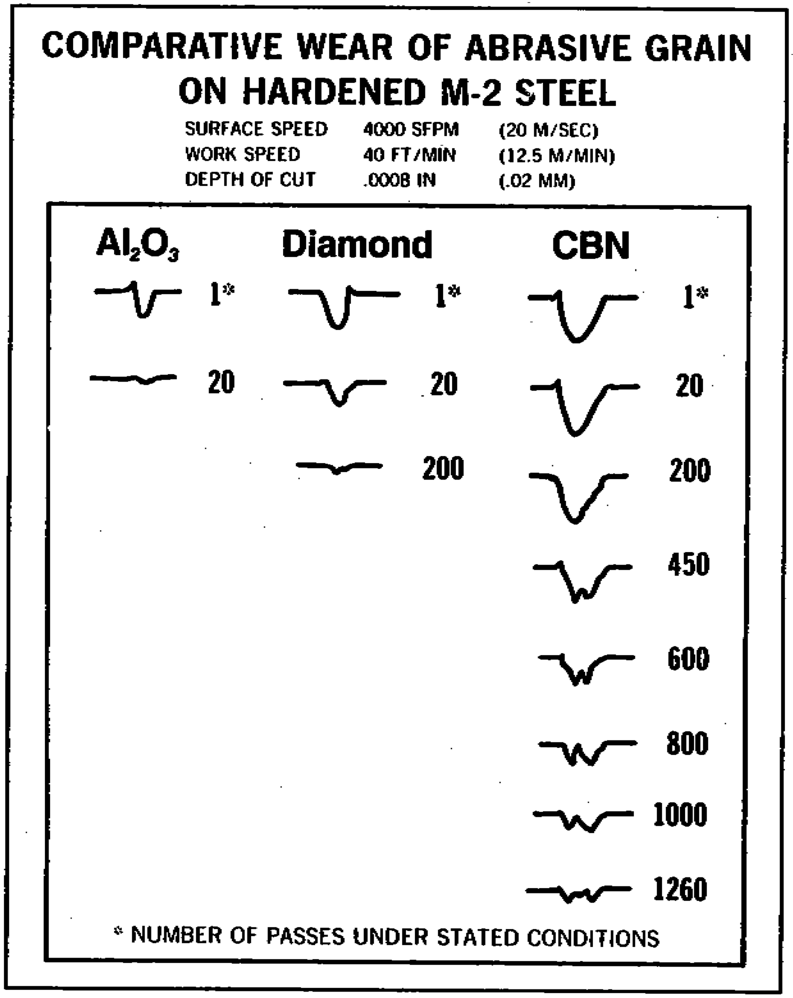


Figure 2.7 Grain wear.

facture of diamond, for sale as a consumable abrasive, was possible. The synthetic diamonds were given the trade name "Man-Made." The first successful industrially manufactured diamond was achieved when iron sulfide, in a graphite tube closed with tantalum end disks, was subjected to a pressure of 95,000 bar (1,400,000 psi) and 1600°C (2900°F) for several minutes. Tests on the crystal produced proved that it was indeed a diamond.

The industrial process for manufacturing diamond now uses pressures in the range of 55,000 to 130,000 bar (808,000 to 1,900,000 psi) at temperatures in the range of 1400 to 2500°C (500 to 4500°F). The catalyst-solvent metal interface is most important. Iron was first used, and since then chromium, cobalt, magnesium, nickel, platinum, rhodium, ruthenium, and tantalum have been used successfully. Different temperatures, solvents, and pressures produce different diamond types. Each crystal may be tailored to the best possible combination of size, shape, surface, and crystal structure for specific applications.

The metallic coating of the diamonds with nickel and/or copper provides better mechanical bonding in a variety of bond systems, as well as providing a path for the heat from the process to be conducted away from the diamonds, particularly in dry grinding applications.

Diamond is suited to grinding tungsten carbide, natural stones, granite, and concrete, as well as more sophisticated ceramics and cermets. Diamond, however, is most unsuitable for the grinding of steels due to the very aggressive chip formation which tends to tear the diamonds from their bond. Also, it is postulated that diamond, being a carbon-based material, has an affinity for the carbon in the steel and suffers accelerated wear by the dissolution of the diamond into the carbon in the steel, producing an iron carbide (Fe_3C) with most unsatisfactory results. These are two of the prime reasons for the introduction of CBN, which is less reactive in the presence of carbon steel alloys and has better mechanical bonding properties, making wheel fabrication that much easier.

2.7 The Properties of Abrasives

For an abrasive to function properly it must be harder than the material being machined. The abrasive particle must be of sufficient hardness and shape to be able to penetrate the surface of the material to be machined and form a chip or particulate. However, the abrasive must be tough enough to withstand both the thermal and mechanical shock of grinding, and at the same time be friable enough to fracture and produce new and sharp cutting edges.

Hardness is a term used in abrasive machining which is often confused. Hardness is usually referred to as a property of the grinding wheel. This will be discussed later. It must therefore be emphasized that hardness, as referred to in this chapter, is the property of the abrasive grain alone. The relative hardness of some popular abrasives is shown on this Knoop Scale:

Hardened Steel Rc 60	740
Quartz	820

Aluminum Oxide	2100
Silicon Carbide	2480
Cubic Boron Nitride	4700
Diamond	7000

Both mechanical and thermal shock resistance are the most important properties of an abrasive. The working abrasive grain endures not only intermittent cutting, but also thermal cycling. The heat of grinding may be detrimental to the abrasive in the presence of certain chemical elements, which could dramatically reduce the sharpness and hardness of the grain by diffusion into the grain matrix at high temperatures. This can be put into perspective when we consider that diamond is the hardest substance that we have discovered, and we assume that it is virtually indestructible. This is not a sound assumption because the hardness was measured by indentation hardness measurement. There was no sliding wear, frictional heat generation, or cyclical mechanical shocks. Hardness does not necessarily mean that the substance has good wear resistance. Diamond conducts heat tremendously well, six times better than copper and with very low thermal expansion. Though the diamond will not expand with increasing temperature, inclusions in the diamond will expand at a rapid rate and destroy the grain. Diamond quality is therefore an important area of concern when specifying natural or synthetic diamonds.

The need for toughness and friability in an abrasive seems to be contradictory. However, an abrasive must possess both qualities to a certain degree. In the extreme, a tough grain with little friability will become dull quickly and the grinding wheel will glaze. Dressing this type of grinding wheel with a single point diamond will tend to pull the abrasive grain from the bond, instead of breaking the grain to leave a sharp edge. Going to the other extreme, a friable grain with little toughness has a very aggressive nature, and will crack and fracture very quickly under load, revealing another layer of sharp-edged grains. This rapid shattering of the friable grain results in a cool cut, but at the expense of high wheel usage.

To reinforce the concept of toughness and friability it is worth considering glass as a material. Glass, which is significantly harder than a piece of mild steel, is a candidate for a tool material to machine steel, but glass has little toughness. If a drill or a milling cutter were able to be made from glass, we would see that the glass would shatter under the machining forces. If the glass were to get hot and then be quenched by the cutting fluid, again it would shatter into pieces. Glass is therefore too friable and lacks toughness. Toughness is the ability to hold shape without compromise in hardness.

There are a number of abrasive types as well as forms. Our choice of abrasive will be governed by a number of factors, all relating to the overall economics of the machining process, along with the type of material being machined, the surface finish required, dimensional accuracy, profile detail, and form tolerance. Particularly in the case of precision grinding, the type of machine tool being used and its physical condition also will influence the choice of an abrasive system.

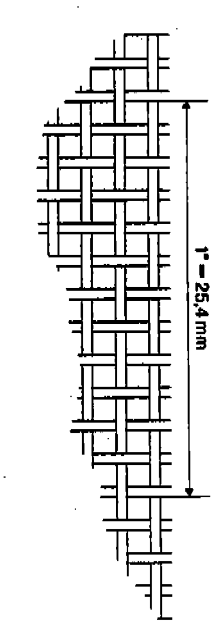
When an abrasive type is first selected, it is graded into grain sizes. The system used to do this is a series of fine mesh wire grids (see Fig. 2.8). The mesh size corresponds to the number of openings per linear inch in a wire gauze. The gauze categorization is carried out for sizes 4 to 240. In many applications where fine finishes are required, the abrasive is categorized into much finer mesh sizes, which are too fine to be segregated by gauzes. The fine grain may be as fine as 4000 on the mesh scale. Wheels of such fine grain are sometimes referred to as "flour" wheels. Grains finer than 240 are separated by a flotation method where the grain is suspended in water. At given time intervals, the grain, which has settled, is extracted and as the settling time progresses, the grain is graded finer and finer. The "flour" grain is so fine that it will float on the surface of the water, held afloat by the surface tension.

Once the grain has been manufactured, processed, and graded into sizes, it is then bonded into a tool. The bonding system is the method by which the grains are held together in the shape of a grinding tool. If the grain is to be bonded into the shape of a precision grinding wheel, then the most common bonding systems are vitrified, resinoid, rubber, metal and plated. Approximately 50 percent of all grinding wheels manufactured are vitrified. If the grain is to be used as a coated abrasive then it will typically be bonded to a paper or a cloth backing.

2.8 Concentration

When a superabrasive grinding wheel is made there is an additional factor called concentration, which appears in no other abrasive system. It refers to the amount of abrasive per unit volume of usable wheel. Concentration numbers are typically in the range 30 to 175, 30 having only 1.32 carats/cm^3 (22 carats/in^3) and 175 having 7.7 carats/cm^3 (126 carats/in^3). The grain size will affect the achievable concentration level, as it is easier to completely fill a space with many smaller particles as opposed to very large randomly shaped blocks (see Fig. 2.9).

The concentration of the selected grinding wheel is based upon the area of contact between the wheel and workpiece. A large area dictates a low concentration and a small area a high concentration. A rule of thumb to establish a concentration number is as follows:



Grain numeral		Dimension mm	Grain numeral		Dimension mm
8	very coarse	2,83–2,0	90	fine	0,18 –0,13
10	very coarse	2,38–1,68	100	fine	0,15 –0,11
12	very coarse	2,0 –1,41	120	fine	0,13 –0,09
14	very coarse	1,68–1,19	150	fine	0,11 –0,06
16	coarse	1,41–1,0	180	fine	0,09 –0,05
20	coarse	1,19–0,84	220	fine	0,075–0,045
24	coarse	0,84–0,60	240	very fine	0,047–0,043
30	coarse	0,71–0,50	280	very fine	0,038–0,035
36	coarse	0,60–0,42	320	very fine	0,031–0,028
46	medium	0,42–0,30	400	very fine	0,018–0,016
54	medium	0,35–0,25	500	very fine	0,014–0,012
60	medium	0,30–0,21	600	very fine	0,010–0,008
70	medium	0,25–0,18	800	very fine	0,008–0,006
80	medium	0,21–0,15	1000	very fine	0,005–0,004
			1200	very fine	0,004–0,003

Figure 2.8 Grain size.

If the contact area between the grinding wheel and the workpiece is less than 15 mm² (0.025 in²), then use 100 to 150 concentration; between 15 and 50 mm² (0.025 to 0.075 in²), then use a 75 concentration; and for larger areas use 50 and maybe as low as 30 concentration, particularly for materials like glass which are prone to chipping.

Unfortunately, the industry sees concentration as more of an economic factor than a technical one. Confusion also arises with respect to the meaning of 100 concentration which is often misinterpreted as 100 percent and the maximum concentration. This is *not* so. A concentration of 100 means that there are 4.4 carats of abrasive per cm³ (72 carats per in³).

Grain Size		Grain Concentration				
US Mesh	FEPA	60	120	180	240	300
240	64	416	833	1250	1666	2082
190	91	142	284	426	569	711
150	107	86	173	259	345	432
120	126	51	101	152	203	254
100	151	32	63	95	126	158
80	181	18	36	54	72	90
60	251	6.6	13	20	26	33

Table of grain density - Number of grains per mm³.

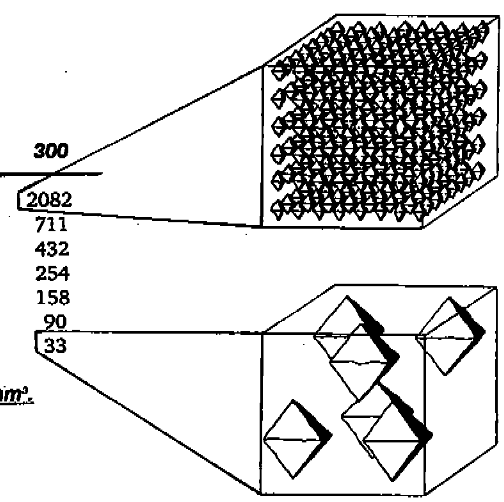


Figure 2.9 Grain concentration.

2.9 Vitrified-Bonded Grinding Wheels

- Standard wheel designation symbol V.

A vitrified bond is made of clay or feldspar which fuses at a high temperature to form a glass-like structure. During the firing operation, the clay or feldspar melts, surrounding the abrasive grain, bonding each grain to the next, and forming a homogeneous structure. When the wheel cools, each grain is surrounded by a hard glass-like bond which has high strength and rigidity. This type of bond system is well suited to abrasive machining as it fractures readily when the grinding forces build up on the abrasive grain. The grinding forces will increase on the grain as it dulls; generally, it is the dull grains that we wish to be broken free from the wheel in order to expose the keener, sharper cutting grains. The amount of bond material mixed in with the grain prior to firing will determine the strength of the grinding wheel and determine the grade of the wheel with respect to the hardness of the grinding wheel. The bond strength is the holding power of the bond to hold a grain in position under the grinding forces. In this instance hardness refers to the overall hardness of the grinding wheel, composed of the grain held into a bonding system. A balance may therefore be struck between the friability and toughness of the grain versus the strength and brittleness of the bonding agent. In one case the grain might be the first to fracture, while in another case the bond might be weak and the whole grain might be plucked or broken from the wheel periphery.

Grinding wheel hardness is determined by the grinding wheel manufacturer. One method of wheel hardness measurement is to take a hard spade-type drill with a constant thrust force and literally drill the grinding wheel. The depth of penetration of the drill is measured after a set period of time. The depth of penetration determines the wheel hardness and is the basis for a grinding wheel grade in the range of A through Z, with A being the softest and Z the hardest. The deeper the penetration over a given period of time, the softer the grinding wheel. Another method is to use an air/abrasive blast to break the grain from the bond system. After a blast at a given pressure for a given time using a known size of abrasive particle, the depth of erosion is measured and the wheel hardness determined. One other method utilizes a natural frequency of vibration measurement technique, a system called "Grind-O-Sonic," developed in Belgium (see Fig. 2.10). The grinding wheel is supported on four equally spaced points on an isolated rubber pad, such that the wheel may vibrate when given a sharp blow with a hard rubber hammer or similar object. The frequency of vibration is detected and measured through a pickup. The numerical value is entered into a formula which relates the size, shape, and mass

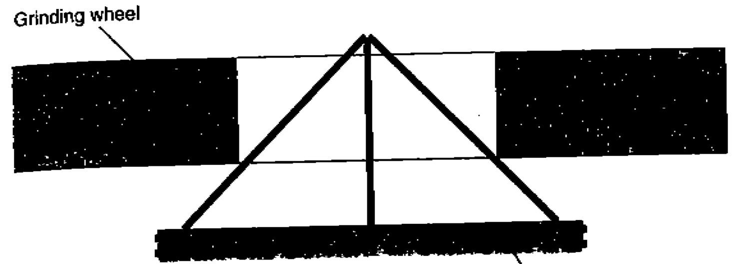


Figure 2.10 Grind-O-Sonic.

of the grinding wheel to the frequency of vibration, and determines a bulk Young's modulus for the grinding wheel. The Young's modulus can then be related with surprising accuracy to the hardness and performance of the grinding wheel. This technique has proved to be a major contributor to hardness "balancing" of rotary honing stones (see page 192).

A further property of a grinding wheel is its structure (see Fig. 2.11). The structure refers to the skeletal structure of the bond system. The structure is a measure of the density/porosity of the grinding wheel. Supposing a great deal of very fine abrasive grain were mixed with an equal amount of very strong bond material and pressed under high pressure, a dense, low porosity grinding wheel would result. If a small amount of grain were mixed with a small amount of bond material and another media (to space the grains apart), the result, once the spacing media were removed, would be a very open, highly porous structure grinding wheel. The latter method is used to manufacture the high porosity grinding wheels necessary for creep-feed grinding. The spacing media used to create the large and consistent porosity is paradichlorobenzene (moth ball crystals), which is removed from the wheel in its green state in a steam autoclave prior to firing. In the past, many different materials were used to increase the porosity of a grinding wheel; sawdust and walnut shells were quite common and usually left in the mix to burn out during the firing operation.

A vitrified grinding wheel is manufactured by selecting the correct abrasive and grain size, and thoroughly mixing the abrasive with the correct amount of bonding agent and porosity media, along with a little water. The mix is then packed and pressed into a grinding wheel mold, with pressures varying from 10 to 675 bar (150 to 10,000 psi). The mold is then fully dried, forming a grinding wheel in a green state. Shaping or recessing the grinding wheel by machining is more easily performed in the green state. If there is a pore inducing media in the mix it is removed in a steam autoclave. The wheel is then dried and fired in a kiln, in a similar manner to firing a piece of pottery, at temperatures approaching 1400°C (2500°F) for several days, depending on the size of the grinding wheels and the charge. The wheels are then removed from the kiln and slowly cooled. They are then checked for distortion, shape, and size. After machining to a final size, the wheels are balance tested, balanced, and overspeed tested, generally at 1.5 times the rated Maximum Operating Speed (MOS), to ensure operational safety.

An alternative to pressing the grinding wheel mix to form a wheel in the green state is a method called puddling. A puddled wheel is typically mixed to such a consistency that the mixture can be poured into a shaped mold and allowed to set before firing in the kiln. This method of wheel manufacture allows a larger and more consistent porosity throughout the grinding wheel, particularly across the wheel width, where pressing tends to develop a wheel much harder at the edges than in the center. This method usually results in a very open and soft structure suitable for creep-feed grinding.

It should be understood that the vitrified bond system is hard and brittle. The great majority of wheel wear takes place by the mechanical action of stressing the bond with a high grinding force, breaking the bond bridges, and allowing the exposure of a new, sharper, grain deeper in the wheel's structure.

There is an interesting note to be made with respect to silicon carbide and superabrasive wheels in a vitrified bond system as we have

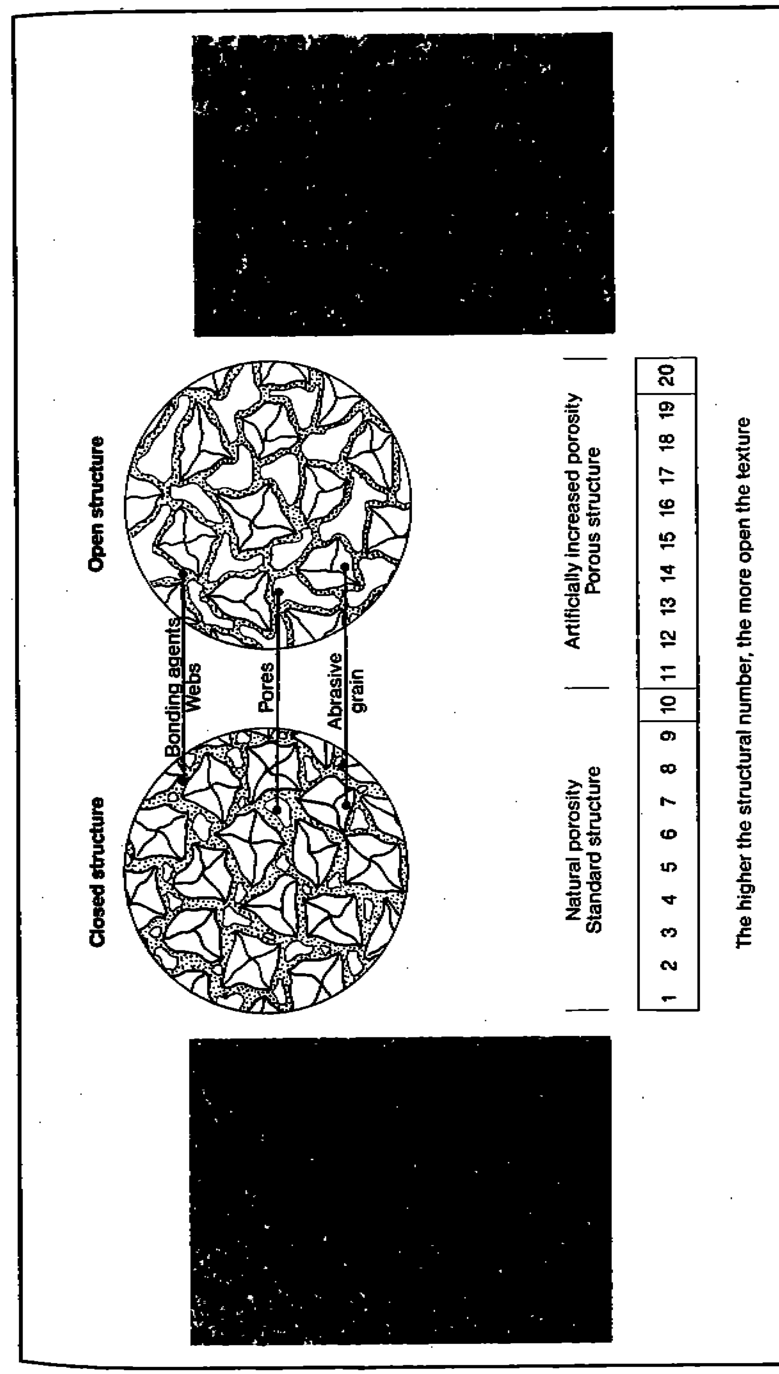


Figure 2.11 Grinding wheel structure.

described it. A silica, glass-like, vitrified bond media reacts adversely with a silicon carbide grain, so a porcelain/ceramic type bond system has to be used for silicon carbide wheels. Superabrasive grain can be bonded in a vitrified bond. However, diamond turns into graphite at 700°C (1300°F) and CBN begins to oxidize at 1000°C (1850°F) and completely oxidizes at 1900°C (3500°F). Therefore, lower temperature vitrified bonding systems had to be developed; remember, vitrification of Al_2O_3 wheels takes place at 1400°C (2500°F) (see Fig. 2.12).

2.10 Resin-Bonded Grinding Wheels

- Standard wheel designation symbol B.

Resin-bonded wheels are manufactured in a very similar manner to the vitrified wheels. However, the bonding medium is a resin. A thermosetting synthetic resin is mixed in either powdered or liquid form (latex) with the abrasive grain and a plasticizer (catalyst) to allow the mixture to be molded. The mixture is then pressed and cured at a temperature of 150 to 200°C (300 to 400°F) for periods of as little as twelve hours and as long as four to five days, depending on the size of the wheel. During this curing, the mold first softens and then hardens as the oven reaches curing temperature. Upon cooling, the mold retains its cured hardness.

Two disadvantages of resin-bonded wheels are their low porosity and, when in the presence of a cutting fluid, their tendency to soften and wear excessively. Much research is being carried out to improve the compatibility between cutting fluids and resin bond systems. Their prime areas of use are for high-speed grinding, where they can withstand much higher bursting forces than vitrified grinding wheels. Special resin-bonded wheels have been safely run at speeds up to 125 ms^{-1} (25,000 sfm), whereas vitrified wheels tend to be safe only up to 60 ms^{-1} (12,500 sfm). The limitation of a resin bond at very high speeds is the result of overheating the bond, which cokes and breaks out of the wheel periphery. Another prime area of use for resin-bonded wheels is steel mill snagging operations, and hand grinders, which suffer rough handling and abuse. The amount of hand grinding and snagging in the industry, as well as high-speed, superabrasive, and precision grinding, means that resin-bonded wheels account for 30 to 40 percent of the grinding wheel market.

It should be understood that the resin bond system is somewhat soft and forgiving, and that the great majority of wheel wear takes place because of thermal action, which melts the bond with frictional heat, thus softening the bond and allowing the dull grains to become dislodged and eventually torn from the wheel periphery.

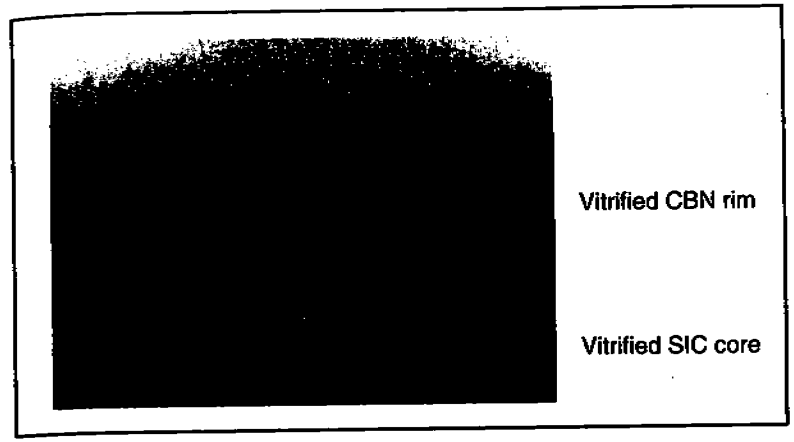


Figure 2.12 A rim section of a vitrified CBN grinding wheel.

2.11 Rubber-Bonded Grinding Wheels

- Standard wheel designation symbol R.

Rubber-bonded wheels are made by selecting the grain, sieving it like before, and then kneading the grain into a natural or synthetic rubber. Sulfur is added to the mix as a vulcanizing agent and then the mix is rolled between steel rollers to form a sheet of the desired thickness. The grinding wheels are then cut out of the rolled and sized sheet rather like cookies, using a cookie cutter. The wheels are then vulcanized under pressure at temperature of 175°C (350°F).

Rubber wheels claim a little less than 10 percent of the market. They can be made extremely thin, as thin as 0.050 mm (0.002 in). These very thin wheels are used for slitting fountain pen nibs. Conversely, very thick wheels can be produced for centerless grinding control wheels. Other applications for rubber-bonded grinding wheels are in the bearing industry, where extremely high surface finishes are required.

2.12 Metal-Bonded Grinding Wheels

- Standard wheel designation symbol M.

There are two divisions of metal-bonded wheels: those which have been plated, and those which have been cast. Included in the plating or cast matrix is the grain, usually CBN or diamond.

In the case of a plated grinding wheel, the wheel hub is manufactured very accurately with respect to the form profile and the profile's concentricity to the bore of the wheel. The profile is machined with an offset in the true shape, which allows for the size of a single layer of grain being plated. The abrasive is then carefully plated onto the form, using a hard, typically nickel or chrome plating to hold the grains in place. The plating does not completely cover the grains, and they are exposed with their sharpest cutting edges outermost. The thickness of the plating, a function of the grit size, corresponds to approximately 1 to 1.5 times the grit thickness. Most metal-plated wheels have a periphery of only one or two abrasive grains deep. Such wheels do not require dressing; however, they have to be very carefully assembled onto the machine spindle in order to run true to the spindle rotation. Most wheels of this type have a truing groove to assist in the proper mounting of the wheel. Wheel run out of less than 0.012 mm (0.0005 in) TIR is generally acceptable. Electroplated grinding wheels can run at very high speeds, since the central hub of the grinding wheel can be made from high-strength alloys.

A new technology has been developed called "Diamesh," which allows the superabrasive grain to be deposited and plated in a very tightly controlled pattern (see Fig. 2.13). There is no random placement of the grain, which is typical in conventionally plated wheels. Each grain is located in a mesh cavity to provide a regular pattern and even coverage of the grain across the wheel periphery. Diamesh provides a more consistent wheel performance, longer life, and better part surface integrity.

In the case of cast metal bond wheels, they are typically small grinding wheels used for Internal Diameter (ID) grinding and made from a soft bronze or other copper alloy, although there are some made from cast iron. The metal bonding is achieved using a sintering process and provides a very strong, solid bond, which has very good form retention properties. There is little to no porosity in a metal bond, but it can be enhanced somewhat by the addition of graphite fillers. Truing and dressing of these types of wheels is best performed by Electro-discharge Machining (EDM). The EDM process erodes the metal matrix, as well as what is usually a diamond abrasive, and allows relatively complex forms to be dressed into the wheel periphery. The EDM process can be sufficiently controlled to cause a pitting of the surface, which can act as a cavity for chip clearance and cutting fluid flow. Diamond is often used in this bond system, and finds a niche in the machining of hard ceramic materials and glass. Large wheels, above 150 mm (6 in) in diameter, can be manufactured in a sintered metal bond; however, the wheel is generally assembled from a series of separately sintered segments adhered to the wheel periphery. The separately sintered segments suffer from density changes and inconsistencies among the various segments. Such segmentation, and therefore separation, of the

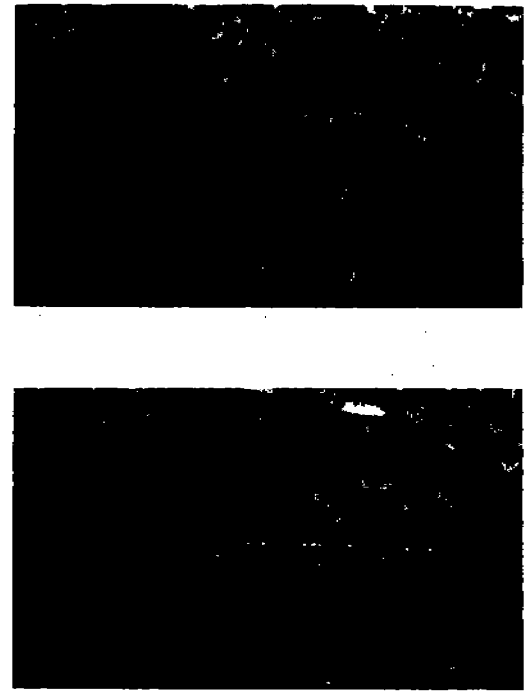


Figure 2.13 Type S/1 Diamesh which has a single abrasive particle per mesh opening (top) and type M/1 Diamesh with two abrasive particles per mesh opening (bottom). (*Diamesh is a trade name of UAS Inc.*)

wheel periphery can result in high vibration levels and poor surface integrity.

A crush dressable metal bond has been developed, which, by its name, suggests that it can be dressed to a given form profile by a crushing action, but is actually more like a compressing action of a very porous metal matrix.

The bonding and structure of a grinding wheel determine its safe operating speed. The safe speed is printed on every grinding wheel and must never, under any circumstances, be exceeded. Every grinding wheel is tested for safe operation to 1.5 times the Maximum Operating Speed (MOS). Should a grinding wheel burst, there is a high risk of very badly wrecking the machine, the fixture, and the workpiece, and quite possibly injuring the operator. Be very careful, treat the process with respect, and never over-speed a grinding wheel. Maximum speeds are often printed in RPM. However, in new machine tool designs and control systems, wheel speeds are controlled to maintain a constant peripheral speed. This means that as the grinding wheel gets smaller in diameter, the RPM has to increase in order to maintain a constant surface speed. Therefore, the rule is that the maximum operating RPM is with respect to the largest wheel diameter when the wheel is new. It is fast becoming the norm to see both maximum RPM and maximum peripheral speed (MOS in ms^{-1} or sfm) marked on the wheel.

Not only should proper care be taken to operate a grinding wheel, but also safe mounting, handling, and storage of grinding wheels should be most important. The American National Standards Institute Safety Code, ANSI B 7.1, outlines the recommended methods for storage and handling (see Fig. 2.14).

2.13 Abrasive Belts—Coated Abrasives

The term coated abrasives refers to abrasive grain which has been adhered to a backing. There are three components to a coated abrasive product: the abrasive grain, the adhesive or coat, and the backing material (see Fig. 2.15).

All of the abrasives discussed previously are used in the manufacture of coated abrasive products. Aluminum oxide is the most popular and is used in the majority of coated abrasive applications. The abrasive is hard and durable, as well as being low in cost. Aluminum oxide is a tough abrasive and lends itself to applications that require heavy pressure. Grinding high tensile strength steel, metals, and hard woods are the prime reasons for using aluminum oxide.

Garnet is a semiprecious stone formed from a natural spinel. A spinel is a chemical crystal formation of a metal and aluminum oxide, e.g., $FeO{\cdot}Al_2O_3$ and $MgO{\cdot}Al_2O_3$. It is deep red in color and is used as a natural abrasive, in particular by the woodworking industry. It is often heat treated to increase its friability and improve its cutting ability in coated abrasive applications.

A new abrasive which is an agglomerated grain has been created by the 3M Company. Small grains of abrasive have been bonded together to make a grain somewhat like the microcrystalline CBN. Such an agglomerated grain will break down under heavy load and give the abrasive belt a property much like the self-dressing capability of a vitrified bonded grinding wheel.

The coated abrasive is selected according to the grain size which will yield the required surface finish. Both aluminum oxide and silicon carbide are available in grain sizes from 12 to 600. However, very intricate and detailed forms cannot be machined using coated abrasives. The coated abrasive belt can be made to conform to a shoe or formed platen, allowing the finishing of contoured parts, such as golf club heads, water faucet spouts, and surgical implants.

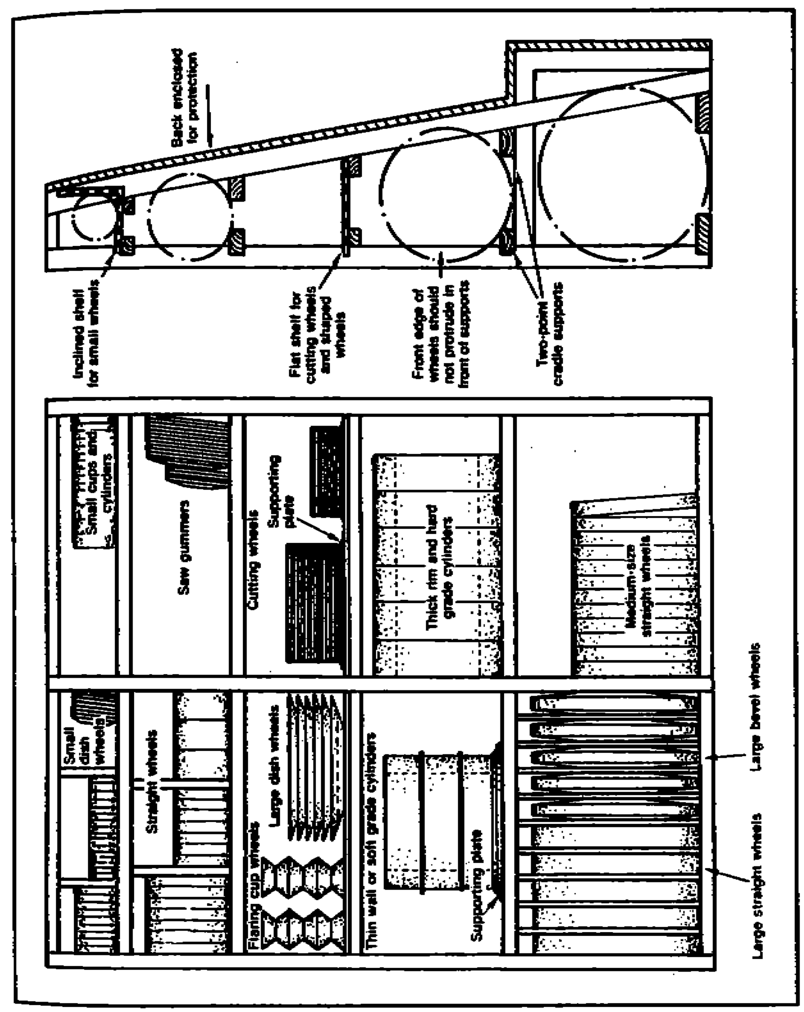


Figure 2.14 Methods for storing grinding wheels.

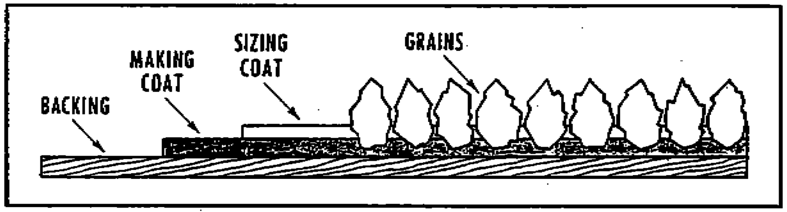


Figure 2.15 Cross section of a coated abrasive product.

2.14 Backing Materials for Coated Abrasives

Having selected an abrasive type and size, the next choice is backing. Coated abrasive backings are made from paper or cloth. Paper backings are the least costly and come in a variety of weights. The weight is measured by the weight of a ream (480) of 24- by 36-in sheets and given a letter code: A, B, C, D or E. "A" weight is 18 kg (40 lb), "B" weight is 23 kg (50 lb), "C" weight is 30 kg (60 to 70 lb), "D" weight is 45 kg (90 to 100 lb), and "E" weight is 60 kg (130 lb). Paper belts are nearly always "E" weight; lighter papers are termed cabinet papers. Paper backings are used when pliability and strength of the backing are not important. Paper-coated abrasives are most commonly used in the woodworking industry.

Cloth backings fall into a number of categories. There are two twill weave cloths: "drills," marked with an "X," and "jeans," marked with a "J." The main differences are that drills are made from heavier threads with fewer threads per square inch than jeans. Drills are the stronger of the two and used primarily with coarse abrasives for heavy work. Jeans are more flexible and ideally suited to finishing type operations.

The key factor in the selection of a cloth belt is its tearing limit under pressure. Cloth belts are pushed to their limit with today's demands of cutting speeds and stock removal rates. Synthetic belts are now being manufactured with complex weave patterns, which provide directional strength and longevity.

2.15 Adhesives for Coated Abrasives

The choice of adhesive is dependent upon the application. If the application is dry, then a straight glue (animal hide) can be used. If a cutting fluid is used, then a liquid phenolic resin is used. A balance has to be struck between the curing times and properties of the adhesives. Depending on the adhesive, some may soak into the backing and cause the belt to become stiff or too lightly coated, so that the abrasive is easily torn or flexed from the backing in operation.

2.16 The Manufacture of Coated Abrasives

The key step in coated abrasive manufacture is the application of the abrasive. This may be done by pouring the abrasive in a controlled stream onto the adhesive-impregnated backing, or more commonly running the impregnated backing through a tray of abrasive and allowing it to pick up the grain. Electrostatic attraction and orientation is also used to cause the grain to imbed itself firmly into the adhesive, oriented "sharpest point uppermost," resulting in a very aggressive and fast cutting tool.

The pattern and amount of abrasive being placed onto the backing can be very closely controlled to provide two types of abrasive systems: an open coating (covering 50 to 70 percent of the surface), which has spaces between the abrasive grain for chip clearance, or a closed coating, where there are virtually no spaces between the grains. Open coating is best suited for more flexible applications and closed coated for very arduous conditions. Once the grain has been deposited, the belt is coated with the final "sizing" coat to anchor the abrasive onto the backing, and then rolled into a giant roll for storage.

Before the coated product is used, it has to be processed into a marketable form. The adhesive will cause the belt to become very stiff and has to be "broken" in a controlled manner, usually perpendicular to the edge of the belt. The break lines are determined by the grain size of the

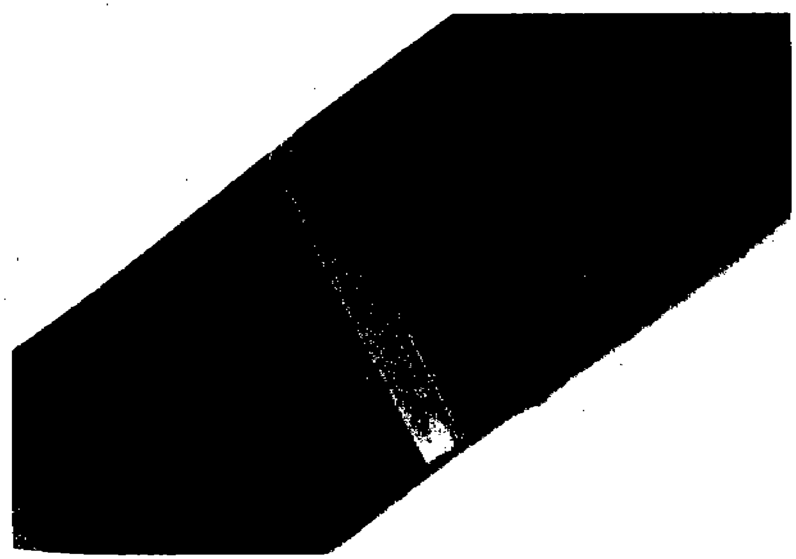


Figure 2.16 Lap joint in a 100 mm (4 in) wide abrasive belt.

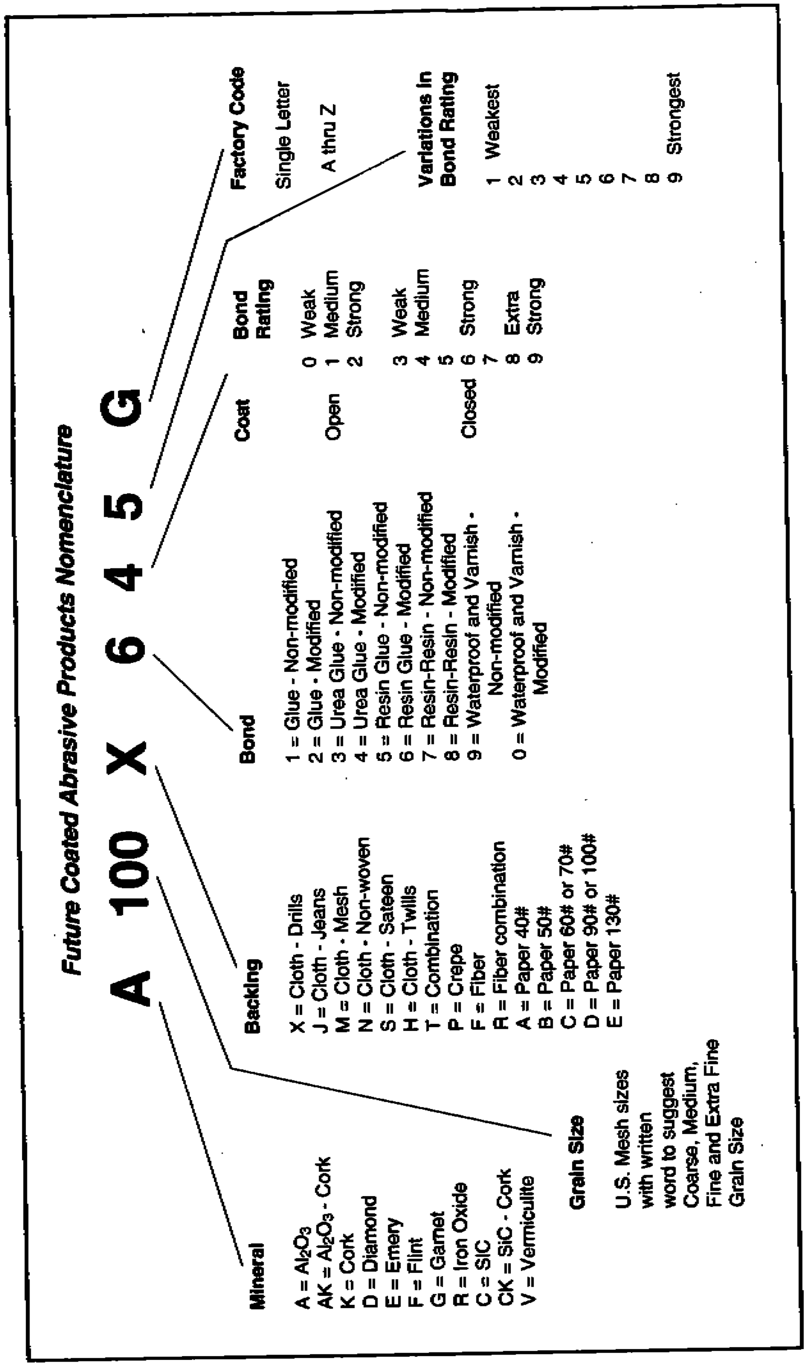


Figure 2.17 Coated abrasive designation system.

abrasive—closer for fine grain and wider for coarse grain. Other break line patterns are used for a variety of applications. Too much flexing and breaking of the bonding reduces the life of the belt and, therefore, is kept to a minimum.

Papers and sheets are cut from the large production rolls of coated abrasives and packed. Belts have to be cut and joined. The joint is a lap joint (see Fig. 2.16), generally 45 degrees to the edge of the belt. However, for narrow belts the angle is usually more acute, and for wider belts more obtuse. To form the lap joint without a significant lump in the belt, one end of the belt has the abrasive removed from the backing and the other end has a very small amount of the backing removed, so that when the joint is made, it is virtually invisible and will not upset the surface finish of the workpiece being machined. Coarse grain belts, which are not expected to produce high quality surface finishes, are usually lap jointed by removing the abrasive from only one end of the belt. The lump in the belt will not effect the resultant, rough surface finish.

Unlike the system for grinding wheels, there is no standard nomenclature for coated abrasives. However, there is a proposed unofficial system with similar information (see Fig. 2.17).

2.17 The Storage of Coated Abrasives

The backings and adhesives used in coated abrasives are very sensitive to climatic variations in temperature and humidity; resin bonded grinding wheels suffer the same fate. It is therefore most important to store coated abrasive and resinoid products in an environment which reduces their degradation by atmospheric conditions. The ideal environment is a temperature between 16 and 24°C (60 to 75°F) and relative humidity between 35 and 50 percent. Abrasive belts, in particular, should be hung in an attitude similar to the curvature of the wheels on which they will be used, in order to prevent undulations in the belt, which may upset the machined surface finish.