Chapter 2
Abrasives

Look at this small grit, this tiny grain, so small one must rub hundreds of them between finger and thumb to feel their sharpness. Insignificant little grits and easily slighted in our sophisticated technological world, but without this small fragment of abrasive, transformed, when viewed under a microscope, into jagged heroic blocks - without these small grits ours might still largely be an agricultural society and the conquest of space merely a dream. With these grits are grinding wheels made. [LEWI76, p. 3]

The main task of the abrasive grits is to conduct material removal that arises from chip formation, surface shattering, or pressure softening. In most applications, the grits have to be harder than the machined workpiece material. Moreover, abrasive grits need a high toughness and thermal and chemical resistance for a sustainable tool life. In addition, appropriate fracture behavior of the grits enables tool self-sharpening and results in efficient machining processes. A wide variety of abrasive materials is used in abrasive processes (Fig. 2.1).

Tool performance is defined by the grit material. It affects economic, technological, environmental and social sustainability of the tool and the abrasive process. Since grit materials compose a large portion of the tool volume, the raw material processing defines embodied energy, resource intensity, labor intensity, etc. which are indicators of tool sustainability.

Though there are still some applications with natural materials, most abrasive grits are made of synthesized materials [KLOC09]. Over the years, a large variety of trade names for abrasive grits have arised, sometimes leading to confusion [MARI04, p. 371].

The following review focuses on the prominent abrasive grit types used for grinding and honing tools. These abrasive grits can be subdivided into so called conventional abrasives [corundum (Al_2O_3) and silicon carbide (SiC)] and superabrasives (cubical boron nitride (CBN) and diamond). Superabrasives stand out by their higher hardness and wear resistance.

Abrasive blasting	Grinding Honing	Lapping	Polishing
		Hard abrasives:	Hard abrasives:

silicon carbide (SiC)
corundum (Al$_2$O$_3$)

diamond

| | **cubic boron nitride (CBN)** | boron carbide (B$_4$C) chromium oxide | |

boron carbide (B$_4$C)
quartz (SiO$_2$)
garnet

pumice
beryllium oxide (BeO)
chrome oxide (Cr$_2$O$_3$)
iron oxide (Fe$_2$O$_3$)
garnet (X$_3$Y$_2$(SiO$_4$)$_3$)
emery
quartz (SiO$_2$)

Soft abrasives:
quartz (SiO$_2$)
garnet
emery

Soft abrasives:
kaolin
chalk
barite (barium sulfate)
talc
tripoli
Vienna lime

Fig. 2.1 Common grit types in abrasive machining

2.1   Corundum

2.1.1   Chemistry, Types and Characteristics of Corundum

Corundum is crystalline aluminum oxide, Al$_2$O$_3$, and also known as alumina. Al$_2$O$_3$ is also the active element in the natural abrasive material emery [LEWI76, p. 9] and in the gemstones sapphire and ruby. Aluminum oxide occurs in at least five modifications, α-Al$_2$O$_3$, β-Al$_2$O$_3$, γ-Al$_2$O$_3$, δ-Al$_2$O$_3$, and ε-Al$_2$O$_3$. The technologically most important modification is the rhombohedral crystalline α-Al$_2$O$_3$, being the basis for corundum (Fig. 2.2). The proportion of covalent atom bonds to

c-axis

○ Aluminum
◐ Oxygen
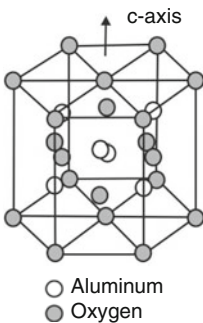
Density	3.97 g/cm^3	[MÜLL01]*
Hardness Knoop	21 - 24 GPa	[MÜLL01]*
Fracture toughness	2.2 MPa m$^{1/2}$ (3.8 MPa m$^{1/2}$ for sol-gel-corundum)	[KLOC02]
Melting temperature	2,027 ºC	[SALM07]
Thermal stability	Up to 1750 ºC	[MÜLL01]
Thermal conductivity	35 W/ m K	[ROWE09]

*after 3M, GE, Norton, Treibacher

Fig. 2.2 Basic properties of α-corundum, picture source [BOTS05]

ionic atom bonds is 40–60 % [MÜLL01, p. 25]. The cubic form γ-Al$_2$O$_3$ (clay, German "Tonerde") is the basis for vitrified bonds and other ceramic products.

Industry applies several corundum types with different chemical composition and manufacturing routes:

- Molten or fused corundum, such as

    – Brown corundum (also known as brown fused alumina, BFA, semi-friable corundum, regular corundum),
    – White corundum (also known as pure white alumina),
    – Pink corundum,
    – Ruby corundum (also known as red alumina),
    – Zirconium corundum (also known as alumina zirconia),
    – Mono crystalline corundum (also known as single crystal alumina),
    – Micro crystalline corundum,
    – Hollow sphere corundum (also known as bubble alumina)

- Sintered corundum
- Sol-Gel corundum

Table 2.1 gives the chemical composition of several types of molten corundum.

2.1.1.1   Shape, Morphology

Corundum appears as polycrystalline material and is broken down to the desired grit sizes. The size of the single crystals within the larger abrasive grits depends on the manufacturing route. Pink corundum appears as blocky grits with sharp edges and an average crystal size of 750 μm [WASH12b]. Zirconium corundum can have much smaller crystal sizes down to 10–12 μm [WASH12b]. Sol-gel corundum is known for the very fine crystals below 500 nm, enabling a very distinctive fracture behavior [ENGE02, p. 7].

### 2.1.1.2   Toughness, Breaking Behavior, Friability, Hardness

The different corundum types have a broad bandwidth of hardness and friability from 1300 to 2300 HK and a friability index between 5 and 75 (Fig. 2.3). Contents of Cr$_2$O$_3$ and TiO$_2$ increase the toughness, whereas Na$_2$O contents are disadvantageous, because Na$_2$O induces the softer β-11Al$_2$O$_3$·Na$_2$O [TYRO03b].

Corundum is considered to be the softest of the four main abrasives for grinding tools with a Knoop hardness of 2100–2400 kg$_f$/mm^2 for the purer molten corundum types, down to around 1600 kg$_f$/mm^2 or less for zirconium corundum (Fig. 2.3) [KLOC09, p. 27]. The compressive strength of Al$_2$O$_3$ is around 569 N/mm^2 [MERB03, p. 6].

Table 2.1 Chemical composition of typical molten corundum for grinding applications [TYRO03b, WASH12b]

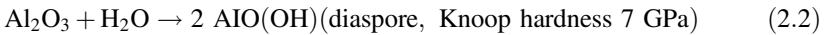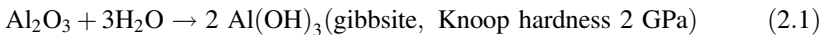|	Al_2O_3 (%)	Na_2O (%)	Cr_2O_3 (%)	TiO_2 (%)	SiO_2 (%)	Fe_2O_3 (%)	Others (%)	Hardness (HK)
Brown corundum	96.1			2.70	0.67	0.11		2090
White corundum	99.8	0.2						2000–2160
Pink corundum	99.5	0.2	0.25–0.3		0.05	0.03		2160
Ruby corundum	97.4	0.2–0.26	2.1–2		0.01	0.08		2150
Mono-crystalline corundum	99.3	<0.09		0.3–0.6				
Zirconium corundum (40 %)	59–60	≤0.03		0.15–0.3	≤0.35	≤0.15	39–40 % ZrO_2 0.6–0.8 % Y_2O_3	1600–1700
Zirconium corundum (25 %)	75	0.08		0.1	0.3	0.3	23 % ZrO_2	1450

Fig. 2.3 Hardness and friability for several corundum abrasives, grit size 12 mesh [LEWI76, p. 12, WINE12]
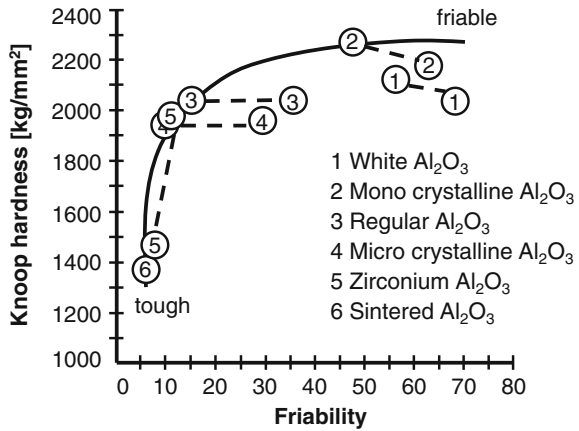
Polycrystalline corundum experiences increasing toughness and hardness when the crystal grain sizes get smaller [KLOC03, KREL95]. Presumably, the yield stresses from dislocations lead to micro cracks at the grain boundaries, which increase the toughness [EVAS90].

2.1.1.3 Temperature Stability, Chemical Reactions

Corundum (α-Al_2O_3) and water (H_2O) can result in gibbsite ($Al(OH)_3$, Eq. 2.1) or diaspore ($AlO(OH)$, Eq. 2.2) [LUDE94, p. 77]. The reaction to the relatively soft gibbsite in Eq. 2.1 is likely at temperatures from 0 to 300 °C and pressures up to 1000 bar [LUDE94, p. 79].

$$Al_2O_3 + 3H_2O \rightarrow 2\ Al(OH)_3 (\text{gibbsite, Knoop hardness 2 GPa}) \tag{2.1}$$

$$Al_2O_3 + H_2O \rightarrow 2\ AlO(OH)(\text{diaspore, Knoop hardness 7 GPa}) \tag{2.2}$$

Kumagai and Kamei found heavy attrition wear at the corundum grits when grinding titanium and titanium alloys [KUMA84]. A possible reaction for machining of titanium and titanium alloys with corundum is shown in Eq. 2.3 [KUMA84].

$$2Al_2O_3 + Ti \rightarrow 3TiO_2 + 4Al \tag{2.3}$$

In the grinding contact between corundum and steel, an iron spinel $FeO \cdot Al_2O_3$ can form [KLOC09, KIRK74]. This happens according to the reaction 2.4, after the chip surface has oxidized to FeO [LAUE79, p. 59]. Iron spinels can form an interim

layer between corundum grits and chip adhesions, which are more likely to adhere onto the spinel than onto bare corundum [LAUE79, p. 68 f.].

$$FeO + Al_2O_3 \rightarrow FeAl_2O_4 \tag{2.4}$$
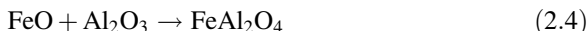
2.1.1.4 Thermal Conductivity, Electric and Magnetic Properties

Corundum has the comparatively lowest thermal conductivity of the common abrasives with $\lambda = 6$ W/m °C for brown corundum [KLOC09, p. 27]. This leads to a comparatively higher heat flux into the workpiece compared to heat flux into the grit material during grinding [BRIN82, p. 128].

2.1.2 *Manufacture of Corundum by Electrofusing*

Molten corundum, such as regular, white or pink corundum, is produced by electrofusion from bauxite. Charles B. Jacobs developed the method, which worked at temperatures above 2200 °C, in 1897 [LEWI76, p. 9, MARI07, p. 76, JACO00]. In 1904, Aldus C. Higgins of the Norton Company introduced the Higgins furnace, an arc oven, which is still used today [MARI07, p. 76]. Besides this stationary electric furnace type, the worldwide trend switches to the tilt pour furnace type [NN00]. The tilt pour furnace typically has a higher throughput and more consistency in brown fused alumina quality [NN00].

The Higgins furnace consists of a metal shell on a heavy metal hearth (Fig. 2.4). [MARI07, p. 76, HIGG04]. The shell builds the crucible and can be moved up and down relative to the electrodes, which are inserted into the raw materials. An arc builds between the electrodes through the processed material. The shell and bottom are water-cooled.
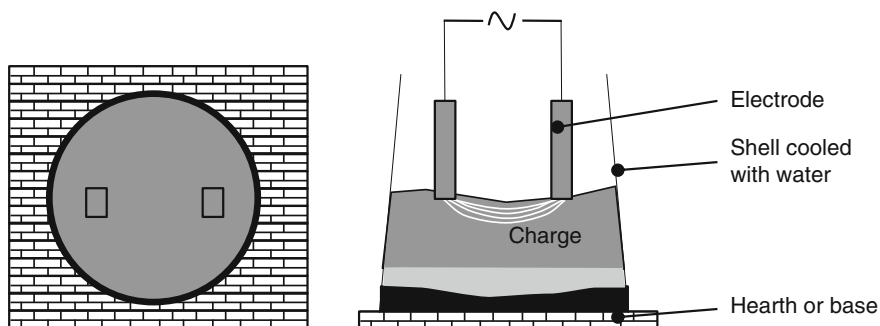

Fig. 2.4 Cross-section of a Higgins furnace for corundum production after [TYRO03b, MARI07, p. 76, HIGG04]

Melting times depend on the applied method and the furnace size (block furnace/Higgins furnace 15–24 h, tilting furnaces 3–5 h) [KLOC05a, p. 23]. The subsequent cooling and solidification of the molten mass also depends on the oven size (4–20 tons weight) and can take up to 14 days [ENGE02, p. 6, KLOC05a, p. 24]. The size of the corundum crystals depends on the block size and cooling rate and can range from 0.2 mm to several millimetres [ENGE02, p. 6].

The cooling procedure happens either through the billet method or the tilting method. In the billet method, a huge block of up to 20 tons cools down slowly in air, which takes up to 10–14 days, and large crystals are formed. In the tilting method, the molten mass cools in flat casting pans. Fine crystals result from the quicker cooling.

The main raw material, bauxite ($Al_2O_3 + SiO_2 + TiO_2 + Fe_2O_3$), is an impure aluminum oxide found in nature. The name refers to Les Baux in France where it was first quarried [LEWI76, p. 9]. Natural Bauxite contains 80–90 % alumina with impurities such as 2–5 % TiO_2, and Fe_2O_3, $Fe(OH)_3$, silicic acid, $Al(OH)_3$, and aluminum oxide hydrates [KLOC05a, p. 23, MARI07, p. 76]. Before fusion, the bauxite is either calcinated or purified by the Bayer-process.

The pre-processed bauxite is fused with carbon from coke or coal, metallic iron, and other additives. Carbon reduces the impurities in the bauxite to the elemental state, and the iron unites with the reduced impurities. The compound of impurities solidifies as a magnetic mass, so called button, at the furnace bottom [LEWI76, p. 9].

Changes in the ingredients or in the fusion procedure result in several different types of fused or molten corundum as follows: **Brown and semi-friable corundum** is made from calcinated bauxite (Fig. 2.5) [KLOC05a, p. 23, LEWI76, p. 9]. The calcination process takes place at about 950 °C and dehydrates the bauxite [LEWI76, p. 9]. Around 80 % calcined bauxite, 16 % iron and 4 % coke are used [KLOC09, p. 21]. The fusion of 1 ton of of brown corundum needs around 2.2 MVA [JACK07, p. 24].

White corundum is produced from relatively pure raw materials, in particular from >99 % pure alumina (Fig. 2.6) [MARI07, p. 77]. These pure clays of Al_2O_3
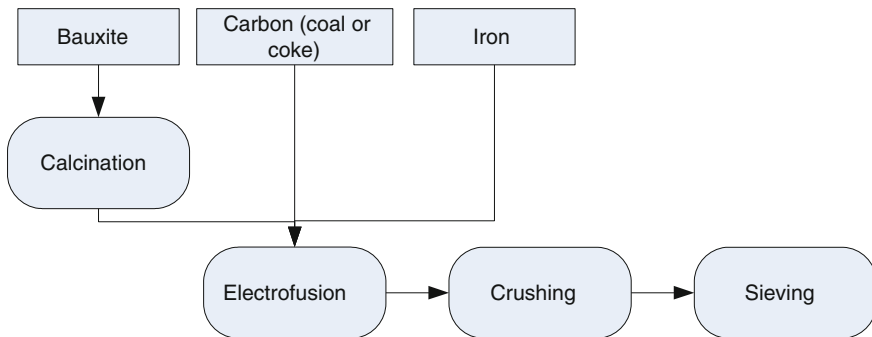

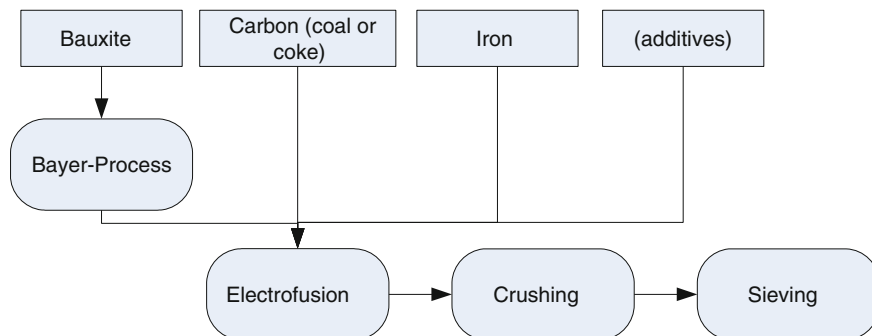**Fig. 2.5** Production of brown corundum after [JACK11, p. 22]

Fig. 2.6 Production of white, pink or ruby corundum after [JACK11, p. 22]

are produced from Bauxite by the Bayer-method [KLOC05a, p. 23]. Fusion of 1 ton of white corundum needs around 1.5 MVA [JACK07, p. 24]. Due to a small amount of sodium oxide, this grit type is friable and "cool cutting" [LEWI76, p. 10].

Pink corundum and **ruby corundum** are made like white corundum, but chromium oxide Cr_2O_3 is added in amounts of 0.3 or 2 % respectively to the fusion process (Fig. 2.6) [KLOC05a, p. 27]. The chromium oxide is built into the Al_2O_3 crystal structure. Additions of vanadium oxide give a green corundum abrasive [LEWI76, p. 10].

Mono-crystalline corundum is produced like white corundum, but iron sulphide is added besides coke to the molten mass, so that a pure, mono-crystalline aluminium oxide forms in a ferrous sulphide matrix [KLOC05a, p. 27, TYRO03b]. The Na-content is beneficially low [TYRO03b]. The sulphidic matrix is crushed and treated with water so that the monocrystalline corundum grits are washed out [MALK08, p. 23]. The crystal structure is defectless and, therefore, a higher toughness than conventionally molten corundum is obtained [ENGE02, p. 6]. In addition, no high crushing forces are used to acquire the grits [MALK08, p. 23]. Environmental complications accompany the process [TYRO03b].

A more or less regular, spherical form characterizes **hollow sphere corundum** [KLOC05a, p. 27 f.]. It can be obtained from different manufacturing routes. One way is to melt the raw materials in an electric arc oven and pour the material out of the furnace through a high-pressure air stream [HAUE07]. The molten stream transforms into smaller particles, which cool while flying through the air. Surface tension forces the particles into spheres. The exterior of the spheres cool quicker than the inside, so that material shrinks away from the sphere center and leaves an open core [HAUE07]. The high cooling rate results in a fine-crystalline structure [HAUE07]. The air stream velocity controls the sphere size between 5 mm to 100 µm [HAUE07].

Zirconium corundum is generated through adding of up to 40 % zirconium dioxide ZrO_2 to the fusion process and a subsequent chill casting [WASH12b]. During solidification, eutectic structures of Al_2O_3 and ZrO_2 are formed [KLOC05a,

p. 27]. Mechanical load or heating of up to 700 °C induces a transformation of the zirconium oxide from the tetragonal into the monocline phase. Herein, the oxide volume increases and micro-cracks build inside the abrasive grit, which inhibit cracks under load [ENGE02, p. 7]. The wear mechanism of zirconium corundum can be influenced by the content of ZrO_2 to a certain degree. A decreasing ZrO_2 content results in falling toughness and the breakage of bigger grit particles as a consequence, but the tendency towards larger wear areas by abrasion is also diminished [LUDE94, p. 99]. Zirconium corundum grits cannot be used in vitrified bonds because the sintering process with temperatures above 900 °C leads to destruction of the abrasives by volumetric change [ENGE02, p. 7].

2.1.3   Manufacture of Corundum by Sintering

Sintered corundum is a family of grains produced from unfused alumina by sintering processes [JACK11, p. 29]. The aim of sintering is to form a solid ceramic body of α-Al_2O_3 with a regular, fine-crystalline structure [KLOC05a, p. 25]. This structure is supposed to have a good wear resistance in the abrasive grinding process [KLOC05a, p. 25]. Different manufacturing methods exist based on raw or purified bauxite.

2.1.3.1   Sintering of Bauxite

Sintering of bauxite is one process method (Fig. 2.7). Raw bauxite, water, binders, and pressing auxiliary agents are mixed and the resulting compound is extruded and cut into short cylinders [KLOC05a, p. 25, JACK11, p. 29]. The cylinders are then sintered in rotary kilns at temperatures of 1350–1500 °C [JACK11, p. 29]. The impurities in the bauxite act as auxiliary sintering agents [JACK11, p. 29]. This manufacturing procedure results in a homogeneous, fine-crystalline grit structure with increased toughness [ENGE02]. The extruded long corundum particles are also known as "Spaghetti corundum" [ENGE02, p. 6].
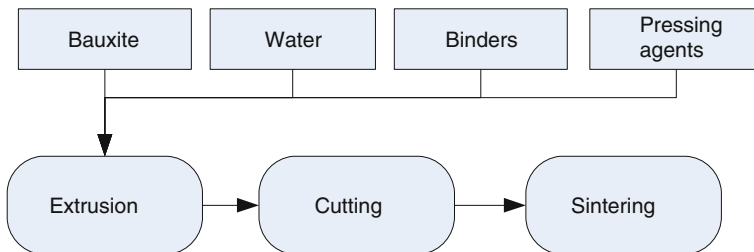

Fig. 2.7   Production of sintered corundum from bauxite after [JACK11, p. 29]

2.1.3.2 Sintering of Fused Corundum

Sintered corundum can be also produced from fused corundum, which is crushed and sintered with auxiliary agents such as glass phase agents [KLOC05a, p. 25].

2.1.4 Manufacture of Corundum by Sol-Gel Process

Sol-Gel corundum is produced by the sol-gel procedure and a subsequent pressure-less sintering procedure (Fig. 2.8) [KLOC05a, p. 25]. The crystal sizes are below 500 nm [ENGE02, p. 7]. Growth inhibitors or nucleating agents themselves can still be present in the sol-gel corundum grits.

Bauxite is purified by the Bayer process and then transformed through the Ziegler process into boehmite, which is γ-aluminum oxide hydroxide (γ-AlOOH) [JACK11, p. 29]. Powdered boehmite (γ-AlOOH) is transformed into a clear sol by mixing with water. Modifying agents are added, such as grain growth inhibitors (MgO, ZrO_2, TiO_2, lanthanum and other noble earths) or nucleating agents (Al_2O_3 or Fe_2O_3) [KLOC03]. Adding the nucleating agents is called seeding. Sol-gel corundum can either be produced with or without seeding [KOMA07].

Then a peptisator, being nitric acid (HNO_3) in most cases, is added. Agglomerates are dissolved and the sol is stabilized. The boehmite is now finely dispersed and homogeneously distributed. After adding of a diluted acid or nitrate solution, the sol reacts to a gel including dehydration and polymerisation. The gel is rolled into thin layers or lines and dried at about 80–100 °C. The resulting solid and brittle body is milled and sieved if necessary. Heating at about 450–550 °C for
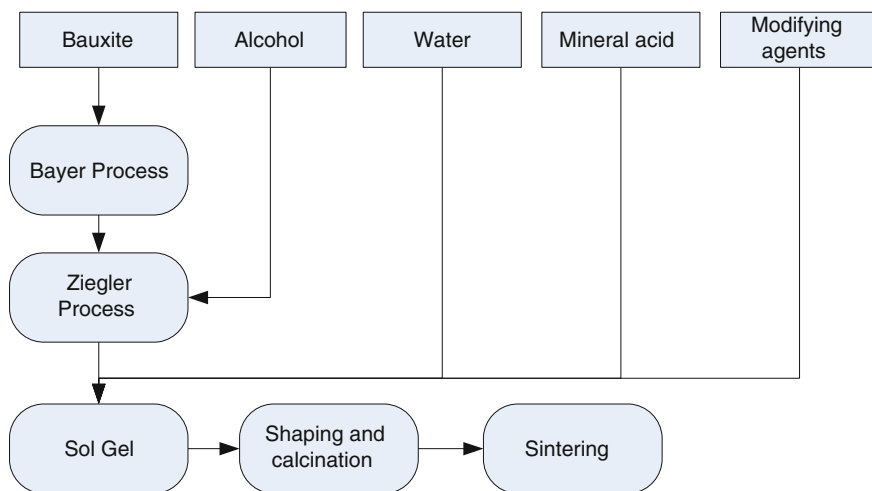

Fig. 2.8 Production of sol-gel corundum [LUDE94, JACK11, p. 35]

about 16 h transforms the boehmite grits into γ-Al_2O_3. During this so called cal-
cination, nitrogen (NO_x) and water are set free. Afterwards, the γ-Al_2O_3 is sintered
pressure-less for about 30 min. Generally, seeded sol-gel material is sintered at
1300–1400 °C, nonseeded sol-gel at temperatures that are about 100 °C higher
[ENGE02, p. 11, KLOC05a, p. 26, KOMA07]. With additional extrusion processes,
needle-shaped, extruded sol-gel corundum is manufactured with aspect ratios of 8:1
[MARI07, p. 113].

2.1.5   Performance of Corundum

All corundum types have individual performance profiles. Various mechanisms to
increase grit toughness take effect in the different corundum grits [LUDE94, p. 74 ff].

2.1.5.1   Molten Corundum

Pure white corundum is one of the hardest, but most friable corundum grit types and
is used most in vitrified grinding wheels for precision grinding processes [MARI07,
p. 77]. The low sodium content of pure white corundum deters tool breakdown
from cooling lubricant attack [MARI07, p. 77].

Zirconium corundum undergoes a martensitic phase, which increases the
toughness transformation and depends on the process load (see Sect. 2.1). This can
be an advantage, but this mechanism needs a certain load level [LUDE94, p. 77].

2.1.5.2   Comparison of Sintered Corundum and Molten Corundum

The most dramatic differences in performance occur between the grinding behavior
of molten and sintered corundum. The introduction of sintered corundum led to
tremendous tool life enhancements.

The higher wear resistance and larger material removal rates of micro crystalline
corundum compared to molten corundum results not only from the higher tough-
ness of the abrasive material but also from the specific wear behavior [MÜLL01,
p. 122 f., UHLM97]. Sintered corundum types consist of small crystals, which wear
by breakout [LUDE94, p. 74]. The longer crystal boundaries that have to be broken
lead to higher grit toughness. The specific wear mechanisms are based on
micro-crystalline fracture, so that only small particles break out of the sol-gel
corundum grits and establish a self-sharpening effect [MÜLL01, p. 122 f.,
UHLM97]. However, this micro-crystalline fracture only appears above a certain
load. Below this minimum load, corundum grits wear mainly by surface flattening
(Fig. 2.9) [MÜLL01, p. 122 f., UHLM97]. The right process design, e.g. working
with high material removal rates, is crucial for an efficient, sustainable process.
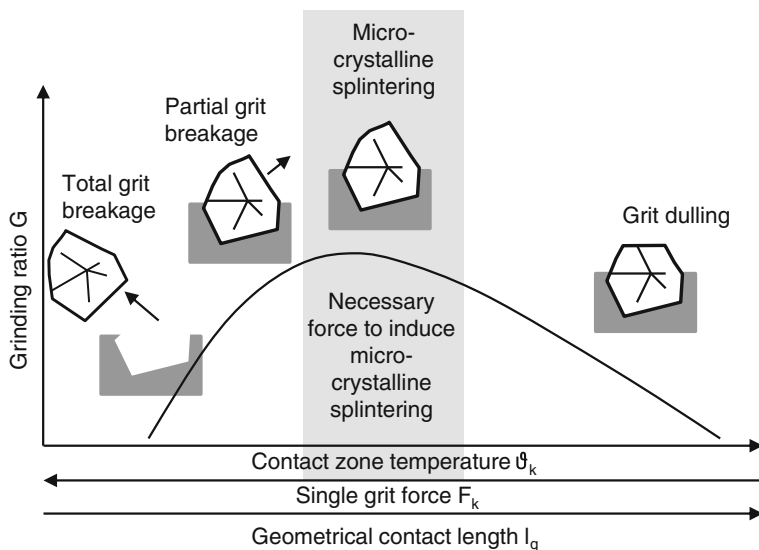
Fig. 2.9 Wear behavior of sol-gel corundum depending on the single grit load, after [UHLM97]

Another mechanism is the presence of cavities in the abrasives [LUDE94, p. 76]. They act like hindrances and split cracks in smaller micro cracks. Furthermore, comparatively long crystals with high tear strength (whiskers) in a tough matrix can increase grit toughness [LUDE94, p. 76]. The crystals are pulled out off the matrix during crack propagation. This leads to a zipper effect, which absorbs the crack energy.

The high aspect ratio of extruded sol-gel corundum results in a low packing density of these grains of only 30 % by volume [MARI07, p. 113]. So grinding tools of very high porosity can be manufactured for high performance processes where pores get clogged easily. Vitrified grinding wheels with this grit type are on the market with an interlinked porosity of 65–70 % and they prove to be well suited for high efficiency grinding with low process heat [MARI07, p. 113, WEBS04].

2.1.5.3 Comparison of Sol-Gel Corundum and Molten Corundum

In the beginning, sol-gel corundum was used as the solitary abrasive grit type in grinding tools (percentage of 100 %). However, its toughness led to excessive grinding forces. Today typical blends are 50, 30 and 10 % of sol-gel corundum with white corundum or mono-crystalline corundum as secondary grits [KLOC03, MARI04, p. 378, MÜLL01]. In 2003, sol-gel corundum was about 15–20 times more expensive than pure white corundum [KLOC03].

Furthermore, the usage of sol-gel corundum in vitrified bonds was limited by the sintering temperatures of the bond. Temperatures above 1200 °C result in aggregation of the micro-crystals, which reduces the efficiency of the abrasive grits. Therefore, low-fired bonds were developed resulting in spreading of sintered corundum grinding tools [KLOC03].

Compared to superabrasives, sol-gel corundum has much lower production costs. Therefore, it can be used in solid body grinding tools instead of thin abrasive layers. As a consequence, the sol-gel corundum tools can be reprofiled more often and are flexible for different workpiece profiles [KLOC03].

Sol-gel corundum wears by favorable micro splintering when a minimum load is exceeded (Fig. 2.9) [MÜLL01, ENGE02]. Especially for high material removal rates, sol-gel corundum has a higher performance than conventional abrasives, but is less expensive than CBN. Thus, the full potential of sol-gel corundum evolves only at high cutting speeds and high material removal rates. Sol-gel corundum shows a quasi stationary cutting performance even at higher grit load until the break-down of the abrasive layer. Therefore, high surface qualities are possible at shorter machining times [KLOC03].

In applications with low process loads, sol-gel corundum grinding tools have only minor advantages in performance and wear resistance against conventional abrasives [KLOC03, MÜLL01, p. 123]. In fact, sol-gel corundum grinding tools have to be applied at high process loads to maximize their potential [KLOC03, MÜLL01, p. 123]. Sol-gel corundum showed much lower radial wear and a higher maximum specific material removal rate than pure white corundum at high load or cutting speeds (e.g. v_c = 63–125 m/s) [KLOC03].

In single grit scratching tests, a highly viscous oxide layer formed on the grit edge of sol-gel corundum [KLOC02]. This oxide layer presumably reduces the strain energy between the workpiece and the abrasive grit, so that friction coefficient and grit wear are decreased [KLOC02].

2.2   Silicon Carbide

2.2.1   Chemistry, Types and Characteristics of Silicon Carbide

Silicon carbide, also known as carborundum and SiC, is used as abrasive material in its hexagonal form, α-SiC (Fig. 2.10) [MALK08, p. 24]. It is composed of 70.05 wt % Si and 29.95 wt% C [LIET08]. Each C atom is surrounded by four Si atoms and vice versa. The proportion of covalent atom bonds to ionic atom bonds is 90–10 % [MÜLL01, p. 25]. Silicon carbide occurs in two modifications: cubic β-SiC and α-SiC (mostly hexagonal and rhombohedral).
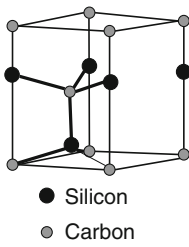
Density	3.21 g/cm³	[LIET08]
Hardness Knoop	24 - 26 GPa	[MÜLL01]*
Fracture toughness	3.1 MPa m$^{1/2}$	[MÜLL01]*
Thermal stability	Up to 1500 °C	[MÜLL01]*
Thermal conductivity	100 W/ m K	[ROWE09]

● Silicon
● Carbon

*after 3M, GE, Norton, Treibacher

Fig. 2.10 Basic properties of α-silicon carbide, picture source [PRES08]

Silicon carbide was the first abrasive to be synthesized. Two main types of silicon carbide are characterized by their color:

- Green silicon carbide has higher purity and is mainly used for precision grinding [TYRO03b].
- Black silicon carbide has higher toughness and is used for rough grinding operations [TYRO03b].

The chemical composition is shown in Table 2.2.

2.2.1.1 Shape, Morphology

Pure α-SiC is colorless, but inclusions of nitrogen in the crystal lattice give a green or yellow color [LIET08]. Aluminum or boron gives a blue-black color [LIET08].

2.2.1.2 Toughness, Breaking Behavior, Friability, Hardness

SiC has a Knoop micro hardness between 21 and 29 GPa in general and SiC abrasive grits between 24–26 GPa [LIET08, MÜLL01]. The impurities in black SiC do not seem to affect grit toughness negatively [LEWI76, p. 8]. Green SiC has a slightly higher friability than black SiC [LEWI76, p. 8, TYRO03b]. The compressive strength of SiC is around 2943 N/mm^2 [MERB03, p. 6].

Table 2.2 Composition of SiC green and SiC black [TYRO03b, KLOC05a]

	SiC (%)	C (%)	Si (%)	Fe (%)	others
SiC green	99.3–99.6	0.05–0.5	0.01–0.3	0.01–0.1	N contents of 10^{-4} to 10^{-3} %
SiC black	98.8–99.3	0.15–0.4	0.1–0.4	0.01–0.5	With parts of Al or Al_2O_3

2.2.1.3 Temperature Stability, Chemical Reactions

SiC is resistant to organic solvents, alkalies, acids, salt solutions, and even aqua regia and fuming nitric acid [LIET08]. Nevertheless, SiC undergoes several reactions with oxygen, such as a passive oxidation of pure SiC above 600 °C and an active oxidation above 1000 °C [LIET08]. Presser and Nickel as well as Moser discuss more potential reactions of SiC [PRES08, MOSE80, p. 142 ff].

In abrasive machining, Komanduri and Shaw describe the oxidization of SiC with oxygen at high temperatures to SiO_2 (Eq. 2.5) [KOMA76b]. This exothermic reaction produces SiO_2 layers [PRES08]. The layers are removed mechanically in the grinding process [KOMA76b].

$$SiC + O_2 \rightarrow SiO_2 + C - 183.6 \text{ kcal} \tag{2.5}$$
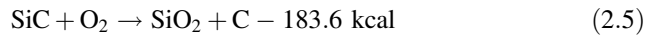
SiC is inclined to react with oxygen above temperatures of 800 °C and when in contact with metals (Eq. 2.6) [LUDE94, p. 31].

$$SiC + 3O \rightarrow SiO + CO_2 \tag{2.6}$$

Reactions of SiC with Fe are also suspected (Eq. 2.7) [LUDE94, p. 31]. Molten iron dissolves SiC, forming iron carbide and iron silicide [LIET08].

$$SiC + 4Fe \rightarrow FeSi + Fe_3C \tag{2.7}$$

When grinding cobalt alloys with silicon carbide grits, Komanduri and Shaw found diffusion of silicon into the workpiece material and formation of metal silicides. In addition, carbon from the grit material diffused into the work material and formed unstable metal carbides such as Ni_3C and Co_3C [KOMA76b].

SiC proves to be a good abrasive material for machining titanium and titanium alloys, despite the possible reactions in Eqs. 2.8 and 2.9 [KUMA84].

$$Ti + SiO_2 + (O_2) \rightarrow TiO_2 + SiO_2 \tag{2.8}$$

$$Ti + SiC + (O_2) \rightarrow TiC + SiO_2 \tag{2.9}$$
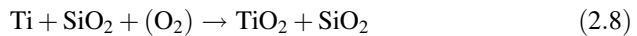
2.2.1.4 Thermal Conductivity, Electric and Magnetic Properties

The thermal conductivity of silicon carbide is comparatively high for a ceramic material with around 100 W/mK [ROWE09]. Silicon carbide is a semiconductor with a broad energy band gap with a resistivity between $0.1–10^{12}$ Ω cm depending on purity [LIET08].

2.2.2 Manufacture of Silicon Carbide

Silicon carbide (SiC) cannot be found in nature in sufficient quality for technical applications [TYRO03b]. For the use as abrasive, SiC is molten from quartz sand in resistance furnaces by a process that was invented by Edward Goodrich Acheson in 1891 on an industrial scale [MOSE80, p. 119]. Originally, Acheson had intended to synthesize diamond. After finding the compound of carbon and alumina from the synthesis process, he called the material "carborundum" [PRES08].

The raw materials are silicon dioxide (SiO_2) in the form of white quartz sand with a purity of 97–99.5 % SiO_2, and petroleum coke (C) (Fig. 2.11) [LEWI76, p. 8, STAD62, p. 25]. Both materials are ground to particle sizes of 1–2 mm [STAD62, p. 25]. In addition, sawdust and salt are inserted. The sawdust carbonizes during the reaction process and leaves pores, through which the resulting carbon monoxide (CO) can escape (Eq. 2.10) [STAD62, p. 25]. The salt turns impurities such as aluminum or iron to chlorides. An example composition of raw materials is 53 % quartz, 40 % coal, 5 % sawdust, and 2 % salt [KLOC09, p. 34].

Commonly, resistance furnaces are used. The furnace is half filled with the raw material mixture (Fig. 2.12). A central core of petroleum coke, nut-coal or graphite is inserted in the middle of the furnace [LEWI76, p. 8, STAD62, p. 25]. The rest of the quartz, coke, sawdust mixture is put on top. At each end of the oven are electrodes [LEWI76, p. 8]. The central core conducts the electric current and acts as resistor. At a voltage of for example 240 V the current heats the furnace to the reaction temperature of around 2000 °C [STAD62, p. 25]. Coke and sand react after Eq. (2.10) to hexagonal α-SiC [LUDE94]. It has to be noted that SiC production inherently produces CO emissions. The resistor core can be straight or zig-zag-shaped [MOSE80, p. 123].

$$SiO_2 + 3C \rightarrow SiC + 2CO \qquad (2.10)$$

At higher temperatures the core resistance drops and the reaction mass begins to conduct, so that the applied voltage and power input have to be controlled [LEWI76, p. 8, STAD62, p. 25]. The voltage is reduced so that the furnace has a constant power consumption of for example 1000 or 3000 kW [STAD62, p. 25].
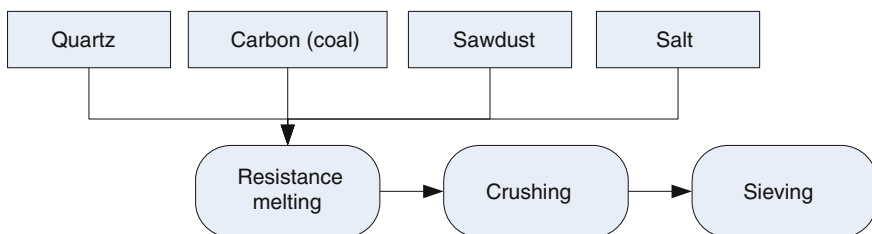

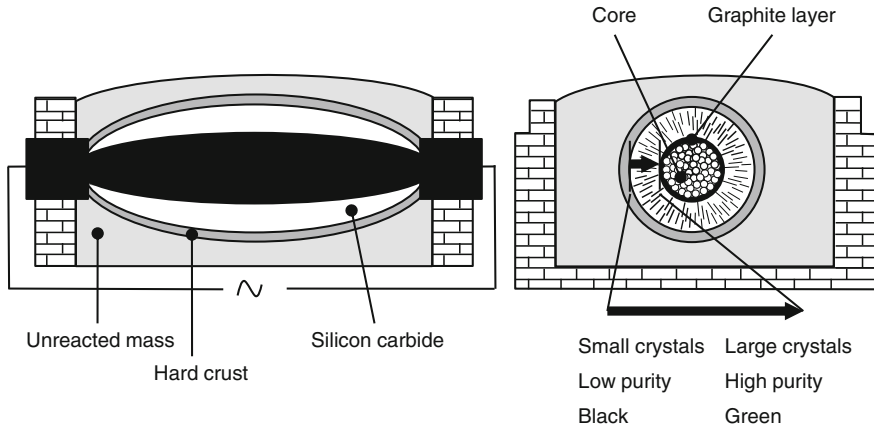**Fig. 2.11** Production of silicon carbide

Fig. 2.12 Cross-section of a resistance furnace for silicon carbide production after [STAD62, p. 25; TYRO03b, BORC07, p. 49 ff]

The energy per kg of α-SiC produced is around 8 kWh/kg [TYRO03b]. The reaction ends after 36–40 h and results in several reaction products (Fig. 2.12).

After cooling and stripping the furnace walls, unreacted mass is obtained that can be used for further reactions [LEWI76, p. 8]. The ingot of silicon carbide is surrounded by a hard crust consisting of salt and silicon carbide dioxide. The crystals in the silicon carbide layer increase in size and purity from outside to inside; also, the color of the crystals shifts from black to green [STAD62, p. 25]. Graphite from decomposed SiC surrounds the electrode core [LIET08].

Different grades of pureness, toughness, and color can be produced depending on the process control [LEWI76, p. 8]. Like in corundum production, the material blocks are crushed and milled to the according size (see Sect. 2.6 "Grit Post-Processing").

Waste from the manufacturing process is unreacted coke and partly reduced "firesand", which can be returned to the furnace [MALK08, p. 24 f.]. In some furnaces, the gases from the reaction are collected and used for energy production [LIET08].

2.2.3   Performance of Silicon Carbide

SiC reacts heavily with many Al_2O_3 containing vitrified bonds leading to grit damage [TYRO03b]. Therefore, special bond types for SiC are applied.

Silicon carbide is known for wearing mainly by splintering in the medium FEPA size ranges. Instead of steady and slow wear by adhesions, abrasion or chemical mechanisms, SiC wears by breaking into bigger grit particles. In contrast, the tougher mono-crystalline corundum can sustain dynamical and sudden loads better,

like present in grinding of hardened bearing steels. Additionally, SiC wears dominantly anisotropic depending on the loaded crystal plane. Nevertheless, the wear behavior enables good self-sharpening abilities of the tool. Under small process loads such as for small chip thicknesses, SiC wears by tribochemical mechanisms, likely oxidation and silicization [LUDE94, p. 71].

2.3 Diamond

2.3.1 *Chemistry, Types of Diamond and Performance*

Carbon forms several allotropes: hexagonal graphite, diamond in the cubic zinc blende structure, non-graphitic carbon, and the cage-like fullerene (C_{60}), discovered in 1985 [JAEG10]. Diamond is the hardest material in nature and very resistant against compaction. This is due to the dense packing of the carbon atoms, their regular, symmetrical order, and the energy rich covalent atom bonds [SEN02, TOLA68].

The crystal unit cell of diamond consists of eight carbon atoms (Fig. 2.13). Four of these ($8 \cdot 1/8 + 6 \cdot 1/2$) define a cubic area-centered lattice. The left four atoms are positioned on the centers of the eighth dice and build a second cubic area-centered lattice that is displaced in the direction of the body diagonal with a quarter of its length [HÜTT72]. The lattice constant of diamond is a = 0.355 nm. Every carbon atom in diamond is surrounded tetrahedrally by four atoms, in which the angle between two neighboring atoms amounts consistently to 109.5° and the distance is 1.5445 Å [HOLL95, HÜTT72, MORT87]. These angles originate from the geometrical crystal structure due to the sp^3-hybridization: when one of the 2s-electrons is lifted into the empty p-orbit from the basic state ($1s^2 2s^2 2p^2$). From three p-orbits and one s-orbit four new similar orbits are generated. The four hybrid orbits push each other away, so that the orbits are directed into the edges of a regular tetrahedron [HOLL95, MORT87].
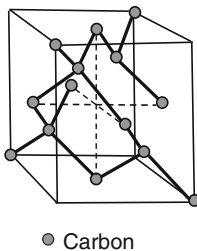
Density	3.53 g/cm³	[ROWE09]
Hardness Knoop	65 GPa	[ROWE09]
Fracture toughness	3 - 3.7 MPa.m^0.5	[GRAN12]
Thermal stability	500 – 700 °C	[GARD88]
Thermal conductivity	600 – 2,000 W/m K	[ROWE09]

Carbon

Fig. 2.13 Basic properties of diamond

Several diamond materials are used in abrasive tools today [MARI04]:

- Natural diamond grits,
- Synthetic diamond grits,
- Synthetic mono-crystalline diamond logs (MCD),
- Synthetic poly-crystalline diamonds in Co-matrix as logs or plates (PCD) and
- Chemically disposed diamonds without binder as logs or plates (CVD).

2.3.1.1 Shape, Morphology

The diamond crystal structure belongs to the cubic system and is expected to grow in the octahedron form [MOOR85]. This can be explained by crystal growth through atoms adhering to the surface, so that facets are built. The slowest-growing facets will dominate the crystal morphology. In the case of diamond, these are the octahedral planes in ideal growth conditions. Nevertheless, structure, purity, and morphology of diamonds depend on the growth circumstances [FIEL79, WEDL77]. Crystal morphology of synthetic diamonds ranges from a perfect cube to a perfect octahedron (Fig. 2.14). Synthetic diamonds appear often as cuboctahedrons with {100}- and {111}-planes [FIEL79, TOLA68]. Natural diamonds occur commonly as octahedrons or rhombic dodecahedrons, but often they are distorted, their edges rounded or their surfaces convex [FIEL79, MARI04].

Nitrogen atoms are the most common impurity in diamond material. Since 1934, diamond has been classified into two main groups: type I (up to 0.25 % of nitrogen) and type II (nitrogen-free) according to their nitrogen content [FIEL79, LENZ86]. 98 % of all diamonds belong to type I and 99 % of the natural diamonds are classified as type Ia, where nitrogen appears as small platelets. Nearly all synthetic diamonds belong to type Ib with finely-dispersed nitrogen inclusions. In the crystal structure, the nitrogen atoms substitute carbon atoms at isolated spots. This leads to a changed light absorption and the diamonds appears yellowish [EPPL94, LENZ86].

2.3.1.2 Toughness, Breaking Behavior, Friability

The density of atom bonds in the different diamond planes defines hardness and cleavage behavior (Fig. 2.15) [BRUN62, FIEL79]. The octahedral plane (111) is the main cleavage plane [FIEL81, LENZ86]. This can be explained by the lower toughness and, therefore, smaller necessary breakage energy along this plane

Octahedro   Cube

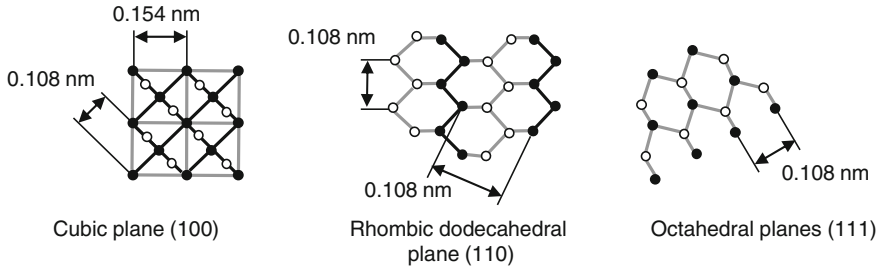**Fig. 2.14** Crystal morphology of diamond [BAIL98]

Fig. 2.15 Density of carbon atoms in different diamond planes after [LINK07, p. 16]

[TELL00, WILK62]. However, cleavage occurs also along the planes (211), (110), and (322) [FIEL79]. Similar mechanisms decide on the lapping behavior of the diamond grits. The smaller the bonding density in a crystal plane is, the easier the material removal. The (110) plane can be machined best via lapping, followed by the (100) plane and (111) as most difficult to machine [BOUW99, YUAZ03].

Natural and synthetic diamond grits show different breakage behavior. Natural diamond collapses in several breakage events; synthetic grits, however, fail with one breakage event [HIMM90]. Grit structure, types and occurrence of crystal growth defects define the breakage behavior [BENE03].

2.3.1.3 Hardness

Diamond density is about 3.52 g/cm^3 depending on pureness. Diamond hardness and toughness are determined by crystal purity, regardless of size, shape, and genesis [BENE03]. The hardness of single crystal diamond is anisotropic depending on the crystal orientation (Fig. 2.16). This results from the different distances of the carbon atoms in different crystal planes. The highest density of atom bonds occurs in the octahedral plane (111), which results in the highest hardness [TOLA68]. The cubic plane (100) is the softest direction [TOLA68]. In the (110) plane the hardness iis as high as 123 % of the hardness in the (111) plane, in the (100) plane even 138 % [KLOC05a].
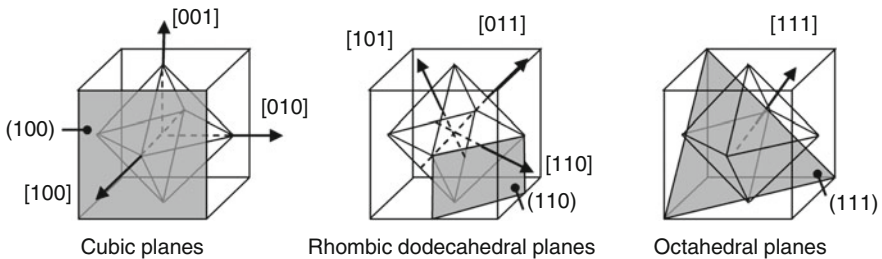

Fig. 2.16 Crystal structure of diamond after [HÜTT72, LINK07, p. 16]

Hardness and cleavage behavior are not only defined by the crystallographic structure but also by the occurrence of structural defects and diamond purity [BRUN62, WILK91]. Smaller grits are commonly tougher than bigger diamonds because they have fewer and smaller defects and inclusions [FIEL79, WILK91].

Synthetic diamonds often contain metal inclusions of the catalysts [YIN00]. All crystal defects like substituted atoms, atoms between lattice sites, or lattice vacancies are imperfections of diamond structure and enable micro-splintering [ODON76]. In addition, macroscopic inclusions can act as initial points for crack growth.

### 2.3.1.4   Temperature Stability, Chemical Reactions

At room temperature, diamond is nearly inactive regarding chemical reactions. At temperatures above 800 °C, diamond burns to carbon dioxide with air oxygen (Formula 2.11) [HOLL95, MARI04]. Depending on the grit size, the specific surface area, and the grit crystal type, reactions with oxygen occur even already at 500–700 °C [GARD88].

$$C + O_2 \rightarrow CO_2 \qquad (2.11)$$

Diamond performs further reactions with different groups of carbide builders [GARD88, WEDL77]:

- Transition elements of the 8th group and the metals Mn, Cr, Ta, and Nb compose carbides with diamond.
- Strongly electro-positive elements like Ca build stable carbides with an ionic bond.
- Further carbide builders like Si, B, Al, etc. form covalent bonds with carbon.

A commonly known transition of diamond is the so called graphitization. The carbon atoms in diamond are activated by the sp^3-hybridization, so that diamond is meta stable at room temperature and atmospheric pressure. Furthermore, diamond has more energy than graphite (Formula 2.12) [HOLL95, HÜTT72, UHLM01a]. However, the activation energy for the phase transition to the stable modification of graphite is so high, that graphitization rather does not occur at room temperature [EVAN62, WILK91]. When diamond is heated above 1800 K in an inert environment, graphite is formed in a slightly exothermic reaction, which is called true graphitization [FIEL79, HOLL95, WILK91]. In the presence of oxygen, the diamond surface graphitizes already at temperatures of 900 K [FIEL79].

$$C_{Diamond} \leftrightharpoons C_{Graphite} + 1.899 \text{ kJ} \qquad (2.12)$$
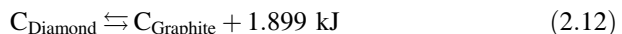
2.3.1.5 Thermal Conductivity

At room temperature, diamond is the material with the highest known temperature conductivity, which can reach up to 2100 W/(m K) depending on crystal purity [SEN91]. Furthermore, diamond exhibits a low electric conductivity, which can increase significantly with Boron assembled into the diamond crystal structure. In oxygen atmosphere, diamond has a low friction coefficient of $\mu = 0.05$–0.1 with most materials, including diamond itself [MARI04].

2.3.1.6 Electric and Magnetic Properties

Electric and magnetic conductivity of diamond depends on the inclusions [YIN00]. In particular, catalyst inclusions in synthetic diamonds change the electric and magnetic behavior, which can negatively affect electroplating processes or enable to align the abrasive grits on grinding belts or wheels.

2.3.2 Natural Diamond Genesis

Diamond forms only at high pressures and temperatures. Its natural genesis is assumed to happen in depths from 100 to 300 km beneath earth's surface at temperatures above 1200 °C and pressures above 50,000 bar [EPPL94]. It can be distinguished between primary deposits where diamond is located within parent rock and secondary sources where diamond is accumulated in rivers, in the sea, or in dunes by erosion [EPPL94]. However, the source of diamond has a main influence on the chemical and physical properties. Bigger natural diamond grits are mechanically broken down to smaller grits [FIEL81]. Grit suppliers and tool manufacturers sort natural diamonds and treat their surface to work best in different bonding systems and machining applications. Natural diamonds, especially high-quality diamonds for jewelry are closely related to social sustainability in two ways: Mining practices are to be reviewed and diamonds might be used to feed conflicts.

Natural polycrystalline diamonds are known as carbonado, ballas, boart, framesite, stewartite, etc. They occur in various different structures. Since the synthesis of fragile diamond was invented, the importance of fragile natural diamond for manufacturing technology has decreased.

Jewel industry uses the "4 C's" to appraise diamond grits, i.e. the criteria carat (weight), clarity (purity), color, and cut. In fine machining, however, grit morphology, purity, and size are most important. In natural diamonds, inclusions of minerals can be found, which were present at diamond genesis. Possible contaminations are SiO_2, MgO, FeO, Fe_2O_3, Al_2O_3, TiO_2, graphite, etc. [MARI04]. Cracks in diamonds can also be of natural origin, e.g. from geological mechanical load [LENZ86].

2.3.3   Artificial Synthesis of Diamonds

2.3.3.1   Monocrystalline Diamonds

The first artificial diamond synthesis was conducted by the Swedish company ASEA with a six-anvil press in February 1953 [TOLA68, WEDL77]. In 1955, company GE followed with the synthesis in a belt press and in 1958 company De Beers [MARI04].

Graphite can be transformed to diamond directly at temperatures above 1800 K and pressures above 60 kbar (Fig. 2.17) [WILK91]. However, the use of appropriate catalysts can reduce the temperature-pressure-range significantly. Metals of the 8th main group (nickel, cobalt, iron, et al.) enable synthesis even at pressures of 5–8 GPa and temperatures of 1500–2100 K [ODON76, YIN00]. This method takes advantage of the fact that graphite solves easier in metal than diamond. Graphite is also less thermodynamically stable within the working range. As consequence, carbon precipitates as diamond from the supersaturated metal carbide solution [HOLL95, MARI04].

The belt press consists of a hollow cylinder of tungsten or carbide with two anvils moving in vertical direction (Fig. 2.18 left). The high pressure high temperature (HPHT) chamber forms inside the hollow cylinder. Shrunked-on steel rings compress and pre-load the cylinder and anvils [LUND68]. Graphite as reaction mass is put into the HPHT chamber and coated concentrically with pyrophyllite, which is an aluminum silicate and isolates the reaction mass [LUND68]. The anvils are pressed
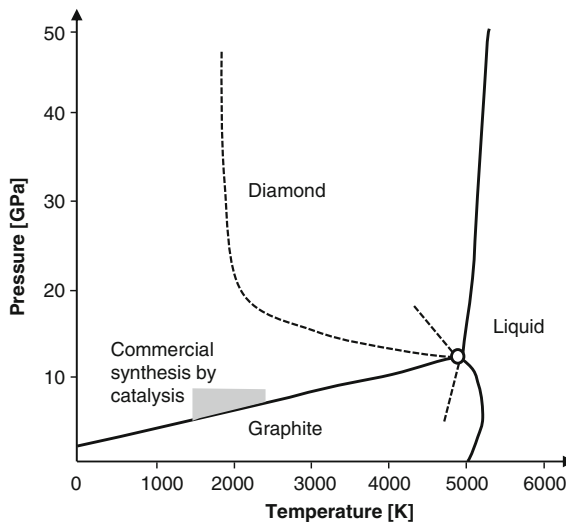

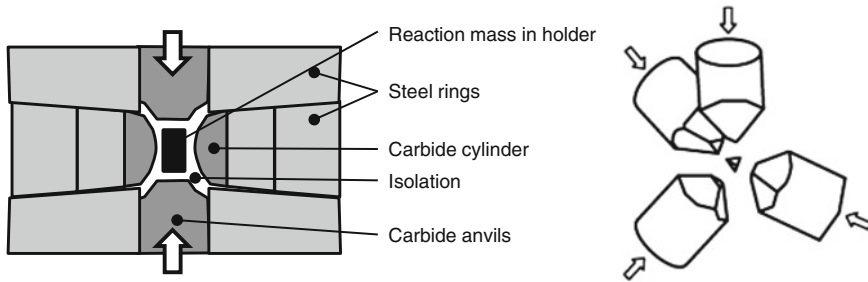**Fig. 2.17**   Pressure-temperature diagram of carbon [BUND96]

Fig. 2.18 Presses for diamond production, *left* belt-press [HALL60, KOMA01, LUND68, KHVO08, COES71], *right* anvil press [KHVO08]

together and generate the needed high pressure. Pyrophyllite creeps through the press joints and seals them enlarging the internal pressure in the reaction chamber [LUND68]. Resistor elements in the chamber walls generate the high temperatures needed for diamond synthesis [LUND68]. State of the art belt-presses reach a pressure of 8–10 GPa [KHVO08].

Today, another press type, the six anvil press, is widely used. It has the advantage of reaching higher pressures of 20–30 GPa in relatively large chamber volumes (around 10 mm^3) (Fig. 2.18 right). In Russia, diamond synthesis is conducted in chambers of a toroid and lentil type with even higher pressures. [KHVO08]

Quick temperature and pressure changes during diamond synthesis can force segregation of many diamond seeds. They will interfere during growth so that polycrystalline and irregularly grown diamonds develop [ODON76, PIRA03]. Before industrial use, synthetic and natural diamonds are often broken mechanically or prepared with acid to change their surface [TOLA68]. Whereas natural diamond must be crushed before use in grinding tools, diamond synthesis produces abrasive particles in appropriate size for abrasive applications [METZ86, p. 38].

2.3.3.2 More Synthesis Methods

Besides a direct transformation of graphite into diamond and the most common synthesis technique with molten catalyst, there are more synthesis methods [WEDL77]. These are Shock Wave Synthesis, growth from carbon molt and chemical diamond deposition from gas phase (Chemical vapor deposition, CVD). During CVD synthesis, carbon-containing gas like methane is disintegrated in presence of hydrogen at 2000 °C or in plasm sparks. At normal pressure, the dissoluted products condense on appropriate areas. Graphite seeds are hydrated quickly to methane, but diamond seeds grow faster than they are decreased by hydrogenation [HOLL95]. The resulting diamond layer is polycrystalline.

2.3.4   Performance of Diamonds

2.3.4.1   Grinding Tools

After the successful synthesis of diamond, natural diamond in grinding tools was replaced more and more by synthetic diamond [NOTT80]. The first commercially available synthetic diamond in 1955 was friable and polycrystalline, arising presumably from a lack of control in the early days of diamond synthesis [DYER79]. However, this type of grit had advantageous self-sharpening abilities not displayed by natural diamond.

Today, grinding tools of resin bond consist mostly of friable diamond, such as natural diamonds of lesser purity or synthetic diamonds with defined defects. In metallic bonds, cubic diamond grits with high toughness are applied. Naturally, a grinding wheel with blocky diamonds has lower wear rates than a tool with friable grits; in contrast, the grinding forces are higher due to the higher friction between flat grit areas, workpiece, and chips [WIMM95, BAIL99].

Diamond wears because of diffusion and graphitization during grinding of ferrous materials with low carbon content [KOMA76]. The diamond turns to graphite in the surface layers, which is accelerated by oxygen as catalyst [KOMA76]. Then the carbon diffuses from graphite into the ferrous material.

Research is ongoing on engineered wheels with defined grit patterns or CVD diamonds as abrasive layer (see Sect. 9.2 "Innovative and More Sustainable Tools").

2.3.4.2   Honing Tools

Other than in grinding, diamond has far fewer limitations when machining steel by honing. This can be explained by the low cutting speeds, cooling and lubrication conditions in honing, which tend to suppress the reaction between diamond and workpiece materials with carbon affinity [KOPP81].

2.3.4.3   Dressing Technology

Natural diamonds of high purity are commonly used in dressing tools [ODON76, KAIS97, SEN02]. In addition, synthetic diamond logs are common in dressing technology. Mono-crystalline diamonds (MCD) have the advantage of keeping their geometry despite of wear [COEL00, LIER02]. Depending on their orientation, only the properties of one crystal plane are present. In polycrystalline diamonds (PCD), the single diamond crystals are arranged in a Co-matrix, so that the hardness anisotropy of each crystal is equalized. PCD logs are quasi isotropic and have no preferred direction of mechanical properties [LIER02, SEN02]. Sometimes dressing tools with PCD logs are called "geometrically defined dressing tools" because of

their uniform wear behavior [MINK88]. The second polycrystalline dressing log material CVD diamond consists of diamond micro-crystals that grew together without binder [MARI04].

2.3.4.4   Diamond Powder

Micron diamond powder is widely used in suspension for lapping and polishing, as fine abrasive in bonded tools, and as loose abrasive in die stone production, gem stone polishing, and jewel bearing manufacture [HERB81]. Smaller grits have normally higher toughness, due to their lower number of defects [FIEL81]. Diamond performance is determined by grit shape, type, number of inclusions, cracks, and structural defects [SEN91]. Grit surface roughness and grit morphology define bonding adherence [BAIL02]. Diamonds are etched to roughen their surface or are coated with metallic deposits to optimize bonding retention [MARI04].

2.4   Cubic Boron Nitride

2.4.1   Chemistry, Types and Characteristics of CBN

The invention of the superabrasive cubic boron nitride (CBN) is linked closely to the synthesis of artificial diamond. CBN has the same crystal structure as diamond (cubic zinc blende structure), but the carbon atoms are replaced by the elements boron and nitrogen (Fig. 2.19 left). Boron nitride (BN) appears in forms isostructural to carbon: hexagonal α-BN similar to graphite, diamond-like β-BN, γ-BN in the wurtzite structure, and others [GREI06, HAUB02].

In CBN and diamond each of their atoms is bonded to four others in a perfect tetrahedrally alignment (bond angle 109° 28′). In CBN, each nitrogen atom is bonded to four boron atoms and vice versa. Cubic boron nitride has predominantly covalent bonds with a small degree of ionic bonding because boron and nitrogen are dissimilar atoms [BAIL98].

● Boron
○ Nitrogen
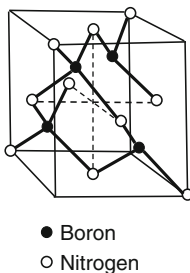
Density	3.47 g/cm³	[MÜLL01]*
Hardness Knoop	42 - 45 GPa	[MÜLL01]*
Fracture toughness	3.7 MPa m$^{1/2}$	[MÜLL01]*
Thermal stability	Up to 1200 ºC	[MÜLL01]*
Thermal conductivity	240 – 1,300 W/m K	[ROWE09]

*after 3M, GE, Norton, Treibacher

Fig. 2.19 Basic properties of cubic boron nitride

2.4.1.1 Shape, Morphology

As cubic boron nitride is less symmetric than diamond due to the alternation between boron and nitrogen, its morphology is more complex. In CBN, four of the octahedral (111) faces are terminated with boron and four with nitrogen. If the growth rates of the two types of octahedral faces are equal, an octahedron will result (Fig. 2.20 left). If one face type grows to the exclusion of the other, then a tetrahedron will form. Therefore, the morphology of CBN can vary between cubic and octahedral like diamond and between octahedral and tetrahedral (Fig. 2.20 right) [BAIL98]. The synthesis conditions adjust the CBN morphology to a certain range. Nitrogen dominated CBN particles appear red brown colored.

2.4.1.2 Toughness, Breaking Behavior, Friability, Hardness

Diamond has four cleavage planes, whereas CBN has six. All are {110}, one of which is indicated in Fig. 2.21. Young`s modulus is accounted to 4500 kg/mm^2 [HAUB02]. The compressive strength of CBN is around 7063 N/mm^2 [MERB03,
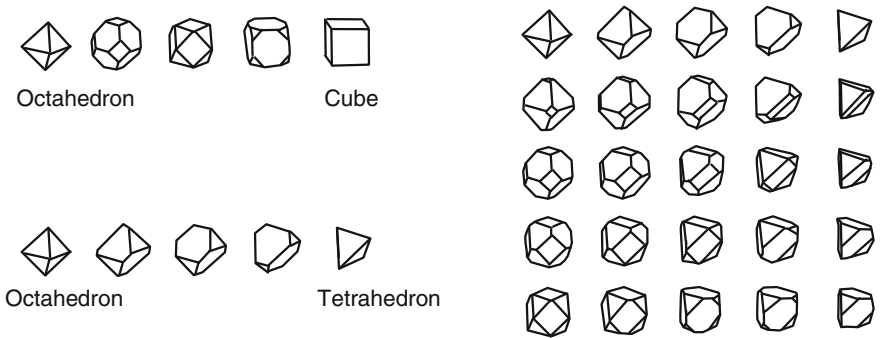

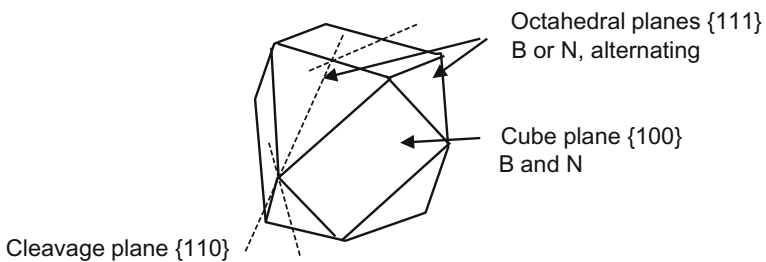**Fig. 2.20** *Left* crystal morphology; *right* morphology of CBN [BAIL98]

**Fig. 2.21** Typical CBN crystal [BAIL98]

p. 6]. The Knoop hardness is around 4700 HK, so that CBN is the second hardest mineral compared to diamond [GREI06].

2.4.1.3   Temperature Stability, Chemical Reactions

In air, CBN is stable up to 1400 °C [GREI06]. When grinding titanium, CBN shows attrition wear and fractures [KUMA84]. A possible reaction for machining of titanium and titanium alloys with CBN is shown in Eq. 2.13 [KUMA84].

$$BO_2 + Ti + O_2 \rightarrow TiO_2 + BO_2 \qquad (2.13)$$

CBN is covered with boron oxide, B_2O_3, in dry air at temperatures of 1200 °C (Eq. 2.14). In grinding, this layer has supposedly a wear-inhibiting effect [KLOC09, p. 36].

$$4BN + 3O_2 \rightarrow 2B_2O_3 + 2N_2 \qquad (2.14)$$
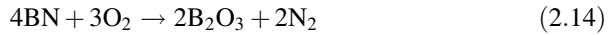
Hydrolysis of CBN occurs above a temperature of 1000 °C (Eq. 2.15) [KLOC09, p. 36, MOSE80, p. 166]. It is presumed that this reaction needs longer contact times than present in grinding and is therefore not relevant for this technology [KLOC09, p. 36].

$$BN + 3H_2O \rightarrow H_3BO_3 + NH_3 \qquad (2.15)$$

2.4.1.4   Thermal Conductivity, Electric and Magnetic Properties

Pure CBN is colorless and a good electrical insulator, but doping with Li_3N, Be, Si, C, or P changes color, conductivity, and toughness [GREI06]. The electrical resistivity of CBN varies between 10^{10}–3.3×10^{13} Ω m at room temperature [HAUB02].

The thermal conductivity ranges from 240 to 1300 W/m K [ROWE09, HAUB02]. This high thermal conductivity is caused by phonons and not electrons like in metals [HAUB02].

2.4.2   Synthesis of CBN

The first synthesis of cubic boron nitride was conducted in 1957 [KLOC05a, p. 35, WENT60]. Direct conversion of hexagonal BN into CBN without any catalyst is possible at pressures up to 18 GPa (Fig. 2.22) [BUND63]. However, the direct conversion is not used on an industrial scale [HAUB02]. In the industrial synthesis, the cubic boron nitride crystals are produced from boron and nitrogen in a HPHT
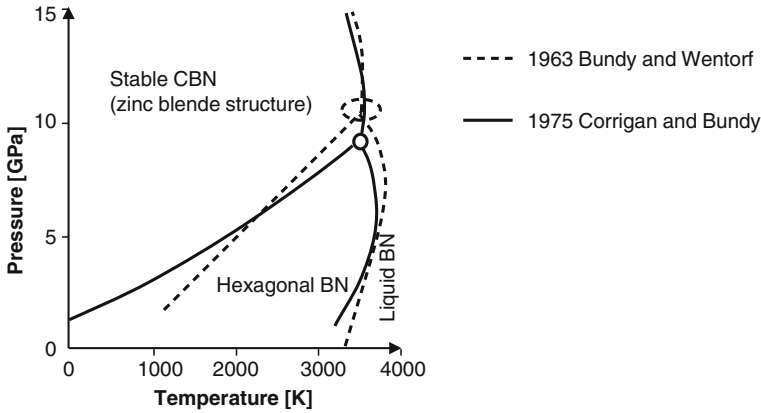
Fig. 2.22 Pressure-temperature phase diagram for boron nitride, after [HAUB02, BUND63, CORR75]

process with the help of a catalyst. The catalyst has the function of a solvent with different solubilities for CBN and hexagonal BN [HAUB02]. The hexagonal, graphitic BN is used as raw material and the catalyst metal can be elemental metal, such as Mg, Ca, Sn, Li, Ba, and a catalyst compound that decomposes to the catalyst metal or catalyst metal nitride, in particular Li_3N [WENT60].

The first synthesis processes used Li_3N catalysts and applied pressures of 4–6 GPa at temperatures between 1400 and 1700 °C [GREI06, WENT61]. Later, the use of the compound $Ca_3B_2N_4$ was investigated to gain highly pure CBN material [GREI06, ENDO81]. Today, the pressures are still between 4 and 6 GPa and the temperatures between 1300 and 1600 °C [CERA10].

First, the hexagonal α-BN reacts with the molten metals to nitrides (such as Li_3N) and to elemental boron (Eq. 2.16). Then the nitride reacts with hexagonal α-BN to a eutectic mixture. The cubic form CBN crystallizes when it becomes the stable phase depending on pressure and temperature (see Fig. 2.22).

$$3Li + BN \rightarrow Li_3N + B \qquad (2.16)$$

Hexagonal boron nitride is produced by the pyrolysis, i.e. the thermochemical composition, of boron chloride ammonia (BCl_3NH_3) at room pressures and temperatures (Eq. 2.17) [MARI07, p. 93].

$$BCl_3 * NH_3 \rightarrow BN + 3HCl \qquad (2.17)$$

The synthesized material is cleaned in acid baths to dissolve the residues of the synthesis process [KLOC05a, p. 36]. Sieving or further treatment can narrow down the quality of the abrasives. In general, CBN is produced with closer shape tolerances than diamond.

2.4.3　Performance of CBN

In the first years of CBN at the market, it was seen as competitor to diamond. However, CBN proved soon to be an ideal complement for machining of hard to machine ferreous materials [JUCH78]. In addition, CBN has advantages in its higher thermal stability over diamond. In the beginning, CBN was bonded in metal or resin bonds, however, vitrified bonds featured the intrinsic advantages of CBN best. The first vitrified bonded tool needed additional profiling processes [STUC88, p. 113]. With newer bondings, now the dressing process with diamond dressing tools provides a sharp grinding wheel topography in one conditioning process.

Thermally induced damage with CBN tools is less of a problem compared to conventional abrasives [MALK08, p. 215; MALK85]. Not only are the specific grinding energies normally smaller for CBN grinding, but the abrasive grit material CBN has also a much higher thermal conductivity (e.g. 35 times bigger than that of corundum) [MALK08, p. 215 f.]. The comparably lower heat flux into the work-piece results in smaller tensile stresses and even favorable compressive stresses at the surface [BRIN82, p. 128].

CBN proves especially useful in high-speed grinding operations. The wear resistance of CBN is much higher than for conventional abrasives, so that CBN grinding wheels excel with G-ratios up to 1000× higher for steel grinding compared to Al_2O_3 tools [JACK11, p. 9 f.].

In honing tools, the usage of CBN instead of diamond enables the use of emulsion instead of oil lowering the cleaning costs for workpieces [JUCH78].

2.5　Other Types of Abrasives

2.5.1　Natural Abrasives

Before the development of appropriate grit synthesis methods, natural abrasives were used. Today, some natural materials are still used for polishing applications. The disadvantages of natural abrasives are their lower strength with the exception of natural diamond, as well as the non-reproducible grit quality [KLOC09, p. 17].

Quartz (silica, SiO_2) includes the abrasives flint and tripolite with impurities of iron oxide (FeO) and titanium dioxide (TiO_2) [KLOC09, p. 18]. Natural corundum has an Al_2O_3 content of 80–95 % [KLOC09, p. 18]. Emery consists of 37–70 % Al_2O_3 plus iron oxide Fe_2O_3, which can be considered as abrasive material itself [LEWI76, p. 8]. Garnet includes a group of minerals with similar crystal structure and is composed as $X_3Y_2(SiO_4)_3$. Most garnet grits for abrasive applications is from almandite ($Fe_3Al_2(SiO_4)_3$) [MENA00].

2.5.2 Boron Carbide (B₄C)

Boron carbide (B_4C) is used as polishing, lapping, blasting, and grinding media for hard materials, in particular cemented carbide and fine ceramics [GREI06, KOMA97]. B_4C is produced by different methods, such as carbothermic reduction of boric oxide B_2O_3 or magnesiothermic reduction of boric oxide B_2O_3 [GREI06].

2.6 Grit Post-Processing

2.6.1 Crushing

Especially for conventional abrasives, crushing and milling are applied to change the size and shape of the abrasive grits [KLOC05a, p. 24]. For this purpose, jaw crushers, roll mills (roll crushers), gyratory crushers, ball mills, or pipe mills are utilized [LIET08]. Crushing with rollers can create needles in extreme cases; crushing with impact mills (hammer mills) produces cubical, blocky grits; crushing with roll mills causes grit splintering [MARI07, p. 79]. The crushing and milling processes are always carried out so that the abrasive grits remain sharp-edged [STAD62, p. 7].

Abrasion of the crushing equipment cannot be avoided [LIET08]. Steel equipment is preferred because the abraded particles can be removed by magnetic separators [LIET08].

2.6.2 Heat Treatment

Heat treatment in general increases toughness in conventional abrasives [SCHT81]. However, the grit toughness in one-phase systems such as white corundum and SiC is not affected much, whereas regular corundum shows a larger toughness increase at temperatures up to 1350 °C [SCHT81]. Heat treatment takes place at temperatures of 1100–1400 °C in an oxide containing, oxidizing atmosphere. The cracks and flaws created by the crushing process anneal and the containing TiO_2 converts [MARI07, p. 79, TYRO03]. Above 1350 °C grit toughness is rapidly decreased [SCHT81]. During heating, regular corundum changes its color from dark brown to dark blue and grey [SCHT81].

2.6.3 Chemical Processes

The abrasives are processed chemically with acids and water damp to obtain wanted size, shape, and purity. SiC is washed with alkali or acid to remove adhesions of silicon, metals, metal compounds, graphite, dust, and SiO_2 [LIET08].

Diamonds undergo an etching process to roughen their surface [MARI04]. Some abrasives like white corundum undergo special treatments only for marketing aspects, such as washing with acid to remove remaining particles from crushing processes. These remainings would otherwise lead to unwanted grinding tool discoloration.

2.6.4   Electrostatic Processes

Electrostatic methods separate sharp-edged grit shapes from blocky grits [MARI07, p. 79].

2.7   Grit Coatings

Grit coatings are either non-metallic or metallic coatings; the first ones being mostly applied to conventional grits.

2.7.1   Non-metallic Coatings

Grit coatings based on silane (SiH_4) are applied onto conventional grits to enhance retention in resin bonds and to resist interactions with the cooling lubricant [KLOC05a, p. 25, JACK11, p. 27, WASH12b, UAMA09]. Silane coating includes mixing of grits and silane solution, then the silane treated grits are cured [SETH11]. Dispersed silicon dioxide is either mixed directly with the grits or applied to the grits in a suspension [KUNZ91].

Red iron oxide coatings are ceramically bonded to the grit in an electronically controlled high temperature heat treatment [WASH12b]. Red iron oxide coatings protect grit surface areas and link well with resin or rubber bonds [JACK11, p. 27, WASH12b]. Corundum grits for cutoff wheels are sometimes coated with red iron oxide [MARI07, p. 79].

Ceramic coatings based on Al_2O_3 basis are also available for phenolic resin bonded tools [FACT12]. Their advantage is the high coating hardness.

2.7.2   Metallic Coatings

Metal coatings (also called claddings) came up in the mid 1960s for diamond grits in resin bonded wheels [DYER79]. The metallic coatings were in weight equal or exceeded the weight of the diamond grit [DYER79]. Earlier attempts with very thin

metallic coatings, primarily in metal bond wheels, had not been successful [DYER79].

Diamond in resin bonded tools, in particular for grinding cemented carbides, are usually coated with nickel comprising about 55 % by weight of the grit and coating [MALK08, p. 25, DYER79]. The optimum percentage of nickel coating does not change significantly with the grit size [DYER79].

2.7.2.1 Manufacture of Metallic Coatings

Grit coatings are applied by various technologies, such as chemical vapor deposition (CVD), physical vapor deposition (PVD), electroless coating, electrolytic wet chemical methods, or dry deposition (Table 2.3) [KOMP05, [FARK72]. The different coating processes lead to certain chemical signatures, coating morphologies, and effects on the grit material [KOMP05].

Several layers can be applied sequentially; for example, the diamond is coated with a Ti layer by electroplating, electroless plating or PVD processes first, then a Ni-coating is applied by electroplating [CAVE75]. An additional heating process induces the formation of alloys between the layers and the substrate [CAVE75]. The coated grains can additionally be etched to enhance grinding performance in resin bonded wheels [SEAL70].

The tool manufacturer has to control the tool production process carefully, because grit coatings change the grit weight and grit size. Therefore, the theoretical and real grit concentrations differ. Measuring of coating weight for diamond and CBN grains is also introduced in the FEPA 62/93 standard [MENA00].

2.7.3 Purpose of Coatings

Grit coatings are applied for various reasons, such as grit retention in the bonding, grit protection, grit alignment, or heat transfer during the tool manufacturing process or tool use. One coating can have several useful purposes, which are described in the following.

2.7.3.1 Grit Retention in the Bond

Grit morphology and grit surface define grit retention in the bonding matrix [BAIL02]. The metal nodules of coatings enlarge the effective grit surface and increase the roughness of the grit leading to a better mechanical grip (Fig. 2.23) [METZ86, p. 42, YEGE86]. In addition, the coating changes the wettability of the coated grit by the bond ingredients [METZ86, p. 42]. Especially for diamonds in resin bonds, metal coatings form a more cohesive connection with the bond than uncoated diamond surfaces [DYER79].

Table 2.3 Metal grit coating methods

Coating method	Processing temperature (°C)	Coating types	Bonding and example applications	Reference
Electroless coating–the abrasive grits are immersed in a metal alloy solution with reducing agents	<100	Ni, Cu, Ag alloys, thick layer	Phenolic and polyimide resin bonds for carbide and cermet grinding	[KOMP05]
Electrolytic coating, electroplating—the abrasive grits are wired as cathode; the metal to be deposited is the anode.	<100	Thick layer	Phenolic and polyimide resin bonds for carbide and cermet grinding, bronze saw tools for tile trimming and stone polishing	[KOMP05]
Physical vapor deposition (PVD)	∼500	Elemental metals, such as Ti, W, thin, 2–10 μm layer	Unproven utility in metal bonds	[KOMP05]
Chemical vapor deposition (CVD)	600–800	On diamond: Carbides of transitional metals, on CBN: Metal nitride or boride, thin, 2–10 μm layer	Metal bond saws for reinforced concrete sawing, stone or rock-drilling; glass grinding wheels; ferrous material honing stones	[KOMP05]
Dry deposit method —grits are mixed with metal powder until they are covered, then the covered grits are heated	350–1000	Transition metals		[FARK72]

Fig. 2.23 Schematic appearance of two common grit coatings

Copper   Ti
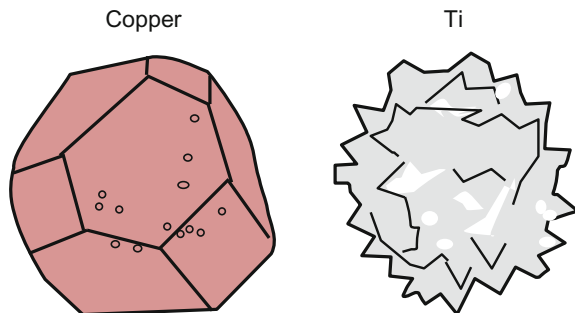
In the manufacturing of vitrified bonded tools, chemical reactions between superabrasives and the bond likely occur leading to sufficient grit retention. In resin or metal bonds chemical reactions between grit and bond are less likely. Therefore, grit coatings are applied on superabrasives to allow chemical alloying between coating and bonding and to enhance grit retention [KOMP05]. For metal bonds, common coatings for Ni-, Co- or Fe-based bonds consist of Ti; for bronze-based bondings Cr is used as grit coating material [MARI04].

2.7.3.2   Grit Protection During Tool Manufacturing

Coatings on diamond grits enable the tool manufacturer to choose an inexpensive bond material with iron, which otherwise would shorten the diamond life time [KOMP05]. In addition, elevated tool manufacturing temperatures can be applied [KOMP05].

2.7.3.3   Grit Alignment During Tool Manufacturing

Grits for coated tools are coated to enhance their electrostatic properties. A grinding belt passes through an electrostatic field so that each grit is polarized and aligns with the field. [UAMA09]

2.7.3.4   Grit and Bond Protection During Tool Use—Heat Transfer

In resin bonds, coatings work as a heat sink absorbing temperature peaks during grit-workpiece contact and prevent the resin bond from burning up [DYER79]. In particular, diamond with its high thermal conductivity transfers the grinding heat fast to the resin mass, which might burn. Grit coatings disperse the heat first into the coating and thermal stresses of the bonding can be reduced [METZ86, p. 42]. The grinding processes can be more efficient due to the coating's ability to act as heat sink [HERB81]. Büttner [BÜTT68, p. 82] described one example for the heat insulating effect of nickel-phosphor coating on diamond grits in resin bond.

Metal coatings transport the process heat from the grit into the wheel bonding. The life time of heat sensitive diamond grits increases. Copper coating is a more conductive metal layer than nickel alloy for specialized bonds, so that there are some applications where copper coated diamond in resin bonds works well for grinding tungsten carbide [NOTT76].

2.7.3.5   Grit Protection During Tool Use—Grit Coherence

New coatings based on silicon dioxide or silane are modified to have hydrophilic or hydrophobic properties [KUNZ91, SETH11]. The coatings repel infiltration of

cooling lubricant between grit and bond and therefore protect the resin bond [KLOC05a, p. 25, MARI04, p. 377]. Corundum grits can be coated with silane to optimize their performance in some resin bonds. Coated abrasive tools for example can fail if water separates the backing material from the bond [SETH11].

Another advantage of coatings is a more controlled breakdown behavior of the abrasive grits [HERB81]. Metal coatings envelope friable grit particles and retain their integrity even if parts are removed by impacts in the abrasive process [DYER79].

2.8   Grit Characteristics

The characteristics of the abrasive grits are important variables controlling the process. Evaluating the characteristics is a complex problem due to the non-uniform grit geometry [BREC73]. The grit properties are influenced by the chemical composition, crystal structure, grit size, and much more. Unfortunately, many properties for ideal process performance are contradictory, such as toughness and hardness. Furthermore, tool manufacturing is affected substantially by the grit properties. Grit properties have always to be balanced between optimal properties for tool use and for tool manufacturing. The following discussion of grit characteristics aims to clarify the difficulties in the choice of abrasives.

2.8.1   Grit Size

2.8.1.1   Effect on Tool Performance

In bonded abrasive tools, grit size in combination with grit concentration influences the number of cutting edges (Sect. 6.2 "Cutting Edge Density"). As consequence, the undeformed chip thickness during grinding is affected [WERN71]. Grinding tools with smaller grit sizes commonly cause higher machining forces and shorter tool life. [LINK15]

Grit size is also connected to grit toughness. Smaller single-crystal grits, especially superabrasives, are commonly tougher because of fewer defects [FIEL81]. Conventional abrasives expose higher toughness because they are often broken down from larger grits [MALK08, p. 21].

Oversize particles in lapping and polishing can have negative effects on workpiece quality. In lapping, the stock removal rate drops as abrasive size is reduced. One reason for this are the wear particles between the workpiece and lapping plate, which perform as non-abrasive load carriers and interfere with the cutting action. A second explanation is that smaller abrasive particles lead to increased workpiece material displacement rather than cutting action. A third explanation is that the lapping plate embraces smaller particles to a bigger extent and limits the cutting action. [DAVI74]

2.8.1.2 Effect on Tool Production

Tool production is affected by grit particle size and size distribution [BENE10]. The mold packing density can be increased by mixing different sizes of grit and bond material [WEBS04]. The finer material will fill spaces between larger grit sizes and affect the homogeneity of the abrasive layer.

2.8.2 Shape, Morphology

Synthesis conditions and post-processing steps (such as crushing) influence grit shape and morphology. For diamond grits, the shape correlates well with grit toughness and grit performance [LIEB96, GESU00]. There are several measurable characteristics to describe the shape of abrasive grits, such as ellipticity or roundness (see Sect. 2.9.2 "Grit Shape Selection and Analysis"). However, one value is not sufficient to classify a grit explicitly and the single values differ for different grit morphologies.

2.8.2.1 Effect on Tool Production

Grits for bonded tools should expose a rough surface to provide mechanical adherence in the bonding [DYER79]. For the production of bonded tools, abrasives of a given size and shape have a limiting natural packing density that can be reached by shaking and pressing. Coarser and blockier grits have a higher packing density than finer and less symmetrically shaped grits [MALK08].

2.8.2.2 Effect on Tool Performance

The shape itself is less important than the breakage behavior and the number of cutting edges. This relates to the chip thickness, process forces, and workpiece roughness. The sharpness of a cutting edge defines the engagement into the workpiece, the proportion of elastic or plastic deformation and chip forming. Many grinding models for superabrasive grits work with simplified grit geometries like balls, ellipsoids, or octahedrons [DOMA06, HEIN09b, KOSH03]. For CBN grits, octahedrons give realistic simulation results [YEGE86]. Metallic grit coatings change the grit surface and support bond retention, especially in resin and vitrified bonded grinding wheels (Sect. 2.7 "Grit Coatings").

In the same way, grit shape, size, size distribution, and breakdown characteristics are important variables for process control in abrasive processes with loose abrasives [DAVI74].

2.8.3 Hardness and Temperature Hardness

The hardness of abrasives is defined in terms of the static indentation hardness as determined by Knoop or Vickers hardness test [MALK08]. Chip formation needs a high degree of grit hardness and toughness [KLOC05a]. Moreover, cutting edge sharpness over a longer period is affected by the grit hardness and wear resistance. There is no direct physical relation between hardness and toughness, but commonly harder abrasive grains are more friable [MALK08].

Jackson gives the rule of thumb that a grit has to be at least 20 % harder than the workpiece to be suitable as abrasive [JACK11, p. 9]. He regards hardness as the key factor in controlling attritious grit wear (see Sect. 6.4.2 "Grit Surface Wear"). In addition, hardness can change with the temperature, meaning temperature hardness has to be also considered in tool use [JACK11, p. 9].

2.8.4 Toughness, Breaking Behavior

Today, grits are available in a large range of toughness suitable for many applications [MARI04, p. 347]. Hard and friable abrasives are generally applied in precision grinding, whereas tough, large grits are more suitable for heavy-duty grinding [MALK08]. Grit types for resin bonds are usually more friable than for bronze bonding [BÜTT68, p. 73].

Toughness is the resistance of a material against breakage and crack propagation and is often measured under dynamic conditions [LINK15]. Higher toughness implies that the grit is less likely to fracture when engaging the workpiece. The breaking or fracture behavior describes how the grits break, i.e. breakout of large or small particles, leaving a rough surface with many cutting edges or a smooth surface with only one cutting edge (see Sect. 2.1.5 "Performance of Corundum"). Jackson and Davim introduce the term friability as inverse term of fracture toughness [JACK11, p. 11]. The sum of toughness and friability, both in [N], accounts to 100 [SCHT81]. The "toughness index" is one industrial measure [VOLL12]. Temperatures during grinding can induce grit defects that change the grit breaking behavior, so "temperature toughness index" is another useful measure. The "friability index" is a measure for the loss of abrasive material by splintering [JACK11, p. 11].

On the one hand, grits that are too tough for a special application will become dull and increase friction. This leads to unnecessary thermal damage of the workpiece material and the danger of process vibrations. On the other hand, too friable grits wear away quickly resulting in short tool life and possibly form errors. As optimum, the grits should have a controlled breakdown behavior, so that they regenerate sharp cutting edges and the tool works in the so called self-sharpening mode.

Conventional grits are usually produced by crushing of coarser material resulting in fewer surface defects and in less friable grits [BREC73, MALK08]. In the same

way, smaller diamond grits are commonly tougher because of fewer structural defects [FIEL81]. The toughness of conventional abrasives can be changed through the sintering temperature of the grinding tool [SCHT81].

Natural and synthetic diamond grits show different breakage behavior. Natural diamond collapse with several breakage events, synthetic grits, however, fail with one breakage event [HIMM90].

2.8.5   Thermal, Electric and Magnetic Properties

2.8.5.1   Effect on Tool Production

High sintering temperatures over 1300 °C can occur in manufacturing of vitrified bonded tools. In particular, diamond features low thermal wear resistance in air, which forced manufacturers to develop special low-temperature sintered bonds and to apply inert atmospheres [LINK15].

Electric and magnetic properties are important for electro-plated bonds because they affect the deposition of the galvanic bond on grit and tool body [LINK15]. In particular, synthetic diamonds contain metallic inclusions, mostly of ferromagnetic character [YIN00]. For the tool manufacturing process, it is therefore necessary to separate between magnetic and non-magnetic grits.

2.8.5.2   Effect on Tool Performance

In the use phase of abrasive grits, the most important thermal properties are the thermal conductivity, the point of softening under load, and the melting point [KLOC05a, p. 34]. Thermal conductivity describes the material`s ability to level temperature differences. The grits will be loaded with a nearly punctiform heat source at the cutting edges during chip formation. With high thermal conductivity, the heat will distribute quickly along the grit volume.

For corundum, the temperature conductivity decreases rapidly with increasing temperature [KLOC05a, p. 34 f., COES71]. For high temperatures, it can be expected that the heat load concentrates more and more on the cutting edge leading to heat peaks. Thermal stresses inside the grit increase, being intensified by the simultaneously increasing thermal expansion coefficient. Thermal stress can occur between grit and bonding for strongly distinct thermal expansion coefficients [KLOC05a, p. 34 f.]. In synthesized diamonds, the thermal expansion of the metallic inclusions can induce grit fracture [MARI07].

High chemical resistance is desired for the grits when they interact with the air, cooling lubricant, or workpiece material. Chemical reactions could weaken the grit and need to be avoided also at higher pressures and temperatures [KLOC05a, p. 19].

2.8.6 Distribution of Characteristics Within Batch

Grit characteristics in a batch appear always in a range. A narrow distribution of characteristics allows a good predictability for the later tool performance [DYER79]. Abrasive layers should be homogeneous to have constant performance during lifetime and no imbalance during tool rotation. Grit density and grit size are related to the number of cutting edges in a bonded abrasive tool [YEGE86].

In the case of grit sizes, the use of a wider range facilitates the wheel manufacture, because it becomes easier to pack the abrasive grits tightly together in molding the wheel [MALK08]. Control of grit size and size distribution lowers the danger of high rejection rates [BENE10]. Grit size distribution is defined as the percentage of particles of different size in the defined grit size range.

2.9 Methods for Grit Selection and Analysis

2.9.1 Grit Size Selection

2.9.1.1 Sieving

The size distribution of abrasive grits is adjusted by sieving for coarser grits and sedimentation for finer grits [KLOC05a, p. 27, MARI07]. Sieving is the simplest method to separate particles and works with sieves of defined mesh sizes [SALM07, p. 132]. Sieving can be performed manually or automatically on dry or wet batches.

Several national and international standards exist to define the size ranges (Tables 2.4 and 2.5). It has to be noted that most standards define the grit sizes as a range and not as single values. European standards are mainly based on DIN ISO 8486-1 and the so called FEPA standard from the European Federation of Abrasives Producers (FEPA) [KLOC05a, p. 28]. As example, the FEPA standard ranges from the largest grit size F4 (diameter 3 mm) to the finest F1200 (diameter 3 µm).

Most standards define conventional abrasives by a pair of numbers corresponding to the mesh size of two sieves [ANSI01]. The mesh size is given in number of meshes per linear inch. The lower number is the mesh number, through which the grit just passes, while staying on the sieve with the upper number mesh size (Eq. 2.18) [MARI07].

ANSI, FEPA conv. = [mesh per inch upper sieve/mesh per inch lower sieve]

(2.18)

Superabrasive grits are commonly defined by the mesh size, through which the grit will just pass, given in micrometer (Eq. 2.19) [MARI07, KLOC05a].

Table 2.4 International standards for grit sizing for bonded tools [MENA00, BENE10, MARI07, ANSI01]

Norm	Grit type and size		Sizing method
ANSI B74.12	Conventional grits, in particular fused Al_2O_3, SiC	Macrogrits	Sieving
ANSI B74.10 [ANSI77]		Microgrits	
DIN ISO 8486-1 [DIN97]		Grit sizes F4–F220	Sieving
DIN ISO 8486-2 [DIN97]		Grit sizes F230–F1200	Sedimentation
FEPA 42-1:2006		Macrogrits F4–F220	
FEPA 42-2		Microgrits	
ISO R565-1990 and DIN 848-1988	Superabrasives		
FEPA 61/97		Macrogrits	
FEPA 60/77		Microgrits	
ANSI B74.16		Macrogrits	
ANSI B74.20 [ANSI81]	Diamond grits	Microgrits (powder)	Microscopical

Table 2.5 International standards for grit sizing for coated abrasives [MENA00, ANSI01]

Norm	Grit type and size	Sizing method
FEPA 43/93	Microgrits and macrogrits	
ISO 6344 (part 1and 2)	Macrogrits, P12–P220	
ISO 6344 (part 3)	Microgrits, P240–P2500	
ANSI B74.18-1984 [ANSI84]	Al_2O_3, SiC, garnet, size 220–12 Flint, size 220. 180. 150 Emery, fine–extra coarse Flint, extra fine–extra coarse	Sieving
	Al_2O_3, SiC, garnet, flint, size 600–240	Sedimentation

FEPA superabrasives $=$ [size of mesh hole through which grit just passes in microns]

$$(2.19)$$

The size definition by mesh implies no absolute value, but rather a size band. The tolerances, i.e. the permitted particles with sizes above and below the defining band, are based on the total weight. Consequently, the proportion or number of finer particles to coarser ones within a given size is not fixed [ENGL03]. This leads to variations in number of particles per carat and average grit size within a specified size. Therefore, abrasive tool performance can fluctuate.

2.9.1.1.1 Sieving Procedure

Each grit size has a set of five sieves of metal wire cloth with decreasing mesh size,
e.g. defined by ISO 3310 [DIN97]. The reason for the five sieve setup is to simulate
the actual mass when using the sieves for test grading [ANSI01]. The sieves are
arranged with the roughest sieve above and the finest below it, on a cup. The
aperture size decreases technically by a factor of $\sqrt{2}$ in the stack of sieves
[MALK08, p. 12]. A certain mass of a representative grit probe is put onto the top
sieve. After a certain time on a test-sieving machine (defined by ISO 9284 or ANSI
B74.12) the amount of particles on each sieve is weighted [ANSI01].

   As example, the total probe volume of a F10 grit sample has to pass sieve 1
(mesh size 3.35 mm) (Fig. 2.24). Sieve 2 (mesh size 2.36 mm) can be passed fully,
but a maximum of 20 % mass can be withheld. On sieve 3 (mesh size 2 mm) a
minimum of 45 % probe mass has to retain, but 100 % may have passed sieve 2.
The combination of sieve 3 and 4 (mesh size 1.7 mm) has to hold a minimum of
70 % of the total weight, so sieve 4 has to retain the difference, i.e. a maximum of
25 %. There are no definitions for the finest sieve 5 (mesh size 1.4 mm), but only
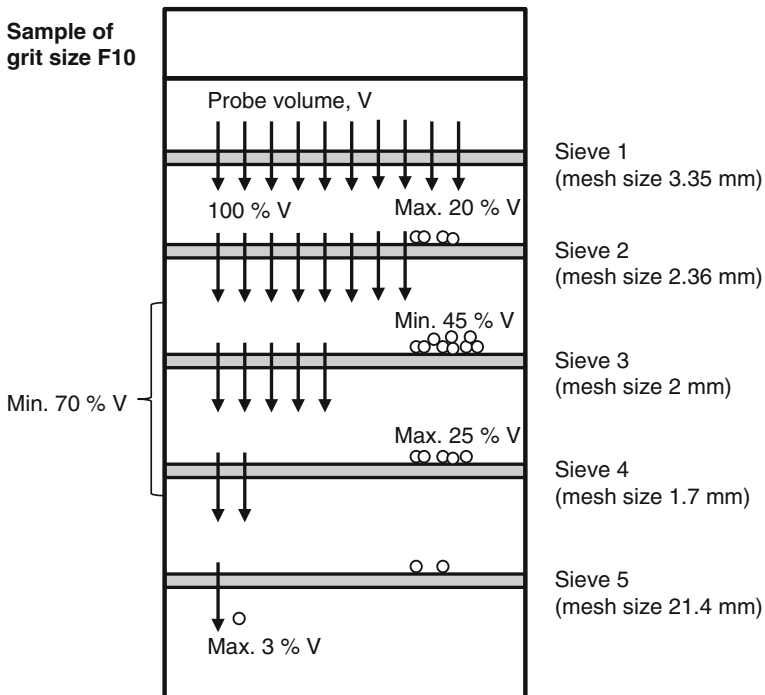3 % of probe mass is allowed to pass sieve 5 and to be collected in the bottom cup.

Fig. 2.24 Example for mesh sizing [DIN97]

Metrological variances are considered in percentage deviations of 3 to 4 % of retained probe mass [DIN97, ANSI01].

2.9.1.2   Sifting

Sifting is a separating procedure where the falling particles are exposed to a contrary flow [SALM07, p. 134]. If the flow rate meets the falling velocity of a certain particle size, these particles hover. Smaller particles stay in the flow, coarser particles decant.

One method is to suspend the particles in an aerosol beam and measure the movement time of the particles between two points of known distance apart [UAMA09]. If a fluid is used as medium, the process is called elutriation [SALM07, p. 137]. Air forms the medium for wind sifting and the time of flight defines the mass and grit size.

2.9.1.3   Sedimentation

Stokes' law can be used for evaluating the particle size distribution (Eq. 2.20) [ANSI77]. Sedimentation or Stokesian methods work with a stationary medium and the particles are in free fall [SALM07, p. 138]. Sedimentation methods are usually used for grading finer grit, such as in ANSI B74.10 [ANSI77].

$$\text{Stokes' law for small spheres} \quad v = \frac{2 \cdot g \cdot r^2 \cdot (p - d)}{9\eta} \tag{2.20}$$

v   settling velocity in (cm/s)
g   gravity acceleration in (980 cm/s^2)
r   effective particle radius in (cm)
p   density of the particles in (g/cm^3)
d   density of the settling medium in (g/cm^3)
η   viscosity of the settling medium in [g/(s cm)]

The FEPA 43 and DIN ISO 8486-2 standards define a calibrated US-Sedimentometer. The water in the sedimentation tube should be thermally controlled. In an automated system, light barriers can measure the sedimentation height per time [TOPA10]. This data is then used to calculate the particle size distribution with Stokes` law. Another method is to apply abrasive grits in a carrier medium onto the surface of a rotating fluid ring.

Stokesian methods work best for spheres. Flat particles and needles experience a greater drag per unit mass than spheroidal particles. As consequence, they settle in a viscous medium as fast as smaller round particles and will therefore cause oversizes in the grading. Especially for fine finishing operations such as lapping and polishing, these oversizes can ruin the workpiece quality. [DAVI74]. Overall, irregular, less

blocky grit shapes can present severe problems in size grading [HERB81]. In addition, sedimentation can be a very time consuming method (more than 24 h for very fine particles) [UAMA09]. The operator has to constantly tap the settling tube during the test to insure even packing and level settling [UAMA09].

2.9.1.4   Counting Methods

Counting methods work for single particles or on their projection [SALM07, p. 140]. A common procedure for counting abrasive grits is laser granulometry. Herein, a mixture of loose samples in a fluid medium flows through a ring. Laser light leads to different shadowing effects depending on the grit size. Commonly, three proportions of different grit sizes are measured, i.e. grit sizes of 10 % of biggest and of smallest grit proportion of the complete grit mixture and the size, which is 50 % of sample, in total 10, 50, 90 % [HORI10].

Especially for coarse diamond grits, the number of particles per carat (PPC) is an important characteristic. Coarser diamonds with high purity are used in electro-plated tools, rotary dressing tools or as so called "saw grits" in saw blades, circular saws, drill bits, wire saws, and milling tools, e.g. for stone cutting or drilling operations. Since PPC may vary if the average grit size is defined by the sieving method, significant variations in tool performance can occur [ENGL03]. Therefore, the number of particles per carat offers an additional measure for the consistency of the diamond batch [LIST08]. The PPC value can be obtained directly by weighing and counting or indirectly by two-dimensional digital image processing [LIST08].

2.9.1.5   Other Methods

Several more methods for particle size characterization exist, such as laser light diffraction, dynamic light scattering, photon correlation spectroscopy, Brownian motion turbidity, etc. [BENE10].

The size of microgrits can be analyzed by their electrical resistance as defined in the ANSI standard B74.10-2001 [UAMA09]. The underlying principle is that a particle causes a change in the strength of the current proportional to the particle volume [UAMA09]. Problems, however, arise for irregular grit shapes, which will be graded with finer sizes than by sedimentation methods.

2.9.2   Grit Shape Selection and Analysis

2.9.2.1   Picture Analysis

Picture analysis is based on a two-dimensional projection of the grit, e.g. via back light microscopy or film scanners, or on a picture, e.g. by transmitted light

microscopy or scanning electron microscopy. Picture analysis has some restrictions. The equipment defines the minimum grit size that is measurable. In addition, the grit placement interferes with the measured results. For example, when the grits are dispersed on the scanner plate, the probability of grits to fall on certain grit planes varies.

Picture analyses work mostly on a two dimensional projection of the abrasive grits. Figure 2.25 gives an example for different measurement values from a two-dimensional picture, such as maximum and minimum grit diameter, grit circumference, and grit cross-sectional area in the projection plane. Some shape characteristics are derived in comparison with a coextensive circle, i.e. a circle with the same area as the projected grit (Fig. 2.25).

Equations 2.21 [LIEB96] and 2.22 [LIEB96, SCHI02] define shape factors indicating grit roundness. The ratio in Eq. 2.23 is another characteristic for the roundness or compactness [PIRA03, LIST06]. The grit ellipticity can be evaluated by Eq. 2.24 [GESU00, SCHI02]. Further characteristics are derived from the proportion of convex parts in the grit perimeter [LIST06].

$$\text{Max. grit diameter/diameter of coextensive circle} \tag{2.21}$$

$$\text{Grit perimeter/perimeter of coextensive circle} \tag{2.22}$$

$$4\pi \text{ grit area}/(\text{grit perimeter})^2 \tag{2.23}$$

$$\text{Max. grit diameter/min. grit diameter} \tag{2.24}$$

Two methods to define the particle size are possible, such as the grit`s largest dimension or the average of the maximum grit dimension and the largest dimension rectangular to it [DAVI73, DAVI74, BENE10]. Taking a round grit, both values are similar. For an elongated grit, the largest dimension is much bigger than the average dimension calculated by the second method. Thus, the greater the deviations from the ideal blocky shape, the bigger the difference of both measurement methods. One
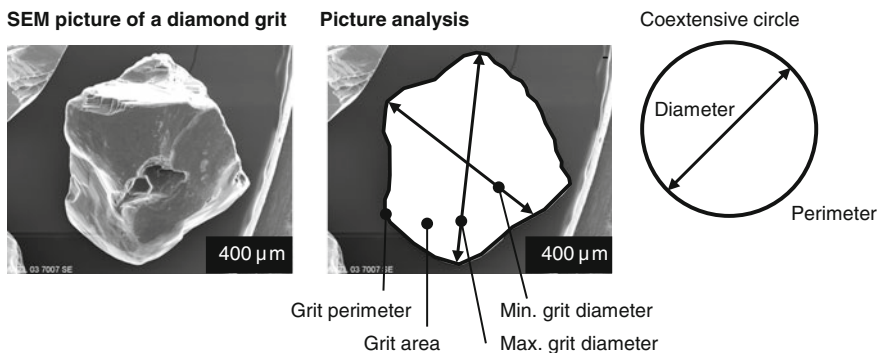

Fig. 2.25   Example for picture analysis of a grit

method for grit size analysis of micron powder recommended by FEPA is to take the smallest circle, which circumscribes the particle [HERB81].

2.9.2.2   Packing Density

Packing density or bulk density depends on grit size and shape. For example, equidimensional shapes pack to a higher bulk density than flat shapes [MENA00]. The packing density is a rather simple but effective measure for the dominant grit shape of a batch, if grit size and size distribution are known [MALK08, SCHT81].

Measurement procedures for the packing density of conventional abrasive grits are defined in ISO 9136, parts 1 and 2, or ANSI B74.4 [MENA00]. ANSI B74.17 specifies the packing density for superabrasives [MENA00]. One method is to determine the weight of grits required to fill a cylinder of known volume when the grits are allowed to flow through a funnel and fall from a fixed height [ANSI92]. The packing density is given in (kg/l), (g/l) or (g/cm^3) [SCHT81, ANSI92].

2.9.2.3   Shape Sorter

The shape sorter, also called vibration table (German "Rütteltisch") consists of an inclined table, which by oscillating causes the abrasive grits to move up or down depending on their shape. Boxes at the edge of the table collect the different shape fractions. Diamonds are sorted from cubic crystals and cubooctahedrons to broken particles of irregular shapes, such as needle-like crystals or platelets. The principle works only for batches of the same grit size range [VOLL10, LINK15].

2.9.3   Toughness and Breaking Behavior Analysis

2.9.3.1   Friatest

Manufacturers of superabrasives evaluate the grit fracture behavior by impact strength tests, so called friability test or friatester [ODON76, MARI04]. A grit sample with a defined weight and a steel ball are encased in a capsule, which is then shaken with a defined cycle number [VOLL12]. The impact load breaks a portion of the grits. The percentage of the non-destroyed grits is defined as toughness index (TI) [VOLL12]. The friability index (FI) defines the number of cycles needed to break 50 % of the grits [VOLL12]. Diamond grit manufacturers qualify their grits by room temperature toughness (TI) and thermal toughness after heating (TTI), for example at 1000 °C [MARI07]. [LINK15]

In general, the friability characteristics do not have a sufficient correlation to the grit performance and more research is needed. Another problem of the friability test method is that several characteristics intermingle in the test results.

2.9.3.2   Single Grit Toughness Test

The single grit breakage test enables a particle related description of grit strength. This method is based on the maximum force to break a particle, measured along one axis [VOLL03a, VOLL03b]. Some systems allow combining a two-dimensional picture analysis of grit size and grit shape, and measurement of the specific breakage force. In the procedure, a single grit is positioned between two anvils, which are pressed together with increasing, pneumatic force until the grit brakes [LIST06]. The maximum uniaxial force needed to break the particle is measured. The force divided by the grit area defines the breakage strength.

Diamonds with a diameter of 250 µm can have average breakage strength of 5000 N/mm^2, so that the pressing forces have to be sufficiently high [LIST06]. The single grit fracture test has similarities to the real grinding process, where the normal forces are higher than the tangential forces.

Benea and Griffin introduced a strength testing method for micron powder [BENE03b].

2.9.4   Analysis of Residual Stress via Polarisation Microscopy

Polarisation microscopy can detect stresses inside of transparent single-crystals, which is in particular important for monocrystalline diamond for jewelery [KLEB98, LENZ86]. Lattice defects in the crystals result in interference patterns and are recorded in double refraction pictures [MALZ00]. The results can be improved by embedding the grits into material with the same refractive index so that light refractions are avoided at the grit surface and only the internal refractions due to lattice defects appear.

2.9.5   Magnetic Susceptibility Selection and Analysis

ANSI B74.19 presents a test method to determine the magnetic content of conventional abrasive grits [MENA00, ANSI90]. A standardized magnetic analyzer is used on a sample size of 150 g. Its two coils, one as a reference, one for the sample, are excited with an odd frequency AC source (390 Hz) [ANSI90]. The unbalance is measured and translated to the relative magnetic content of the sample [ANSI90]. Other analyzers on the market work with 80 Hz excitation and are mobile [VOLL11a].

A sorting process for magnetic and non-magnetic grits can be based on lifting one sort of grits from a drum or a belt with a magnetic force higher than the grit gravity force [VOLL11b]. A related task is to recover abrasives from blasting material containing magnetic, metallic particles [DREN97].

2.9.6 Other Analyses

Grit hardness is usually tested by a Knoop micro indenter test [SCHT81, MENA00]. By means of an electrostatic separator, particles with conductive surfaces can be selected. Capillarity is a measure for the wettability of abrasive grits [UAMA09, SCHT81]. Capillarity gives an indication of grit cleanliness and is particularly important for aqueous glues for coated abrasive tools [UAMA09]. The test procedure foresees to fill glass tubes with the grit sample and measure the capillarity height of water [SCHT81, ANSI64].

Several chemical analyses are in practice, such as atomic absorption, emission spectroscopy, and X-ray fluorescence [MENA00]. Silicon carbide can be heated in a 27 % potassium hydroxide solution for 9 h to detect free silicon dioxide [SCHT81]. Other chemical analyses are based on classical wet methods, such as FEPA 46/93, ISO 9285, and ANSI B74.14 for fused aluminum oxides and ISO 9286, FEPA 45/93, and ANSI B74.15 for silicon carbides [ANSI86, MENA00].

2.9.7 Evaluation of Grit Analysis and Sorting Techniques

The sorting method affects the variance of grit characteristics in a batch. This has a direct correlation to tool manufacturing and tool performance. One has to be aware that variances in the process chain add up. A narrow distribution band of grit characteristics defines the tool performance more precisely. This potentially leads to highly efficient and well balanced abrasive processes. Low scrap rates and high product quality are important for sustainable manufacturing technologies. However, the sorting method to obtain the narrow band might be more expensive. Additionally, a broad grit size distribution can facilitate tool manufacturing by lower mold pressure and higher packing density. Both, selection method and tool manufacturing affect the tool price.

Uniformity of the grit batch is a useful characteristic for the quality of grit selection; however, the overall quality of the batch has to be judged according to the application. Novikov et al. [NOVI08] describe a calculation method for uniformity, which allows assessing powder uniformity from diverse characteristics. Uniformity can be improved during the abrasive grit production, at the stage of grit selection, and by grit sizing [NOVI10].

In Table 2.6 the most important analysis and selection methods are compared. Criteria are the applicability for superabrasives or conventional grits, use as selection method, or non-destructive method. Some methods are only applied for macrogrits or for powders. In addition, measurement methods can be characterized by the following criteria [BENE10]:

- Accuracy = closeness of the measured value to the true value,
- Precision = variation in repeated measurements,

Table 2.6 Comparison of grit analysis and sorting methods, na = not applied, + = yes, – = no [LINK15]

Method	Characteristics	Apt for conv. grits?	Apt for superabrasives?	Selection /sorting method?	Non-destroying method?	Other comments
Sieving	Size	+	+	+	+	Size is important for mold pressure, macrogrits
Granulometry	Size			–	+	
Sedimentation / Stokesian Methods	Size			+	+	Used for microgrits
Picture analyses	Size, shape	+	+	–	+	Only applicable for macrogrits, processing time
Shape sorter	Shape (toughness)	–	+	+	+	Avoid electrostatic
Packing density	Shape	+	+	–	+	Combined with sieving
Friatest	Toughness	+	+	–	–	
Single grit breakage tests	Toughness	+	+	–	–	
Magnetic separator	Magnetic susceptibility	na	+	+	+	Magnetic inclusions
Magnet susceptibility analyzer	Magnetic susceptibility		+	–	+	
Electrostatic separator	Electric conductivity	na	+	+	+	Adjusted grit direction
Polarisation microscopy	Stresses in single crystals	–	+	–	+	

- Reproducibility = variation between different instruments, operators and sample preparation,
- Resolution = minimum detectable differences between features,
- Upper and lower limits.

These criteria were not evaluated in Table 2.6 because they differ for the equipment and are in constant development. Future research should focus on the effort per sorting method and the achievable tool performance and productivity. This could be connected to the sustainability analysis in Chap. 7 "Sustainability of Grinding".

2.10   Sustainability Dimensions to Abrasive Grits

2.10.1   Technological Dimension

Table 2.7 summarizes the most important grit characteristics in grinding technology. In general, the grit type is chosen with regard to the machined material and the grit size is defined by the desired workpiece quality. The individual performance profiles of the grit types can be visualized in radar charts [HELL11].

The abrasive material should be harder than the machined material. In general, corundum and CBN are used for long-chipping, ductile materials, whereas silicon carbide and diamond are used for short-chipping, brittle materials or titanium alloys [KLOC09, HELL11, LINK12b]. Superabrasives are chosen in particular for the higher precision or higher performance applications due to their low wear rate and ability to achieve close size tolerances [ROWE09, LINK12b]. The reactivity of diamond with transition metals such as nickel and iron limits the use of diamond to machine these metals, especially steels. However, there are some applications with ferrous materials where diamond is the tool material of choice, e.g. honing of cast iron [MARI07]. Diamond covers many applications formerly conducted by SiC [JUCH78].

The higher thermal conductivity of superabrasives compared to conventional abrasives can reduce grinding temperatures drastically [ROWE09, LINK12b]. For a specific application, the use of corundum could lead to unfavorable tensile stresses in the part surface layer, whereas CBN could produce favorable compressive stress [BRIN82, BRIN04b]. However, there is a common understanding that the surface finish is rougher with CBN grits than with conventional wheels [LINK12b]. It is believed that sharper and more pointed cutting edges lead to earlier chip formation and shallower initial depth [MALK08]. CBN grits have typically chip angles between $-60°$ and $-70°$ and have sharper cutting edges than conventional abrasives [FERL92, p. 31].

Table 2.7 Relevant properties of abrasives for tool manufacturing and use [MALK08, KLOC05a, JUCH78, MÜLL01, GRAN12]

	Diamond	CBN	SiC	Al$_2$O$_3$
Main elements components	≈100 % C	≈43.6 % B ≈56.4 % N	≈97 % SiC	95–99 % Al$_2$O$_3$
Crystal structure	Cubic	Cubic	Hexagonal	Hexagonal
Manufacture of abrasives	HPHT-synthesis	HPHT-synthesis	Melting in resistance furnace	Melting in arc furnace or sintering or sol-gel procedure
Density (g/cm^3)	3.52	3.48	3.22	3.8–3.98
Effect on tool performance				
Chemical reaction relevant to tool use [JUCH78]	Chemical reaction with non carbon saturated steels above 875 K	Possible chemical reaction with water above 1075 K	Chemical reaction with ferrous materials	Chemically neutral
Knoop hardness (HK)	7000–8000	4700	2400–3000	1600–2160
Thermal stability up to K	1173	1643	1573	2273
Thermal conductibility (W/m K)	600–2100	200–700	55	6
Fracture toughness K$_{IC}$ (MPa m$^{1/2}$)	3–3.7	3.7	3.1	2.7–4.3
Effect on tool production				
Chemical affinities relevant to tool manufacture [JUCH78]	Chemical reaction with oxygen above 1075 K	Heat-resistant up to 1375 K	Chemical reaction with flux like boron acid, water glass, above 975 K	Chemically neutral
Melting point (°C)	≈3700 °C at 130 kbar (triple point)	≈3200 °C at 105 kbar (triple point)	≈2830 °C	2040 °C

2.10.2   *Economic Dimension*

The fusion of corundum began at the Niagara Falls using cheap hydro-electric power. Today China has huge capacities for producing fused corundum, and Eastern Europe, India, South Korea, and South America are growing manufacturers in the world production of fused corundum [JACK11, p. 27]. Low cost energy has become an important factor for the competitiveness of corundum producers, as well as furnace capacity, and low costs of raw material sourcing [JACK11, p. 27]. Similar challenges apply for manufacturers of all abrasive grit types.

Today, tool producers can choose between several grit toughnesses amongst one grit type [MARI04, p. 347]. A high toughness does not necessarily lead to the longest grit life. On the one hand, grits which are too tough for a special application will become dull and increase friction. This leads to unnecessary thermal influence and process vibrations. On the other hand, too friable grits wear away quickly resulting in short tool life and possible form errors.

The tool user can choose between conventional and superabrasive grits, which both generate highly efficient grinding wheels. The decision has to consider the grit properties in the abrasive layer on the one hand. For example, superabrasives have higher raw price costs than conventional abrasives, but also a better wear resistance leading to higher efficiency of superabrasives. On the other hand, the production environment has to be taken into account. For example, the usage of CBN can be very cost-effective in serial and mass production with appropriate machine tools. In contrast, in small and middle-size companies, flexible production with conventional tools follows the trend towards product diversification and stock reduction.

The price of grinding tools is strongly influenced by the price of the grit material, accounting for up to 50 % of CBN tools. The grit price increases with the pressure during the production process, the length of the process, and the overall energy consumed (Fig. 2.26 left). Although diamond synthesis needs very high pressures, the process happens only in several minutes. In contrast, corundum synthesis takes hours or even days and needs therefore power longer. Grit costs and hardness, which indicates wear resistance against abrasive wear, shows some correlation (Fig. 2.26 right).

2.10.3 Environmental Dimension

The ecological hazard of abrasive grits themselves is minor (Table 2.8 left), but some problems arise from the grit production emissions and waste. Emissions from the production of conventional abrasive grits are likely to consist primarily of particulate matter (PM), and carbon monoxide (CO) from the furnaces [EPA94].

In the sintering process of SiC from quartz and coal (with salt and sawdust as auxiliary materials), a considerable amount of greenhouse gas CO_2 is produced
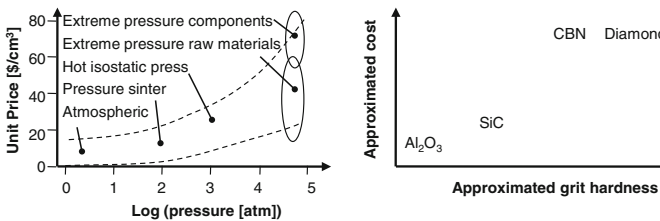

Fig. 2.26 Economic correlations for abrasive grits, *left* price and manufacturing pressure [LUCE13], *right* price and hardness [UAMA09]

Table 2.8 Examples for information the material safety data sheets [WASH12]

	Known ecological information	Chemical safety assessment
Emery	–	Irritant (eye, respiratory system)
Boron carbide	Low order of aquatic toxicity, low potential for bioaccumulation	Harmful (oral, inhalation) suspect reproductive hazard
Zirconia corundum	Low potential for bioaccumulation	Irritant (skin, eye, respiratory system)
Brown corundum	Low potential for bioaccumulation	Irritant (skin, eye, respiratory system), suspect carcinogen (inhalation—repeated exposure only)
White corundum	Low potential for bioaccumulation	–
Silicon carbide	Low potential for bioaccumulation	Irritant (skin, eye, respiratory system)

(Eq. 2.10). Salt and sawdust are likely to produce chlorides and volatile organic compounds (VOC) [EPA94]. Moreover, the SO_2 and dust in the waste gases cause pollution [LIET08]. Furnaces collect and trap the reaction gases, so that CO can be purified and used [LIET08]. The gases can be desulfurized so that elemental sulfur is obtained as well [LIET08].

The production of corundum is likely to emit fluorides, sulfides, and metal constitutes of the raw materials. Sol-gel processing of sol-gel corundum emits NO_x [EPA94].

The re-processing steps of conventional abrasives like cleaning and refinement also use diverse acids and complex machinery. Grit crushing emits PM [EPA94]. Also in the synthesis process of superabrasives, metallic catalysts and refractories remain as waste material. Moreover, metallic grit coatings are common to improve retention and heat-flow in resin and vitrified bondings, but may involve hazards in their production.

Because of the different synthesis routes for the different grit types, the energy consumption to produce a gram of abrasives is different (Table 2.9). Furthermore, the energy consumption per machined part material will be different due to the different wear resistances (see Sect. 8.1 "Case Study on Conventional Abrasives vs. Superabrasives for Vitrified Bonded Tools").

Solid or chemical waste from grit production processes needs to be classified and may be treated as hazardous waste. Some manufacturing approaches re-use scrap material. For example, one grit manufacturer fuses recycled aluminum oxide into high quality fused aluminum oxide, so that a completely closed loop process is possible recycling 100 % of the spent material [WASH12]. In another example, grit producers invented a process using alumina/zirconia/silica scrap, because zirconia for the production of zirconium corundum has a high cost [ASHL96]. By adding a reducing agent, the silica content of the final abrasive grit can be kept below 0.8 % by weight [ASHL96].

Table 2.9 Environmental material data (* estimated data) [GRAN10]

	Embodied energy, primary production (estimated) (MJ/kg)	CO_2 footprint, primary production (estimated) (kg/kg)	Water usage (estimated) (l/kg)	Raw materials
SiC	*70.2–77.6	6.25–6.91	*33.5–101	Si and carbon are plentiful
Al_2O_3 (99.5 % purity)	49.5–54.7	2.67–2.95	29.4–88.1	Al_2O_3 is one of the most plentiful chemical compounds in the earths crust
H-BN	120–133		126–139	

2.10.4 Social Dimension

Mining for raw materials is known for having many physical, chemical, biological, ergonomic and psychosocial occupational health hazards [DONO04]. In addition, the processing of grits can be harmful to workers. For example, the emissions from melting corundum from bauxite in electric arc furnaces can lead to a lung disease known as corundum smelters lung, bauxite worker`s lung, or bauxite fibrosis (German "Korundschmelzerlunge") [KONE94, p. 473].

The abrasive grits and powders themselves can create nuisance dust, which can cause respiratory tract irritation, coughing, and shortness of breath. Human skin and eyes can be harmed by mechanical, abrasive action of the grits (Table 2.8 right). In particular, mining and processing of silica, or sandblasting operations with silica are tied to respiratory diseases [MADL08, DONO04]. The protection of workers in these applications is crucial.

2.10.5 Sustainability Model for Abrasive Grits

Raw material extraction, manufacturing, and choice of abrasive grits for later processing and use affect different stakeholders. The grit manufacturer is mostly concerned with the following aspects:

- The **grit price** depends on raw material availability, raw material price, local energy costs, labor costs as well as equipment costs and maintenance.
- The **location** defines energy and material availability, labor and energy costs, and logistics.
- **Hazards to the environment and the workers** need to be reduced and evaluated by local regulations.

Most important aspects for the tool manufacturer are as follows:

- The **grit price** affects the later tool price strongly, up to 50 % in the case of CBN.
- **Grit availability and quality** defines the constancy of tool quality.

The tool user is concerned about

- **Technology**, in particular how the abrasive grit material interacts with the workpiece material and how the tool wears in the use phase.
- The **tool price** ist affected by the grit price and important for the tool user`s competitiveness.

Society worries about

- **Mining hazards** from emissions and particulate matter to the local community and to the workers.