Chapter 5
Grinding Wheel Macro-design—Shape, Body, and Qualification

*Tools are graded by the manufacturer according to the coarseness or fineness of the particles of the abrasive material they contain, but the working qualities of the tools depend not only on the size of the particles, but also upon the quality of the binder. It thus results that tools which have the same commercial grade number, vary greatly, in cutting or abrasive qualities. Harey La Vercombe, Patent on Grinding-wheel-test-device, 1923 [*LAVE23*].*

After having introduced the basic components and types of abrasive tools, the following chapters will focus on grinding wheel design. This chapter focuses on wheel macro-design, which includes body shapes and material. Depending on shape and application, clamping and balancing need special attention and will be described here. Furthermore, grinding wheels have to be tested for hardness, elasticity and tool breakage. The chapter closes with discussions on sustainability dimensions for all these macro-design subjects.

5.1 Body Concepts

Grinding wheels with superabrasives or tools for high-speed operations consist of an abrasive layer fixed on a body. The body is also called core, base, carrier or hub material. The body has to withstand several static and dynamic stresses such as centrifugal forces, acceleration forces, cooling lubricant friction forces, air friction forces and grinding process forces. Furthermore, the body needs to provide sufficient heat conductivity, high mechanical strength, and good vibration dampening.

Common body materials are aluminum, steel, bronze, synthetic resin with metallic or non-metallic fillers, fiber-reinforced synthetic resin, or ceramics [KLOC09]. The design of carriers has to regard expansion at rotation speed, damping behavior, thermal expansion, etc.

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5.1.1 Body Shapes—Stresses and Special Design for High-Speed Applications

Grinding wheel rotation leads to centrifugal forces and stresses within the tool body. For a generic homogeneous cylinder, the tangential stresses, σ_{tx}, at the diameter D_x follow (Eq. 5.1); the radial stresses, σ_{rx}, follow (Eq. 5.2) [HELL05b, FRAN67].

The tangential stress has its maximum at the inner hole diameter, $H = D_x$; the radial stress reaches the maximum at $\sqrt{(DH)} = D_x$ [HELL05b]. Equations 5.1 and 5.2 show that the stresses increase with the square of the wheel speed, v_s^2, and with the ratio of hole diameter to outer diameter, $(H/D)^2$. Helletsberger [HELL05b] discusses several body designs and composite bodies in detail.

$$\sigma_{tx} = \frac{\rho \cdot v_s^2}{8}(3+\nu)\left[1+\left(\frac{H}{D}\right)^2+\left(\frac{H}{D_x}\right)^2-\frac{1+3\nu}{3+\nu}\left(\frac{D_x}{D}\right)^2\right] \tag{5.1}$$

$$\sigma_{rx} = \frac{\rho \cdot v_s^2}{8}(3+\nu)\left[1+\left(\frac{H}{D}\right)^2-\left(\frac{H}{D_x}\right)^2-\left(\frac{D_x}{D}\right)^2\right] \tag{5.2}$$

σ_{tx} tangential stress at diameter D_x
σ_{rx} radial stress at diameter D_x
ρ density
v_s wheel speed
ν Poisson ratio
H hole diameter
D outer wheel diameter

Because the wheel speed has such a big influence on the internal stresses, high-speed applications have particular requirements for the grinding tool body [FERL92, p. 66]:

- High strength of body material,
- Quasi isotropic material behavior,
- Small radial elongation,
- Small weight,
- Good damping ability.

High wheel circumferential speeds, v_s, are favored for low cutting forces and wheel wear. High wheel speed can be achieved with a large wheel diameter, d_s, or a high number of revolutions, n_s (Eq. 5.3).

$$\text{Grinding wheel speed } v_s = \pi \cdot d_s \cdot n_s \tag{5.3}$$

High numbers of revolutions require special tool spindles. Not only do these spindles have to provide a high number of revolutions (such as 10,000–30,000 min^{-1}), but they should have high maximum power, convenient compliance behavior, high radial and axial runout accuracy, smallest axial deviation, and small space for installation [FERL92, p. 59 f.].

Large wheel diameters go along with large wheel perimeters and high volumes of abrasive grits. Tool life increases with diameter, however, not always in the same proportion as tool costs rise with the grit costs [FERL92, p. 53]. Whereas the grinding wheel perimeter, P, and the number of grits increase linearly to the tool diameter, d_s, (Eq. 5.4), the mass rises with the square of the diameter (Eq. 5.5). Heavier tools are harder to handle for the machinist during clamping and machine set-up. Moreover, additional disadvantages lie in the higher rotational energy and higher loss drive power [FERL92, p. 53].

The rotational energy depends on the wheel diameter to the power of 4 (Eq. 5.6) [FERL92, p. 53]. The higher the rotational energy of the tool, the more worker protection and machine encapsulation needs to be in place.

Air friction and grinding wheel mass increase the loss power of the tool drive. Ferleman [FERL92, p. 55] gives an equation for the loss drive power by air friction for turbulent flux. Here, the loss drive power depends on the wheel diameter to the power of 4.6 and the number of wheel revolutions to the power of 2.8. This emphazises that the diameter should be as small as possible for high-speed grinding operations.

$$\text{Tool perimeter } \mathrm{P} = \pi \cdot \mathrm{d_s} \tag{5.4}$$

$$\text{Tool mass } \mathrm{m} = \frac{\pi}{4} \cdot \rho \cdot \mathrm{b_s} \cdot \mathrm{d_s^2} \tag{5.5}$$

$$\text{Rotational energy } \mathrm{E_{rot}} = \mathrm{K_1} \cdot \rho \cdot \mathrm{b_s} \cdot \mathrm{d_s^4} \cdot \mathrm{n_s^2} \tag{5.6}$$

ρ wheel density
b_s wheel width
d_s wheel diameter
K_1 constant factor
n_s number of wheel revolutions

An increase in grinding wheel circumferential speed induces a decrease in the single grit chip thickness. This can be used for two different principles, enhancing quality or performance. With smaller chip thickness, the grinding process achieves similar or higher material removal rates, but with higher surface quality and extended tool life compared to lower speed applications [GÜHR67]. In addition, high efficiency grinding with much higher material removal rates is possible and often substitutes turning, milling or reaming applications [FERL92, p. 1].

Resonance vibrations can be calculated via Finite Element Analysis and measured through laser holography [FERL92, p. 66]. The number of spindle revolutions as excitation frequency should have a security distance of 20 % to the first resonance frequency of the tool body [FERL92, p. 66]. However, the centrifugal forces are much higher than the grinding forces and need to be the focus of design optimizations for high-speed grinding operations [KIEN63].

Strain builds around the inner hole, so wheels without inner holes or special reinforment around the hole are in use. Already in the 1930s, Krug suggested to counter the strain around the inner hole by strengthing the material by resin [KRUG35]. In 1963, Kienzle et al. suggested a two material grinding wheel with an internal ring of a material with higher Young's modulus than the abrasive layer [FERL92, p. 5, KIEN63]. Thus, the rupture circumferential speed of the grinding wheel increases in comparison to a conventional wheel with the ratio between the adhesive layer strength to the abrasive layer strength [KIEN63]. A larger inner ring increases the rupture speed further [KIEN63].

In 1967, Gühring increased the cutting speed up to $v_c = 90$ m/s with the usage of conventional vitrified grinding wheels with an optimized shape [GÜHR67, FERL92, p. 6]. The tools taper off from the inner boring to the rim to reduce the centrifugal forces. König and Ferlemann [KÖNI90] examined grinding wheel bodies for cutting speeds up to $v_c = 500$ m/s and define design features for high-speed grinding wheel bodies (Fig. 5.1).

The cutting speed has increased from 1935 to 1990 from 25 to 200 m/s; simultaneously, the specific material removal rate increased from 8 to 110 mm^3/mms or even 800 mm^3/mms in special cases [FERL92, p. 5]. The success of high-speed grinding applications between 1980 and 1990 was combined with the use of superabrasives, especially CBN [FERL92, p. 1].

The use of high grinding wheel speeds is tied to the development of appropriate bondings. Table 5.1 gives a range of possible wheel speeds and material removal rates for different bonding systems.

Oliveira et al. [OLIV09] found in 2009 that still a comparably low proportion of grinding machine tool manufacturers use high grinding wheel speeds with CBN.

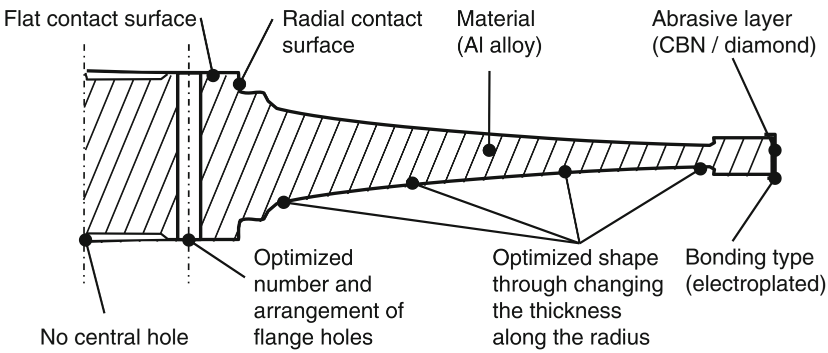

Fig. 5.1 Design features of high-speed grinding wheels [FERL92, p. 79], with copyright permission by VDI Verlag/Springer Verlag

Table 5.1 Wheel and bonding types, wheel speeds, and specific removal rates in 1997 [KLOC97]

Wheel type	Max. wheel speed, v_s (m/s)	Specific material removal rate, Q'_w (mm^3/mms)
Vitrified bonded conventional grinding wheel	≈120	10–100
Resin bonded CBN grinding wheel	≈140	50–150
Vitrified bonded CBN grinding wheel	≈140 (to 200)	50–150
Metallic bonded CBN grinding wheel	≈180 (to 250)	50–250
Electroplated CBN grinding wheel	>300	1000–10,000

Around 39 % of the 23 interviewed manufacturers use cutting speeds of mainly v_s = 40–80 m/s, only 13 % of up to v_s = 200 m/s [OLIV09]. The major reasons given for the comparably low proportion of high wheel speeds were the complex machine tools needing additional systems and economic reasons.

5.1.2 Body Materials

The body material has to withstand the grinding forces, the centrifugal forces from wheel rotation, and the resulting internal stresses. In the grinding process, the body material should dampen vibrations and transfer heat. Furthermore, the body material needs to be shaped easily into the wanted geometry and should have low weight. These requirements translate into physical material properties:

- Young’s modulus,
- Compressive strength,
- Coefficient of expansion,
- Isotropy,
- Heat conductivity.

For galvanic bonding systems, there are additional requirements for the body [FERL92, p. 66], like being electrically conductive and having a good corrosion resistance. For superabrasive grinding wheels, a couple of different body materials are used. Table 5.2 gives an overview on damping, heat conductivity, and mechanical strength. The expansion coefficient correlates with density and Young’s modulus, so metal bodies have higher expansion than carbon fiber-reinforced polymers.

Table 5.2 Body materials after [WINT88, p. 9, UAMA09, KRAF08]

	Density [kg/dm^3]	Expansion coefficient (10^{-6}/K at 20 °C)	Vibration damping	Heat conductivity	Mechanical strength
Steel	7.84	12.2	−	+	++
Aluminum	2.80	23.5	−	++	++
Titanium	4.51	8.8			++
Powdered aluminum			o	o	+
Copper			o	++	+
Resin with metallic fillers (phenol aluminum)			o	o	+
Resin with non-metallic fillers			+	−	o (− for thin bodies)
Fiber reinforced resin	1.54	4.4	++		++

++ very high, very good
+ high, good
o medium, satisfactory
− low, poor

5.1.2.1 Metal Body

Metallic bodies made of steel, aluminum, aluminum resin composite, bronze, and copper are applied. For example, the aluminum and bronze blanks are turned to the proper dimensions on a lathe as bodies for resin bonded wheels [METZ86, p. 62]. The turning operation is a big portion of the manufacturing costs, because dimensional accuracy ranges from 0.01 to 0.1 mm [METZ86, p. 62].

The body for electroplated wheels is precision machined. After use, electroplated wheels are generally returned to the tool manufacturer, stripped and re-plated. Commonly, low alloy carbon steels are used or tempering steels or ball bearing steels for higher wheel speeds [KLOC07, p. 195]. Soft steels are easier to machine, but hardened and annealed steels are more wear resistant during clamping operations [KLOC07, p. 195 f.].

Grinding wheels with large diameter or large width are made from aluminum alloys to reduce weight [KLOC07, p. 196]. Breaking point and expansion are similar because the ratio of Young’s modulus to density are similar for steel and aluminum [KLOC07, p. 196].

5.1.2.2 Resin Bodies with Metallic Fillers and Non-metallic Fillers

Bakelite/aluminum or Bakelite/graphite bodies are elastic and tend to dampen vibrations from the grinding system [METZ86, p. 63, SEXT82]. This body type is connected to the abrasive layer by direct pressing without glueing [METZ86, p. 63]. Bakelite graphite or glass fiber reinforced resins can be pre-pressed to blanks and have the advantages of being light [METZ86, p. 62].

A common body material is a phenolic resin with a large amount of aluminum powder [SIOU80, VANP39]. The proportion is 25 V% or less of resin and 75 V% or more of metallic powder. The mixture is hot pressed in a mold at temperatures of around 160 °C [VANP39]. Sioui and Carver [SIOU80] introduced enhancements of powder metallic bodies, such as incorporating iron powder together with aluminum and a bonding aid (resin, tin, or zinc) into the hot pressed body. In addition to enhancing bond strength, thermal expansion, thermal conductivity, and turning characteristics, the retention on magnetic chucks is optimized for this material [SIOU80].

Thermal conductivity of phenol aluminum is more than 100 times better than bakelite [NOTT79]. In fact, the temperatures of the abrasive layer on phenol aluminium bodies is always lower than on bakelite bodies. As consequence, grinding wheels with bakelite bodies showed lower G-ratios for dry grinding of carbides [NOTT79].

5.1.2.3 Fiber Reinforced Resin

Asen [ASEN08] has patented a wheel body made from a fiber composite, specifically with carbon fibers, glass fibers, or synthetic fibers. Different fiber structures are undergoing investigation, in particular uni-directional, orthotroph (fibers in different orthogonal directions) or transversal-isotrop [KRAF08]. The fiber structure affects body strength and isotropy.

Vitrified and resin bonded abrasive layers are glued to the fiber composite body, whereas electroplated layers need an additional thin, metallic ring on the fiber composite body [ASEN08]. The mass of a fiber composite body can be as low as 1/10 of the mass of conventional metal bodies and has therefore lower energy consumption, needs shorter time to revert rotation, and is easier to change [ASEN08]. In grinding tests, tools with carbon fiber-reinforced polymer (CFRP) bodies proved to have a significantly lower contact stiffness than tools with steel bodies, which is advantageous for vibration damping [TAWA12].

Disadvantages of carbon fiber reinforced polymer bodies are the possibility of softening, unclear recyclability, and low performance in detecting the initial cut by acoustic emission. Machining of glass fiber body materials can emit hazardous particles. Furthermore, fiber reinforced resin bodies do not resonate well enough for today`s Acoustic Emission systems for process monitoring [KRAF08].

5.1.2.4 Connection Between Abrasive Layer and Body

Four major processes connect the abrasive layer with the tool body: adhesive sealing, sintering, shrinking, and electroplating [KRAF08]. With electroplating, the

Table 5.3 Mechanisms in connecting abrasive layer and body [MARI04, p. 212]

	Resin bonded layer	Vitrifed bonded layer	Electroplated layer	Sintered metal bonded layer
Metal body	Adhesion	Adhesion	Cohesion	Cohesion
Ceramic body	(rare:adhesion)	Cohesion	–	(not usual: adhesion)
Resin/metal body	Adhesion/cohesion	Adhesion	–	(rare:adhesion)
Resin/non-metallic filler body	Adhesion/cohesion	(rare: adhesion)	–	(not usual: adhesion)

abrasive layer is directly deposited on the metallic body or on a metal ring. Abrasive layers of other bond types are either shrunk or sintered directly on the body or glued with adhesives.

For resin bonded tools, shrinking takes place during the resin hardening process. The inner surface of the mold is coated with a release agent to prevent adhesion of the resin and to ensure safe demolding. Oil based liquids might be used as release agents and can easily be sprayed onto the mold surface. The interface between the resin bond and the body is equipped with a first primer coat to ensure excellent bonding.

Glues connecting the abrasive rim layer and the body are often two component epoxy glues, but the exact composition of the glue is confidential information. Any thermal dilatation will disable the grinding tool [METZ86, p. 63]. Table 5.3 shows the basic mechanisms that connect the abrasive layer to wheel bodies of different materials. After combining abrasive layer and wheel body, the abrasive layer is post-processed by profiling, sharpening, and balancing for wheels of a diameter larger than 150 mm [METZ86, p. 63]. The centrifugal forces lead to radial and tangential stresses in the connection zone [HELL05b]. The Young's modulus can be changed at a constant density through different bonding systems (resin or vitrified bond) [HELL05b].

5.1.3 Layout and Reinforcements of Cut-off Wheels

Cut-off wheels need to be thin to reduce the removed material in the cut-off operation and to reduce power consumption. Reinforcement is necessary, because the resin bond of cut-off wheels is too brittle and unsafe for side forces. Therefore, cut-off wheels are reinforced with glass fibers, nylon discs, carbon, cotton cloth, linen, wood, silk, materials on aramide basis, or other materials [COLL88, p. 908 f., FRAC10]. In particular, fiberglass reinforcements unleashed great potential of manual and automated cut-off grinding with their introduction in 1952 [TYRO03b].

Fibers can be woven into different weave or interlace types. For example, glass fibers with a thickness of about 5 μm are combined into threads of rovings and then weaved like textile fabrics [TYRO03b]. The type of fiber yarn and of weave affect

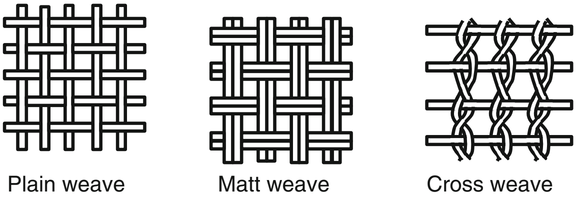

Fig. 5.2 Example weave types for reinforcements after [COLL88, p. 909]

the extension behavior of the reinforcement body [TYRO03b]. The different interlace types have different performance profiles (Fig. 5.2) [COLL88, p. 908]. For example, the plain weave is isotropic and feasible for thin wheels; the matt weave is applied as inner layer of roughing tools and large cut-off wheels; the cross weave does not experience displacements and is applied for roughing wheels and the outer layer of cut-off wheels [COLL88, p. 908 f.].

Reinforcement material is impregnated with resins that have to be similarly adhesive and wetting for both the textile and the grinding layer mixture [COLL88, p. 909]. Then the reinforcement body is put into the mold with the mixture for the abrasive layer and pressed.

During grinding, glass fiber particles can be released and inhaled by the worker. Fiber glass can induce alterations of the cellular and enzymatic components of the deep lung [ABBA06]. Natural fiber cloth such as hemp is an alternative and does not release mineralic particles during wheel use [ESCH05]. Challenges, however, are the lower strength of the natural material, inhomogeneous composition, susceptibility to micro organisms and strong water assimilation. With cleaned and preprocessed hemp fibers, Eschner et al. [ESCH05] successfully produced cut-off wheels.

Joshi et al. [JOSH04] state that the production of natural fiber reinforced resins (NFR) is more environmentally friendly than the production of glass fiber reinforced resins (GFR). Furthermore, natural fibers can be incinerated and might even give energy credit (e.g. the incineration of china reed gives an energy credit of 14 MJ/kg) [JOSH04].

5.2 Clamping and Balancing

5.2.1 Flanges

Cylindrical grinding wheels are often mounted on a hub and clamped between flanges [ROWE09, p. 49]. The adapter flange consists of a fixed flange, a lose flange, and head screws [DIN06]. Standards define the flange design, e.g. BS 4581:1970, and DIN ISO 666 [DIN06]. Some flanges have special features such as a centering section with three lobes in an angle of 120° to ensure a centricity of 2 μm and below [HIME08].

The flanges need to provide friction to accelerate and decelerate the grinding wheel and overcome grinding forces [ROWE09, p. 50]. Four forces act during wheel usage: force of gravity, centrifugal force due to speed and imbalances, contact force between workpiece and tool, and lateral force at the median clamping diameter resulting from the tangential cutting force [DIN06]. The minimum clamping force needs to counter slipping of the grinding wheel; the maximum clamping force is defined by the strength of the grinding wheel material and the stiffness of the clamping device [VOLK72]. Volkmann [VOLK72] calculated appropriate clamping forces and justified the theoretical anaysis with a friction test. The clamping force for industrial applications can be calculated from guidance values in [DIN06].

An interim layer between the flanges and the conventional wheel prevents local stresses on the abrasive structure [ROWE09, p. 49]. The interim layer can be a ring and has to be made of a flexible material that has to match the application requirements, e.g. paper [DIN07]. As example, the material has to be water resistant if the grinding operation is conducted with an emulsion [DIN07].

5.2.2 *Balancing Methods*

Imbalances in rotating grinding tools can be static or dynamic and are caused by excentricity, form errors, or structure errors (Fig. 5.3). Imbalance, *U*, is defined as the product of the mass, *m*, that is out of symmetry and the excentricity, *e*, towards the rotational axis (Eq. 5.7) [KLOC09, p. 284, DIN05]. Standards, such as DIN EN ISO 6103 define the tolerable imbalance for conventional grinding wheels depending on their application [DIN05]. Large masses can lead to spindle bearing damages [MPM12].

$$\text{Imbalance U} = \text{m} \cdot \text{e} \tag{5.7}$$

The form induced imbalances such as excentricity or tool shape errors can be eliminated by the conditioning process [KLOC09, p. 282]. Non-dressable tools such as electroplated, superabrasive grinding wheels are manufactured with a high precision, so that the abrasive layer generally is aligned to the core hole to 1 μm cylinder running [KLOC09, p. 282 f.]. Imbalances due to structural inhomogeneities or form induced errors are minimized by additional tool balancing [KLOC09, p. 283].

Most balancing systems work as static systems, i.e. in only one plane. Dynamic balancing happens in two planes and is mostly important for wide grinding wheels such as centerless grinding wheels [KLOC09, p. 283, WECK05, p. 245]. Imbalances result in vibrations, which are commonly detected by piezo sensors and oscillators.

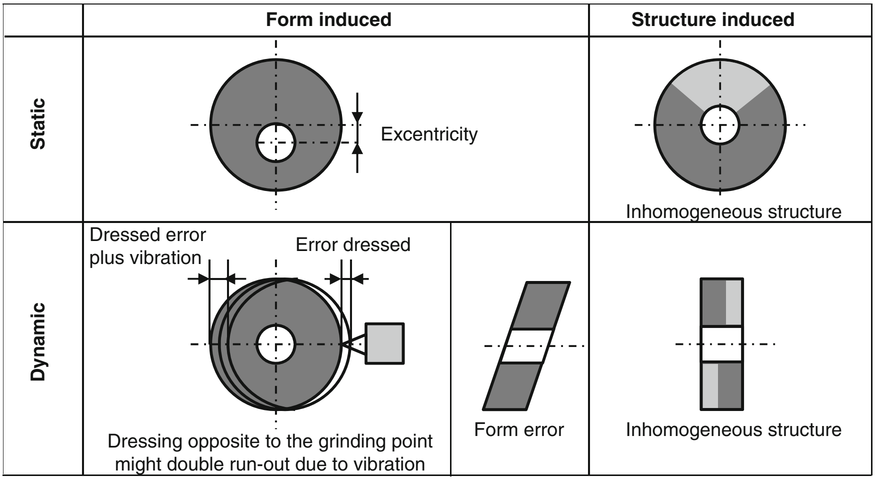

Fig. 5.3 Example causes of imbalances after [KLOC09, p. 283, MARI04, p. 347]

5.2.2.1 Balancing of Stationary Wheels

Stationary wheels can be balanced with one or more counter-weights, whose positions are determined when the grinding tool hangs freely on a cylinder rod through its inner hole [DIN05, KLOC09, p. 284]. Wheels with flanges have a notch on the circumference to hold two or three sliding blocks [WECK05, p. 245 f.].

5.2.2.2 Balancing of Rotating Wheels Outside of the Machine Tool

Tool grinding wheels are often balanced on their exchangeable spindle outside of the machine tool. Higher process stability, higher workpiece surface quality, and longer grinding wheel life are advantages of grinding tool balancing [MPM12]. A balancing device can detect imbalance mass and angular position.

5.2.2.3 Balancing of Rotating Wheels in the Tool Spindle by Hydro Compensators

Hydro compensators use the cooling lubricant present in the machine tool. These balancing devices have several compensation chambers around the grinding wheel axis either inside the tool spindle or as balancing container on the front face of the spindle [KLOC09, p. 285]. The chambers are filled with the cooling lubricant in opposing direction to compensate the detected imbalance [KLOC09, p. 285]. One disadvantage is that the system has to be reset when one chamber has been filled completely.

5.2.2.4 Balancing of Rotating Wheels in the Tool Spindle by Automatic Balancing Systems

Weights are moved electromechanically inside the balancing system to compensate for the original imbalance. The balancing systems can be mounted on the tool flange or inside the tool spindle [MPM12]. The position of the two masses inside the balancing system results in one angle between the masses and another angle between resulting force and tool spindle [WECK05, p. 247].

5.3 Tool Qualification

Wheel specification includes abrasive grit type, mean grit size or mesh size, bond type, structure, and effective hardness (see Sect. 6.1 "Abrasive Layer Composition"). However, the wheel specification does not give information about the topography of the abrasive tool [MARI04, p. 349]. Furthermore, the tool specification is only a rough guideline for the tool users [KLOM86, p. 14]. Unfortunately, often grinding tool specification and process results correlate only poorly. Grinding tools of different manufacturers perform differently despite similar specification, or even tools from one manufacturer from different charges [KLOM86, p. 11]. Several attempts to correlate the mechanical tool characteristics with technological performance characteristics rarely found significant correlations [KUEN98].

The properties of grinding tools show fluctuations, which may have unpredictable impacts on the grinding process. Therefore, quality control for grinding wheels is important [KLOM86, p. 11]. Fluctuations in the characteristics of grinding wheels can result in process instability and varying results. Testing the characteristics and quality of abrasive tools helps to predict process deviations [KLOC05c]. Companies apply abrasive tool testings to evaluate constant quality of self-produced products or to release newly or further developed products to market [STRA75].

Methods for tool qualification should be user-independent. Testing can be time and material intensive, in particular for testing of diamond tools [STRA75]. Consequently, tool testings have to be rigorously supported by statistical methods, not only to reduce costs but also to ensure reliability of the results [STRA75]. However, many methods are not user-independent or applicable to superabrasives because of destructive testing. Detailed material analysis of the grinding layer gives reliable information about tool performance, but is destructive and time intensive [KLOM86, LINE92].

5.3.1 Tool Hardness and Tool Elasticity

Important mechanical characteristics are tool hardness, density, and elasticity [KUEN98]. The mechanical properties of grinding tools result from their inhomogeneous structure [QUIR80, p. 6].

Grinding tool hardness is defined as resistance of abrasives to be pulled out, so hardness is a property of the whole tool not single components [DECN70]. Tool hardness is proportional to the pull-out force [TYRO03]. Tool hardness results from the relative bond volume, the breakage strength of the bond bridges, and the retention strength of the grits within the bond [TYRO03].

A grade letter represents the hardness of an abrasive tool in the tool specification (Table 4.2). Hardness is defined in terms of bond resistance against grit pull-out due to grinding forces. Ideally, the abrasive grits are pulled out as soon as they reach a certain degree of dullness, but not sooner.

5.3.1.1 Hardness Testing with Penetration Methods

Opitz and Rumbach [OPIT42] give an overview on a multitude of hardness test methods. An easy, but subjective method is to break out grits with a hand chisel. The user will relate the breakout resistance to the wheel hardness based on his or her experience [OPIT42]. This method can be improved by measuring the applied force with a spring. During the so called "Winterling" method, a rotating blade under load gives a penetration depth that relates to wheel hardness [RAMM74].

The first sand blasting test worked with blasting of sand during a defined time (e.g. 2 min) to the grinding wheel. The weight loss of the wheel indicates the wheel hardness, but the test cannot be performed more than one time per tool [KLOC05a]. The sand blasting test method invented by Mackensen is applied on a Zeiss apparatus and known as Zeiss-Mackensen method. Here a defined volume of sand (e.g. 20 cm^3) is blasted by compressed air onto the grinding wheel [OPIT42]. The depth of the generated crater relates to wheel hardness and grit breakage behavior [OPIT42]. Disadvantages of this method are potential damage to the abrasive layer, deviating results for soft and coarse-grained grinding wheels, and the necessity to assume a homogeneous body [KLOC05a].

5.3.1.2 Hardness Testing by Grit Breakout Test or Scratch Test

Merbecks developed the grit breakout test and scratch test following ideas from Opitz and Peklenik [MERB03, PEKL60]. These tests are well applicable to superabrasive grinding tools as they do not damage the abrasive layer, leave holes, or measure the whole body elasticity [KLOC05c, MERB03]. In the single grit breakout test, a cemented carbide tip is fed in a defined angle towards a single grit on the wheel surface. In the grinding wheel scratch test, the carbide tip is fed along the grinding wheel surface at a certain depth and with a defined scratch rate. Its depth of should be one third of the smallest grit size tested, e.g. depth of 30 μm for a B91 CBN grit. The breakage phenomena are monitored by video, force measurement, and/or acoustic emission measurement. Grit breakage, grit pullout, and bond breakage are the three breakage phenomena. The grinding wheel hardness is characterized by the proportion of these wear mechanisms.

As example, higher bond hardness results in an increased portion of grit breakage as consequence of the stronger bond bridges and stronger grit embedding [KLOC05c]. Larger grit sizes at a constant scratch depth results in higher proportion of grit pull-out due the larger lever arm and resulting momentum on the grits [KLOC05c]. Linke used the test method to understand the wear behavior of vitrified bonded grinding tools after dressing [LINK07].

5.3.1.3 Elasticity Testing by Bending Tests

The static properties of a grinding wheel can be tested by compression, tensile or bending tests, in which the deformation of tool samples in the form of cylinders or rods is measured [QUIR80, p. 6]. Industrial practice is the three-point bending test, for example after DIN EN 993-7 [MERB03, p. 25, BOTS05, p. 88]. The bending strength is appropriate to assess the quality of brittle materials. Decneut et al. [DECN70] found a direct correlation between the Young's modulus measured by bending tests and by grindo-sonic tests.

5.3.1.4 Elasticity Testing with the Grindo-Sonic Method

There is a direct correlation between Young's modulus and hardness of the grinding wheel [DECN70, KLOC05a, RAMM74]. However, the Young's modulus of the abrasive layer cannot be calculated from a given volumetric proportion and Young's moduli of each component [RAMM74]. Therefore, the Grindo-Sonic method is used to determine the Young's modulus of grinding wheels from the tool`s natural frequency (Eq. 5.8) [KLOC05a]. The Grindo-Sonic equipment measures the natural frequency of a wheel body that is positioned on three tips. The support defines the natural vibration mode. The Grindo-Sonic method can be also used for mounted points [KLOC05a].

$$\text{Natural frequency } f = F(a, \mu) \cdot C_I = F(a, \mu) \cdot \sqrt{\frac{E}{\rho}} \tag{5.8}$$

$F(a, \mu)$	form coefficient depending on body dimensions, body form and μ
μ	Poisson's ratio

C_I velocity of propagation of the longitudinal elasticity oscillation
ρ density
E Young's modulus

Cracks change the natural frequency of grinding tools and can therefore be detected via Grindo-Sonic methods [RAMM74].

5.3.1.5 Further Analyses

Ceramographic material analysis helps to understand and qualify the grinding wheel structure by picture analysis [KLOM86, LINE92]. However, samples from the abrasive layer have to be cut and prepared by embedding and polishing. Additional element analyses unveil material composition and chemical reactions during the tool production process [LINE92, p. 39 f.]. Back pressure is a pneumatic measurement method which allows to define the smallest cross-section of a flow channel [LINE92, p. 74]. In the case of an abrasive layer, the back pressure difference indicates porosity and grit distance [LINE92, p. 74 f.].

5.3.1.6 Conclusion on Hardness and Elasticity Tests

Today, the Zeiss-Mackensen and Grindo-Sonic test methods are industrial practice for qualifying conventional grinding tools [KLOC05c]. However, they are not applicable for superabrasive tools (Table 5.4).

Rammerstorfer and Hastik [RAMM74] state that the hardness definition via E-Modulus is more reliable than via penetration methods. Künanz et al. [KUEN98] critize that Young's modulus and sand blasting depth show no technological useful relation to the grinding ratio, i.e. the ratio between removed workpiece volume and worn grinding tool volume.

Table 5.4 Comparison of different tool qualification methods after [MERB03]

Method	Non-destroying method?	User-independent?	Reproducible results?	Applicable for superabrasive tools	Applicable for conventional tools
Zeiss-Mackensen (Sand blasting)	−	o	+	−	++
Grindo-Sonic	++	o	+	−	++
Bending strength	−	++	−	−	++
Single grit breakout test [PEKL60]	+	o		++	++
Material analysis [KLOM86, LINE92]	−	o	+	++	++

5.3.2 Tool Breakage

A robust, untroubled grinding process needs safety parameters for tool production [KLOM86, p. 11]. Tool breakage might be caused by wrong tool design, manufacturing defects, inappropriate choice, faulty handling or storage, improper use, and clamping, etc. [DIN11].

Several organizations define safety measures for grinding wheel use, such as Berufsgenossenschaft or OSHA (Occupational Safety and Health Administration). Different standards exist on tool safety (DIN EN 12413 for conventional grinding wheels, DIN EN 13236 for superabrasive grinding wheels, DIN EN 13743 for coated grinding tools, BVG D12, BGI 543, ANSI B7.1) [DIN07, DIN11].

The bursting speed of grinding tools needs to be larger than the maximum wheel speed. The standard DIN EN 13236 defines safety factors against breakage due to centrifugal forces (Eq. 5.9) [DIN11]. For example, in open grinding machines the grinding wheel speeds need to be 80 m/s or lower and the safety factor is 3.0; in housed grinding machines with safety guards wheel speeds can be up to 320 m/s and the safety factor is 1.75 [DIN11]. For manual grinding tools, safety factors of 3.5 at 80 m/s and 3.0 at 63 m/s and below apply [DIN11].

$$\text{Safety factor } S = \left(\frac{v_{br}}{v_s}\right)^2 \tag{5.9}$$

v_{br} bursting speed
v_s maximum grinding wheel speed

Vitrified bonded grinding tools with a diameter larger than 80 mm have to be tested with a ring test [DIN07]. Here the grinding tool is tapped with a non-metallic item and the tone has to be well-defined, not hollow or rattling like at a broken grinding tool [DIN07]. Spin burst tests and tests with bombardment of a retard plate give the burst energy of grinding wheels [KÖNI70] Langbein made burst tests with high-speed cameras [EVER06, p. 391, LANG76]. External cylindrical grinding has the highest safety danger [EVER06, p. 391, LANG76].

Malkin and Guo [MALK08, p. 38 f.] show how the bursting speed increases with wheel hardness and decreases with grit size. Münnich estimated the bursting speed of grinding wheels [MÜNN56, BEHR07]. However, measured bursting speeds and speeds calculated with Münnich's approach deviate up to 20 % [MÜNN56, BEHR07]. Behrens and Kammler derived a new equation based on FEA analysis, which can be used for one-sided recessed grinding wheels [BEHR07].

The guard material has to absorb the energy of broken tool pieces. Safety guards designed with pipes, pipes with intermediate metal sheets or foamed plastic covers with metal sheets provided good results [KÖNI70].

5.4 Sustainability Dimensions to the Grinding Wheel Macro Design

5.4.1 Technological Dimension

For bonded superabrasive tools, bodies of steel, aluminium, resin and resin-aluminium are common. New body designs with carbon fiber reinforced resin enable even higher circumferential speeds over 200 m/s. The productivity seems to be improved and consumed spindle power decreased.

Abrasive layers can be fixed with adhesives as segments. Glue type and tool preparation steps, e.g. degreasing, are crucial for adhesive quality.

Tool macro-design depends on process kinematics and the desired workpiece shape. Furthermore, the effective wheel width defines overall grinding power or surface quality in the case of traverse grinding processes. For example, cup wheels with a higher layer width can achieve significantly lower workpiece roughness than cup wheels with a small layer width due to the higher number of passes [JUCH78].

5.4.2 Economic Dimension

The scale of abrasive tool production and the scale of the individual tool components both are interesting for the product price, possible automation, and near-net-shape manufacturing. Superabrasive grinding tools, for example, are near-net-shape products whereas conventional tools have to be machined after the hardening/sintering process to achieve appropriate concentricity, evenness of the faces and desired profile. This leads to additional waste during shaping, auxiliary time, energy, etc.

5.4.3 Environmental Dimension

The different body materials affect the tool manufacturing chain and energy demands in tool use. Grinding tool bodies can be re-used or recycled. In particular, the following options for recycling exist:

- Bodies from steel, aluminum, or bronze can be easily recycled as metal scrap.
- Aluminum resin bodies, however, are disposed as landfill today. Since these bodies are built-into mass produced cup wheels for tool grinding, a considerable amount of material is produced.
- Bakelite bodies might be incinerated to produce heat energy or they are landfilled.

- Bodies with glass fiber reinforcements are not recyclable and have to be landfilled.
- Carbon fiber reinforced resin bodies, in contrast, can be incinerated.
- In the future, renewable fibers (e.g. hemp) in cut-off wheels might give advantages in production, emissions, and disposal.

Re-use of tool bodies accounts for only a very small percentage of the total number of these tools. Exceptions are special tools, e.g. saw blades for stone cutting. These saw blades consist of soldered or welded segments with diamond grits. The single segments can be removed mechanically and the tool body might be re-used if wear and residual stress condition allows. Re-use of these tool bodies is therefore realistically limited.

5.4.4 Social Dimension

Grinding machines need to be equipped with safety features. In particular, wheel bursting and flying wheel parts are dangerous to workers. The safety guards around the grinding wheel are designed according to the maximum allowed wheel speed and the specific bursting energies.

Above a circumferential speed of 20 m/s, bursting grinding tools are potentially harmful to machinist and machine tool [MARI07, ROWE09]. Therefore, appropriate machine encapsulation is necessary. Tool clamping needs to follow safety rules so that the tools do get loose during use. Housing is also necessary if the coolant mist and emissions should be exhausted. In particular, the dangers of manual grinding are often underestimated and accidents with manual tools account for 2/3 of accidents with grinding machines [BGI10]. In addition, vibrations from manual tools can lead to long-term damage [DIN07]. In manual grinding operations vibrations can move from the tool to the operator's hand and arm. Vibrations from hand-held grinding tools can cause permanent health effects, such as hand-arm vibration syndrome, carpal tunnel syndrome, neurological problems, and musculoskeletal disease [WILL11].

5.4.5 Sustainability Model for Grinding Wheel Macro-design

Grinding wheel design follows technological, economic, environmental and social considerations. The tool manufacturer is mainly concerned about

- **Safety** during tool use. Tools must not burst at the high rotational speeds during grinding.

Tool users care about this and additional aspects:

- **Safety** during grinding wheel use has to be ensured through wheel design, but the **grinding machine tool** has to be equipped with appropriate safety guards against tool breakage.
- The **maximum cutting speed** of the tool results from tool and body design and affects the tool performance significantly. The cutting speed defines the maximum material removal rate and therefore productivity.

Grinding tool components, also components of superabrasive tools, are rarely re-used today. This is due to economic and technological reasons as explained above. Nevertheless, it will become important to review current practices in the future. This chapter described and analyzed qualitatively capabilities and environmental impacts of grinding tool components at the end of life.