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CUTTING TOOLS.
GRINDING

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The objective of this handbook is to provide a student understanding of grinding and finishing processes applied to metallic workpieces. The mechanics of chip formation, temperature generation, tribology and interactions between workpiece material and the single abrasive particle are described. The selection of grinding wheels, dressing wheels and process parameters are considered.

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INTRODUCTION

Grinding and other finishing processes are fast becoming the standard choice of machining, especially in the rapidly growing areas of automotive and aerospace industrial sectors. This handbook provides theoretical and practical data for the selection of grinding operations and includes a guide on the selection of grinding wheels, dressing wheels and process parameters.

1. GRINDING PROCESS

Grinding is a metal removal process that employs an abrasive **grinding wheels** whose cutting elements are grains of abrasive materials of high hardness and high refractoriness. Grinding is generally among the final operations performed on manufactured products. It is not necessarily confined to small-scale material removal; it is also used for large-scale material removal operations and specifically compete economically in this domain with some machining processes such as milling and turning. The development of abrasive materials and better fundamental understanding of the abrasive machining have contributed in placing grinding among the most important basic machining processes.

Abrasive processes are important commercially and technologically for the following reasons [1]:

1. They can be used on all types of materials ranging from soft metals to hardened steels and hard nonmetallic materials such as ceramics and silicon.
2. Some of these processes can produce extremely fine surface finishes, to 0.025 mm.
3. For certain abrasive processes, dimensions can be held to extremely close tolerances.

Grinding can be likened to the milling process. Cutting occurs on either the periphery or the face of the grinding wheel, similar to peripheral and face milling. Peripheral grinding is much more common than face grinding. The rotating grinding wheel consists of many cutting teeth (the abrasive particles), and the work is fed relative to the wheel to accomplish material removal.

Despite these similarities, there are significant differences between grinding and milling:

1) the abrasive grains in the wheel are much smaller and more numerous than the teeth on a milling cutter;

2) cutting speeds in grinding are much higher than in milling;

3) the abrasive grits in a grinding wheel are randomly oriented and possess on average a very high negative rake angle;

4) a grinding wheel is self-sharpening – as the wheel wears, the abrasive particles become dull and either fracture to create fresh cutting edges or are pulled out of the surface of the wheel to expose new grains.

When the single cutting edges penetrate tangentially e. g., during grinding, the process generally resembles cutting with a geometrically defined cutting edge. In principal, the same separating mechanisms occur during the processes of both groups (fig. 1) [2]. In grinding, however, the cutting edges are formed by hard material abrasive particles at which one abrasive particle can have several active cutting edges. In general, the dimensions of the elements involved are considerably smaller than in cutting with geometrically defined cutting edges. Cutting with bond abrasive particles generally occurs with a strongly negative cutting angle. When cutting with rotating tools, the paths of the cutting edges correspond to epicycloids (by means of cutting and feed motions).

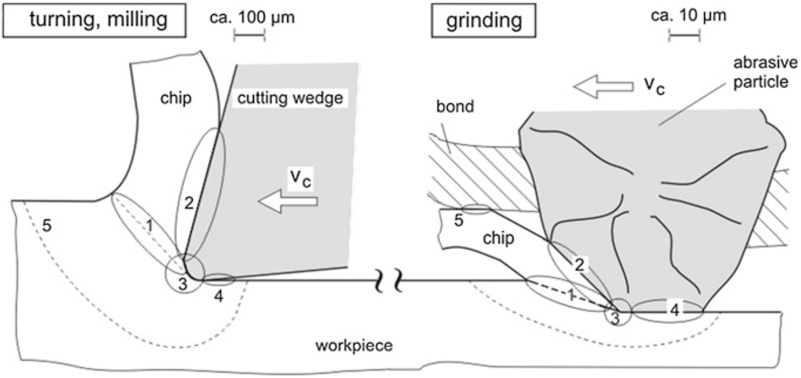


Fig. 1. Chip formation [2]:
1 – primary shearing zone; *2* – secondary shearing zone at the rake face; *3* – secondary shearing zone at the stangnant and seperation zone; *4* – secondary shearing zone at the flank; *5* – advancing deformation zone

The cutting thicknesses during grinding are so small that elastic shares in the deformation are not to be disregarded. Fig. 2 illustrates the different phases in chip formation.

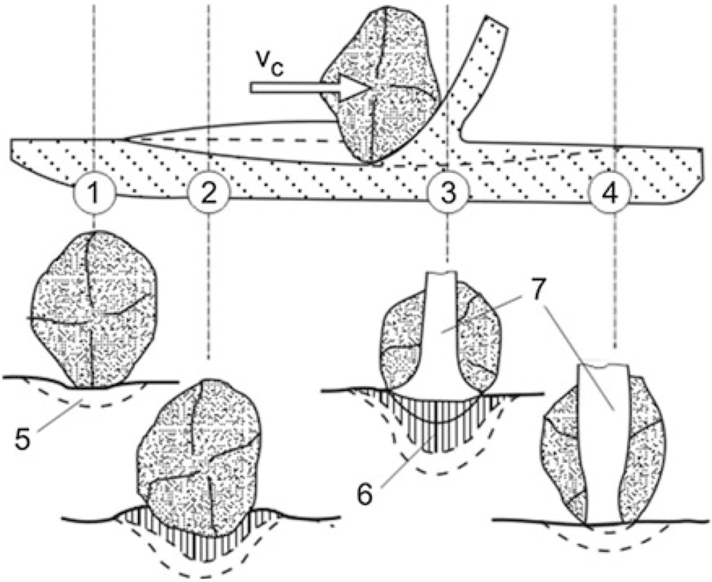


Fig. 2. Phases of chip formation during grinding [2]:
1 – elastic deformation; *2* – elastic-plastic deformation; *3* – elastic-plastic deformation (ploughing) and shearing of the chip; *4* – elastic deformation and shearing of the chip; *5* – zone of elastic deformation; *6* – zone of plastic deformation; *7* – chip

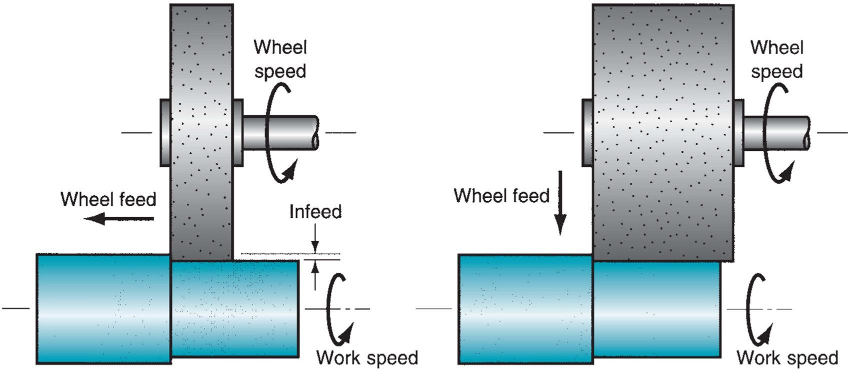
During the cutting edge penetration, after a purely elastic deformation *1*, the plastic flow of the material occurs *2*. The actual chip formation takes place after penetration of the cutting edge into the material *3*. Apart from the shearing of the chip *4*, this area is characterised by elastic as well as plastic deformations. Compared with this, immediately before the abrasive particle leaves the material, there are only elastic deformations and the shearing of the chip *4*.

Despite the similarity between grinding and the processes of cutting with geometrically defined cutting edges, several basic differences do exist: in grinding, lateral material flow occurs in front of the cutting edge, the deformation status is triaxial in contrast to a mainly biaxial flow in cutting with a geometrically defined cutting edge [2].

2. TYPES OF GRINDING OPERATIONS

The basic types of grinding operations are as follows [3]:

1. **Traverse external cylindrical grinding** (refer to fig. 3, *a*). Work-piece and grinding wheel are rotating about parallel axes. The diameter of the wheel d_{wh} is much larger than the diameter of the workpiece d_w. The wheel (or workpice) is fed at the longitudinal feed (mm/rev) along the axis of the workpiece. The feed value is set as a fraction of the grinding wheel width B. The peripheral speed V_{wh} (m/s) of the grinding wheel is much higher than the peripheral speed of the workpiece V_w (m/min). The width t (mm) of the stock that is being removed depends on the infeed value F_{cr} (mm/double stroke). In **plunge grinding** (fig. 3, *b*) the traverse feed is not active and the grinding wheel has only infeed (mm/rev).



a *b*

Fig. 3. External cylindrical grinding:
a – traverse; *b* – plunge

2. In **internal cylindrical grinding** (fig. 4), the workpiece and grinding wheel are rotating about parallel axes, as in external grinding, but the diameter of the grinding wheel is smaller than the hole diameter. Traverse feed is specified the same way as for external grinding. Internal grinding can be performed as the plunge

grinding with infeed. Grinding machines are equipped with a special drive for high rotational speeds of the grinding wheel in internal grinding.

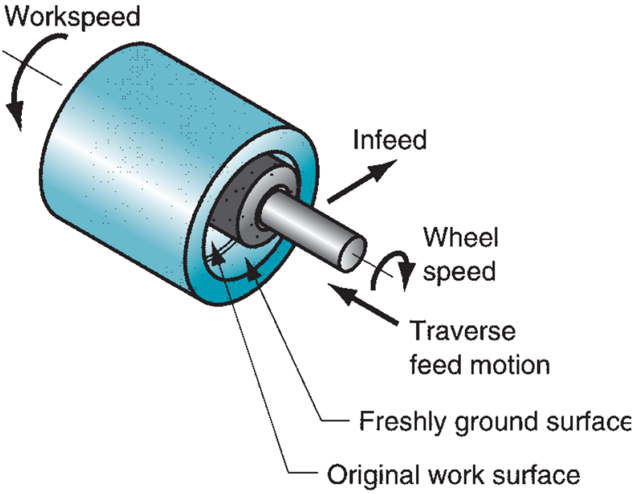
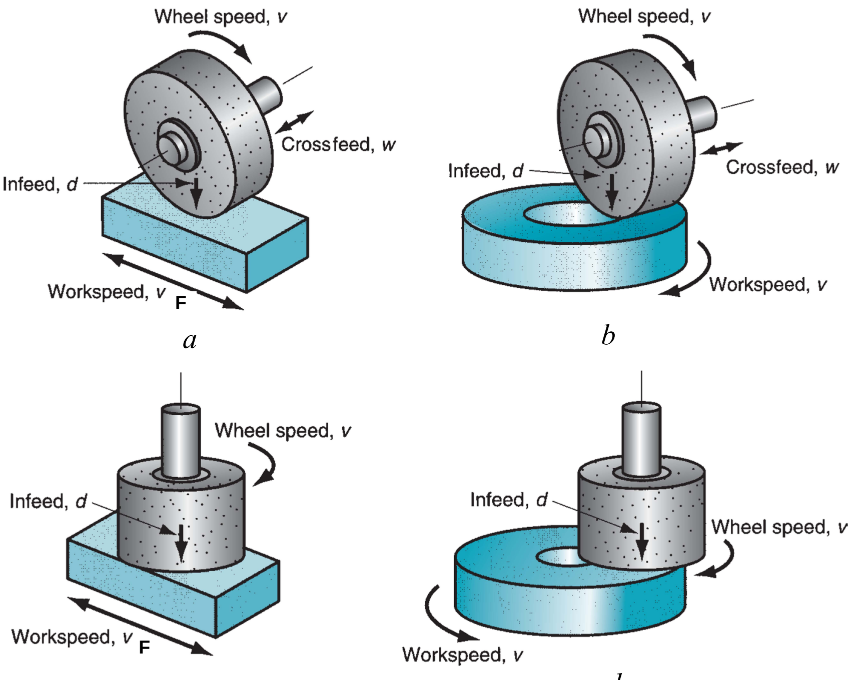


Fig. 4. Internal cylindrical grinding

3. **Surface grinding** is used to produce flat surfaces. The kinematics of this process is similar to a milling operation kinematics. Two types of surface grinding are commonly used. Depending on the position of the grinding wheel axis relative to the workpiece surface, the grinding can be performed by the periphery of the grinding wheel (fig. 5, *a, b*) or by the face of the grinding wheel (fig. 5, *c*, *d*). The linear reciprocating motion of the workpiece $\boldsymbol{F}_{work}$ (m/min) is usually executed by the magnetic table of the surface grinding machine, on which the workpiece is fixed. In case of a surface grinding machine equipped with a round table rotating at the speed $\boldsymbol{V}_{work}$, a few workpieces can be clamped for continuous grinding (fig. 5, *b, d*). Owing to the relatively large surface contact area between wheel and workpart, vertical spindle-rotary table grinding machines are capable of high metal removal rates when equipped with appropriate grinding wheels.



a *b* *c* *d*

Fig. 5. Surface grinding:
a – horizontal spindle with reciprocating worktable; *b* – horizontal spindle with rotating worktable; *c* – vertical spindle with reciprocating worktable; *d* – vertical spindle with rotating worktable

4. **Centerless grinding** is an alternative process for grinding external and internal cylindrical surfaces. As its name suggests, the workpiece is not held between centers. This results in a reduction in work handling time; hence, centerless grinding is often used for high-production work. The setup for external centerless grinding (fig. 6), consists of two wheels: the grinding wheel and a regulating wheel. The workparts, which may be many individual short pieces or long rods (e. g., 3 to 4 m long), are supported by a rest blade and fed through between the two wheels. The grinding wheel does the cutting, rotating at surface speeds of 20 to 30 m/s. The

regulating wheel rotates at much lower speeds and is inclined at a slight angle to control throughfeed of the work.

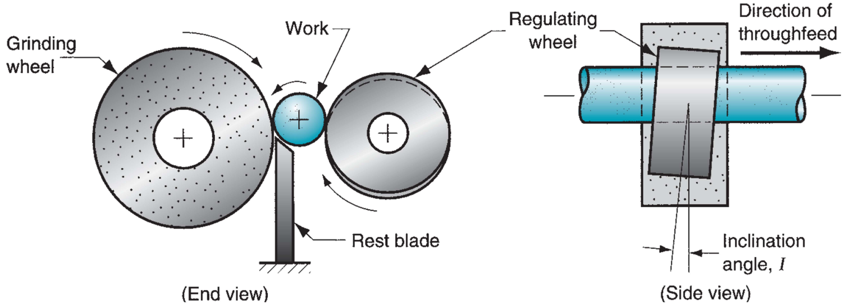


Fig. 6. External centerless grinding

3. THE CUTTING CONDITIONS IN GRINDING

The cutting conditions in grinding are characterized by very high speeds and very small cut size, compared to milling and other traditional machining operations. Using surface grinding to illustrate, fig. 7, *a* shows the principal features of the process [3].

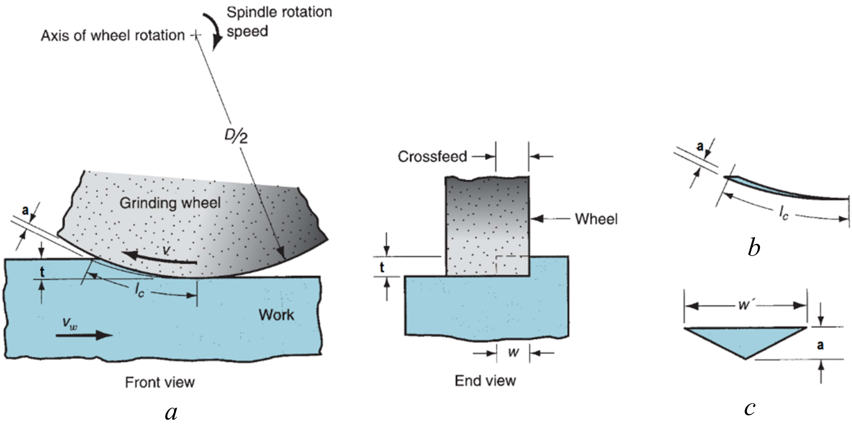


Fig. 7. Cutting conditions in grinding:
a – the geometry of conventional surface grinding; *b* – assumed longitudinal shape; *c* – cross section of a single chip

The peripheral speed of the grinding wheel is determined by the **rotational speed of the wheel**:

$$V = \frac{\pi DN}{1000 \cdot 60},$$

where V – surface speed of wheel, m/s; N – spindle speed, rev/min; and D – wheel diameter, mm.

Depth of cut *t*, called the **infeed**, is the penetration of the wheel below the original work surface. As the operation proceeds, the grinding wheel is fed laterally across the surface on each pass by the work. This is called the **crossfeed**, and it determines the width of the grinding path ***w*** in fig. 7, *a*. This width, multiplied by depth ***t***

determines the cross-sectional area of the cut. In most grinding operations, the work moves past the wheel at a certain speed $\boldsymbol{V_w}$.

Each grain in the grinding wheel cuts an individual chip whose longitudinal shape before cutting is shown in fig. 7, *b* and whose assumed cross-sectional shape is triangular, as in fig. 7, *c*. At the exit point of the grit from the work, where the chip cross section is largest, this triangle has height $\boldsymbol{a}$ and width $\boldsymbol{w'}$.

A another form of grinding is deep grinding. Deep grinding is performed at very high depths of cut and very low feed rates. The comparison with conventional surface grinding is illustrated in fig. 8.

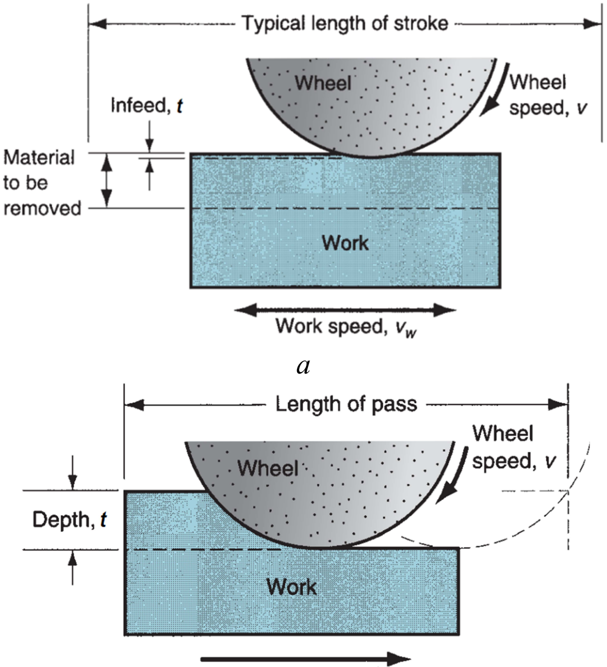


Fig. 8. Comparison of grinding type:
a – conventional surface grindin; *b* – deep grinding

Depths of cut in deep grinding are 1000 to 10 000 times greater than in conventional surface grinding, and the feed rates are reduced by about the same proportion. However, material removal rate and productivity are increased in deep grinding because the wheel is continuously cutting. This contrasts with conventional surface grinding in which the reciprocating motion of the work results in significant lost time during each stroke.

Deep grinding can be applied in both surface grinding and external cylindrical grinding. Surface grinding applications include grinding of slots and profiles. The process seems especially suited to those cases in which depth-to-width ratios are relatively large. The cylindrical applications include threads, formed gear shapes, and other cylindrical components.

In a both grinding operations, we are interested in how the cutting conditions combine with the grinding wheel parameters to affect:

1) surface finish;
2) forces and energy;
3) temperature of the work surface;
4) wheel wear.

Cutting parameters for grinding are selected in the following order:

1. Depending on the grinding process conditions, required accuracy and surface finish the characteristics of a grinding wheel, such as size, shape, grain size, bond and etc. are selected.
2. The depth of cut, infeed, traverse feed and speed of workpiece rotation are selected.
3. The cutting speed, which relates to the wheel peripheral speed, is assigned in m/s. Here, the influence of the wheel speed on surface finish, accuracy, grain load is taken into account. The wheel speed shouldn't exceed the maximum permissible speed, which is labeled on the wheel. So, for example, the maximum permissible speed for vitrified aluminum oxide wheels is equal to 20–35 m/s, for high-speed grinding wheels it is 40 m/s, and for the cut-off wheels with rubber bond it is equal to 60 m/s.
4. Then the grinding parameters are corrected in accordance with the grinder kinematics parameters.
5. Then the cutting force components $\boldsymbol{P_z}$ and $\boldsymbol{P_y}$ as well as power consumption are calculated.

4. TEMPERATURES AT THE WORK SURFACE

Because of the size effect, high negative rake angles, and plowing and rubbing of the abrasive grits against the work surface, the grinding process is characterized by high surface temperatures. Unlike conventional machining operations in which most of the heat energy generated in the process is carried off in the chip, much of the energy in grinding remains in the ground surface [1], resulting in high work surface temperatures. The high surface temperatures have several possible damaging effects, primarily surface burns and cracks. The burn marks show themselves as discolorations on the surface caused by oxidation. Grinding burns are often a sign of metallurgical damage immediately beneath the surface. The surface cracks are perpendicular to the wheel speed direction. They indicate an extreme case of thermal damage to the work surface.

A second harmful thermal effect is softening of the work surface. Many grinding operations are carried out on parts that have been heat-treated to obtain high hardness. High grinding temperatures can cause the surface to lose some of its hardness. Third, thermal effects in grinding can cause residual stresses in the work surface, possibly decreasing the fatigue strength of the part.

By calculations and experiments it was found that, depending on the grinding parameters the 60–80 % of the heat goes to the workpiece, 1–30 % – to the chips, and 10–13 % – to the grinding wheel.

The types of temperature found in grinding are as follows: 1) instantaneous temperature, formed immediately in the microcutting area, this one is high and short-duration; 2) contact temperature, found in the workpiece-wheel interface; 3) average temperature, found on the ground surface of the workpiece [4].

Experimentally measure the **instantaneous temperature** at high cutting speeds is rather difficult. However, it can be determined by indirect means, for example, by structural transformations in thin surface layers of the ground surface. In grinding very hard materials (such as hardened steels) the instantaneous temperature is in the range from 1000 ^{o}C to the melting point of the material. This is demonstrated by the flow of sparks flying out of the cutting area, even with abundant cooling.

Contact temperature is much lower than instantaneous temperature (especially when using a water-based emulsion) due to the intense heat removal from the wheel-workpiece interface to the workpiece, which usually has large mass compared to a very small volume of the heated layer. Contact temperature affects the residual stresses value and determines the probability of burn marks on the surface layers of the workpiece. Depending on the grinding conditions and thermal conductivity of the workpiece material the contact temperature is in the range of 200–1000 ^{o}C.

Average temperature of the workpiece varies between 20–350 ^{o}C and influences on accuracy, as it causes thermal deformations of the workpiece.

5. GRINDING WHEELS

A grinding wheel consists of abrasive particles and bonding material. The bonding material holds the particles in place and establishes the shape and structure of the wheel. These two ingredients and the way they are fabricated determine the five basic parameters of a grinding wheel:

1) abrasive material;
2) grain size;
3) bonding material;
4) wheel grade;
5) wheel structure.

To achieve the desired performance in a given application, each of the parameters must be carefully selected.

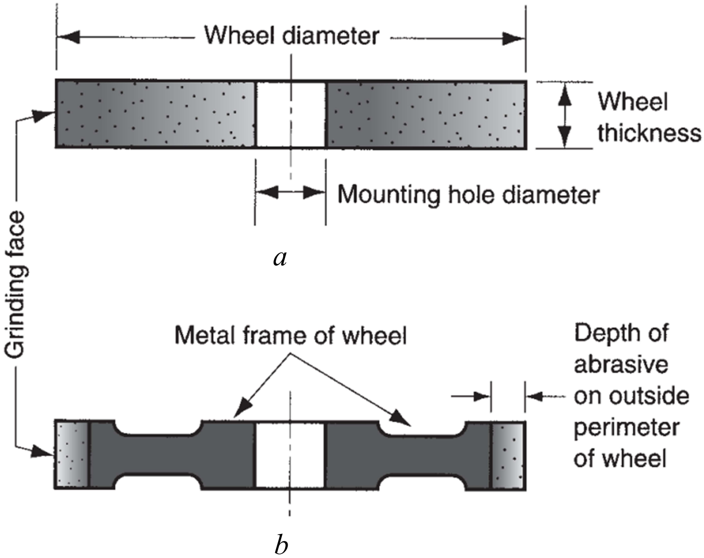
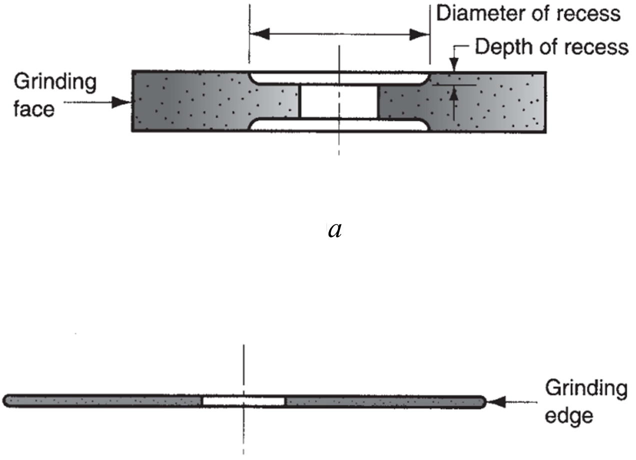


Fig. 9. Some of the standard grinding wheel shapes:
a – straight; *b* – metal wheel frame with abrasive bonded to outside circumference



a

b

Fig. 10. Some of the standard grinding wheel shapes:
a – recessed two sides; *b* – abrasive cutoff wheel

Grinding wheels come in a variety of shapes and sizes, as shown in fig. 9 and 10. Configurations fig. 9 and fig. 10, *a* are peripheral grinding wheels, in which material removal is accomplished by the outside circumference of the wheel. A typical abrasive cutoff wheel is shown in fig. 10, *b*, which also involves peripheral cutting. There are also face grinding wheels, in which the flat face of the wheel removes material from the work surface (fig. 11, *e*, *f*, *g*) [3].

Grinding wheels shapes must permit proper contact between the wheel and the surfaces to be ground. Fig. 11 illustrates eight standard shapes of grinding wheels, whose applications are as follows:

1. Shapes *a*, *c* and *e* are intended for grinding external or internal cylindrical surfaces and for plain surface grinding.
2. Shape *b* is intended for grinding with the periphery or the side of the wheel.
3. Shape *d* is of a safely tapered shape to withstand breakage during snagging.

4. Shape *f* is a straight cup intended for surface grinding.

5. Shape *g* is a flaring cup intended for tool sharpening.

6. Shape *h* is a dish type intended for sharpening cutting tools and saws.

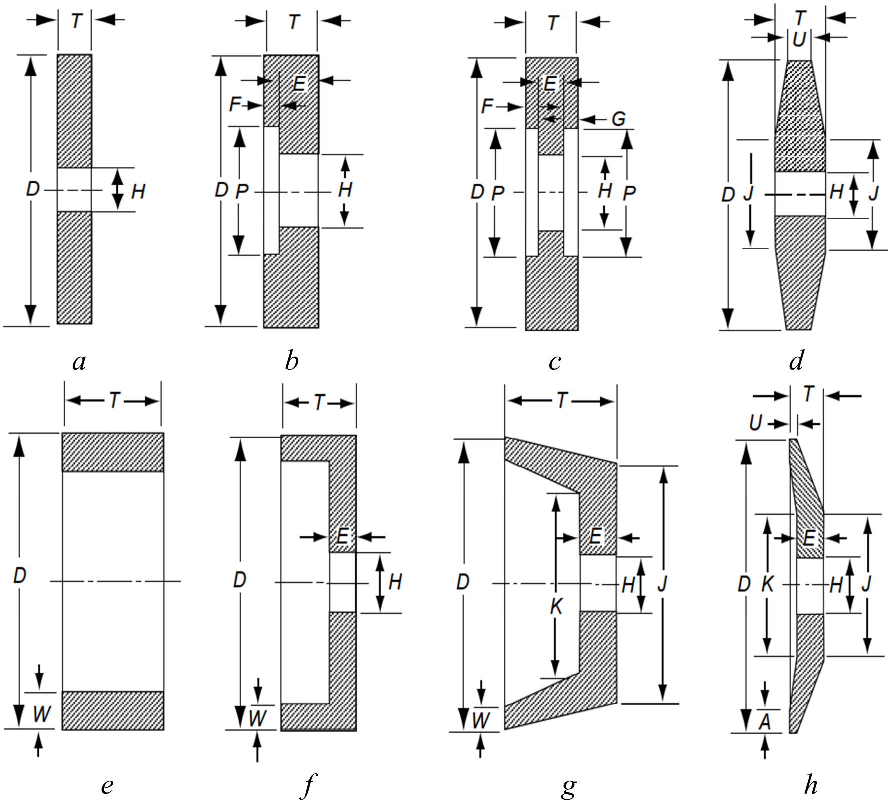


Fig. 11. Standard shapes of grinding wheels:
a – straight; *b* – recessed one side; *c* – recessed two side; *d* – tapered;
e – cylinder; *f* – straight cup; *g* – flaring cup; *h* – dish

6. GRINDING MATERIALS

The usual hard materials for grinding are aluminum oxide, silicon carbide, cubic crystalline boron nitride, and diamond. Nowadays, these hard materials for grinding purposes are exclusively produced synthetically, because that way favourable material properties can be reached within tight limits. The grinding materials differ considerably in their degree of hardness and thus in their wear resistance (fig. 12). However, there are also large differences in the other physical characteristics (tab. 1) [5]. Here, the hardness of diamond has been converted into Knoop resp. Vickers hardness. A direct measurement of diamond hardness is not possible with this process, in fact the hardness is determined indirectly via Young's modulus (E module). Apart from the hardness, the friability of grinding materials is of interest with regard to the wear behaviour.

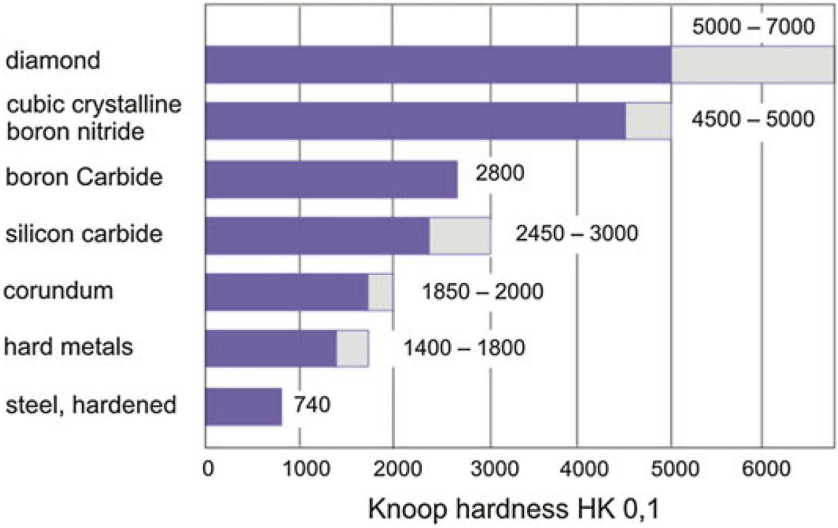


Fig. 12. Hardness of abrasives and other materials

Table 1

Physical properties of different grinding materials [2]

		Al_2O_3	SiC	CBN	Diamond
Density (g/cm^3)		3.96	3.15	3.48	3.52
Hardness	HK01	1850–2000	2450–3000	4500–5000	5000–7000
	HV01	2100	2500	6000	
Young's modulus (GPA)		400	400	680	890
Poisson ratio		0.2	0.17	0.17	0.2[4]
Friction coefficient		0.34	2.300	0.19	0.05–0.15[4]
Melting point (°C)		2,050		2,730	3,700
Temperature stability (°C)		1,750	1,500	1,200	900
Heat expansion coefficient (10^{-6}/K)		7.4(<500 °c) 7.5–8.5 (>500 °c)	4.7	3.6	0.8 (RT)[4] 1.5–4.8 (>500 °C)
Heat conductivity (W/mK)		30 (RT) 14 (400 °C)	110 (RT)[2] 55 (600 °C)	200 (400 °C)[3]	600–2,000 (RT)[4]
Related heat (J/gK)		1.08 (400 °C)	1.1 (500 °C)	1.57 (400 °C)[3]	6.19 (RT)[4]

Corundum is a crystalline aluminum oxide (also called alumina) (Al_2O_3). The mechanical properties are determined by the purity degree to a large extent. We differentiate between regular or brown, white and modified aluminum oxide.

In the production of corundum, bauxite serves as a raw material for all qualities, a mixture of different aluminum oxide hydrates which is polluted with ferric hydroxides, silicates and titanium alloys. In the most frequently used Bayer process, ground bauxite with an Al_2O_3 content of 55–60 % is treated with caustic lye at approx. 250 ^{o}C under a pressure of 4 MPa [2]. The aluminum oxide hydrates dissolve as sodium aluminate, the pollutions are separated as so-called red mud. The sodium aluminate lye is stowed with finely dispersed aluminum hydroxide, which as a crystallisation seed, leads to the growth of $Al(OH)_3$ crystals. The calcination of the aluminum hydroxide in fluidised-bed furnaces at 1200–1300 ^{o}C produces Al_2O_3 (alumina) [2].

Depending on the degree of purity aluminum oxide have a different color, structure and properties. Three basic types are available: normal or general purpose, white and monocrystalline alumina. Depending on their properties and application, these in turn are divided into groups with special markings, for example, general purpose aluminum oxide is indicated as 12A–16A, and white aluminum oxide is indicated as 22A–25A. Here, the higher is the number, the higher is the degree of purity and the higher are the physical and cutting properties.

Monocrystalline alumina or monokorund (43A, 44A, 45A) contains up to 99 % of aluminum oxide crystals and is manufactured by a special process by melting bauxite with iron sulfide and reducing agent. Monokorund grains are freed from sulfides, undergo enrichment and screening. Monokorund has high cutting ability and is used for machining of difficult-to-machine steels and alloys.

Alloyed aluminum oxides: chromium, titanium, zirconium, which have better cutting properties and high durability are used in recent years.

A performance increase of corundum grinding materials can be obtained by altering the structure and shape of the abrasive particles (fig. 13) [2]. During the grinding process, the number of sharp cutting edges per abrasive particles can be increased, thus improving the tool life and the power conversion compared with untreated melted corundum. On the other hand, an increase in wheel porosity at unaltered wheel strength allows an easier removal of the chips from the effective zone. In addition, the feed of cutting fluid to the contact zone is better at an increased wheel porosity.

During the grinding process, suitably distributed abrasive particles may wear to such a degree that extensively sharp cutting edges are generated. This resharpening or self-sharpening process can be obtained by using compact abrasive particles or particles with a micro crystalline structure. The compact abrasive particles consist of a multitude of small grains, which have been clinkered into a large abrasive particle by means of a bond. The process-related wear on each small grain leads to a local increase in the specific grinding force on the worn abrasive particle. When the bonding forces are surpassed, the blunt abrasive particle detaches itself from the compound of the compact abrasive particle and exposes a new sharp abrasive particle located underneath. This type of re-sharpening process of abrasive particles is preferably used for abrasives on backing materials, e. g., belt grinding processes [2].

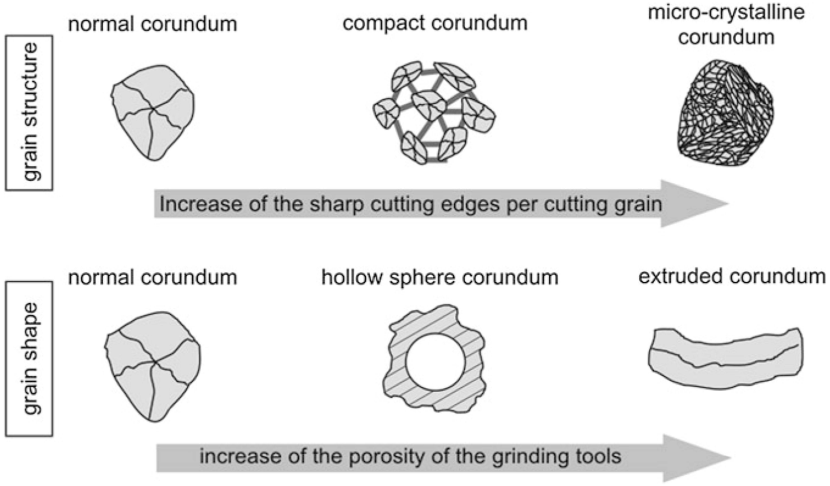


Fig. 13. Possibilities of power increase when using aluminum oxide

Resharpening is also transferable to each single grain by producing micro crystalline Al_2O_3 according to the sol-gel process. At this, grain fracture and thus sharp cutting edges can occur during the grinding process. In contrast with the coarsely crystalline melting corundums, this mechanism leads to a considerably reduced wear with decreased grinding force and temperature at the same time. This results in longer wheel life, longer dressing intervals and allows an increase of the material removal rate. At this, different micro crystalline corundums differ considerably in the height of the initial force required for resharpening [2].

In grinding processes with a high material removal rate, grinding wheels with high pore proportions are applied. The maximum porosity readily accounts for about 50 %. A further increase leads to a lower strength, which limits the maximum cutting speed and increases the wear rate. By inserting hollow ball corundum, a hollow corundum grain, into the grinding wheel structure, the porosity can mount to 60 %. Special machining processes can produce grains with large length/diameter relations (aspect ratio) of up to 8. In comparison, the normal corundum grain has an aspect ratio of 1. An advantage of elongated particles is the extension and improvement of the natural packing porosity of the particles. Grinding wheels with a porosity of up to 80 % can be produced without artificial pore builders [6].

Silicon carbide is one of the important ceramic materials. It is also used as a grinding material. The technical production of SiC takes place according to the Acheson process from quartz sand (SiO_2) and petrol coke at a temperature of 2000–2300 ^{o}C after the stoichiometric reaction.

The colour allows the differentiation of the two qualities of SiC, which are characterised by their chemical composition. Black SiC (98 %) (indicated as 53C, 54C) compared to green SiC (99.5 %) (indicated as 63C, 64C) shows greater pollutions of free carbonate and elements such as Fe, Al, Ca, Mg and free silicon. The pollutions show no influence on the hardness. However, the ductility of black SiC is higher than that of green SiC.

Grinding materials made of **cubic crystalline boron nitride**, also called **Cubic Boron Nitrides (CBN)** and diamond are extremely hard grinding materials, which are summarised under the term "superabrasives" in English language use. The production of CBN is only synthetic, diamond can be differentiated into natural and synthetic. As grinding materials in grinding wheels, exclusively synthetic diamond is used nowadays. CBN has a cubic face centred crystal lattice of nitrogen and boron atoms similar to diamond, which also has a cubic face centred lattice with four additional carbon atoms [2]. Different crystal forms can occur due to the different sliding planes (fig. 14). For synthetic diamond, these range from the octahedron (111 plane) to the cube (100 plane).

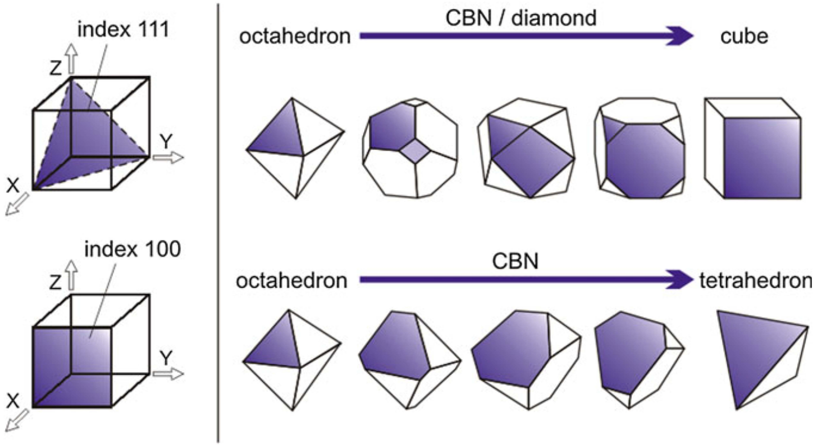


Fig. 14. Possible crystal forms of CBN and diamond

The diamond is anisotropic, e. g., the hardness is higher in the 111 plane than in the 100 plane (fig. 14). Because of the slightly different crystal structure, CBN crystals can take up further shapes from the octahedron to the tetrahedron [2].

Due to their crystal structure, the grains contain cleavage planes, which they preferably split along. During the grinding, the abrasive particles blunt. Thus, they are loaded more strongly and split. This generates new cutting edges, which is called self-sharpening. According to the type and number of cleavage planes, one can differentiate mono, macro and micro crystalline structures.

Diamond is the hardest known material. In connection with its high wear strength, it is predestined for the use as a cutting material for the machining of hard materials such as glass, hard metal and ceramic. However, at temperatures above 650 ^{o}C in the air, diamond transforms into the energetically more convenient modification of graphite with iron and nickel acting as catalysts and shifting the transformation point to lower temperatures [6]. Carbon also shows a high affinity to iron so that chemical wear occurs at higher temperatures – thus at higher cutting speeds. Both effects, the graphitisation and the chemical wear lead to the fact that diamond is not used as a grinding material for the machining of steel materials. In contrast, CBN shows no reaction of this kind and is stable at an atmospheric pressure of up to a temperature of 1400 ^{o}C and thus suitable for the machining of ferrous workpieces.

The friability test is a recognised method for the strength determination of diamonds. It is based on the measurement of the impact strength of a defined number of diamonds of a certain abrasive particle size. The number of diamonds that resist the "crushing effort" is a measure for the strength of the examined type of diamond. To determine their thermal stability, diamonds are thermally loaded under protective gas at 1100 ^{o}C for 20 min and then again submitted to the friability test. The difference between the strength before and after the thermal load is a measure for the thermal stability of the material. This thermal stability is relevant for the application of the tool, but also in the manufacturing of a grinding wheel by sintering [2].

7. GRINDING WHEEL SPECIFICATION

The material classification of conventional grinding wheels takes place according to GOST R 52781-2007 [7] and ISO 525:2020 [8] (fig. 15). It contains eight codes including two free codes, i. e., they can be freely chosen by the producer.

The preceding parameters can be concisely designated in a standard grinding wheel marking system defined by the [8]. This marking system uses numbers and letters to specify abrasive type, grit size, grade, structure, and bond material. Fig. 15 presents an version of the ISO Standard, indicating how the numbers and letters are interpreted. The standard also provides for additional identifications that might be used by the grinding wheel manufacturers.

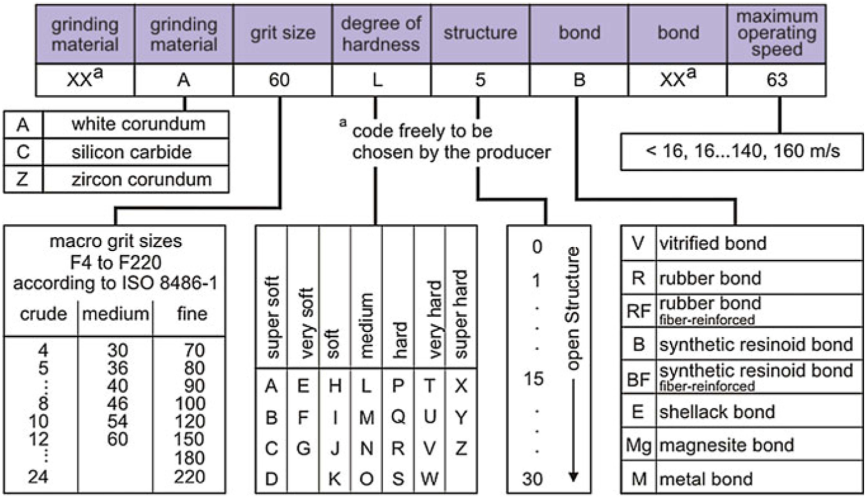


Fig. 15. Classification of corundum and silicon carbide grinding wheels (according to ISO 525:2020)

Abrasive Material

Different abrasive materials are appropriate for grinding different work materials. General properties of an abrasive material used in grinding wheels include high hardness, wear resistance, toughness, and friability. Hardness, wear resistance, and toughness are desirable properties of any cutting-tool material. Friability refers to the capacity of the abrasive material to fracture when the cutting edge of the grain becomes dull, thereby exposing a new sharp edge. Today, the abrasive materials of greatest commercial importance are aluminum oxide, silicon carbide, cubic boron nitride, and diamond. They are briefly described in tab. 2, together with their relative hardness values [5].

Table 2

Abrasives of greatest importance in grinding

Abrasive	**Description**	**Hardness, HV**
Aluminum oxide (Al2O3)	Most common abrasive material, used to grind steel and other ferrous, high-strength alloys	1900–2400
Silicon carbide (SiC)	Applications include ductile metals such as aluminum, brass, and stainless steel, as well as brittle materials such as some cast irons and certain ceramics. Cannot be used effectively for grinding steel because of the strong chemical affinity between the carbon in SiC and the iron in steel	3300–3600
Cubic boron nitride (CBN)	CBN grinding wheels are used for hard materials such as hardened tool steels and aerospace alloys	9250
Diamond	Diamond wheels are generally used in grinding applications on hard, abrasive materials such as ceramics, cemented carbides, and glass	10 000

Grain Size

The grain size of the abrasive particle is important in determining surface finish and material removal rate.

The size of an abrasive grain is identified by the grit number, which is a function of sieve size. The sieve size is measured using a screen mesh procedure. In this procedure, smaller grit sizes have larger numbers and vice versa. Grain sizes used in grinding wheels typically range between 8 and 250. Grit size 8 is very coarse and size 250 is very fine. Even finer grit sizes are used for lapping and superfinishing

Small grit sizes produce better finishes, whereas larger grain sizes permit largermaterial removal rates. Thus, a choice must be made between these two objectives when selecting abrasive grain size. The selection of grit size also depends to some extent on the hardness of the work material. Harder work materials require smaller grain sizes to cut effectively, whereas softer materials require larger grit sizes.

Bonding Materials

The bonding material holds the abrasive grains and establishes the shape and structural integrity of the grinding wheel. Desirable properties of the bond material include strength, toughness, hardness, and temperature resistance. The bonding material must be able to withstand the centrifugal forces and high temperatures experienced by the grinding wheel, resist shattering in shock loading of the wheel, and hold the abrasive grains rigidly in place to accomplish the cutting action while allowing those grains that are worn to be dislodged so that new grains can be exposed. Bonding materials commonly used in grinding wheels are identified and briefly described in tab. 3 [3].

Table 3

Bonding materials used in grinding wheels

Bonding material	Description
Vitrified bond	Consists chiefly of baked clay and ceramic materials. Most grinding wheels in common use are vitrified bonded wheels. They are strong and rigid, resistant to elevated temperatures, and relatively unaffected by water and oil that might be used in grinding fluids
Silicate bond	Consists of sodium silicate (Na_2SO_3). Applications are generally limited to situations in which heat generation must be minimized, such as grinding cutting tools

End of the table 3

Bonding material	Description
Rubber bond	Most flexible of the bonding materials and used as a bonding material in cutoff wheels
Resinoid bond	Consists of various thermosetting resin materials, such as phenol-formaldehyde. It has very high strength and is used for rough grinding and cutoff operations
Shellac bond	Relatively strong but not rigid; often used in applications requiring a good finish
Metal bond	Metal, usually bronze, is the common bond material for diamond and CBN grinding wheels. Particulate processing is used to bond the metal matrix and abrasive grains to the outside periphery of the wheel, thus conserving the costly abrasive materials

Wheel Structure and Wheel Grade

Wheel structure refers to the relative spacing of the abrasive grains in the wheel. In addition to the abrasive grains and bond material, grinding wheels contain air gaps or pores, as illustrated in fig. 16. The volumetric proportions of grains, bond material, and pores can be expressed as

$$P_g + P_b + P_p = 1,$$

where P_g – proportion of abrasive grains in the total wheel volume; P_b – proportion of bond material, and P_p – proportion of pores (air gaps).

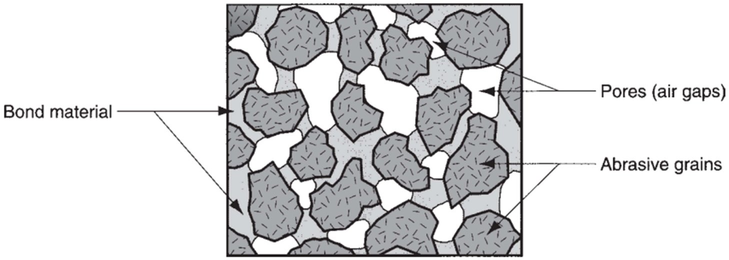


Fig. 16. Typical structure of a grinding wheel

Wheel structure is measured on a scale that ranges between "open" and "dense". An open structure is one in which $\boldsymbol{P_b}$ is relatively large, and $\boldsymbol{P_g}$ is relatively small. That is, there are more pores and fewer grains per unit volume in a wheel of open structure. By contrast, a dense structure is one in which $\boldsymbol{P_b}$ is relatively small, and $\boldsymbol{P_g}$ is larger. Generally, open structures are recommended in situations in which clearance for chips must be provided. Dense structures are used to obtain better surface finish and dimensional control.

Wheel grade indicates the grinding wheel's bond strength in retaining the abrasive grits during cutting. This is largely dependent on the amount of bonding material present in the wheel structure – $\boldsymbol{P_b}$.

Grade is measured on a scale that ranges between soft and hard. "Soft" wheels lose grains readily, whereas "hard" wheels retain their abrasive grains. Soft wheels are generally used for applications requiring low material removal rates and grinding of hard work materials. Hard wheels are typically used to achieve high stock removal rates and for grinding of relative soft work materials.

The preceding parameters can be concisely designated in a standard grinding wheel marking system defined by the GOST [7] and ISO Standard [8]. This marking system uses numbers and letters to specify abrasive type, grit size, grade, structure, and bond material. Fig. 17 presents an abbreviated version, indicating how the numbers and letters are interpreted.

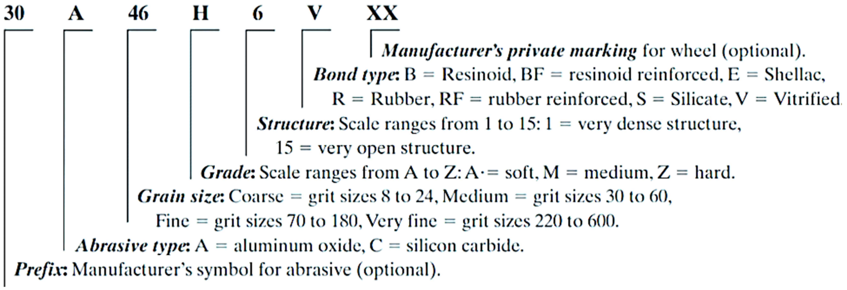


Fig. 17. Example of marking system for conventional grinding wheels

8. GRINDING WHEEL SELECTION

The selection of grinding wheels for high performance grinding applications is focused on three basic grinding regimes, namely: rough, finish, and fine grinding. The grain size of the grinding wheel is critical in achieving a specified workpiece surface roughness. The general guidelines for high performance grinding require a 40–60 mesh for rough grinding; a 60–100 mesh for finish grinding; and a 100–320 mesh grain for fine grinding. When selecting a particular grain size one must consider that large grains allow the user to remove material economically but make the material easier to machine by producing longer chips. However, finer grain sizes allow the user to achieve better surface roughness, and achieve greater accuracy by producing shorter chip sizes with a greater number of sharp cutting points. Tab. 4 shows the relationship between abrasive grain size and workpiece surface roughness for aluminum oxide grains [6].

Table 4

Relationship between abrasive grain size and workpiece surface roughness

Surface roughness, R_a, μm	Abrasive grain size
0.7–1.1	46
0.35–0.7	60
0.2–0.4	80
0.17–0.25	100
0.14–0.2	120
0.12–0.17	150
0.1–0.14	180
0.08–0.12	220

Grinding wheel specifications are specific to a particular operation and grinding wheels are formulated to account for the differences in grinding operations. In general, the following guidelines are considered when selecting a grinding wheels marking:

a) choose Al_2O_3 for steels and SiC for carbides, and nonferrous metals;

b) choose a hard grade for soft materials and a soft grade for hard materials;

c) choose a large grit size for soft ductile materials and a small grit for hard brittle materials. Choose a small grit for a good surface finish and a large grit for a maximum metal removal rate;

d) choose an open structure for rough cutting and a compact one for finishing;

e) choose a resinoid, rubber, or shellac bond for a good surface finish, and a vitrified bond for maximum removal rate;

f) do not choose vitrified bonded wheels for cutting speeds more than 32 m/s;

g) choose softer grades for surface and internal cylindrical grinding and harder grades for external cylindrical grinding;

h) choose harder grades on nonrigid grinding machines;

i) choose softer grades and friable abrasives for heat-sensitive materials.

9. CONDITIONING OF GRINDING TOOLS

Wear by splintering or break out of particles or wear caused by bonding erosion leads to the resharpening of grinding tools. This effect may be desired for rough grinding so as to avoid a conditioning of the tool. However, in finishing and fine grinding, conditioning is generally indispensable. The conditioning can serve three purposes (fig. 18) [2].

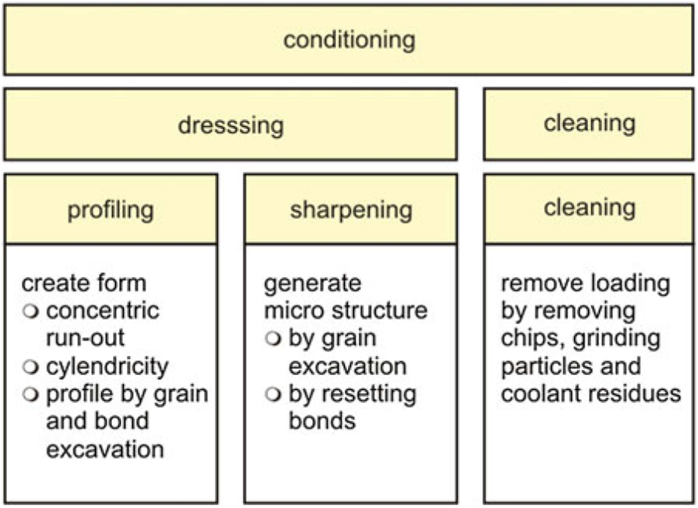


Fig. 18. Conditioning of grinding wheels [2]

Profiling: This is about the restoration or new generation of a grinding wheel contour. If the cylindricity or the concentricity get lost or waves develop on the active grinding surface due to the wear of a grinding wheel, profiling becomes necessary, i. e., in this case a cylindric surface is generated. By profiling, even noncylindric tool shapes can be generated for profile grinding. Profiling acts macro-geometrically.

Sharpening: If grinding tools are no longer suitable for grinding due to rounded cutting edges or loading (clogging of the chip spaces), sharpening can generate a new layer of particles or cutting edges. Sharpening acts micro-geometrically.

Cleaning: Cleaning removes residue consisting of workpiece and tool material or cutting liquid deposits. Cleaning does not alter the topography of the grinding tool; neither the particles nor the bonding are removed.

Profiling and sharpening together are also called **dressing**. Since in finishing or fine grinding the chip formation all the resulting effective parameters depend decisively on the dressing, i. e., the type and the adjustment parameters of this process, a grinding process can never be regarded by itself but must always be seen as a combination of conditioning/dressing and grinding. Fig. 19 illustrates dressing processes, which are distinguishable according to their kinematics [2].

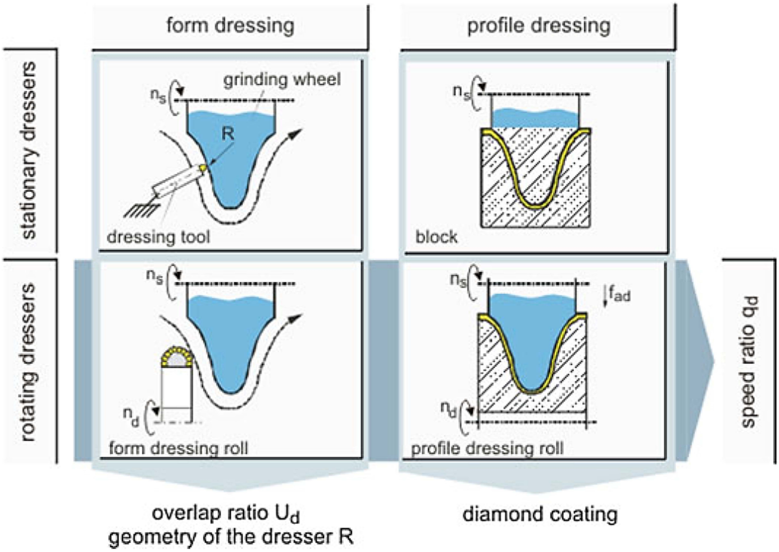
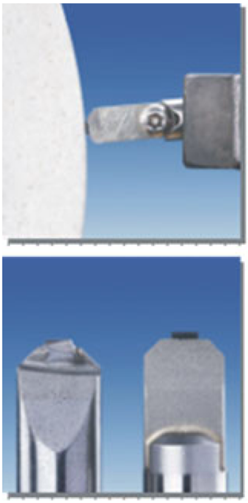


Fig. 19. Dressing process

Grinding wheels can be dressed with rotatory and non-rotatory, fixed tools (fig. 19). A second aspect of order is the type of shape generation. We distinguish **form dressing**, i. e., the controlled operation of the dressing tool, and **profile dressing**, at which the dressing tool receives the contour of the profile by copying.

Dressing tools can be handled with one or several cutting edges (consisting of one or several particles) (fig. 20). The illustration shows the typical application of the process, at which the profile of the grinding wheel is generated by the controlled dressing of single diamonds.



application

- dressing profiles with highest accurary (corundum, SiC)
- Inclined position by < 5° avoids wear of the bottom side, thereby
- useable twice
- radius accuracy: +/– 0,02 mm

diamond qualities

- natural strones (triplett)
- PCD diamond (without importance)
- CVD-diamond

Fig. 20. Single particle dressers

The cutting elements consist of artificial or natural diamonds and are cased in a metal matrix. These diamonds can be coarse, form-cut or exist in another geometrically defined condition. They can be arranged in a stochastic distribution or according to a defined pattern on cylinder-, board- or slice-shaped carriers.

Form rolls are rotating dressers studded with diamonds at the circumference (fig. 21). They are bi- or triaxially controlled so as to generate the wheel profile. Due to their multi-studding with diamonds, their durability is considerably higher than that of a single diamond. An additional advantage is that they are largely independent from the profile to be generated series, rotating profile tools, diamond profile rolls are used.

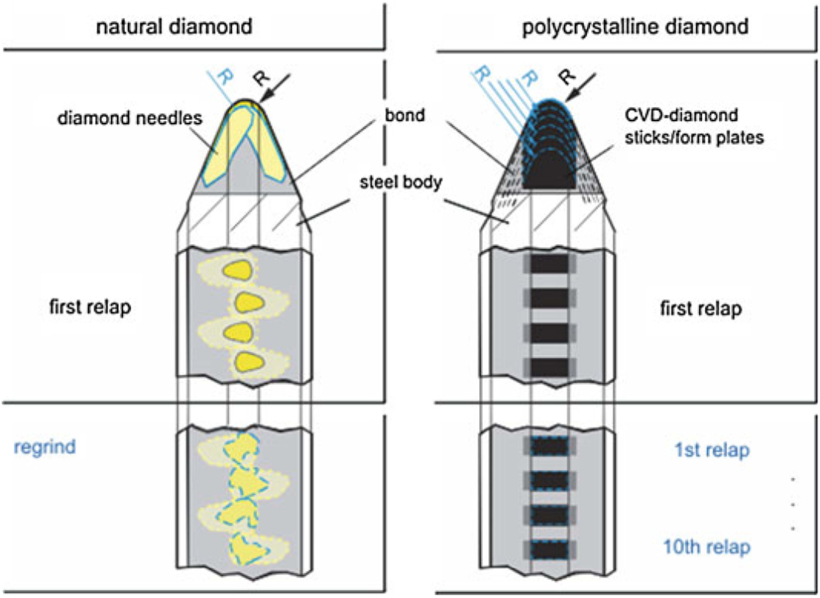


Fig. 21. Form rolls with set natural and poly-crystalline diamonds

Therefore, the form rolls (fig. 21) are suitable for small and medium-sized series. For large series, rotating profile tools, diamond profile rolls are used. They bear the contour of the wheel profile. Due to the mostly necessary high-precision machining of such profile rolls and because of the entirely circumferential diamondization they are expensive, but do have a high durability and permit short dressing times, since only a short radial infeed is required.

10. SELECTION OF COOLING LUBRICANT TYPE AND APPLICATION

The most important aspect of improving the quality of workpieces is the use of a high quality cooling lubricant. In order to achieve a good surface roughness of less than 2 µm, a paper-type filtration unit must be used. Air cushion deflection plates improve the cooling effect. The types of cooling lubricant in use for grinding include emulsions, synthetic cooling lubricants, and neat oils.

1. **Emulsions**: oils emulsified in water are generally mineral-based and are concentrated in the range 1.5–5 %. In general, the "fattier" the emulsion, the better the surface finish but this leads to high normal forces and roundness is impaired.
2. **Synthetic cooling emulsions**: chemical substances dissolved in water in concentrations between 1.5–3 %. Resistant to bacteria and are good wetting agents. They allow grinding wheels to act more aggressively but tend to foam and destroy seals.
3. **Neat oil**: highest metal removal rates achievable with a low tendency to burn the workpiece. Neat oils are difficult to dispose of and present a fire hazard.

The proper application of cutting fluids are effective in reducing the thermal effects and high work surface temperatures. Reducing friction and removing heat from the process are the two common functions. In addition, washing away chips and reducing temperature of the work surface are very important in grinding [4].

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VOCABULAR

Grinding – шлифование.
Grinding wheel – шлифовальный круг.
Machining – обработка резанием.
Cutting – резание.
Turning – точение.
Milling – фрезерование.
Workpiece – обрабатываемая деталь, изделие.
Work surface – обрабатываемая поверхность.
Machined surface – обработанная поверхность.
Cutting tool – режущий инструмент.
Chip – стружка.
Cutting edge – режущая кромка.
Primary motion – главное движение.
Cutting speed – скорость резания.
Feed motion – движение подачи.
Feed speed – скорость подачи.
Finishing cutting – чистовая обработка.
Rough cutting – черновая обработка.
Cylindrical grinding – круглое шлифование.
Traverse external cylindrical grinding – продольное наружное круглое шлифование.
Plunge grinding – врезное шлифование.
Internal cylindrical grinding – внутреннее круглое шлифование.
Surface grinding – плоское шлифование.
Centerless grinding – бесцентровое шлифование.
Grain – зерно.
Grain (grit) size – зернистость, размер зерна.
Bond – связка.
Vitrified bond – керамическая связка.
Resinoid bond – бакелитовая связка.
Rubber bond – вулканитовая связка.
Metal bond – металлическая связка.

Wheel grade – твердость шлифовального круга.
Soft grade wheel – мягкий круг.
Hard grade wheel – твердый круг.
Wheel structure – структура шлифовального круга.
Dense structure – плотная структура.
Open structure – открытая структура.
Wear – износ.
Dull grain – затупленное зерно.
Sharpening – правка (удаление слоя затупившихся и засалившихся зерен).
Cleaning – очистка.
Profiling – профилирование.
Dressing – правка шлифовального круга.
Dresser – правящий инструмент.
Diamond dresser – алмазный правящий инструмент.
Form roll – накатный ролик.
Singl-point diamond dresser – однокристальный алмазный правящий инструмент.
Multi-point diamond dresser – алмазно-металлический карандаш.
Cooling lubricant – смазочно-охлаждающая жидкость (СОЖ).
Emulsions – эмульсия.
Synthetic cooling emulsions – синтетические СОЖ.
Neat oil – масляные СОЖ.

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