13 Grinding

13.1 Definition

Grinding is a metal cutting procedure in which a multi-edged tool, whose cutting edges are geometrically undefined, removes the chips.

During grinding, the tool carries out the cutting motion. The cutting speeds commonly used in grinding are approximately 20 times those used in turning (25 to 45, sometimes up to 120 m/s). The feed movement is executed as a function of the cutting technique, the tool or the workpiece.

The grinding techniques are categorised according to the workpiece shape - in face- and cylindrical grinding, or according to component mounting - as grinding between centres or centreless grinding. It would also make sense to further subdivide these methods according to their ranges of application, such as grinding of slide ways or tools.

The grain cutting edges in the grinding tool may be bonded (grinding wheel, separating disk, grinding belt, honing stone) or loose (lapping). Abrasive cutting is described in Chapter 14, whereas abrasive belt grinding with grinding belts is explained in Chapter 15. Honing is illustrated in Chapter 16, short stroke honing (super finishing) in Chapter 17 and lapping is dealt with in Chapter 18.

13.2 Grinding techniques

13.2.1 Flat grinding

Plane or flat grinding is the grinding of plane surfaces. During flat grinding, the tool performs the cutting motion, whereas the workpiece executes the feed motion. The grinding procedure can be performed by the circumference or face of the grinding tool. Consequently, the following types are distinguished:

13.2.1.1 Circumferential grinding

In circumferential grinding (Figure 13.1), the wheel spindle is in horizontal position. The machine table with the workpiece travels back and forth in a straight line.

As a rule, the lateral feed per stroke is carried out by the table. Machines with a rotary table are an alternative. In these machines, the workpiece moves in a circle on a face chuck, and the lateral feed is performed by the grinding tool.

Since the grinding wheel contacts the workpiece only on a small portion of its circumference during circumferential grinding, the metal removal rate is limited for these methods. Feed and in-feed values are given in Tables 13.17 and 13.18.

Using special wheels and appropriate machines, the full-width grinding method is competitive with milling.

13.2.1.2 Face grinding

In face grinding, the grinding procedure is carried out with the front end of the grinding wheel (Figure 13.2). During face grinding, the grinding wheel (designed as segmented grinding wheel or as a ring wheel) performs the cutting motion, whereas the workpiece carries out the lateral feed motion.

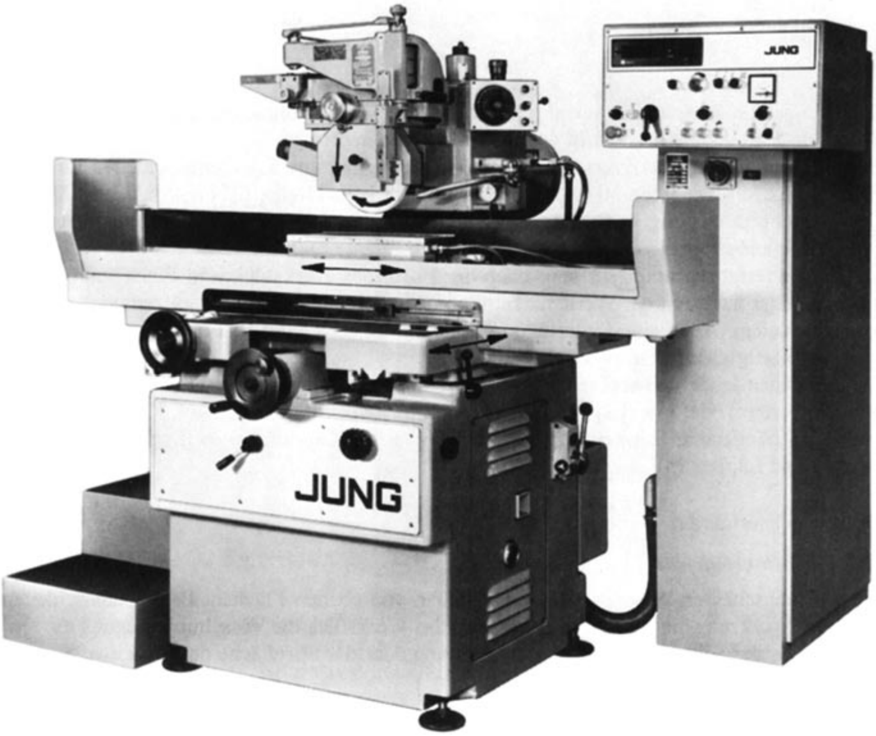


Figure 13.1
Face- and profile grinding machine
(*photo by Jung GmbH, Göppingen*)

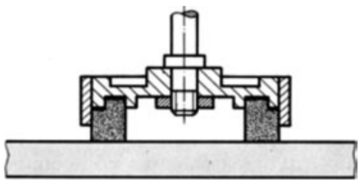


Figure 13.2
Face grinding principle with vertical wheel spindle

In contrast to circumferential grinding, the contact area between workpiece and tool is much greater in face grinding. Consequently, this method makes it possible to achieve higher metal removal rates. In face grinding, the tool axis may be vertical (Figure 13.2) or horizontal (in case of larger machines, see Figure 13.3).

Due to their compact design and great cutting capacity, machines with vertical wheel spindle axis are predominantly used for face grinding. Machines with horizontal wheel spindle axis are used only if the surface pattern is decisive, usually just for appearance's sake, such as in profile grinding operations (Figure 13.3).

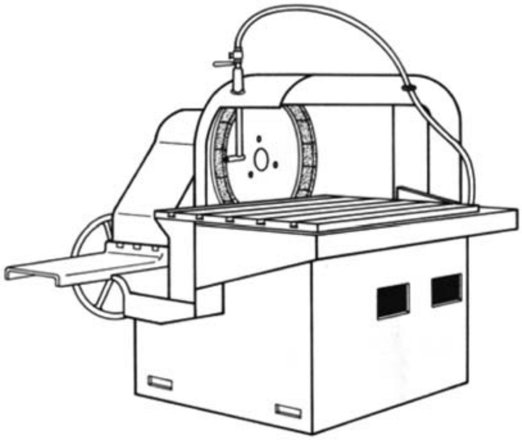


Figure 13.3
Segmented- surface grinding machine with horizontal wheel spindle axis

The face grinding procedures are distinguished according to the surface pattern generated (Figure 13.4): In cross grinding K, the grinding contours cross each other, whereas in arc grinding S, the grinding contours are allocated radially at one side. The mutually crossing grinding contours in cross grinding are generated if the wheel spindle axis is located normally to the workpiece. The radial allocation in arc grinding is created if the wheel spindle axis is inclined towards the workpiece.

For numerical infeed values, see Table 13.18.

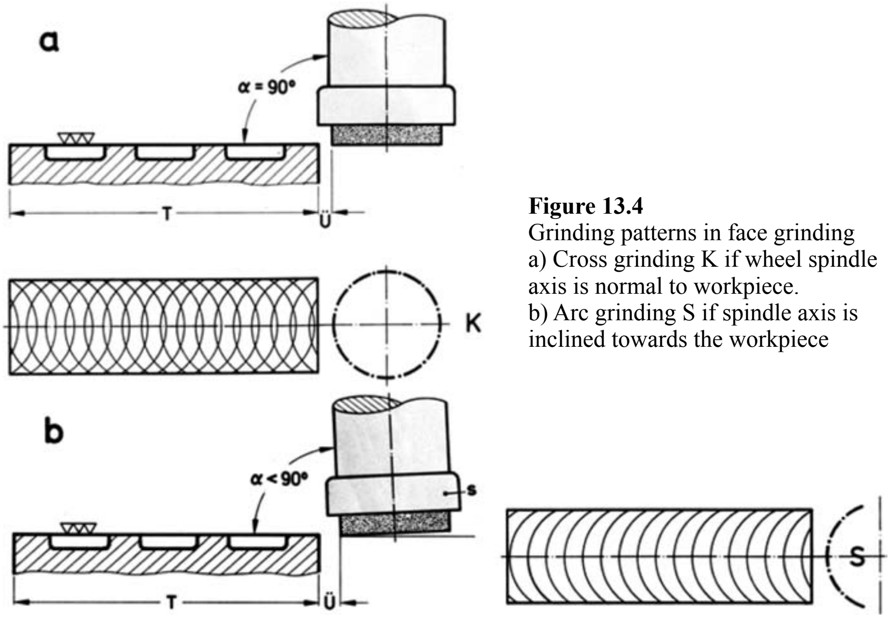


Figure 13.4
Grinding patterns in face grinding
a) Cross grinding K if wheel spindle axis is normal to workpiece.
b) Arc grinding S if spindle axis is inclined towards the workpiece

13.2.1.3 Profile grinding

Profile grinding is a circumferential grinding method carried out with profiled grinding wheels. In this procedure, as a rule, lateral feed is inapplicable. There are two common methods used to profile grinding wheels.

Simple profiles like radiuses, angles and grooves are generated with the common dressing attachments.

Complicated profiles are created with the so-called diaform attachment. This attachment is used to profile the grinding wheel along a template following the copying principle. Making use of CNC equipment, dressing and profiling are more and more being implemented by means of controlled motions.

13.2.2 Cylindrical grinding

Cylindrical grinding refers to the grinding of rotary parts.

In machining, a distinction is made between grinding from the outside (grinding the outer diameter of a shaft) and from the inside (grinding of a hole).

Another distinctive feature is the type of workpiece mounting, for example, whether the workpiece is held with or without a centre. Centreless grinding is explained in Chapter 13.2.4.

13.2.2.1 External cylindrical grinding

During external cylindrical grinding, the wheel performs both the cutting- and die infeed motion. The workpiece, which is fixed between centres or clamped in the chuck, is brought into rotation by a driving plate. Grinding wheel and workpiece have the same direction of rotation.

13.2.2.1.1 External cylindrical grinding with longitudinal feed

In grinding with longitudinal feed (Figure 13.5), as a rule, the table of the cylindrical grinding machine, and thus the workpiece, performs the longitudinal feed.

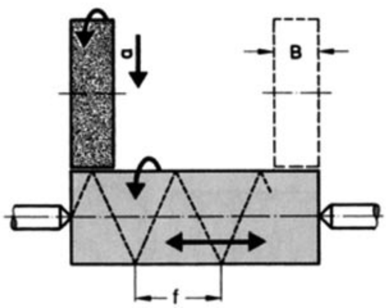


Figure 13.5
External cylindrical grinding with longitudinal feed – working principle

It is necessary to harmonize longitudinal feed and workpiece speed. If selecting longitudinal feed is set too high, the result is spiral-like markings on the workpiece.

A clean grinding pattern is obtained if feed *s* per workpiece rotation is less than grinding wheel width *B*. For numeral values for longitudinal feed, see Table 13.17.

Thin shafts may only be ground with small depths of cut due to the risk of deflection. For thick shafts, infeed is limited by the machine's input power. Too high depths of cut lead to greater contact areas between workpiece and wheel. Consequently, they result in increased cutting forces. For this reason, extreme infeed values may result in grinding wheel fracture.

To work with greater depths of cut, decrease longitudinal feed.

Depth of cut values are summarised in Table 13.18.

13.2.2.1.2 Plunge grinding

In plunge grinding (also plunge-cut grinding, see Figure 13.6), there is no longitudinal feed. The grinding wheel only performs the motion for depth setting. This method is needed, for example, to grind chamfers of shafts. For the infeed amount, the same criteria as for external cylindrical grinding with longitudinal feed are valid (see Table 13.18).

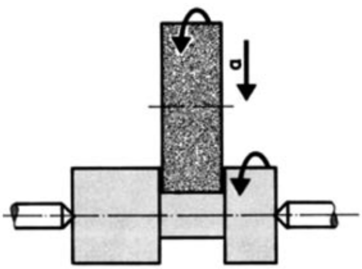


Figure 13.6
Plunge grinding – working principle

13.2.2.1.3 Thread grinding

Thread grinding is defined as cylindrical grinding with profiled grinding wheels. In this method as well, a distinction is made between longitudinal grinding (grinding with longitudinal feed of the workpiece) and plunge grinding.

During thread grinding with longitudinal feed, the thread can be generated with a "single-edged" wheel or a "multi-edged" wheel.

The narrow single-edged wheel, which has the profile of the thread to be generated (Figure 13.7), has a width of 6 to 8 mm.

The width of the multi-edged wheel is about 40 mm. This wheel is dressed conically. The threads (grooves) of the grinding wheel that first come into contact with the profile rough-grind it, while the two threads at the end (Figure 13.8) finish-grind it. This way, the entire chip removal is distributed over several grooves of the grinding wheel. This reduces the load per groove. For this reason, multi-edged wheels have a longer tool life than single-edged wheels.

Since the multi-edged wheel (Figure 13.8) is dressed conically, it is impossible to grind a thread directly on a shoulder with this wheel. As a result, this wheel can only be used for through threads.

Single-edged wheels are preferred to generate exact threads, since with these wheels one can achieve accuracy values of ± 2 µm for the effective diameter and ± 10 angular minutes for the thread angle.

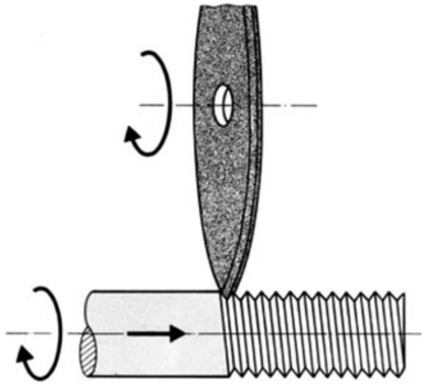


Figure 13.7
Longitudinal grinding of a thread with single-edged wheel

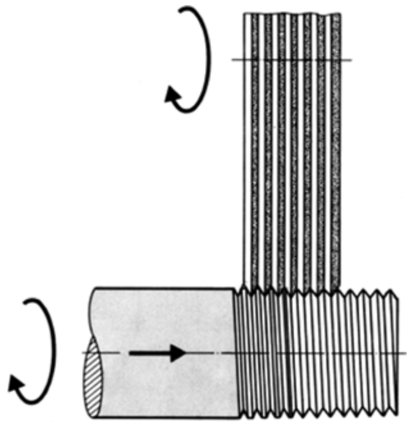


Figure 13.8
Longitudinal grinding of a thread with multi-edged wheel

During thread -plunge grinding (Figure 13.9), the thread is generated with a multi-edge grinding wheel. Here, the grinding wheel is dressed in parallel. During plunge grinding, as in the milling of short threads, the workpiece performs only $1^{1}/_{6}$ rotation. On each side, the grinding wheel should be about 2 mm wider than the thread to be generated.

For internal thread grinding, the same conditions as external thread grinding are valid; however, the grinding wheel diameters are correspondingly smaller in this case. Depending on workpiece size, they range from 20 to 150 mm.

During thread grinding, workpiece and grinding wheel have the same rotation direction. A motion for depth setting, which is executed by the grinding wheel, only exists in plunge grinding.

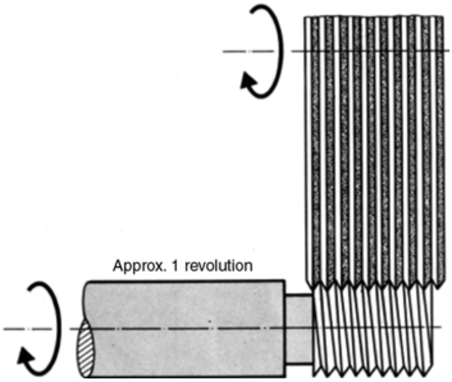


Figure 13.9
Plunge-thread grinding with multi-edged wheel

For thread grinding, the grinding result depends to a great extent on selecting an adequate wheel. The range of grain sizes (80 to 600) is the same for all leads, and the choice depends only on the minor thread radius.

The bonding of the grinding wheel to be chosen depends on the lead as well as the common selection criteria (compare 13.7.1.5).

13.2.2.2 Internal cylindrical grinding

Internal cylindrical grinding (Figure 13.10) corresponds to external cylindrical grinding in terms of its main criteria.

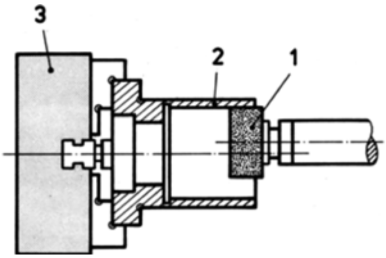


Figure 13.10
Internal cylindrical grinding –principle view
1 grinding wheel, 2 workpiece, 3 three-jaw chuck

The contact area between workpiece and wheel (Figure 13.11) is greater.
The contact length *l* depends on depth of cut *a* and the diameter ratio between grinding wheel and workpiece.

Cutting motion, longitudinal feed and the motion for depth setting are carried out by the workpiece.

In internal grinding, the cutting speeds that are optimal for grinding can generally not be reached due to the small grinding wheel diameter.
Optimal conditions are obtained when the following are selected

$$\boxed{D \approx 0{,}8\, d}$$

D	in mm	wheel diameter
d	in mm	diameter of the workpiece hole

For feed- and infeed values, see Tables 13.18 and 13.19.

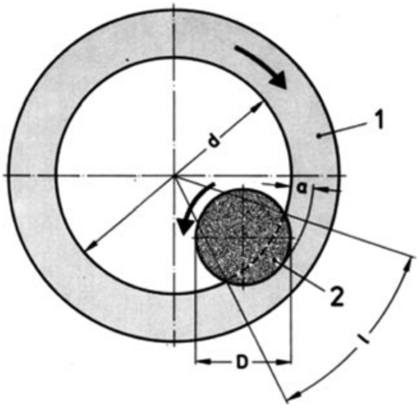


Figure 13.11
Contact length *l* of the grinding wheel in workpiece *d* workpiece diameter in mm, *D* grinding wheel diameter in mm

13.2.3 Cutting data for flat grinding and cylindrical grinding with clamped workpiece

The depth of cut *a* (infeed *e* of the grinding wheel) chosen depends on the wheel's grain size and the dimensions of the workpiece that is to be ground. Coarse-grained wheels allow greater depths of cut than fine-grained ones. Also, when fine-grained wheels are used, the pores clog more quickly. When this occurs, the wheel no longer cuts, but rather squeezes and lubricates. The general rule for common grinding is:

"Depth of cut must be less than the height of the abrasive grains protruding out of the bonding."

In full-width grinding, this rule is broken. This is made possible by open-porous wheels of special design.

In finishing, the following must be observed:

1. The speed of the grinding wheel must be kept high and that of the workpiece low, if excellent surface quality is required;
2. Sparking emanating from the grinding wheel means that the wheel needs to be guided over the workpiece without infeed until no sparking no longer appears;
3. Reversal of the longitudinal feed must be adjusted so that the grinding wheel travel exceeds the workpiece only by one third of its width (1/3 B); otherwise the workpiece dimensions will be smaller than specified.

13.2.3.1 Grinding wheel speed, workpiece speed

Grinding wheel speed *n* arises from the permissible peripheral speed of the grinding wheel, which can be taken from reference tables (compare Tables 13.20, 13.21, 13.13).

$$n = \frac{v_c \cdot 60\ \text{s/min} \cdot 10^3\ \text{mm/m}}{D \cdot \pi}$$

n	in $\min^{-1}$	wheel speed
v_c	in m/s	cutting speed of the grinding wheel = peripheral speed
D	in mm	grinding wheel diameter

Workpiece speed v_w is much lower than the wheel's peripheral speed. It is also drawn from reference tables. For cylindrical grinding, the workpiece speed is:

$$n_w = \frac{v_w \cdot 60\ \text{s/min} \cdot 10^3\ \text{mm/m}}{d \cdot \pi}$$

n_w	in $\min^{-1}$	workpiece speed
v_w	in m/s	peripheral speed of the workpiece
d	in mm	workpiece diameter

Both speeds v and v_w should be in a predefined mutual speed ratio q.

$$q = \frac{v_c}{v_w}$$

q		speed ratio
v_c	in m/s	cutting speed of the grinding wheel (peripheral speed)
v_w	in m/s	peripheral speed of the workpiece

For the corresponding q values of different materials, see Table 13.0.

Table 13.0 Speed ratio q for different materials

Material	Q
Steel	125
Grey cast iron	100
Ms and Al	60

13.2.4 Centreless grinding

Centreless grinding is a grinding procedure in which the workpiece is located freely on a guide bar, in contrast to external- or internal cylindrical grinding in which the workpiece is between centres or clamped in a chuck (Figure 13.12).

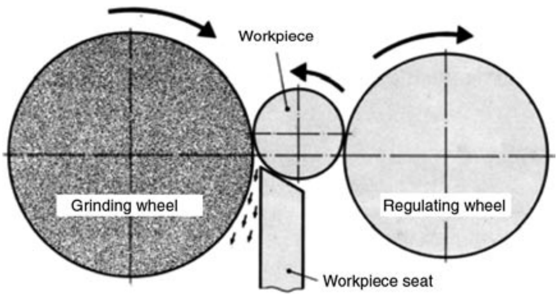


Figure 13.12
Centreless grinding principle

The workpiece rotation is generated through frictional resistance between the grinding- and regulating wheels. The axes of both wheels are located horizontally in one plane. The workpiece centre is situated above the connecting line of grinding- and regulating wheel centre.

The 3 major elements for centreless grinding are:

grinding wheel
regulating wheel
workpiece seat

The workpiece seat is made of steel. It is hardened or equipped with a cemented carbide bar.
The resting angle β (Figure 13.13) is 30°on average. For workpieces with a large diameter, an angle of 20° is common practice.

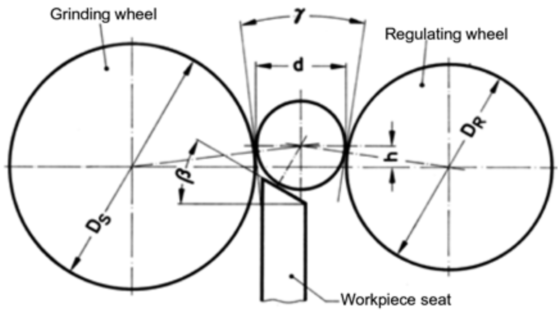


Figure 13.13
Height offset h, workpiece resting angle β and tangential angle γ during centreless grinding

Optimal height offset h can be calculated as an approximation according to Reeka (Figure 13.13) for a resting angle β = 30° and a tangential angle γ = 12° with the following equation.

$$h = 0{,}1 \cdot \frac{(D_R + d) \cdot (D_s + d)}{D_R + D_s + 2 \cdot d}$$

h	in mm	height offset
D_R	in mm	regulating wheel diameter
D_s	in mm	grinding wheel diameter
d	in mm	workpiece diameter

The size h can be calculated with the following rule of thumb as an approximation:

For workpieces up to 20 mm diameter:

$$h = \frac{d}{2}$$

h	in mm	height offset
d	in mm	workpiece diameter

For workpieces with a greater diameter (> 20 mm)

$$h = \sqrt{1{,}6 \cdot d}$$

More exact values related to the design of the grinding machine can be obtained from the grinding machine manufacturers.

The diameter ratio of regulating wheel to grinding wheel ranges from 0,6 to 0,8

$D_R/D_s = 0{,}6 – 0{,}8$

On average, the following equation is valid:

$$D_R = 0{,}7 \cdot D_s$$

D_R	in mm	regulating wheel diameter
D_s	in mm	grinding wheel diameter

Workpiece seat and regulating wheel support the workpiece in the grinding region and bear the appearing grinding forces that are generated.

The regulating wheel consists of normal corundum grains and is rubber-bonded. In special cases, also rubber-bonded steel wheels or hardened steel wheels without rubber bonding are used.

The high friction coefficient of the regulating wheel material makes that the peripheral speeds of regulating wheel and workpiece are identical. The peripheral speed of the grinding wheel is much greater. As a result, a relative speed is generated between grinding wheel and workpiece, and this speed affects the material removal on the workpiece. Effective cutting speed on the workpiece results from the difference between the working speed of the grinding wheel and the peripheral speed of the regulating wheel.

The speed of the regulating wheel can be adjusted infinitely variably in a range from approximately 1 : 6 to 1 : 8.

Assuming an average value for the required workpiece-peripheral speed v_w,

$$v_w = 0{,}3 \text{ m/s}$$

then speed and diameter of the regulating wheel can be calculated as follows:

$$n_w = \frac{v_w \cdot 60 \text{ s/min} \cdot 10^3 \text{ mm/m}}{d \cdot \pi} = \frac{0{,}3 \cdot 60 \cdot 10^3}{d \cdot \pi} = \frac{5730}{d}$$

$$D_R = 0{,}7 \cdot D_s$$

$$n_R = \frac{d \cdot n_w}{D_R} = \frac{5730}{D_R} = \frac{5730}{0{,}7 \cdot D_s} = \frac{8180}{D_s}$$

n_R	in min^{-1}	regulating wheel speed
n_w	in min^{-1}	workpiece speed
d	in mm	workpiece diameter
D_s	in mm	grinding wheel diameter
D_R	in mm	regulating wheel diameter
v_w	in m/s	necessary peripheral workpiece speed
8180	mm/min	constant (rounded)

The adjustment of the wheel speed can be determined from peripheral wheel speed.

$$n_s = \frac{v_c \cdot 60 \text{ s/min} \cdot 10^3 \text{ mm/m}}{D_s \cdot \pi}$$

n_s	in min^{-1}	grinding wheel speed
v_c	in m/s	cutting speed of the grinding wheel
D_s	in mm	grinding wheel diameter
(v_c = 35 m/s		for grinding of steel – see table with reference values 99)

Even in centreless grinding, the speed ratio q should have the value given in Table 13.0.

$$q = \frac{v_c}{v_w}$$

q		speed ratio
v_c	in m/s	cutting speed of the grinding wheel
v_w	in m/s	peripheral workpiece speed

In centreless grinding, a distinction is made between two methods: Plunge grinding and through grinding.

13.2.4.1 Plunge grinding

In plunge grinding, grinding- and regulating wheels are inclined towards each other by 0,5°.

The slight axial thrust generated on the workpiece this way ensures that it rests on the stop in an unambiguous position.

The plunge grinding procedure is as follows:

First, the workpiece is laid on the support rail with the regulating wheel retracted. Next, due to the motion for depth setting of the regulating wheel slide, the rotating regulating wheel is travelled in the direction of the grinding wheel (Figure 13.14), until the workpiece has been pressed against the grinding wheel.

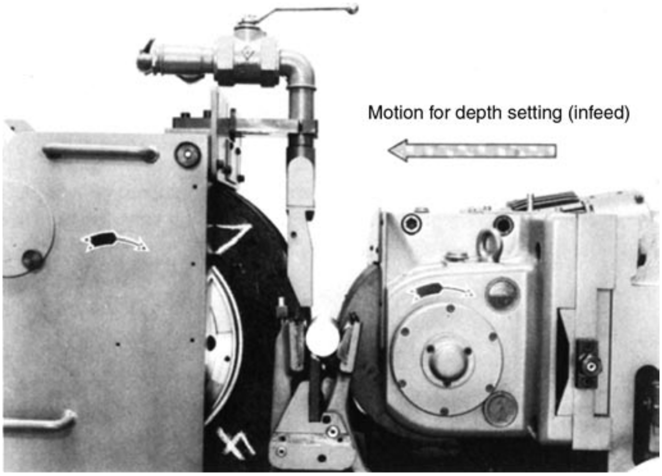


Figure 13.14
Centreless grinding with motion for depth setting (infeed)
(*photo by DIAG, plant Fritz Werner, Berlin*)

The grinding wheel grasps the workpiece and brings it into rotation. However, the speed of the workpiece is controlled by the regulating wheel, which acts as a frictional disk, and corresponds to the peripheral speed of the regulating wheel.

The grinding wheel, which rotates at a much higher peripheral speed (100-fold), makes a cut in the workpiece due to the speed difference between grinding- and regulating wheels.

At a given speed of the grinding wheel, the relative cutting speed and the number of grindings are set on the workpiece due to the regulating wheel speed.

13.2.4.2 Through grinding

During through grinding, the regulating wheel axis is inclined towards the grinding wheel axis in horizontal direction.

The range of the tilt angle α is given below:

$$\boxed{\alpha = 2{,}5° - 3°}$$

Thus, the workpiece has an axial thrust and moves in the axial direction. The passing speed v_A can be calculated as follows:

$$\boxed{v_A = D_R \cdot \pi \cdot n_R \cdot \sin\alpha}$$

D_R	in mm	regulating wheel diameter
n_R	in min^{-1}	regulating wheel speed
α	in °	tilt angle of regulating wheel axis
v_A	in mm/min	passing speed of the workpiece

13.3 Application of grinding techniques

13.3.1 Flat grinding

Flat grinding is applied to generate plane-parallel and profiled surfaces. Typical parts with plane-parallel surfaces are die blocks for cutting dies, die shoes for press- and draw dies, clutch lamellae, rings of different design (Figure 13.15) and many other machine elements.

Grinding of external splines and punches with gear-tooth profiles (Figure 13.16), as well as grinding of profiled tools with complicated profiles from solids, are examples of uses of profile grinding (Figure 13.17).

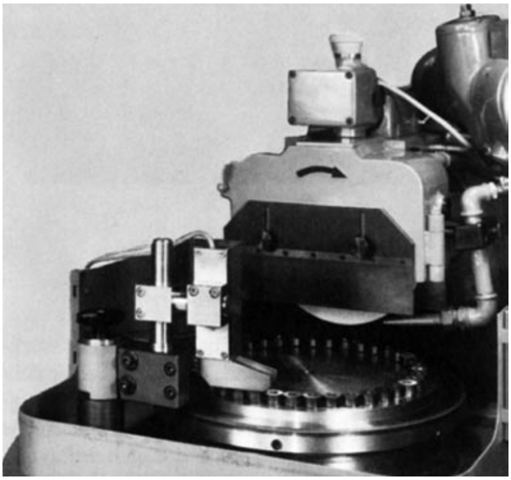


Figure 13.15
Flat grinding machine with rotary table Type HFR 30
(*photo by Jung, Göppingen*)

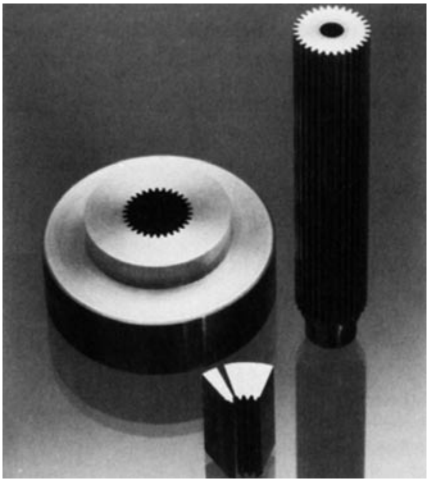


Figure 13.16
Grinding a profile into a complete cut for a toothed wheel
(*photo by Jung, Göppingen*)

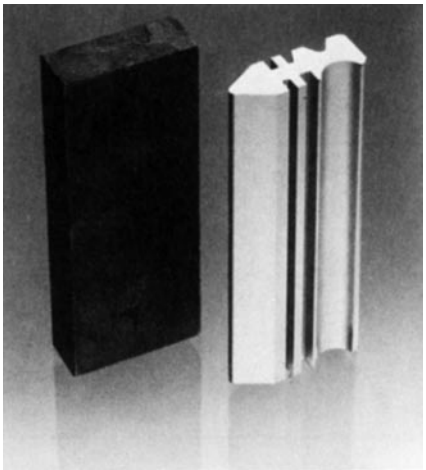


Figure 13.17
Grinding the profile into a punch, grinding from the solid
(*photo by Jung, Göppingen*)

13.3.2 Cylindrical grinding

Both external- and internal cylindrical grinding are used to machine rotary parts of any design (Figure 13.18).

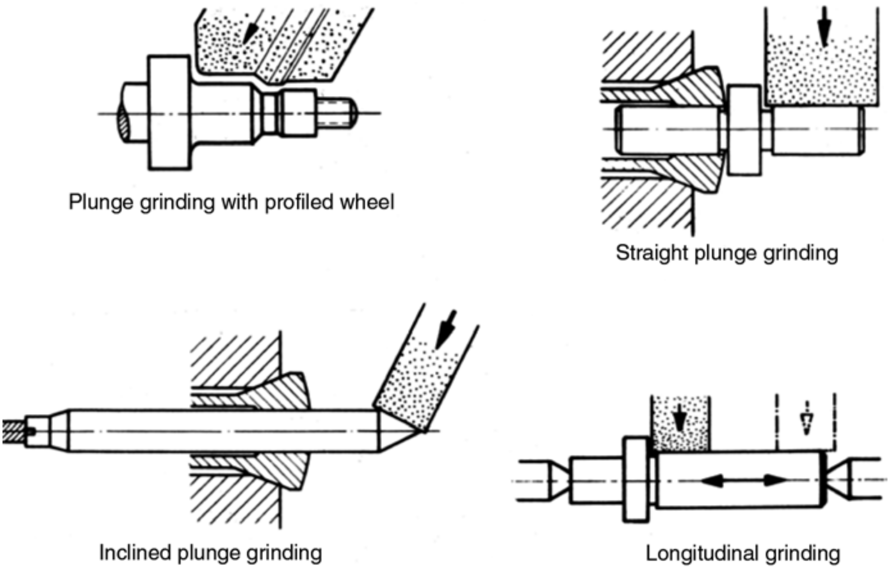


Figure 13.18
Examples of external cylindrical grinding

Special ranges of application for centreless grinding are:

Industry	Through grinding	Plunge grinding
Roll bearing industry	Ball bearing outer rings Rolling elements	–
Automotive industry	Brake pistons Shock absorber bars Bushings	Valves Valve lifters Camshafts (Figure 13.33) Crankshafts
Tool industry	Drills Pins (cylindrical)	Drills Taps Reamers Taper pins

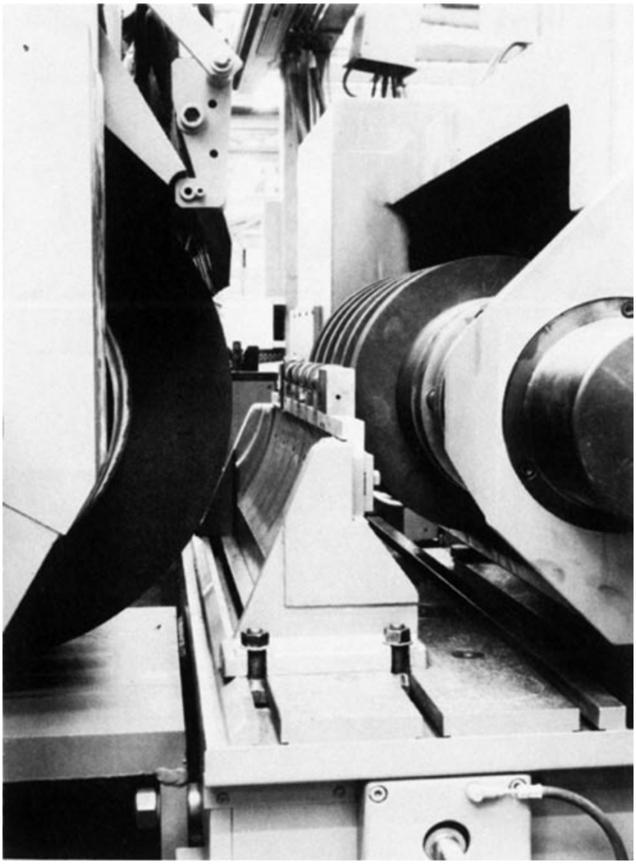


Figure 13.19
Grinding of a camshaft (plunge grinding) on a centreless grinding machine with roundtable, produced by DIAG, plant Fritz Werner, Berlin

13.4 Achievable accuracy values and allowances during grinding

Table 13.1 Allowances and achievable accuracy values

Grinding techniques	Allowance			Achievable accuracy	
	for one work piece length, in mm	Machining diameter or thickness of the work-piece, in mm	Allowance related to diameter, in mm	Accuracy to size	Peak-to-valley height R_t, in µm
Flat-	up to 100	up to 50	0,2–0,25	IT 8–IT 9	3–8
	150–200	up to 150	0,3–0,35	(IT 5–IT 6)	(1–3)
Profile-	20–100	–	Partially ground from the solid	IT 4–IT 5	2–4
External cylindrical-	up to 150	up to 50	0,2–0,25	IT 6 IT 8	5–10
	200–400	100–150	0,25–0,30		
Internal cylindrical-	up to 50	up to 20	0,1–0,15	IT 8 IT 10	10–20
	80–100	21–100	0,2–0,25		
Centreless-	up to 100	up to 300	0,2–0,3	IT 4 IT 6	2–4
		31–100	0,2–0,3		

As a general rule: The greater the machining diameter or the machining thickness and the longer the workpiece, the higher the allowance.
The allowances are valid for unhardened workpieces. For hardened workpieces, increase the values from the tables by 20–40%.

13.5 Calculation of force and power

Since the cutting edges are geometrically ambiguously defined, it is impossible to perform an exact calculation of the major cutting force and the machine input power.

Research work by Salje aimed at finding the average thickness of cut and the number of cutting edges in contact should provide a more exact power calculation.

Preger's paradigm attempts to deduce the cutting force calculation from milling to grinding.

According to Preger, it is possible to calculate mean thickness of cut from infeed e, grinding wheel diameter and feed per grinding cutting edge f_z.

For flat grinding, it follows

$$h_m = f_z \cdot \sqrt{\frac{a_e}{D_s}}$$

h_m in mm mean thickness of cut
f_z in mm feed per grinding cutting edge
D_s in mm grinding wheel diameter

Feed f_z per grinding cutting edge can be calculated from the effective grain distance λ_{Ke} (distance between 2 abrasive grains really acting) and the ratio q.

$$f_z = \frac{\lambda_{Ke}}{q}; \quad q = \frac{v_c}{v_w}$$

λ_{Ke}	in mm	effective grain distance
q		speed ratio
v_c	in m/s	cutting speed of the grinding wheel
v_w	in m/s	peripheral speed of the workpiece

For calculation of force and the necessary machine input power, the following equations can be derived:

1. *Mean thickness of cut*

1.1. *Flat grinding*

$$\boxed{h_m = \frac{\lambda_{Ke}}{q}\sqrt{\frac{a_e}{D_s}}}$$

1.2 *Cylindrical grinding*

$$\boxed{h_m = \frac{\lambda_{Ke}}{q}\sqrt{e \cdot \left(\frac{1}{D_s} \pm \frac{1}{d}\right)}}$$

+ for external cylindrical grinding

– for internal cylindrical grinding

h_m	in mm	mean thickness of cut
λ_{Ke}	in mm	effective grain distance
q		speed ratio
a_e	in mm	infeed during grinding (cutting contact)
D_s	in mm	grinding wheel diameter
d	in mm	workpiece diameter

Table 13.2 Effective grain distance λ_{Ke} in mm, as a function of infeed e in mm and grain size of the grinding wheel

a_e in mm → / Grain size ↓	Finishing				Roughing		
	0,003	0,004	0,005	0,006	0,01	0,02	0,03
60	39	38	37	36	33	23	15
80	47	46	45	44	40	31	24
100	54	53	52	51	48	38	30
120	60	59	58	57	53	44	37
150	64	63	62	61	56	48	40

2. *Specific cutting force* k_c

$$k_c = \frac{(1\text{mm})^z}{h_m^z} \cdot k_{c1,1} \cdot K$$

k_s	in N/mm²	specific cutting force
$k_{s1,1}$	in N/mm²	specific cutting force for $h_m = b = 1$ mm
K		correction factor considering grain size influence (Table 13.3).

3. *Mean major cutting force* F_{cm} *per cutting edge*

$$F_{cm} = b \cdot h_m \cdot k_c$$

F_{cm}	in N	mean major cutting force per cutting edge
b	in mm	width of cut = effective grinding width
h_m	in mm	mean thickness of cut
k_c	in N/mm²	specific cutting force

Table 13.3 Correction factor K as a function of grain size and mean thickness of cut

Grain size ↓ / h_m in mm →	0,001	0,002	0,003	0,004
40	5,1	4,3	4,0	3,6
60	4,5	3,9	3,5	3,2
80	4,0	3,6	3,2	3,0
120	3,4	3,0	2,8	2,5
180	3,0	2,6	2,4	2,2
280	2,5	2,2	2,0	1,9

4. *Angle of approach* φ

4.1 *Flat grinding*

4.1.1. Circumferential grinding (*Figure 13.20*)

$$\cos\varphi = 1 - \frac{2a_e}{D_s}$$

φ		angle of approach
a_e	in mm	infeed (grinding contact)
a_p	in mm	width of cut

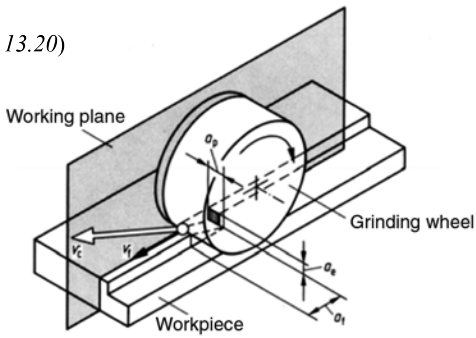


Figure 13.20

a_f	in mm	feed contact
D_s	in mm	grinding wheel diameter

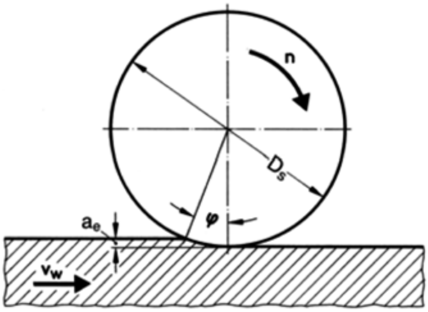


Figure 13.20a
Angle of approach during circumferential grinding

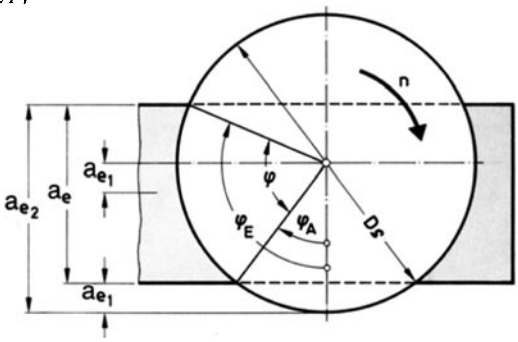
4.1.2 *Face grinding* (*Figure 13.21*)

$$\varphi = \varphi_E - \varphi_A$$

φ	angle of approach
φ_E	final angle
φ_A	initial angle

$$\cos \varphi_A = 1 - \frac{2a_{e1}}{D_s}$$

$$\cos \varphi_E = 1 - \frac{2a_{e2}}{D_s}$$



a_e in mm width of cut

Figure 13.21
Angle of approach during face grinding

a_{e1}, a_{e2} in mm components of the width of cut according to Figure 13.21

D_s in mm grinding wheel diameter

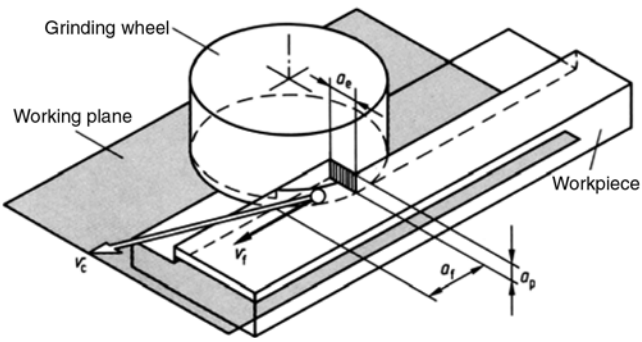


Figure 13.22
Depth of cut a_p, grinding contact a_e and feed contact a_f during side grinding (draft for DIN 6580 page 9)

4.2. *Cylindrical grinding*

$$\varphi \approx \frac{360^\circ}{\pi} \cdot \sqrt{\frac{a_e}{D_s \cdot \left(1 \pm \frac{D_s}{d}\right)}}$$

+ for external cylindrical grinding

– for internal cylindrical grinding

φ	in °	angle of approach
a_e	in mm	infeed
D_s	in mm	grinding wheel diameter
d	in mm	workpiece diameter

The approximation formula is valid for $\varphi \leq 60°$

5. *Number of cutting edges in contact*

This quantity can be determined according to an approach by Preger:

$$z_E = \frac{D_s \cdot \pi \cdot \varphi}{\lambda_{Ke} \cdot 360^\circ}$$

z_E		number of cutting edges in contact
D_s	in mm	grinding wheel diameter
λ_{Ke}	in mm	effective grain distance
φ	in °	angle of approach

6. *Mean total major cutting force* F_m

$$F_m = F_{cm} \cdot z_E$$

F_m	in N	mean total major cutting force
F_{cm}	in N	mean major cutting force per cutting edge
z_E		number of cutting edges in contact

7. *Machine input power*

$$P = \frac{F_m \cdot v_s}{10^3 \text{ W/kW} \cdot \eta_M}$$

P	in kW	machine input power during grinding
v_s	in m/s	peripheral speed of the grinding wheel
η_M		machine efficiency (η_M = 0,5 to 0,7)

13.6 Calculation of the machining time

13.6.1 Flat grinding

13.6.1.1 Circumferential grinding

$$t_h = \frac{B_b \cdot i}{f \cdot n}$$

t_h	in min	machining time
B_b	in mm	grinding wheel path in cross direction
i		number of grounds with sparking out
f	in mm/DH	feed per double stroke (DH)
n	in DH/min	number of double strokes (DH) per minute

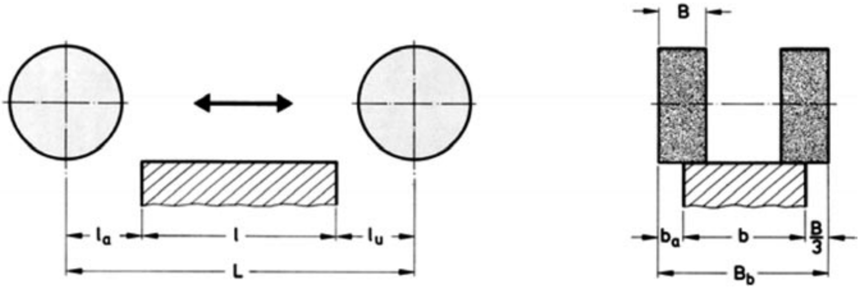


Figure 13.23
Flat grinding principle – circumferential grinding

$$B_b = \frac{2}{3} \cdot B + b \qquad b_a = \frac{1}{3} \cdot B$$

b	in mm	workpiece width
B	in mm	grinding wheel width
b_a	in mm	grinding wheel overrun

$$L = l_a + l + l_u$$

L	in mm	grinding wheel path in longitudinal direction
l_a	in mm	approach
l_u	in mm	overrun
l	in mm	workpiece length

$$l_a = l_u = 10 \text{ bis } 40 \text{ mm}$$

$$l_a \approx 0{,}04 \cdot l$$

$$n = \frac{v_w}{2 \cdot L}$$

n	in DH/min	number of double strokes (DH) per minute
v_w	in mm/min	workpiece speed
L	in mm	grinding wheel path in longitudinal direction

$$i = \frac{z_h}{a_e} + 8$$

i		number of grindings
z_h	in mm	allowance
a_c	in mm	infeed per double stroke (cutting contact)
8		number of double strokes for sparking out

13.6.1.2 Face grinding

In circumferential grinding (face grinding), as a rule, grinding wheel diameter D_s (Figure 13.24) is equal to or slightly greater than the workpiece width. Consequently, there is no path in cross direction in this method. This has the following effect on the machining time:

$$t_h = \frac{i}{n}$$

i		number of grindings
n	in DH/min	number of double strokes (DH) per minute

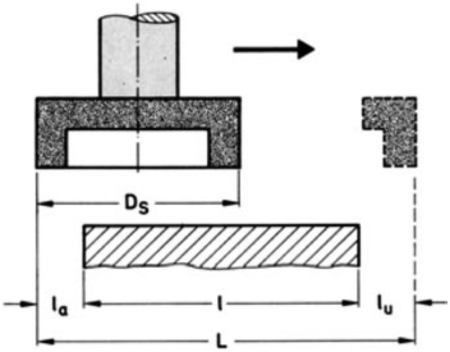


Figure 13.24
Flat grinding principle – face grinding

13.6.2 External- and internal cylindrical grinding

13.6.2.1 Longitudinal feed

For this method, the same conditions as in turning are given.

$$t_h = \frac{L \cdot i}{f \cdot n_w}$$

$$L = l - \frac{1}{3} B$$

t_h	in min	machining time
i		number of grindings
f	in mm	feed per workpiece rotation
n_w	in min^{-1}	workpiece speed
L	in mm	grinding wheel path in longitudinal direction
l	in mm	workpiece length
B	in mm	grinding wheel width

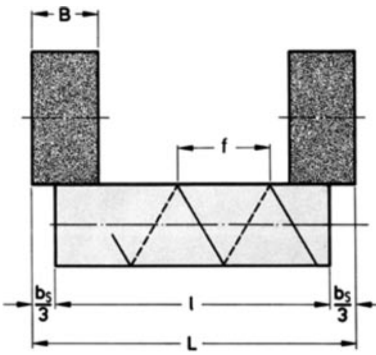


Figure 13.25
External grinding with longitudinal feed

The number of grindings i results from the diameter difference of the workpiece measured before and after the grinding procedure.

$$i = \frac{\Delta d}{2 \cdot a_e} + 8$$

8		number of double strokes for sparking out	
Δd	in mm	diameter difference	
a_e	in mm	infeed per ground	
d_v	in mm	diameter before grinding	On workpiece
d_n	in mm	diameter after grinding	On workpiece

$$\Delta d = |d_v - d_n|$$

For Δd, the absolute value is valid, without considering the sign, which becomes negative during internal grinding.

13.6.2.2 Plunge grinding

$$t_h = \frac{L}{v_f} = \frac{\Delta d}{2 \cdot a_e \cdot n_w}$$

t_h	in min	machining time
a_e	in mm	infeed per workpiece rotation (cutting contact)
n_w	in min^{-1}	workpiece speed
Δd	in mm	diameter difference
v_f	in mm/min	feed rate

13.6.3 Centreless grinding

13.6.3.1 Through grinding

$$t_h = \frac{L \cdot i}{v_A}$$

v_A	in mm/min	workpiece passing speed
n_R	in min^{-1}	regulating wheel speed
α	in °	tilt angle ($\alpha = 2{,}5° – 3°$)
i		number of grindings

$$L = l + B$$

L	in mm	workpiece path
l	in mm	workpiece length
B	in mm	grinding wheel width
b_R	in mm	regulating wheel width

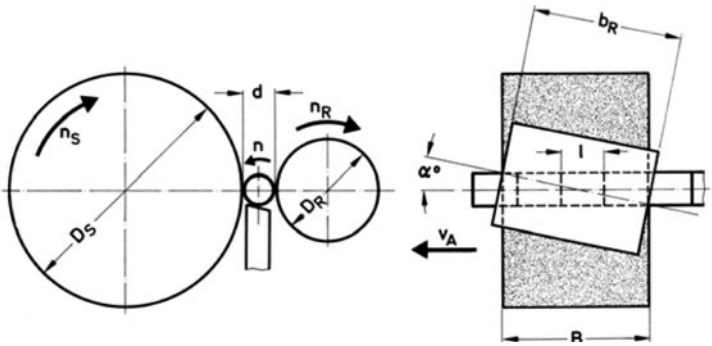


Figure 13.26
Centreless through grinding - principle

When grinding many workpieces without clearance in the through grinding mode, such as rollers for roller bearing, then the following is valid

$$\boxed{L = n \cdot l + B}$$

n number of rollers ground without clearance

13.6.3.2 Plunge grinding

$$\boxed{t_h = \frac{L}{v_f} = \frac{\Delta d}{2 \cdot a_e \cdot n_w}}$$

13.7 Grinding wheels

13.7.1 Tool materials

13.7.1.1 Abrasives

The most essential abrasives are corundum, silicon carbide, boron carbide, boron nitride and diamond.

The types of corundum, whose main component is aluminium oxide, are subdivided into natural corundum and electrocorundum.

Electrocorundum is derived from bauxite by means of electrochemical melting. The solidified fusion is reduced in size and milled to wheel size. Hardness and brittleness of the corundum abrasive grain increase as a function of increased crystalline Al_2O_3 content.

Consequently, three qualities are distinguished:

normal corundum NL:	95%	Al_2O_3
semi-precious corundum HK:	98%	Al_2O_3
precious corundum EK:	99,9%	Al_2O_3

The corundum types are classified in DIN 69100.

Silicon carbide (*SiC*) is also made in an electrochemical procedure, from petroleum coke, which is rich in carbon, and silica sand. Silicon carbide is one of the hardest artificial abrasives; it is harder than electrocorundum.

Boron nitride is a boron nitrogen bond. It is known as "Borazone", a name copyrighted by the manufacturer (General Electric Company).

Diamond is the hardest abrasive.

Today, given the synthetic manufacturing technologies available, artificial diamonds can be produced in predefined grain size according to the requirements for different purposes.

Allocation of hardness according to the hardness scale by Knoop is elucidated in Table 13.4.

Table 13.4 Hardness of abrasives

Material	Hardness in kN/mm^2
Corundum	20
Silicon carbide	28
Boron nitride	48
Diamond	70

Table 13.5 The most essential abrasives - properties and ranges of applications

Abrasive	Properties	Common ranges of application
Normal corundum NK	Very hard and tough	Low alloyed steel, cast steel, malleable cast iron, heavy rough grinding with high metal removal rate
Semi-precious corundum HK	High hardness, but less tough than normal corundum	Hardened steel, heat-treated steel
Precious corundum EK	White precious corundum, very hard, brittle and easy-to-cut abrasive grain pink precious corundum, very hard, slightly less brittle than 81A dark-red special corundum, tougher for its hard ness than 81A and 82 A monocrystal corundum, very hard, wear-resistant abrasive grain	Hardened, alloyed steel, tool- and high speed steel, stainless steel unhardened, alloyed steel with high strength, hardened steel highly alloyed tool steel highly alloyed, heat-sensitive tool- and high-speed steel
Silicon carbide SC	Green silicon carbide, extremely hard and brittle, shock-sensitive dark silicon carbide, extremely hard, slightly less brittle than 1C	White cast iron, cemented carbide, non-ferrous metals, hard, non-metallic materials Grey cast iron, metallic and non-metallic materials with low tensile strength
Diamond DT	Very hard	Lapping and grinding of carbide-tipped tools, simultaneous grinding of cemented carbide and steel

13.7.1.2 Grain sizes

The abrasive grain sizes are marked by numbers according to DIN 69100. The higher the code number, the finer the grain size. The ident number is also the sieve number. It specifies the number of meshes per inch over the length of the sieve.

Table 13.6 Grain sizes according to DIN 69100 (grain sizes in mm)

Very coarse		**Coarse**		**Medium**	
No.	Grain size	No.	Grain size	No.	Grain size
8	2,830–2,380	**14**	1,680–1,410	**30**	0,710–0,590
10	2,380–2,000	**16**	1,410–1,190	36	0,590–0,500
12	2,000–1,680	20	1,190–1,000	**46**	0,420–0,350
		24	0,840–0,710	50	0,350–0,297
				60	0,297–0,250

Fine		**Very fine**		**Dust-fine**	
No.	Grain size	No.	Grain size	No.	Grain size
70	0,250–0,210	150	0,105–0,088	**280**	0,040–0,030
80	0,210–0,177	**180**	0,088–0,074	320	0,030–0,020
90	0,177–0,149	200	0,074–0,062	400	0,020–0,016
100	0,149–0,125	220	0,062–0,053	**500**	0,016–0,013
120	0,125–0,105	240	0,053–0,040	600	0,013–0,010
				800	0,007–0,003

The grain sizes printed in **bold** letters are most commonly used.

13.7.1.3 Hardness grades

For a grinding wheel, hardness is understood as the resistance to grain-break off from the bond. It is not identical with the hardness of an abrasive grain. The bonding hardness should be adjusted so that the abrasive grains break off when they become dull. This way, the grinding wheel regulates its own sharpness (self-dressing). The hardness grades are defined in letters

Table 13.7 Hardness grades of the grinding wheels according to DIN 69100

Very soft	Soft	Medium	Hard	Very hard	Extremely hard
E F **G**	**H I Jot K**	L **M** N **O**	**P Q R** S	T U V W	X Y Z

The hardness grades printed in bold letters are most commonly used.

13.7.1.4 Grinding wheel structure

The grinding wheel structure (Figure 13.27) is similar to a honeycomb. It is defined by the spatial ratios for the abrasive grain, the binder and the pores. The maximum ratio is covered by the pores. The international structure denomination is given in Table 13.8.

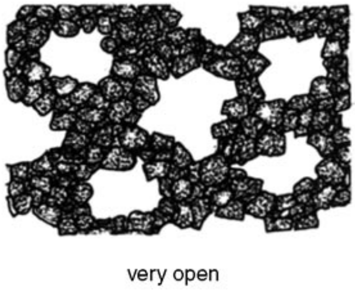


Figure 13.27
Structure of a highly porous grinding wheel

Table 13.8 Marking of grinding wheel structures

Very dense	Dense	Medium	Open-porous	Very open-porous
1, 2	3, 4	**5, 6, 7, 8**	9, 10, 11	12, 13, 14

The structures printed in **bold** letters are most commonly used.

13.7.1.5 Bond types

The abrasive grains are mixed with binders and pressed or cast into the desired shape. Afterwards, they are baked depending on the binder at 1200 to 1400 °C (for example, ceramic binders), or dried at 300 °C (for example, silicate bonds). The most frequently used bonds according to DIN 69100 are given in Table 13.9:

Table 13.9 Bond types

	Name of the binder	Main components	Advantages	Disadvantages
Rigid, inelastic bonds (mineral bonds)	Ceramic – Ke	Clay with additives	Unaffected by water, oil, heat very handy	Limited strength, long manufacturing time
	Magnesite – Mg	Sorel – cement	Dense structure provides a smooth ground	Low strength, for this reason v_{zul} low
	Silicate – Si	Soluble glass	Not baked, but dried at 300 °C, and thus quickly produced, water-proof	
Elastic bonds (organic bonds)	Artificial resin – Ba	Bakelite Phenol resins (80%) and Cresole (10%) or formaldehyde (10%)	Handy, easily cut, higher strength than ceramic bond, allowing high cutting speed, short manufacturing time	Dry storage required, limited operating time
	Rubber– Gu Natural resin – Nh	India rubber with filling materials Shellac	Dense structure, high strength, particularly suitable for grinding wheels of less thickness and wheels with sharp profile	Temperature-sensitive, softening at 120°C

13.7.2 Design types and denomination of grinding wheels

13.7.2.1 Design types

Some frequently used shapes and the associated standards according to which the dimensions of these grinding wheels are defined are shown in Figure 13.28.

Due to the large number of standards existing for grinding wheels, only selected examples are given on this and the following pages. A complete summary is given in the bibliography.

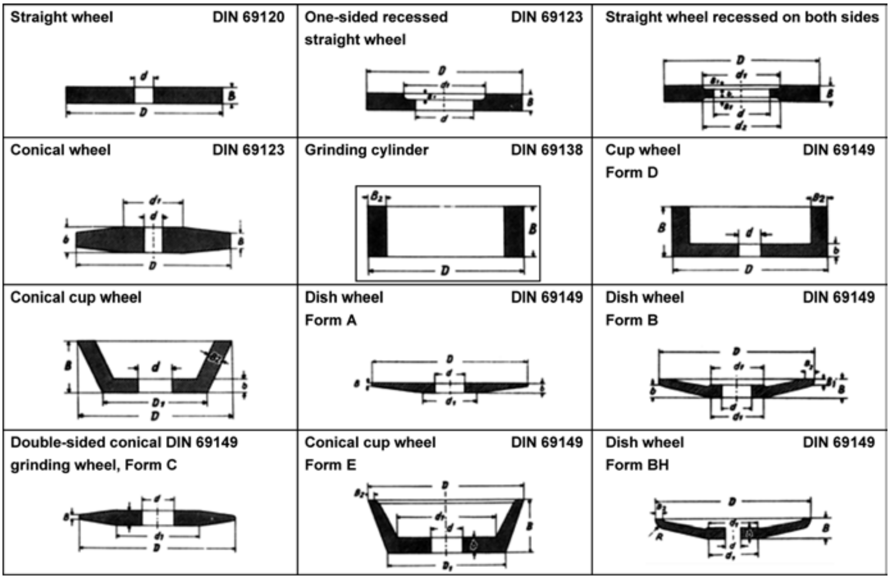


Figure 13.28
Widely used wheel shapes

Figure 13.29 shows the possible wheel profiles.
An overview of the dimensions of the grinding wheels for tool grinding according to DIN 69149 includes Table 13.10.

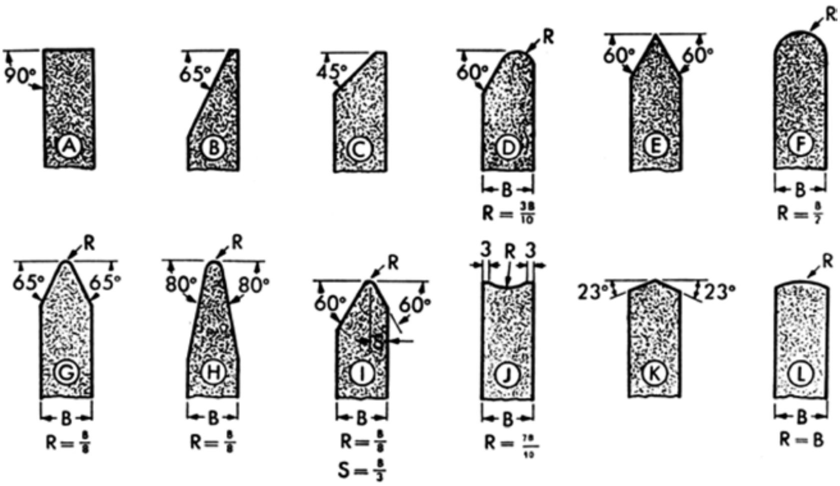


Figure 13.29
Grinding wheel profiles

Table 13.10 Ranges of dimensions for grinding wheels according to DIN 69149 (denominations see Figure 13.28)

Wheel type	Main sizes of the grinding wheel, in mm		
	D	B	d
Cup wheel Form D	50–150	32–80	13–20
Conical cup wheel	50–150	25–50	13–20
Dish wheel Form A and B	80–250	8–21	20–32
Wheel, conical on both sides Form C	80–250	8–19	20–32
Conical cup wheel Form E	50–150	25–50	13–20
Dish wheel Form BH	200	25	32

The dimensions of the residual forms are defined in the following standards.

DIN 69120 Straight wheel from 4 to 900 mm external diameter
DIN 69125 Straight wheel, recessed, for internal grinding
DIN 69138 Grinding cylinder with floor flange for flat grinding
DIN 69139 Straight cup wheels for flat grinding of 40–200 mm ø
DIN 69159 Cutting-off wheel

In addition to these types, the wheel manufacturers produce grinding wheels in all dimensions up to 1200 mm ø for special ranges of application and grinding machine types.

13.7.2.2 Denomination of grinding wheels according to DIN 69100

Wheel dimension $D \times B \times d$	Wheel according to DIN	Abrasive	Hardness	Structure	Bond
175 × 32 × 51	DIN 69120	EK	M	5	Ke

The grinding wheel demonstrated in this example is a grinding wheel according to DIN 69120 (Figure 13.30) with the following parameters:

External diameter:	$D = 175$ mm
Width:	$B = 32$ mm
Hole diameter:	$d = 51$ mm
Abrasive:	precious corundum (EK)
Hardness:	M
Structure:	5
Ceramic bond:	Ke

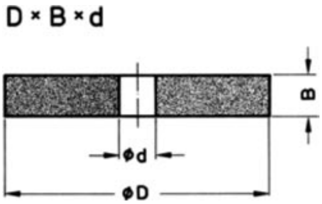


Figure 13.30
Straight wheel according to DIN 69120

Table 13.11 Wheel parameter according to DIN 69100

Abrasive		Grain size		Hardness		Structure		Bond	
		8		D		2			
Normal corundum	NK	10		E		3	Dense		
		12	grob	F	Soft			Ceramic	Ke
		14		G		4			
Semi-precious corundum	HK	16		H		5			
		20		I					
		24		J		6		Synthetic resin	Ba
		30		K		7			
Precious corundum	EK	36		L					
		46		M		8	Open	Rubber	Gu
		54		N					
		60		O		9			
Corundum (black)	KS	70		P				Silicate	Si
		80		Qu		10			
		90		R		11			
		100		S					
Natural corundum	KO	120		T		12		Magnesite	Mg
		150		U		13	hochPorous		
		180		V					
Silicon carbide	SC	220		W		14		Natural resin	Nh
		140		X		15			
		280		Y					
Diamond	DT	320		Z	Hard	16			
		400							
		500	staubfein						
		600							

Each grinding wheel has to be fitted with a label, which includes the characteristics of the bonded abrasive and the name of the manufacturer (Figure 13.31). The abrasive is specified by the label's ground colour.

Table 13.12 Label colours and associated abrasives

Label colour	Abrasive
Brown	Normal corundum (NK)
Yellow	Semi-precious corundum (HK)
Red	Precious corundum (EK)
Green	Silicon carbide (SC)

In addition to this colour, the label also has a coloured diagonal stripe. The colour of this stripe specifies the maximally permissible peripheral speed of the wheel.

Figure 13.31
Grinding wheel label

Table 13.13 Colour of the diagonal stripes on the label assigned to permissible peripheral wheel speed

Diagonal stripe colour	Maximally permissible peripheral wheel speed, in m/s
White	15–25
Blue	45
Yellow	60
Red	80
Green	100

13.7.3 Wheel mounting

Since grinding wheels work at high peripheral speeds, severe accidents may result if a wheel bursts.

For this reason, wheels have to be checked for soundness before assembly. When the wheel is struck lightly, the resulting sound will be impure if the wheel is cracked or damaged. Wheels that make this sound must not be used!

When clamping into the flanges (Figure 13.32), pay attention to the following:

1. Put elastic interpass materials (rubber, soft paperboard, felt or leather) between flanges and grinding wheel.
2. The flanges should have rotation grooves from 0,5 to 1,0 mm depth.
3. Flange diameter should be minimally ⅓ of the grinding wheel diameter.
4. The flanges should cover at least ⅙ of the wheel sidewise height.

In case of large grinding wheels up to 1000 mm diameter and 40 mm thickness without any recess, the conditions shown in Figure 13.32a are valid.

If it is impossible to use protective hoods, then conical wheels (Figure 13.32b) with a sidewise inclination 1 : 16 are preferable.

Clamp large wheels with a large hole between flanges (Figure 13.32c) set up for balancing.

Abrasive cups (Figure 13.32d) are fixed with a counter flange that receives the sidewise pressure.

Ring wheels (Figure 13.32e) are luted on a supporting plate with dove-tail groove.

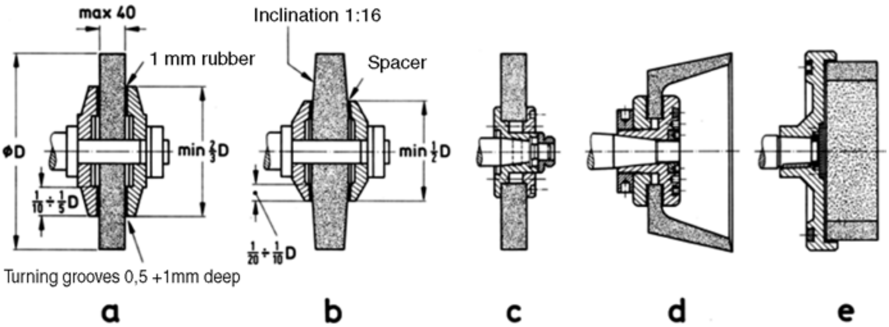


Figure 13.32
Wheel mounting
a straight-, *b* conical wheels, *c* with large hole, *d* grinding cups (cup wheels), *e* ring wheels

13.7.4 Grinding wheel selection for special ranges of application

Table 13.14 Guidelines for the selection of abrasive, grain size, hardness and structure for ceramically bonded grinding wheels (excerpt from DIN 69102 and documents by the firm Elbe-Schleifmittelwerk)

Material	Cylindrical grinding					Flat grinding		
	External grinding		Internal grinding			Peripheral cut up to 200 mm wheel diameter	Face grinding	
	between centres	centreless	grinding wheel diameter in mm				Cup wheel 200–350 ∅	Segments
			up to 16	16–36	36–80			
Case-hardening- and tool steels Alloyed steels hardened up to 63 HRC	EK 50 L 6	HK 60 L 5	EK 80 L 5	EK 60 K 5	EK 46 Jot 6	EK 46 Jot 12	EK 30 Jot 10	EK 30 Jot 10
High-speed steels hardened up to 63 HRC	EK 50 Jot 6	EK 50 K 5	EK 80 Jot 6	EK 60 I 6	EK 46 H 9	EK 46 G 11	EK 36 G 10	EK 30 I 10
High-speed steels hardened > 63 HRC	EK/SC 50 I 6	EK 60 L 5	SC 80 I 6	SC 60 H 6	SC 46 G 9	EK 46 G 11	EK 36 G 10	EK 30 H 10
Cemented carbide	SC 60 H	SC 60 I	SC 80 M	SC 60 L	SC 46 K	SC 60 G	SC 50 G	SC 50 H
Steel, unhardened up to 700 N/mm^2	NK 50 M 6	NK 60 M 5	HK 80 M 6	HK 60 L 6	HK 46 K 6	EK/NK 46 K 10	EK/NK 36 K 10	EK/NK 24 K 10
Heat-treated steel up to 1200 N/mm^2	NK 50 L 6	HK 60 M 5	EK 60 L 6	EK 60 K 6	EK 46 Jot 6	EK 46 I 14	EK 36 I 10	EK 24 Jot 10
Grey cast iron	SC/EK 50 Jot 6	SC 50 K 5	SC 80 K 6	SC 60 Jot 6	SC 46 I 8	EK/SK 46 I 12	EK/SK 36 I 10	EK/SK 30 Jot 8
Zinc alloys and light metals	SC 46 I 3[1]	SC 60 K 9	SC 60 I 8	SC 60 19	SC 46 Jot 10	SC 36 I 12[1]	SC 24 I 10[1]	SC 20 I 10[1]

[1] Bond from artificial resin

This table includes:
abrasive – grain size – hardness – structure
for example EK 50 L 6

13.8 Failures during grinding

13.8.1 Parameters influencing the grinding procedure

An optimal grinding result may only be expected if the grinding tool and the – conditions (peripheral speed, feed values, infeed) are correctly aligned for the workpiece.

The following Table 13.15 shows the extent to which an alteration of the individual factors affects the grinding result.

Table 13.15 Parameters influencing grinding and their effects on the grinding result

Alteration		Effects on the grinding result
Grinding wheel		
Grain size	Coarser	Higher metal removal rate. Peak-to-valley height on workpiece increases.
	Finer	Lower metal removal rate. Peak-to-valley height on workpiece decreases. Wheel appears harder and has higher form stability.
Hardness	Harder	Metal removal rate decreases. Dull grains break off later or not at all. Increased heating of the workpiece (grinding cracks, structural change).
	Softer	Abrasive grains break off earlier. Wheel wear increases. Peak-to-valley height on workpiece increased. Defects of form increase.
Structure	Denser	Wheel is harder. Wheel has higher form stability. Decreased peak-to-valley height on workpiece.
	More open	Wheel is softer. Wheel grinds at lower temperature. Increased peak-to-valley height on workpiece.
Wheel peripheral speed		
Higher		Wheel is harder. Decreased peak-to-valley height on workpiece.
Lower		Wheel is softer.
Workpiece speed		
Higher		Wheel is softer.
Alteration		Effect on grinding result
Workpiece form		
Small contact zone between wheel and workpiece (for example external cylindrical grinding)		Harder wheel required so that abrasive grain does not break off too early.
Large contact zone between wheel and workpiece (for example, in flat grinding with cup wheel)		Use softer or more open-porous wheel to get close to the range of self-sharpening and to limit heating
Interruptions in the workpiece surface		Wheel is softer.

(excerpt from the records of the Elbe-Schleifmittelwerke)

13.8.2 Table of failures

Table 13.16 Failures during grinding

Effects on the workpiece	Failure reason	Remedy
Grinding cracks Scorch marks soft zones or distortion on the workpiece	Wheel too hard infeed too high cutting speed too high insufficient cooling	Softer grinding wheel lower infeed diminish *v* better cooling
Feed markings (in cylindrical grinding helix lines on surface)	Wheel too hard Wheel incorrectly dressed, one-sided wheel contact	Redress Use softer grinding wheel
Chatter marks	Vibrations Wheel too hard or incorrectly balanced workpiece incorrectly mounted	Softer grinding wheel rebalance check workpiece mounting
Particles coming off wheel	Grains come off the wheel and get into the coolant cycle	Improve coolant cleaning Check grinding wheel
Grinding grooves	Wheel too rough Sparking out time too short	Use smaller grain size longer sparking out

13.9 Reference tables

Table 13.1 Accuracy values and allowances during grinding
(see Chapter 13.4 page 245).

Table 13.14 Abrasive, grain size, hardness and structure of the grinding wheels
(see Chapter 13.7.4, page 263)

Table 13.17 Feed values during grinding

Kind of machining	Cylindrical grinding with longitudinal feed	Flat grinding (peripheral grinding)
	Feed in longitudinal direction	Lateral feed
	f in mm/revolution	*f* in mm/stroke
Roughing	$\frac{2}{3} \cdot B$ bis $\frac{3}{4} \cdot B$	$\frac{2}{3} \cdot B$ bis $\frac{4}{5} \cdot B$
Finishing	$\frac{1}{4} \cdot B$ bis $\frac{1}{2} \cdot B$	$\frac{1}{2} \cdot B$ bis $\frac{2}{3} \cdot B$
Precision machining	–	2,0 mm

B in mm grinding wheel width

Table 13.18 Infeed *e* in mm (depth of cut a_e) during grinding

Kind of machining	Material	Cylindrical grinding			Flat grinding
		External	Internal	Recessing	
Roughing	Steel	0,02–0,04	0,01–0,03	0,002–0,02	0,03–0,1
	Grey cast iron (GG)	0,04–0,08	0,02–0,06	0,006–0,03	0,06–0,2
Finishing	Steel	0,002–0,01	0,002–0,005	0,0004–0,005	0,002–0,01
	Grey cast iron (GG)	0,004–0,02	0,004–0,01	0,001–0,006	0,004–0,02

Table 13.19 Cutting speeds of grinding wheel v_c in m/s, workpiece speeds v_w in m/s and speed ratios $q = v_c/v_w$ for circular- and flat grinding. Excerpt from the firm document by Naxos-Union, Frankfurt, and DIN 69103.

<table>
<tr><th rowspan="4">Material</th><th colspan="9">Cylindrical grinding</th><th colspan="6">Flat grinding</th><th rowspan="3">Parting off (grinding)</th></tr>
<tr><th colspan="6">External cylindrical grinding</th><th colspan="3" rowspan="2">Internal cylindrical grinding</th><th colspan="3" rowspan="2">Circumferential grinding</th><th colspan="3" rowspan="2">Face grinding</th></tr>
<tr><th colspan="3">Pre-</th><th colspan="3">Finish-</th></tr>
<tr><th>v_c</th><th>v_w</th><th>q</th><th>v_c</th><th>v_w</th><th>q</th><th>v_c</th><th>v_w</th><th>q</th><th>v_c</th><th>v_w</th><th>q</th><th>v_c</th><th>v_w</th><th>q</th><th>v_c</th></tr>
<tr><td>Steel, soft</td><td>30</td><td>0,22</td><td>130</td><td>30</td><td>0,17</td><td>180</td><td>25</td><td>0,32</td><td>80</td><td rowspan="3">30</td><td rowspan="3">0,16 up to 0,58</td><td rowspan="3">180 up to 50</td><td rowspan="3">25</td><td rowspan="2">0,1 up to 0,42</td><td rowspan="2">250 up to 60</td><td rowspan="4">45 up to 80</td></tr>
<tr><td>Steel, hardened</td><td>35</td><td>0,27</td><td>130</td><td>35</td><td>0,17</td><td>210</td><td>25</td><td>0,38</td><td>65</td></tr>
<tr><td>Grey cast iron</td><td>25</td><td>0,22</td><td>115</td><td>25</td><td>0,18</td><td>135</td><td>25</td><td>0,38</td><td>65</td><td>0,1 to 0,5</td><td>250 to 50</td></tr>
<tr><td>Brass and bronze</td><td>30</td><td>0,32</td><td>95</td><td>30</td><td>0,27</td><td>110</td><td>25</td><td>0,40</td><td>60</td><td>25</td><td rowspan="2">0,25 to 0,67</td><td rowspan="2">40 to 100</td><td>–</td><td rowspan="2">0,33 to 0,75</td><td rowspan="2">60 to 27</td></tr>
<tr><td>Al-alloys</td><td>20</td><td>0,58</td><td>35</td><td>20</td><td>0,45</td><td>45</td><td>20</td><td>0,58</td><td>35</td><td>20</td><td>20</td><td>–</td></tr>
<tr><td>Cemented carbide</td><td>8</td><td>0,08</td><td>100</td><td>8</td><td>0,07</td><td>120</td><td>8</td><td>0,13</td><td>60</td><td>8</td><td>0,07</td><td>115</td><td>25</td><td>0,07</td><td>115</td><td>45</td></tr>
</table>

With special permission of the DSA (German committee for grinding wheels), it is possible to exceed the peripheral speeds of the grinding wheels v_c in the case of special wheels (see also Table 13.20)

Table 13.20 Increased peripheral speeds for grinding wheels by Naxos-Union, Frankfurt (excerpt from records of Naxos-Union) permitted by the DSA

DSA permission number	Denomination	Bond	Lowest hardness	Coarsest grain size	Da maximal diameter.	B max. thickness	Max. hole	Min. wall thickness.	Minim. Floor thickness	Operating speed w m/s
952	grinding wheels highly compressed without hole	Ba	Z	10	610	76	–	–	–	80
966	grinding wheels highly compressed with fine grain centre	Ba	Z	10/12	610	76	305	–	–	80
969	grinding wheels with fine grain centre	Ba	L	12	610	76	0,5 Da	–	–	60
969	grinding wheels with fine grain centre	Ba	L	12	800	100	0,5 Da	–	–	60
1079	grinding wheels	Gu	O P	60 46	500 760	50 30	0,5 Da	–	–	60
1097	grinding wheels even on wet ground	Ba	L	24cb	610 1000	510 250	} 0,5 Da	–	–	60
1207	Minimal abrasive material (minimal wheel)	Ke	I	24 {	50 45 40 35	30 35 45 50	} 0,18 Da	–	–	45
1208	Cutting-off wheels with fibre reinforcem.	Ba	–	24	230	1/50 Da	22,3	–	–	80
1211	Cutting-off wheels with fibre reinforcem.	Ba	–	16	800	1/50 Da	0,1 Da	–	–	100
1297	Minimal wheel	Ba	N	20	50	25	Shank 10 mm	–	3/5 B	45
1300	Separating disks reinf. by fibrous mat., for hand-cutting-off machines	Ba	N	24	300	1/50 Da	0,14 Da	–	–	80
1310	Grindg. wheels re-inforc. by fibrous mat.	Ba	–	10/16	500	65	DIN 69120	–	–	80
1414	Cup wheels with fine grain floor and reinforcement	Ba	O	10/27	400	260	0,25 Da	0,25 Da	0,19 B	45
1705	Separating disks reinforced by fibrous material	Ba	R	20	1200	1/50 Da	0,6 Da max 250	–	–	80
1706	Separating disks hot pressed reinf. by fibrous material	Ba	Z	14	1200	14	0,25 Da	–	–	100
1744	Grinding wheels hole, tinctured with artificial resin	Ke	L	100	610	50	0,5 Da	–	–	80
1767	Separating disks rein-forced by fibrous mat.	Ba	–	24	1200	1/50 Da	0,2 Da	–	–	100
1827	Grinding wheels with recess	Ke	H	46	300	50	127	60	20	45

Other abrasive manufacturers have similar permissions similar to those shown above.

Table 13.21 Grinding wheels and their speeds, diameters and peripheral speeds

Diameter in mm	Peripheral speed in m/s										Diameter in mm
	15	20	25	30	35	40	45	60	80	100	
	Revolutions per minute										
3	95500	–	–	–	–	–	–	–	–	–	3
5	57300	76400	95500	–	–	–	–	–	–	–	5
8	35800	47800	59700	71600	83600	95500	–	–	–	–	8
10	28600	38200	47700	57300	66800	76400	86000	–	–	–	10
15	19100	25500	31800	38200	44600	51000	57500	76500	–	–	15
20	14300	19100	23900	28600	33400	38200	43100	57300	76500	–	20
25	11500	15300	19100	23000	26750	30550	34370	45840	61000	–	25
40	7160	9550	11320	14320	16700	19100	21500	28600	38100	–	40
50	5730	7650	9550	11450	13400	15275	17185	22900	30500	38200	50
65	4400	5900	7350	8800	10300	11750	13200	17600	23500	29300	65
75	3825	5100	6370	7650	8910	10185	11455	15300	20400	25500	75
90	3185	4245	5300	6370	7430	8490	9560	12700	17000	21200	90
100	2865	3825	4775	5730	6700	7640	8600	11450	15300	19100	100
115	2490	3320	4150	4980	5815	6640	7470	9965	13200	16600	115
125	2300	3050	3800	4600	5300	6110	6875	9200	12200	15250	125
150	1900	2550	3200	3800	4450	5100	5730	7640	10200	12750	150
175	1625	2200	2730	3270	3800	4365	4910	6550	8750	10900	175
200	1440	1910	2390	2865	3350	3820	4300	5 730	7640	9550	200
225	1275	1700	2100	2550	2975	3395	3820	5100	6800	8500	225
250	1150	1525	1900	2300	2675	3055	3440	4575	6100	7625	250
300	950	1275	1590	1900	2230	2550	2865	3820	5100	6375	300
350	820	1090	1370	1640	1900	2180	2450	3275	4360	5450	350
400	725	960	1200	1450	1675	1910	2150	2870	3810	4775	400
450	635	850	1060	1275	1485	1700	1910	2550	3400	4250	450
500	575	770	960	1150	1340	1525	1720	2290	3050	3820	500
550	515	700	850	1030	1200	1390	1565	2080	2780	–	550
600	475	640	800	950	1110	1275	1430	1910	2550	–	600
650	440	590	730	875	1030	1175	1320	1750	–	–	650
700	405	540	675	810	950	1090	1225	1640	–	–	700
750	380	510	635	765	890	1020	1145	1530	–	–	750
800	360	475	600	715	835	955	1075	1430	–	–	800
850	340	450	565	675	790	900	1010	1350	–	–	850
900	320	425	530	640	750	850	955	1270	–	–	900
950	300	400	500	600	700	805	905	1205	–	–	950
1000	285	380	480	570	670	765	860	1145	–	–	1000
1050	275	365	455	550	640	730	820	1100	–	–	1050
1100	260	350	430	520	600	695	780	–	–	–	1100
1150	250	330	415	500	580	665	745	–	–	–	1150
1200	240	320	400	480	560	640	720	–	–	–	1200
1300	220	295	365	440	515	585	660	–	–	–	1300
1400	200	270	340	405	475	545	615	–	–	–	1400
1500	190	255	320	380	445	500	575	–	–	–	1500
2000	142	190	–	–	–	–	–	–	–	–	2000

Table 13.22 Permissible imbalances of grinding wheels (in g) as a function of wheel weight (in kg), diameter (in mm) and peripheral speed (in m/s)

Wheel weight, in kg	Grinding wheel diameter, in mm								
	to 305			305–610			Greater than 610		
	Peripheral speed, in m/s								
	up to 40	40–63	63–100	Up to 40	40–63	61–100	Up to 40	40–63	63–100
0,5	5,6	4,5	3,6	7,2	5,6	4,5	8,9	7,2	5,6
1,0	7,9	6,4	5,1	10	8,0	6,3	13	10	8
2,0	11	9	7	14	11	9	18	14	11
3,0	13	11	9	18	13	11	22	18	13
4,0	16	13	10	20	16	13	25	20	16
6,0	19	16	12	25	19	16	31	25	19
10	25	20	16	32	25	20	40	32	25
15	31	25	20	39	31	25	49	39	31
20	35	28	23	45	35	28	57	45	35

Example: Assuming a grinding wheel of 500 mm diameter, 6 kg weight, to be run at a peripheral speed of 60 m /s, an imbalance of 19 g is permissible.

Table 13.23 Weight of some straight wheels, in kg, according to DIN 69120

Wheel diameter, in mm	Wheel width, in mm						
	6	10	16	25	40	63	100
25	0,008	0,013	0,020	0,033	0,052	–	–
50	0,030	0,050	0,075	0,125	0,200	–	–
100	0,12	0,20	0,32	0,50	0,80	–	–
150	0,26	0,45	0,72	1,13	1,80	–	–
200	0,48	0,80	1,28	2,00	3,20	–	–
300	1,1	1,8	2,9	4,5	7,2	–	–
400	–	3,2	5,1	8,0	13	20	32
500	–	–	–	13	20	32	50
650	–	–	–	–	33	52	83
750	–	–	–	–	–	69	110
900	–	–	–	–	–	102	162

Table 13.24 Metalworking fluids (cooling and lubrication) for grinding

Medium	Additional agents	Suitable for	
		Kind of process	Material
Water	–	Simple machining	Non-ferrous metals
Watery solutions	Soda or abrasive powders (salt) (3–5%)	Simple machining with low requirements in terms of surface quality	Steel Grey cast iron
Emulsions (mix of H_2O and drilling oil, share of drilling oil 2%)	Emulsifiers that keep the oil distributed in water	Flat-, cylindrical- and profile grinding operations	For all metals
Grinding oils (mineral oils with viscosities 16–36 cSt at 50 °C) not suitable for wheel with natural resin or rubber bond	Extreme pressure additives (for example sulphur, chlorine- or phosphor compounds) corrosion inhibitors	External- and internal cylindrical grinding under hard machining conditions, grinding of gears, threads and grooves grinding with v_s 60 m/s	Steel, hardened stainless steels highly alloyed steels light metals Magnesium
Spindle oil	Petroleum (mixture 1 : 1)	Honing	Steel, copper aluminium magnesium
Petroleum	–	For fine grinding and honing	Steel and copper alloys

13.10 Calculation examples

Example 1

Case hardened shafts (60 ∅ × 140 long), made of 16 MnCr 5 (Figure 13.33), with a grinding allowance of 0,2 mm, have to be ground to final size.

Sought for:

1. Feasible grinding techniques
2. Choice of grinding technique
3. Choice of wheel
4. Definition of cutting parameters
5. Determine machine input power ($\eta_M = 0{,}6$)
6. Calculate machining time

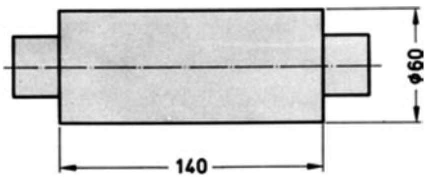


Figure 13.33
Shaft to be ground

Approach:

1. Cylindrical grinding with longitudinal feed or cylindrical grinding – plunge grinding
2. For shaft manufacturing, cylindrical grinding with longitudinal feed is chosen
3. Choice of wheel

3.1. Abrasive, grain size, hardness and structure
a grinding wheel of the quality EK 50 L 6 was chosen from Table 13.14

3.2. Wheel dimension
400 ∅ × 40 mm width was chosen from Table 13.23

4. The following values were chosen from the Tables 13.17, 13.18 and 13.19:
v_c = 35m/s; v_w = 0,27m/s; q = 130; a_e = 0,003 mm
Feed in longitudinal direction: $f = 0{,}7 \cdot B = 0{,}7 \cdot 40$ mm = 28 mm/U

5. Machine input power

5.1. Mean thickness of cut

$$h_m = \frac{\lambda_{Ke}}{q} \cdot \sqrt{a_e \cdot \left(\frac{1}{D_s} + \frac{1}{d}\right)} = \frac{39\,\text{mm}}{130} \cdot \sqrt{0{,}003\,\text{mm}\left(\frac{1}{400\,\text{mm}} + \frac{1}{60\,\text{mm}}\right)}$$

$$h_m = \frac{39\,\text{mm}}{130} \cdot 0{,}0076 = 0{,}0023\,\text{mm}$$

(λ_{Ke} = 39 from Table 13.2)

5.2. Specific cutting force

$$k_c = \frac{(1\,\text{mm})^z}{h_m^z} \cdot k_{c1,1} \cdot K = \frac{(1\,\text{mm})^{0,26}}{0{,}0023^{0,26}} \cdot 2100\,\text{N/mm}^2 \cdot 4 = 40800\,\text{N/mm}^2$$

K = 4,0 interpolated from Table 13.3

5.3. Mean major cutting force per cutting edge
$F_{cm} = b \cdot h_m \cdot k_c$

Effective grinding width b corresponds to about 0,7fold of the grinding wheel width B and was consequently assumed as b = 28 mm.
F_{cm} = 28 mm · 0,0023 mm · 40800 N/mm^2 = 2627,5 N

5.4. Angle of approach φ

$$\varphi = \frac{360^\circ}{\pi} \cdot \sqrt{\frac{a_e}{D_s \cdot \left(1 + \frac{D_s}{d}\right)}} = \frac{360^\circ}{\pi} \cdot \sqrt{\frac{0{,}003\,\text{mm}}{400\,\text{mm}\left(1 + \frac{400\,\text{mm}}{60\,\text{mm}}\right)}} = 0{,}11^\circ$$

5.5. Number of cutting edges in contact z_E

$$z_E = \frac{D_s \cdot \pi \cdot \varphi^\circ}{\lambda_{Ke} \cdot 360^\circ} = \frac{400\,\text{mm} \cdot \pi \cdot 0{,}11^\circ}{39\,\text{mm} \cdot 360^\circ} = 0{,}0098$$

5.6. Machine input power

$$P = \frac{F_{cm} \cdot z_E \cdot v_s}{10^3\ \text{W/kW} \cdot \eta_M} = \frac{2627{,}5\,\text{N} \cdot 0{,}0098 \cdot 35\,\text{m/s}}{10^3\ \text{W/kW} \cdot 0{,}6} = 1{,}5\,\text{kW}$$

6. *Machining time*

6.1. Number of cuts i_{ges}

$$i = \frac{\Delta d}{2a_e} + 8 = \frac{(60{,}2\,\text{mm} - 60\,\text{mm})}{2 \cdot 0{,}003\,\text{mm}} + 8$$

$$i = 41$$

6.2. Wheel path in longitudinal direction

$$L = l - \frac{1}{3}B = 140\,\text{mm} - \frac{40\,\text{mm}}{3} = 126{,}7\,\text{mm}$$

6.3. Feed per revolution (Table 13.17)
$f = 0{,}7 \cdot B = 0{,}7 \cdot 40$ mm = 28 mm/revolution   revolution: U

6.4. Workpiece speed (see Chapter 13.2.3.1.)

$$n_w = \frac{v_w \cdot 60\,\text{s/min}}{d \cdot \pi} = \frac{0{,}27\,\text{m/s} \cdot 60\,\text{s/min}}{0{,}06\,\text{mm} \cdot \pi} = 86\,\text{min}^{-1}$$

$n_w = 90\,\text{min}^{-1}$ selected from Figure 7.47, page 81, standard speed

6.5. Machining time

$$t_h = \frac{L \cdot i}{f \cdot n_w} = \frac{126{,}7\,\text{mm} \cdot 41}{28\,\text{mm/U} \cdot 90\,\text{U/min}} = 2{,}06\,\text{min}$$

The product $f \cdot n_w$ results in the feed rate v_f of the grinding machine table.
$v_f = f \cdot n_w$ = 28 mm/U · 90 U/min = 2520 mm/min

If the grinding machine is driven hydraulically, then one can in effect infinitely adjust each calculated table speed in the regulating range of the machine.

For mechanical drives, there are only special fixed feed rates.

In this case, select the feed rate next to the calculated value v_f, and insert it into the equation for the machining time.

v_{ftat} in mm/min   Feed rate of the table actually available or adjustable on the machine.

Example 2
The task is to grind a plate made of E 360, 400 mm length × 200 mm width × 30 mm thickness, on one surface.

The 2nd surface has already been ground. Allowance is 0,8 mm.

Sought for:

1. Grinding technique
2. Choice of grinding wheel
3. Choice of cutting parameters
4. Machining time

Approach:

1. The applied grinding technique is flat grinding (face- or circumferential grinding). Here, the chosen technique is circumferential grinding.

2. Choice of grinding wheel

2.1. Abrasive, grain size, hardness and structure from Table 13.14: EK 46 K 14

2.2. Wheel dimensions

200 ∅ × 25 mm width, selected from Table 13.23.

3. Choice of cutting parameters

3.1. Peripheral speeds from Table 13.19

$$v_c = 30 \text{ m/s}; v_w = 0{,}3 \text{ m/s} = 18 \text{ m/min}; \; q = \frac{v_c}{v_w} = \frac{30}{0{,}3} = 100$$

3.2. Lateral feed (Table 13.17)
$f = 0{,}7 \cdot B = 0{,}7 \cdot 25$ mm = 17,5 mm/stroke
$f = 35$ mm/double stroke

3.3. Infeed e from Table 13.18
$a_e = 0{,}06$ mm selected for calculation, on average
For the first strokes, $e = 0{,}1$ mm is chosen, and for a residual allowance of approx. 0,1 mm,
$a_e = 0{,}03$ mm is selected.

4. Machining time (Chapter 13.6.1.)

4.1. Wheel path in cross direction

$$B_b = \frac{2}{3} \cdot B + b = \frac{2}{3} \cdot 25 \text{ mm} + 200 \text{ mm} = 216{,}7 \text{ mm}$$

4.2. Wheel path in longitudinal direction
$L = l_a + l + l_u$
$l_a = l_u = 0{,}04 \cdot l = 0{,}04 \cdot 400$ mm = 16 mm
$L = 16$ mm + 400 mm + 16 mm = 432 mm

4.3. Number of grindings (number of infeeds)

$$i = \frac{z_h}{a_e} + 8 = \frac{0{,}8 \text{ mm}}{0{,}06 \text{ mm}} + 8 = 13{,}3 + 8 = 21{,}3 \rightarrow 21$$

4.4. Number of double strokes per minute n

$$n = \frac{v_w}{2 \cdot L} = \frac{18 \text{ m/min}}{2 \cdot 0{,}432 \text{ m}} = 20{,}8 \text{ DH/min}$$

4.5. Machining time

$$t_h = \frac{B_b \cdot i}{f \cdot n} = \frac{216{,}7 \text{ mm} \cdot 21}{35 \text{ mm/DH} \cdot 20{,}8 \text{ DH/min}} = 6{,}25 \text{ min}$$

Example 3

The task is to grind 1000 rollers for ball bearings, made of alloyed steel, with 64 HRC hardness and the dimension

20 mm ∅ × 30 mm length.

Allowance is 0,1 mm.

A grinding wheel with

$D_s = 300$ mm ∅ and a width of $B = 150$ mm

is used.

Sought for:

1. Manufacturing process
2. Regulating wheel diameter
3. Height offset of the support ruler

4. Machining time

Approach

1. *Centreless through grinding* is selected as the operational principle.

2. Regulating wheel diameter
$D_R = 0{,}7 \cdot D_s = 0{,}7 \cdot 300\text{ mm} = 210\text{ mm}$

3. Height offset

$$h = 0{,}1 \cdot \frac{(D_R + d)\cdot(D_s + d)}{D_R + D_s + 2\cdot d} = \frac{0{,}1\cdot(210\,\text{mm} + 20\,\text{mm})\cdot(300\,\text{mm} + 20\,\text{mm})}{210\,\text{mm} + 300\,\text{mm} + 2\cdot 20\,\text{mm}}$$

$$h = \frac{0{,}1\cdot 230\,\text{mm}\cdot 320\,\text{mm}}{550\,\text{mm}} = 13{,}38\,\text{mm}$$

According to the rule of thumb:

$$h = \frac{d}{2} = \frac{20\,\text{mm}}{2} = 10\text{ mm}$$

4. Machining time

4.1. Path of 1000 workpieces
$L = n \cdot l + B = 1000 \cdot 30\text{ mm} + 150\text{ mm} = 30150\text{ mm}$

4.2. Number of grindings (Chapter 13.6.2.1.)

$$i = \frac{\Delta d}{2\cdot a_e} = \frac{0{,}1\,\text{mm}}{2\cdot 0{,}01\,\text{mm}} = 5$$

($a_e = 0{,}01$ mm selected)

4.3. Regulating wheel speed (Chapter 13.2.4.)

$$n_R = \frac{8{,}18}{D_s} = \frac{8{,}18\,\text{m/min}}{0{,}3\,\text{m}} = 27{,}26\,\text{min}^{-1}$$

4.4. Passing speed
(Inclination of regulating wheel assumed with $\alpha = 3°$)
$v_A = D_R \cdot \pi \cdot n_R \cdot \sin\alpha = 210\text{ mm} \cdot \pi \cdot 27{,}26\text{ min}^{-1} \cdot 0{,}0523 = 941{,}2\text{ mm/min}$

4.5. Machining time

$$t_h = \frac{L\cdot i}{v_A} = \frac{30150\,\text{mm}\cdot 5}{941{,}2\,\text{mm/min}} = 160{,}2\,\text{min}$$