MAAG Gear Grinding Methods

E. Günter and A. Rust

It is not intended in this paper to describe the individual types of grinding machines produced by MAAG and to enter into details. Such detailed information can be found in sales literature, operating mannuals etc.

The intention of this brief paper is rather to highlight some of the fundamental aspects and innovations of the MAAG gear grinding processes. The current capabilities of the corresponding machines will be illustrated by some production examples.

1. Optimum basic principle secures high precision

Dish grinding wheels having a concave-conical shaped active side are used exclusively on MAAG gear grinding machines. Only the outer rim of the grinding wheels contacts the tooth flanks. This annular zone provides so to speak an ideally accurate plane grinding wheel surface in contact with the tooth flanks being ground (Fig. 1).

A constant axial position of this rotating grinding wheel plane is maintained by a wheel wear sensing and compensating system.

The tooth profile is generated on the grinding machine entirely by kinematic processes.

With the 0° pressure angle and the K (Kurzhub=short stroke) processes the involute tooth profile is generated by rolling the gear on its base circle. The longitudinal tooth form is produced by a relative motion between the tooth flank and the grinding wheel in line with the tooth trace. A 0° pressure angle gear grinding machine (type SD-36X) and the resulting contact path along the tooth flank are shown in Figs. 2 and 3 respectively.

A vertical $15^{\circ}/20^{\circ}$ pressure angle gear grinding machine is shown in Fig. 4. The motion for generating the tooth profile is produced by slowly rolling the gear on its reference circle. The longitudinal tooth form is produced by a relatively rapid movement of the grinding zone in line with the straight line generators. The resulting contact path, shown in Fig. 5, is approximately in line with the straight line generators due to the combination of the two previously mentioned motions.

The two main characteristics described - the use of dish grinding wheels with narrow active rim and purely kinematic generation of the tooth flanks - result in the following principal advantages associated with the MAAG gear grinding processes:

a) High gear grinding accuracy

The tooth profile is generated by purely kinematic means and is therefore basically independent of the form and therefore also the wear of the grinding wheel.

As the machine components and movements governing the tooth profile accuracy can be produced with a high degree of precision without difficulty, an excellent basis for high precision gear grinding is created.

b) Gear grinding of uniform quality

The kinematic chain involved in generating the tooth profile is virtually free from wear. The boundary conditions for grinding all the teeth of a gear, all gears within a batch or for repetition of a previous grinding operation thereby remain constant. The result is uniform product quality, which also enables quality control to be minimized. Spot checks of the profile and tooth alignment accuracy therefore suffice in many cases. This offers significant cost advantages compared with processes where the tooth profile is adversely effected by the (unavoidable) grinding wheel wear.

c) Easily controlled and constant tooth profile modifications

All MAAG gear grinding machines with exception of types SHS-180/240 and JHSS-90, are equipped for the production of profile and longitudinal tooth flank modifications. These enable the right and left hand tooth flanks to be modified individually to the required extent within the same operation.

Due to the fact that the entire tooth flank is ground by the same zone of the grinding wheel rim and that the position of the contact zone on the tooth flank relative to the instantaneous axial feed and roll positions are always known exactly, above average control can be exercised over the tooth flank modifications. As the form of these modifications is again determined only by kinematic elements, very accurate modifications independent of grinding wheel wear can be produced with great consistency.

d) Grinding of profile and longitudinal modifications by the 0^o pressure angle method

With the 0^o pressure angle method the geometrical point of contact between grinding wheel and tooth flank is known accurately for each roll and axial feed position. On the one hand there is a direct relation between the position of the generating mechanism and the roll angle of the gear being ground, i.e. between the position of the generating mechanism and the position of the point being ground on the involute profile. On the other hand the geometrical point of contact of the grinding wheel moves longitudinally along the flanks with the feed motion. This provides the basis for grinding profile and longitudinal modifications. The profile modification is controlled in relation to the roll motion and the longitudinal modification in relation to the feed.

The system for tooth flank modifications with the 0^o pressure angle grinding method is shown diagrammatically in Fig. 6.

The modifications are produced by pulses by cams linked with the generating motion and the feed. These pulses are transmitted to and amplified by slave units, which control the wheel heads accordingly.

The cam plate drums 3 for the profile modification are mounted coaxially with the crank drive 1 of the generating slide 2. The cam plate drums 4 for the longitudinal modification are driven mechanically by the feed slide 5. The pulses for the modification are transmitted hydraulically to the hydromechanical slave units 6, which scale down the movement mechanically and transmit it to the wheel heads 7.

Great versatility in applying intentional modifications to the involute tooth flanks is offered by topological modifications, whose form and magnitude changes over the face width. The system for producing topological modifications will be described subsequently.

e) Grinding of profile and longitudinal modifications by the $15^o/20^o$ generating pressure angle method

The nature of the contact between grinding wheel and tooth flank is more complex for the $15^o/20^o$ method. It is nevertheless possible to define the geometrical points of contact between grinding wheel and tooth flank by the coordinates of the grinding machine.

The coordinates of the contact zone are the face width b and the contact depth g. The coordinates of the machine are the ram position H and the generating slide position W.

A diagram of the contact zone is shown in Fig. 7. The left hand diagram shows a tooth flank complete with generators and the two geometrical points of contact P_a and P_i between the grinding wheel and a generator.

The position of the two points P_a and P_i is determined by the position of the ram and the roll angle of the involute. The same position plotted by Cartesian coordinates g_α/b is shown in the right hand diagram.

The same points are shown in Fig. 8, but using the generating slide position W and the ram position H as grinding machine coordinates. Certain geometrical relationships exist between the two systems of co-ordinates g_α/b and W/H.

Thus the coordinates b_1 and g_1 of point P_1 in the contact zone diagram are related to the coordinates W_1 and H_1 of the machine coordinate system.

For the criss-cross grinding process (Fig. 9) it must also be taken into account that each position W, H in the machine coordinate system is associated with two geometrical grinding wheel contact points P_a and P_i.

Pulses for tooth flank modifications can therefore only be initiated when one of the two geometrical points of contact is outside the actual contact zone, with exception of the region of the root of the tooth, where the two contact points are very close together.

The geometrical relationships are somewhat simpler for broad rim grinding, where the grinding wheel always only has one geometrical point of contact with the tooth flank.

Microprocessor technology has enabled a topological modification system to be developed for the $15^0/20^0$ method, despite these complex geometrical relationships. This system is shown diagrammatically in Fig. 10 and has already been incorporated in the HSS-460B gear grinding machine in this form.

The modifications are specified in the form of a co-ordinate grid covering the entire tooth flank. The amount of modification z at each point in the contact zone g_α/b can be specified individually.

The desired modifications are entered at the microprocessor 2 of the grinding machine by tape 1. During the grinding process the wheel head coordinates W and H are signalled continuously to the microprocessor by the position transducers 6 and 7.

On the basis of this data, the electronic control system transmits the pulses necessary for the tooth flank modifications through the amplifier 4 and the control valve 9. This valve controls the hydraulic piston 10, which produces the movements of the wheel head 11 for the tooth flank modifications.

Apart from carrying out all the usual profile and longitudinal modification, this system can also produce any other desired pattern of modifications, such as variations of profile modifications over the face width.

f) <u>Feasibility of dry (environmentally desirable) grinding</u>

As already mentioned, the dish shaped grinding wheel only contacts the tooth flanks at its outer rim.

For roughing, where infeeds in the order of a tenth of a millimeter are employed, the main cutting action does not take place at the side of the rim, but at the periphery of the grinding wheel, due to the axial feed of the grinding wheel along the path of contact. This is an appreciable advantage compared with processes where the cutting takes place mainly at the side, e.g. with form or tapered grinding wheels. It is an established fact that a grinding wheel making contact along its periphery produces an appreciably higher rate of stock removal, as confirmed by experiments conducted by a company in Brno, Czechoslovakia, many years ago (Fig.11).

As can be seen in Fig. 12, during roughing the stock removal takes place at small, elongated contact zones, whose location on the tooth flank also changes rapidly.

Due to these circumstances, namely small contact areas moving rapidly over the tooth flank coupled with the favourably directed action of the grinding wheel, only a small amount of heat is transmitted to the ground surface. The MAAG grinding processes therefore form a rare exception in allowing grinding to be carried out economically without the use of coolant.

Apart from operational and environmental advantages, the dry grinding method also provides good conditions for the reliable and accurate operation of the wheel wear sensing and compensating system, which again improves accuracy. The wheel wear sensing and compensating system shown diagrammatically in Fig. 13 is part of the standard equipment of each MAAG gear grinding machine. As the accuracy of the tooth profile produced is only effected to a negligible extent by wheel wear, highly porous and relatively soft grinding wheels can be used, where the grains are released automatically once a certain degree of glazing has been reached, so that fresh grains can take over the cutting action. This self sharpening effect of the grinding wheel ensures a high rate of stock removal with little risk of burning.

2. The 0^{o} and K grinding methods

The contact geometry between the grinding wheels and the tooth flanks in the transverse plane is shown in Figs. 14, 15 and 16. The two extreme positions of the generating motion are shown, which represent the dead centre positions of the crank mechanism. For greater clarity the relative generating motion has not been represented as being between a fixed grinding wheel and a workpiece with an oscillating centre (the true situation on the machine) but as a workpiece with a fixed centre and reciprocating grinding wheels.

2.1 The classical 0^{o} method

For the normal 0^{o} process, which has been practised for many years, the bottom edge of the grinding wheels is set level with the tangent to the base cylinder.

The minimum stroke required for generating the tooth profile is equal to the developed length of the involute between the root and the tip circles. If, as shown in Fig. 14, the actual base tangent dimension (W_S) on the gear happens to coincide with this developed length, then one grinding wheel reaches the extremity of the generating motion at the tip of the tooth whilst simultaneously the other grinding wheel reaches the other extremity of the root of the tooth.

As this geometrical coincidence ($W_S = \sqrt{r_a^2 - r_b^2} - \sqrt{r_{fs}^2 - r_b^2}$) rarely occurs in practice, the distance between the grinding wheels must be made equal to the base tangent over the next larger or the next smaller span of teeth (Fig. 15). A larger generating slide stroke (H_G) is then required in order to cover the full grinding depth in this new situation. The increase in the distance between the grinding wheels and in the generating slide stroke necessarily results in an overrun at the tip (movement of the grinding wheel beyond the tip circle). Normally this "tip overrun" is a principal characteristic of the classical 0^{o} setting. The tip overrun has the disadvantage that each grinding wheel does not contact the tooth flank during the proportion of the oscillating motion shown shaded in Fig. 15. This results in an appreciable reduction of the rate of stock removal.

The newly developed K grinding method eliminates the tip overrun and simultaneously exploits a few other technological advantages.

2.2 The new K grinding method

With the K grinding method, the grinding wheels are set to such a level (H_{Sk}) that one grinding wheel in its extreme position contacts the lowest point to be ground,when the other grinding wheel contacts the tooth profile at the tip circle (Fig. 16). For this purpose, the grinding wheels are raised or lowered by a certain amount compared with the r_b setting of the classical 0^{o} method, depending which is the more favourable base tangent dimension W_s setting on the gear.

If the grinding wheels are set lower by an amount ($r_b - H_{Sk}$), which is the most frequent case, then the grinding wheels have to be inclined at an angle γ_s, so that there is no interference with the zones of the tooth profile immediately above the root circle.

Advantages:

The K grinding method offers the following advantages compared with the classical 0^{o} grinding method:

- The shorter generating stroke enables a higher number of generating strokes per minute to be employed for the same dynamic loading of the pitch block tapes and the generating system and therefore also permits higher feed rates. The grinding time can be shortened appreciably thereby.

- As can be seen in Fig. 16, the generating pressure angle along the tooth profile varies. Where the grinding wheels are set lower, the pressure angle is a minimum at the root of the tooth (γ_{fs}) and a maximum at the tip of the tooth (γ_a). More grains on the grinding wheel are used due to this variation of generating pressure angle, which results in a further increase in the rate of stock removal.

- Due to the elimination of the tip overrun, the forces applied by the left and right hand grinding wheels are more nearly equal. Profile errors due to shocks during entry of the grinding wheels are avoided.

- In the event of tooth profile modifications, the region available near the ends of the generating slide stroke for both tip and root relief cover a greater roll angle than is available for grinding tip reliefs with tip overrun (Fig. 17). This results in a gentler rise on the cam and hence lower wheel head acceleration. A reduction of the number of the generating strokes per minute, as may be necessary for grinding with tip overrun, is avoided. This can also increase significantly the optimum rate of stock removal.

Limitations

Apart from the appreciable advantages described, a number of other consequences of the K method must be mentioned:

- The lowering or lifting of the grinding wheels below or above the tangent to the base circle has the consequence that the kinematic system does not produce a theoretically correct involute. In the overwhelming number of cases the resulting deviation of the profile is still within the dimensional tolerance for the grade of tooth profile. This is all the more so, as the deviation due to the geometry is partly compensated by the varying rate of displacement of the grinding zones along the tooth profile and the consequent variation of stock removal. For large values of $(H_{SK}-r_b)$, the profile deviations, if too large, can be eliminated by the profile modification system without any penalty in productivity.

- For extreme K settings, i.e. for large values of $(H_{SK}-r_b)$ and large variations of the generating pressure angle (γ_{var}), there is a tendency for the ground tooth flanks to have a slightly greater surface roughness. By limiting the two grinding parameters mentioned and choosing appropriate grinding wheels, as well as reducing the traverse rate, an adequate surface finish can however be achieved for normal gears.

- The K method is somewhat more sensitive to any machine errors than the classical 0° method. With competent handling of the machine and avoidance of setting errors, such as asymmetric or non-level positioning of the grinding wheels, this does not have a significant detrimental effect.

Field of application

The K grinding method can be used with advantage for practically all gear grinding. It is used particularly for regular production runs, due to the potential saving of grinding time and cost.

Production examples

Some results obtained by the K method are listed in the table below. Depending on the tooth geometry of the individual case hardened gear, the reduction in grinding time compared with the classical 0° method lies between 0 and 60 %.

Gear data						Grinding allowance u_S	DIN grade	Grinding time (K-method) min.
z	m	α^0	β^0	b	x			
24	5	24	11	90	0.623	0.12	6	22.8
45	4.5	24	13	54	0.466	0.13	6	30.6
25	6.5	20	2	75	0.204	0.11	7	30
23	3.75	20	20	32	0.655	0.12	3	15
31	5.5	20	15	60	0.26	0.14	3	23.5
50	3	20	0	2x32	-0.01	0.15	5	17
57	2.5	20	21°24'	25	-0.028	0.1	7	22.5
75	3	20	0	30	-0.015	0.12	5	39
28	4	20	0	30	-0.01	0.12	5	16.5
20	2	20	0	40	-0.015	0.12	5	11.5
35	3	20	0	16	0.441	0.2	6	14
17	7	20	0	110	0.453	0.15	6	37.8
41	5	20	14	66	0.037	0.15	5	51
79	3.175	20	0	38	-0.352	0.19	3	80
61	3	20	0	55	-0.019	0.18	3	62

3. Increased productivity due to higher stroke rates and generating motion speeds with the 15°/20° grinding method

On helical teeth, the generators and the grinding wheel contact paths on the tooth flanks are as shown in Fig. 18. From this diagram it can be seen that for conventional machines employing a constant ram stroke the grinding wheels are only in contact with the tooth flank for part of the time. It is therefore possible to achieve an appreciable increase in productivity by varying the ram stroke to suit the length and the position of the path of contact, whilst simultaneously adapting the generating motion speed to the momentary length of stroke. As can be seen in the diagram, if a ram stroke H_s covering the entire face width with some overrun and a generating slide stroke H_w are used, the area covered by the grinding wheel is the parallelogram ABCD, while the area actually required for grinding of the tooth flanks is defined by the two vertical lines A_1D_1 and B_1C_1. The actual grinding zone $A_1BB_1C_1DD_1$ is emphasized in the diagram and for the example shown amounts to approximately 50 % of the area of the parallelogram ABCD.

On the HSS-460B gear grinding machine, the length, the position and the points of reversal of the ram stroke, as well as the speed of the generating motion are controlled by a microprocessor.

The stroke H_{Smin} corresponding to DD_1 is first steadily increased to H_{Smax} corresponding to $C_1A''_1$. In the central region of the generating slide stroke H_{Gm}, the length of the stroke is kept the same but its position is lowered vertically to B''_1A_1. Thereupon the stroke is steadily shortened to H_{Smin} corresponding to B_1B. The speed of the generating motion is varied to suit the length of stroke so as to keep the distance between the contact paths on the involute surfaces constant.

Fig. 1 Ideally accurate, plane grinding wheel surface

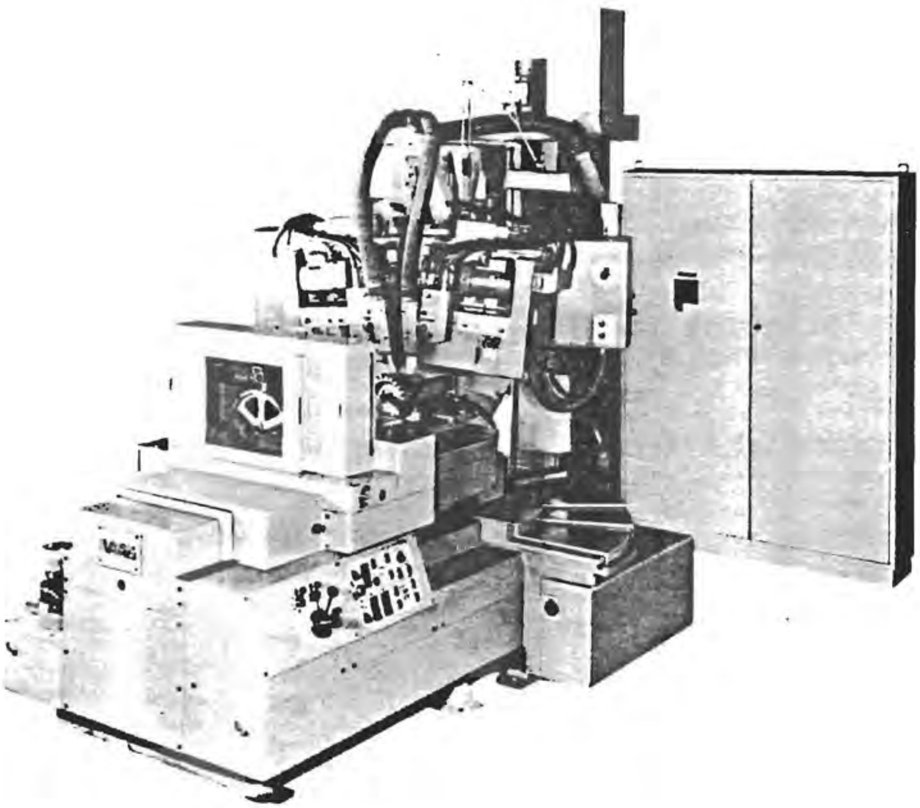


Fig. 2 Horizontal SD-36X gear grinding machine for the 0^{o} and K processes

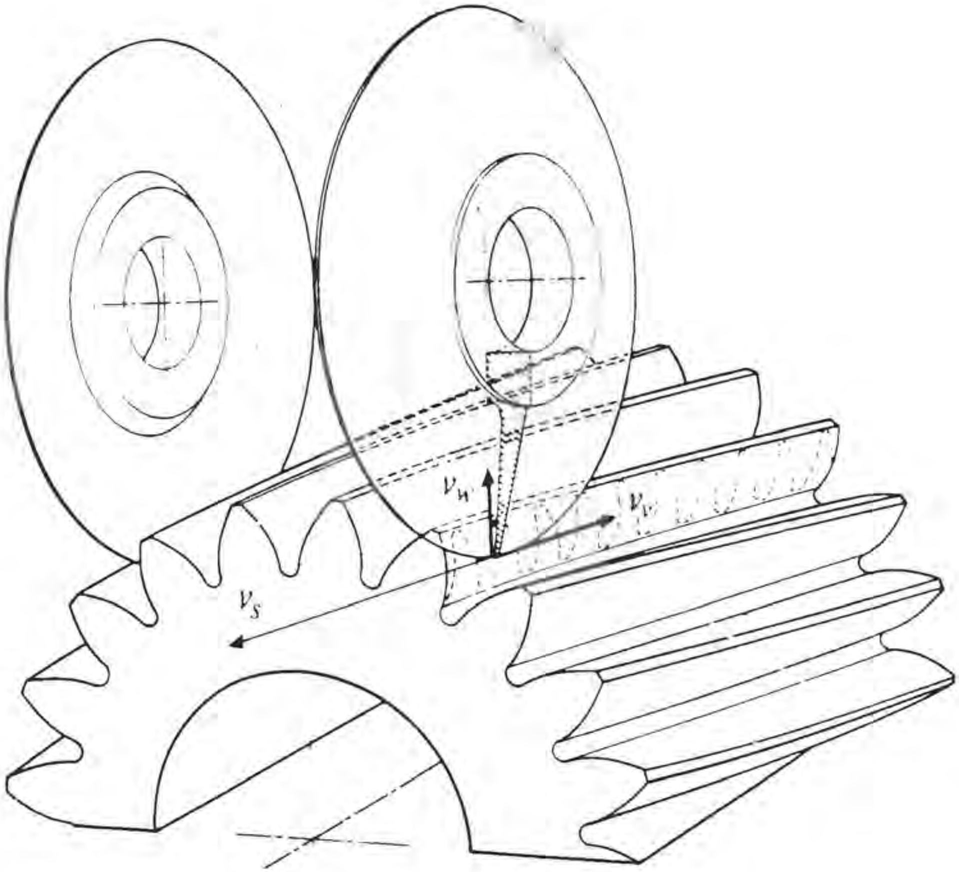


Fig. 3 Grinding wheel contact path on the tooth flank for the 0° and K grinding processes

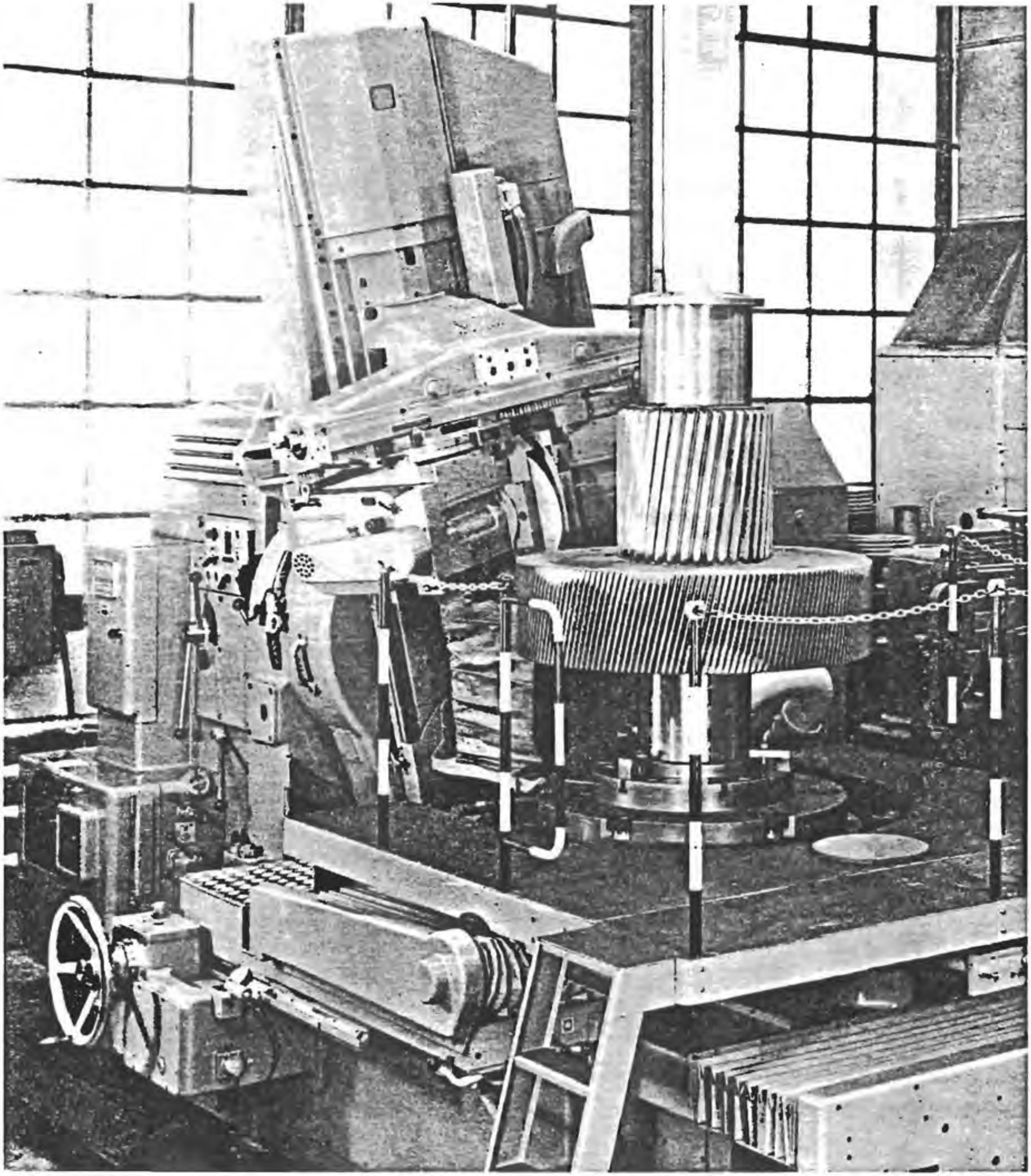


Fig. 4 Vertical SHS-180/240 gear grinding machine for the $15^{\circ}/20^{\circ}$ process

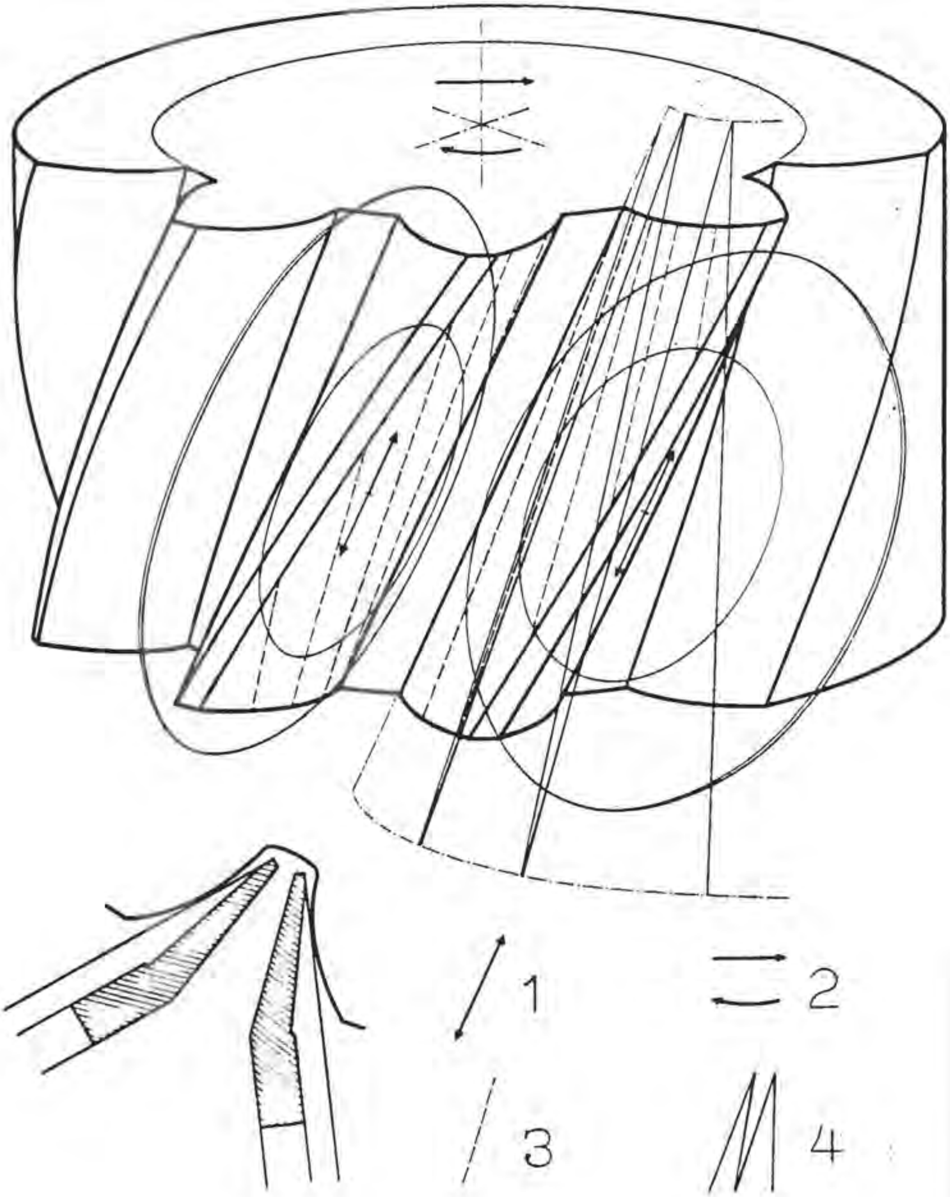


Fig. 5 Grinding wheel contact path on the tooth flank for the $15^0/20^0$ process

1 - feed motion
2 - generating motion
3 - generator
4 - contact path

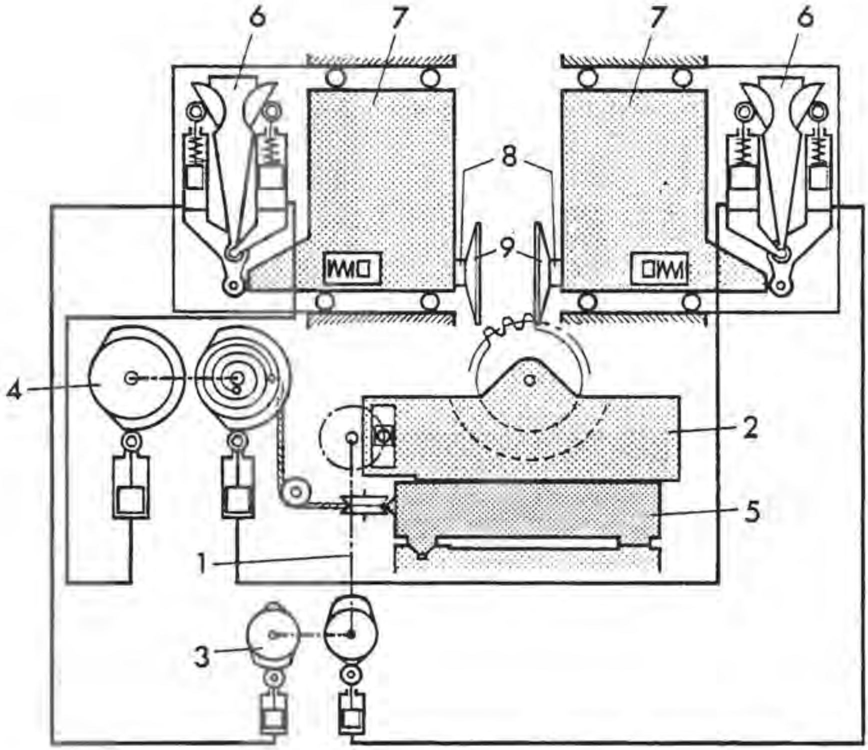


Fig. 6 Diagrammatic arrangement of the profile and longitudinal modification system for the 0° grinding method

1 - common shaft between profile modification cams and crank disks
2 - generating slide
3 - cam for profile modification
4 - cam for longitudinal modification (tooth trace modification)
5 - feed slide
6 - hydro-mechanical lever system
7 - moveably mounted wheel heads
8 - wheel spindles
9 - grinding wheels

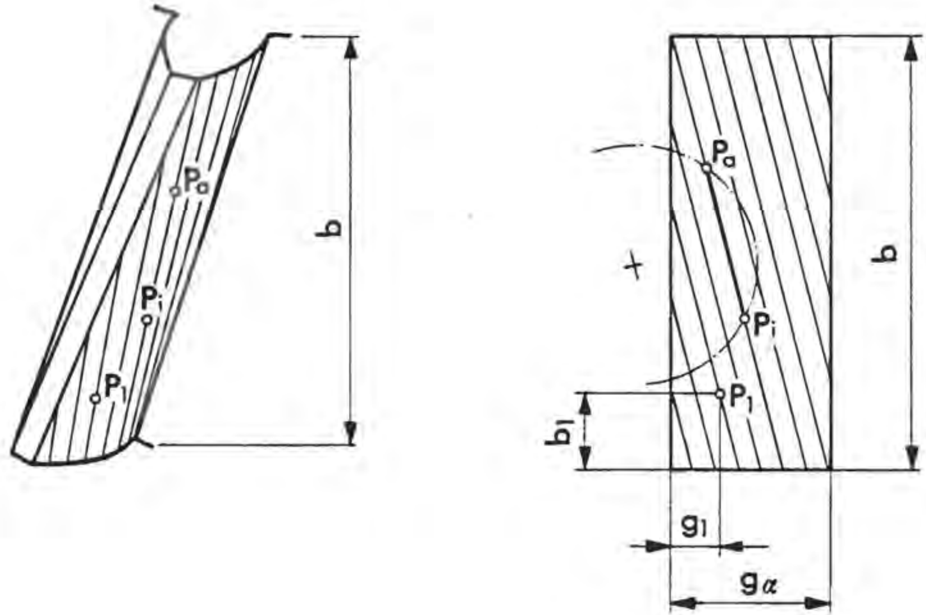


Fig. 7 Diagram of contact zone ($15^0/20^0$ grinding method)

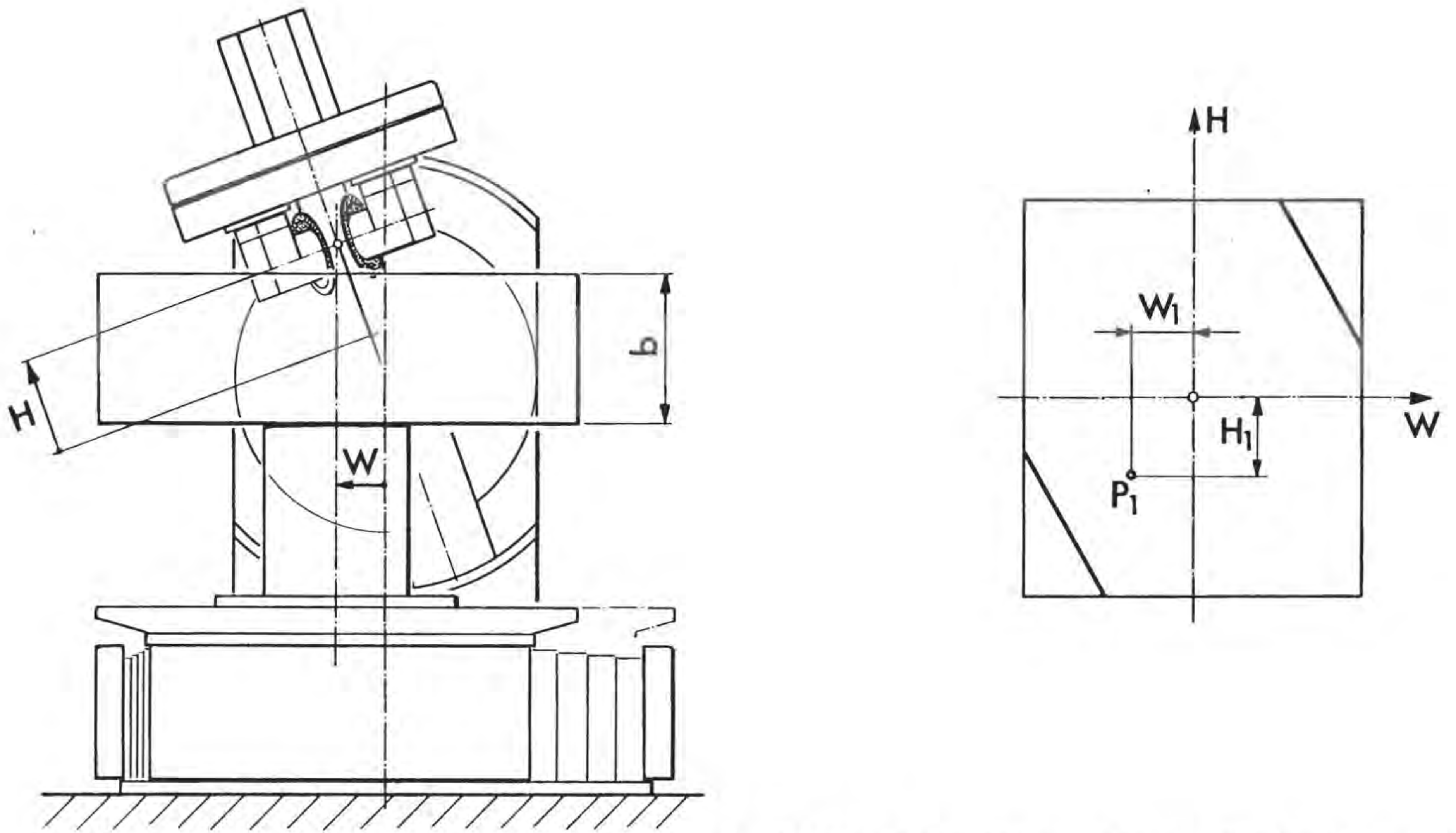


Fig. 8 Grinding machine coordinates ($15^{o}/20^{o}$ method)

Generating slide position W
Ram position H

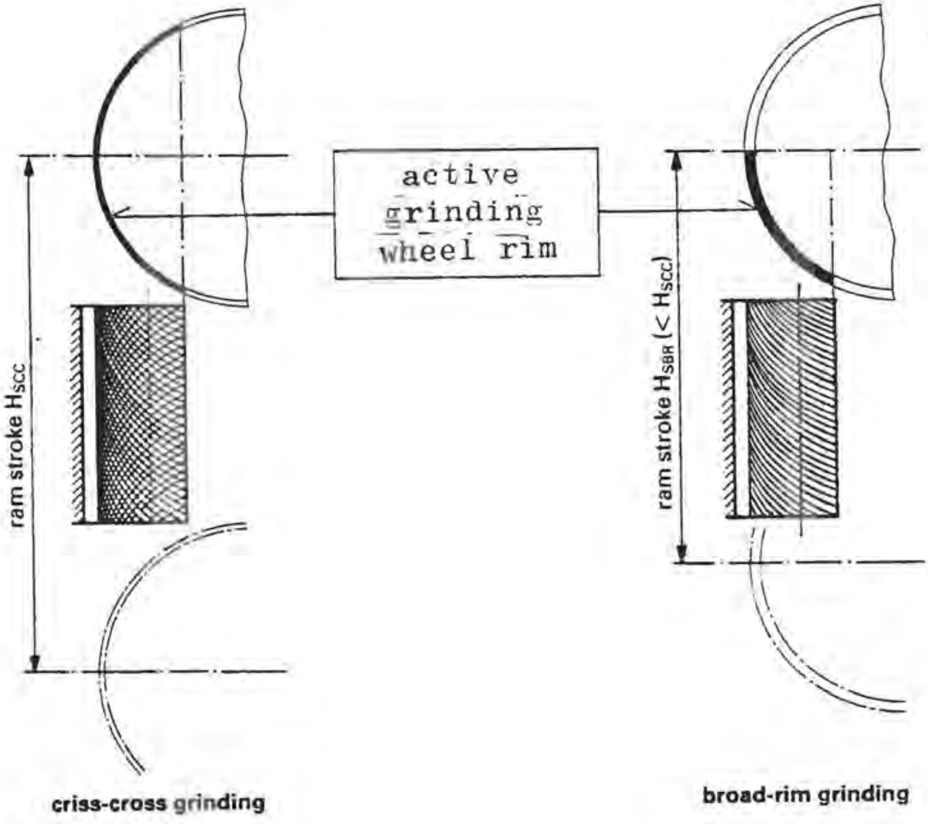


Fig. 9 $15^0/20^0$ grinding method (grinding patterns)
active grinding wheel rim
ram stroke
criss-cross grinding
broad-rim grinding

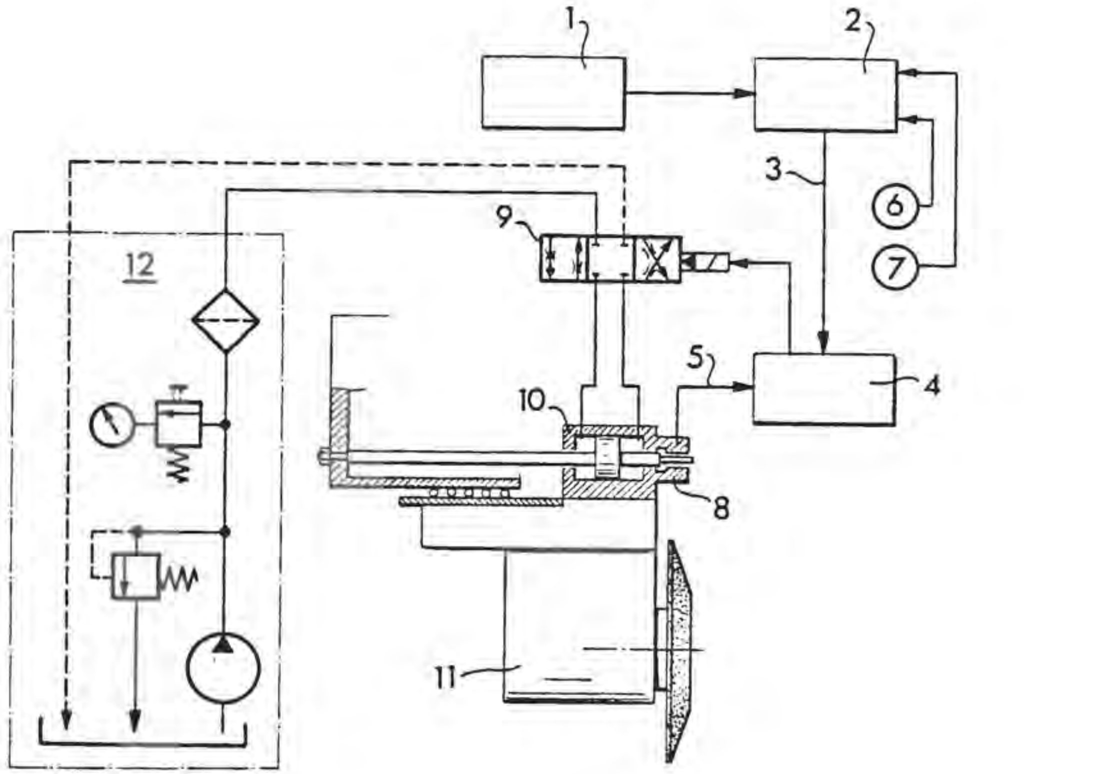


Fig. 10 Diagrammatic arrangement of the profile and longitudinal modification system for the 15°/20° grinding method

1 Data input
2 Microprocessor
3 Command signal
4 Amplifier
5 Feed back
6 Transducer, generating slide position
7 Transducer, ram position
8 Transducer, wheel head actual position
9 Control valve
10 Hydraulic piston
11 Wheel head
12 Hydraulic power pack

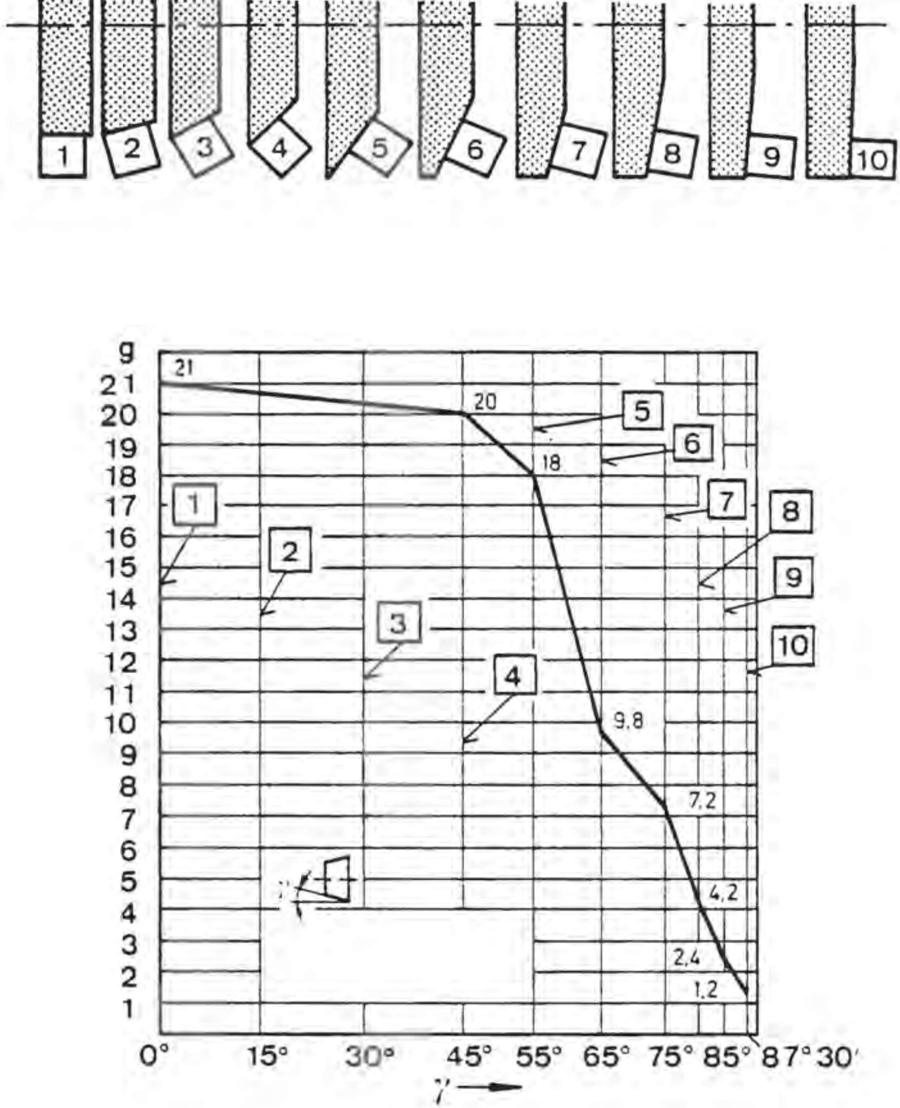
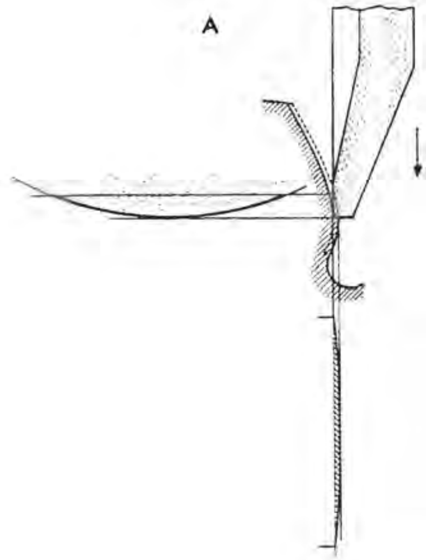
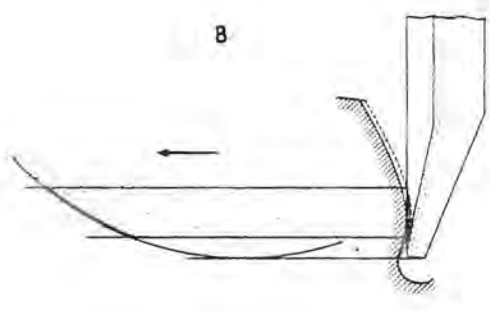


Fig. 11 Stock removal in relation to grinding wheel cutting face angle



A With the 0° and K processes: main component of contact path is along tooth profile



B With the $15^{\circ}/20^{\circ}$ process: main component is along generator

Fig. 12 Grinding wheel action

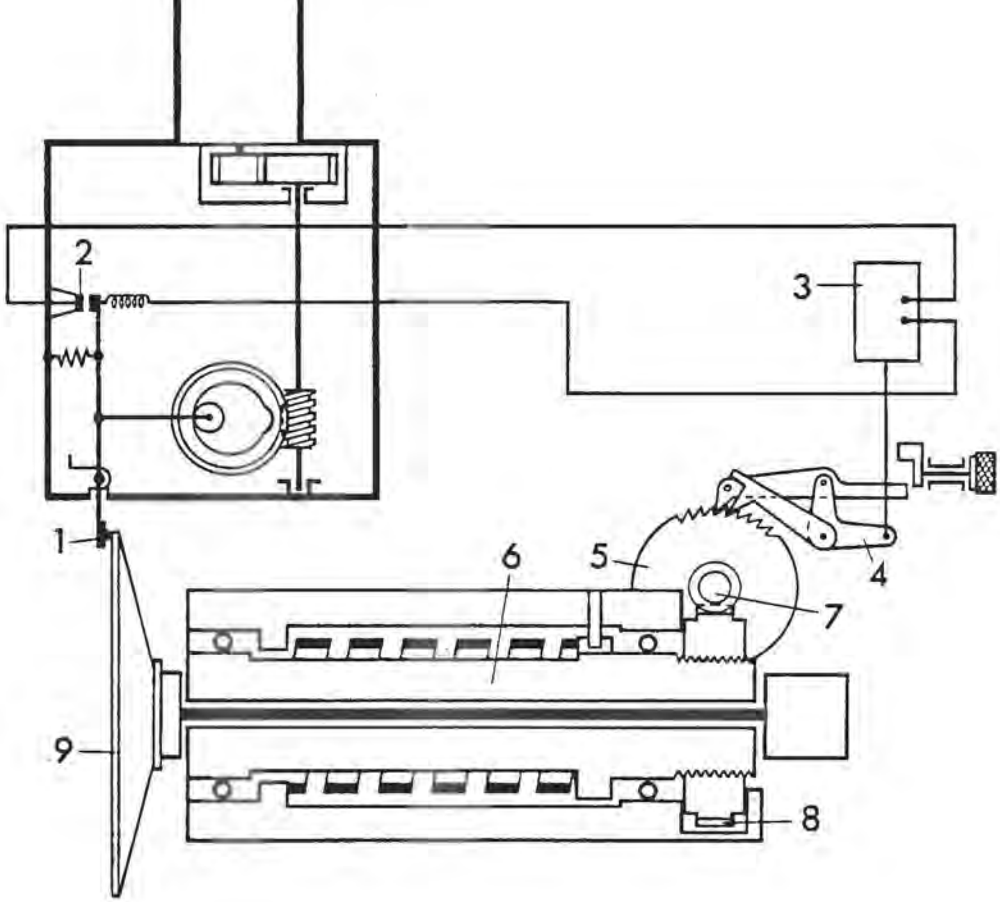


Fig. 13 Wheel wear sensing and compensating system

1 Diamond feeler
2 Normally open contact
3 Solenoid
4 Lever for ratchet wheel actuation
5 Ratchet wheel
6 Wheel spindle
7 Worm
8 Nut and worm wheel
9 Grinding wheel

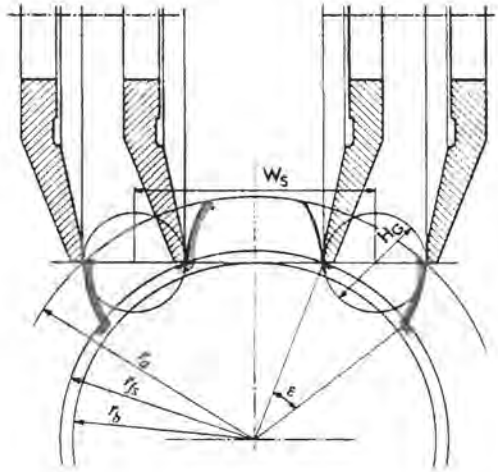


Fig. 14 0^{O} grinding without tip overrun

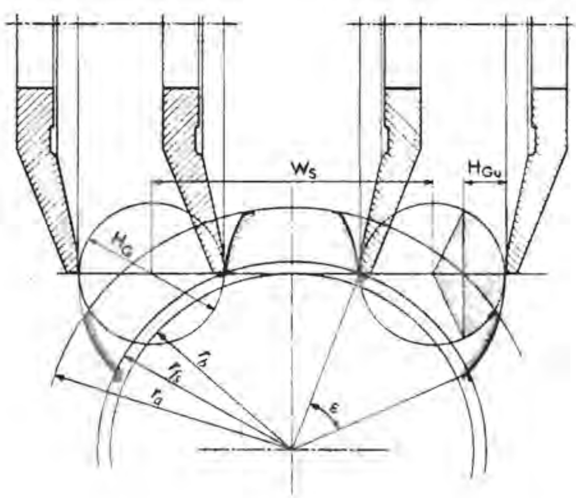


Fig. 15 0^{O} grinding with tip overrun

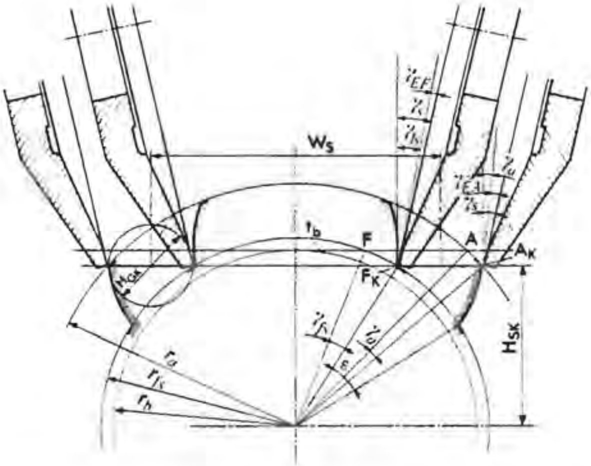


Fig. 16 Principle of the K grinding method

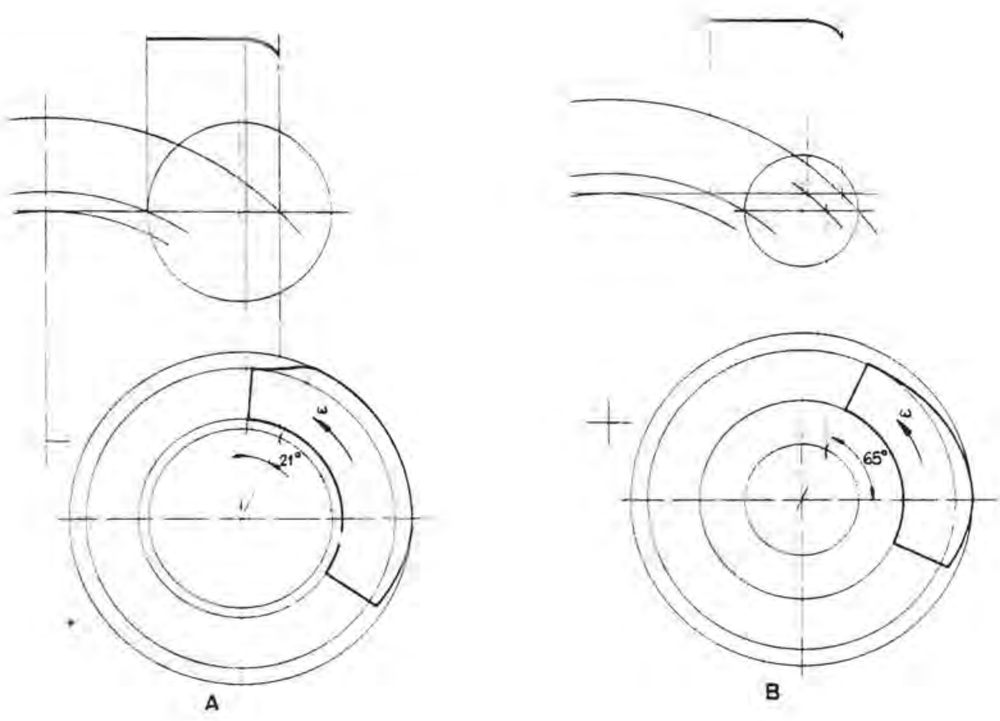


Fig. 17 Cam rises for tip relief

A For 0^{0} grinding: steep rise

B For "K" grinding: gentle rise

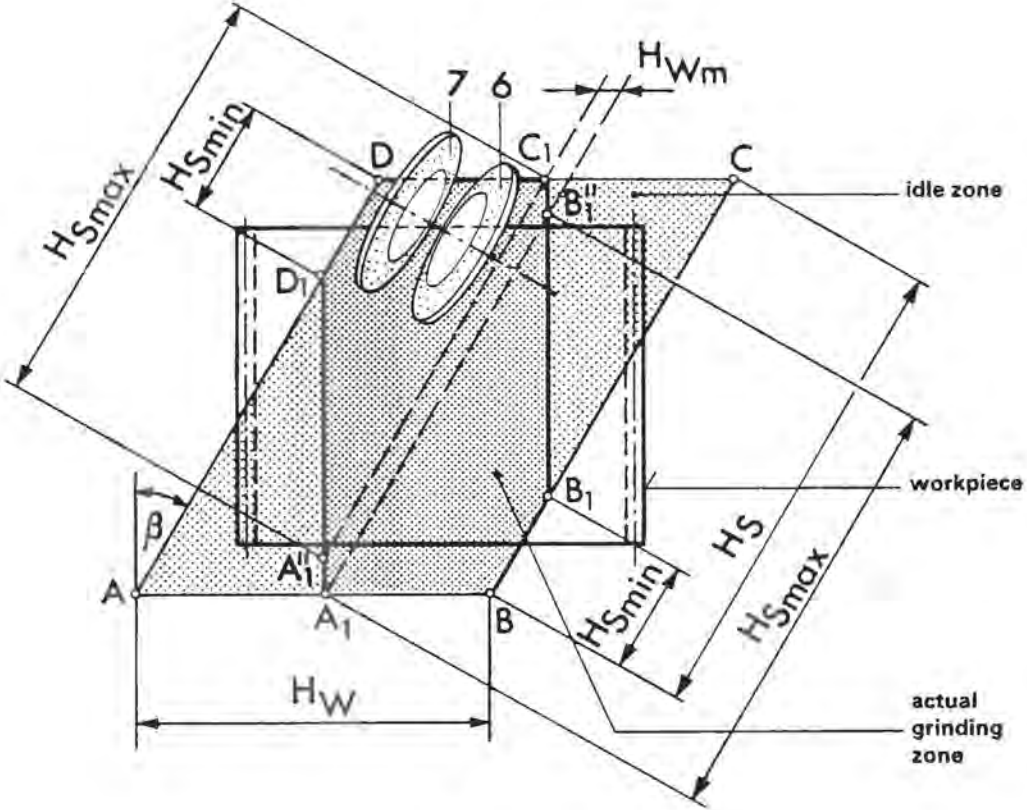


Fig. 18 Active and passive grinding zones for the 15°/20° grinding method