Chapter 10
Processes with Translatory Primary Movement

Cutting processes using a geometrically defined cutting edge that carry out a translatory main motion include, among others:

- broaching,
- shaving,
- planing and
- shaping as whose process variants.

10.1 Broaching

Broaching is a machining process with a multi-toothed tool whose cutting teeth lie in a row, each being separated by the thickness of one chip. Tooth graduation perpendicular to the direction of the cutting speed replaces the feed motion. The cutting motion is translatory, in special cases also helical or circular [DIN8589e].

Broaching can realize a high material removal rate in one stroke, since usually several teeth are simultaneously in engaged. Moreover, high surface qualities and precision are obtainable and tolerances of up to IT 7 maintained. This method can only be utilized economically in serial production due to the high costs of tool production and preparation, as the tools can always only be used for one cross-section of undeformed chip [Kraz77].

DIN 8589-5 draws a distinction between:

- face broaching,
- circular broaching,
- helical broaching,
- profile broaching and
- form broaching.

We also distinguish between internal and external broaching, for which differently designed machined tools and tools are required. The broaching tool is, as shown in Fig. 10.1, pulled/pushed through a borehole (internal broaching) or pulled/pushed along the external surface of the workpiece (external broaching). The final contour is usually created in one stroke.

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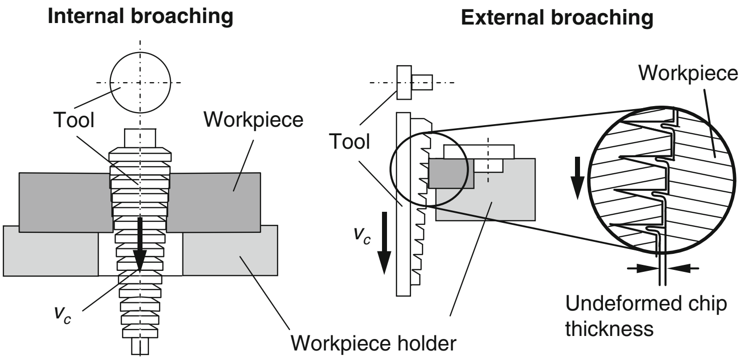

Fig. 10.1 Contact ratios and process variants of broaching

To process unhardened steel materials, in most cases tools made of high speed steel are employed. In certain cases, such as in large-batch production of grey cast iron or broaching hardened steels, cemented carbide or CBN are also used as cutting tool materials. To increase performance and wear resistance, the tools can be coated with hard materials (e.g. TiN, TiCN). The tools are either designed as solid units or fitted with indexable inserts [Wege85, Merk80].

The standard cutting speeds in steel-cutting are between $v_c = 1-30\,\text{m/min}$. Powerful broaching machines can reach cutting speeds of up to $v_c = 120\,\text{m/min}$ so that the surface quality is improved by avoiding built-up edge formation [Schü65, Opfe81]. Further cutting speed increase is only possible to a limited extent because of the process kinematics, since acceleration and deceleration must take place in one stroke.

Cutting fluids are almost always used in broaching processes in order to guarantee chip transport from the chip space in addition to the lubricative effect [Falk70]. To this end, usually oils are used due to the low cutting speeds.

When machining hardened steels, high cutting speeds of $v_c = 60-70\,\text{m/min}$ and cemented carbide tools are used to reduce the high cutting forces and to increase tool life. Cutting fluids are not used in this case [Klin93].

The following description will be restricted to the most important of process variants. Technologically comparable methods will be treated jointly.

10.1.1 Face and Circular Broaching

Figure 10.2 shows the typical structure of a broaching tool. Broaching tools have a roughing, a finishing and a calibrating section. The subsections differ in feed per tooth f_z.

In the roughing section, the feed per tooth f_z is in the range of $f_z = 0.1$–0.25 mm depending on the workpiece to be machined, while in the finishing section is it $f_z = 0.0015$–0.04 mm and in the calibrating section equal to zero. The teeth in the calibrating section possess the geometry required for the workpiece.

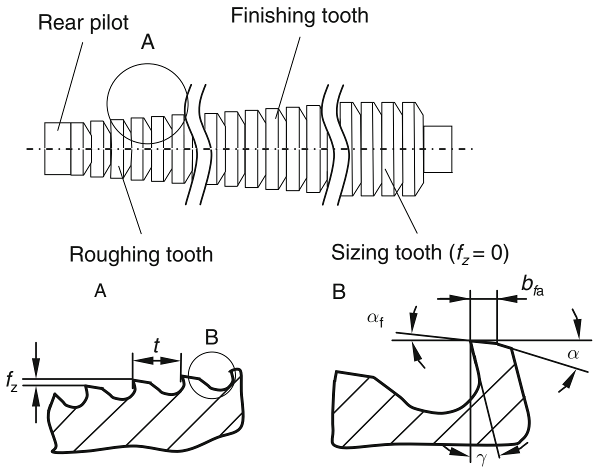

Fig. 10.2 Internal broaching tool (schematic)

The calibrating section makes it possible for the expensive broaching tools to be reground and thus be economically employed. Regrinding the tool shifts the entire tool profile by one tooth towards the calibrating section. In this way, the previously first calibrating tooth now becomes the last finishing tooth.

The tool rake angle γ and the tool orthogonal clearance α of the second flank face are adjusted to the material to be machined. The chamfer width $b_{f\alpha}$ is parallel to the axis in the calibrating section and inclined by the tool orthogonal clearance of the first flank face α_f in the roughing and finishing section.

The cutting pattern determined by the arrangement of the cutting edges along the tool axis is called the offset. If the cut is perpendicular to the broaching surface, it is called offset in depth. If the broaching surface is machined from the side on the other hand, it is called lateral offset. Both offset types can be provided on one tool simultaneously depending on the workpiece geometry [DIN1415].

The pitch t of the broaching tool and thus the size of the chip space as well depend on the height of the workpiece, chip formation of the material and the maximum potential tool length. A large workpiece height and unbroken chip forms require large chip spaces. In the case of small machines and short tools, only a small pitch is required, since only workpieces with a low height can be machined. Figure 10.3 provides an overview of various broaching tools for internal and external machining. Possible tool lengths are in the area of $L = 100$–10000 mm. Internal broaching tools are manufactured up to a diameter of $D = 500$ mm (e.g. for the internal gearing of hollow wheels). To obtain chip fracture, the individual teeth are equipped with chip breakers in the form of tooth grooves [Weul85, Hoff76].

The total cutting force, which is comprised of the individual components of all the cutting teeth in action, is crucial for the minimal cross-section of the broaching tool shank, which in turn limits the maximum size of the chip space. The height

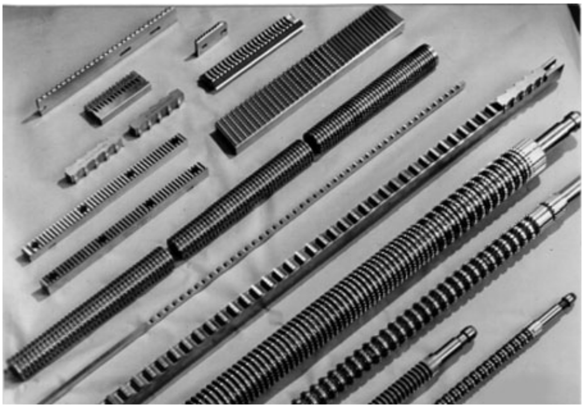

Fig. 10.3 Internal and external broaching tools (Source: Forst)

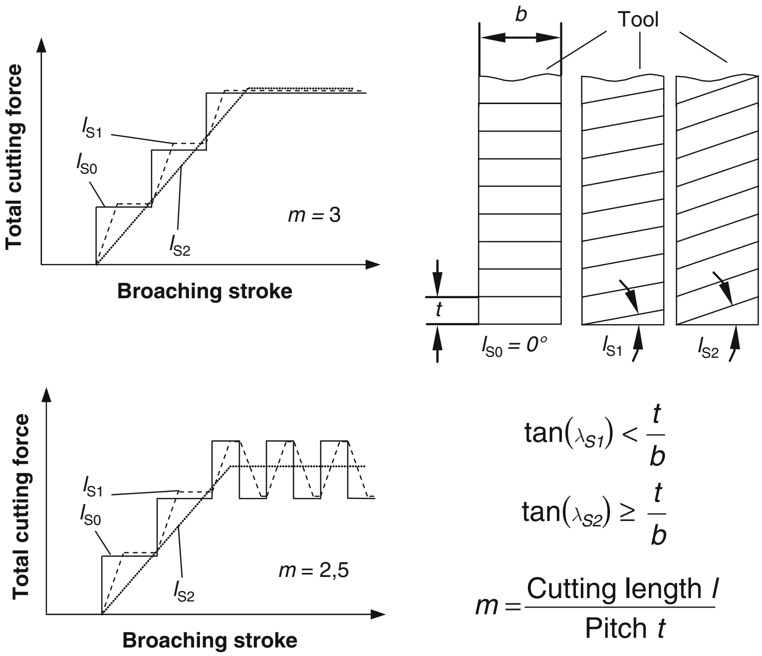

Fig. 10.4 Total cutting force during straight and diagonal toothed external broaching

and variation of the total cutting force are highly contingent on the pitch t and the inclination λ_S; an example is shown in Fig. 10.4.

If the ratio m of the cutting length (i.e. of the workpiece height to be broached) and the pitch t is an integer, we obtain a constant total tensile force. In the case of a non-integer ratio, the tools are highly stressed dynamically by periodic variations [Vict76].

Tools with an inclination λ_s not equal to zero show a slowly increasing cutting force profile and, if the construction is favourable, minimal cutting force variations. In the case of external broaching, lateral forces can arise that sometimes cause tool misalignment. Double helical gearing is characterized by the fact that the teeth of one level have the opposite inclination, thereby compensating the lateral forces. On internal broaching tools, an inclination λ_s not equal to zero can be realized by a coil-shaped cutting edge. In practice, inclinations of up to $\lambda_s = 5°$ are used.

10.1.2 Profile Broaching

One important variant of internal profile broaching is gearwheel broaching of involute-geared hollow wheels, which has become increasingly important because of its high cutting performance and obtainable surface quality. Figure 10.5 shows a few application examples, including hollow wheels for automatic transmissions, sliding sleeves and components with internal splined hub profiles.

In the case of the gearwheel broaching processes used today, all tooth gaps are machined simultaneously, so that a partial device can be dispensed with, and the quality of the broached gearwheel depends above all on the precision of the tool.

For diameters up to 150 mm, solid tools are used, in the 150–300 mm diameter range primarily bushings clamped to a pin. This has the advantage that the tool can be subdivided into several bushings to avoid excessive deflection during hardening, so that the grinding allowance can be kept small.

The efficiency of broaching can be fully exploited by using broaching tools that make it possible to broach involute profiles in one pass. Since, in the case of pure offset in depth (in which the profile of the tooth flank is formed by the minor cutting edges) the profile's dimensional accuracy is insufficient, a lateral offset is provided in the rear of the tool so that one can calibrate to the finished dimensions with a feed motion in the direction of the tooth flank.

Complex broaching tools can be composed of cutting discs that are bolted on a holder as a block. The tooth thicknesses of the cutting discs are graduated so that the

Fig. 10.5 Examples for internal broaching (Source: Forst)

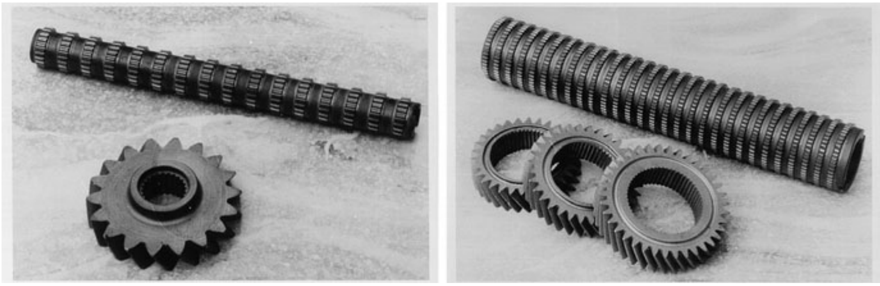

Fig. 10.6 Broaching tools for finishing internal toothed centre gears (Source: Forst)

final tooth cuts to the finished dimensions. It is possible to shift the discs, becoming ever smaller by regrinding, forward always by one position and to append a disc with full dimensions only on the respective end of the broaching tool. Each disc has two cast iron plugs to keep the discs in perfect alignment. These plugs are perforated in case of an exact seating of the discs so that two discs can always be pinned to each other.

Pre- and finish broaching can be executed either on one machine in one clamping (finish broaching tool as an attachment on the pre-broaching tool) or in two clampings with two separate tools (pre- and finish broaching in two clampings). To increase output, one can also work parallel in several clampings if the machine power is sufficient. Pre- and finish broaching can be distributed among two separate machines in order to exclude a mutual influence of the machining processes and to guarantee improved quality [Schw71].

Another tool concept is the one-piece, full-dimension cutting broaching bushing as shown in Fig. 10.6. It also has major cutting edges running parallel to the involute form and is used separately or as an attachment on a broaching tool in order to work in one clamping. The great advantage of calibrating bushings is that they can be used to produce helical gearings among other things (spiral broaching) [Bung74].

The full-dimension cutting broaching bushing is mounted in a floating fashion so that it can centre itself in the pre-broached profile. In the case of helical geared broaching tools, the chip spaces can be arranged both in a ring-shaped or in a helical manner. In the case of helical chip spaces, cutting force variations are much smaller, but they cause considerably higher tool manufacturing and sharpening costs.

"Pot" or "tubular" broaching is used for the external profile broaching of close surfaces. The tool consists of a hollow body in which are inserted the strip-shaped broaching tool segments. In this broaching technique, the tool is the moving element as in conventional broaching. In another process variant, the workpiece carries out the cutting motion. The workpiece is pressed by the broaching tool so that all contours to be produced on the periphery of the workpiece are produced in one stroke [Schw75, Spiz71]. In gearing technology, the use of this method is limited till now solely to the manufacture of dog gears.

Another important area of application of external profile broaching is the manufacture of fir-tree profile grooves in turbine discs. To this end, the fir-tree profiles are broached separately, and then the turbine disc is rotated by one pitch at a time.

The demand for a hard finishing of internal gearings after case-hardening could only be met in a few cases, since internal gearings can only be produced economically by broaching in large-batch production. Internal gearings with adjacent functional surfaces are not suitable for finishing due to an insufficiently large tool oversize by profile grinding, broaching or honing. Individual manufacture or hard finishing of batch sized with up to 100 parts is not economically possible with the gearing processes presently available [Peif91].

10.1.3 Form Broaching

Because they involve shaping with a correspondingly built tool and due to their kinematics, external cylindrical broaching (Fig. 10.7) and rotation external cylindrical broaching (Fig. 10.8) should be classified among manufacturing methods in the broaching subgroup as form broaching [DIN8589e].

External cylindrical broaching is a combination of external cylindrical turning and broaching. By substituting the turning tool with a multi-blade broaching tool, we can combine the advantages of turning (continuous process) with those of broaching (multi-blade tool) [Berk92]. External cylindrical turning is a process that has been known for a long time but was first utilized industrially in 1982 by an American automobile manufacturer for roughing of crankshaft main bearings [Whit84].

Because of the complex tools and very short manufacturing times, this process variant is especially suitable for large-batch and mass production. The dimensional and shape accuracy of the workpieces is high. Minimal deviations from the cylinder shape cannot be avoided as a rule because of the kinematics [Müll86, Ansc86]. In

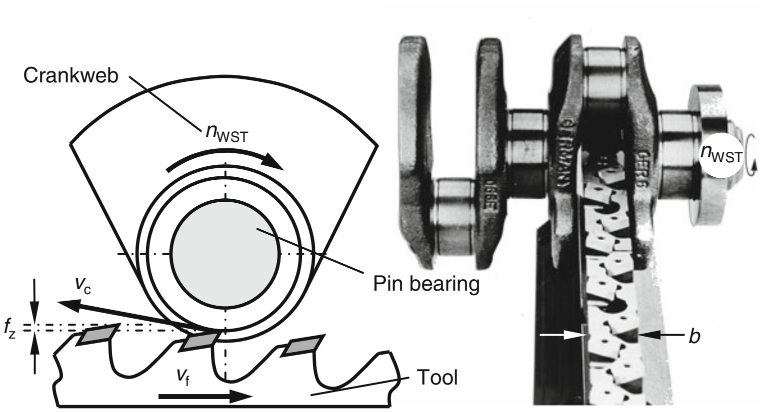

Fig. 10.7 External cylindrical broaching with a reciprocating tool

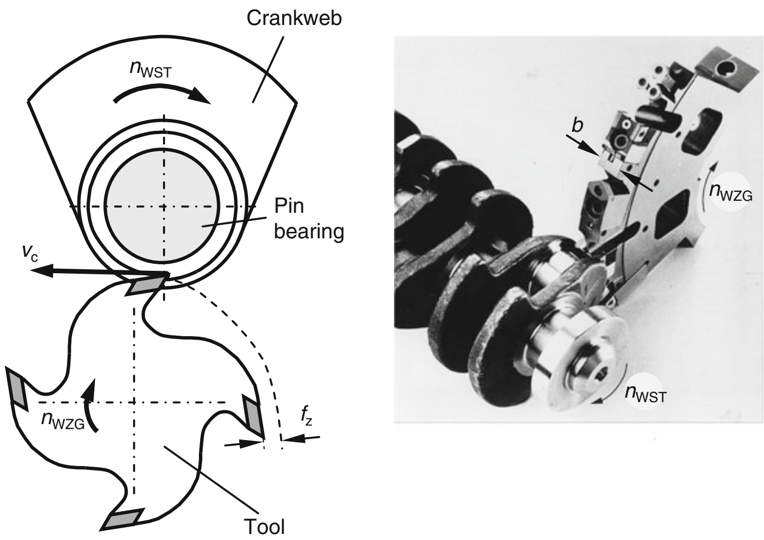

Fig. 10.8 External cylindrical broaching with a rotary tool

the case of diameters typical of crankshafts, these deviations are in the range of 5–10 μm. Measurements at the crankpin resulted in surface characteristic values of $Rt = 6-8$ μm and $Ra = 0.5-0.7$ μm [Müll86, Müll87].

The broaching tools used are built in a modular fashion and consist (as are conventional broaching tools) of a roughing, finishing and calibrating section. The single modules are bolted onto a base body. The tool is fitted with indexable inserts which are arranged according to the external contour to be created and fastened with bolt clampings in a space-saving fashion (Figs. 10.7 and 10.8). Quadratic, rhombic, triangular and round ISO indexable inserts with modified cutting part geometries are used. Both uncoated and coated cemented carbides as well as ceramics or CBN cutting tool materials can be used [Ansc86, Tika86].

The discontinuous tool engagement results in chips of finite length. Problems with chip breakage can be avoided by using indexable inserts with chip breakers. The indexable inserts in the preparation modules are not adjustable. Since the calibrating section is responsible for the manufacturing tolerances to be complied with, the inserts are fastened in adjustably cassettes. Overall, this tool structure allows for a simple tool preparation as well as a fast and cost-efficient adjustment for highly diverse profiles and machining tasks. If ultrahard cutting tool materials are used, both external cylindrical turning and rotation external cylindrical broaching are applicable, even in the case of hardened steel materials. Long tool lives can be realized with mixed ceramics, and especially with CBN as cutting tool materials.

The active motion in external cylindrical broaching with a linear tool motion is produced by a rotating workpiece and a translatory feed motion v_f of a multi-blade tool. The active direction of the feed runs perpendicular to the rotation axis of the

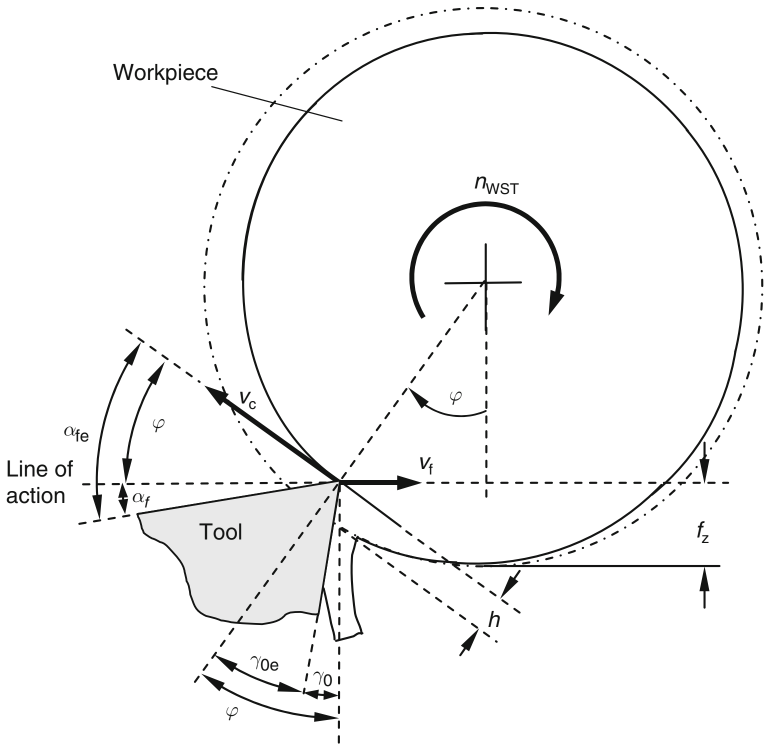

Fig. 10.9 Kinematics of external cylindrical broaching with a reciprocating tool according to BERKTOLD [Berk92]

workpiece and tangential to the workpiece. The tool cutting edge engages with the workpiece eccentrically and moves through the workpiece during the cutting process with feed velocity v_f on the line of action (Fig. 10.9). The cutting speed v_c is created by the rotation of the workpiece. Two effects are caused by the kinematics of the external cylindrical broaching process. On the one hand, the angle of engagement φ changes during a cut – and thus the effective angle as well. For this reason, the rake angle γ_0 and the first orthogonal clearance α_f of the tool are not identical to the effective rake angle γ_{0e} and the effective orthogonal clearance α_{fe}. On the other hand, the chip cross-section changes during a tooth engagement, since the chip thickness is a function of the angle of engagement φ [Berk92].

External cylindrical broaching with a linear tool motion is basically suitable for external machining of wave or ring-shaped workpieces as well as for manufacturing profiled and out-of-line rotation-symmetric outer edges (e.g. gearshafts or sliding sleeves). Currently, the preferred area of application is still machining the main and pin bearings of crankshafts (Fig. 10.7). Similarly to conventional broaching, the amount of depth of cut a_p is determined by the number of cutting edges and the pitch of the tool or by the feed per cutting edge f_z.

Tools are used that have roughing, finishing and profiling elements, so it is possible to do a complete processing (excluding grinding) of individual bearing positions including plane surfaces and recesses in one cycle is possible. As opposed to the former machining sequence – spinning the bearing pin, turning the cut-ins and plane surfaces, hardening, levelling and grinding – it is possible to combine or reduce individual manufacturing steps. Several main bearing positions can be machined at the same time by means of a simultaneous engagement of several tool arranged adjacently to each other. With the help of a suitably designed machine, several pin bearings lying in a rotation axis can be broached at the same time as well by means of a height offset of the workpiece.

External cylindrical broaching with a linear tool motion (Fig. 10.7) requires (especially when machining crank webs with a high radial allowance) very long tools that increase the allowances of the external cylindrical broaching machines and their required floor space to a disproportionate extent. On the other hand, the second process variant, external cylindrical broaching with rotary tool motion (Fig. 10.8) fulfils the demand for a compact design.

In external cylindrical broaching, the tangential cut is obtained with a rotary tool motion by the circular feed motion of a round tool. The individual cutting edges are graduated along the periphery of the tool by the feed per tooth f_z respectively.

External cylindrical broaching tools consist of a large number of cutting edges that are each only in action briefly during the working stroke. The tool life of the entire tool is accordingly high. The complex tool and very short manufacturing times allow for an economical use of external cylindrical broaching mainly in large-batch and mass production.

10.2 Shaving

Shaving is a manufacturing process used for post-processing, in which the crossed axes of the tool (shaving wheel) and the workpiece cause a relative cutting motion. One example of this is the widespread practice of gear shaving (also called "soft shaving") [DIN8589i].

Gear shaving is a process using geometrically defined cutting edges that is used to finish pre-teethed gearwheels. It serves to improve gearing quality and surface quality [Lich64]. Customarily, gears machined by shaving are not hardened. The result of this is that tooth flanks can be machined relatively effectively and using relatively small forces in comparison to hard finishing.

Figure 10.10 shows the principle of gearwheel shaving. The rolling kinematics during shaving resembles that of a helical roller gear. The tool is a gearwheel, the flanks of which are interrupted by flutes and have a different helix angle than the workpiece. The tool and workpiece axes are thus not parallel and form the "axis intersection angle" Σ. The latter generally has values between $\Sigma = 10$ and $15°$, however in exceptional cases axis intersection angles of $\Sigma = 3-20°$ are possible [Beck00]. The axis intersection angle results in a relative speed of the shaving

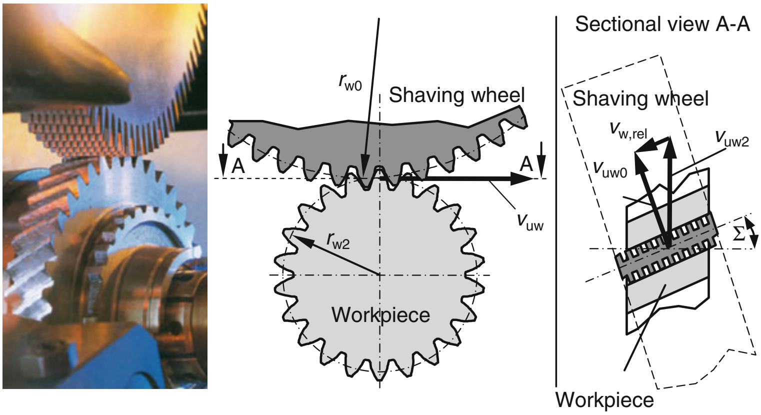

Fig. 10.10 Principle of gear shaving (Source: Gleason Hurth)

base $v_{w,rel}$ in the direction of the workpiece flank, and chips are formed due to the penetration of the cutting edge and the workpiece flank.

The relative speed in the direction of the workpiece flank during shaving corresponds to the cutting speed v_c. It is calculated form the circumferential speeds at the rolling circles v_{uw0} and v_{uw2} and the axis intersection angle as well as the helical angles β_0 and β_2:

$$v_{w,\,rel} = v_c = v_{uw0}\frac{\sin\,\Sigma}{\cos\,\beta_2} = v_{uw2}\frac{\sin\,\Sigma}{\cos\,\beta_0} \tag{10.1}$$

The chips are removed as a result of the tool and workpiece being braced with each other radially with high force and simultaneously shifting on each other. In this way, the tool is propelled while the workpiece, as a rule, runs freely behind.

Because the shaving wheel flanks are only grooved radially in order to form the cutting edges but the remaining tooth flanks are not relief-ground, the result is a constructive tool clearance of $\alpha_{con} = 0°$. Upon entry of the cutting edge in the workpiece flank, we therefore obtain a negative tool clearance, which leads to plastic deformation of the material lying underneath. This is desirable in shaving, as it leads to a levelling of the roughness peaks on the tooth flank and thus improves the surface quality of the tooth flank [Busc75].

Shaving has a few other technological peculiarities compared with other machining processes with geometrically defined cutting edges, above all the small chip thicknesses ($h_{cu,max} = 5-10\,\mu m$), cutting lengths ($l_{max} = 0.1-0.5$ mm) und cutting speed ($v_c = 30-80$ m/min) [Kloc03a]. The high efficiency of the shaving process is the result of using a adequately large number of cutting edges.

Figure 10.11 shows the surface structure of a shaved gearwheel flank. High sliding speeds, which change with tooth height, are generated as the workpiece flank shifts on the tool flank. There is no rolling on the so-called "pitch circle", and so the high sliding speed here is equal to zero. The maxima of the high sliding speeds

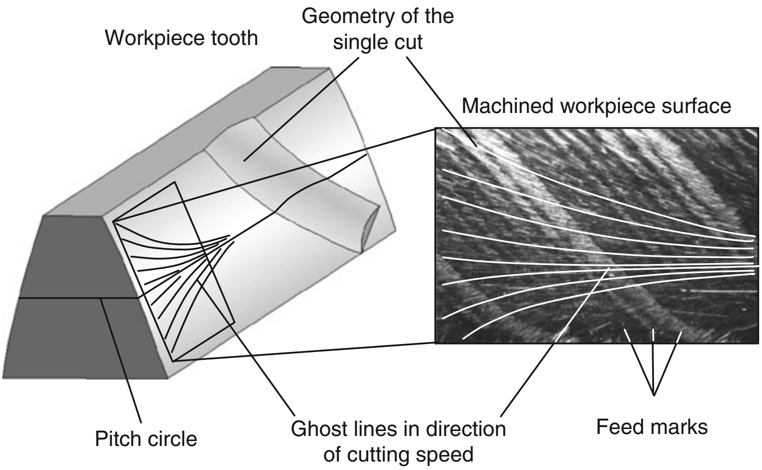

Fig. 10.11 Cut geometry and surface structure during shaving [Schr07]

are located at the tooth tip/base, however with different signs. By superimposing the nearly constant sliding speed in the direction of the tooth flank, which results from the axis intersection angle, we obtain the structure on the tooth flank as shown.

As already described, very small chip thicknesses exist during shaving, a very sharp cutting edge is necessary for a clean chip formation. Even a small amount of wear leads to a disturbance of chip formation and thus to lower workpiece quality. Nevertheless, very high quantities can be produced within the tool life due to the large number of available cutting edges (1000–10,000 workpieces per regrind cycle) [Busc75].

In the case of crossed helical gear transmissions with uncorrected gearings, point contact predominates between two flanks due to the axis intersection angle. During shifting, the point moves along a curved path on the workpiece flank. The cut geometry shown in Fig. 10.11 results from the penetration between the tool cutting edge and the workpiece flank. In order to machine the entire workpiece flank, it is therefore necessary to shift the point of contact between the tool flank and the workpiece flank (the axis intersection *C*) during the process. There are various ways of doing this as shown in Fig. 10.12.

In the case of parallel shaving, the shaving wheel is shifted relative to the workpiece parallel to its axis. The tool must be moved at least along the entire width of the workpiece. In the case of "diagonal shaving", the shaving wheel is not moved parallel to the workpiece axis but under a diagonal angle ε in order to reduce this path and thus the machining time as well. In the extreme case of underpass shaving the diagonal angle is $\varepsilon = 90°$. In this method, the axis intersection is indeed shifted along the workpiece axis as the tool is moved, yet there is no simultaneous shifting of the base in the direction of the workpiece flank. The workpiece would thus be machined at the same locations at each rotation and uncut sections would remain between them. In order to machine the entire workpiece flank evenly nonetheless, the base are offset relative to each other on the shaving wheel flank. This offset is usually about 0.2 mm per workpiece rotation in practice. That means that the base

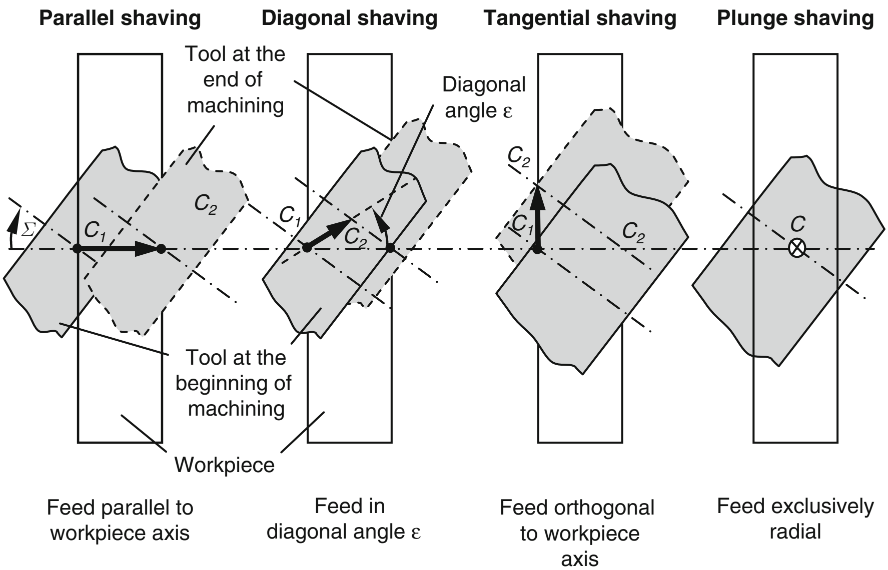

Fig. 10.12 Comparison of different shaving methods

must be arranged on the shaving wheel flank in such a way that the desired offset exists according to the teeth number of the workpiece. The arrangement of the base on the shaving wheel flanks thus depends on the teeth number ratio between the tool and the workpiece. Accordingly, a shaving wheel can only be used for exactly one workpiece geometry.

The most economical shaving method by far is plunge shaving. In this process, the only translatory motion carried out by the shaving wheel relative to the workpiece is a radial infeed. Since the axis intersection is not shifted in this method, line contact must be made between the flanks by “hollow grinding” the shaving wheel flank. In this way, the workpiece is, in principle, simultaneously machined along its entire width, and the productivity of this method is significantly higher than in other shaving methods.

Because many more cutting edges are involved in the cutting process in plunge shaving, much higher forces act on the machine than in other shaving methods. In the case of older shaving machines in particular, this process meets its limits when machining larger gearwheels (beyond $m_n = 3\,\text{mm}$). Both plunge and underpass shaving are primarily suitable for machining larger batches, because it is necessary to design the shaving wheel for the specific workpiece. In the case of smaller batched, diagonal shaving is used as a rule [Beck00].

10.3 Planing and Shaping

Planing and shaping are machining processes using a repeated, usually linear cutting motion and an incremental feed motion perpendicular to the cutting direction. As a rule, these processes are used to cut larger, even surfaces to size [DIN8589e].

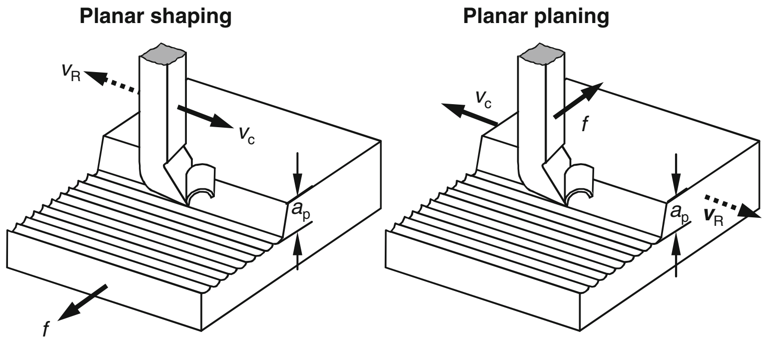

Fig. 10.13 Work movement during shaping and planning

The methods differ in the creation of the relative movement between the tool and the workpiece (Fig. 10.13). In the case of shaping, the tool moves over with workpiece with cutting speed v_c. In the case of planing on the other hand, the workpiece is guided past a stationary tool. In practice, the concepts of planing and shaping are not strictly distinguished.

In analogy to other machining processes with geometrically defined cutting edges, a distinction is drawn between face, round, helical, profile and form shaping/planing. We will dispense with a separate treatment of the individual methods in this context. On the basis of face shaping, relationships will be explained that can be applied to round, helical, profile and form shaping as well [DIN8589d]. Gear shaping and gear planing, because of their importance in gearwheel manufacture, will be treated in more detail.

10.3.1 Face Shaping and Face Planing

Figure 10.13 shows the motion sequences in face shaping and planing. In shaping, the tool carries out the cutting motion, the working stroke, with speed v_c as well as the return motion, the idle or return stroke with v_R. The infeed motion can be executed both by the workpiece (by lifting or lateral shifting of the table) or by the chisel (by lifting and lowering the plunger head). The feed f is realized by the workpiece table. In order to prevent collision between the workpiece and the tool during the return stroke v_R, the tool makes a lifting movement. Due to the technological similarity of these methods, the following will focus on shaping.

In shaping, the tools are manufactured with tool steel, high speed steel or tough cemented carbide (e.g. of application group K40) due to process-related abrupt stresses as well as the low potential cutting speeds. Since in the case of this method large cross-sections of undeformed chip are required for economic reasons, the process mostly uses cemented carbide cutting edges with a large negative inclination. This inclination causes not only a pulling cut but also prevents the lead impact from affecting the chisel tip, reallocating the impact instead to the more stable cutting edge.

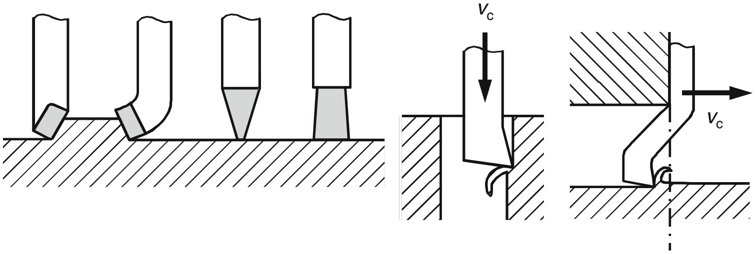

Fig. 10.14 Different types of shaping tools

There is a diverse array of tool forms, some of which are shown in Fig. 10.14. For roughing, generally straight and curved chisels are used, while finishing operations make use of pointed, wide chisels (broad-tool chisel). Chisels must often protrude extensively depending on the workpiece. To prevent clattering and potential hooking of the chisel in such conditions, it is often offset such that its cutting edge is behind the chisel support plate.

The cutting speeds realizable in shaping are low, since in ever stroke masses must be accelerated and decelerated. Roughing takes place with cutting speeds between $v_c = 10-30\,\mathrm{m/min}$ and with large feeds and chip thicknesses in order to exploit the machine's power. In finishing, cutting speeds up to $v_c = 60\,\mathrm{m/min}$ are employed with small feeds.

Due to the return stroke, which is faster than the working stroke, and the single routes and overrun routes in which no chips are removed, the difference between the machine run time and cutting time is considerable. For economic reasons, this method is only used to a limited extent.

Shaping machines, of which the stroke length is normally up to about 1000 mm, are especially suited to machining small workpieces. Vertical shaping machines are used to machine workpieces with difficult-to-access, vertical or sloped external and internal shapes. Especially for machining irregular shapes with a short cutting path and small run-out, such machines are indispensable. The chip volume per time unit is small in comparison to other machining methods. High traction planing machines permit the use of multiple chisel mountings so that the primary and secondary processing times can be reduced.

The advantages of this method in comparison with for example milling include not only the simple and resultantly cheap tools but also the minimal heating of the workpiece. Besides the abovementioned disadvantages of shaping, the frequently required tool change (single-blade tool) and the large machine assembly space (planing) should also be considered.

10.3.2 Gear Shaping

Gear shaping is a method for machining gearwheels and serves primarily as an internal gearing manufacturing process (Fig. 10.15). Gear shaping thus has a role of

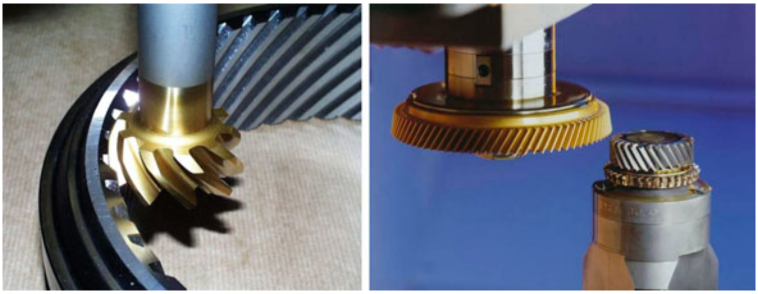

Fig. 10.15 Examples of gear shaping (Source: Gleason-Pfauter)

special importance from the standpoint of the increasing use of planetary gears. Moreover, this method fulfils not only high performance requirements but also high standards with respect to production accuracy so that in internal gearing manufacture we can often dispense with subsequent finishing.

Just as is the case in hobbing, gear shaping can be used to produce spur gears and helical gears. Besides internal gears, gear shaping is also suitable for fabricating herringbone or double helical gears. The special advantage of this method compared with hobbing is the small run-out of the tool, so even gears on profiled shafts or with large coupling collars can be processed.

In the case of gear shaping, which is classified as a continuous gearing process, the gear (workpiece) is created by a gearwheel-shaped cutting disc (tool). Figure 10.16 shows the kinematics of the process.

To produce the rolling motion, the gear and the tool are conjointly driven. As the rolling feed, the distance travelled on the circular pitch per double stroke DH is defined as the sum of the working stroke and the return stroke. In the case of helical gears, the rolling motion is superimposed with an additional periodic rotation corresponding to the helical angle. This additional rotation of the tool is realized by a inclined guide, which can be mechanically fixed or electronically controllable. The cutting disc's teeth also exhibit the corresponding helical angle. The axis offset AV corresponds to a lateral shift of the shaping wheel axis perpendicular to the symmetry axis of the gear shaping machine and is permanently set before the beginning of the process. This offset helps prevent collisions between the shaping wheel and the workpiece during the return stroke motion.

At the beginning of the machining process and between several cutting cycles, the workpiece executes a radial infeed motion in order to obtain the required plunge depth. In one process variant of gear shaping, the radial and rolling feed are superimposed so that machining is done in a spiral shape. The spiral infeed can take place both with a constant and with a degressively sinking radial feed (CCP process).

Currently, several shaping wheel shapes are available as tools [DIN4000, Vuce06], which are shown in Fig. 10.17. Disc gear shaping wheels and bell gear shaping wheels are used for manufacturing large external and internal gearings.

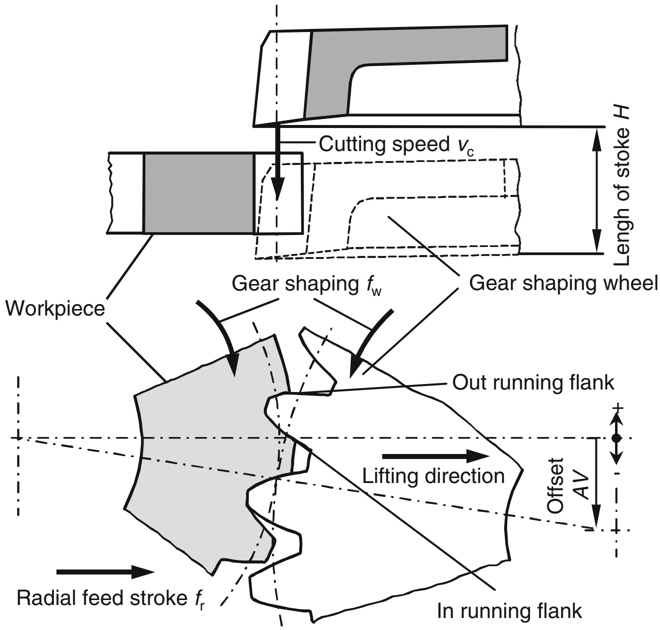

Fig. 10.16 Terms of workpiece and tool during shaping

The bell design assures that the mounting nut does not collide with the workpiece clamping or the workpiece itself. Shank gear shaping wheels are used for internal gears with small circular pitch diameters. Such tools can also be used to produce workpiece contours of embedded internal external gearings. Alternately, often internally toothed shaping wheels are used (hollow shaping wheels) [Baus06].

Fig. 10.17 Types of shaping wheels

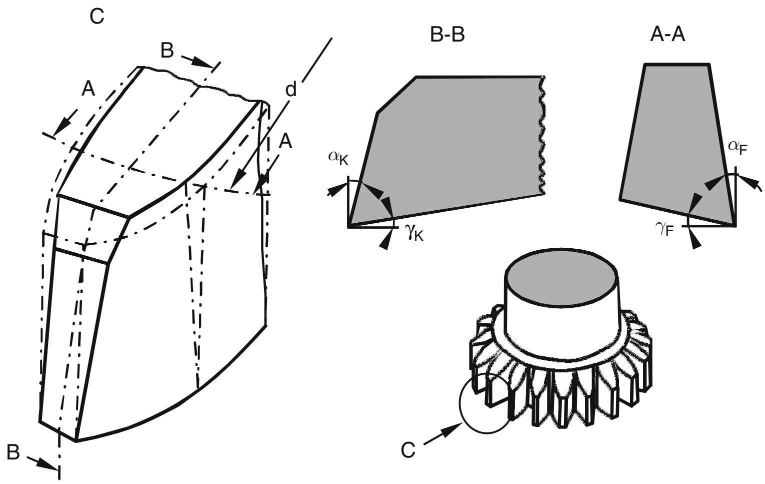

Fig. 10.18 Tooth geometry of a shaping wheel

For gear shaping, HSS with hard material coatings and a tip rake angle between $\gamma_k = 10°$ and $\gamma_k = 0°$ is preferred.

Figure 10.18 shows the cutting part geometry on a shaping wheel tooth. As element C shows, the tool orthogonal clearance is produced by the relief grinding of the flanks and the tooth tip. The tool orthogonal clearance at the circular pitch (cut A-A) is selected small, to achieve a high use of the tool height. The tool orthogonal clearance at the tip α_K (cut B-B) can on the other hand not be freely selected but is calculated with the help of the tool orthogonal clearance on the circular pitch and the tool engagement angle [Bouz76]. In this way, profile deviations during shaping wheel re-sharpening are avoided.

The rake angle at the tooth tip γ_k and on the flanks has no essential effect on the tool's service life and can thus be freely selected from the standpoint of wear.

The machining process in the case of gear shaping has some peculiarities. As opposed to hobbing, in which a hob tooth removes the same chip each time, all chips are cut by one tooth in shaping, so that one shaping wheel tooth produces one workpiece gap. The flanks of a gear shaping wheel are involute-shaped. Figure 10.19 shows the cross-sections of undeformed chip in the manufacture of a tooth gap of a common gear. The cross-section calculated with the help of a digital computer program is plotted over the uncoiled cutting edge every single stroke [Sulz73]. The chip cross-sections remain in the case of spur gears practically constant across the width of the workpiece. Figure 10.19 shows that one-flank, two-flank and even three-flank chips are produced during the machining process. The three-flank chips have the biggest influence on wear. The smallest cross-sections of undeformed chip arise on the wear-endangered location.

The chip forms of the tool life-relevant u-shaped chip cross-sections, caused by various gear geometries, are shown in Fig. 10.20. The cross-sections of undeformed chip are shown schematically in the upper part of the illustration and the flow

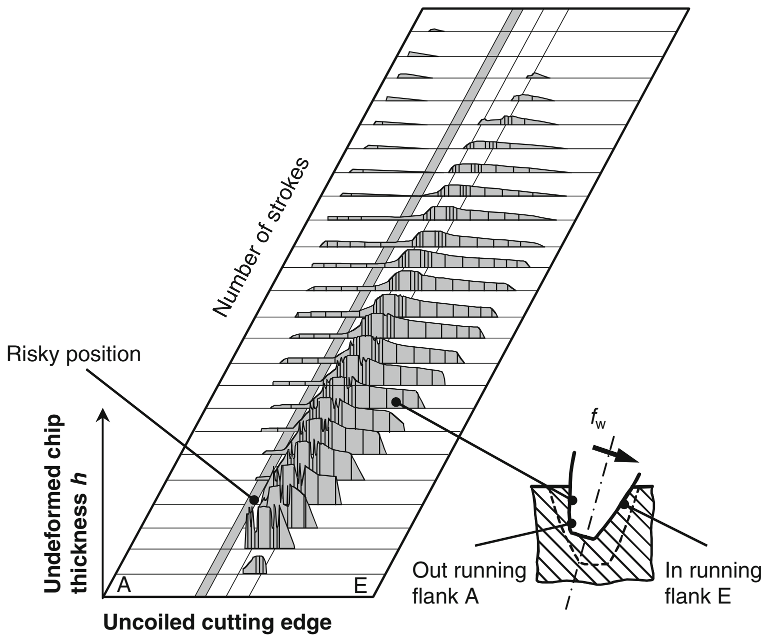

Fig. 10.19 Cross-sections of undeformed chip during gear shaping of a tooth flank

directions of the chip parts on the top and on the flanks are indicated by the plotted arrows. The photographs in the lower half show the associated chips. The second cross-section of undeformed chip in Fig. 10.20 is the most often encountered in practice. The chip on the outgoing flank is very thin in comparison to the chip of the top and entry cutting edge. As a result, this chip is pressed onto the rake face by the top chip and strongly impeded from flowing.

Figure 10.21 shows the typical development of wear on the tooth of an uncoated shaping wheel. The upper part of the illustration shows the width of flank wear land along the uncoiled cutting edge for three different tool operating lives. The wear maximum can clearly be recognized at the transition from the top to the outgoing flank. As opposed to that, wear on the in-running flank is much smaller and evenly distributed. The lower part of the illustration shows the measurement of the crater edge and photographs of the shaping wheel tooth at the end of the tool life. The depth of the craters is basically the same at the three labelled locations of the cutting edge. On the other hand, the wear-endangered location at the transition from the top to the outgoing flank exhibits the smallest crater centre distance and furthermore a shrinking of the crater edge, which prevents further use of the shaping wheel because of the subsequent rapid increase of the width of flank wear land.

Wear protection from a hard material layer reduces the stress on the cutting part significantly, so that it is possible to increase performance compared to uncoated

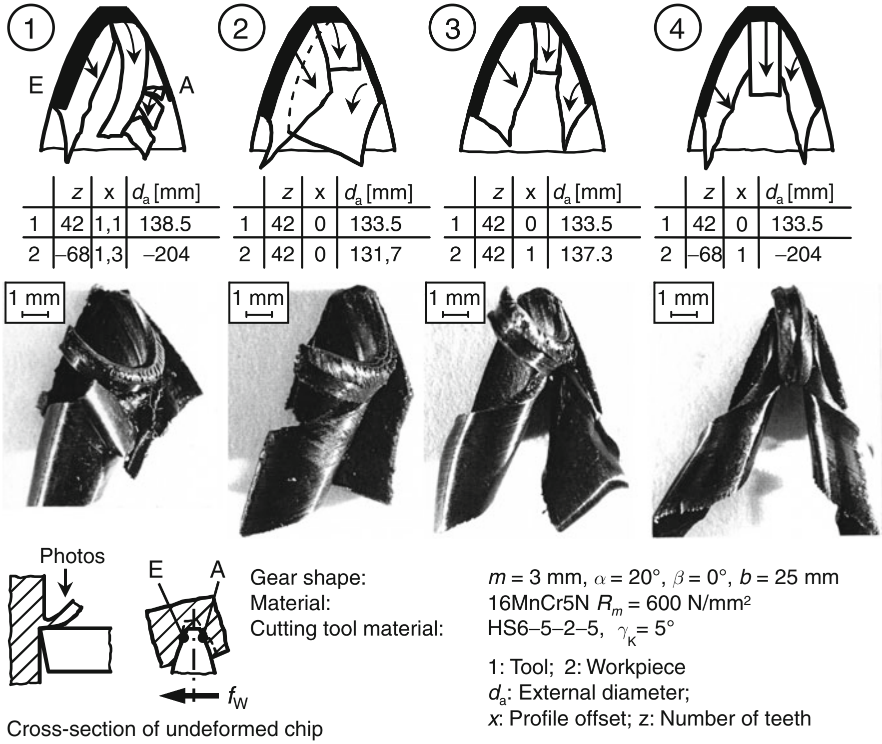

Fig. 10.20 Influence of the cross-section of undeformed chip onto the chip flow during gear shaping

tools in two ways: on the one hand, it is possible to increase the tool operating life by 1.5–4 times while keeping the same cutting parameters. On the other hand, it is possible to maintain the same tool operating life while selecting more productive cutting parameters. Increasing the rolling feed reduces the tool operating life less than increasing the cutting speed.

Eighty percent of the materials used for gearbox gear wheels are case-hardened steels. Otherwise, heat-treated steels (especially in the case of hollow wheels) are used, and more rarely cast iron materials. In special cases, construction steels are used as gearwheel materials (e.g. in crane construction). Case-hardened steels are gear shaped in a technologically sensible way with a cutting speed of $v_c = 40-60\,\mathrm{m/min}$ using a roughing process. For finishing, the cutting speed can be increased to up to $v_c = 140\,\mathrm{m/min}$ if the rolling feeds are reduced. Heat-treated steels with a tensile strength of $R_m = 900-1100\,\mathrm{N/mm^2}$ are ideally machined with a cutting speed of $v_c = 30-40\,\mathrm{m/min}$ with a roughing process [Able04]. Cutting speed selection also depends on the respective workpiece width.

The most practical cutting parameters for industrial applications do not stem from the largest tool life or maximum setting data but rather from an optimal combination of tool life and machining time. A possible measure for machining time in the gear

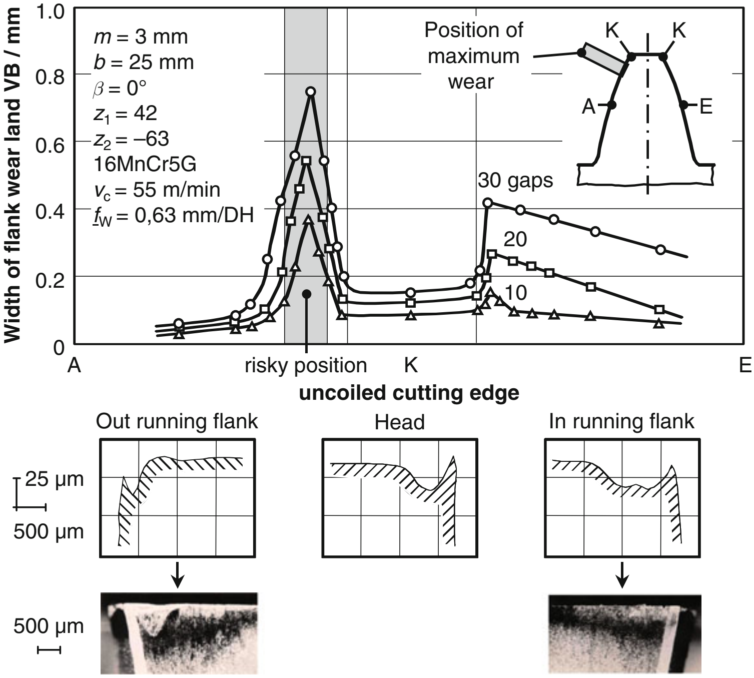

Fig. 10.21 Flank and rake wear on a cutting tooth

shaping process is the rolling speed W, which is related to the machining speed and results from the double stroke number n_{DH} and the rolling feed f_W as follows [Kauv87]:

$$W = n_{DH} \cdot f_W \text{ [m/min]} \tag{10.2}$$

The machining costs result from the tool price, tool life with a given cutting speed/feed combination as well as the overall auxiliary machine and personal costs [VDI3333].

The danger of a cutting wheel/workpiece collision in gear grinding is especially high when the rolling feeds are high. There is a risk that the cutting wheel can collide with the unmachined workpiece material during the return stroke. Due to the continuous rolling feed, penetration between the shaping wheel tooth and the workpiece during the return stroke would occur – as shown in Fig. 10.22 – if measures are not taken to prevent the collision. The largest penetration occurs in the upper face cross section of the workpiece. This is especially problematic when manufacturing internal gearings.

The collision causes a "cut", in which case the flank face of the shaping tooth takes over the role of the rake face. Severe damage to the cutting edge results from these cutting conditions as well as considerable degradation of the gear quality and heavy loading of the machine.

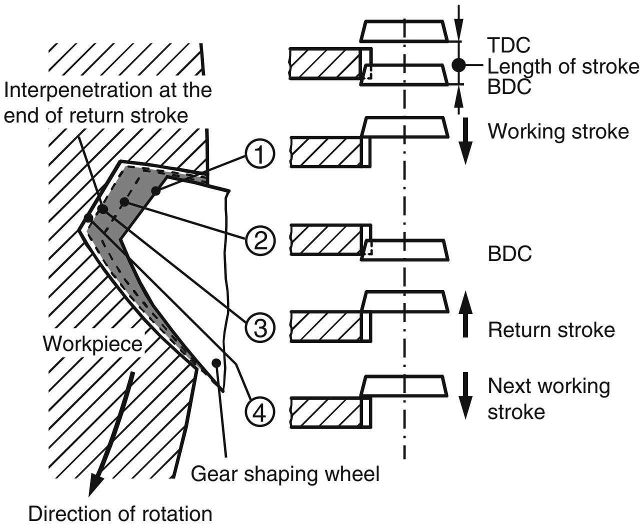

Fig. 10.22 Cause of collision danger during gear shaping

The main influencing variables that affect collision during the return stroke are, besides the rolling feed, the plunge depth, the geometry of the workpiece and shaping wheel, the amount of lift during the return stroke of the shaping wheel and the axis offset. The real variable to avoid collision is the amount of lift off and the axis offset. Since the lifting movement of the shaping spindle is not always sufficient, especially in the case of internal gears, the support of the gear shaping machine is laterally shifted by a certain amount AV, resulting in a slanted lifting motion.

10.3.3 Gear Planing

The motion sequence in gear planing basically corresponds to the kinematics of the shaping process. Nonetheless, the term “gear planing” has become established for this process in industrial practice, and it will also be used in the following. The principle of gear planing is shown schematically in Fig. 10.23.

The tool used in gear planing, the “planing rack”, consists of a gear rack segment with a relief-ground flank (Fig. 10.24). The cutting force is received by a support crest so that the tool can be exploited optimally, i.e. can be re-sharpened to a small residual thickness. Since the planing rack is derived from a gear rack, the rolling motion of the workpiece must be superimposed with a translatory motion in the longitudinal direction of the gear rack when manufacturing involute-shaped gears. Due to the finite length of the planing rack, it is necessary that the workpiece be moved back to the starting position after producing several gaps with a decoupled feed motion. This is referred to as “partial rolling” as opposed to continuous rolling methods such as hobbing, gear shaping and hob peeling.

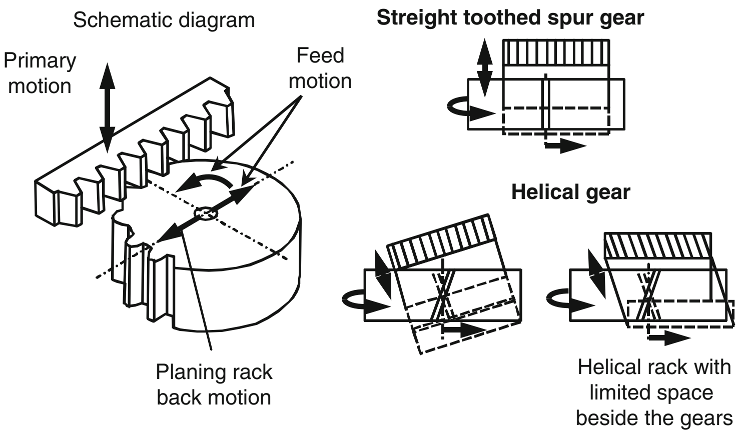

Fig. 10.23 Principle of gear planning

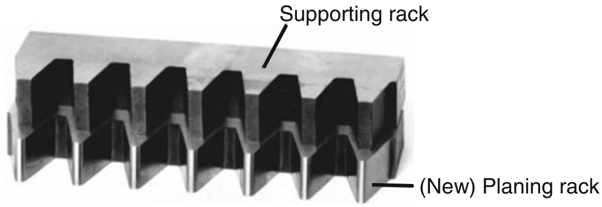

Fig. 10.24 Planing rack (Source: Maag)

Since for this reason gear planing is less economical than other rolling methods, it is only used in special cases, e.g. to produce externally toothed cylindrical gears with large dimensions and high strength. The advantage here is that tool change is easy and can be done without affecting quality during the manufacture of a workpiece.