RWTHedition

Manufacturing Processes 2

Grinding, Honing, Lapping

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DIE FACHBUCHHANDLUNG

2 Principles of Cutting Edge Engagement

Knowledge of the basic principles of a machining method is an essential prerequisite for the full realisation of its potential. Yet research into the essential features of material removal with geometrically undefined cutting edges is beset with great difficulties. The determination of the cutting edges used in the procedure is hampered by the extremely complex microstructure of the tools. Because of the large number of grain points acting on the component part, material removal is made up of the sum of many different cutting edge engagements that remove the individual chips from the material surface (Fig. 2-1).

cutting direction

25 μm

Material: Ck15N

10 μm

Material: Ck45N
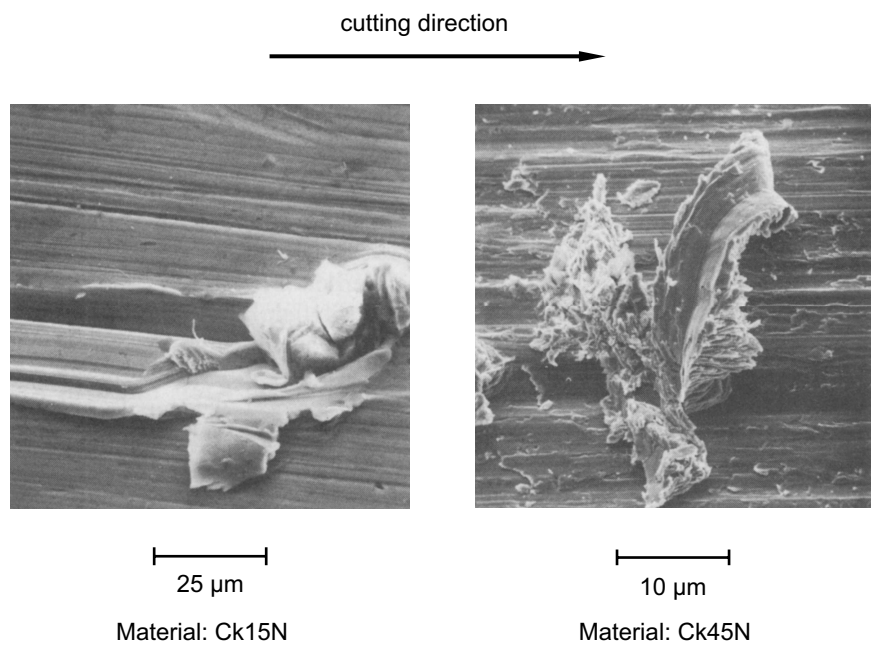
Fig. 2-1. Images of chip roots taken with a scanning electron microscope [LORT75]

Grinding is used primarily as a precision machining method in which chip formation proceeds within the realm of a few micrometers and to a large extent eludes direct observation. However, due to theoretical considerations and with the help of investigations into the physical and chemical processes, we can make assertions about this process as well. Such findings are necessary for basic understanding and are of invaluable help in the optimal design of machining processes.

2.1 Cutting Edge Form

In order to form a chip, the grains cutting into the component must be harder than the material which is to be machined. Crystalline and brittle abrasive materials are used. The grains splinter during the crushing caused by the production process, so that the fragments possess an irregular form with more or less sharp corners and edges. Natural or synthetic abrasive materials that already have the desired form in their raw state are also used.
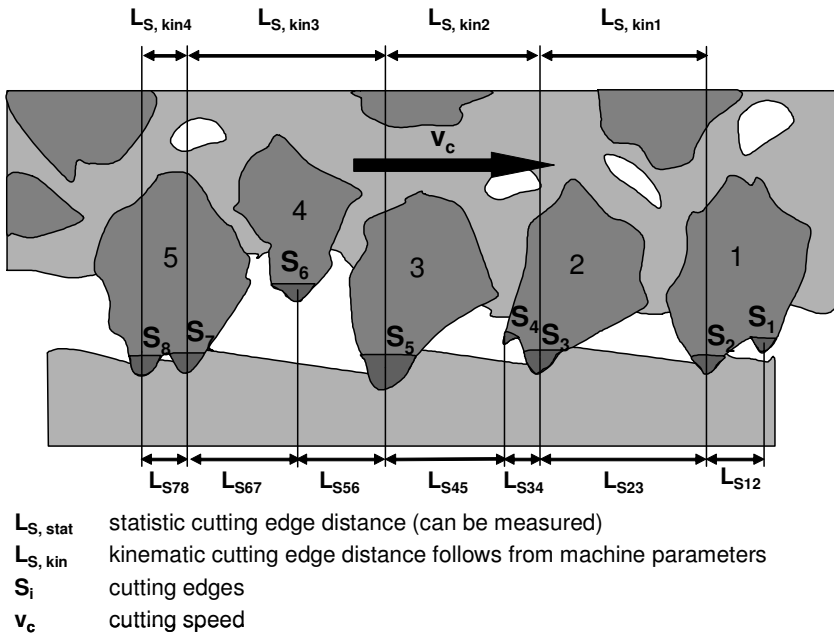

$L_{S, stat}$	statistic cutting edge distance (can be measured)
$L_{S, kin}$	kinematic cutting edge distance follows from machine parameters
S_i	cutting edges
v_c	cutting speed

Fig. 2-2. Statistic and kinematic cutting edges

The grains protrude variably far from the bond material of the grinding wheel, thereby engaging with varying strength. Only especially protruding grains or parts of the grain surface penetrate into the component during the machining process, causing material removal. These are called kinematic cutting edges. The concept of static cutting edges is used when cutting edge distribution on the component is described without consideration of the machining process. This is shown in Fig. 2-2 [PEKL57, PEKL58].

Because of the large number of cutting edges, a metrological ascertainment of the geometry of all individual cutting edges of a tool is only possible at high efforts. Due to wear, the number of cutting edges and their geometry change constantly during removal. We can get an idea of the form of the cutting edges statistically by means of a cutting edge profile, which can then describe on average the

form of a cutting edge. In Figs. 2-3 and 2-4, two characteristic cutting edge profiles are illustrated, acquired by scanning the grinding wheel [GUEH67, STEF78]. To scan the grinding wheel topography, tactile or optical scanning systems are used primarily [GOSE89, POPP91]. Clearance angles are usually ignored in the determination of grinding wheel topology.
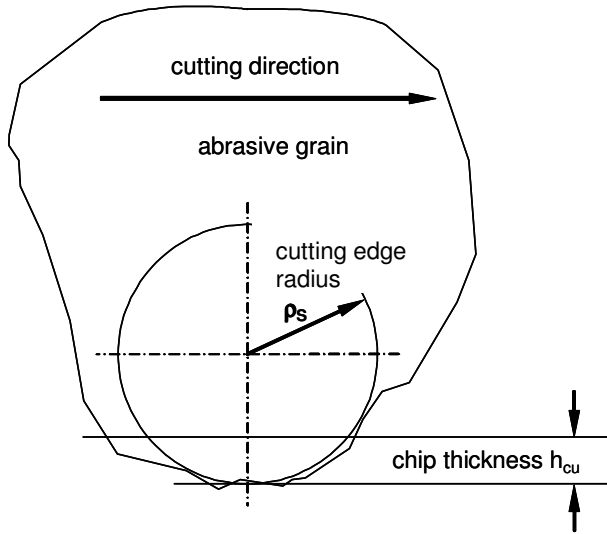

Fig. 2-3. Average form and the analytical description of an abrasive cutting edge

If the average profile of the cutting edges is approximated by a circle of radius ρ_s (Fig. 2-3) [LORT75, MASS52], we can then define a sharpness parameter with the quotient from the chip thickness h_{cu} and the cutting edge radius ρ_s:

$$S = \frac{h_{cu}}{\rho_s} \; .$$

$$(2.1)$$

The sharpness parameter S of machining process with geometrically undefined cutting edges is remarkable under 1, whereas it is several orders of magnitude above 1 in machining processes with defined cutting edges such as turning.

Other typical cutting edge profiles are shown in Fig. 2-4. Individual abrasive grains can splinter during the production process such that its form can be described similarly to tools with defined cutting edges. A tip, the geometry of which should be determined as in Fig. 2-4 by the tool orthogonal rake angle γ, the tool orthogonal clearance angle α and the wear surface A_{vk}, should thus have a negative tool orthogonal rake angle in order to be comparable to the geometry of the grits. Many researchers are of the opinion that the average grit resembles a tip of a rake angle of up to $\gamma = -80°$ [GUEH67, WERN71].

Beyond this, two basic forms are distinguished in Fig. 2-4. Form I shows a cutting edge geometry devoid of wear. Form II illustrates a cutting edge contour with wear surface A_{vk}, which can be considered as part of a flank face, so that the friction conditions are comparable with those of the flank face friction of a turning tool.
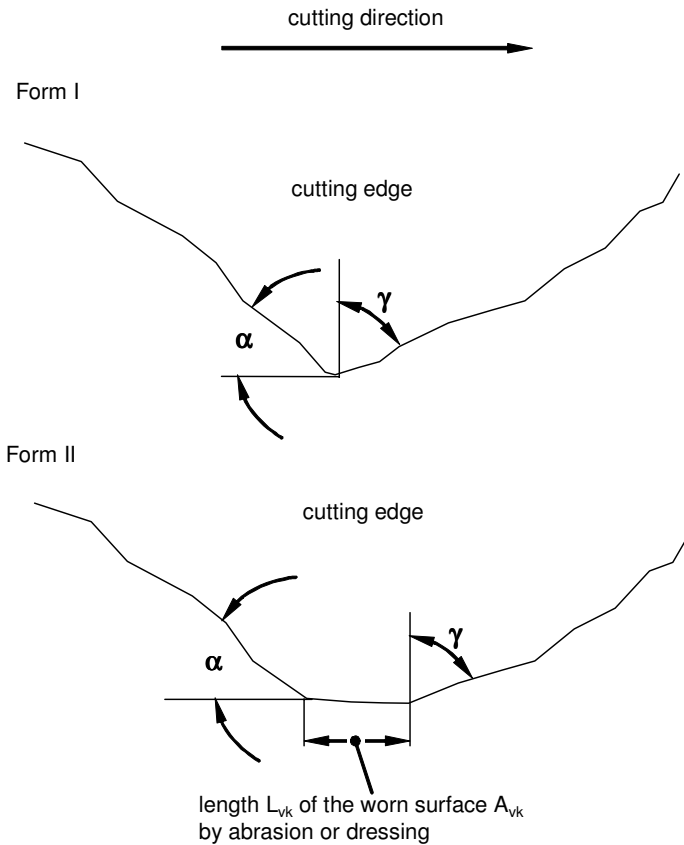

Fig. 2-4. Description of an average grit profile in analogy to cutting edges used in defined machining

2.2 Cutting Edge Engagement

In addition to the geometry of the individual cutting edges, the way in which the hard material grains engage is also important. The four possible operating principles for this are represented in Fig. 2-5.
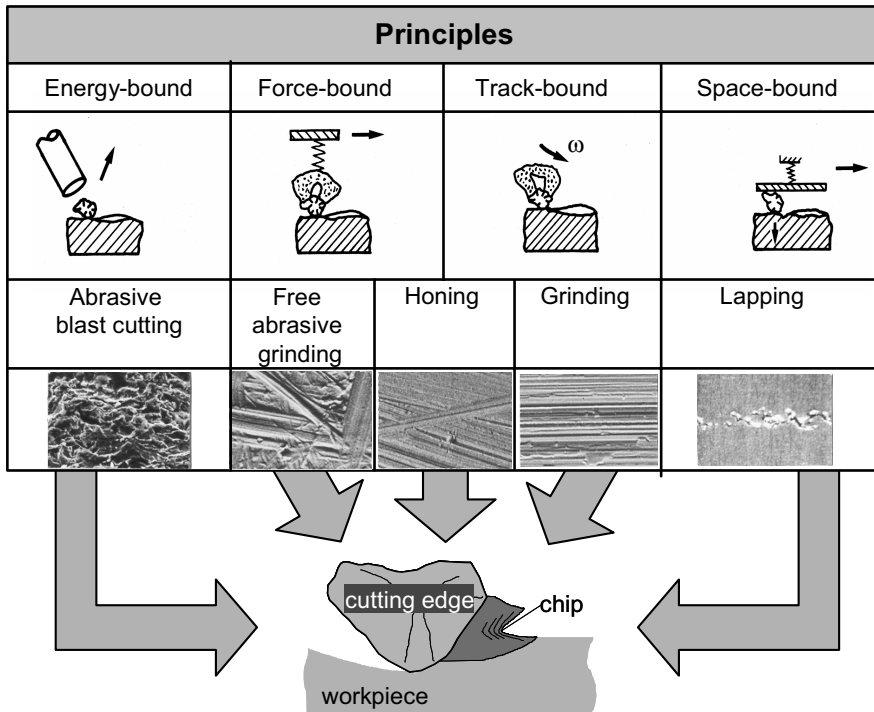
Principles			
Energy-bound	Force-bound	Track-bound	Space-bound
Abrasive blast cutting	Free abrasive grinding	Honing	Grinding	Lapping

Fig. 2-5. Operating principles of cutting edge employment

In the case of abrasive blast cutting, the grains are unbonded and collide with the surface of the workpiece. If the grains come up against a ductile workpiece material, a surface with small craters will result. Crater formation is associated with plastic flow processes, which result in a hardening of the surface. A condition of compressive residual stress initiated by this can also remain in layers of the workpiece near the surface even after machining. On the other hand, if the workpiece surface layer is brittle, entire regions of the layer near the surface chip due to the grains. Since it is primarily the kinetic energy of the grain which influences the effect of the cutting edge, the working principle of cutting edge engagement is energy-bound.

Unbonded grains are used in lapping as well. They are found between the target workpiece surface and a fixed lap tool. A parallel relative movement between the

lap tool and the workpiece surface forces the grains to execute a rolling movement. During the rolling, the grains are constantly pushing into the workpiece, so the machined slot on the workpiece resembles a series of small, consecutive craters. A smoothing and hardening of the workpiece surface also results. Moreover, the constant rolling of the grains produces a fine material removal as a result of workpiece fatigue [MART75]. Since the space between the lap tool and the workpiece determines the sequence of the cutting edge engagement, this is essentially a case of a space-bound operating principle. Depending on the process parameters it can change into a force-bound principle.

We succeed to a third working principle if the tool is pressed against the workpiece with increased force, but constant surface pressure. The grain can no longer roll in these conditions. The cutting edges make fine scratch marks in the machining location. Since the grain is pressed against the surface of the workpiece with limited force due to the constant surface pressure, cutting edge engagement is force-bound.

In the case of some grinding, honing and free abrasive grinding operations with bonded grains, cutting edge engagement is also force-bound. It is hereby often the case that the grain remains relatively fixed and penetrates into the workpiece at a predetermined path by the relative movement between the tool and the workpiece (Fig. 2.6). Cutting edge engagement is thereby conditionally track-bound. This working principle can be found with most machining methods with geometrically undefined cutting edges. It is based on the following observation on the engagement of individual grits.
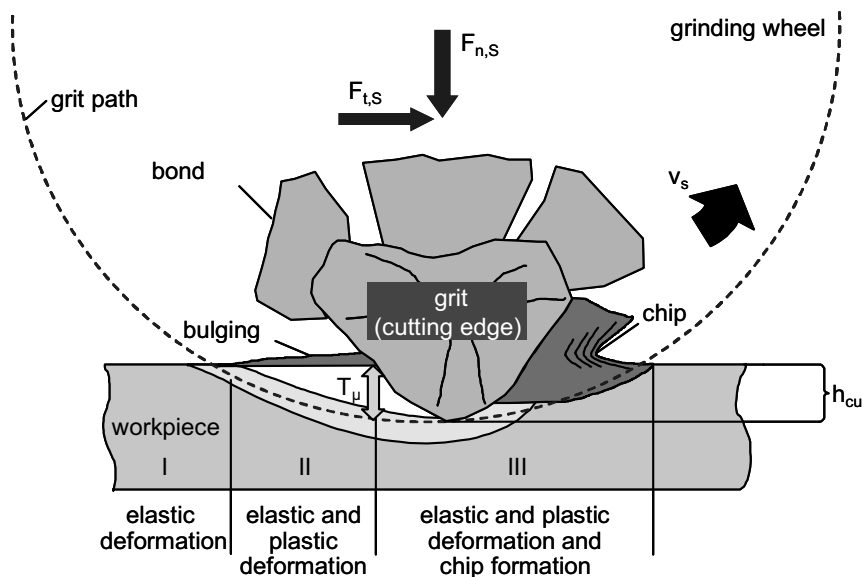

Fig. 2-6. Zones of elastic and plastic deformation in chip removal

During a machining process with a track-bound cutting edge engagement, the cutting edge of the grain penetrates the workpiece upon a flat path and, after a phase of elastic deformation, triggers plastic flow of the workpiece material (Fig. 2-6). Because of the form of the cutting edge, the angle between the cutting edge contour and the workpiece surface is very small at first, so that no chips are formed initially. The workpiece material is merely shifted to the side, forming elevations and/or flows beneath the cutting edge to its flank face.

Only when the cutting edge has penetrated deeply enough into the workpiece that chip thickness h_{cu} corresponds to the grain cutting depth T_μ does actual chip formation begin [LORT75, MASS52, STEF78]. Since, as the sequence continues, deformation processes and chip formation appear simultaneously, it is decisive for the efficacy of material removal just how much of the chip thickness h_{cu} is actually produced as chips and thus how large the effective chip thickness $h_{cu\ eff}$ is (Fig. 2-6).
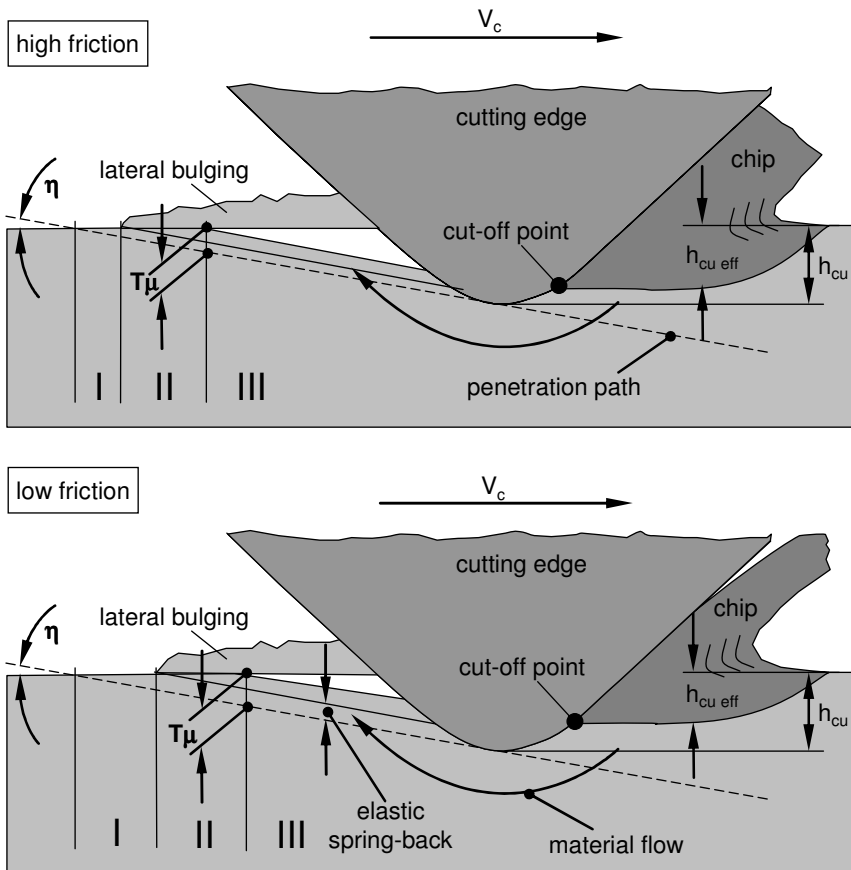

Fig. 2-7. The influence of friction on the cutting depth and machining efficiency

Chip formation and thus $h_{cu\ eff}$ and T_μ are influenced to a large degree by the friction conditions at the cutting edge. For a better understanding of the influence of friction in cutting edge engagement, it is useful first to explain the differences in chip formation with cooling lubrication with oil or emulsions. Fig. 2-7 illustrates the influence of friction on the grain cutting depth and the efficiency of material removal. With increasing lubrication, the grain cutting depth increases, and there is a longer lasting and therefore also stronger plastic material deformation [VITS85].

Increased lubricating capability of the cooling lubricant reduces the efficiency of material removal. At equal undeformed chip thickness h and less friction, a thinner chip (lower $h_{cu\ eff}$) results, with which the ratio of chipped to deformed material volumes decreases.

Investigations have shown that, besides friction, the following quantities influence the amounts of $h_{cu\ eff}$ and T_μ:

- the cutting edge radius ρ_s,
- effective cutting speed angle η,
- cutting speed v_c
- the flow properties of the material.

Usually, blunt cutting edges with a small sharpness parameter and a small angle η tend to promote deformation of the material, leading to larger grain cutting depths and thus to smaller effective chip thickness. With rising machining temperatures, the grain cutting depth increases, since the material becomes more ductile because of the higher temperature. With higher material malleability, the grain cutting depth decreases, since strain hardening has the strongest effect here. The capability of the material to flow beneath the cutting edge is determined by friction: at higher levels of friction, the grain cutting depth decreases.

In considering the entire process, the speed of the grinding wheel should always be seen in relation to the workpiece speed. The cutting speed v_c is defined as the vector sum of the grinding wheel peripheral speed v_s and the workpiece speed v_w. If we consider a cutting edge as a fixed point on the grinding wheel and describe its trajectory curve, cycloidal trajectories appear for both down and up dressing with varying markedness [EICH97, HARB96, SAWL64]. The kinematic roughness in the grinding direction is thus the result of the engagement paths of the grit, as is depicted for flat grinding in Fig. 2-8.
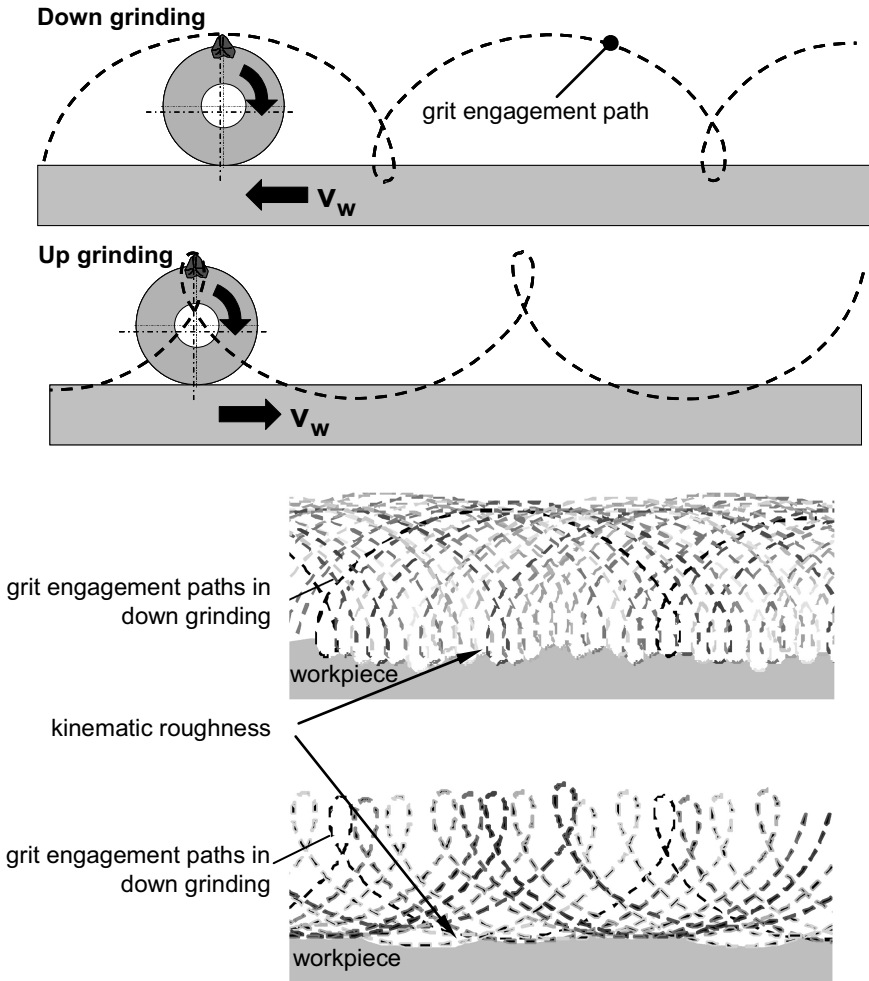
Down grinding

grit engagement path

V_w

Up grinding

V_w

grit engagement paths in down grinding

workpiece

kinematic roughness

grit engagement paths in down grinding

workpiece

Fig. 2-8. Cycloidal trajectories of an abrasive grain in down and up grinding

2.3 Distribution of Force and Energy in the Grinding Process

The distribution of force and energy can be considered both microscopically with relation to the individual grits as well as macroscopically on the scale of the entire grinding wheel. In the following, we will begin with a microscopic observation and then expand this with macroscopic considerations.

The cutting force acting upon the individual grit during a cutting edge engagement can be broken down into a component F_{tS} in the direction of the cutting

speed and a component F_{nS} in the direction normal to this (Fig. 2-6). The quotient F_{tS}/F_{nS} is called the cutting force ratio μ.

The cutting force of the entire tool is the vector sum of the cutting forces that act upon the cutting edges momentarily engaging with the workpiece. The cutting force ratio determined by the machine often largely corresponds to the average cutting force ratio of the individual cutting grits [RUBE67].

During the phase of pure material deformation, the force F_{nS}, with which the cutting edge must be pressed into the workpiece, is considerably larger than F_{tS}; the cutting force ratio thus assumes a relatively small value. As chip formation starts, the tangential force F_{tS} goes up, and so the cutting force ratio increases.

Sharper cutting edges with a small cutting edge radius ρ_S and/or greater friction allow for earlier chip formation during cutting edge engagement and lead to a – in comparison to duller cutting edges – larger cutting force ratio.

Scoring experiments, in which the engagement path of a particular grain is seen in analogy with the grinding process, can give us concrete information about the absolute magnitude of the cutting force components. For the experiments, the results of which are illustrated in Figs. 2-9 and 2-10, conical diamonds with varying peak radii ρ_S served as the scoring tools [BUSC68, VITS85]. In order to obtain conveyable results, the measured tangential force is related to the cross-section of the scratched groove.
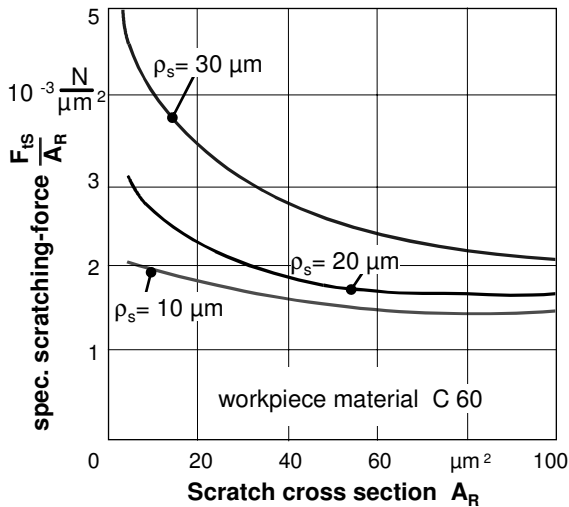

Fig. 2-9. The cutting edge radius and scratch cross-section determine the specific scratching force along with friction

With shrinking cross-sectional areas, the specific scratching force takes on very high values. This reflects the fact that the cutting edge rubs over the workpiece material with the flank face at small amounts of chip thickness, thereby only deforming it. Furthermore, the positions of the curves make it clear that, in the case

of dull cutting edges, there must be a higher cutting force due to the enlarged contact surface. If we broaden the specific scratch force in the numerator and denominator with the dimension of length, a volume controlled work results. The numerical value of the specific scratching force can then be interpreted as that work which is needed to produce a unit volume of score.

The influence of friction on the specific scratching force is also clarified by Fig. 2-10. For varying friction conditions, the specific scratching force reaches higher values with shrinking scratch cross-sections. For example, at small chip thicknesses, the material is only deformed by the cutting edge. Material removal is dominated by the mechanism of micro-groove formation. In the realm of small scratch cross-sections, an improvement in lubrication leads to a higher specific energy requirement, which can be ascribed to the proportionally increased workpiece material deformation. In comparison to scratching without cooling lubrication, with the use of emulsions or oil, an average of ca. 2 to 2.5 µm less scratch depth was realised. In the case of larger scratch cross section on the other hand, the influence of the tangential forces dropping with friction are dominant, so that emulsions and especially oil lower the specific energy requirement [VITS85]. By these machining conditions, the mechanism of microcutting comes to the fore.
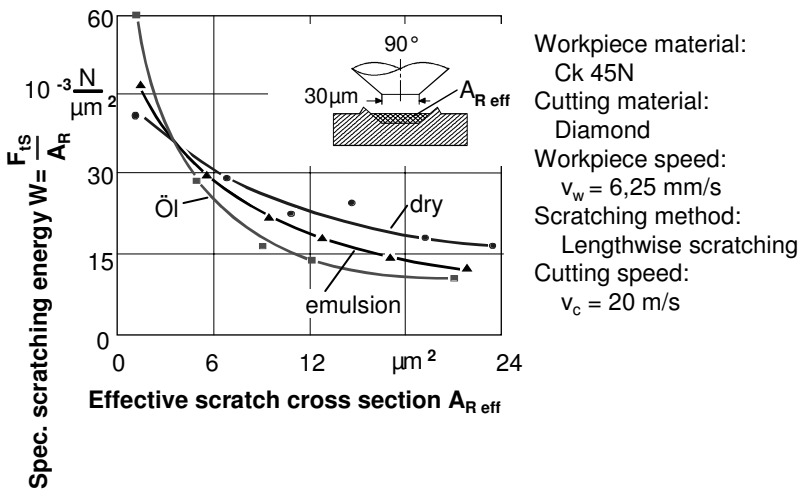

Fig. 2-10. The influence of friction on the specific energy in scratching

The mechanical energy present is transformed into heat basically in four places. Because of the large cutting edge radii, most of the heat generated consists of flank face friction and plastic deformation of the workpiece material. Heat is generated by friction at the chip surface and during chip cropping. Finally, in the case of bonded grains, a small amount of mechanical energy is also converted into heat as the bond rubs against the workpiece.

The main share of the energy inserted into the process is converted into heat. Thus, all system components involved in machining experience thermal stress or dissipate heat. The total heat flow rate q_t spreads in the contact zone to the grinding wheel (q_s), the workpiece (q_w), the chips (q_{span}) and the cooling lubricant (q_{kss}) (Fig. 2-11). How high the particular share of heat flow is depends on, among other things, the heat conduction coefficient of the workpiece material, the cooling lubricant and the grinding wheel as well as the heat transfer coefficient [JAEG42, STEP03].

Heat flow into the workpiece can lead to a local rise in temperature. This increase in temperature can, depending on the magnitude and action time, produce thermal structural changes in the workpiece surface layer. The action time of the heat and the temperature level can be favourably influenced by applying a cooling lubricant.
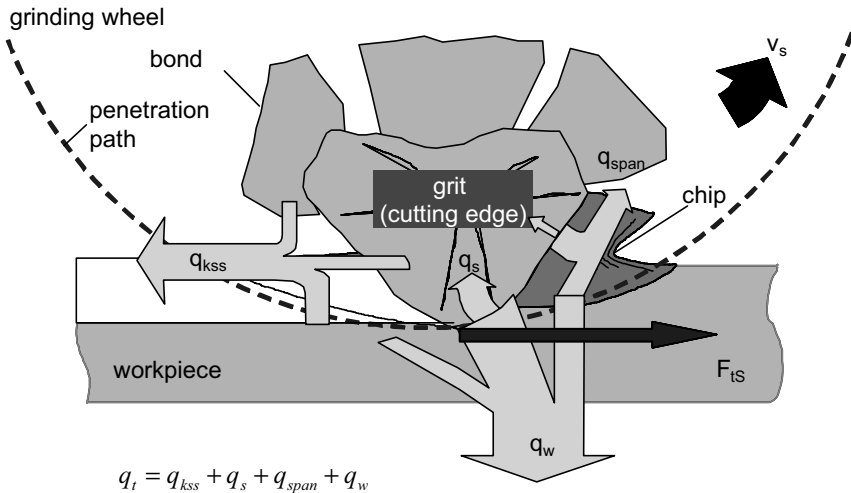

$$q_t = q_{kss} + q_s + q_{span} + q_w$$

Fig. 2-11. Energy distribution and heat flow during cutting edge penetration

2.4 Grit and Bond Wear

Not only the workpiece, but also the tool is subjected to high temperatures and pressures in the contact zone. The result of this is microscopic wear in the grit and the bond (Fig. 2-12).

Grit wear begins in the crystalline layers lying near the surface of the grit. Extreme pressures and temperatures initiate oxidation and diffusion processes there, which decrease the abrasion resistance of the grit material. This pressure-softened layer is removed by mechanical agitation (abrasion). In this way, new crystalline

layers are constantly exposed to wear. By means of tribochemical reactions on the grit surface, the mechanical endurance of the grit can change, intensifying wear.
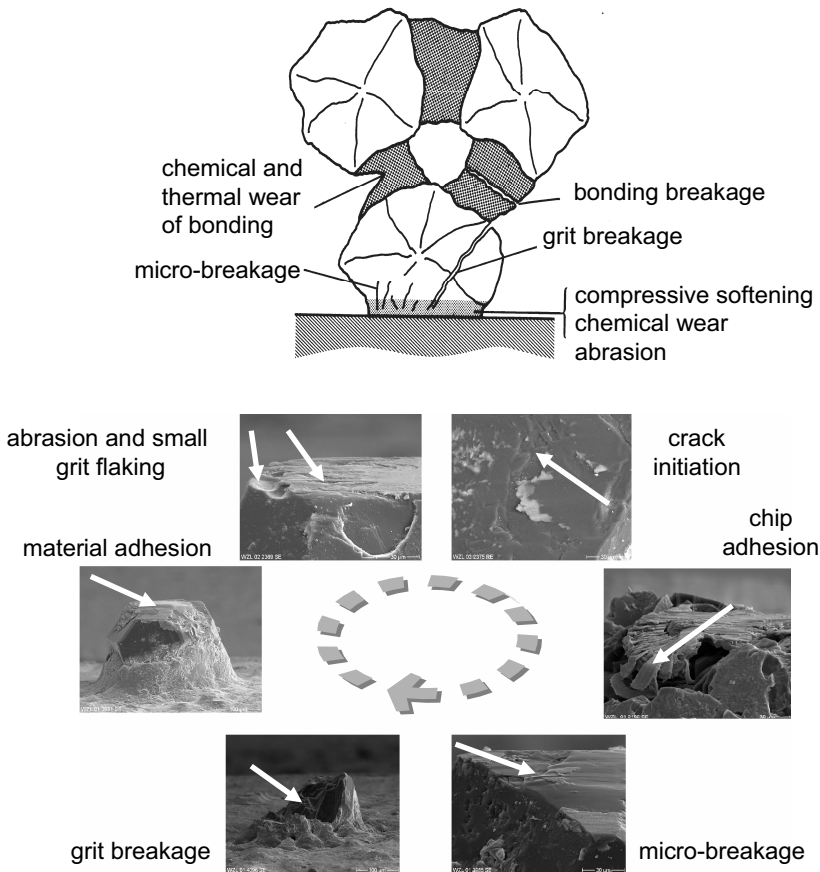

Fig. 2-12. Types of grain and bond wear

Moreover, mechanical and thermal alternating stress can lead to fatigue in the crystal bond. At points of disruption, which exist in every solid body in the form of lattice and grain boundaries, impurities, differences in hardness etc., cracks of fatigue appear. These can lead to disintegration of the surface as well as to the splitting off of individual grain particles or initiate the formation of cracks that cause entire sections of grit to break off.

In many cases, grit wear is the indirect cause for bond wear, since a flattening of the cutting edge of the grit leads, due to an enlarged friction surface, to an increase in cutting force on the individual grit and thus to mechanical overloading of the bond. Entire grits or grit sections can then break out of the bond. The bond can also be directly worn by chemical, mechanical or thermal influences.

Such causes of wear are to be considered in process design and particularly in the choice of grinding wheel specifications.