Principles of Cutting

Simulation Techniques in Manufacturing Technology

Lecture 6

Laboratory for Machine Tools and Production Engineering

Chair of Manufacturing Technology

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Outline

Cutting: Machining with geometrically defined cutting edge

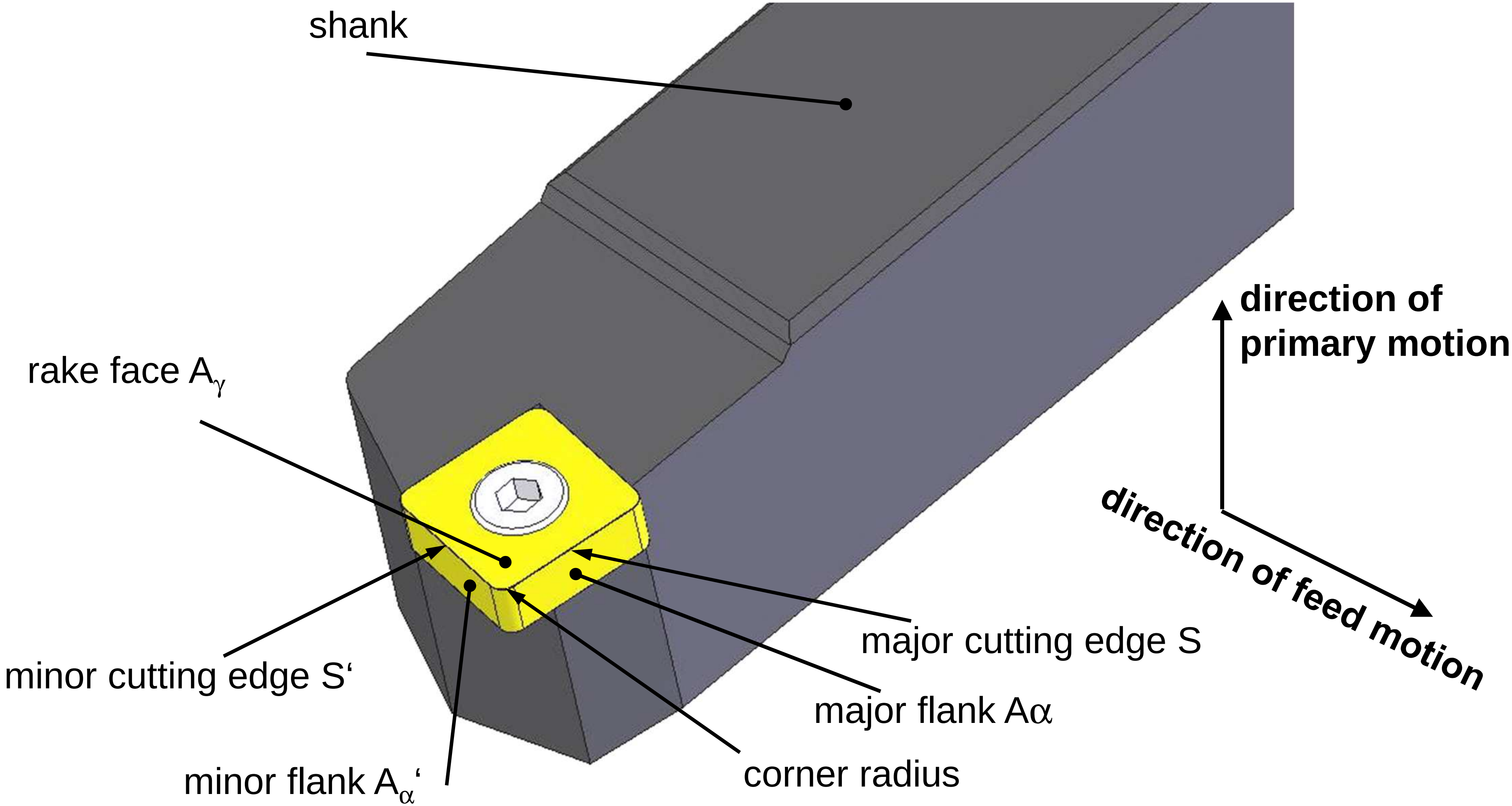
Manufacturing Processes						
major groups	1 primary shaping	2 secondary shaping / forming	**3 cutting**	4 joining	5 coating	6 changing material properties

source: DIN 8580

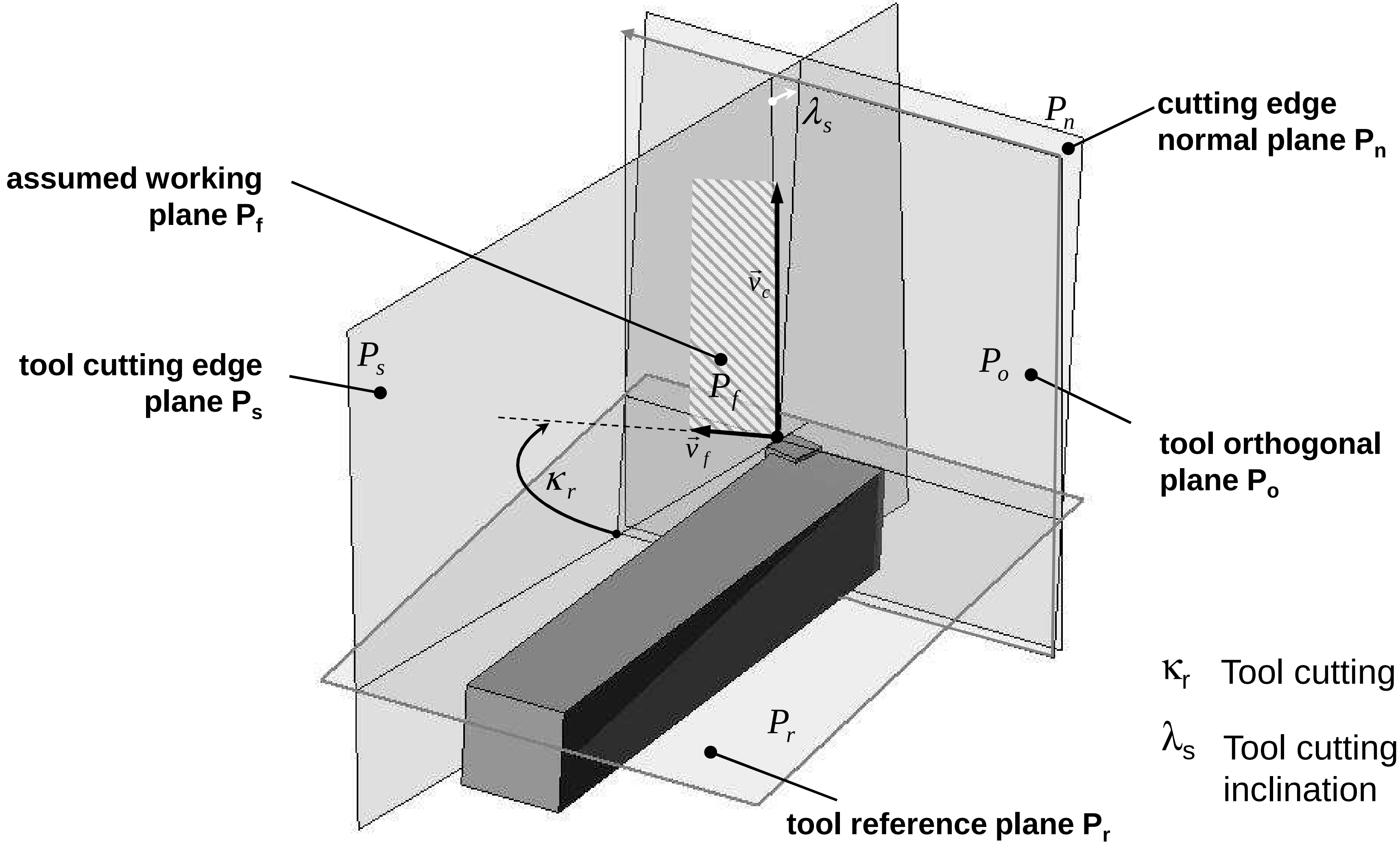
3.2 cutting with geometrically defined cutting edges (DIN 8598-0)

Definition (DIN 8589):
Machining is cutting, in which layers of materials are mechanically separated from a workpiece in the form of chips by means of a cutting tool.

Nomenclature at the wedge



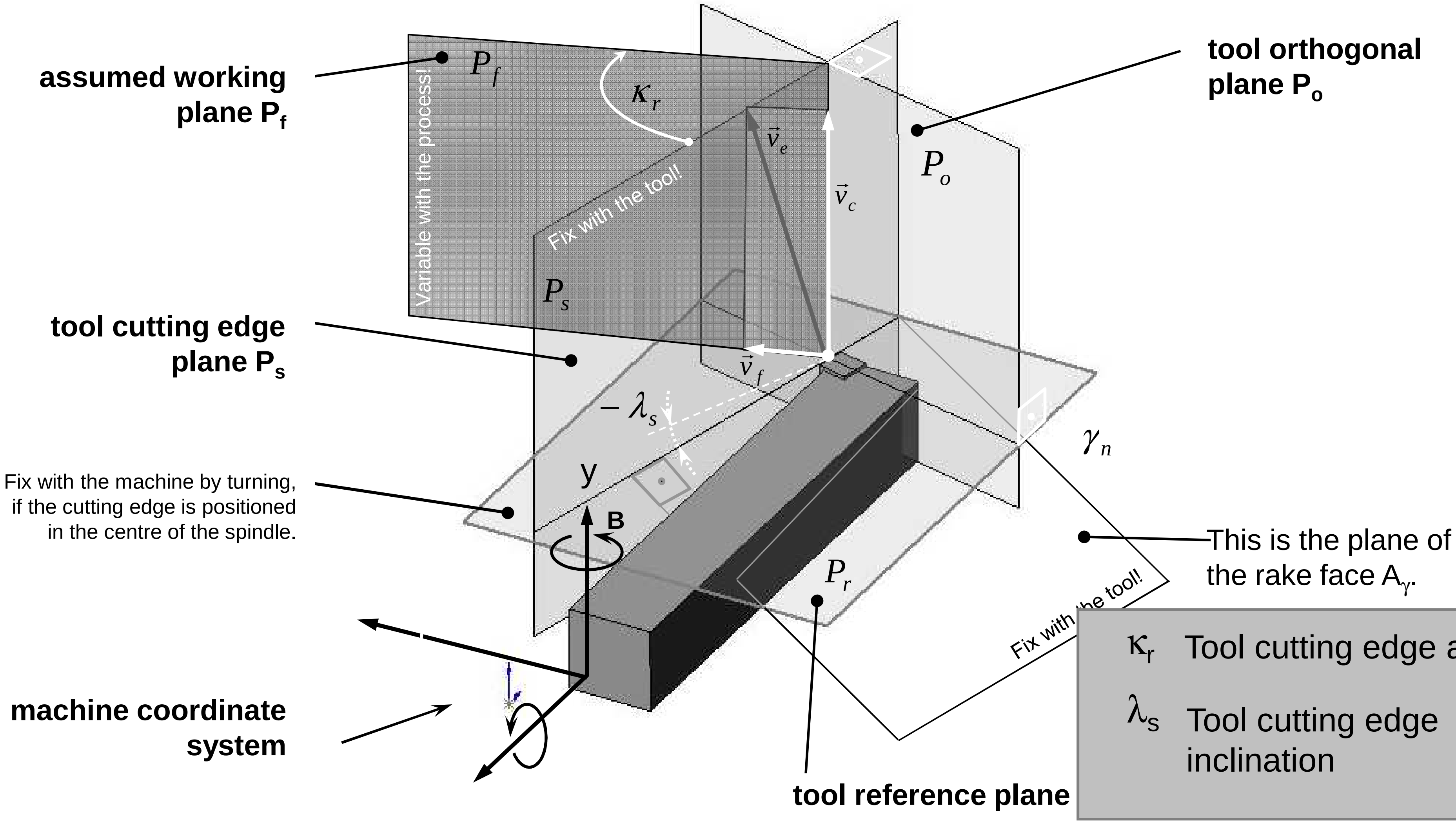
Tool-in-hand system



κ_r Tool cutting edge angle

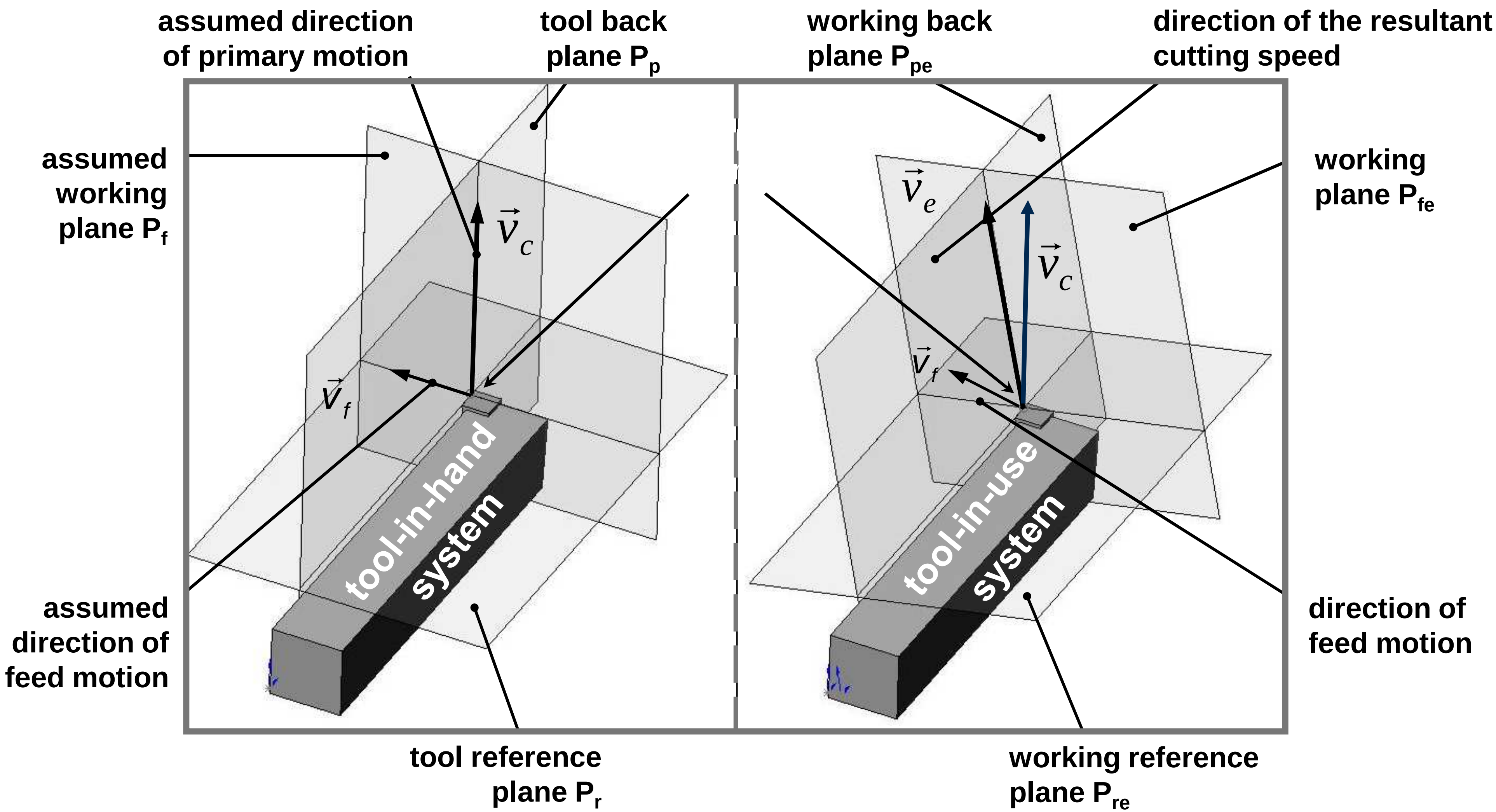
λ_s Tool cutting edge inclination

Tool-in-hand system (ISO 3002)

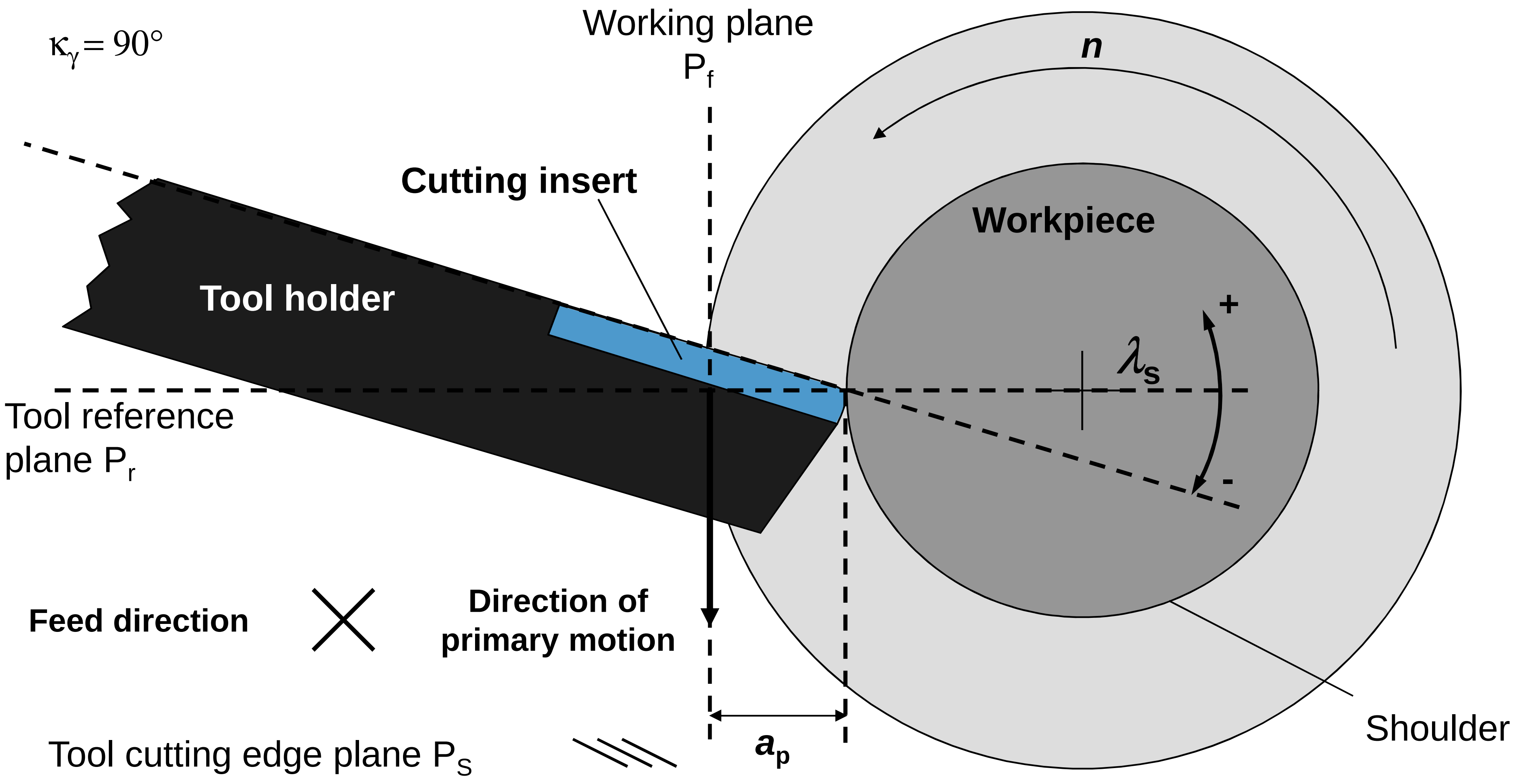


κ_r	Tool cutting edge angle
λ_s	Tool cutting edge inclination

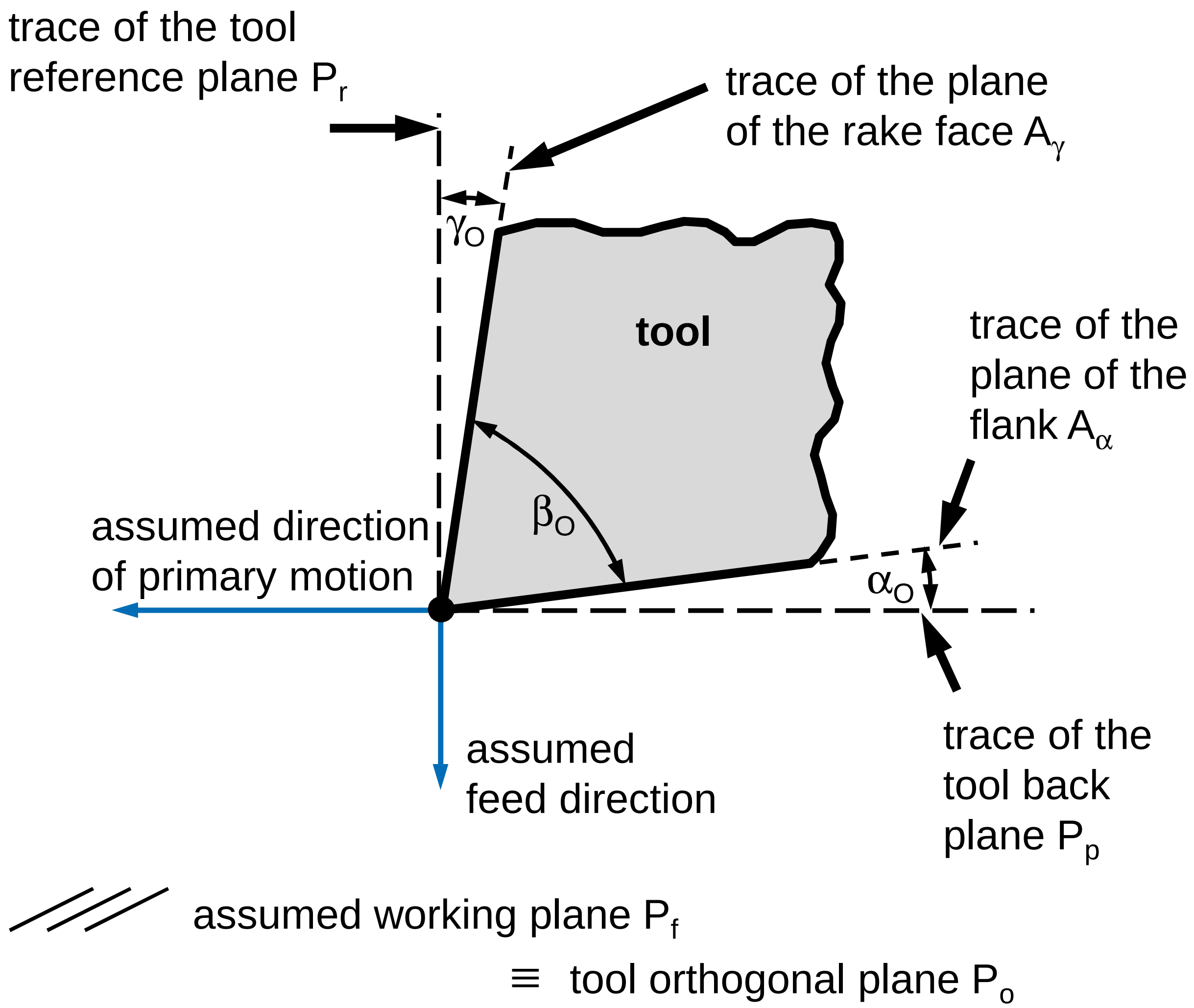
Differences between reference systems



Definition of the tool cutting edge inclination during external cylindrical turning

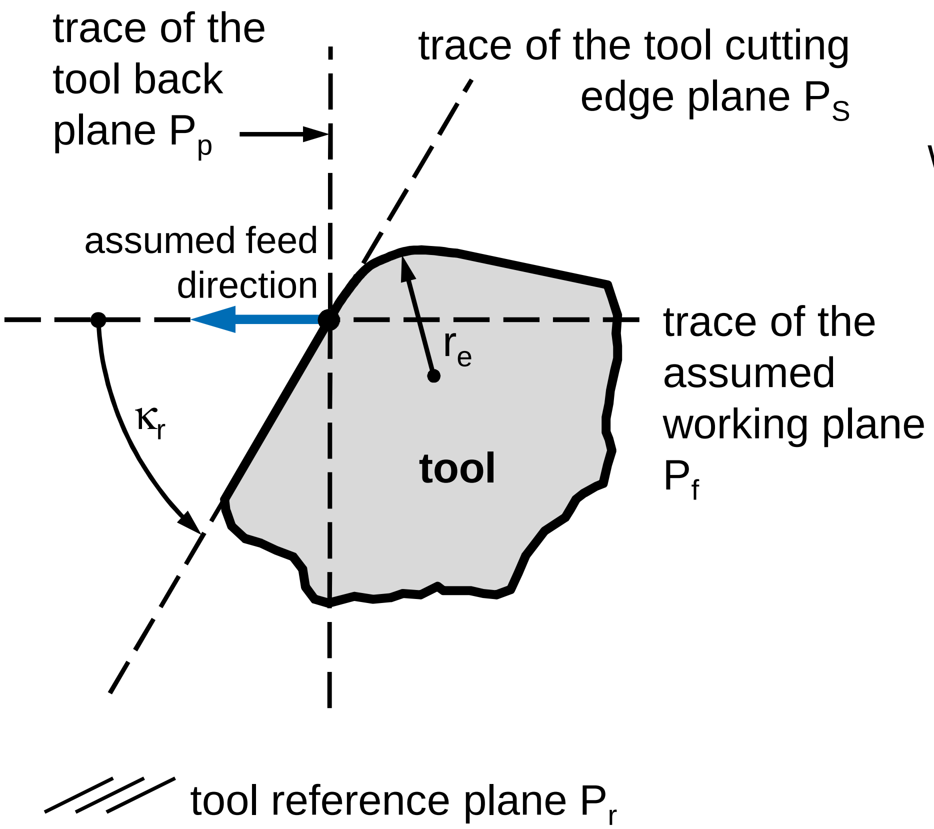


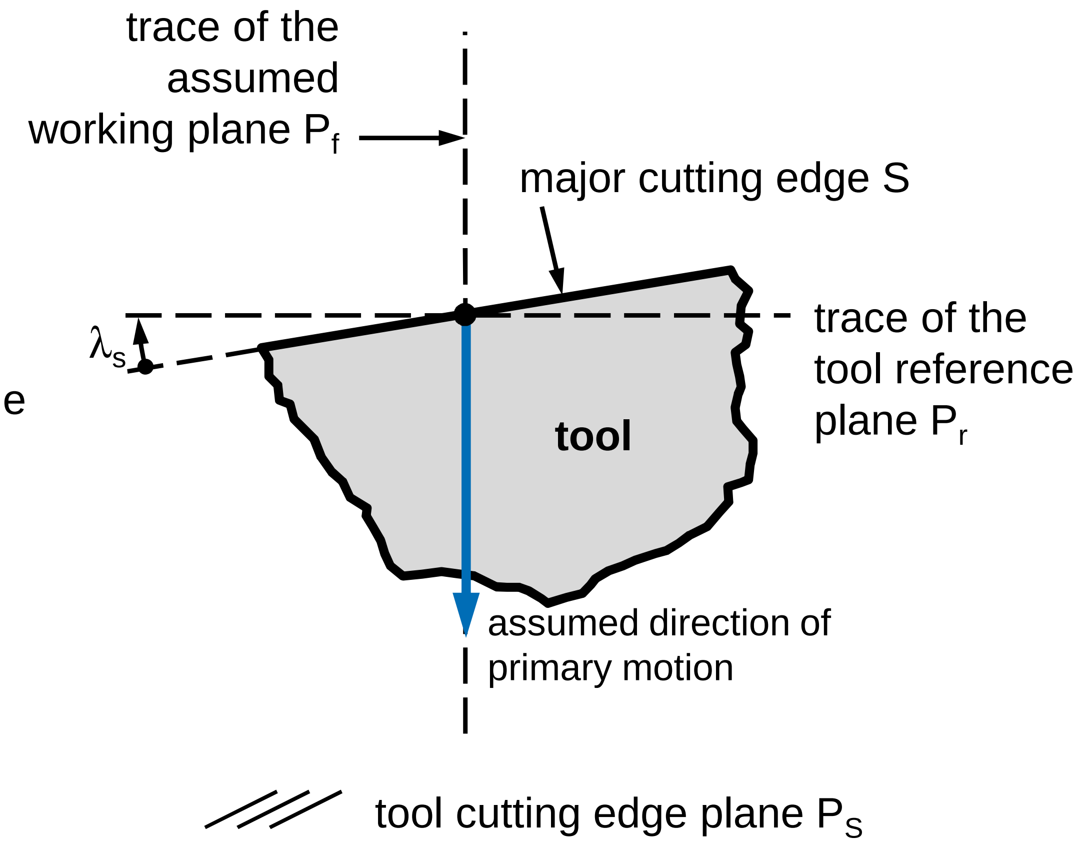
Process kinematics at the wedge



- Idealised wedge in the assumed working plane
- The geometry of the idealised cutting wedge is defined by the rake angle γ_O, the wedge angle β_O and the clearance angle α_O

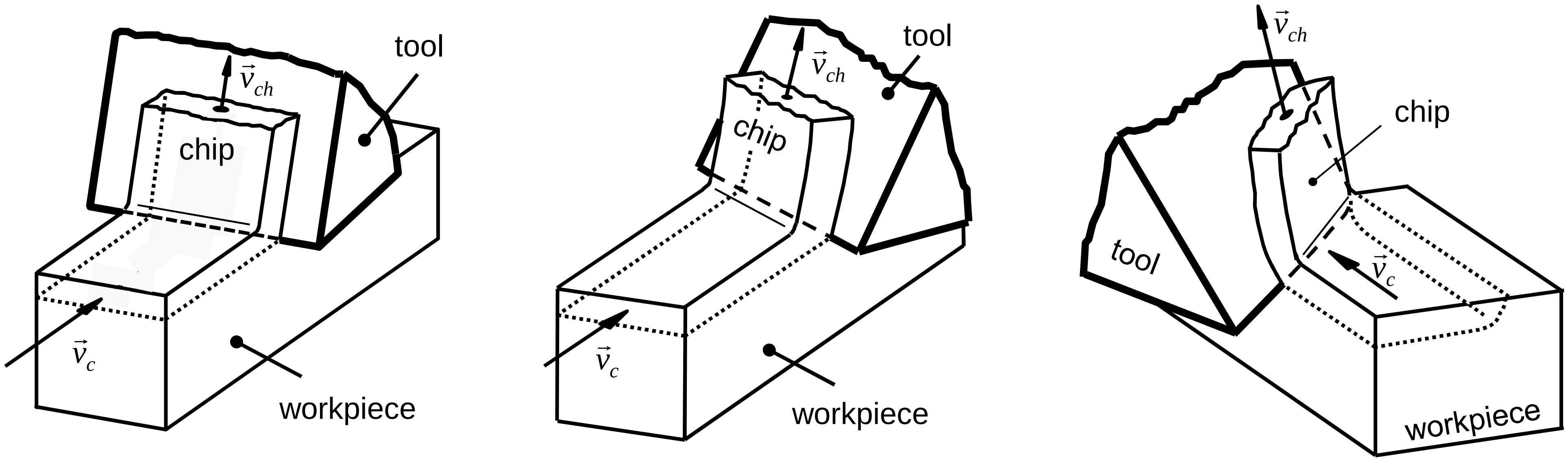
Cutting edge angle and inclination angle





- Tool cutting edge angle κ_r
- Tool cutting edge inclination λ_s

Orientation of the cutting edge: process kinematics

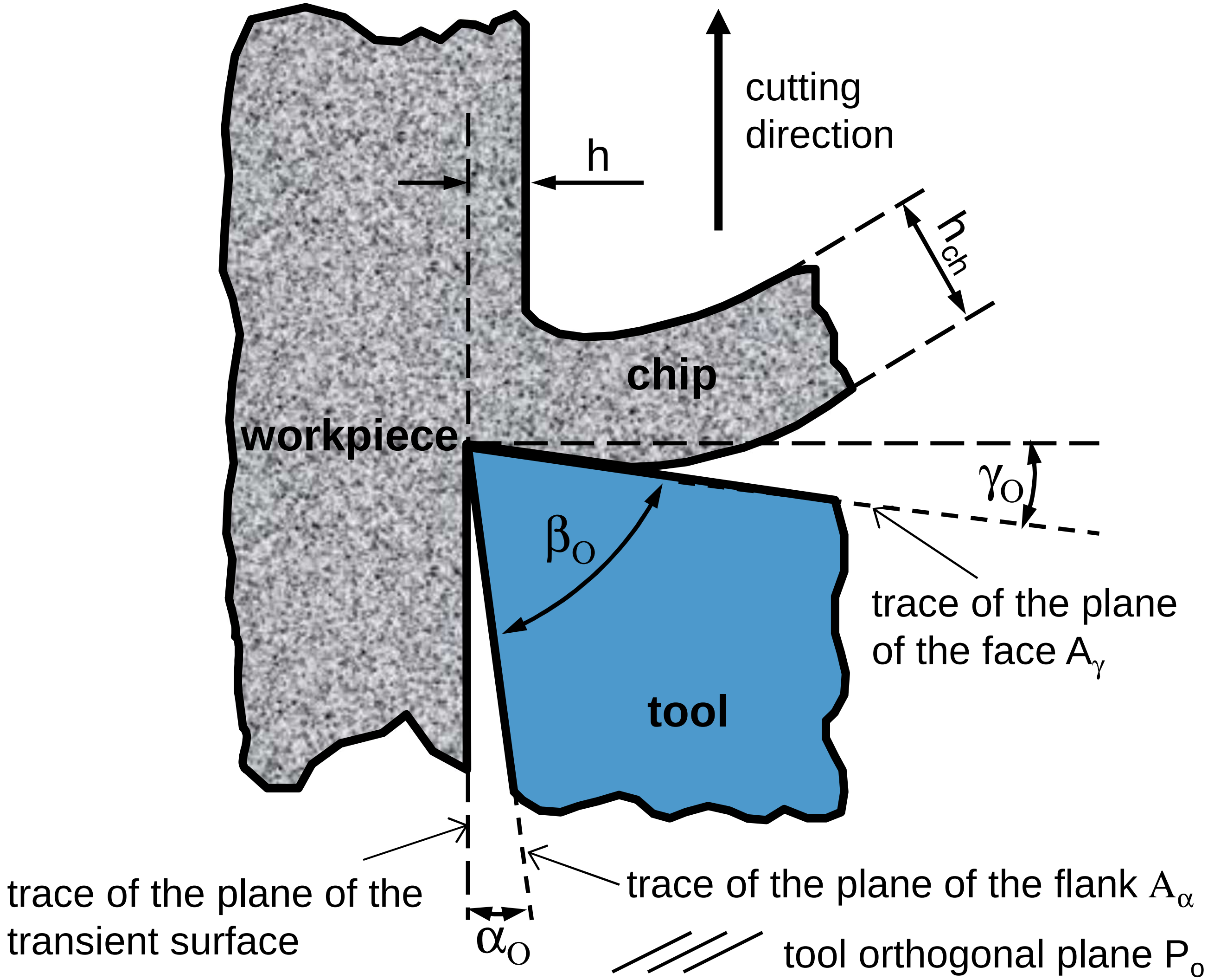


- **free orthogonal cut**
- Tool cutting edge inclination $\lambda_s = 0°$ and $\kappa_o = 90°$

- **free oblique cut**
- Tool cutting edge inclination λ_s not equal to 0°

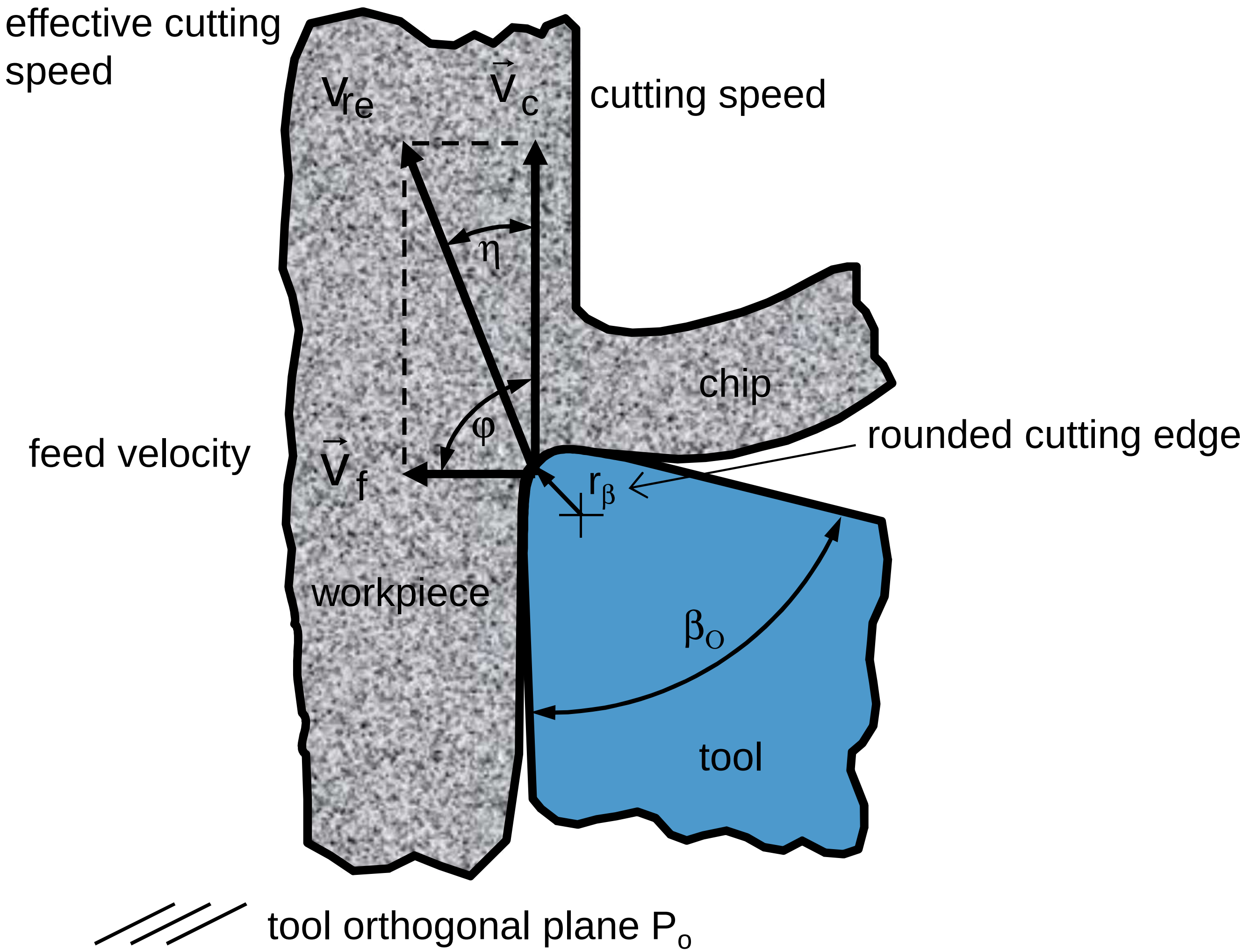
- **non-free oblique cut**

Process kinematics at the idealised wedge



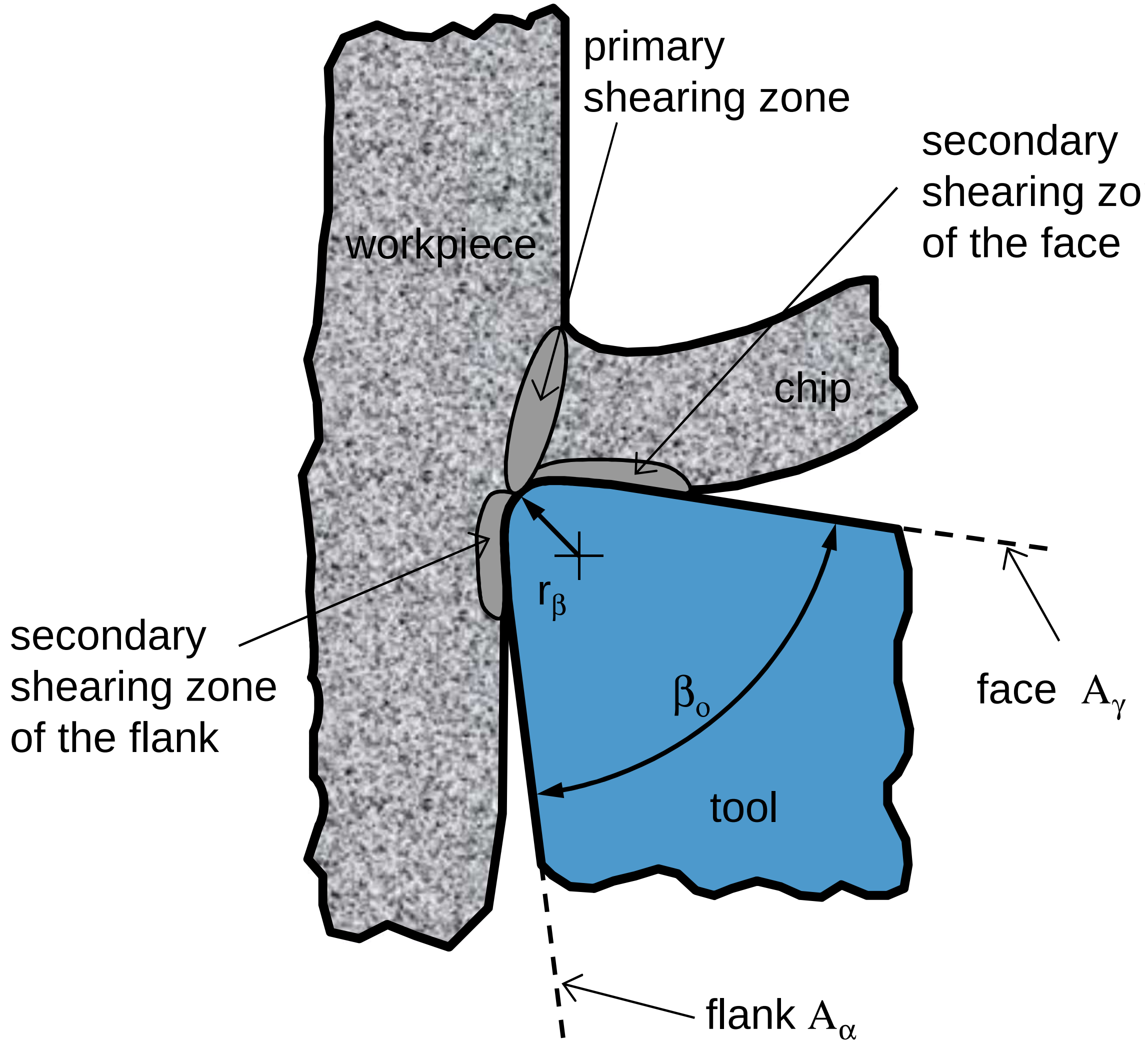
- The wedge geometry is defined by the clearance angle $\alpha_{O,}$ the wedge angle β_O and the tool orthogonal rake angle γ_O
- *The wedge penetrates the material and causes elastic and plastic deformations*
- Due to the given geometry the deformed material is forming a chip which flows across the rake face

Process kinematics and rounded cutting edge radius



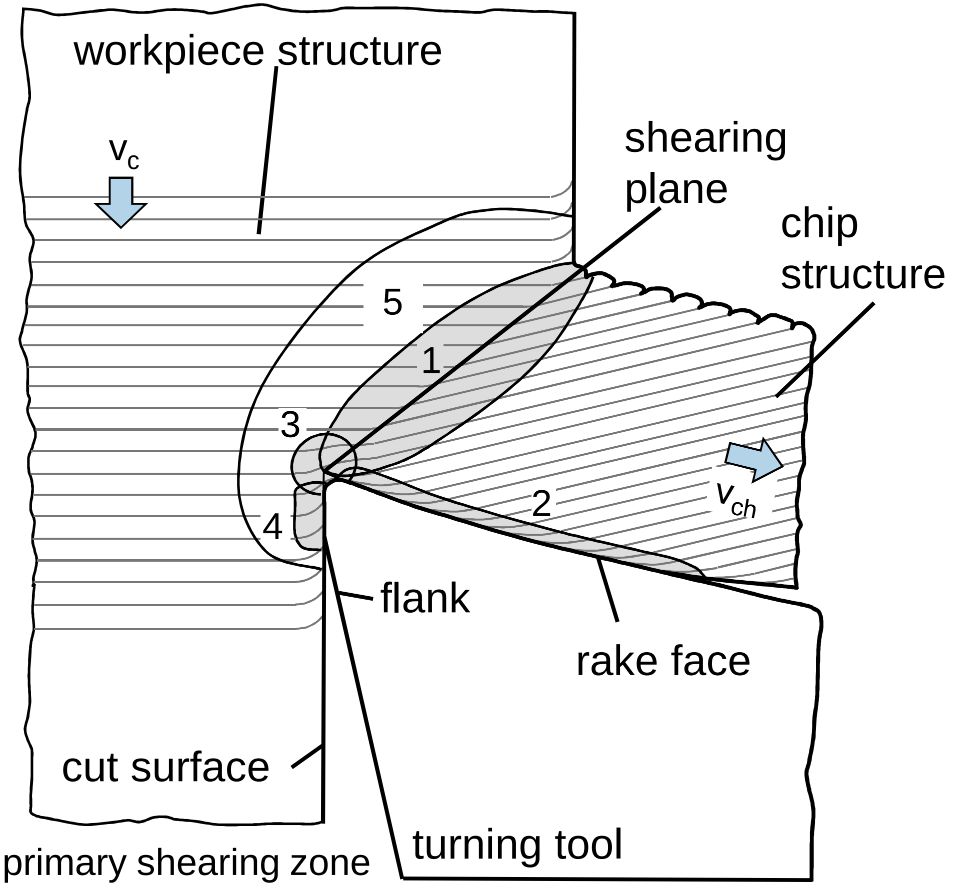
- In reality there are only rounded cutting edges
- The cutting edge radius is usually measured in the tool orthogonal plane P_O
- Feed direction and cutting direction are enclosing the feed motion angle φ
- The directions of effective cutting speed and cutting speed are enclosing the effective cutting speed angle η

Shearing zones in cutting processes

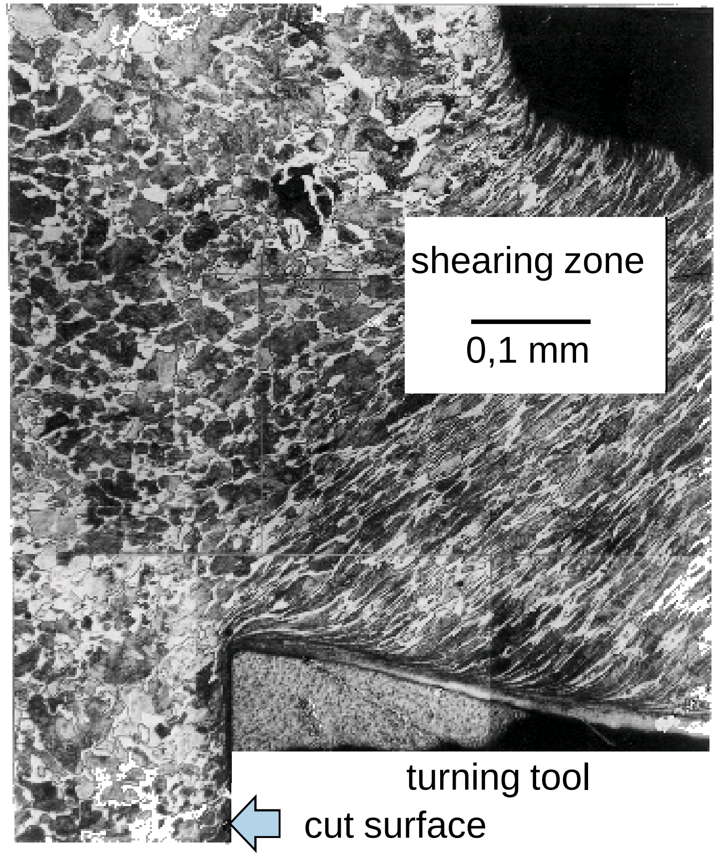


- Shearing is very essential in cutting.
- So-called shearing zones might be formed.
- The most important shearing zone is called primary shearing zone.
- The zones where shearing is caused by friction are called secondary shearing zones.
- Under a wearless con-sideration the secondary shearing zone of the flank drops out.

Chip formation

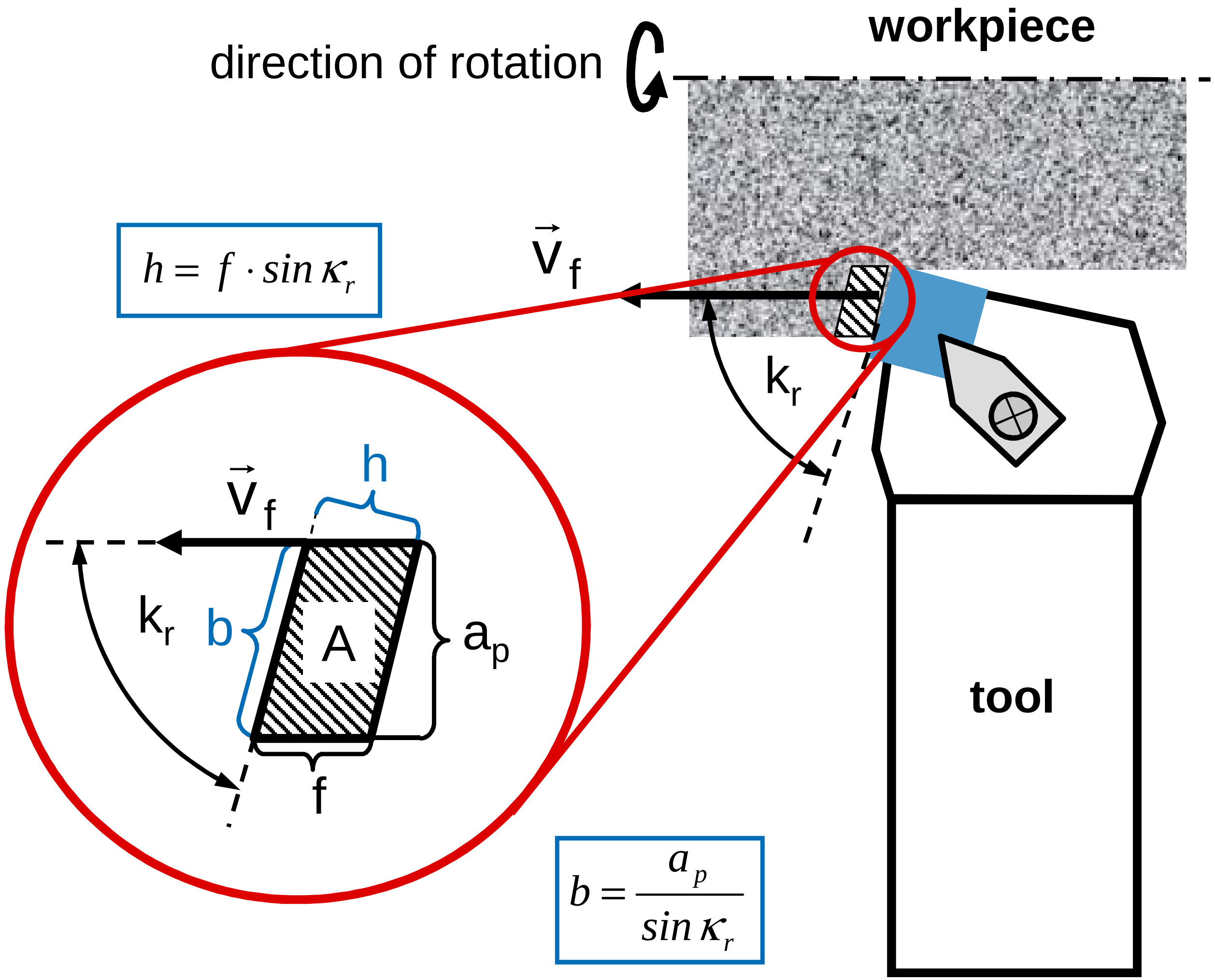


1 primary shearing zone
2 secondary shearing zone of the face
3 seperative zone (stagnation point)
4 secondary shearing zone of the flank
5 preliminary deformation zone



workpiece material:	C53E
cutting edge material:	HW-P30
cutting speed:	v_c = 100 m/min
cross-section area of cut:	a_p x f = 2 x 0,315 mm^2

Penetration of tool and work piece, cross-sectional area



$$h = f \cdot \sin \kappa_r$$

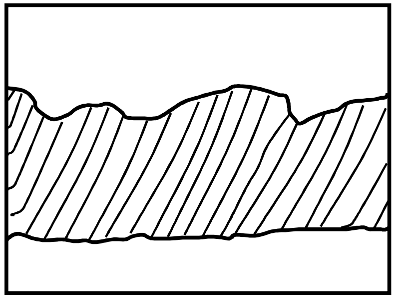
$$b = \frac{a_p}{\sin \kappa_r}$$

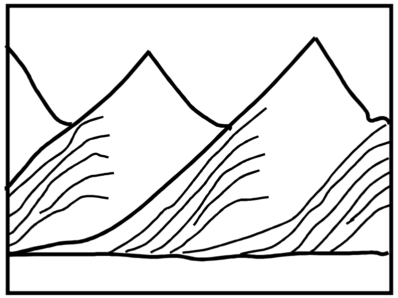
- The cross-sectional area is determined by the tool cutting edge angle κ_r , the feed f and the depth of cut a_p
- The undeformed chip thickness *h and the* width of cut *b* can be calculated from the feed f and the depth of cut a_p respectively, using the cutting edge angle κ_r .

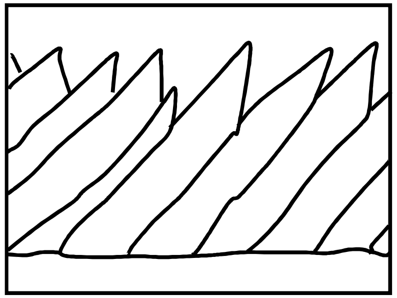
Outline

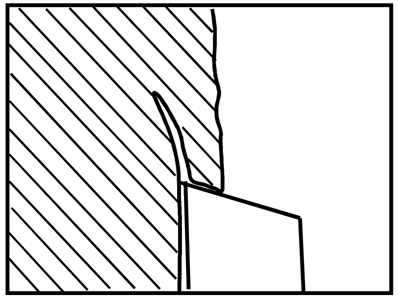
Chip formation depending on the material behaviour

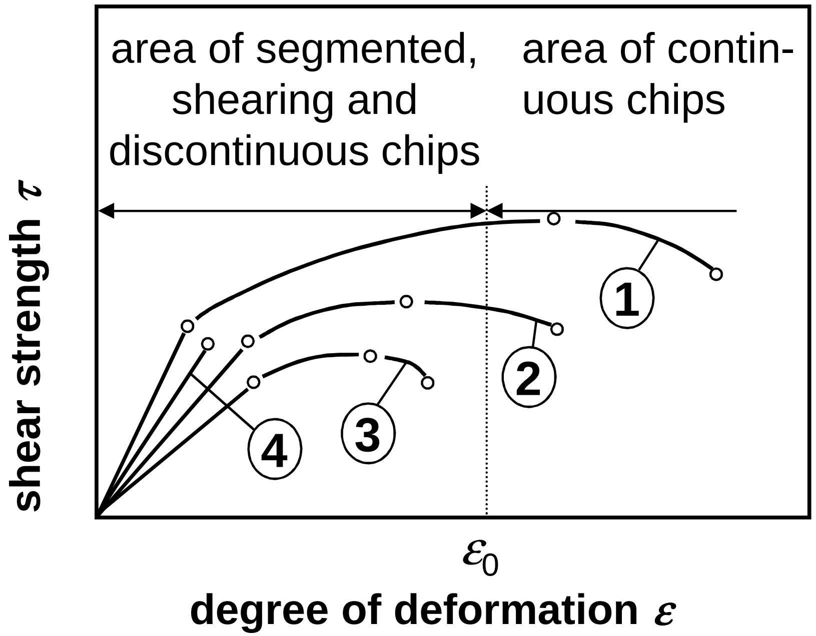
1 continuous chip | 2 segmented chip | 3 shearing chip | 4 discontinuous chip

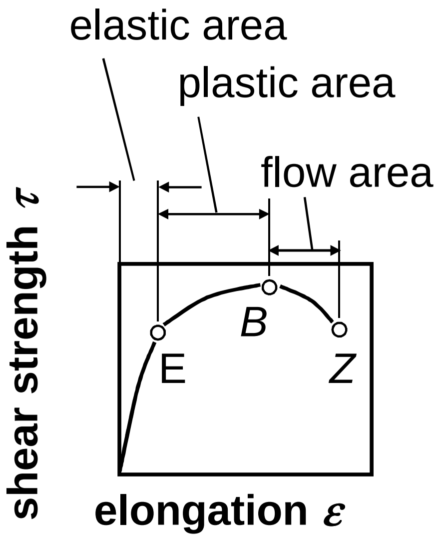






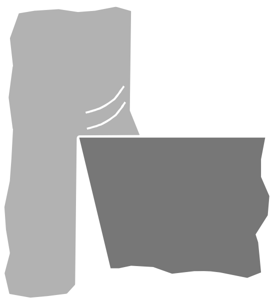




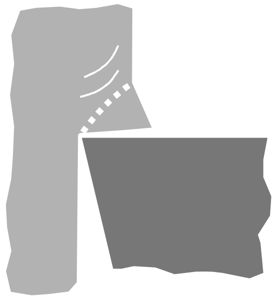


E_0: degree of deformation in the shear zone
E: limit of elasticity
B: breaking limit
Z: tensile strength

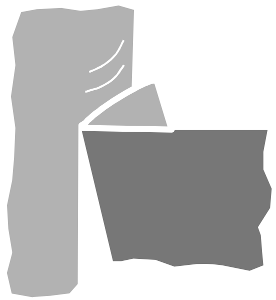
Chip formation for brittle material behaviour



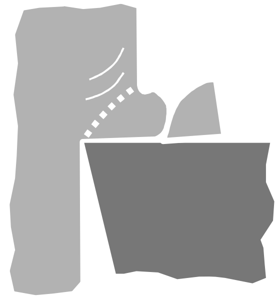
1. bring up gathering



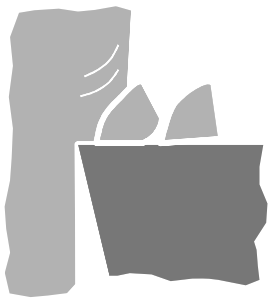
2. split up, crack segment formation



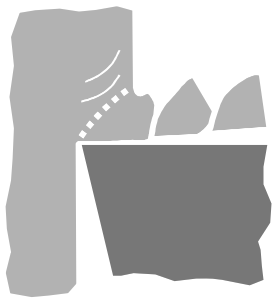
3. shearing and next bring up



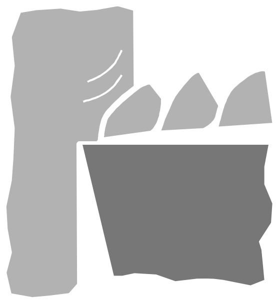
4. second segment formation and bring up



5. shearing and next crack

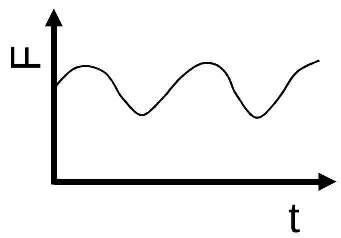


6. third segment formation and bring up



7. shearing and next crack

...

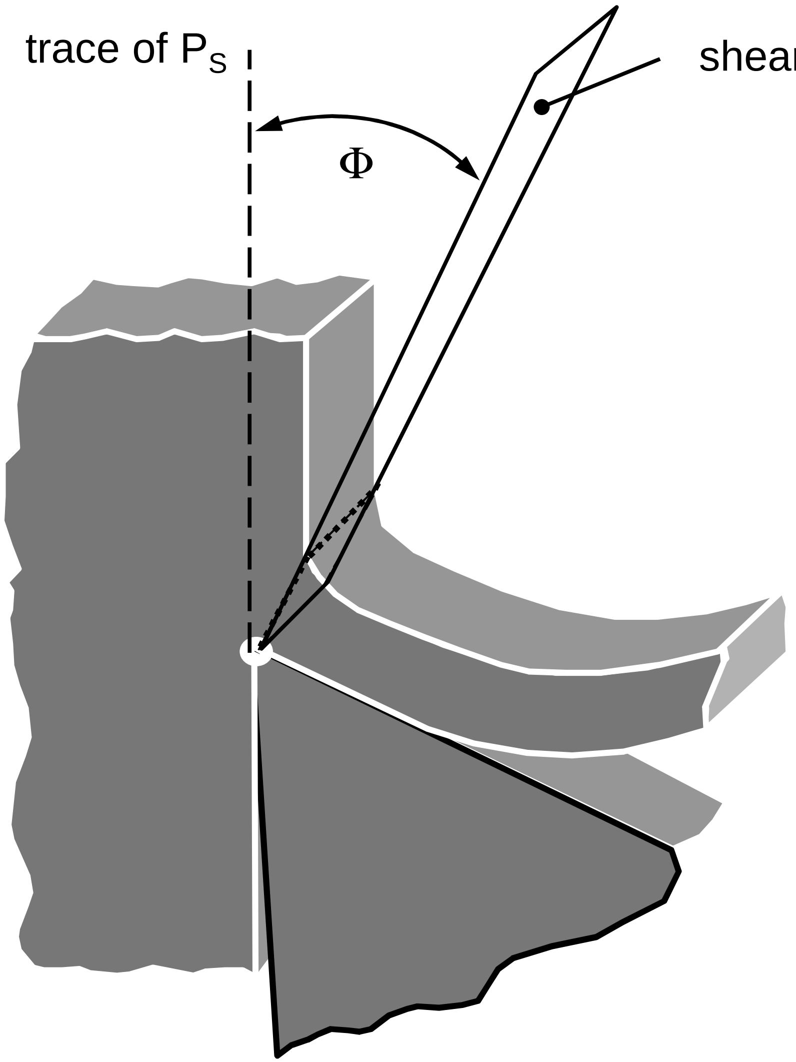


dynamic cutting force

source: Codron 1906

Outline

The shear plane model



accounts:

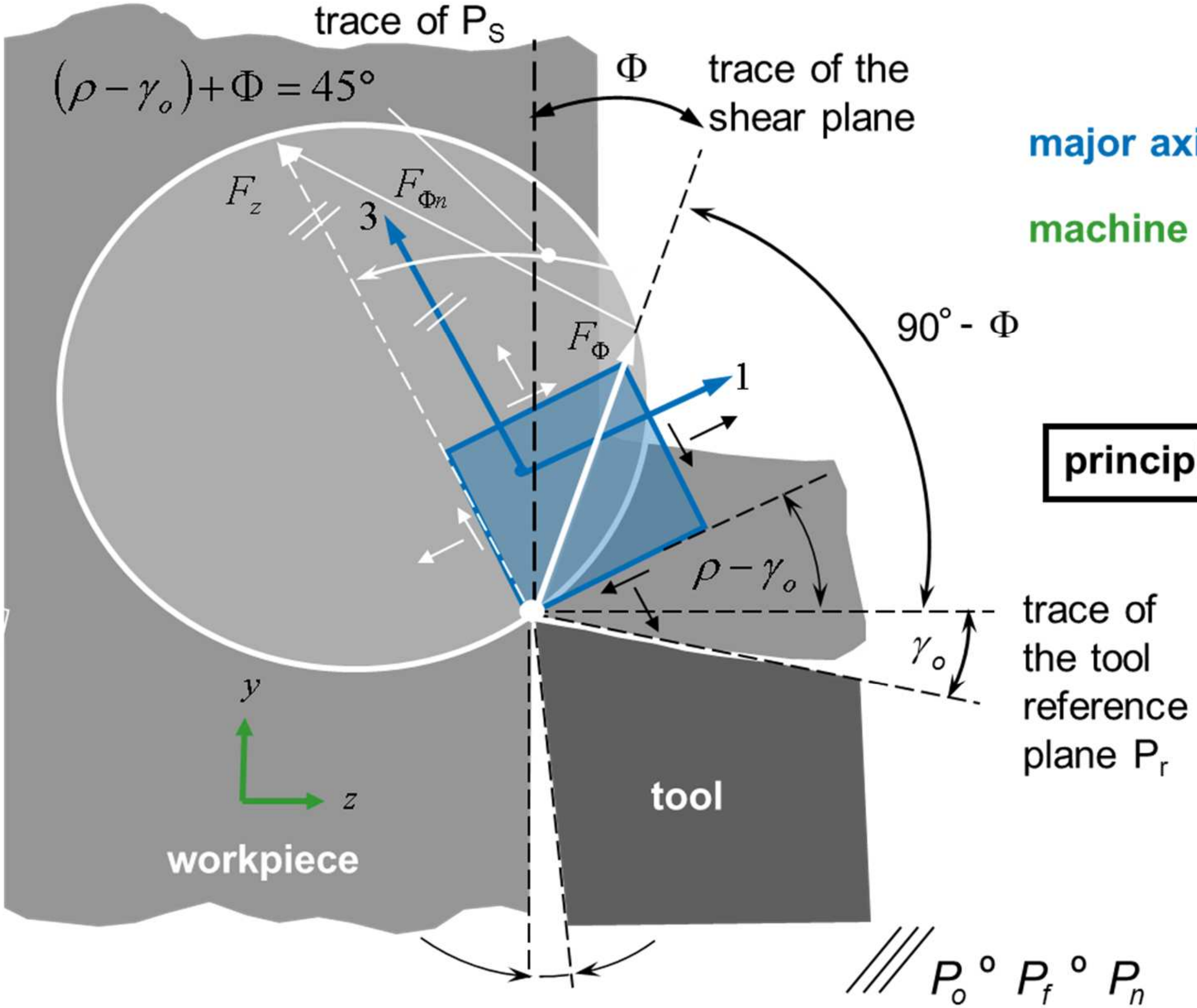
- plastic deformation **only** in the *shear plane*
- plane strain deformation
- ideal sharpness of the cutting edge

realisation: the *orthogonal cut*

All the force components are in the *tool orthogonal plane* P_o.

- tool cutting edge angle k_r= 90°
- tool cutting edge inclination λ_s= 0°

Krystoff 1939: shear angle determination



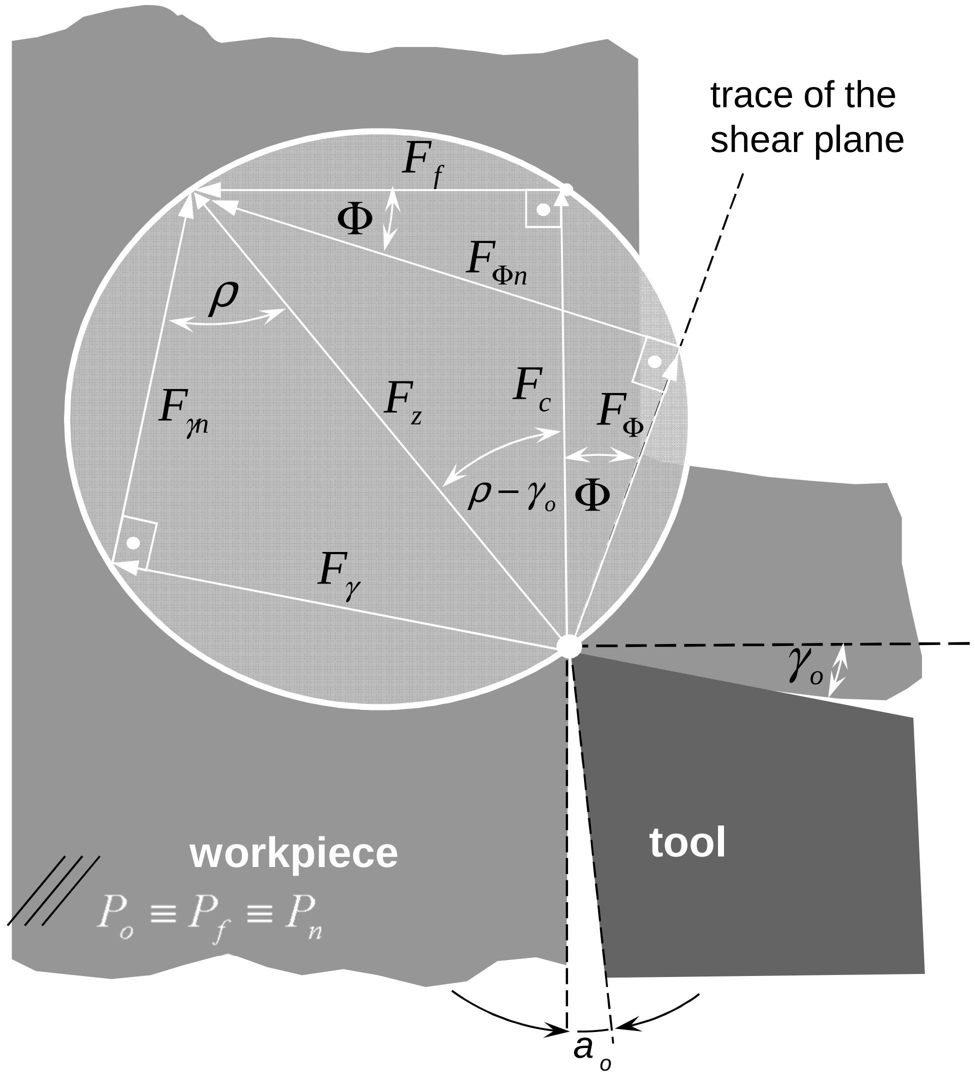
major axis system

machine coordinate system

principle of maximum shear stress

$$\Phi = \frac{\pi}{4} + \gamma_O - \rho$$

Ernst and Merchant 1941: force equilibrium and shear angle



shear plane location is determined by the minimum for cutting energy

nec.: $\frac{\partial E_c}{\partial \phi} = 0$ suff.: $\frac{\partial^2 E_c}{\partial \phi} \neq 0$

nec.: $\frac{l_c \cdot \partial |F_c|}{\partial \phi} = 0$ suff.: $\frac{\partial^2 |F_c|}{\partial \phi} \neq 0$

$$\boxed{\Phi = \frac{\pi}{4} + \frac{1}{2} \times (\gamma_0 - \rho)}$$

$$\tan\rho = \frac{F_\gamma}{F_{\gamma n}} = \frac{F_f \cos\gamma + Fc \sin\alpha}{F_c \cos\gamma - Ff \sin\alpha}$$

Shear plane model: force calculation

demonstration of the total force as a function of the shear stress with consideration of:

- shear work
- friction work at the face

$$F_z = \frac{\tau_\phi \cdot b \cdot h}{\sin\phi \cdot \cos(\phi + \rho - \gamma_0)}$$

By using the *circle of Thales*, the total force can be substitute with the two force components *cutting force* and *feed force*. *(*in the *orthogonal cut)*

$$F_c = \frac{\cos(\rho - \gamma_0)}{\sin\phi \cdot \cos(\phi + \rho - \gamma_0)} \cdot \tau_F \cdot b \cdot h$$

$$F_f = \frac{\sin(\rho - \gamma_0)}{\sin\phi \cdot \cos(\phi + \rho - \gamma_0)} \cdot \tau_\phi \cdot b \cdot h$$

→ Calculation of the force components with a physical and theoretical background!

(advantage of analytical models)

Outline

Overview: Influencing Variables on Machinability

machine tool
- machine tool
- machine condition

production conditions
- production processes
- engagement parameter
- cooling

machinability
- tool life
- surface integrity
- total force
- chip form

tool
- tool type
- geometry of the cutting edge
- clamping

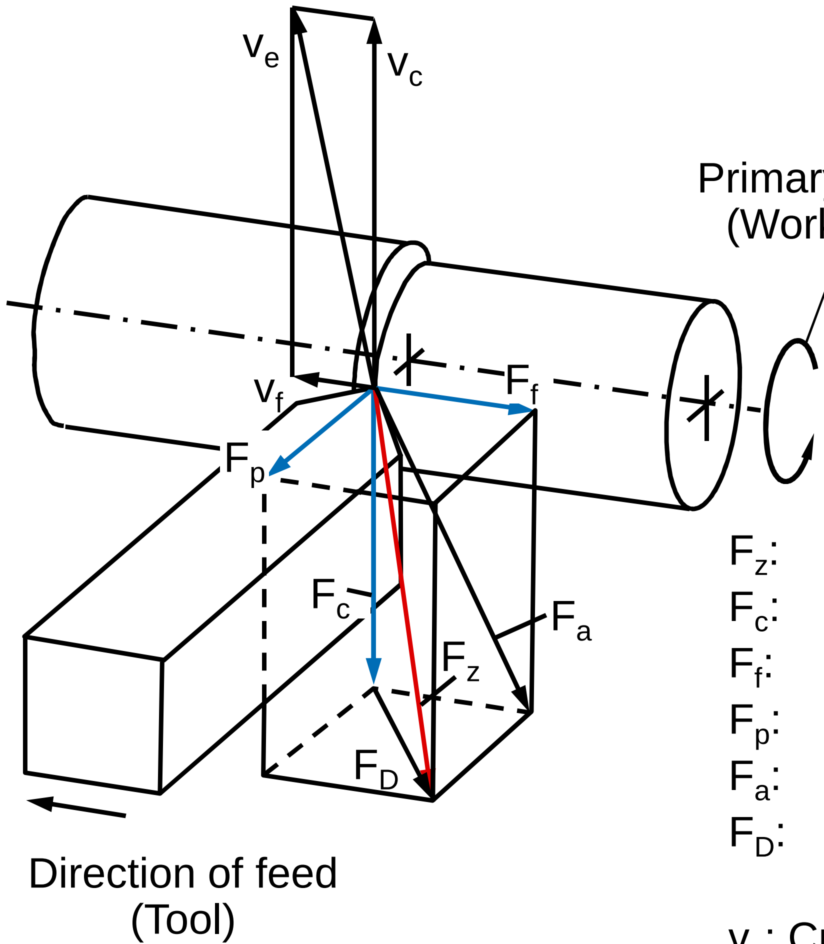
workpiece
- geometry
- surface integrity
- clamping

cutting material
- type of the material
- chemical configuration
- microstructure
- strength property
- surface treatment

material
- type of the material
- chemical configuration
- microstructure
- strength property
- heat treatment

Outline

Resultant force and ist components in the cutting process



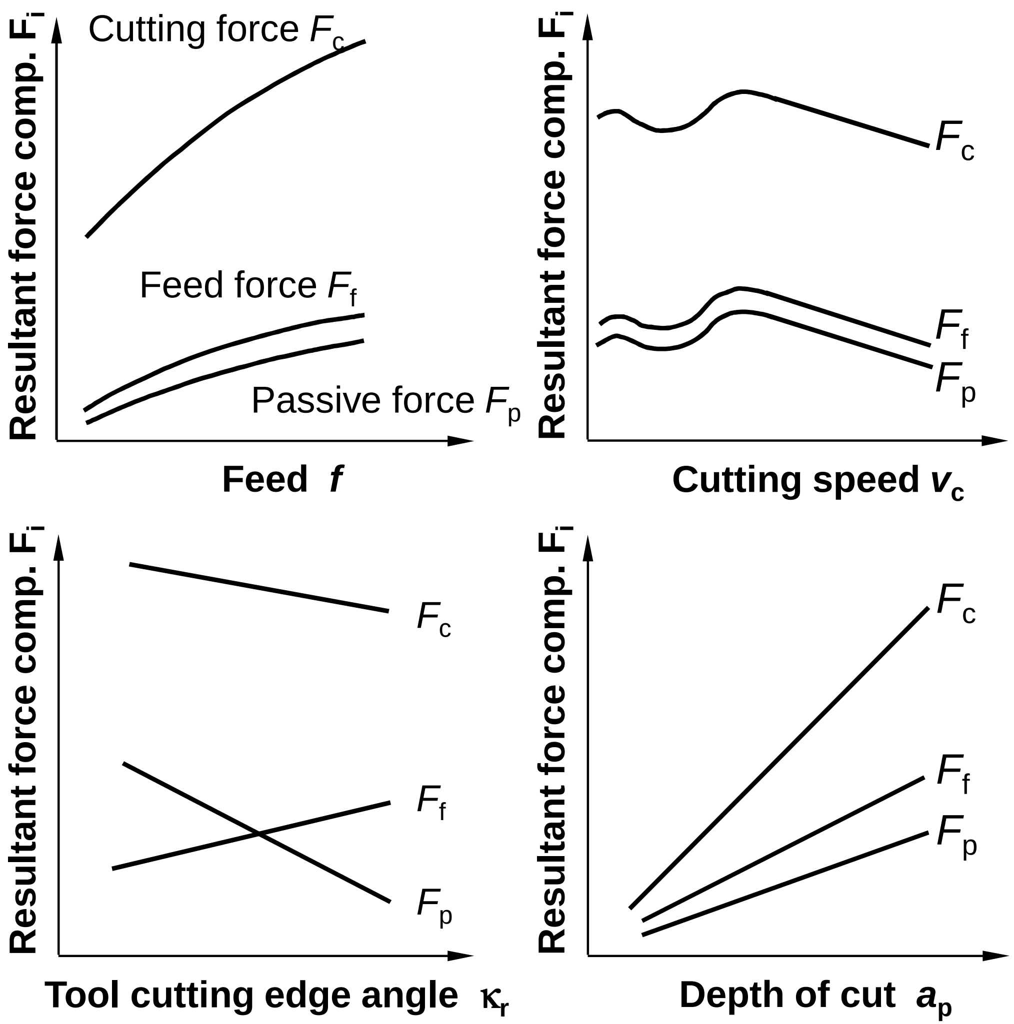
F_z: Resultant force
F_c: Cutting force
F_f: Feed force
F_p: Passive force
F_a: Active force
F_D: Thrust force

v_c: Cutting speed
v_f: Feed velocity
v_e: effective cutting speed

The information about the absolute values and the directions of the force components provide a basis:

- For the construction of machine tools
- For the definition of the cutting conditions
- For the evaluation of the cutting edge stresses and the explanations of the wear process
- For the evaluation of the material‘s machinability

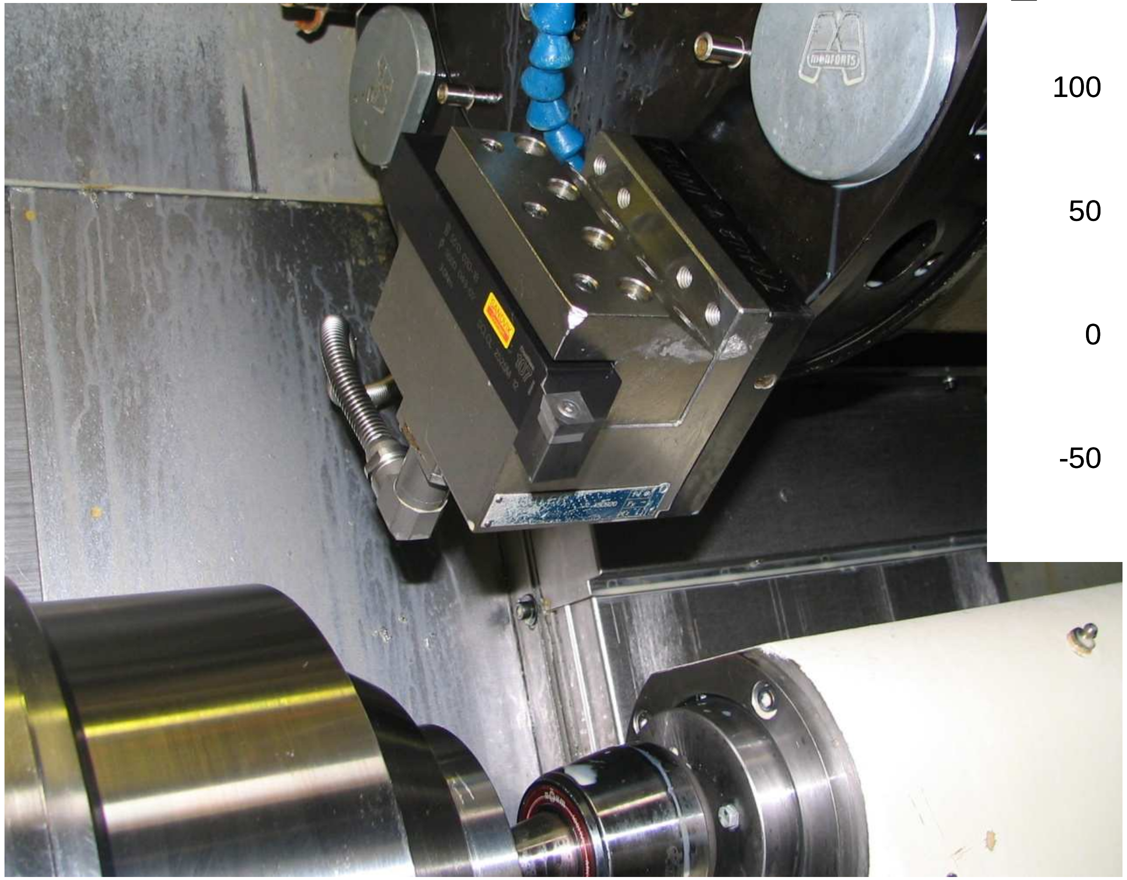
Dependencies of the force components

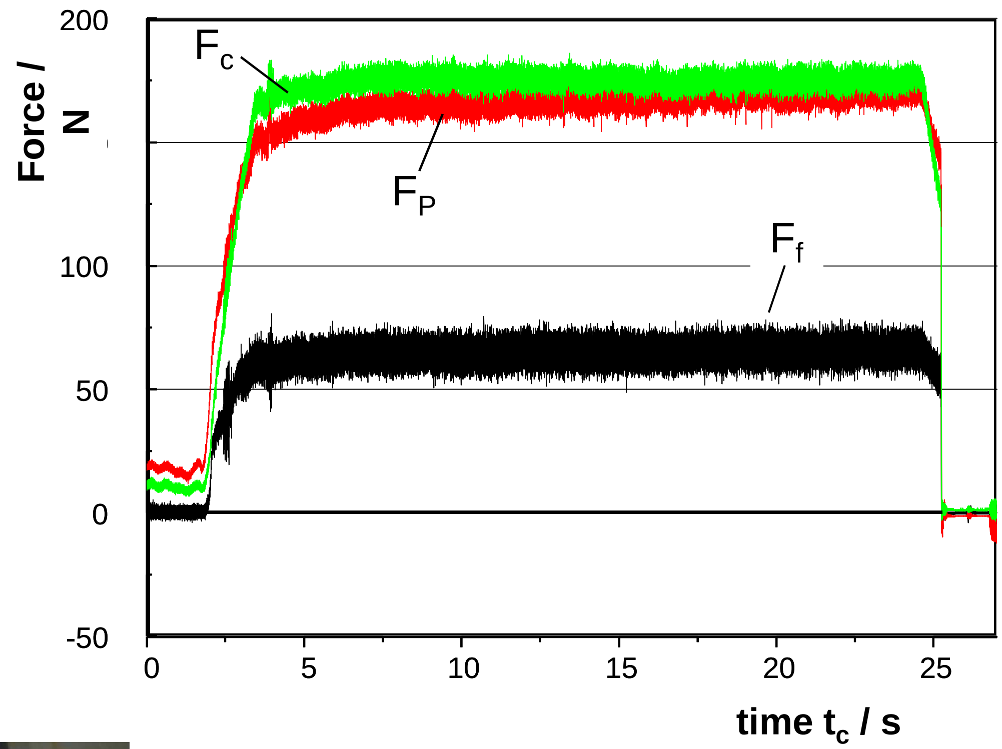


- The peaks in the cutting speed chart are traced back to the fact of built-up edge growth
- The decrease in force along with increasing cutting speed is a result of the material softening
- The force curves F_p and F_f have opposing trends with increasing tool cutting edge angle κ_r, which is the angle between the main cutting edge and the direction of feed
- The increase of the resultant force components dependent on the depth a_p can be traced back to the higher stock removal volume

Cutting force measuring during the turning process

3-component-cutting-force-measuring-platform
Measurement F_c, F_f, F_p





Force approximation: empirical models

linear approximation:

$$F_i = A \cdot b \cdot h + B \cdot b$$

- result of a curve fit
- first part is based on the shear plane theory
- very easy function

- not very precise
- calculations are not sufficiently verified (method is not commonly used)

researchers:

- **Schlesinger (1931)**
- Pohl (1934)
- Klein (1938)
- Richter (1954)
- Hucks (1956)
- Thomson (1962)
- Altintas (1998)

potential approximation:

$$F_i = ki_{1.1} \cdot b \cdot h^{(1-m)}$$

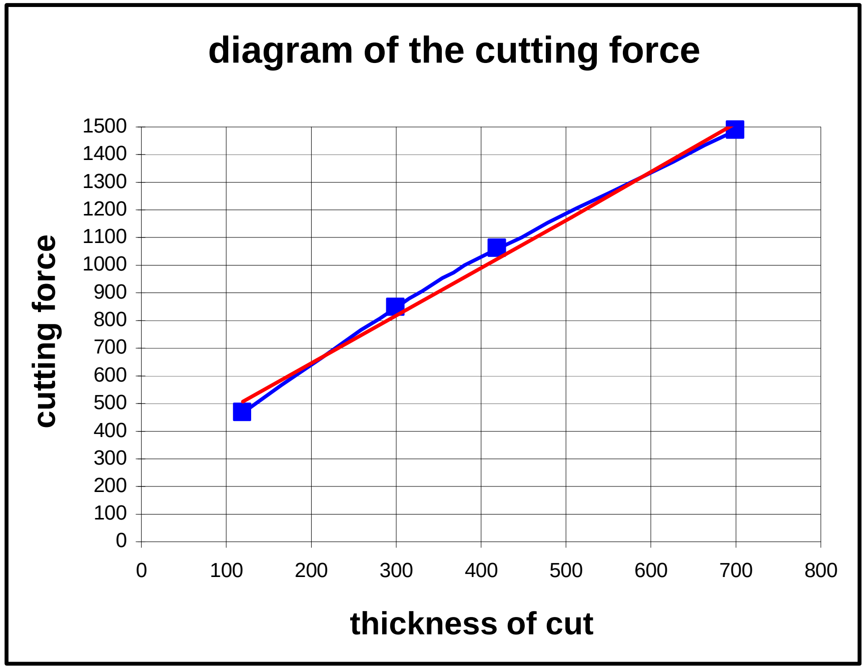
- result of a curve fit
- calculation of the cutting force is statistically verified
- very precise

- no theoretical basis
- calculation of the other force components is not sufficiently verified

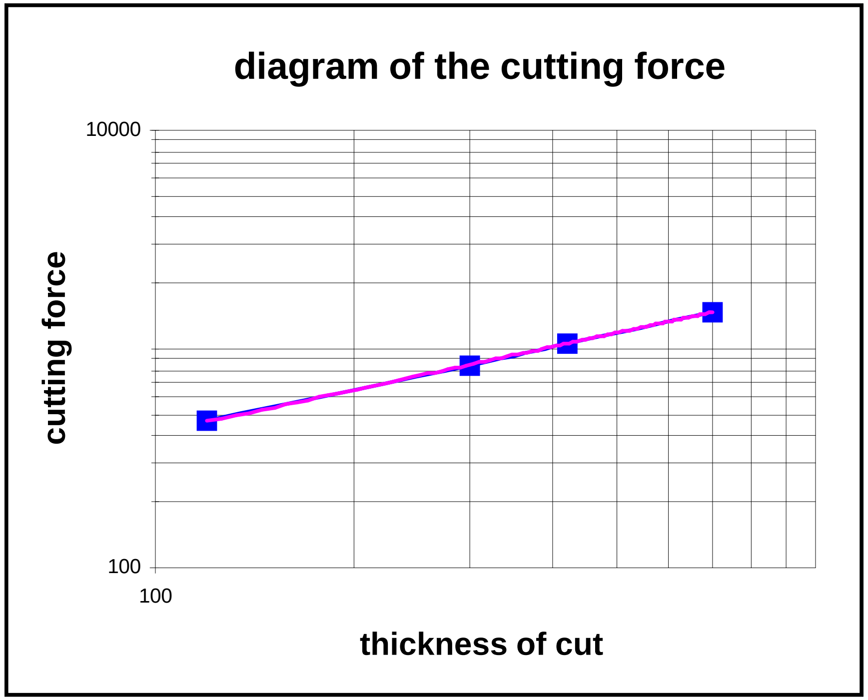
researchers:

- **Taylor (1883/1902)**
- Fischer (1897)
- Friedrich (1909)
- Hippler (1923)
- **Salomon(1924)**
- Kronenberg (1927)
- Klopstock (1932)
- **Kienzle (1952)**

Correlation between the force and the undeformed chip thickness



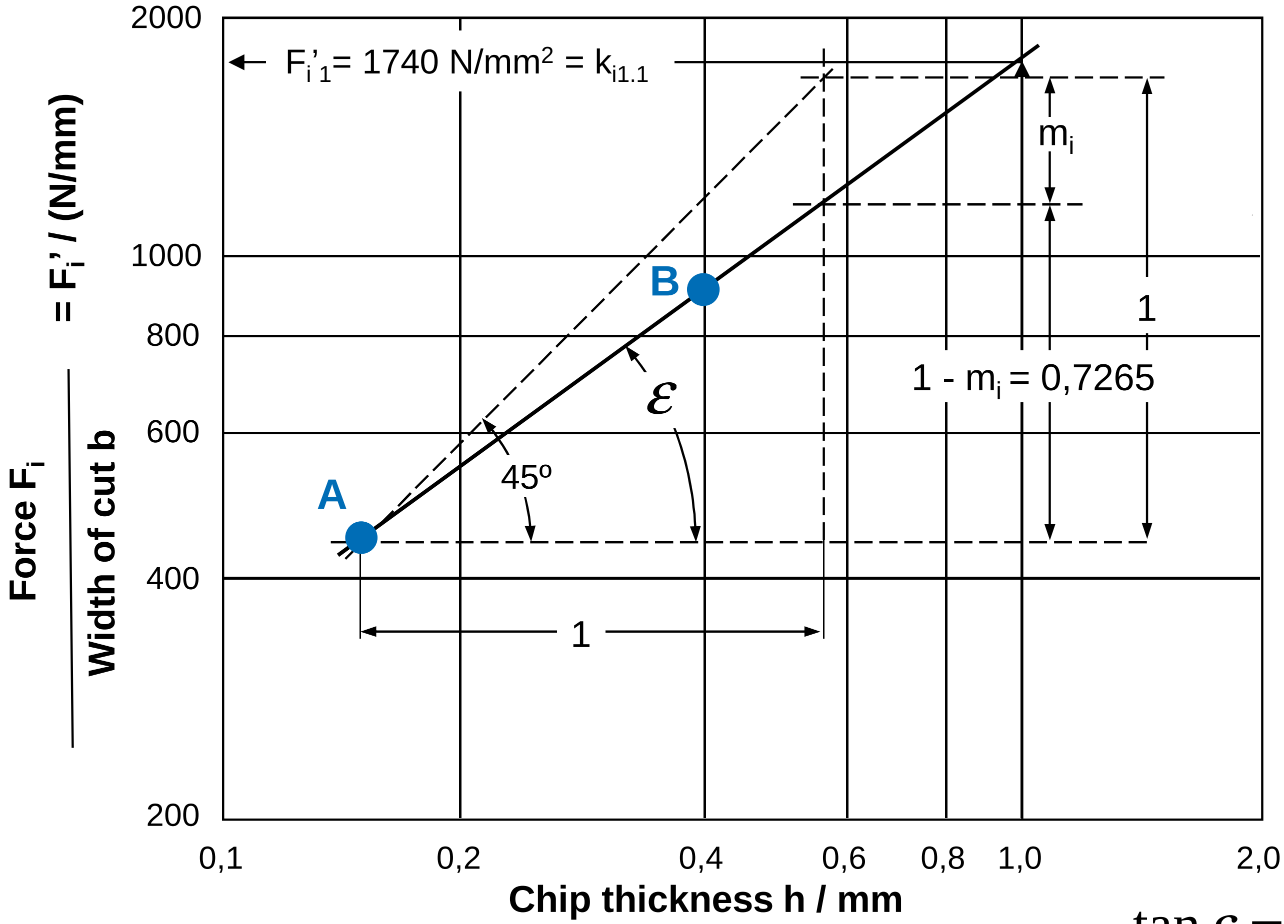
linear system with a trend line



double logarithmic system with a trend line

Today you describe the problem by curve fitting on your computer!

Kienzle Equation to Calculate the Static Cutting Forces



i = c, f, p

Linear equation:

$$y_i = a \cdot x + b$$

$$\Rightarrow \log F_i' = a \cdot \log h + \log F_{i\,1}'$$

$$\log\left(\frac{F_i}{b}\right) = a \cdot \log h + \log F_{i\,1}'$$

$$\frac{F_i}{b} = (h)^{1-m_i} \cdot F_{i\,1}'$$

Kienzle equation:

$$F_i = k_{i1.1} \cdot b \cdot h^{1-m_i}$$

$$\tan\varepsilon = 1 - m_i = \frac{\log F_i'(B) - \log F_i'(A)}{\log h(B) - \log h(A)}$$

Outline

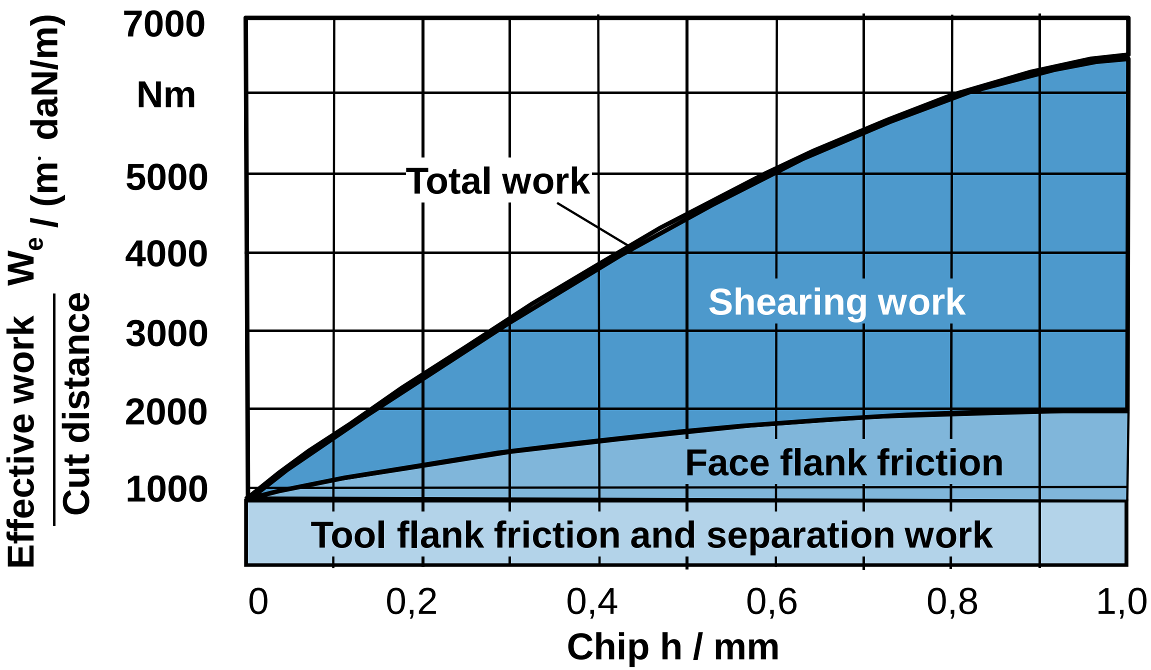
Tool wear

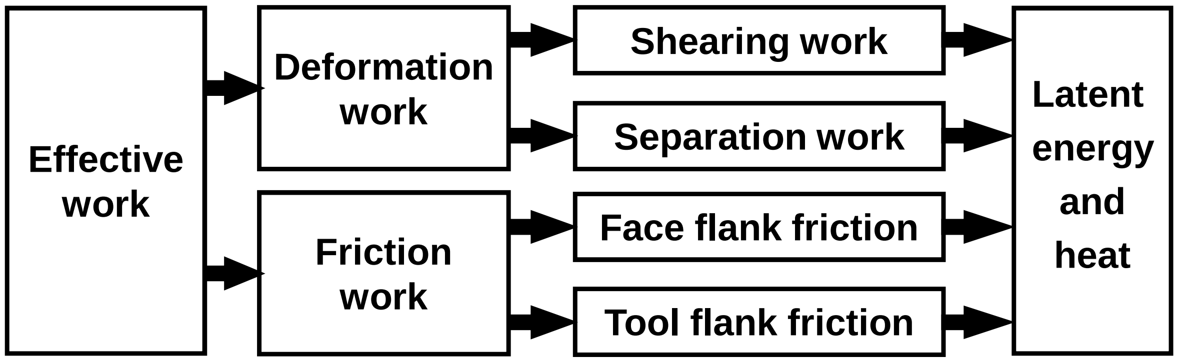
Tool wear
is influenced by high contact stresses, high cutting temperatures and relative sliding velocities

These process values depend on:

- **tool and workpiece materials**
- **tool geometry**
- **interface conditions**
- **machining parameters**

Thermic stress – segmenting the effective work during machining





- The work transformed during the machining relates with the chip width
- Especially the shearing work part increases with wider chips
- Tool flank friciton and Separation work are in independent of the chip width h
- The energy dedicated during the machining process is nearly completely transformed into heat
- The heat emerges in the primary shearing zone and the friction zone at the tool (secondary shearing zone)

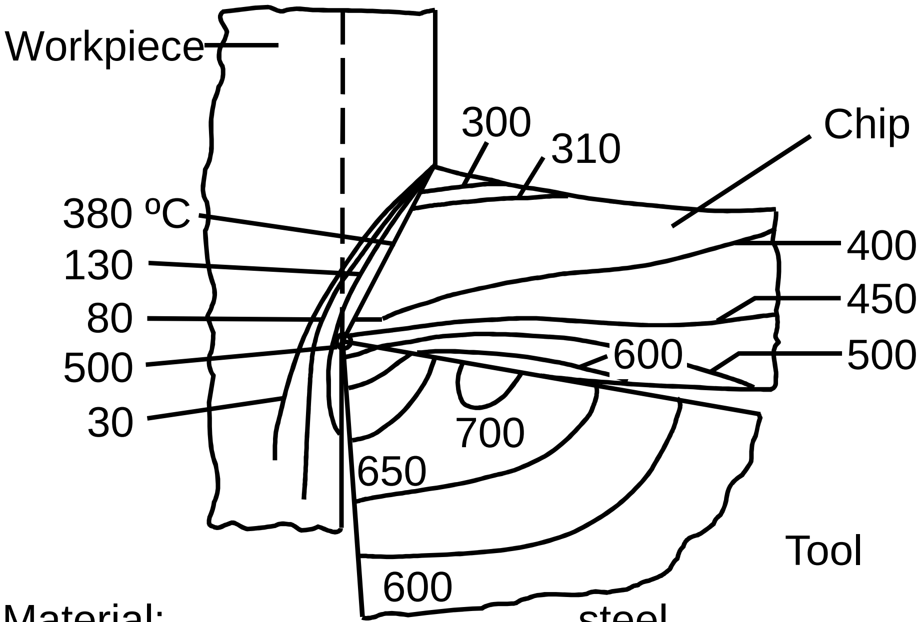
Quelle: Vieregge

Fraunhofer IPT

WZL RWTHAACHEN

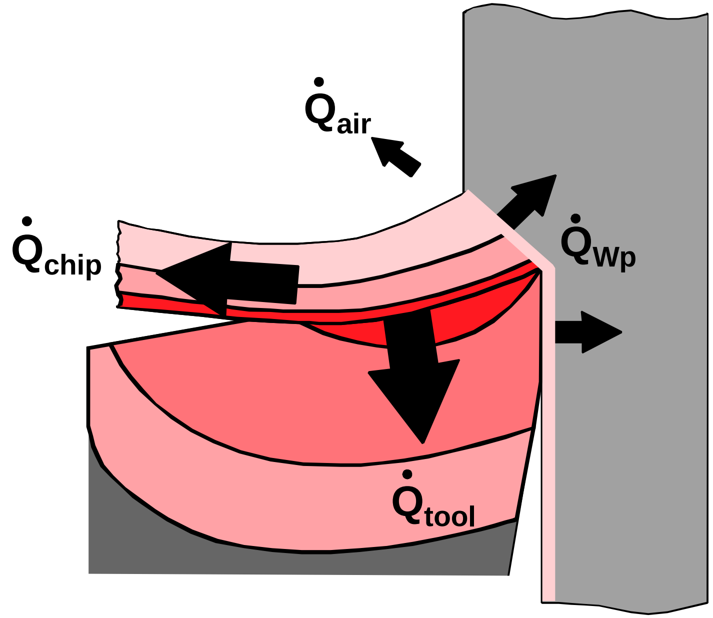
Distribution of heat and temperature in workpiece, chip and tool

Allocation of heat in the machining zone



Material: steel
Yield stress: k_f = 850 N/mm²
Cutting material: HW-P20
Primary speed: v_c = 60 m/min
Chip width: h = 0,32 mm
Chip angle: γ_o= 10°

Heat flows emerging from the machining zone



Q_{air} = Heat flow to environment

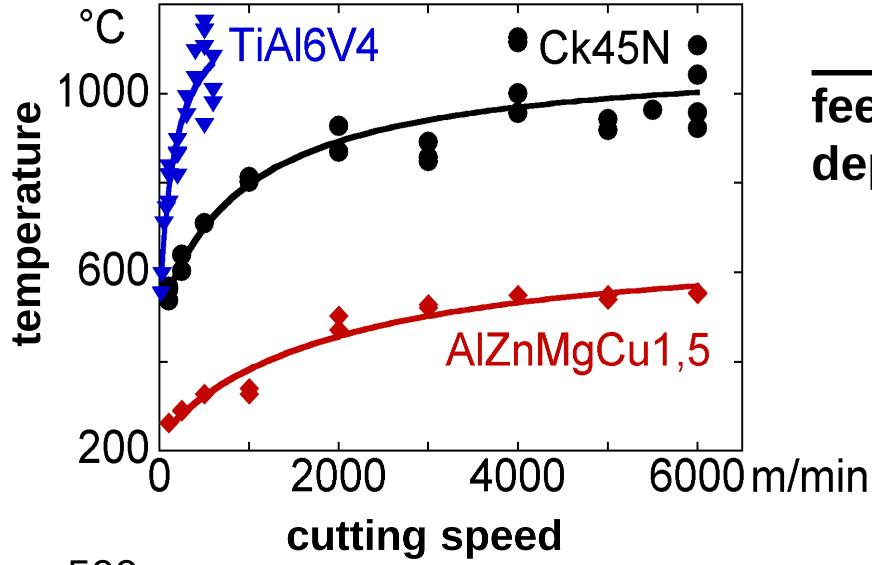
Q_{chip}= Heat flow to chip

Q_{Wp} = Heat flow to workpiece

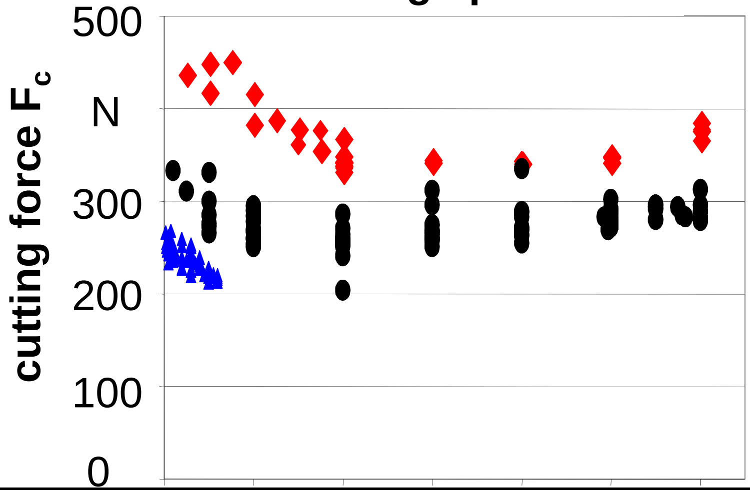
Q_{tool} = Heat flow to tool

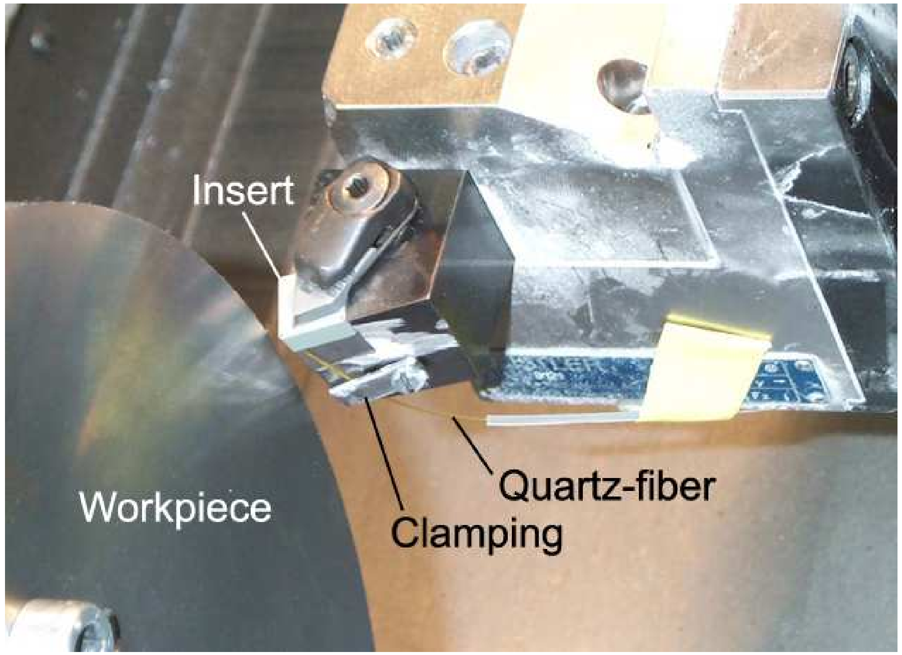
Source: Kronenberg, Vieregge

Cutting forces and chip temperatures in turning



	aluminium	steel / titanium
feed	0,25 mm	0,1 mm
depth of cut	2 mm	1 mm





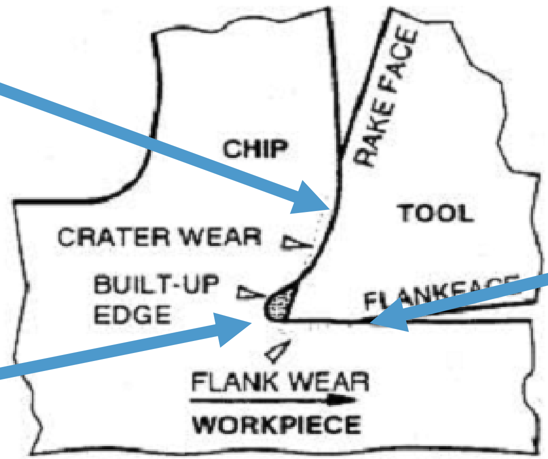
Tool Wear appears at three locations at the cutting tool

Crater Wear

Area of high level of stress and temperature, i.e. of the order of 1200°C.

Built-Up Edge

Observable for ductile materials. Not stable, breaks off frequently

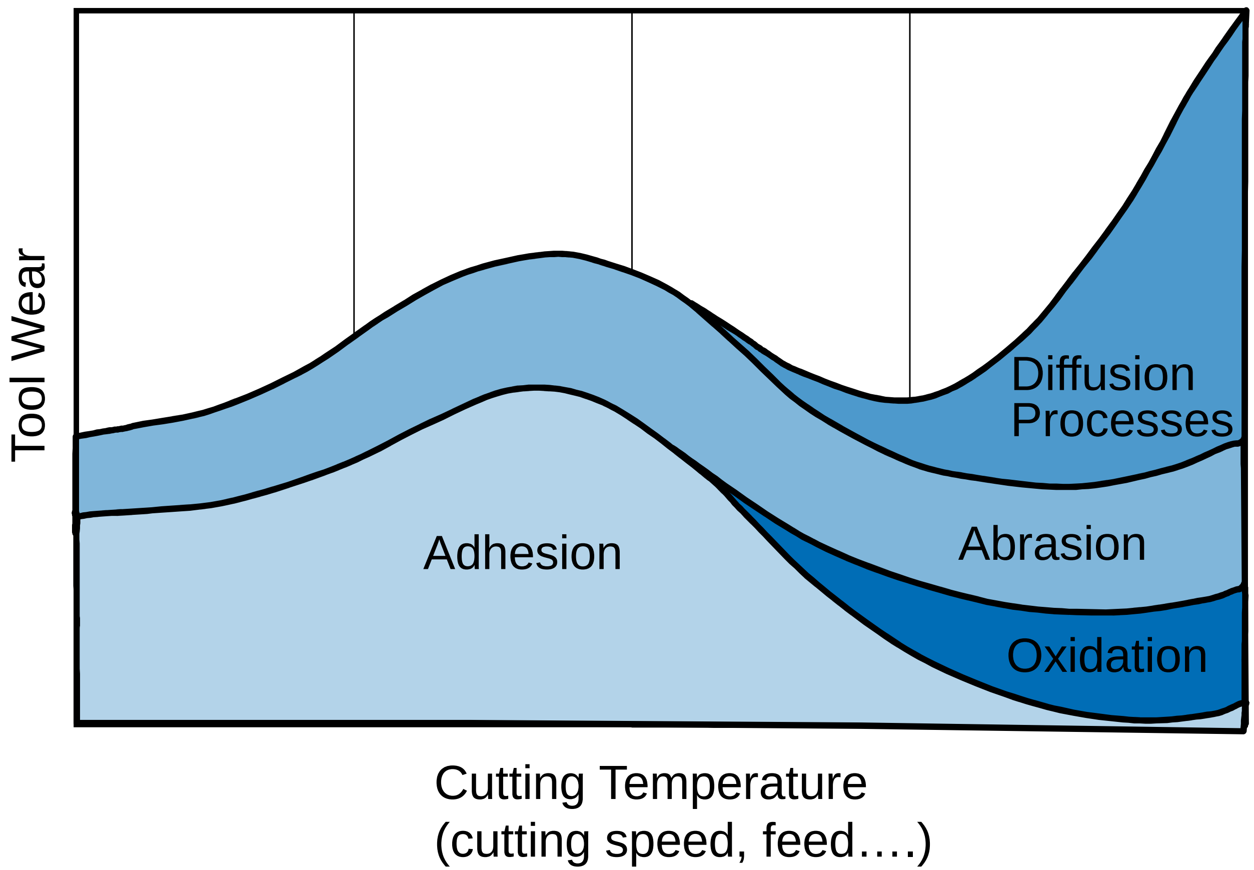


Tool Wear

Flank Wear

Mainly responsible for the resulting surface quality
=> used as failure criteria.

Wear mechanisms



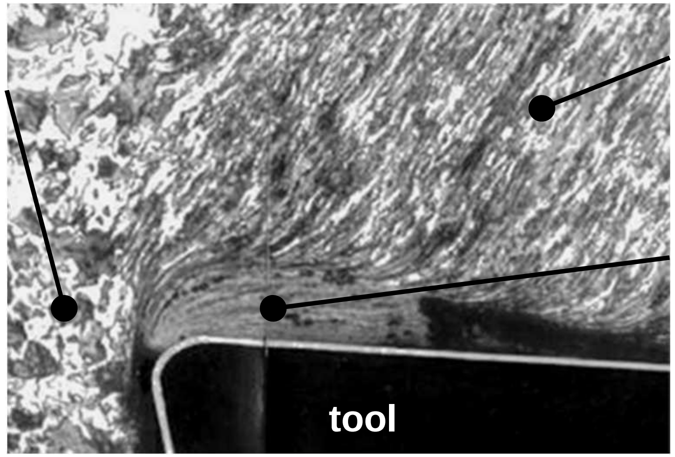
source: Vieregge

- The total wear at the wedge is a superposition of distinct wear mechanisms.
- During cutting all distinct wear mechanisms occur simultaneously.
- Diffusion and oxidation are dependent on the temperature level and occur mainly at high cutting speeds.

adhesion

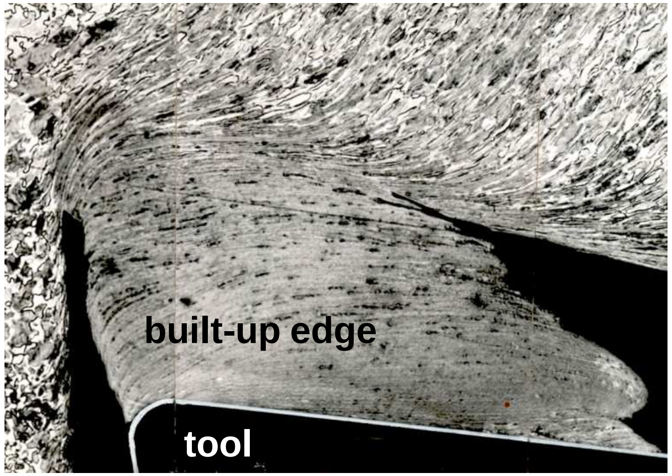
Wear mechanisms at the wedge: adhesion

undeformed bulk of the workpiece



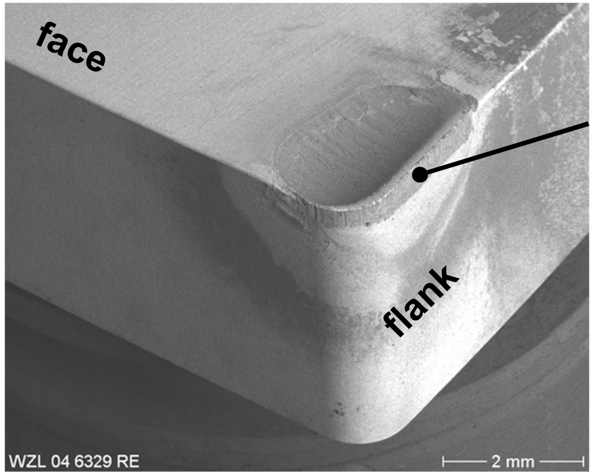
deformed chip

built-up edge

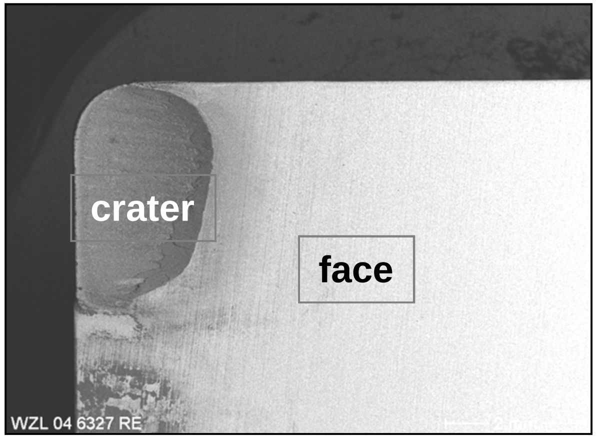


- Low cutting speeds causes low contact temperatures between chip and tool. This goes along with high contact pressure.
- Low contact temperatures, high contact pressure and material affinity lead to adhesion.
- Adhesion at the wedge may cause built-up edges.
- Built-up edges are unstable. They peel away off the edge and slide over the flank and the face periodically.

Wear mechanisms at the wedge: abrasion

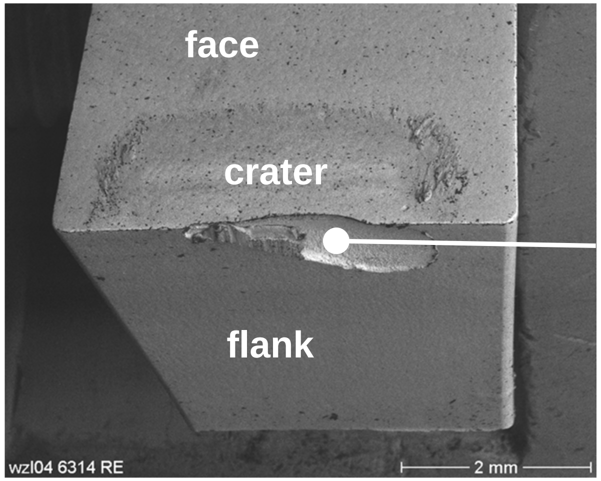


flank wear land

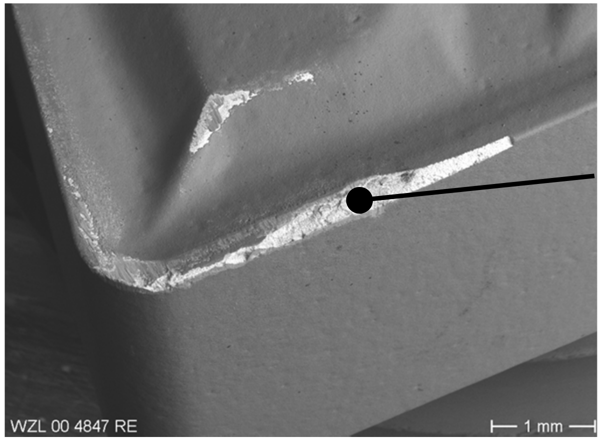


- Abrasion at the wedge is caused by hard particles in the chip, which penetrate into the tool material and slide and scratch over the face.
- As a result on the face a crater is generated.
- As a result on the flank a wear land is generated.

Catastrophic failure of the wedge



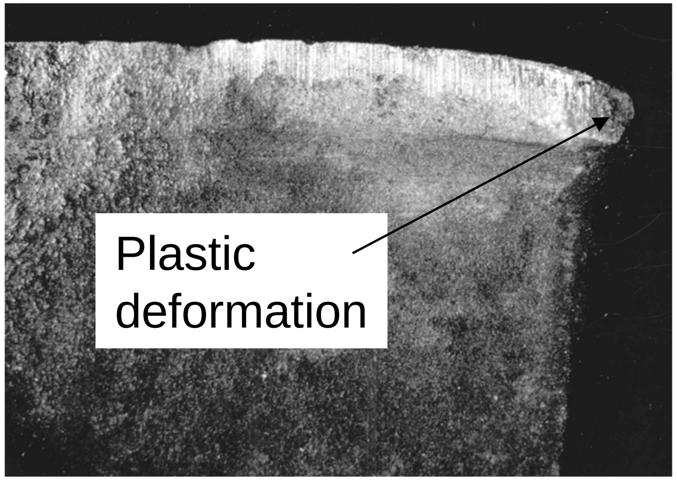
Chipping and break outs at cutting edge

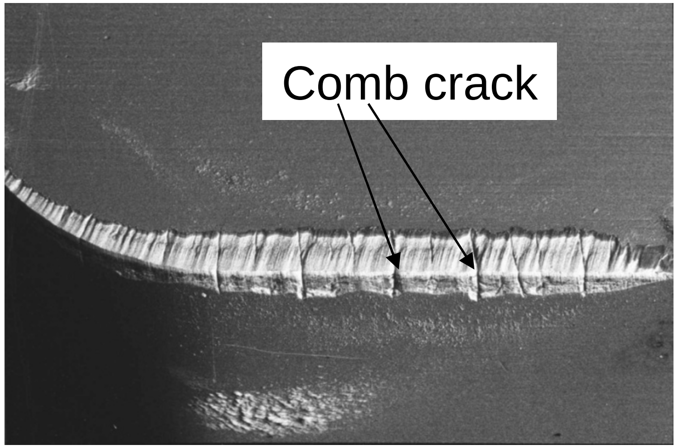


little disruptions at the cutting edge

- If the mechanical load at the wedge surpasses the resistance of the cutting material, the cutting edge fails.

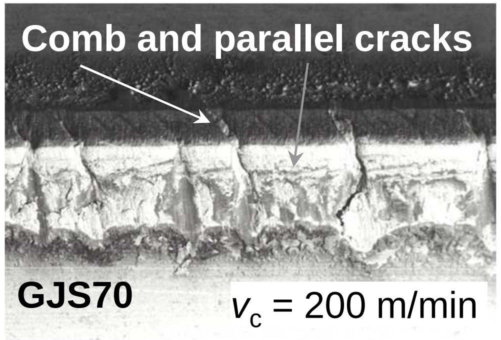
The cutting edge influenced by thermic overload

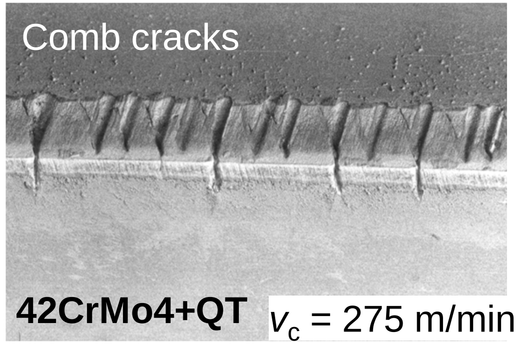


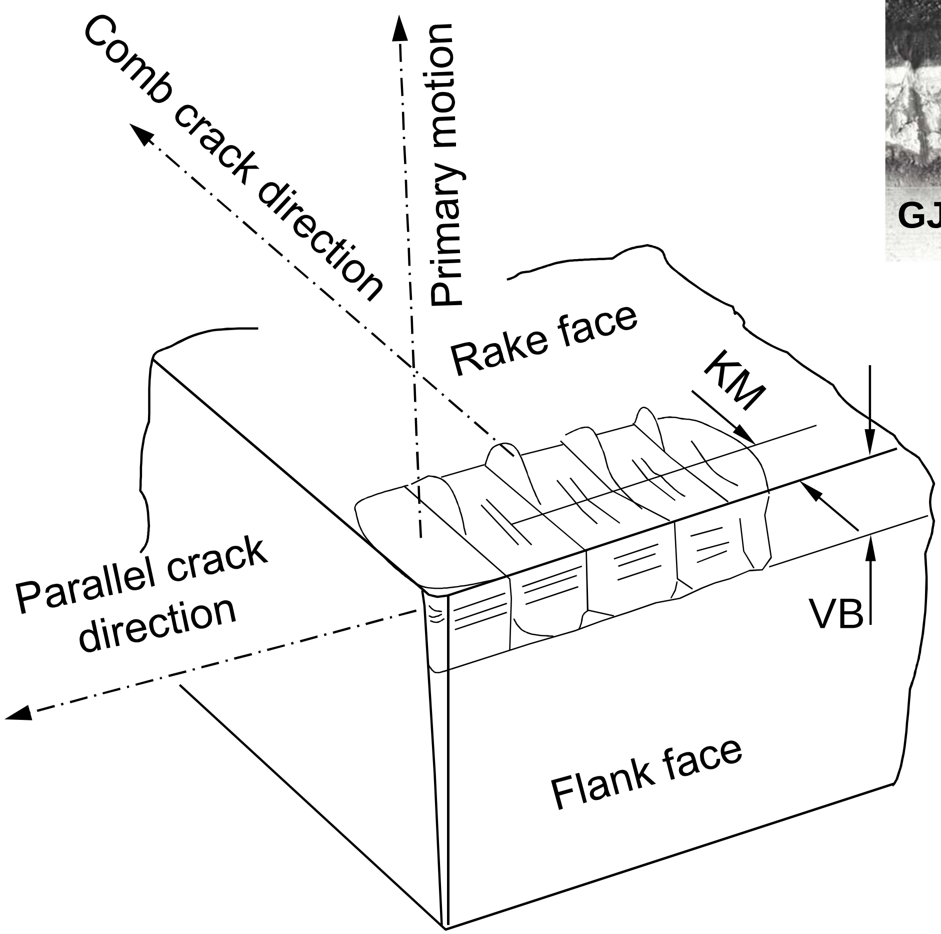


- The cutting material may heat massively through thermic load which reduces its resistance towards mechanical stress; the cutting edge may deform plastically
- The plastic deformation appears basically with high speed steel
- Thermic alternating load may cause comb cracks at the wedge
- They appear mainly during discontinuous cuts whereas the cutting edge heats in circuit and cools down in the disruption
- In order to avoid comb cracks in discontinuous cutting (e.g. during milling) the use of coolant can often be avoided

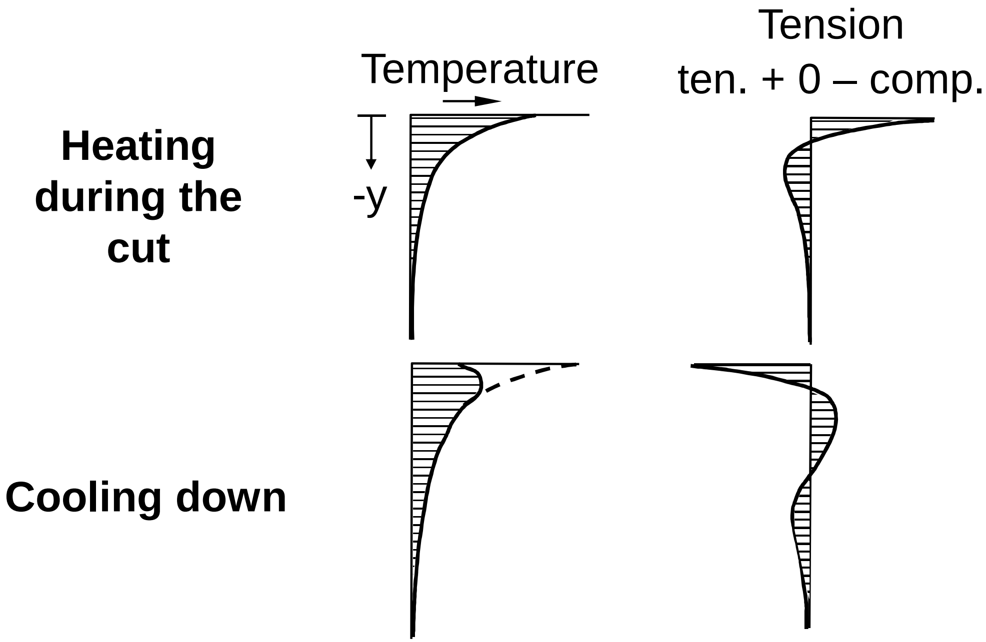
Formation of comb cracks and parallel cracks during milling



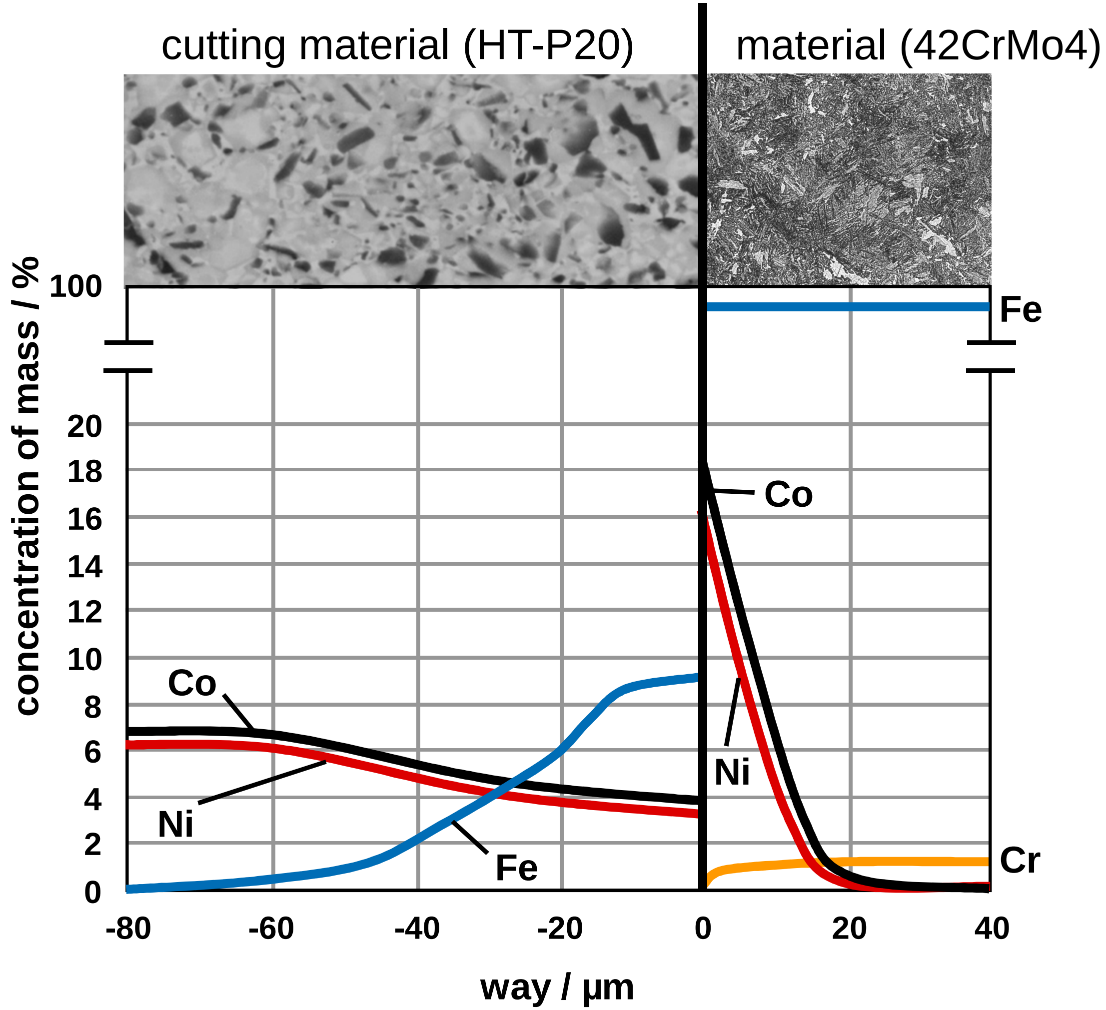




Quelle: Lehwald, Vieregge

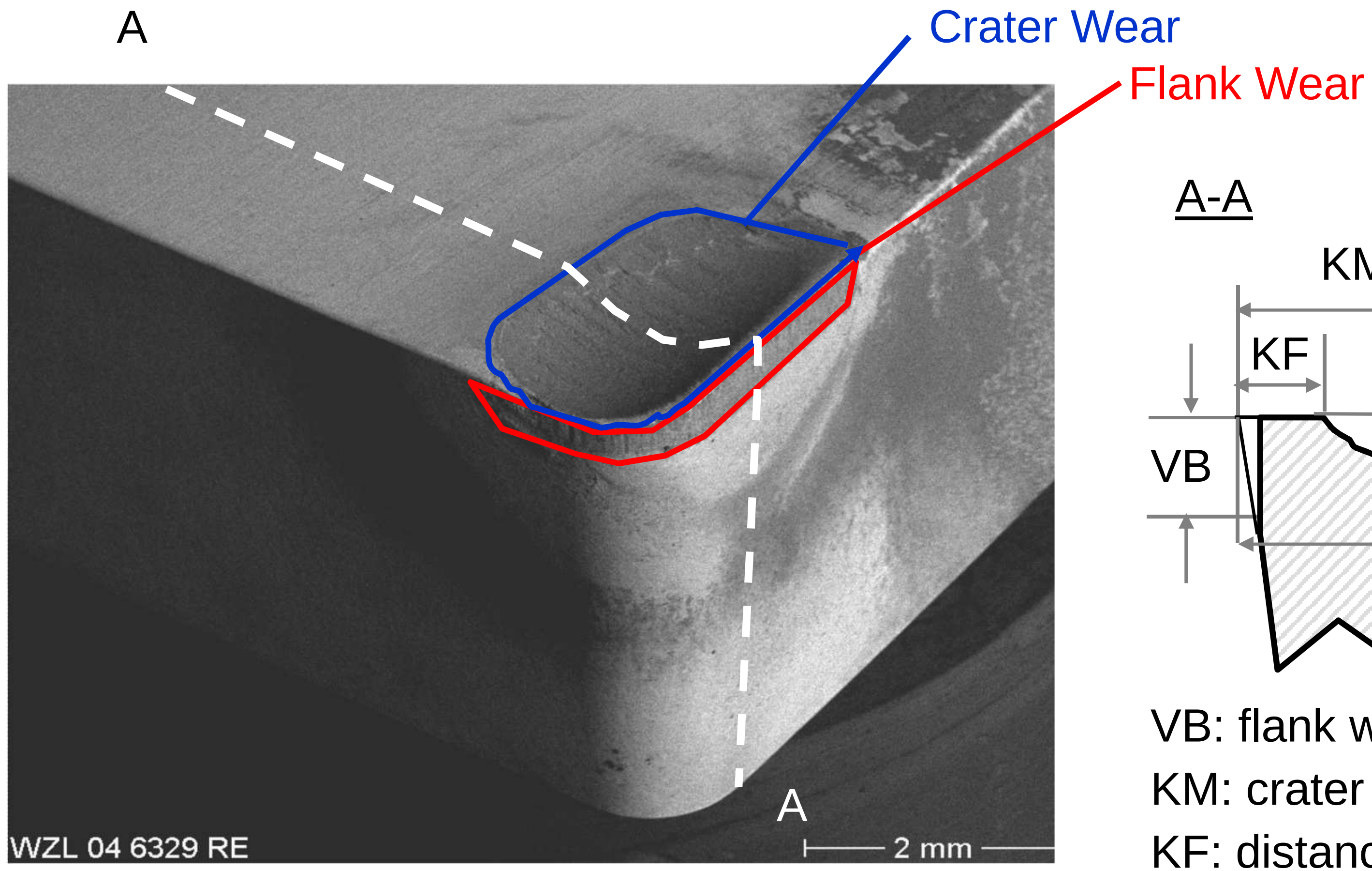


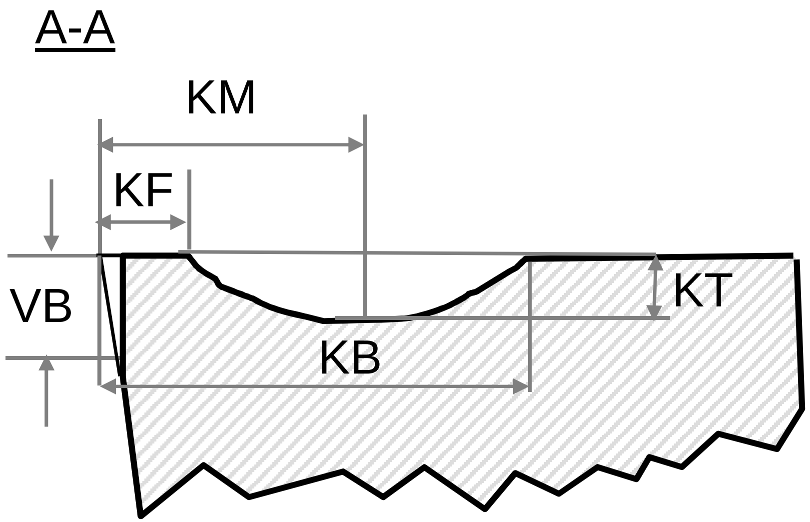
Wear mechanisms at the wedge: diffusion



- If the temperature level of the contact area reaches a limit and affinity of material is given diffusion can be activated.
- The diffusion is shown by an analogue experiment. Here a cemented carbide tool works on quenched steel.
- During cutting only a very short time is available for diffusion to occur.

Types of wear and values for the tool wear characterization

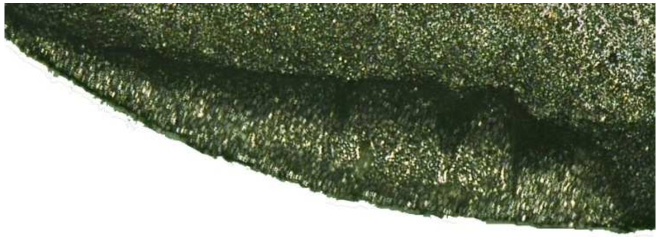


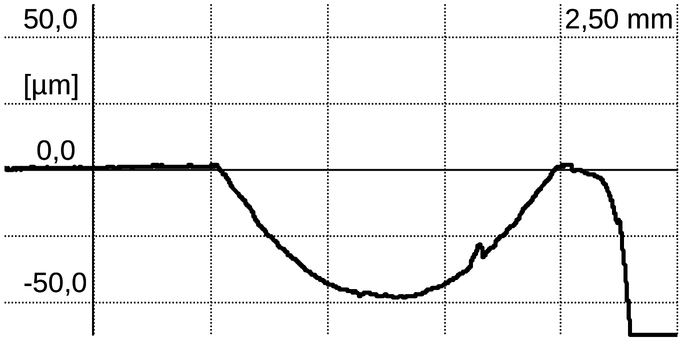


VB: flank wear width
KM: crater center distance
KF: distance from crater to edge
KB: crater width
KT: crater depth

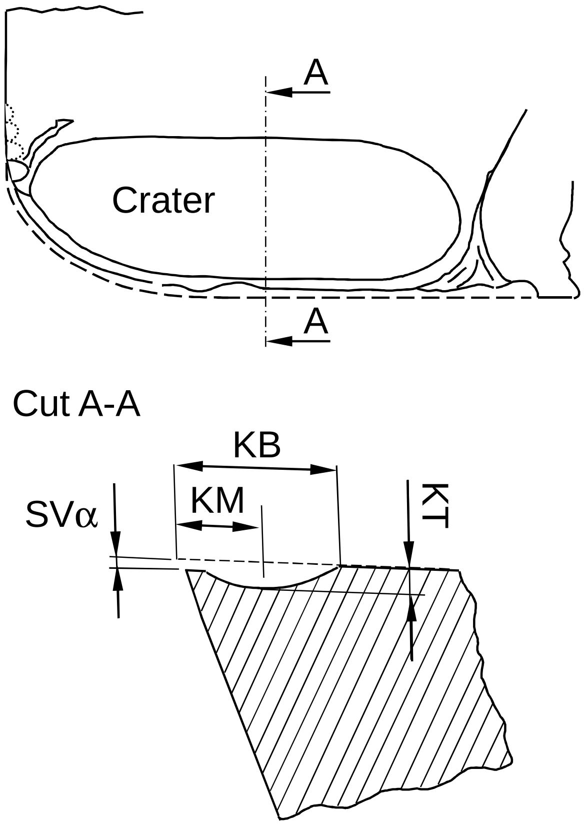
Evaluation of crater wear

Crater wear





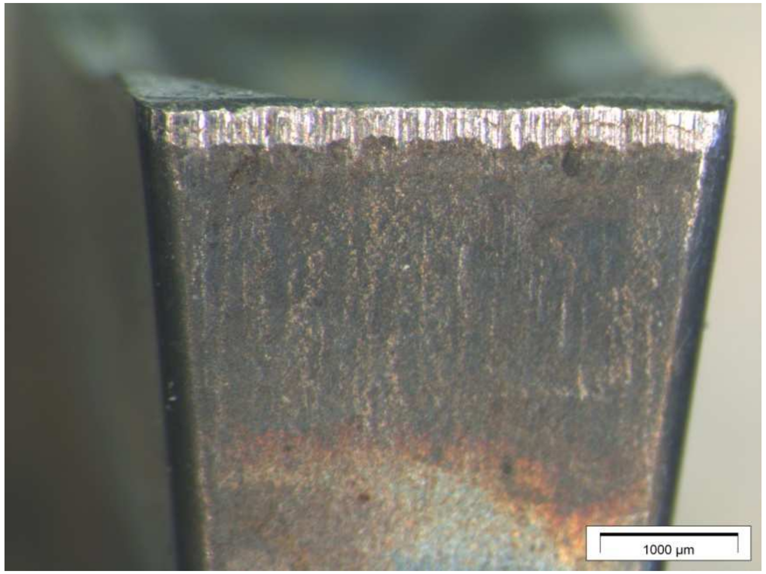
Indicators according to DIN ISO 3685



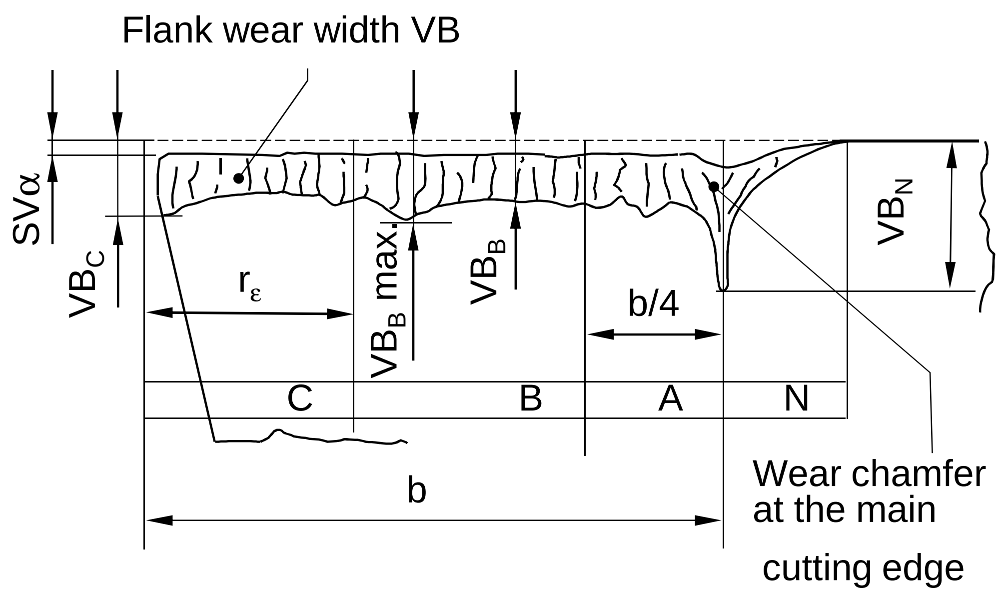
- Measured indicators for the evaluation of crater wear are the crater depth KT, the crater centre distance KM, the crater width KB and the displacement of the cutting edge SV in face flank direction
- Weakening of the cutting edge is a result of massive crater wear
→ Danger of a cutting edge fraction
(crater edge fracture)

Evaluation of flank are wear

Flank wear examined with a microscope

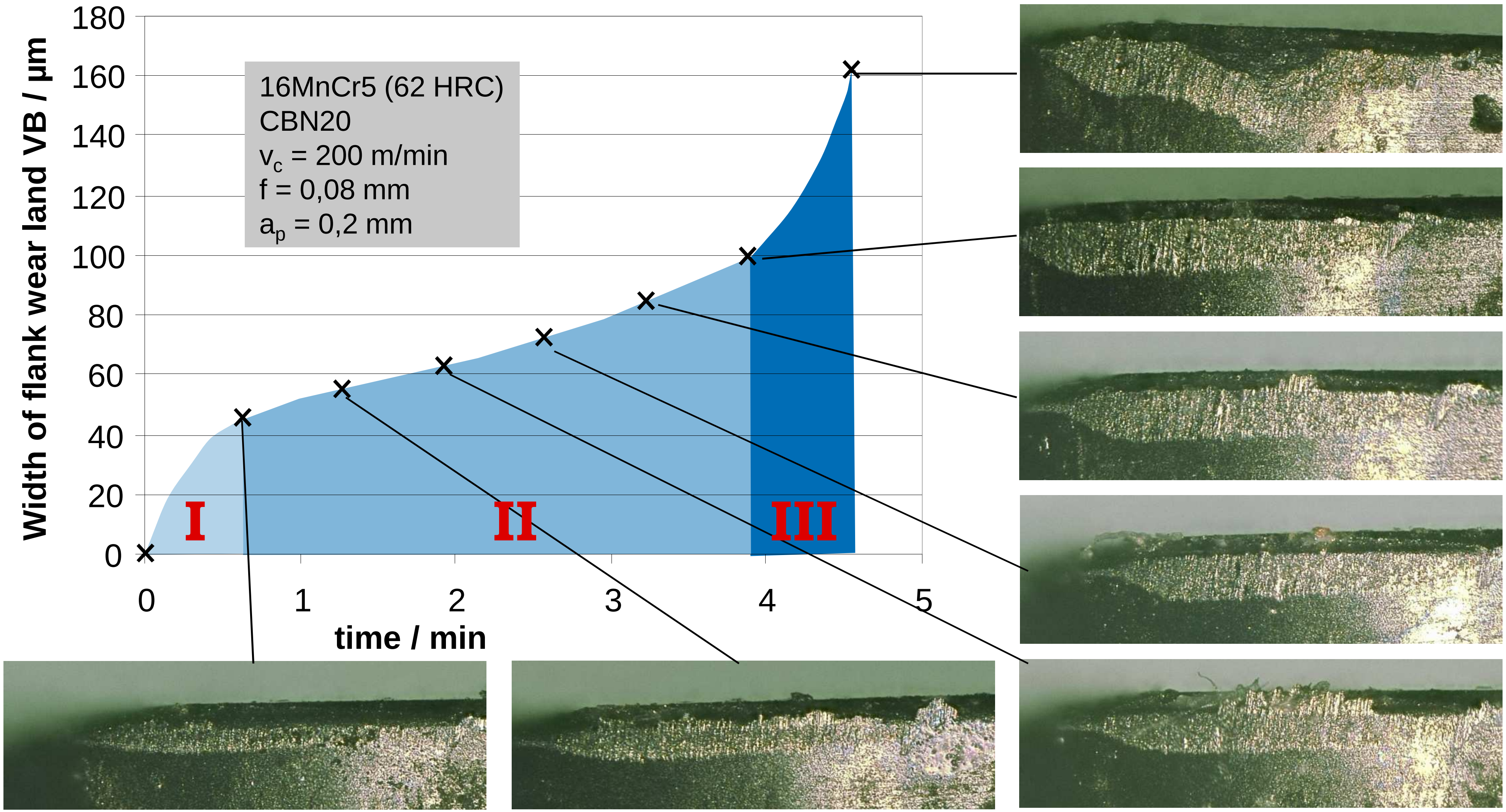


Indicators according to DIN ISO 3685



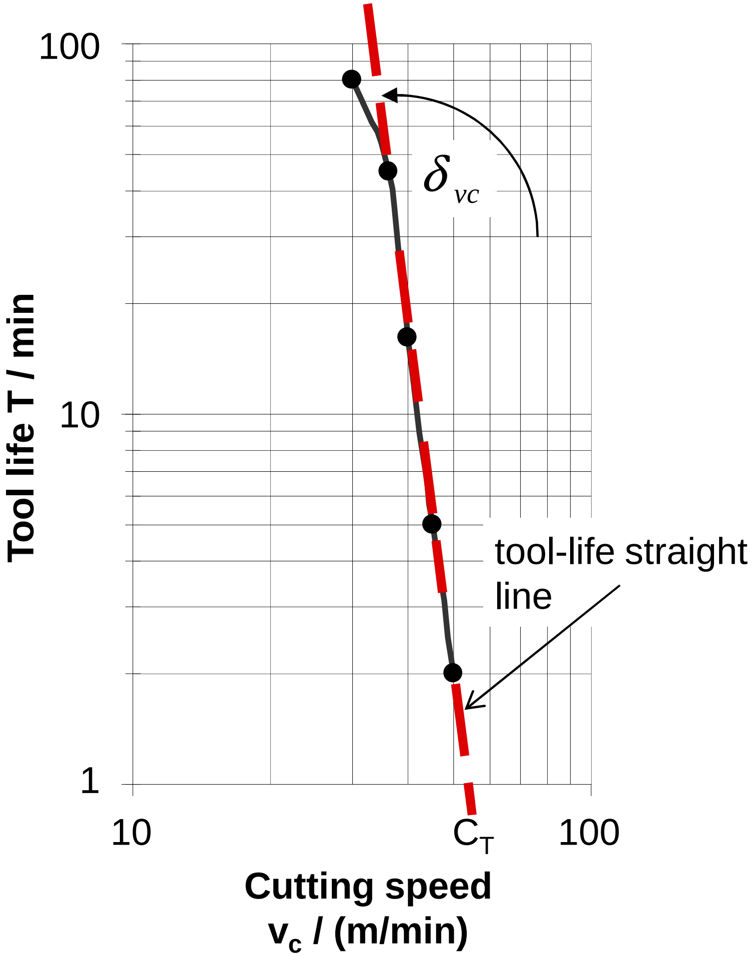
- A distinction is drawn between the measured indicators flank wear width VB and the displacement of the cutting edge in flank direction SV_{α}
- The flank wear width is refered to the cutting edge without wear

The typical course of wear



Taylor Function

Tool life function
(logarithmic scale)



Tool-life function in a double logarithmic system has the shape of a straight line

$$y = m \cdot x + b$$

$$\log T = k \cdot \log v_c + \log C_v$$

with $k = \tan \delta_{vc} = -\dfrac{\log C_V}{\log C_T}$

Frederick Winslow Taylor
(USA, 1856-1915)

Taylor-equation (simple)	$T = v_c^{\,k} \cdot C_v$ $v_c = T^{1/k} \cdot C_T$

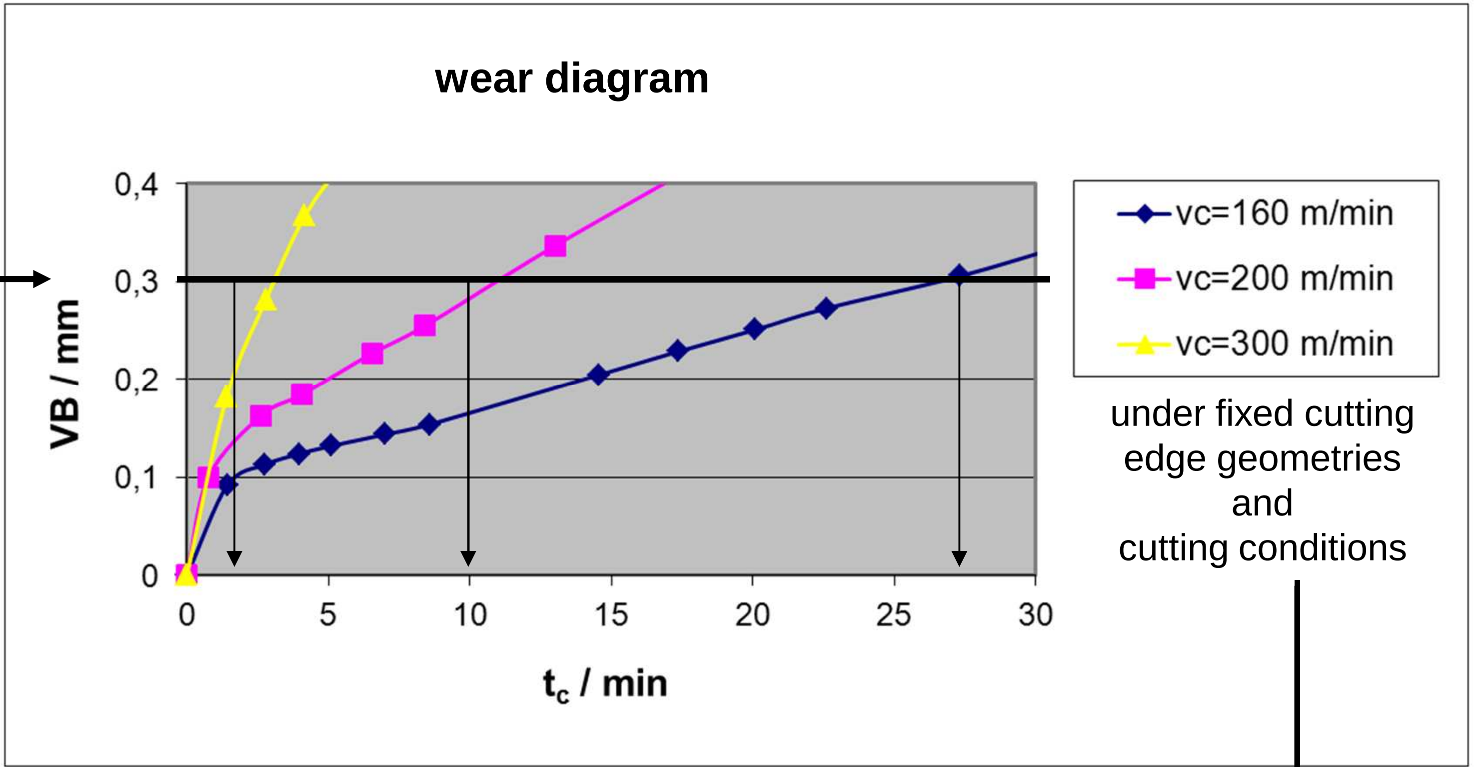
C_v (ordinate intercept): standardised tool life T for v_c = 1 m/min

C_T (abscissa intercept): standardised cutting speed v_c for T = 1 min

Taylor-equation (extended)	$T = C_{vfa} \cdot v_c^{\,k_{vc}} \cdot f_z^{\,k_{fz}} \cdot a_p^{\,k_{ap}}$

Wear diagram: flank wear

the choice of the tool life criterion



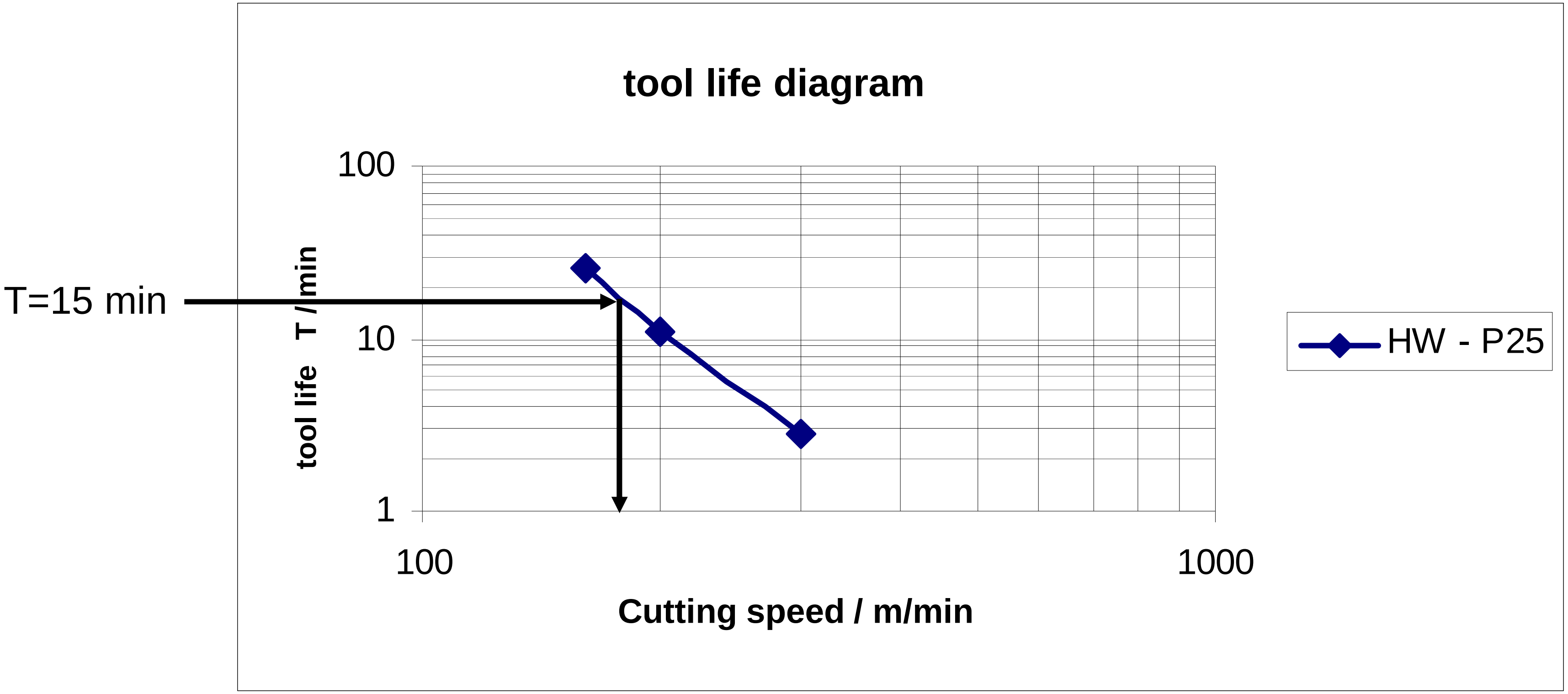
under fixed cutting edge geometries and cutting conditions

determination of the tool life

consideration of the boundary conditions

Tool life straight line

determination of the cutting speed for a tool life of 15 minutes



$$v_{15VB0,3} = 170 \frac{m}{\min}$$

Tool wear modelling

tool wear modelling

- **tool life equations**
  - tool life by Taylor: $$T = v_c^k \cdot C_v$$
  - tool life by Hasting: $$T = \frac{A}{\vartheta^B}$$

T = tool life
υ = temperature
k, A, B = constants
C_v = T for v_c = 1 m/min

- **tool wear rate models**
  - empirical tool wear model
  - physical tool wear model

model by Archard:
$$\frac{dV}{dt} = K \frac{F \cdot S}{3H}$$

model by Usui:
$$\frac{dV}{dt} = \sigma_n \cdot v_{ch} \cdot C_1 \cdot e^{\left(-\frac{C_2}{T}\right)}$$

model by Takeyama:
$$\frac{dV}{dt} = G \cdot v_c + D \cdot e^{-\frac{E}{R\vartheta}}$$

dV/dt = wear volume per time
H = hardness
F = mechanical load
S = cutting path
K, C1, C2, G, D = constants
σ_n = normal pressure
v_{ch} = sliding velocity
υ = temperature

Outline

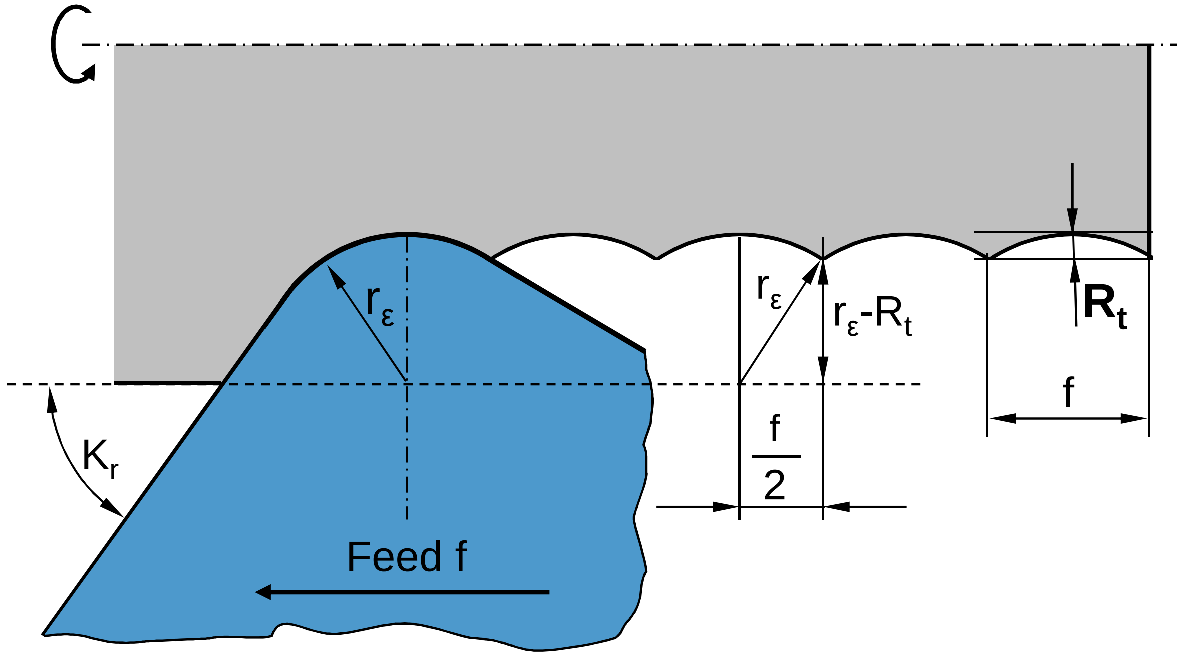
Factors influencing surface quality in metal cutting

influences on surface quality in metal cutting

kinematic roughness		cutting roughness		additional factors
tool motion	cutting edge	chip formation mechanisms, BUE	alteration of cut surface	vibrations, chips, deformation of feed tracks
Influenced by	Influenced by	Influenced by	Influenced by	Influenced by
cutting speed, feed	wear on minor flank, overall wear	tool geometry, work material, temperature, tool material	corner and flank wear, friction and welds, cooling	dynamic stiffness of the system tool-work-machine tool, cutting forces, chip formation, tool micro geometry, work material, cutting parameter

Source: F. Betz

Kinematic (theoretical) depth of roughness

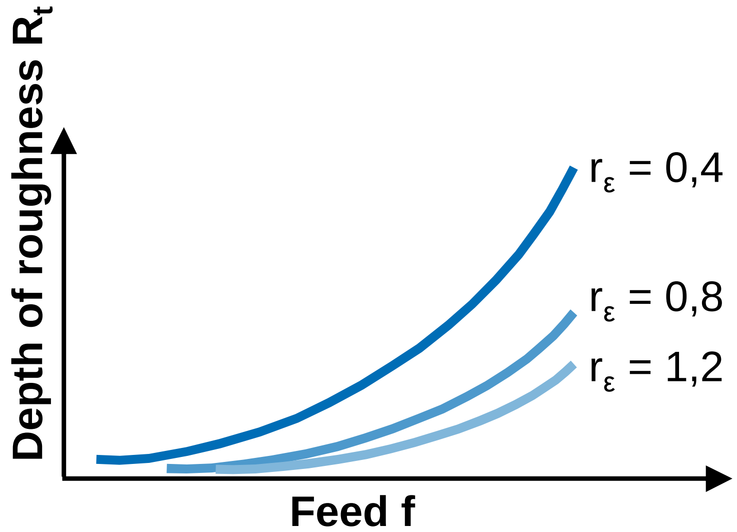


$$R_t = r_\varepsilon - \sqrt{r_\varepsilon^2 - \frac{f^2}{4}}$$

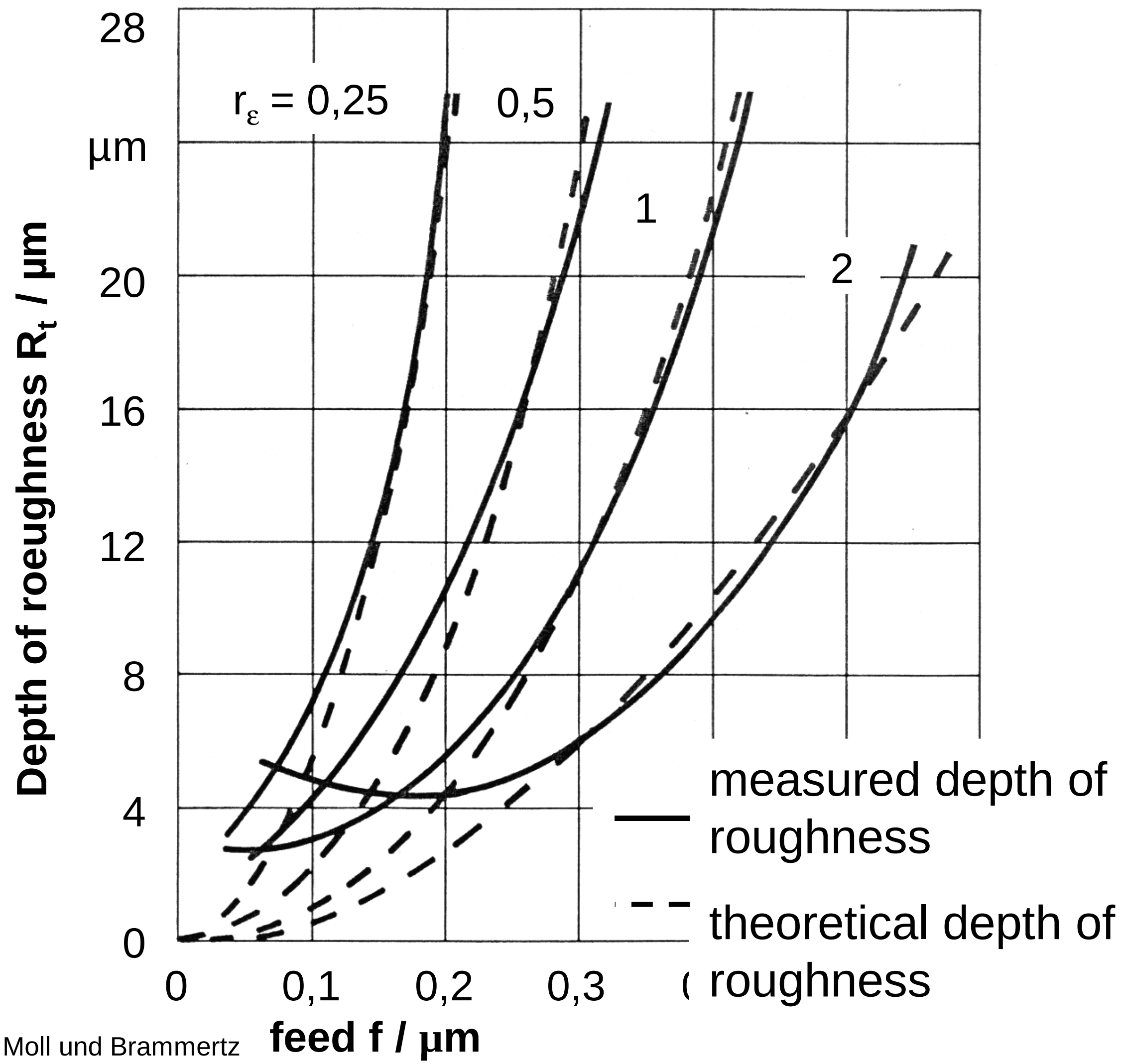
or :

$$R_t = \frac{f^2}{8 \cdot r_\varepsilon}$$

The theoretical depth of roughness R_t can be derived from the geometrical engagement specifications and is a function of the feed and the corner radius r_ε



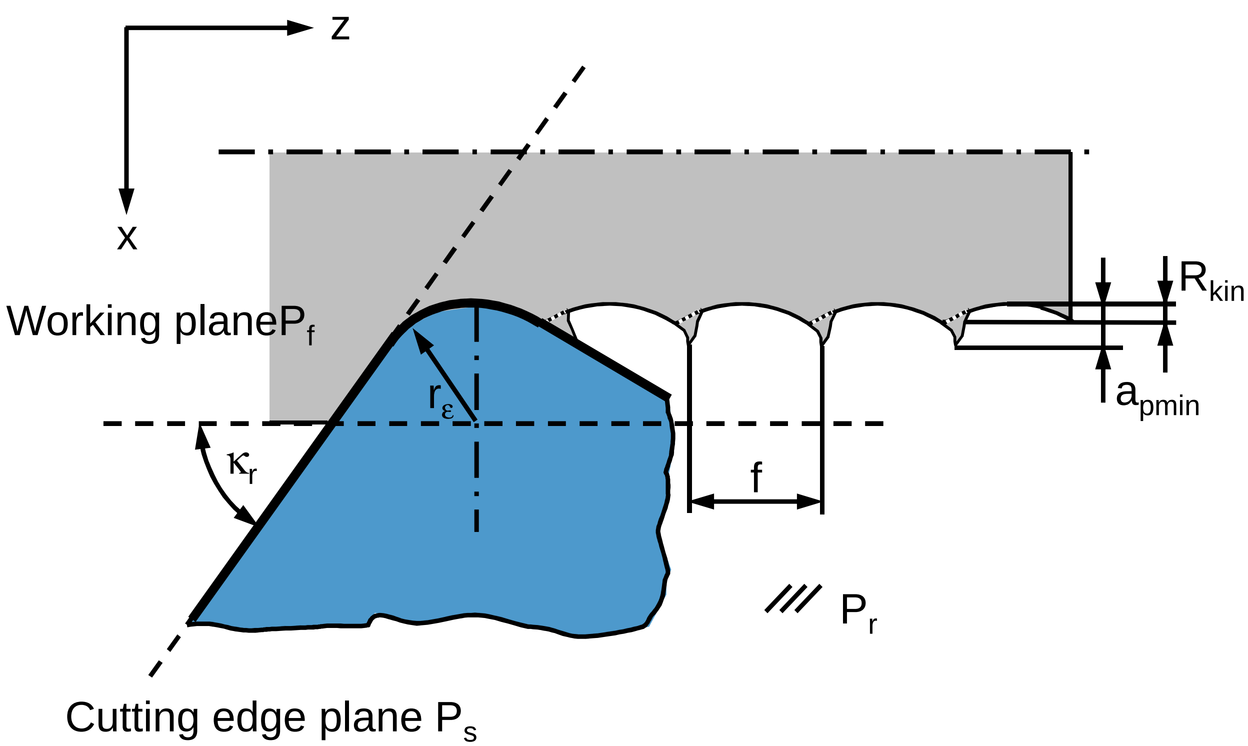
Theoretical and measured depths of roughness



Source: Moll und Brammertz

- The illustration demonstrates a comparison of theoretical and measured depths of roughness
- The divergency between the results in the low feed area can be traced back to the low chip width which grows with increasing rounded cutting edge radius

Chip Tip Theory

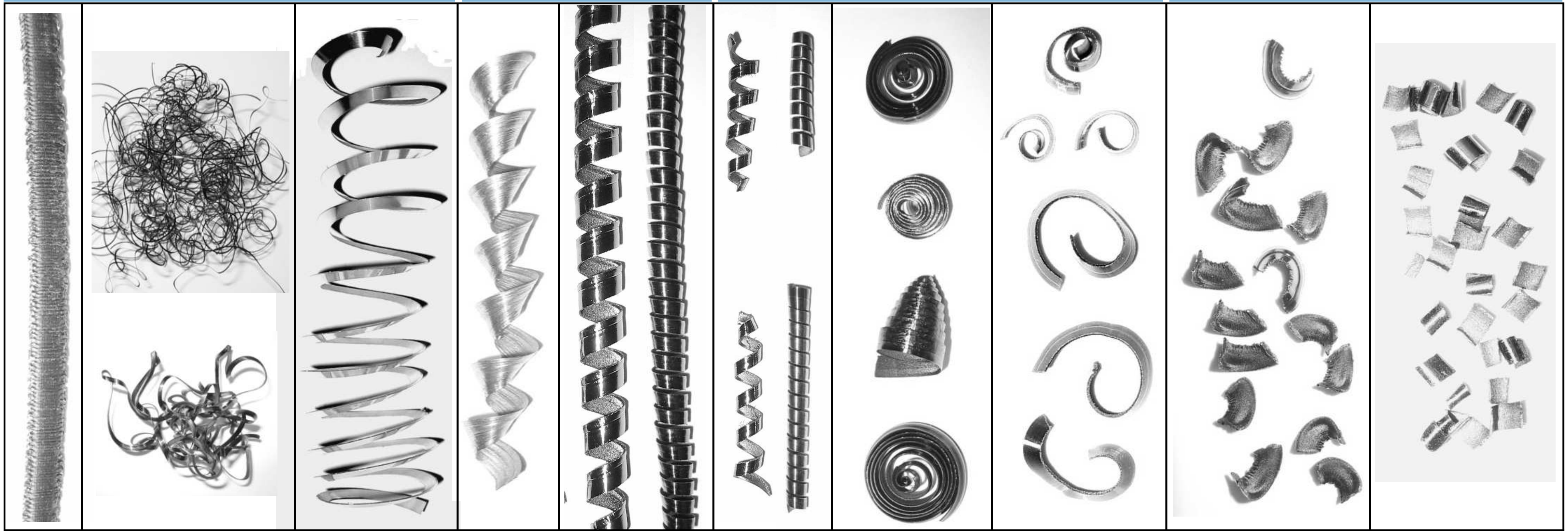


- The geometrical ideal surface profile is determined by the kinematic depths of roughness R_{kin}
- Due to the material resilience and the cutting edge wear, material of the work piece is being displaced which partially springs back afterwards
- Chip tips are created because of this process
- Due to the creation of chip tips the real depth of roughness is higher than the theoretical kinematic depth of roughness R_{kin}.

Source: Brammertz, 1961

Outline

Evaluation criterion: Chip Formation

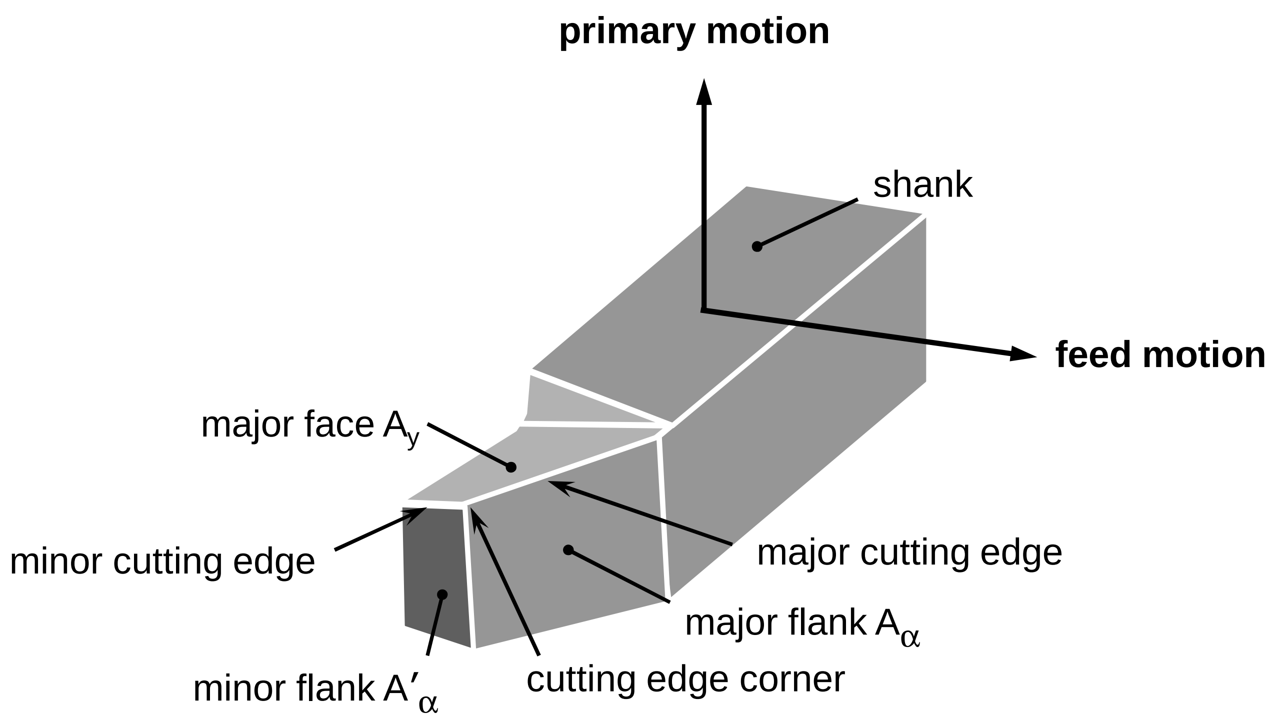
unfavourable			acceptable		good			acceptable	
									
1	2	3	4	5	6	7	8	9	10

1 ribbon chips
2 tangled chips
3 corkscrew chips
4 helical chips
5 long tubular chips
6 short tubular chips
7 spiral tubular chips
8 spiral chips
9 long comma chips
10 short comma chips

Thanks for your attention!

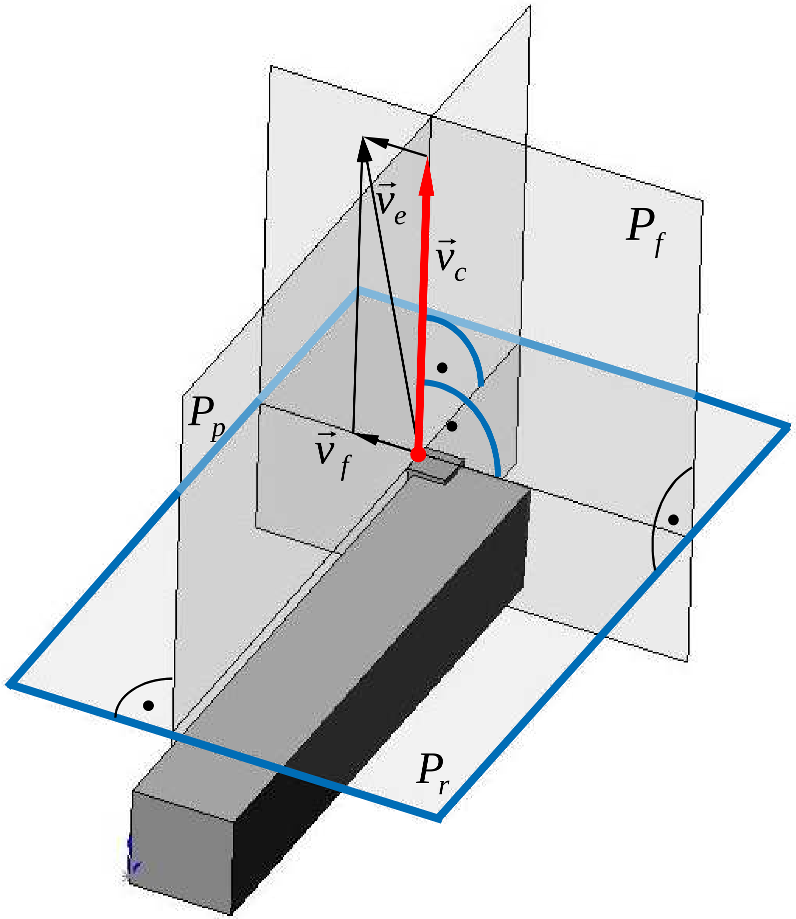
Gliederung

Cutting edges on the cutting part of a turning tool



Standbedingungen: Schneideneingriff und Kinematik

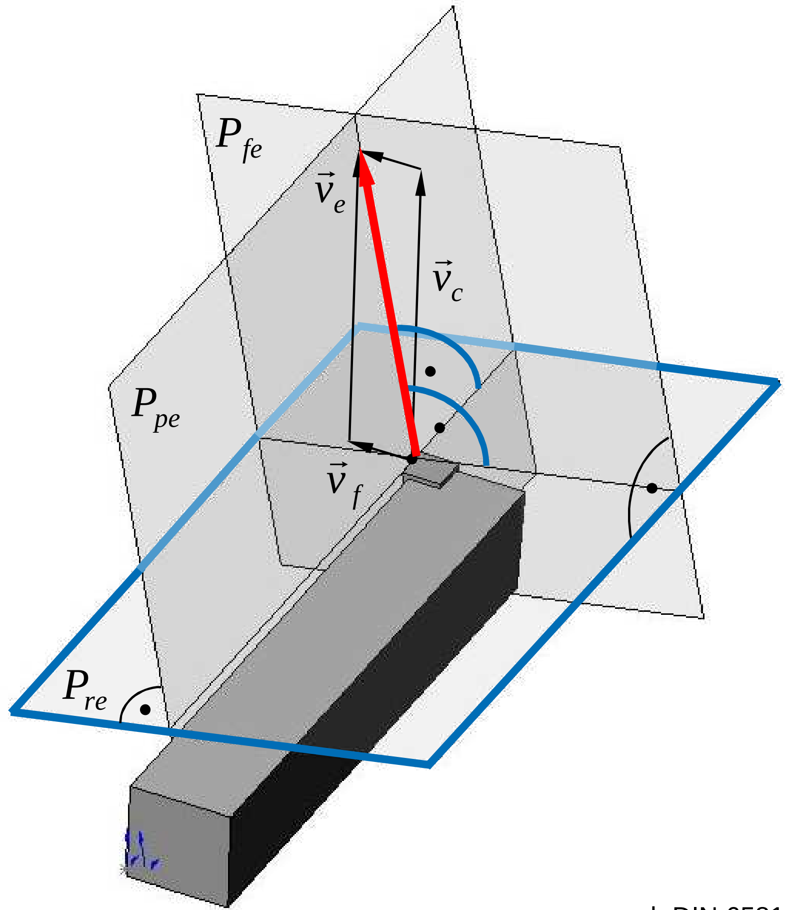
Werkzeug-Bezugssystem



P_r = Grundebene

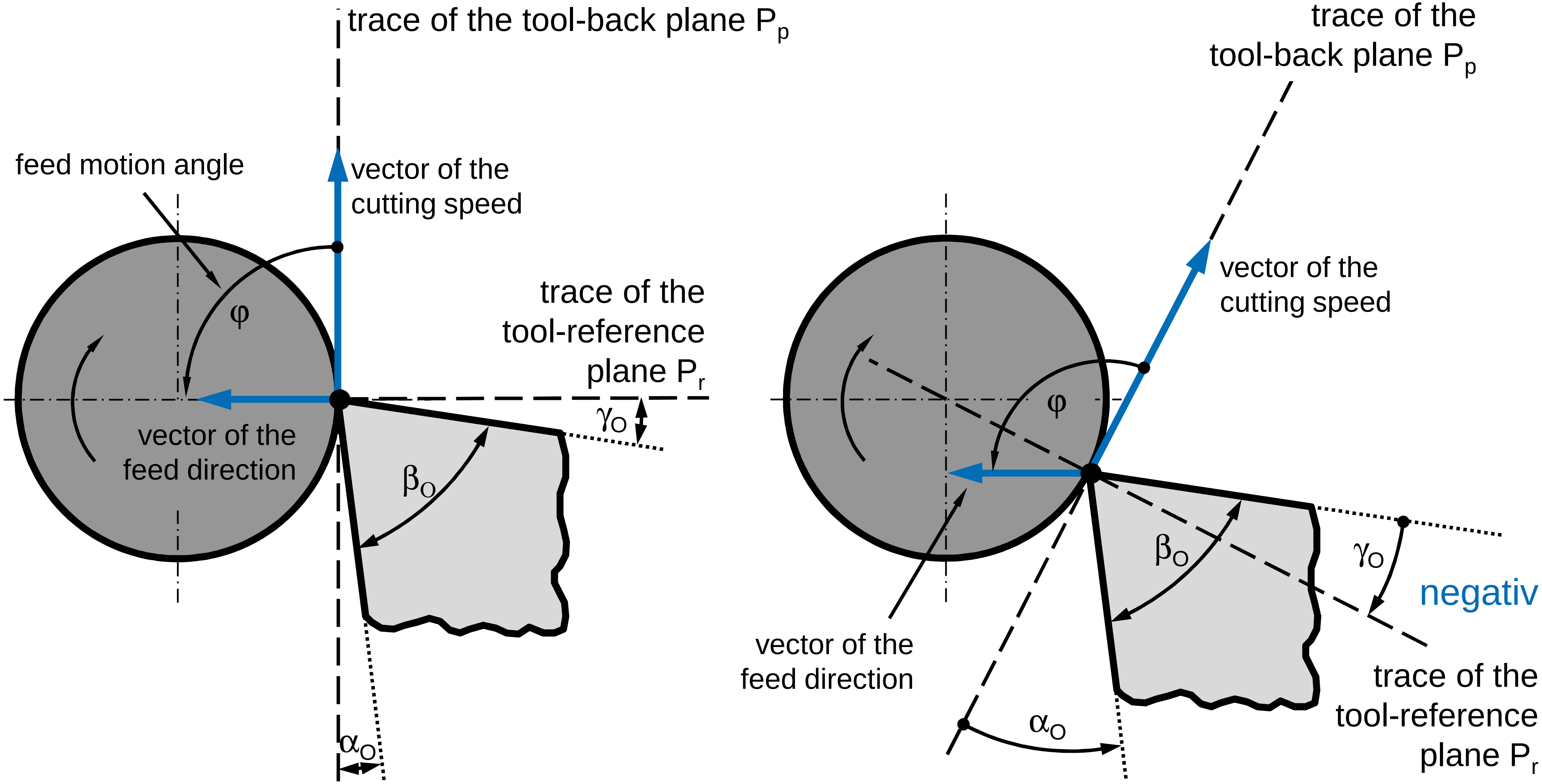
Index e = effective

Wirk-Bezugssystem

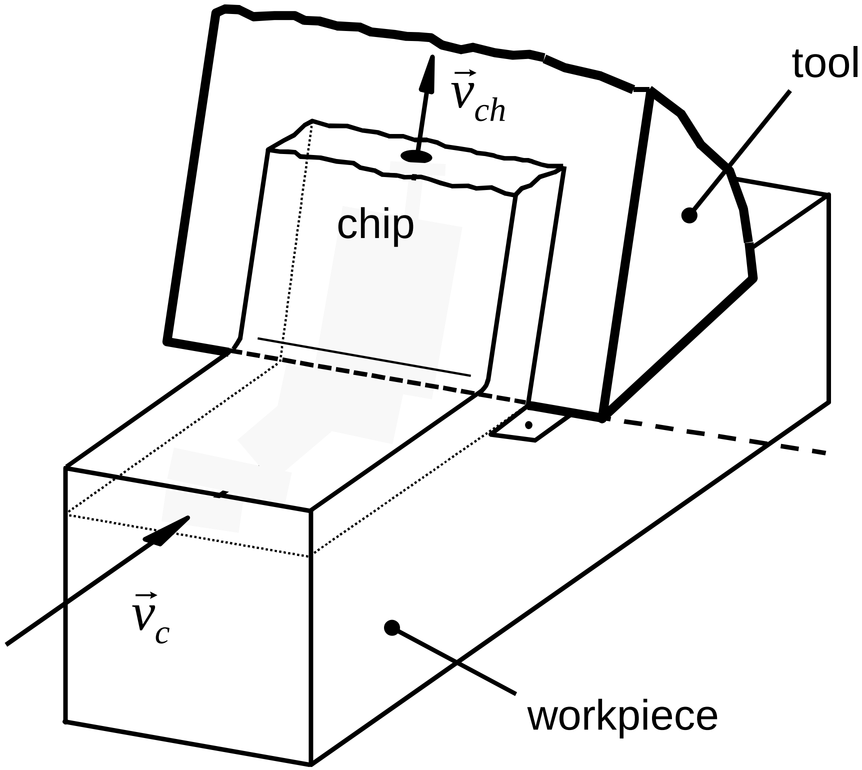


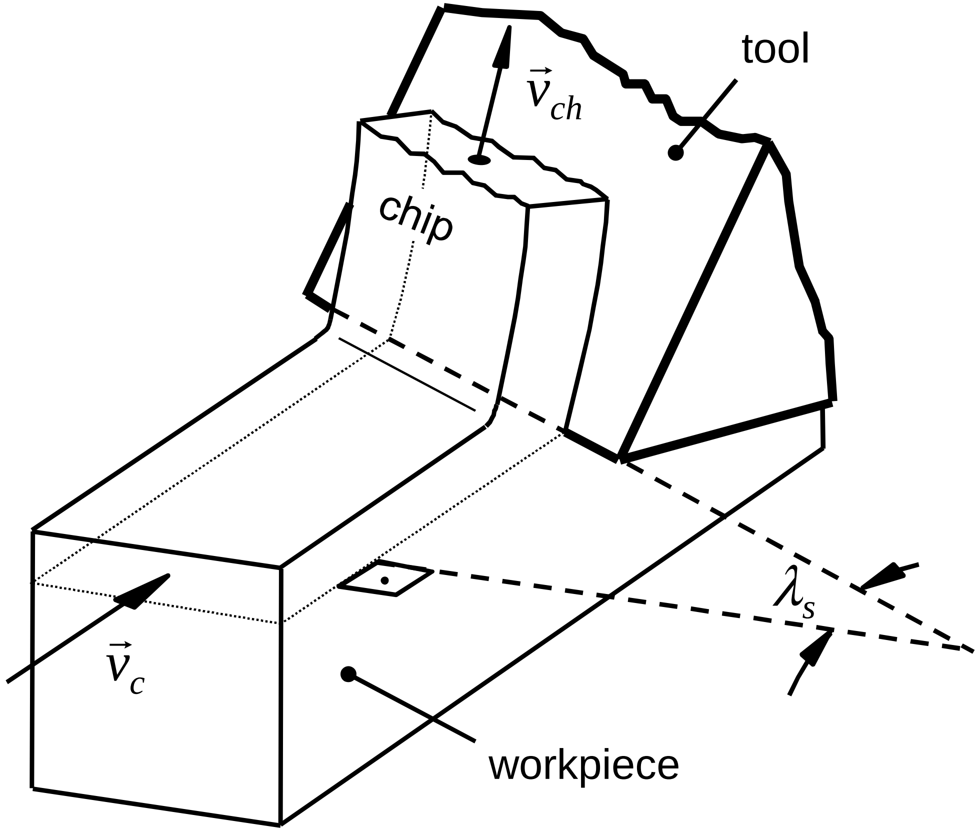
nach DIN 6581

The feed motion angle φ and the tool in use system in turning



Tool cutting edge inclination

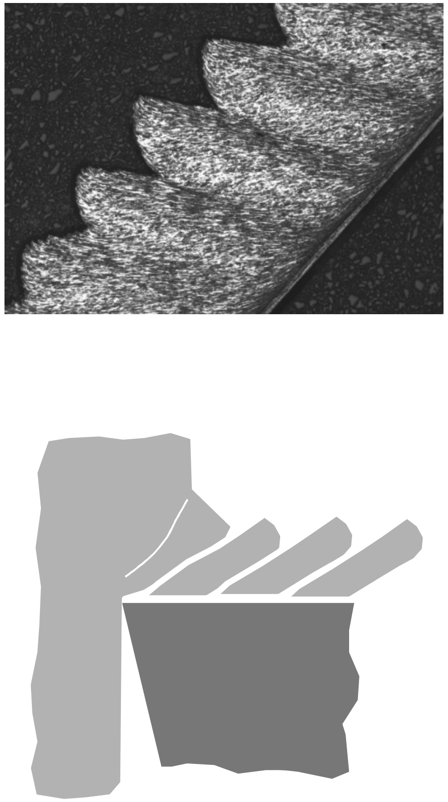




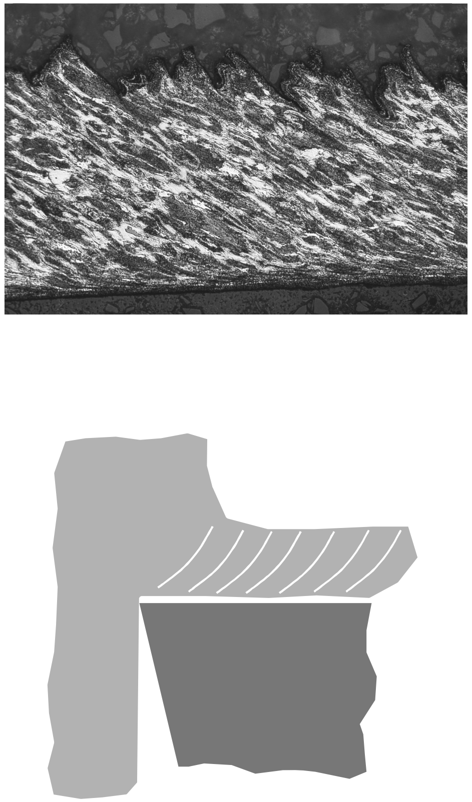
- Tool cutting edge inclination $\lambda_s = 0°$
- Tool cutting edge inclination λ_s not equal to 0°

Chip formation: types of chips I

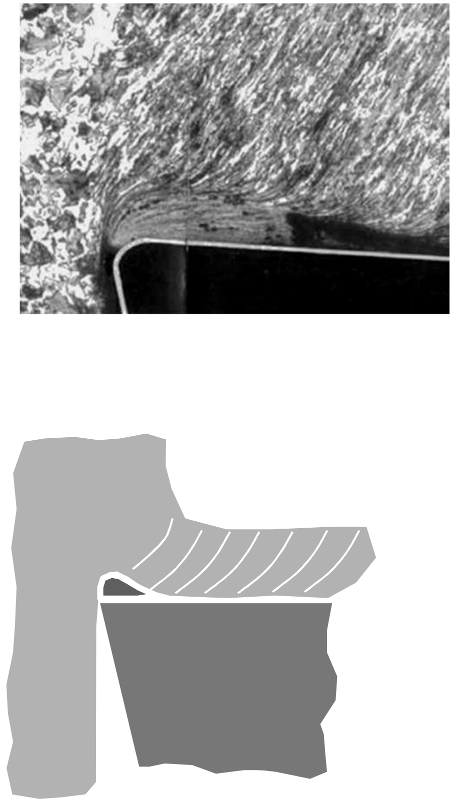
segmented chip



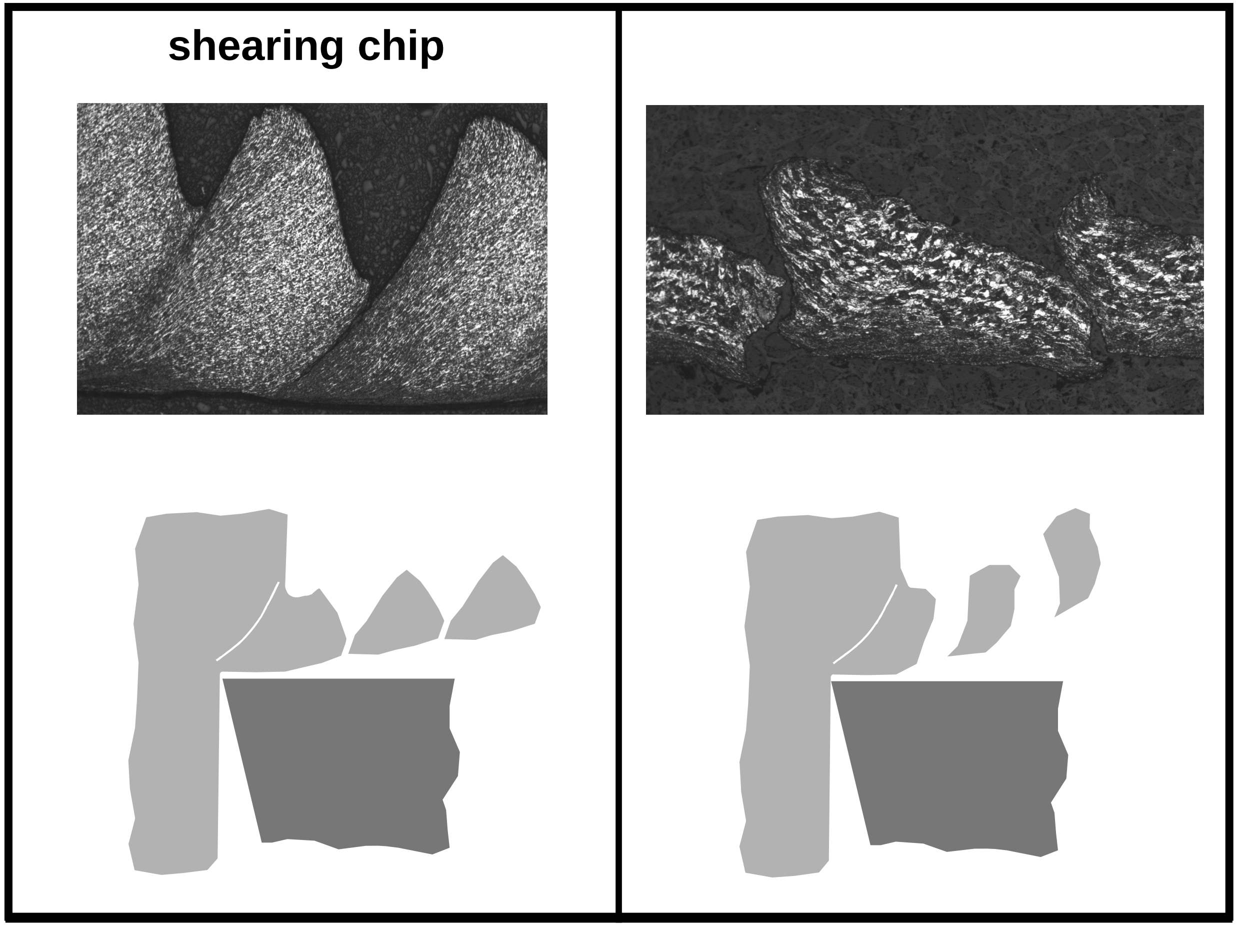
continuous chip



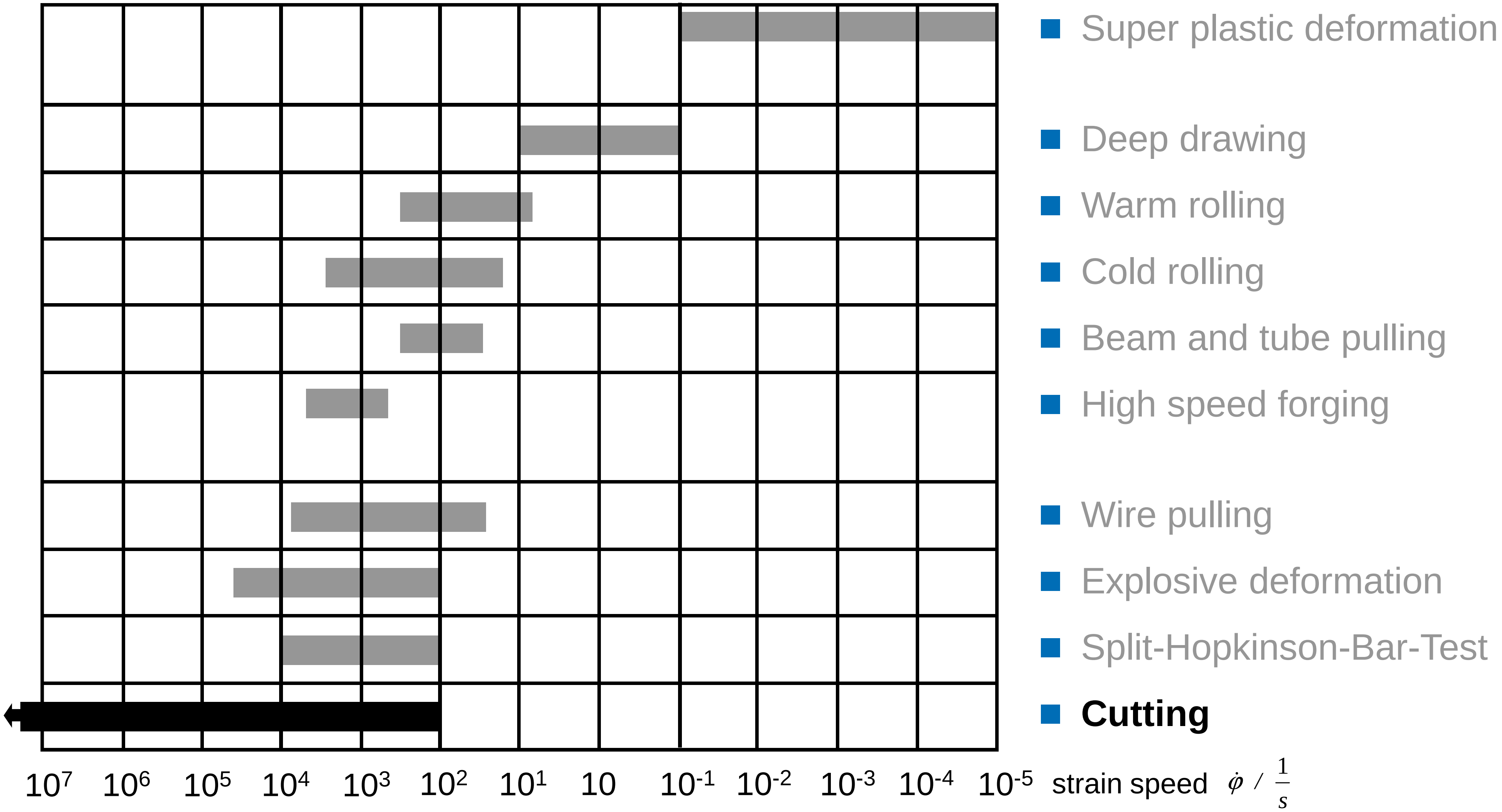
chip with build-up edge



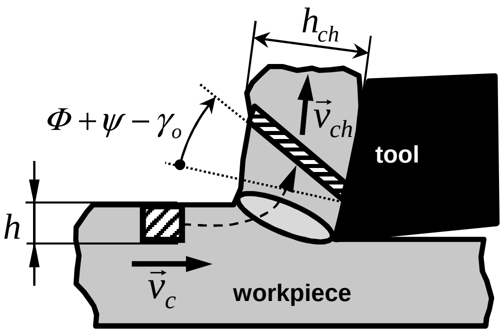
Chip formation: types of chips II

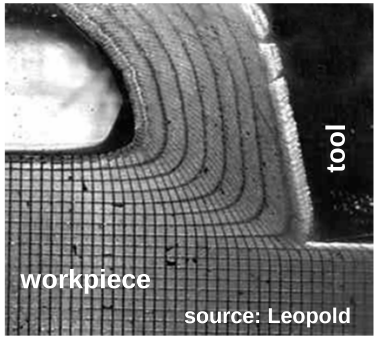


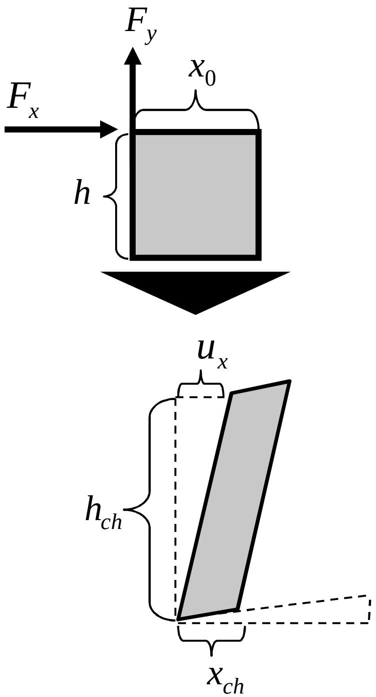
Strain rates in different processes

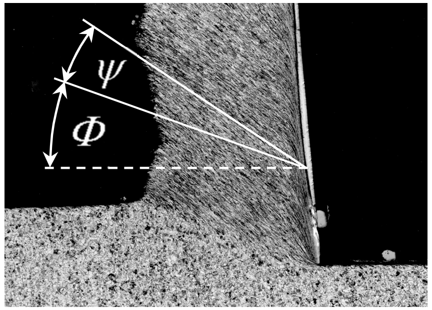


Calculation of the strain rates









$$\varphi_x = ln\frac{x_{ch}}{x_0}$$

$$\varphi_y = ln\frac{h_{ch}}{h} = ln\,\lambda_h$$

$$\Phi+\psi-\gamma_o = arctan\frac{u_x}{h_{ch}}$$

$$\xi = 0$$

strain rate

$$\dot{\varphi}_x = \frac{\partial v_x}{\partial x} \qquad \dot{\varphi}_y = \frac{\partial v_y}{\partial y} \qquad \dot{\varphi}_z = \frac{\partial v_z}{\partial z}$$

shearing strain rate

$$\dot{\gamma}_{xy} = \frac{\partial v_x}{\partial y} + \frac{\partial v_y}{\partial x} \qquad \dot{\gamma}_{yz} = \frac{\partial v_y}{\partial z} + \frac{\partial v_z}{\partial y} \qquad \dot{\gamma}_{zx} = \frac{\partial v_z}{\partial x} + \frac{\partial v_x}{\partial z}$$

strain speed

strain tensor

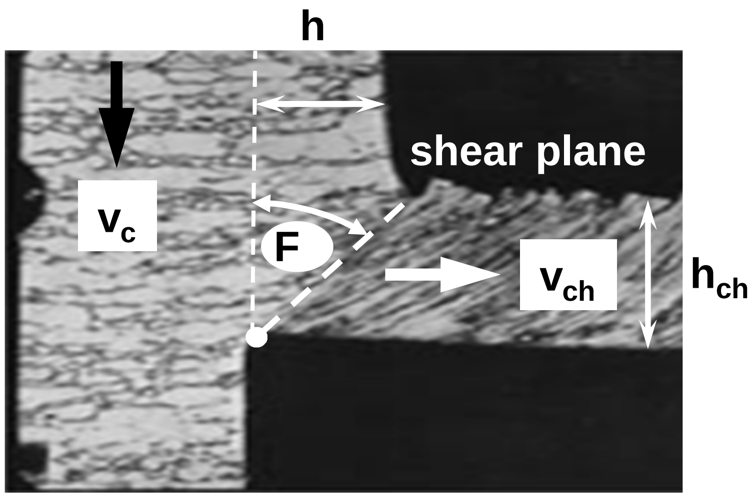
$$2\cdot\varphi_{xy} = \begin{pmatrix} 2\cdot ln\frac{x_{ch}}{x_0} & \Phi+\psi-\gamma_o \\ \Phi+\psi-\gamma_o & 2\cdot ln\frac{h_{ch}}{h} \end{pmatrix} = \begin{pmatrix} 2\cdot ln\,\lambda_l & \Phi+\psi-\gamma_o \\ \Phi+\psi-\gamma_o & 2\cdot ln\,\lambda_h \end{pmatrix}$$

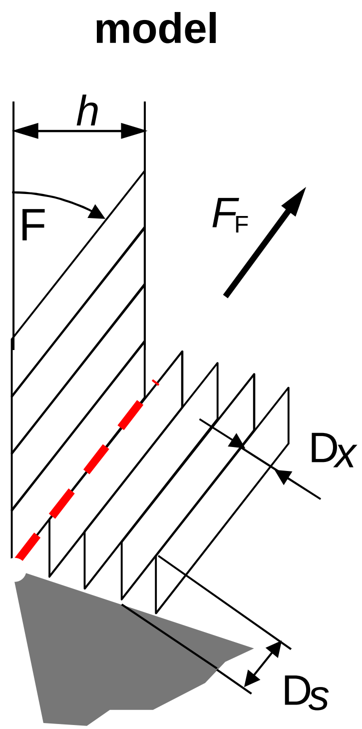
The time based differentiation delivers the strain speed!

$$\gamma_{xy} = \Phi+\psi-\gamma_o$$

$$\dot{\varphi}_y = 2\cdot\frac{\partial}{\partial t}ln\,\lambda_h \qquad \dot{\varphi}_x = 2\cdot\frac{\partial}{\partial t}ln\left(\frac{x_{ch}}{x_0}\right)$$

Consideration of energy



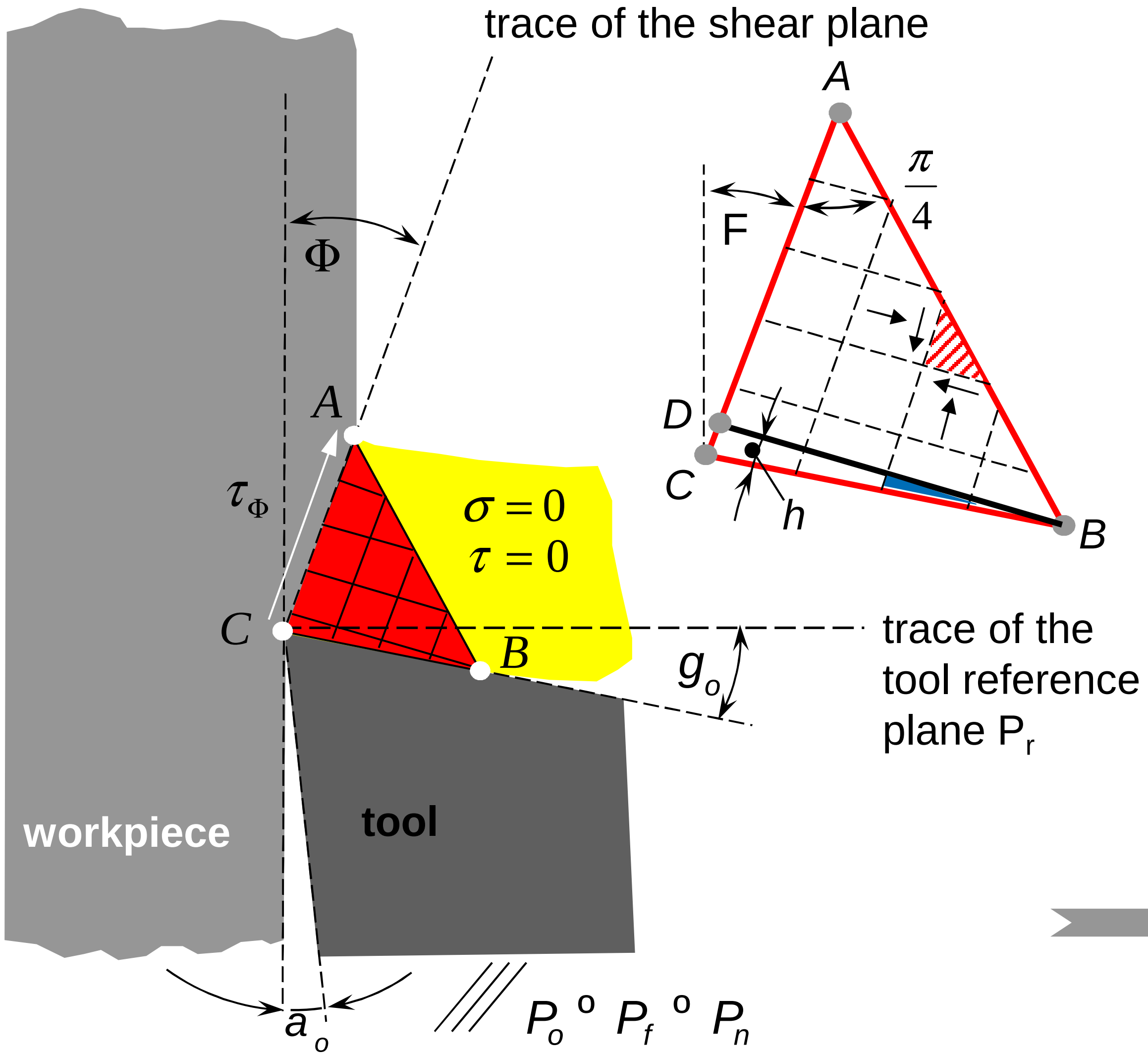


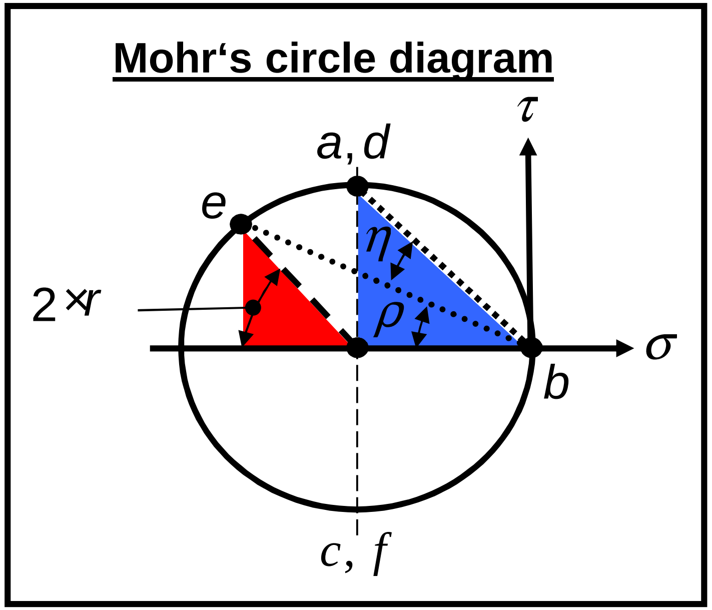
shear energy: $E_\Phi = F_\Phi \cdot \Delta s$

specific shear energy: $e_\Phi = \dfrac{E_\Phi}{V_\Phi} = \dfrac{F_\Phi \cdot \Delta s}{A_\Phi \cdot \Delta x} = \tau_\Phi \cdot \dfrac{\Delta s}{\Delta x}$

$$A_\Phi = \frac{A}{\sin\Phi} = \frac{b \cdot h}{\sin\Phi}$$

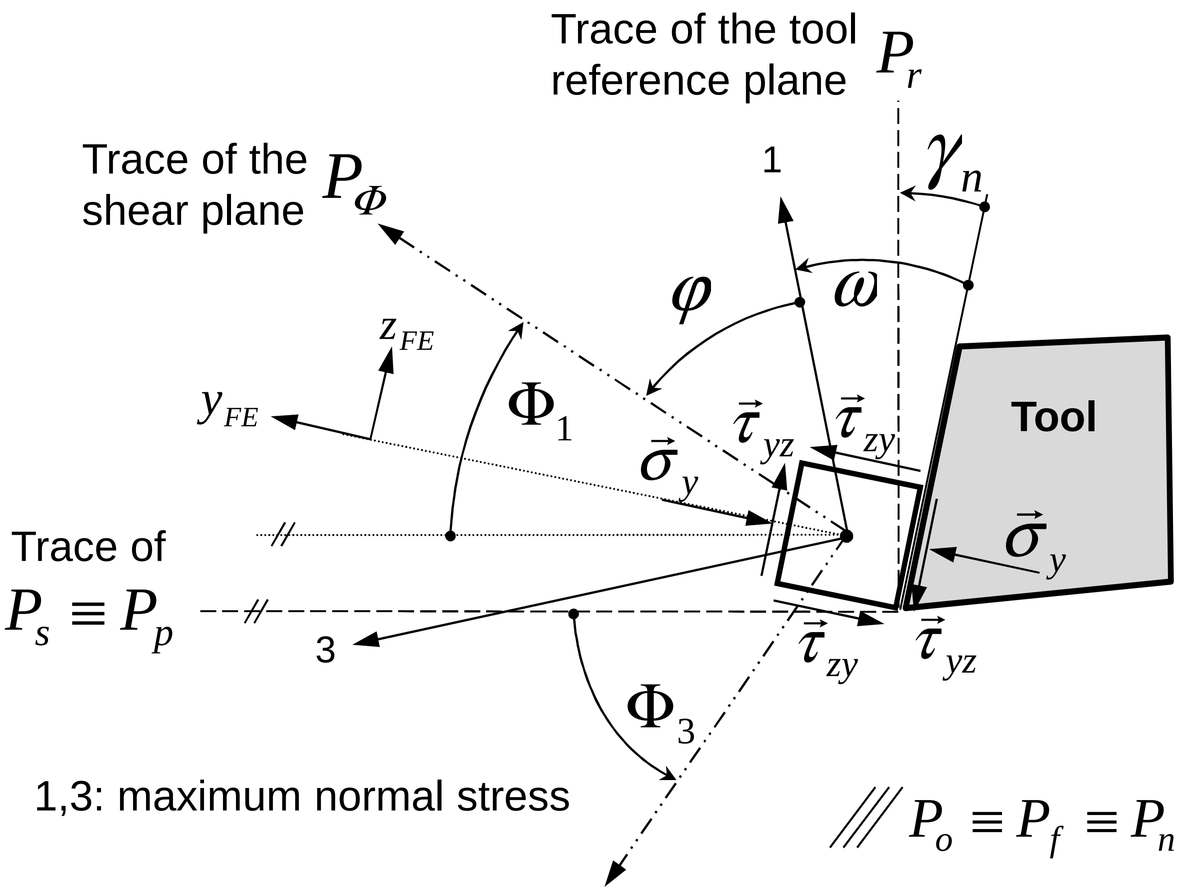
Application: theory of the ideal plastic body Lee/Shaffer (1951)





$$F = \frac{p}{4} + g_o - r$$

Calculation of the shear angle, Hucks (1951)



- Determination of the directions of the maximum normal stresses (1, 3) with Mohr's Circle
- Calculation of the material specific angle φ :

$$\varphi = 45 - \frac{1}{2}\arcsin\left(\frac{\sigma_D - 2\tau_F}{\sigma_D}\right)$$

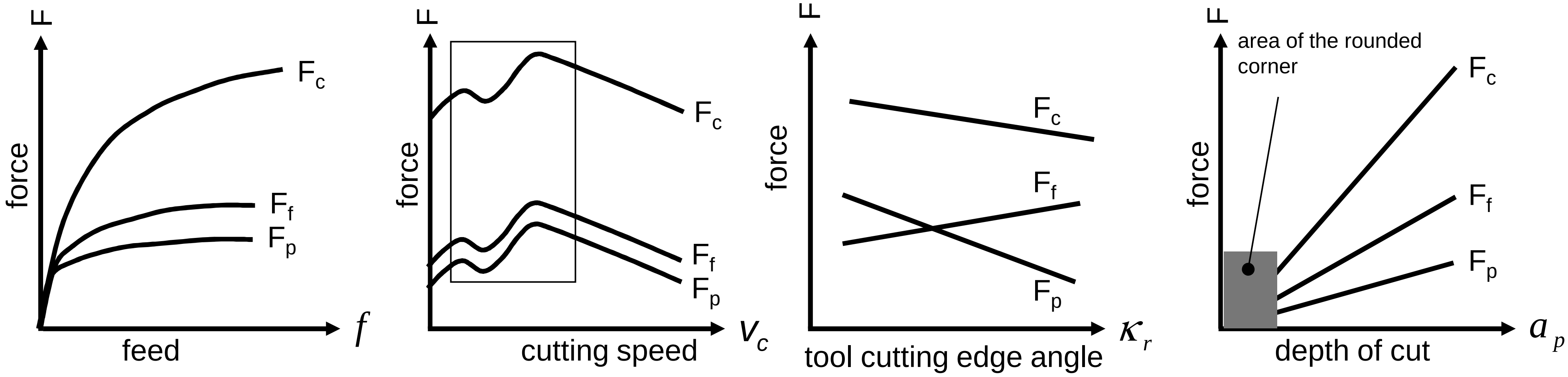
- Calculation of the shear angle:

$$\boxed{\Phi_1 = \varphi - \frac{1}{2}\arctan(2\mu) + \gamma_n}$$

$$\omega = \frac{1}{2} arctan(2 \cdot \mu)$$

Dependencies of the force components

distribution of force



The maxima are produced by the build up cutting edge during the area of low cutting speed.

At the area of the rounded corner the trend line of the force components are not linear!

primary influence of the force components

technical cutting mechanics | **geometrical relation** | **theoretical cutting mechanics**

technical terms: v_c, $v_{f,}$ a_p, …

k_r, l_s, a_o, g_o, …

theoretical terms: b, h, h_{ch}, …

In the **theoretical cutting mechanics,** the cross-sectional area was identified as primary factor and for the calculation the following parameters were defined:

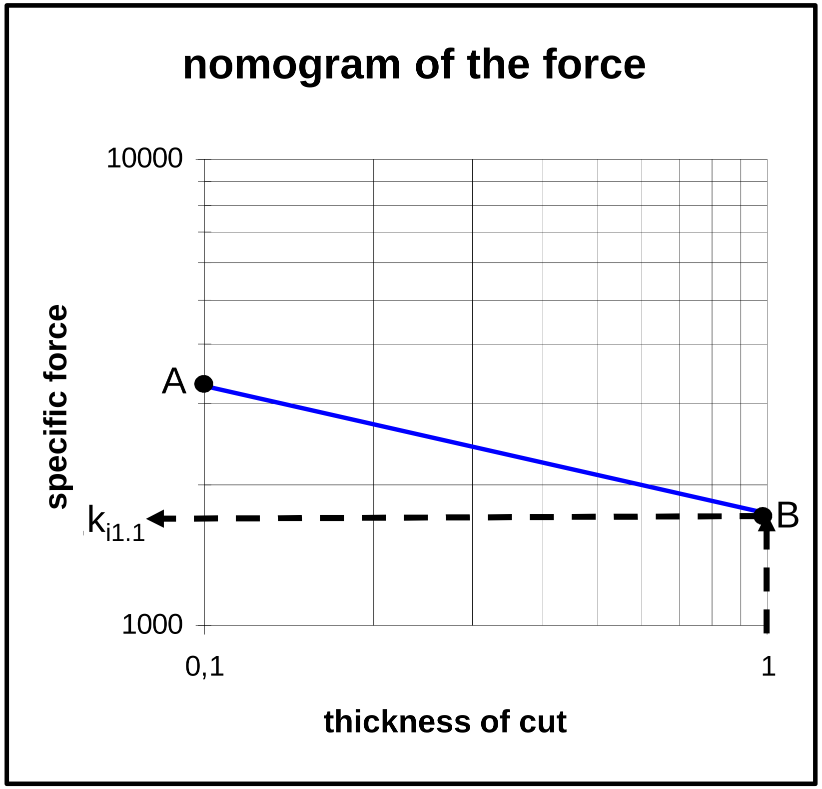
- thickness of cut **h**
- width of cut **b**

$$\boxed{F_z = f\,(b, h)}$$

Plagens has found a good approximation of the cutting force with a linear function of the width of cut (*b*).

The approximation of the force components with a function of the thickness of cut *h* was often discussed and lead to empirical models:

Nomogram of the specific components of the cutting force



You can determine directly the scaled specific components of the cutting force divided by an area of 1 mm² !

equation of the straight line: $y = m \cdot x + b$

$$\log k_i = -m_i \cdot \log h + \log k_{i1.1}$$

$$\longrightarrow \boxed{k_i = k_{i1.1} \cdot h^{-m_i}}$$

slope of the straight line in the double logarithmic system:

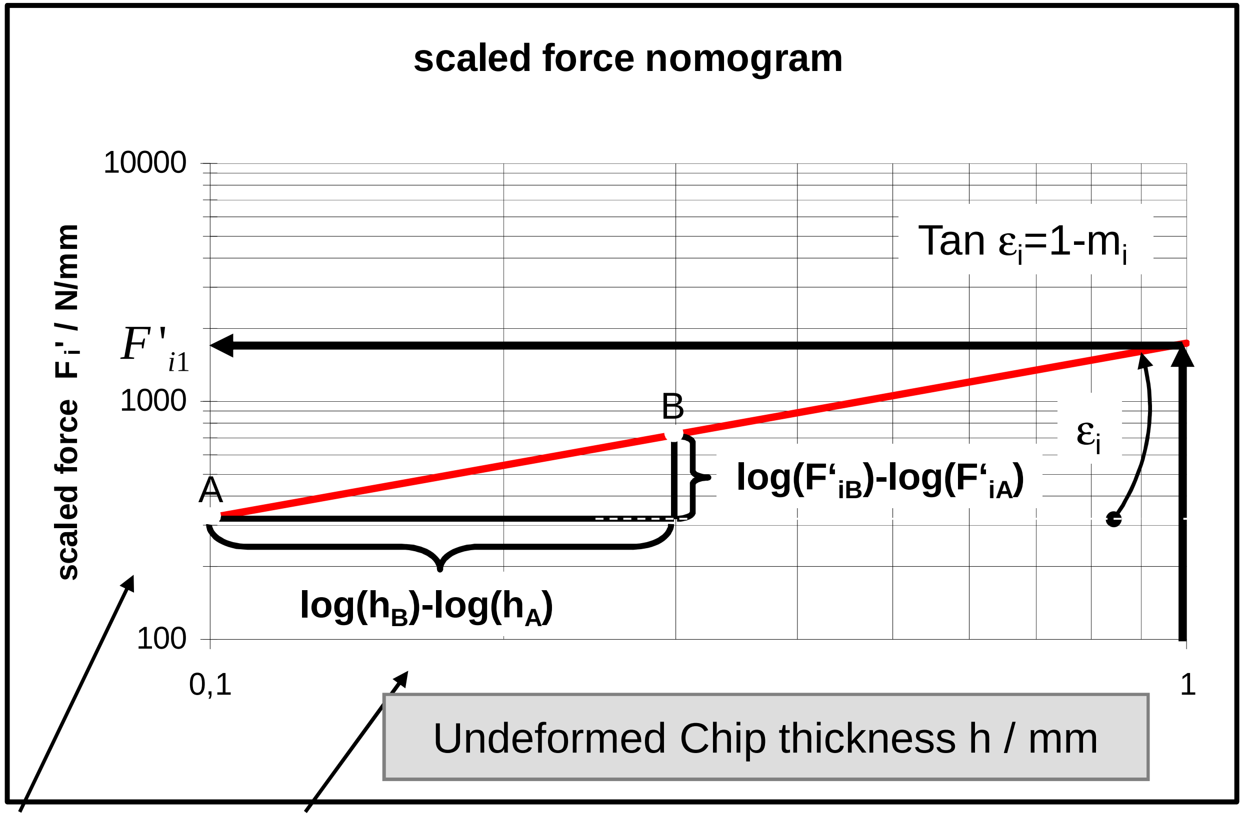
$$-m_i = \frac{\log B_y - \log A_y}{\log B_x - \log A_x} \qquad m_i = \frac{\log A_y - \log B_y}{\log B_x - \log A_x}$$

i.g.: $k_i = \dfrac{F_i}{A} = \dfrac{F_i}{b \cdot h}$ $\boxed{k_{i1.1} = \dfrac{F_i}{1\,mm \cdot 1\,mm}}$

(scaling)

$$\boxed{F_i = k_{i1.1} \cdot b \cdot h \cdot (h / \mu m)^{-m_i}}$$

Example: potential approximation



logarithmic scale of the axes!

triangle of the slope!

$$y_i = a \cdot x + b$$

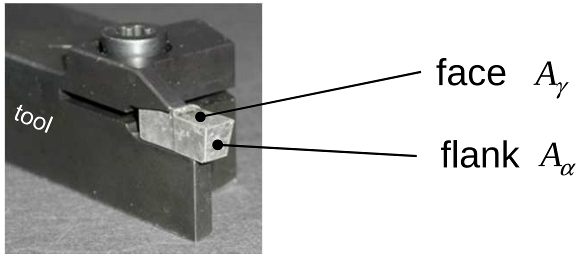
$$\log F_i' = a \cdot \log h + \log F_{i1}'$$

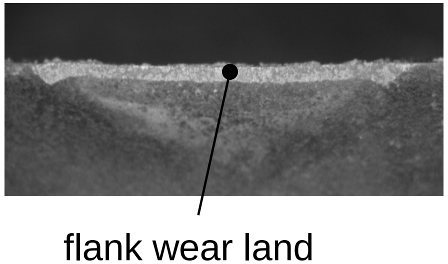
$$F_i' = F_{i1}' \cdot h^{(1-m_i)}$$

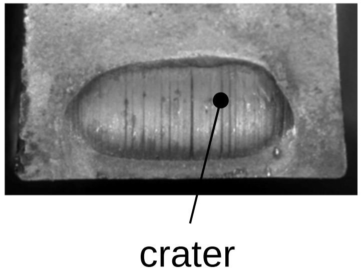
$$F_i = k_i \cdot b \cdot h \qquad \boxed{k_i = \frac{k_{i1.1}}{h^{m_i}}}$$

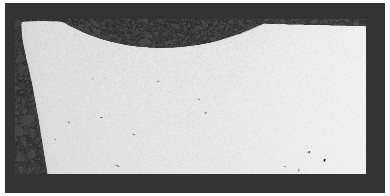
potential approximation: $\boxed{F_i = k_{i1.1} \cdot b \cdot h^{1-m_i}}$

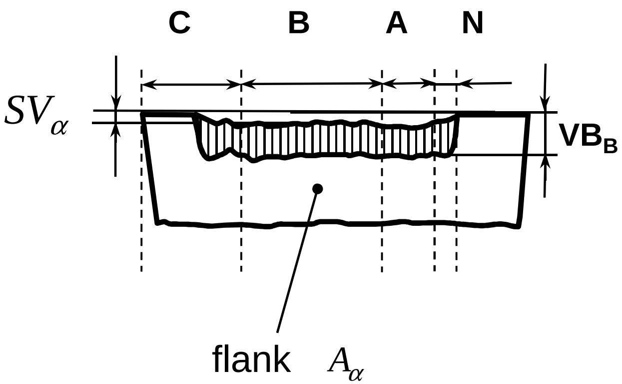
Types of wear

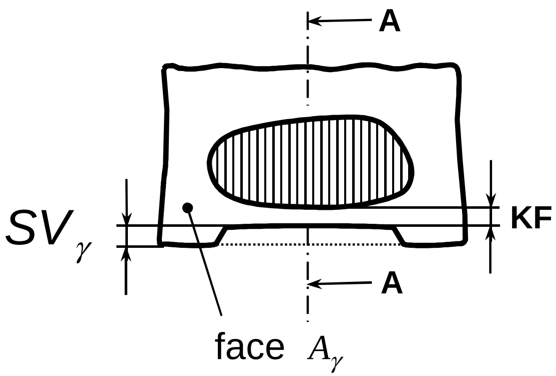


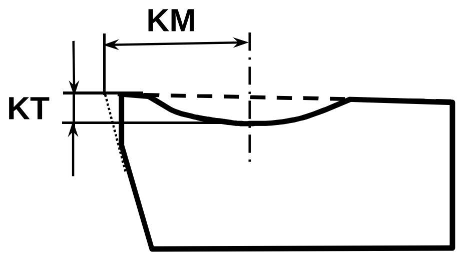




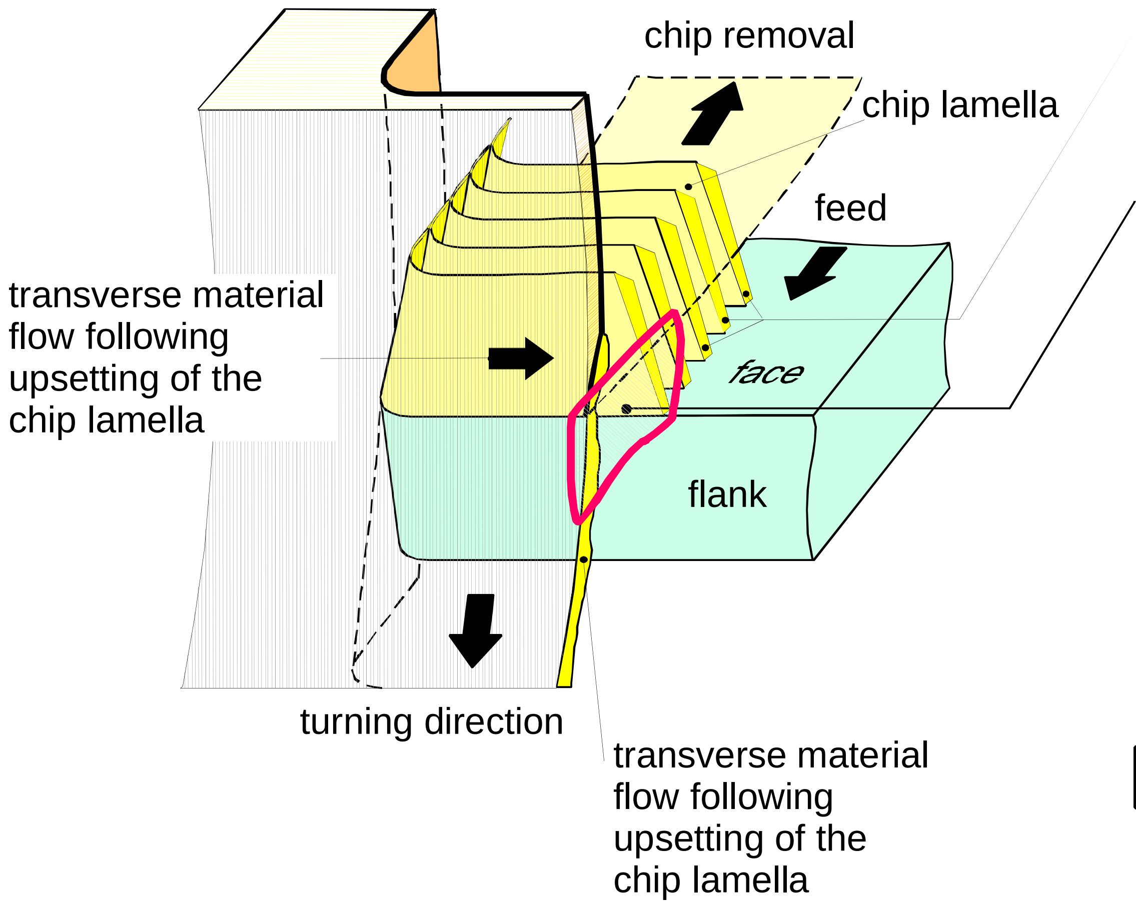






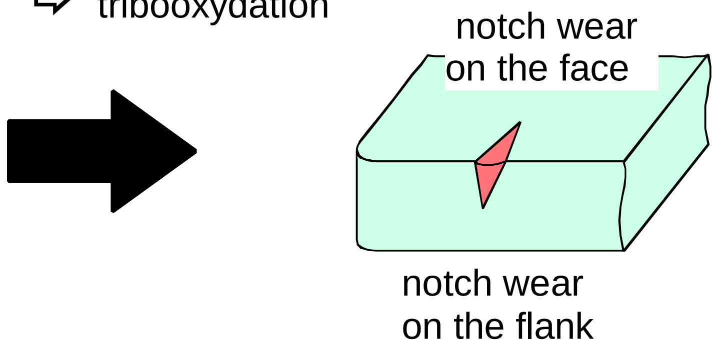


Notch wear in machining of nickel base alloys

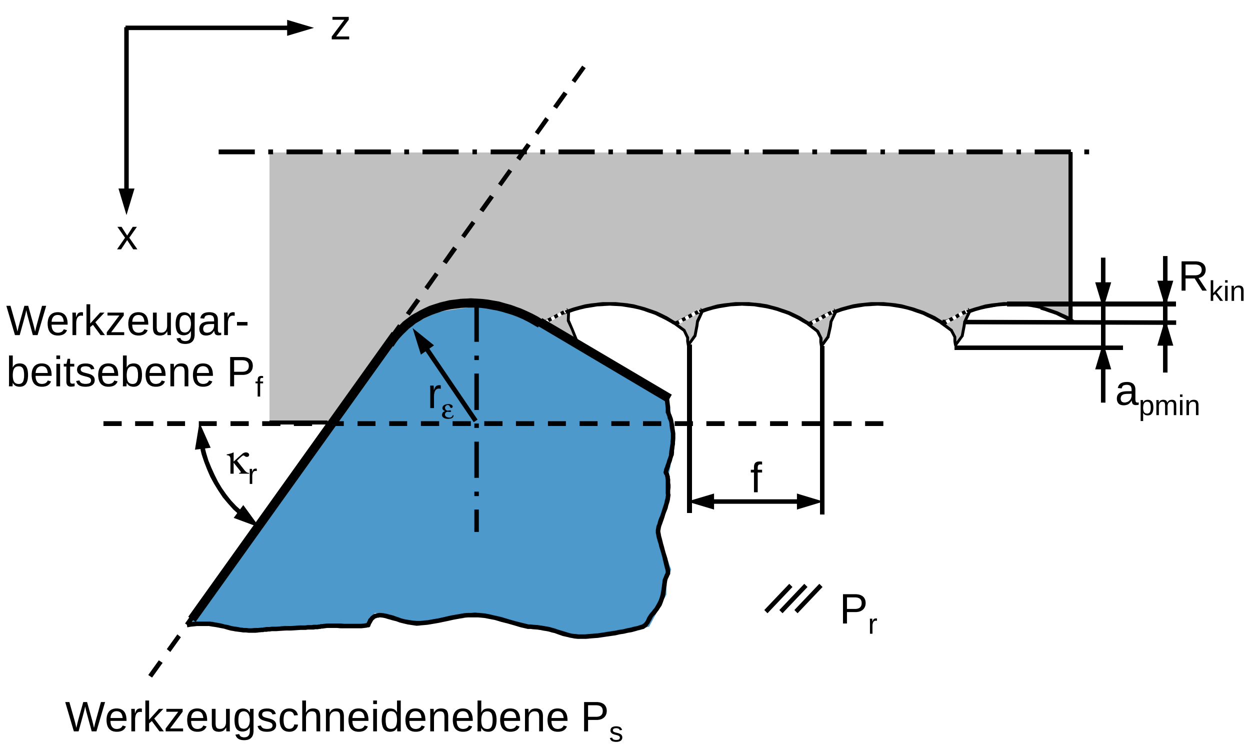


formation of a sawtooth profile at the edge of the chip lamella
⇨ abrasion
⇨ surface damage

cutting edge sector with
- high pressures
- high temperatures
- high shear stresses
- high thermal and mechanical stress gradients
- high thermal and mechanical alternating stresses
⇨ adhesion
⇨ surface damage
⇨ tribooxydation



Spanzipfeltheorie



Quelle: Brammertz, 1961

- Das geometrisch ideale Oberflächenprofil wird durch die kinematische Rauhtiefe R_{kin} beschrieben.
- Aufgrund von Werkstoff-elastizität und Schneiden-verschleiß wird im Bereich der Nebenschneide Werkstoff verdrängt, der anschließend teilweise elastisch zurückfedert.
- Durch diese Effekte entstehen die sogenannten Spanzipfel.
- Die tatsächliche Rauhtiefe ist durch die Bildung der Spanzipfel größer als die theoretisch berechnete kinematische Rautiefe R_{kin}.

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