Applied Machining Technology
Preface

A central issue on which industrial manufacturing is focused is that of metal cutting techniques.

However, given the state of the art in metal cutting, it is impossible in a single book to introduce every method. Instead, the author of this textbook has deliberately chosen to leave out the techniques for gear tooth generation. Following a brief introduction to the basics of metal cutting, all methods will be classified using the same approach and described as briefly as possible in the text.

The tables with guide values are provided to aid in working with this book in teaching and practice. The summarised guide values should be seen as reference figures that provide an initial orientation. More exact values can be obtained from the cutting tool manufacturers themselves. These values are the only ones that are binding, since they correspond to specific products and are determined according to the cutting edge materials used, the cutting edge geometry, and whatever conditions obtain at the manufacturers’ firms.

This book is intended both for students of all kinds at technical colleges and universities and for those working in the industry.

Due to the clarity of its structure and explanations, it is also suitable for technical high schools and vocational schools.

For practical use, it is designed as a compendium for quick information.

Students may use this book as a tutorial text that takes the place of note-taking during the lecture, allowing them to devote their full attention to listening in the auditorium.

Also, every user of this book has the opportunity to compare the earlier DIN notation with the new material denominations that follow the European standards.

He or she is thus free to use either the older names, which are of course still valid, or the new ones.

Other subjects that have been added to the book’s content are

- High-speed cutting (abbreviation HSC), which is becoming more and more important in industrial manufacturing, and two typical HS machining centres
- Advanced coolants and metalworking fluids for machining
- Advanced methods of force measurement and applicable measuring devices for turning and drilling
- Wire cut lapping.

I am especially grateful to my colleague Prof. Dr.-Ing.; Prof. h. c.. Jochen Dietrich, professor in manufacturing techniques and CNC technology at the University of Applied Sciences, Dresden, who was a co-author of this book beginning with the 6th edition.

I would also like to thank my editor, Dipl.-Ing. Thomas Zipsner of Vieweg Publishing, who gave me a great deal of help in redesigning and correcting the 8th edition.

Bad Reichenhall/Dresden, May 2007

Heinz Tschätsch
## Terms, formulae and units

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Formula</th>
<th>Unit</th>
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<tbody>
<tr>
<td>Depth of cut or width of cut</td>
<td>(a_p)</td>
<td>mm</td>
</tr>
<tr>
<td>Cutting engagement</td>
<td>(a_e)</td>
<td>mm</td>
</tr>
<tr>
<td>Thickness of cut</td>
<td>(H)</td>
<td>mm</td>
</tr>
<tr>
<td>Mean thickness of cut</td>
<td>(H_m)</td>
<td>mm</td>
</tr>
<tr>
<td>Width of cut</td>
<td>(B)</td>
<td>mm</td>
</tr>
<tr>
<td>Sectional area of chip</td>
<td>(A)</td>
<td>mm²</td>
</tr>
<tr>
<td>Feed per tooth</td>
<td>(f_z)</td>
<td>mm</td>
</tr>
<tr>
<td>Feed per revolution</td>
<td>(f(s))</td>
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<td>(N)</td>
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</tr>
<tr>
<td>Feed rate</td>
<td>(v_f(u))</td>
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</tr>
<tr>
<td>Feed rate (tangential)</td>
<td>(V_t)</td>
<td>mm/min</td>
</tr>
<tr>
<td>Cutting speed</td>
<td>(V_c)</td>
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<tr>
<td>Cutting speed for turning at (f = 1) mm/U, (a_p = 1) mm, (T = 1) min</td>
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<td>Material constant (exponent)</td>
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<tr>
<td>Feed power</td>
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</tr>
<tr>
<td>Machine input power</td>
<td>(P)</td>
<td>kW</td>
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<td>Formula</td>
<td>Unit</td>
</tr>
<tr>
<td>------------------------------------------------------------</td>
<td>---------</td>
<td>--------------</td>
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<td>Machine efficiency</td>
<td>$\eta$</td>
<td>$-$</td>
</tr>
<tr>
<td>Tool life (turning)</td>
<td>$T$</td>
<td>min</td>
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<tr>
<td>Tool life travel path (drilling, milling)</td>
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<td>M</td>
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<td>Metal removal rate (volume of disordered chips)</td>
<td>$Q_{sp}$</td>
<td>mm$^3$/min</td>
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<td>Chip volume ratio</td>
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<td>$-$</td>
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<td>Surface roughness (max. peak-to-valley height)</td>
<td>$R_t$</td>
<td>$\mu$m</td>
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<td>Mean surface roughness (arithmetic mean out of 5 measuring values)</td>
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<td>$\mu$m</td>
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<td>Peak radius at turning tool</td>
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<tr>
<td>Machining time</td>
<td>$t_h$</td>
<td>min</td>
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<tr>
<td>Workpiece length</td>
<td>$l$</td>
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<tr>
<td>Approach</td>
<td>$l_a$</td>
<td>mm</td>
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<tr>
<td>Overrun</td>
<td>$l_u$</td>
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<td>$L$</td>
<td>mm</td>
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<tr>
<td>Milling cutter diameter</td>
<td>$D$</td>
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<td>Grinding wheel diameter</td>
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<td>Drill- or workpiece diameter</td>
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<td>mm</td>
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<td>Rake angle</td>
<td>$\gamma$</td>
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<tr>
<td>Angle of inclination</td>
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<td>Dihedral angle (turning)</td>
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<td>Chamfer clearance angle (primary clearance)</td>
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<tr>
<td>Chamfer rake angle</td>
<td>$\gamma_f$</td>
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1 Introduction

1.1 The methods of metal cutting

are:

1.1.1 Methods of finishing

1.1.2 They are used when efficiency is called for, predominantly after forming to preshape the workpiece.

1.2 Characteristics of metal cutting

1.2.1 Crystalline alteration of the material

During chip removal, the crystallites are either unchanged or changed only on the surface in the immediate vicinity of the chip removal.

1.2.2 Changes in strength

In most cases, strain hardening in the marginal zones is small as to be negligible.

1.2.3 Stress relief

During metal cutting, under certain circumstances, stresses resulting from, for example, cold working inside the workpiece are relieved.

Stress is also relieved in castings and forgings, or in parts subjected to heat treatment, when cutting marginal zones whose hardness or carbon content differs from that of the core material. The latter may result in workpiece distortion.

1.2.4 Reduction of strength due to the cutting through of fibres

Whereas in forming, for example, the fibre structure is maintained, and the fibre configuration adapts itself to the outer workpiece contour (for instance, in thread rolling), in metal cutting, the fibre is cut through. As a result, strength is reduced in many cases.

1.2.5 Substantial material loss

In metal cutting, the blank diameter has to correspond to the maximal diameter of the part to be manufactured. An allowance is added to this diameter. To machine the bolt (Figure 1), when using rolled material, the blank should have a size of approximately 100 mm (diameter) and 185 mm (length).

When the weights of finished part and the blank are compared, it can be seen that 46% of the blank weight is removed in generating the workpiece.
1.3 Formation of the cutting edges

Metal cutting tools are categorised as:

1.3.1 Tools with defined cutting edge geometry

All of these tools have a shape that is clearly defined in terms of geometry. These tools include turning tools, milling cutters, saw blades, planing tools etc.

1.3.2 Tools with undefined cutting edge geometry

In these tools, the cutting edges are arranged randomly in an undefined manner. Tools of this kind include all grinding tools with bond (grinding wheels) or loose (lapping abrasive) grid.

1.4 Cutting conditions (depth of cut \( a_p \), feed \( f \) and cutting speed \( v_e \))

Select the cutting conditions for metal removal so that:

- the required machine input power is utilised in an optimal manner
- tool life is maintained reasonably well and
- cutting time is kept short.

A “reasonable” tool life mainly results from the cutting time per workpiece and the time necessary for the tool change. In the case of very expensive machines, it is necessary to calculate the most cost-efficient way to maintain tool life (see Chapter 2.8.7) to determine economical cutting conditions.

1.5 Cutting force

At any given cross section of the chip, the cutting force should be kept to a minimum through the right choice of cutting conditions. The smaller the cutting force, the lower the stresses inside the tool and the machine.

Attention should be paid to ensuring that the force diminishes as cutting speed increases in the working range of high-speed steels (compare Chapter 2.6.5.). As
a rule, the limits of permissible cutting speed for high-speed steels should not be exceeded under any circumstances.

1.6 Chips

If possible, the chips should be fractured into short pieces since in this form they are less dangerous for the operator of the machine and may be handled and processed more easily.

1.7 Chip shapes

The shape of the chips formed during metal removal (see Chapter 5.2) depends on the materials being cut and the cutting conditions.

The volume of chips that is to be transported is sorted by specific chip shapes; these are assigned identification numbers R (R for chip space number).

1.8 Cutting edge materials

The following materials are used as cutting edge materials:

- high-performance high-speed steels
- cemented carbides
- ceramics
- diamonds.

Materials that are particularly significant at present are coated cutting edge materials, in which the basic material is coated with thin layers of an especially hard and wear-resistant material, such as coronite (based on TiCN or TiN). Thus, for example, cubic boron nitride is the second hardest substance after diamond. It has high heat hardness (up to 2000 °C) and is brittle, but tougher than ceramics.
2 Fundamentals of machining explained for turning

The terms of machining, as well as tool wedge geometry are defined in the DIN standards 6580 and 6581.
This chapter provides a summary of the most essential data found in these DIN sheets that relate to the turning procedure. These data can be applied to other techniques.

2.1 Surfaces, cutting edges, and corners on wedges according to DIN 6581

![Diagram of wedge with labeled surfaces, edges, and corners]

**Figure 2.1**
Surfaces, cutting edges, and corners on wedges

2.1.1 Flank faces
are those areas on the wedge that are turned toward the cut surfaces. If a flank face is chamfered, then it is called a flank face chamfer.

2.1.2 Rake faces
are the surfaces over which the chip passes. If a rake face is chamfered, then it is called a rake face chamfer.
2.1.3 Cutting edges

2.1.3.1 Major cutting edges
are defined as those cutting edges whose wedge, when viewed in the working plane, points in the direction of the feed motion.

2.1.3.2 Minor cutting edges
are defined as cutting edges whose wedge in the working plane does not point in the direction of the feed motion.

2.1.4 Corners

2.1.4.1 Cutting edge corner
defines the corner at which major- and minor cutting edges meet the common rake face.

2.1.4.2 Corner radius
is the rounding of the corner (corner radius $r$ is measured in the tool reference plane).

2.2 Reference planes

In order to define the angles for the wedge, we assume an orthogonal reference system (see Figure 2.2).

![Figure 2.2](image)

Reference system to define the angles for the wedge

The reference system consists of 3 planes: tool reference plane, cutting edge plane and wedge measuring plane.

The working plane was introduced as an additional auxiliary plane.
2.3 Angles for the wedge

2.2.1 Tool reference plane 1
is defined as a plane through the observed cutting edge point, normal to the direction of primary motion and parallel to the cantilever plane.

2.2.2 Cutting edge plane 2
is a plane including the major cutting edge, normal to the tool reference plane.

2.2.3 Wedge measuring plane 3
describes a plane that is orthogonal to the cutting edge plane and normal to the tool reference plane.

2.2.4 Working plane 4
is a virtual plane, containing the direction of primary motion and the direction of feed motion. The motions involved in chip formation are performed in this plane.

2.3 Angles for the wedge

2.3.1 Angles measured in the tool reference plane (Figure 2.3)

2.3.1.1 Tool cutting edge angle $\alpha$
refers to the angle between the working plane and the cutting edge plane.

2.3.1.2 Tool included angle $\epsilon$
is defined as the angle situated between the primary- and secondary cutting edges.

2.3.2 Angle measured in the cutting edge plane Tool cutting edge inclination $\lambda$ (Figure 2.4)
describes the angle between the tool reference plane and the major cutting edge.
Tool cutting edge inclination is negative in cases where the cutting edge rises from the top. It determines the point on the cutting edge at which the tool first penetrates the material.

### 2.3.3 Angles measured in the wedge measuring plane (Figure 2.5)

#### 2.3.3.1 Tool orthogonal clearance $\alpha$

is defined as the angle between flank face and cutting edge plane.

![Figure 2.5](image)

**Figure 2.5**

Tool orthogonal clearance $\alpha$; wedge angle $\beta$; rake angle $\gamma$

![Figure 2.5a](image)

**Figure 2.5a**

Overview showing the most significant angles on the wedge
2.3.3.2 **Wedge angle** $\beta$

is defined as the angle between flank - and rake face.

2.3.3.3 **Rake angle** $\gamma$

is the angle between rake face and tool reference plane.

Following equation showing the relationship between these three angles is valid in any case:

$$\alpha + \beta + \gamma = 90^\circ$$

If the faces are chamfered (Figure 2.6), then the angles of chamfer are given the following notation:

- Chamfer clearance angle (primary clearance) $\alpha_i$
- Chamfer wedge angle $\beta_i$
- Chamfer rake angle $\gamma_i$

Even in this case, the following relationship is valid:

$$\alpha_i + \beta_i + \gamma_i = 90^\circ$$

![Figure 2.6](image_url)

**Figure 2.6**

wedge, chamfered chamfer angle $\gamma_i$; primary clearance $\alpha_i$; chamfer angle $\beta_i$

2.4 **Angle types and their influence on the cutting procedure**

2.4.1 **Tool orthogonal clearance** $\alpha$

The normal amount of the tool’s orthogonal clearance lies between

$$\alpha = 6 \ldots 10^\circ$$

2.4.1.1 **A large amount of tool orthogonal clearances**

is applied for soft and tough materials, which tend to bond with the cutting edges, and when using tough cemented carbides (e.g. P 40, P 50, M 40, K 40).
A large amount of tool orthogonal clearances:

a) causes heat build-up in the cutting edge tip
b) weakens the wedge (danger of cutting edge chipping)
c) gives under constant wear measure B
   (width of flank wear B – see Chapter 3.)
   great displacement of the cutting edge (SKV) (Figure 2.7).
   great SKV causes the dimensional deviation on the part (diameter increases) to become too large.

2.4.1.2 A smaller amount of tool orthogonal clearance

is used with higher-strength steels and abrasion-proof cemented carbides (e.g. P 10, P 20).

A small amount of tool orthogonal clearance:

a) means that the wedge is reinforced
b) improves the surface as long as the tool does not press on it. However, if the tool does press on the surface, the tool will heat up, and flank face wear will be substantial.
c) contributes to damping of vibrations, e.g. chatter vibrations

2.4.1.3 Tool orthogonal clearance at the shank

Since it is necessary to grind the cemented carbide tip with a grinding wheel different from those used for the soft shank of the turning tool, for soldered cutting edges, the tool orthogonal clearance at the shank (see Figure 2.8) should be 2° greater than the tool orthogonal clearance of the cemented carbide insert.

2.4.1.4 Position relative to the workpiece centre

Effective tool orthogonal clearance $\alpha_x$ depends on the tool position relative to the workpiece axis (see Figure 2.9).
2.4 Angle types and their influence on the cutting procedure

\( k = \) height displacement in mm
\( \psi = \) correction angle in °

\[
\sin \psi = \frac{x}{d/2} = \frac{2x}{d}
\]

If the tool tip is positioned above the workpiece axis (Figure 2.10), then the tool orthogonal clearance is diminished by the correction angle.

In cases where the tool tip is situated below the workpiece axis, tool orthogonal clearance is increased by the correction angle.

**Figure 2.9**
Effective tool orthogonal clearance \( \alpha_x \)

In cases where the tool tip is situated below the workpiece axis, tool orthogonal clearance is increased by the correction angle.

From this geometry, it can be concluded that:

- below centre: \( \alpha_x = \alpha + \psi \)
- in centre position: \( \alpha_x = \alpha \)
- above centre: \( \alpha_x = \alpha - \psi \)

As the above demonstrates, the effective tool orthogonal clearance corresponds to the measured tool orthogonal clearance only in the centre position. If the tool is
located below the centre, then, due to the alteration of the tool orthogonal clearance and the rake angle, the turning tool is pulled into the workpiece.

2.4.2 Rake angle $\gamma$

When turning medium strength steel with cemented carbide tools, the rake angles range from $0$ to $+6^\circ$, in exceptional cases up to $+18^\circ$. For tempering steels and high-strength steels, it is recommended that rake angles from $–6$ to $6^\circ$ be selected.

Whereas the chamfer angle for medium-strength steel is around $0^\circ$, in tempering steels, negative chamfer angles are usually used.

2.4.2.1 Large rake angles

are used with soft materials (soft steels, light alloys, copper), which are machined with tough cemented carbides. The greater the rake angle,

a) the better chip flow  
b) the lower the friction  
c) the smaller the chip compression ratio  
d) the better the workpieces’ surface quality  
e) the less the cutting forces.

Large rake angles have also disadvantages. They

a) weaken the wedge  
b) hinder heat removal  
c) increase the risk of edge chipping.

In short, they diminish tool life.

2.4.2.2 Small rake angles

Small rake angles, down to negative rake angles, are applied for roughing and machining of high-strength materials. For these operations, cemented carbides resistant to abrasion (e.g. P 10; M 10; K 10) are used as the cutting material. Small rake angles:

a) stabilise the wedge  
b) increase tool life  
c) enable turning at high cutting speeds  
d) save machining time due to c).

When a small rake angle is used, the cross section at the wedge increases, thereby compensating for the lower flexural strength of abrasion-proof cemented carbides. However, since the cutting forces increase as a function of diminishing rake angle, small rake angles result in

a) increasing cutting forces  
As an estimate, we can postulate that the major cutting force increases by 1 % at an angular reduction of $1^\circ$.  
b) an increase in machine input power required
2.4.2.3 Optimum rake angle

In a turning tool with a large positive rake angle and negative chamfer angle (Fig. 2.11), the advantages of positive and negative rake angles can be maximised.

This combination is the optimal solution, because

a) the positive rake angle provides adequate chip flow and keeps friction on the rake face low;

b) the wedge’s cross-section is enlarged by the negative chamfer angle;

c) increase of power is diminished (see Figure 2.12).

![Figure 2.11](image)

Positive rake angle with negative chamfer angle, \( b \), width of chamfer

**Figure 2.11**  Positive rake angle with negative chamfer angle, \( b \), width of chamfer

**Figure 2.12**  Negative chamfer angle means less increase in force than with a negative rake angle without chamfer

2.4.2.4 Position of the tool relative to the workpiece axis

With regard to the rake angle effective during the machining process, in principle, the same equations are valid as for tool orthogonal clearance. Here as well, the tool angle is altered by the correction angle \( \psi \) (see Figure 2.10) in the manner shown below.

\[
\begin{align*}
\text{below centre:} & \quad \gamma_a = \gamma - \psi \\
\text{in centre:} & \quad \gamma_a = \gamma \\
\text{above centre:} & \quad \gamma_a = \gamma + \psi
\end{align*}
\]

2.4.3 Wedge angle \( \beta \)

is to be kept large for hard and brittle materials and small for soft materials.

2.4.4 Tool cutting edge angles \( \alpha \)

The tool cutting edge angle defines the location of the major cutting edge relative to the workpiece (see Figure 2.13). At a given depth of cut \( a_p \), engagement length \( b \) of the major cutting edge depends on the tool cutting edge angle (Figure 2.13b).
The smaller the tool cutting edge angle, the greater the engagement length of the major cutting edge. However, the tool cutting edge angle also affects the forces during the cutting process.

The greater the tool cutting edge angle, the greater the feed force and the less the passive force. For this reason, as a rule, instable workpieces demand a large tool cutting edge angle.

### 2.4.4.1 Small tool cutting edge angles \( \alpha \) (approximately 10°)

result in great passive forces \( F_p \), which tend to deflect the workpiece. Consequently, small tool cutting edge angles are only applied for very stiff workpieces (e.g. calendar rolling).

### 2.4.4.2 Medium tool cutting edge angles (45 to 70°)

are used for stable workpieces. A workpiece is regarded as stable, if

\[
\leq \frac{6 \cdot d}{l}
\]

\( l = \) workpiece length in mm
\( d = \) workpiece diameter in mm

### 2.4.4.3 Large tool cutting edge angles \( \alpha \) (70 to 90°)

are used for long instable workpieces. These are workpieces for which

\[
\geq \frac{6 \cdot d}{l}
\]

If \( \alpha = 90^\circ \), the passive force component (Figure 2.14) is zero. As a result, during machining, there appears no force able to deflect the tool.

### 2.4.5 Tool included angle \( \varepsilon \) (Figure 2.14)

In most cases, tool included angle is 90°. Only when machining keen corners, \( \varepsilon \) is less than 90° used.
For copy-turning, use tool included angles from 50 to 58°.

When machining hard materials with rough turning tools, \( \varepsilon \) can be maximally 130°.

### 2.4.6 Tool cutting edge inclination \( \lambda \)

This parameter describes the slope of the major cutting edge and affects chip flow direction.

#### 2.4.6.1 Negative tool cutting edge inclination

It lessens chip flow, but decreases pressure at the cutting edge tip, since, with a negative tool cutting edge inclination, the cutting edge front rather than the tip penetrates the workpiece first. For this reason, negative tool cutting edge inclination is used with roughing tools and tools for interrupted cut. In these cases, it is common practice to use \( \lambda = -3 \) to \(-8^\circ\). Planing tools have, due to discontinuous impact with the start of each cut, tool cutting edge inclination up to approx. \(-10^\circ\).

#### 2.4.6.2 Positive tool cutting edge inclination

It improves chip flow. Consequently, it is used for materials that tend to adhere and others that tend toward strain hardening.

### 2.4.7 Working reference plane

Up to now, angles have been measured against the tool reference plane. Thus, their influence on chip formation and chip flow can be recorded sufficiently in most cases. As Figure 2.15 indicates, at a low circumferential speed-to-feed rate ratio, effective cutting direction angle \( \eta \) increases. Consequently, we must take into account its consequences on rake angle and tool orthogonal clearance. An increase in the effective cutting direction angle \( \eta \) causes the rake angle to increase and tool orthogonal clearance to decrease.
2.5 Cutting parameters

The parameters of the undeformed chip are variables derived from the cutting parameters (depth of cut \(a_p\) and feed \(f\)) (Figure 2.16).

For cylindrical turning,

2.5.1 Width of cut \(b\)

is the width of the chip to be removed, orthogonal to the direction of primary motion, measured in the cut surface.

\[
 b = \frac{a_p}{\sin k}
\]

- \(b\) in mm: width of cut
- \(a_p\) in mm: depth of cut (infeed)
- \(k\) in °: tool cutting edge angle