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Kupferinstitut

Recommended machining parameters for copper and copper alloys

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Foreword

"Recommended machining parameters for copper and copper alloys" continues a long tradition established by the German Copper Institute (DKI). The publication "Processing Copper and Copper Alloys" ("Das Bearbeiten von Kupfer und Kupferlegierungen") first appeared in 1938 and again in 1940. The handbook "Metal cutting techniques for copper and copper alloys" ("Die spanabhebende Bearbeitung von Kupfer und Kupferlegierungen") by J. Witthoff, which was published in 1956, represented a thorough revision and rewriting of the earlier work. The new handbook included for the first time a complete overview of all the standardized copper materials and metal cutting data known at the time. In addition to the easily machinable free-cutting brass, the handbook also gave an account of copper alloys that had been developed for specific applications and that were often far harder to machine. In 1987 large sections of the handbook were reorganized, revised and updated by Hans-Jörn Burmester and Manfred Kleinau and re-issued under the current title "Recommended machining parameters for copper and copper alloys" (German original: "Richtwerte für die spanende Bearbeitung von Kupfer und Kupferlegierungen"). The handbook included recommended machining parameters for all relevant machining techniques for a broad range of copper alloys.

In order to take account of recent technical developments in the field, the handbook has once again been revised and updated while retaining the previous title.

Like its predecessors, this edition of the handbook has been designed to address the concerns of practitioners, helping them to find the most effective and economical solutions to their metal cutting problems. It also aims to assist designers and development engineers when comparing the machinability of different materials, making it easier for them to estimate the fabrication costs of a particular part. Machinability index ratings have therefore been added to the tables included in the handbook. Machinability ratings are commonplace in the specialist literature and not only help to make comparisons between different copper materials but also comparisons with other metallic materials such as steel or aluminium.

The tables have also been brought up to date to reflect the most recent materials standards, and the tables of reference values for the various machining methods have been revised and expanded. As the machinability of a material is highly complex and depends on a large number of factors, the benchmark values provided here can only offer broad guidance. To establish the optimal machining parameters for a specific production process and thus optimize the productivity and cost-efficiency of that process, additional cutting and machining tests under the actual production conditions must be carried out.

1 State of the art

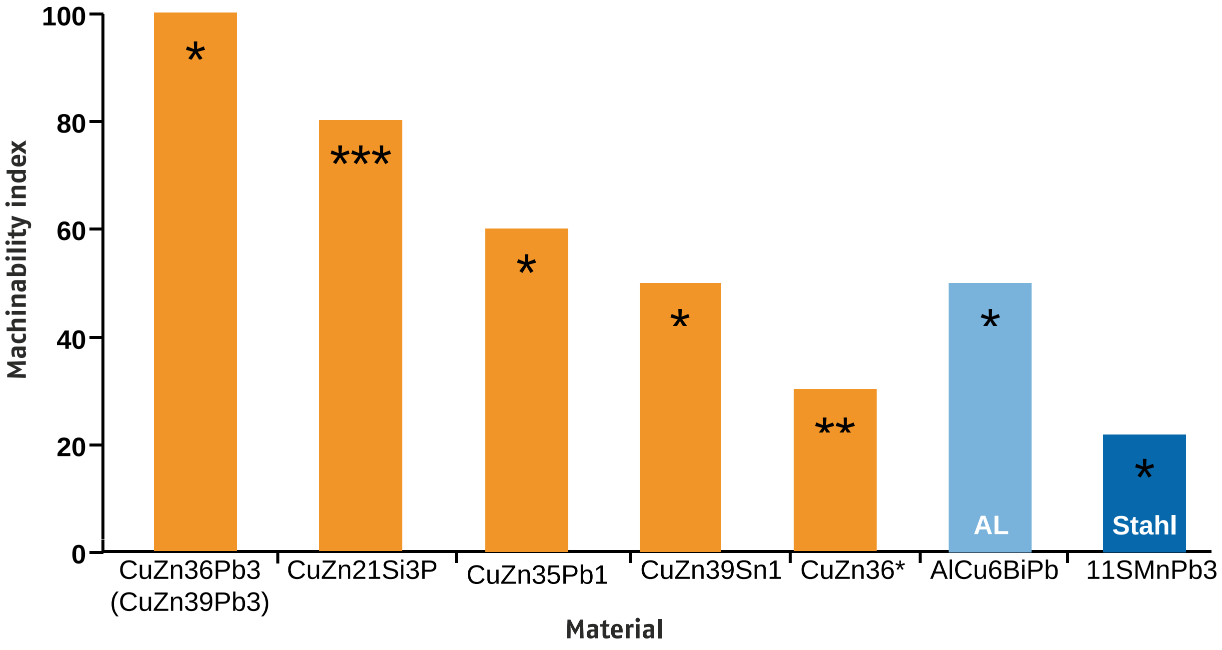
Compared to other metallic structural materials, most copper-based materials are relatively easy to machine. The free-cutting brass with the designation CuZn39Pb3 has established itself as an excellent material for manufacturing all kinds of form turned parts. The excellent machining properties of these copper-zinc alloys is so well-known that they are often used as benchmarks for describing the machining properties of copper and copper alloys

Machining copper alloys is considerably easier than machining steels or aluminium alloys of the same strength (see Figure 1). This is reflected in the significantly lower cutting forces as shown in Figure 2. Unless specific technical requirements dictate the use of another material, free-cutting brass CuZn39Pb3 is the material of choice in contract turning and machining shops and CNC turning shops.

Parts that are mass-manufactured are typically machined from copper materials. In order to meet a very wide range of technical and engineering requirements, a great number of copper-based materials have been developed over the years. Examples of more recent developments include the low-alloyed copper alloys, copper-nickel alloys and lead-free copper alloys. The spectrum of materials available ranges from the high-strength copper-aluminium alloys to the very soft pure coppers with their high elongation after fracture.

The differences in the machinability of one material compared to that of another can be traced to the differences in their mechanical and physical properties. Many machine operators have only a limited knowledge of the machinability of the less commonly used copper materials. As a result, the machining data assumed for one and the same material may differ considerably from one machining shop to another. There is therefore a very definite need for up-to-date reference values and recommended processing parameters for the machining of copper and copper alloys – particularly in view of the ongoing developments in the metal cutting sector. Furthermore, optimizing machining operations by selecting and adapting the relevant machining data is of huge commercial importance in high-volume serial production.

Material development is focused on the continuous improvement of a material's properties. In order to lower machining costs, fabricators frequently demand materials with improved machinability properties but with mechanical and physical properties that are essentially unchanged. Examples of this trend are the CuTeP and CuSP alloys. Although pure copper has very high conductivity values, the fact that it produces long tubular or tangled chips can make it difficult to machine. For this reason alloys have been developed in which tellurium, sulphur or lead have been added to the pure copper as chip-breaking alloying elements. The conductivity of these alloys is only

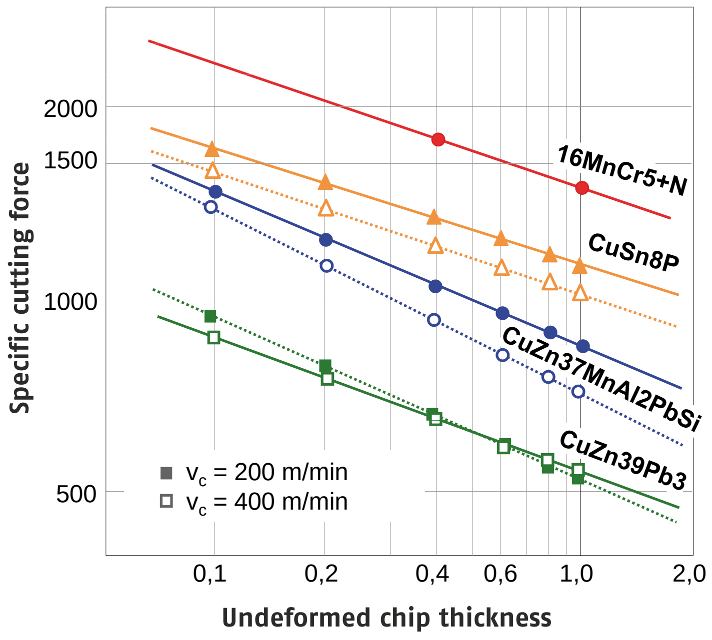


* CDA machinability ratings using the ASTM E618 test method with CuZn36Pb3 as the reference material (in Europe the reference material is the copper-zinc alloy CuZn39Pb3)

** CuZn36: Machinability rating based on the DKI material data sheet

*** CuZn21Si3P: Machinability rating as specified by manufacturer

Fig. 1: *Comparison of the machinability of copper alloys with a free-cutting steel and an aluminium alloy [1, 2, 3]*



Material	v_c m/min	$k_{c1.1}$ N/mm²	$1-m_c$
CuZn39Pb3 Free-cutting brass	200	539	0,7886
	400	521	0,7458
CuSn8P Copper-tin alloy	200	1137	0,8211
	400	1020	0,8059
CuZn37MnAl2PbSi Special brass	200	845	0,7561
	400	715	0,7036
16MnCr5+N Case-hardened steel	200	1302	0,7092

🟩 CuZn39Pb3 ▲ CuSn8P ● CuZn37MnAl2PbSi	N10 - N20 $\alpha_o = 7°; \gamma_o = 0°; \lambda_\sigma = 0°$ $\kappa_r = 93°; \varepsilon_r = 55°;$ $r_\varepsilon = 0,4$ mm; $a_p = 1$ mm
● 16MnCr5+N	P10 $\alpha_o = 5°; \gamma_o = 6\ °; \lambda_s = 0\ °$ $\kappa_r = 70°; \varepsilon_r = 90°;$ $r_\varepsilon = 0,8$ mm; $a_p = 3$ mm

Fig. 2: *Comparison of the specific cutting force of three copper alloys with a case-hardened steel based on data from DKI and from reference [4]*

slightly below that of pure copper, but the presence of the alloying elements means that they can be processed on automatic screw machines or other high-speed machine tools.

The continuous improvements being made to both workpiece and cutting tool materials makes it difficult for today's manufacturers to provide recommended cutting parameters or benchmarks that remain valid for a longer period of time. If supplemented and/or verified by cutting tests conducted under realistic machining conditions, the guideline parameters and recommendations provided in this handbook can help machine operators to find the optimal machining parameters for a specific machining task. If only low-volume production is required, the reference values provided in the handbook should be sufficient to yield a satisfactory machining result.

2 Fundamental principles

In this section explainations are given on the basic terminology of metal cutting relating to cutting tool geometry, tool wear and chip formation, using a standard turning tool (single-point cutting tool) for illustrative purposes. The terminology applies equally to any other machining procedure that uses a tool with a defined cutting edge. Being acquainted with the basic terminology is fundamental to understanding the machining properties of copper and copper alloys.

2.1 Tool geometry and how it influences the cutting process

The fundamental terminology of metal cutting technology has been standardized in DIN 6580, DIN 6581, DIN 6583 and DIN 6584 standards. The surfaces and cutting edges of a single-point cutting tool are shown in Fig. 3.

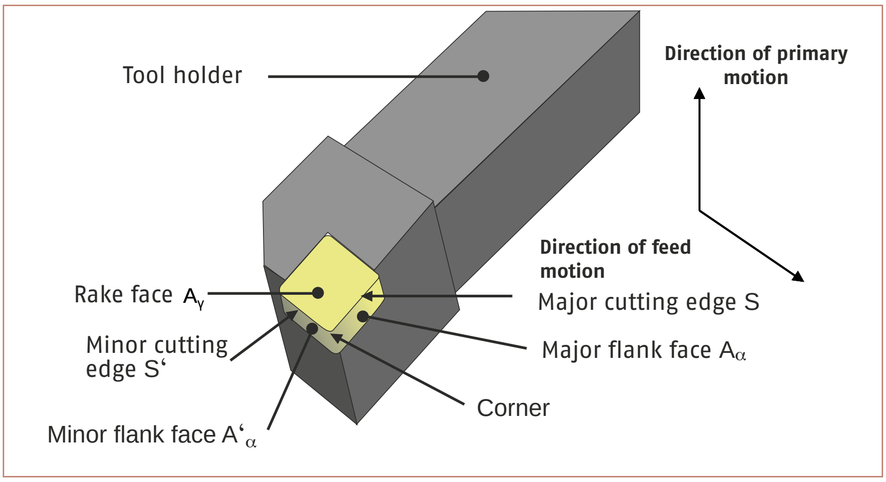


Fig. 3: *Face, flanks, cutting edges and corner of a turning tool (DIN 6581)*

2.1.1 Tool geometry

As Fig. 3 shows, the cutting part of a turning tool comprises the rake face and the major and minor flank faces. The relative orientation of these surfaces to one another determines the tool angles.

To explain the terms and angles used to describe a cutting tool, it is useful to distinguish between the so-called ‘tool-in-hand’ system and the ‘tool-in-use’ system (see Fig. 4). The two systems are based on different sets of orthogonal reference planes.

The tool-in-use system is defined in relation to the relative speeds of the cutting tool and the workpiece during the machining operation. The working reference plane P_{re} passes through a selected point on the cutting edge and is perpendicular to the resultant cutting direction. The orientation of the resultant cutting direction is given by the resultant of the cutting and feed speed vectors.

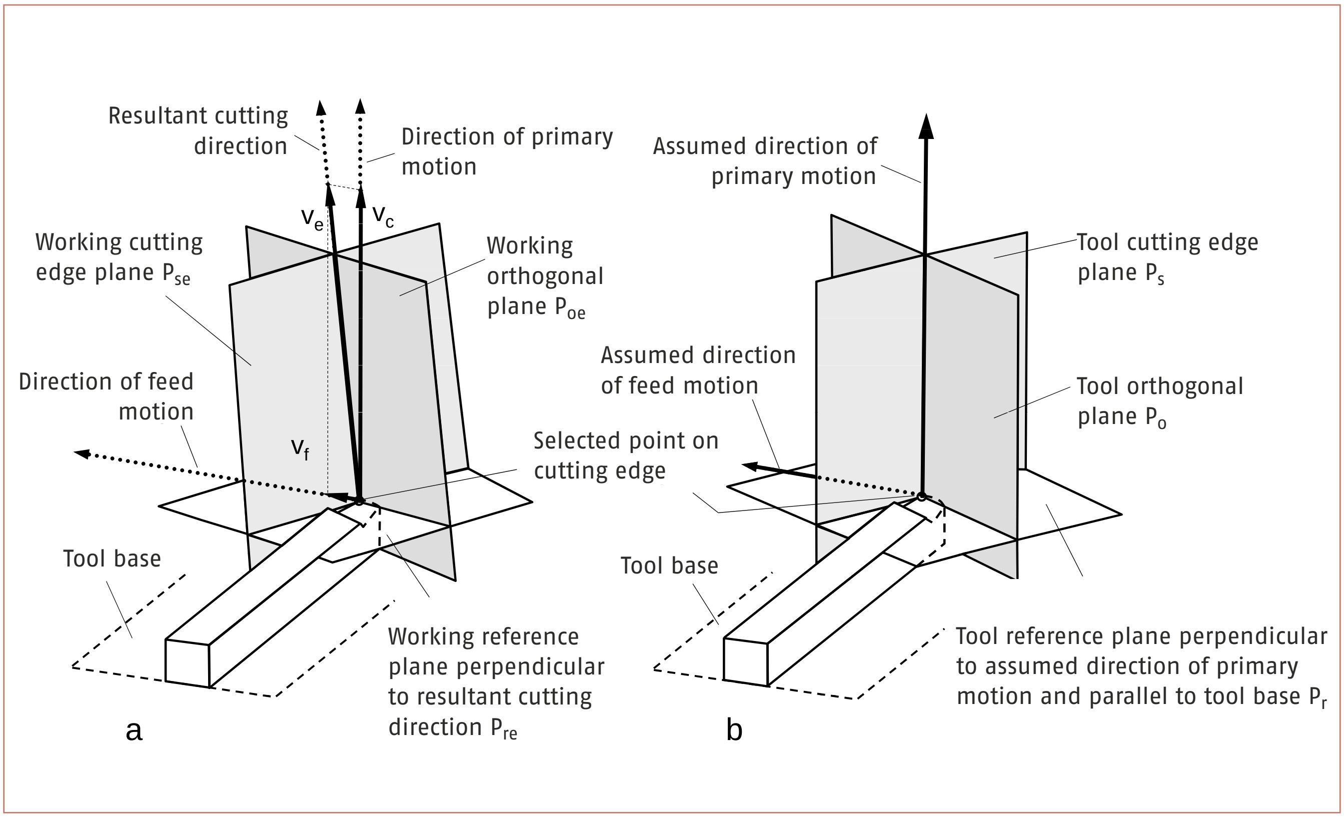


Fig. 4: *(a) Tool-in-use reference system (b) Tool-in-hand reference system (DIN 6581)*

In the tool-in-hand system, the tool reference plane P_r is parallel to the tool base. The tool cutting edge plane P_s is tangential to the cutting edge and perpendicular to the tool reference plane P_r. The geometry of the cutting tool is measured in the tool orthogonal plane P_o. This plane passes through the selected point on the cutting edge perpendicular to both the tool reference plane P_r and tool cutting edge plane P_s.

In the tool-in-hand system, the angles of the wedge-shaped cutting tool are defined as follows (see Fig. 5):

- The tool orthogonal clearance αo is the angle between the flank A_α and the tool cutting edge plane P_s measured in the tool orthogonal plane P_o.

- The tool orthogonal wedge angle β_o is the angle between the flank A_α and the face A_γ measured in the tool orthogonal plane P_o.

- The tool orthogonal rake γ_o is the angle between the face A_γ and the tool reference plane P_r, measured in the tool orthogonal plane P_o.

The sum of these three angles is always 90°:

$$\alpha_o + \beta_o + \gamma_o = 90° \quad (1)$$

- The tool cutting edge angle κ_r is the angle between the assumed direction of feed motion and the tool cutting edge plane P_s measured in the tool reference plane P_r.

- The tool included angle ε_r is the angle between the tool cutting edge plane P_s and the tool minor cutting edge plane P_s' measured in the tool reference plane P_r.

- The tool cutting edge inclination λ_r is the angle between the major cutting edge S and the tool reference plane P_r measured in the tool cutting edge plane P_s.

We have chosen here to describe the terminology and tool angles using a single-point cutting tool, specifically a turning tool, as it permits the clearest illustration of the different quantities. In principle, however, the definitions provided here can be applied to all cutting tools with a geometrically defined cutting edge.

2.1.2 Effect of tool geometry on the cutting process

The choice of cutting angles has a major effect on the results of a machining operation and on the tool life. The greater the emphasis on achieving cost-effective material processing, the greater the importance of determining an optimal tool geometry. The stability and therefore the life of the cutting tool can be raised by selecting appropriate cutting angles and by using chamfered and rounded cutting edges. Optimizing the geometry of a cutting tool always means taking into account the specific requirements of the machining operation to be performed and the machining conditions to be used.

It is also important to remember that the effect of modifying tool angles is two-fold. Changing the tool angles to strengthen the tool impairs chip formation and increases the cutting forces and the extent of tool wear. Conversely, changing the tool angles to

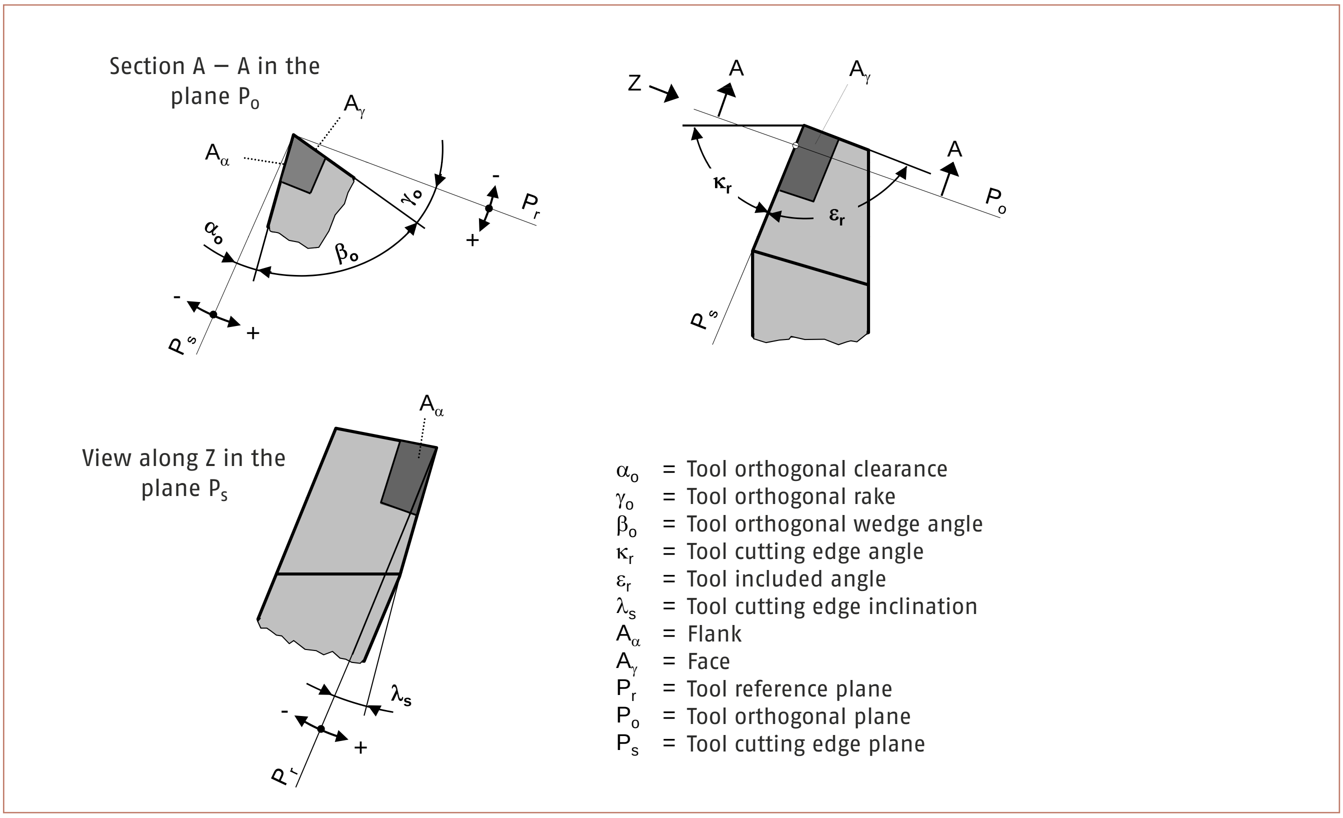


Fig. 5: *The most important tool angles (DIN 6581)*

improve chip formation results in a decrease in tool strength and hence tool life. Any choice of tool angles therefore represents a compromise that can only partially meet the different machining requirements. It is important that this is understood when using the tables of recommended tool geometry parameters included in this handbook. The recommended tool geometry will also need to be modified based on practical operating experience whenever other factors have to be taken into account. In such cases, it is important to know how a specific change in a cutting angle will affect the machining parameters. In view of the considerable progress that has been made in the field of cutting tool materials, modifying tool geometry in order to reduce tool wear is not so important today as it once was. The predominant reason for altering tool angles is to improve chip formation and chip removal.

When machining copper materials with a high-speed steel cutting tool, the clearance is typically between 6° and 8°; if a cemented carbide cutting tool is used, the clearance lies in the range 8° to 10°. Large clearances tend to reduce flank wear and make it easier for the wedge-shaped cutting tool to penetrate the workpiece material. For a given constant value of the flank wear land VB, small increases in the clearance angle will lengthen the service life of the cutting edge due to the increased wear volume. Removing a larger wear volume requires a longer period of time so that the tool life increases accordingly. However, a larger clearance angle also means a weaker tool cutting tip and this therefore places a limit on the extent to which the clearance can be increased. As the clearance angle increases, heat can build up in the tool tip thus increasing the risk of material break-out at the tip. The bending moment resistance of the tip also decreases strongly with increasing clearance angle.

Of all the tool angles, the tool rake γ_0 has the greatest significance. The magnitude of the deformation energy and cutting energy dissipated during chip formation depends on the tool rake.

When machining copper materials, the tool rake typically lies within the broad range 0° to 25°. When machining with a cemented carbide tool, the largest rake angles are chosen for the softest materials with the lowest cutting forces (pure copper, CuZn10) as these are the only materials that do not result in overloading of the cutting edge.

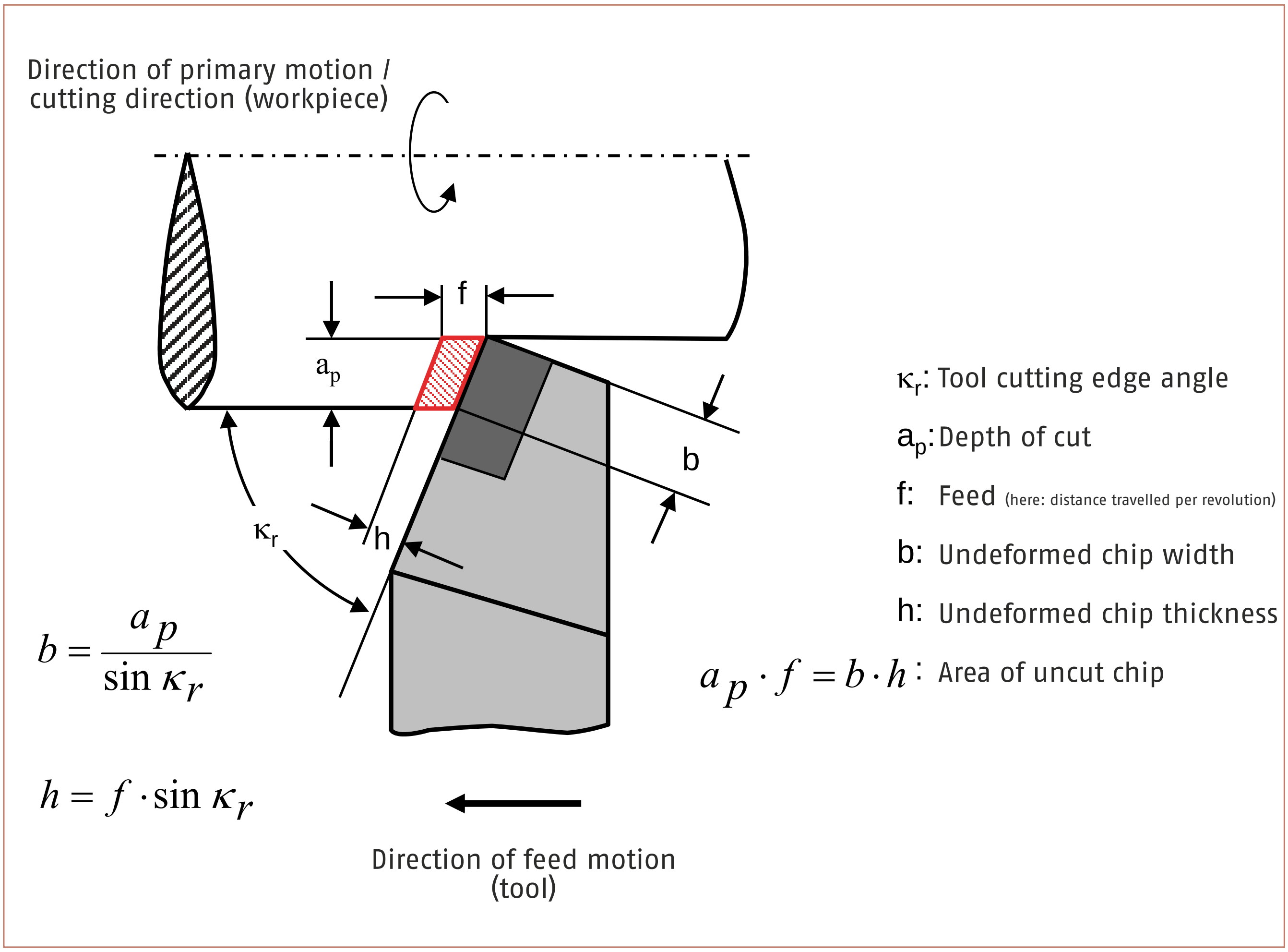


Fig. 6: *Geometry of tool engagement during cylindrical turning (oblique cutting con-figuration) (DIN 6580)*

The larger the tool rake, the lower the deformation and cutting energy and thus the lower the pressure exerted on the cutting edge. The cutting forces are reduced accordingly and the temperature of the cutting edge decreases. The chip compression ratio is reduced and the quality of the machined surface improves accordingly. Large rake angles facilitate chip flow when machining ductile copper materials, but they also facilitate the formation of ribbon chips and tangled chips.

The rake angle must be reduced if the specific cutting force is increased, or if the undeformed (i.e. uncut) chip thickness is increased, or if the transverse rupture strength of the tool material is lowered. This improves the stability of the cutting tool and reduces the risk of tool breakage. When machining copper-based materials, the smallest tool rakes are used for high-strength copper alloys. Strong cutting tools enable the workpiece to undergo high-speed turning. The disadvantage is that as the rake angle is reduced, the cutting forces increase therefore raising the required machine power.

For a fixed depth of cut a_p and a fixed tool feed f, the undeformed chip width b and the undeformed chip thickness h depend on the tool cutting edge angle κ_r (Fig. 6). If the tool cutting edge angle is too small (or equally if the tool's nose radius is too large), the passive forces will be greater, which facilitates deformation and chattering if the work material being machined is weak. A large tool cutting edge angle κ_r in the range 70° to 95° is typically chosen when machining copper and copper alloys. In the case of work materials that are liable to smear, such as soft copper or gunmetal, a tool cutting edge angle of $\kappa_r = 90°$ is preferred. On the other hand, if the depth of cut is held constant, a reduction in the tool cutting edge angle results in an increase in the undeformed chip width b as the stress is distributed over a longer portion of the cutting edge. The tool life rises accordingly and this permits a slight increase in the cutting speeds. The machining parameters listed in the tables apply to large tool cutting edge angles from about 70° to 90°.

The tool cutting edge inclination λ_s (Fig. 5, Fig. 7) offers a simple means of stabilizing the cutting edge if the cut is interrupted, and of influencing chip flow. If the angle of inclination of the tool cutting edge is negative, the first

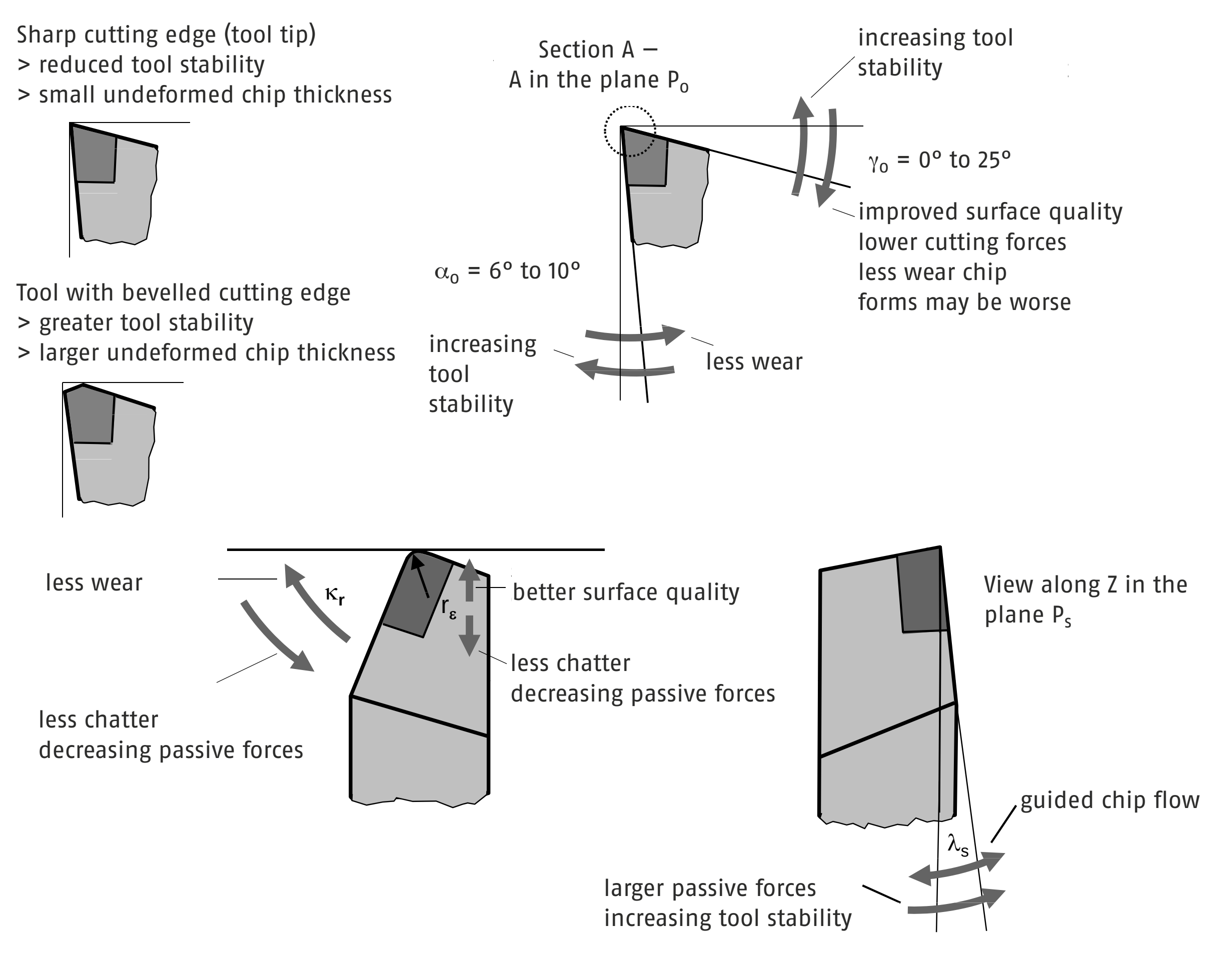


Fig. 7: *Effect of tool geometry on the cutting process*

point of contact between the workpiece and the tool occurs above the tool tip thus protecting the tip, which is the most vulnerable part of the tool. As high impact loading of the cutting edge is unlikely when machining copper materials, λ_s is often set to 0°, particularly when only light machining of the workpiece is required. A negative tool cutting edge inclination is preferred for rough machining work and for interrupted cuts in high-strength copper alloys. A positive angle of inclination improves chip flow across the tool face and is therefore preferred when machining materials such as pure copper that show a propensity to adhere to the working surfaces or to undergo strain hardening.

The tool included angle ε_r (Fig. 5 / Fig. 7) is the angle between the major and minor cutting edges. The size of ε_r has a significant effect on the capacity of the cutting edge corner to withstand stresses. The smaller the tool included angle, the lower the mechanical loading that can be sustained by the cutting edge. In addition, heat generated during machining is less well conducted away from the cutting edge corner so that the tool is exposed to greater thermal stress. The tool included angle should be as large as possible. For most machining operations on copper materials ε_r is chosen to be 90°. However, when machining a right-angled corner in the workpiece, a tool included angle of less than 90° is required. In many cases a compromise has to be found between the tool cutting edge angle and the tool included angle.

The size of the nose radius (also known as the tool corner radius) r_ε (Fig. 5 / Fig. 7) should be selected for the particular machining operation to be performed. If the nose radius is too small, the corner of the cutting edge will suffer premature damage. Small corner radii are consequently reserved for fine machining work. If the selected nose radius is too large, there is a tendency for the tool's minor cutting edge to scrape against surface of the workpiece creating notch wear on the flank of the minor cutting edge (see Fig. 8) that has a detrimental affect on the quality of the machined workpiece surface. The optimal value of the nose radius r_ε depends on the undeformed chip thickness h and thus on the feed displacement f. The nose radius r_ε should generally be between 1.2 and 2 times the feed f; for copper r_ε should be chosen to be less than $1.5 \cdot f$. For soft copper materials, such as Cu-DHP, the machined surface quality is strongly dependent on the nose radius r_ε. When machining very ductile materials, a small nose radius can improve cutting in the region of the

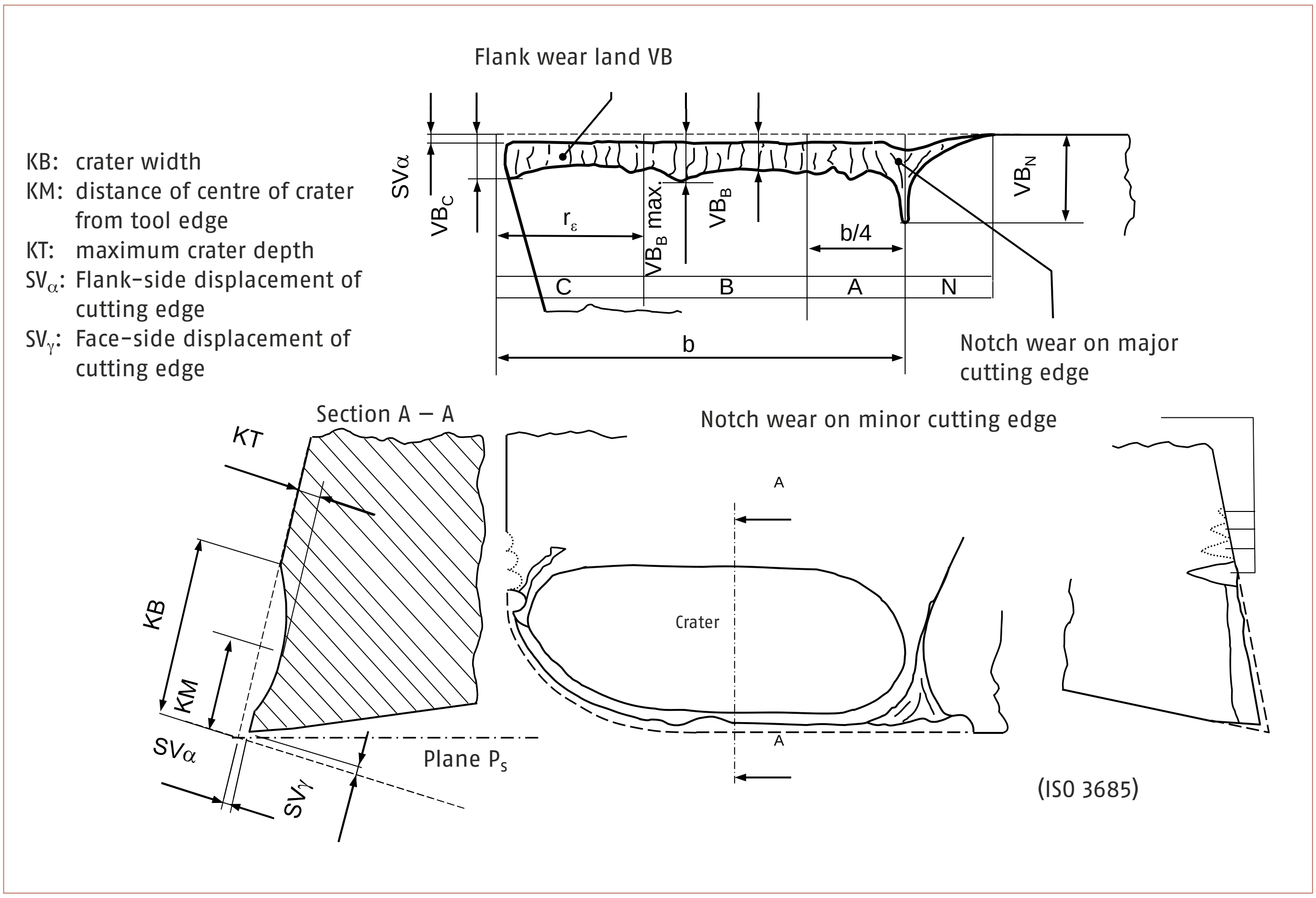


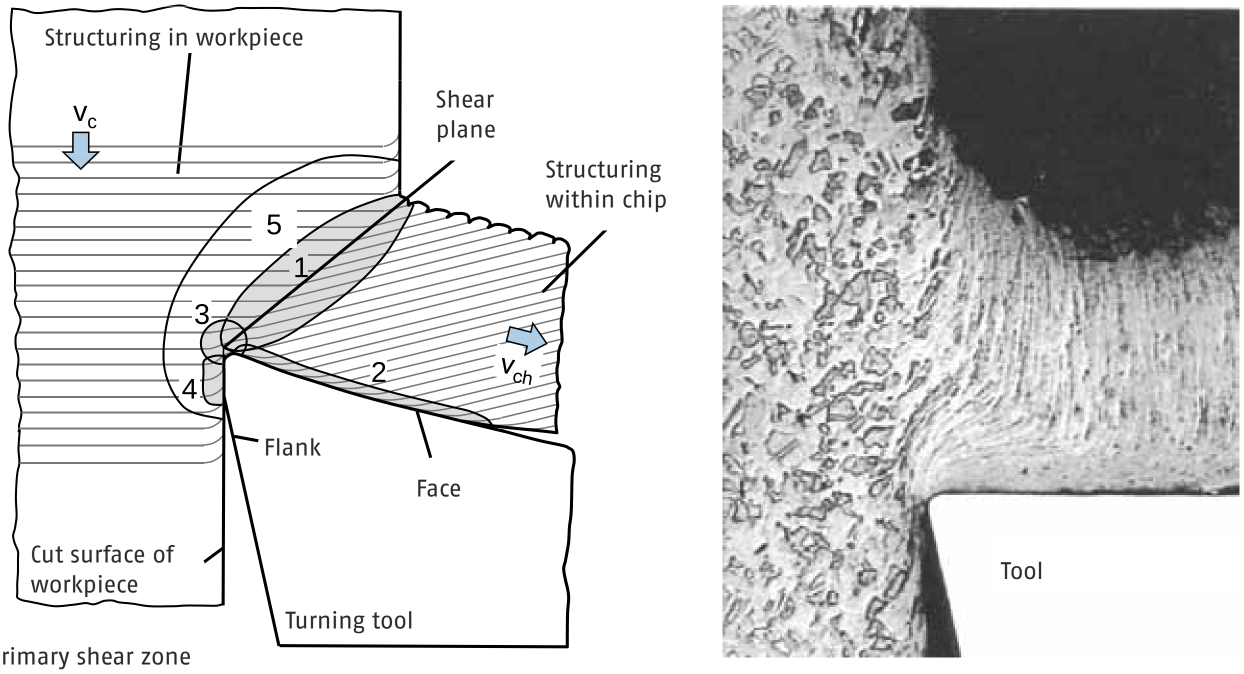
Fig. 8: Types of wear and wear parameters on turning tools (ISO 3685)

minor cutting edge. This is because the larger minimum thickness of cut means that the material can be cut more easily and does not therefore tend to smear so much. This reduces the roughness and improves the quality of the cut surface. As a rule, if the feed is held constant, a larger nose radius will lead to the formation of shallower and less pronounced feed marks on the workpiece. The kinematic roughness is reduced and the quality of the workpiece surface, expressed by the two surface parameters R_a and R_z, is improved. This effect is used in tools with so-called wiper geometry. A wiper nose radius insert features additional larger radii that are located along the minor cutting edge behind the tool nose. Compared to inserts with a conventional nose radius, wiper inserts can produce an improved surface finish with the same feed, or the same surface quality at higher feeds [5].

2.2 Tool wear

During the machining process, wear marks will appear on the tool. The extent of tool wear will depend on the stresses to which the tool is subjected. Wear marks appear on the major and minor flanks of the cutting tool where it is contact with the workpiece, and on the tool face where it is in contact with the chip being removed. As a rule, the greater the amount of wear, the greater the mechanical and thermal stress experienced by the tool. Tempering in the tool material, which occurs in tool steel at about 300 °C and in high-speed steel at around 600 °C, causes a loss in tool hardness and can result in the sudden tool failure as a result of so-called 'bright braking'. In the case of tool inserts made of cemented carbide, which at 1000 °C still exhibits the same hardness that high-speed steel does at room temperature, the wear is predominantly abrasive in nature. In practical applications, it is primarily the wear on the tool's flank and face that are used as the criteria for assessing tool life. The wear that develops on the tool's flank is known as flank wear land (VB). A tool is deemed to be worn and therefore at the end of its useful service life if the flank wear land VB has reached a specified width (Fig. 8). The width of the permissible flank wear land depends on the specific workpiece requirements.

A large flank wear land VB results in a large face-side displacement of the cutting edge SV_γ causing dimensional inaccuracies. Furthermore, the greater area of frictional contact between the tool and the workpiece results in a deterioration in the quality of the workpiece surface and an increase in cutting temperature. When machining on an automatic lathe, the maximum permissible width of the flank wear land is 0.2 mm if cemented carbide tools are used, for rough machining the width of the flank wear land should not ex-



1. Primary shear zone
2. Secondary shear zone on the tool rake face
3. Secondary shear zone at the stagnation and separation zone
4. Secondary shear zone on the flank face
5. Elastic-plastic deformation zone

Material: Cu-ETP
Cutting speed: v_c = 80 m/min
Feed per revolution: f = 0,02 mm

Fig. 9: *Material deformation zones during chip formation (Source: [6])*

ceed a value between 0.4 and 0.6 mm, depending on the diameter of the part being made, the specified tolerances and the required surface quality (Fig. 8). Wear land widths of 1 mm or more can arise during heavy roughing work involving feeds rates of 1.0 to 1.8 mm/rev and cutting depths of 10–20 mm. The wear on the tool's rake face (Fig. 8) is generally less significant than the wear on the flank and is expressed in terms of the crater ratio K = KT/KM. K is a measure of the weakening of the cutting tool as a result of cratering on the rake face and should never significantly exceed a value K = 0.1.

2.3 Chip formation

Chip formation and effective chip removal are important in those cutting techniques in which the cutting zone is spatially limited, such as drilling, reaming, milling and all turning operations on automatic lathes.

The details of chip formation process can be most readily seen using the orthogonal cutting model. In the orthogonal model, chip formation is considered to occur as a two-dimensional process in a plane perpendicular to the cutting edge, as depicted photographically and schematically in Fig. 9.

During the machining process, the cutting tool penetrates the work material, which deforms first elastically and then plastically. As soon as the shear stress induced by the tool reaches or exceeds the shear strength of the work material in the shear zone, the material begins to flow. Depending on the tool geometry used, the deformed work material forms a chip that flows across the face of the cutting tool.

Friction between the contact planes of the tool and the underside of the chip or the new workpiece surface creates shear stresses in the secondary shear zones (see Fig. 9). These shear stresses cause plastic deformation in the secondary shear zones thereby compressing the chip. The result of this deformation is that the thickness of the chip after separation h_{ch} is greater than the original thickness of cut h (= thickness of the undeformed chip), and the width of the chip b_{ch} is greater than the original width of cut b (= width of the undeformed chip):

Chip thickness compression:
$$\frac{h_{ch}}{h} > 1 \qquad (2)$$

Chip width compression:
$$\frac{b_{ch}}{b} > 1 \qquad (3)$$

Four main types of chip can be formed: continuous chips, continuous segmented chips, semi-continuous segmented

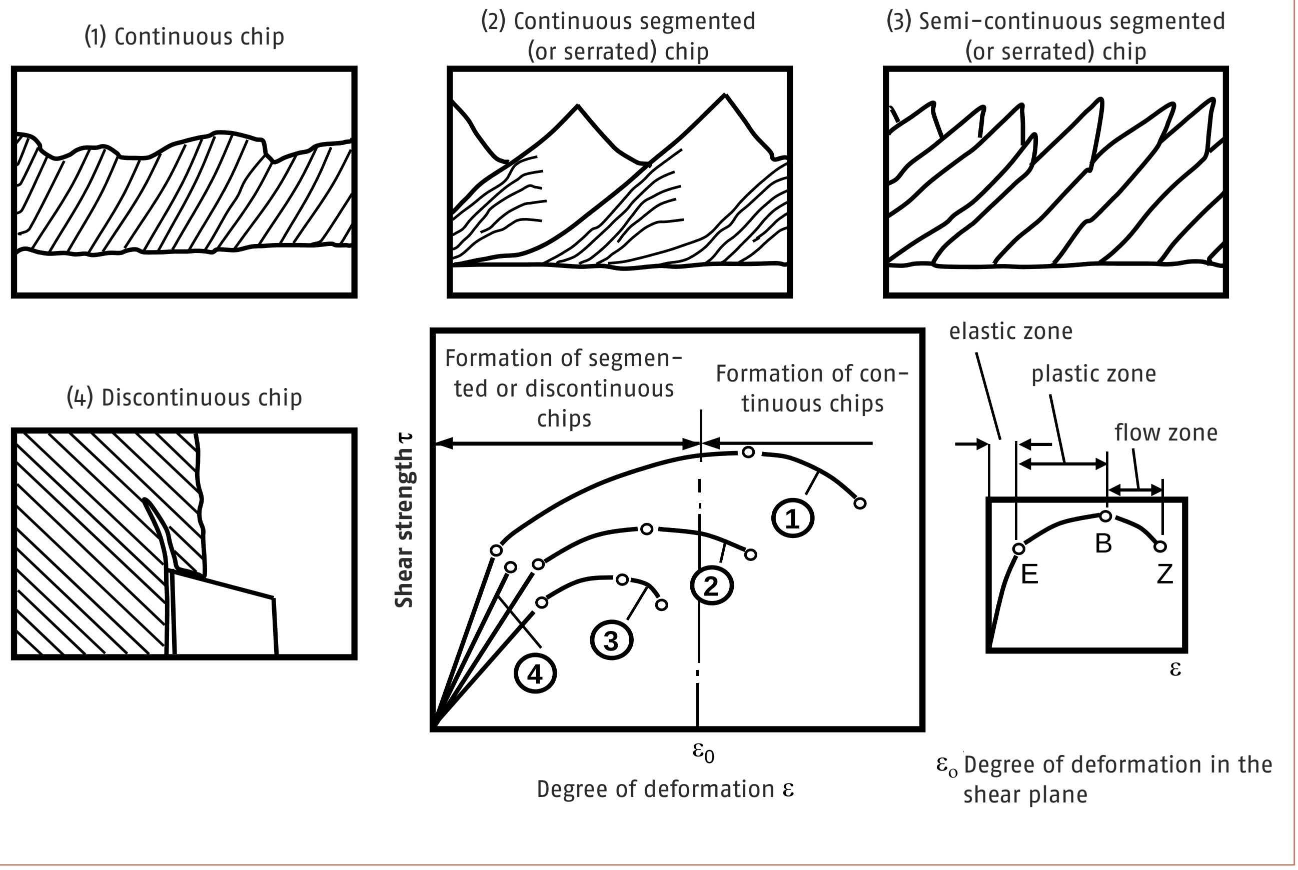


Fig. 10: *Influence of mechanical properties of workpiece material on type of chip formed (Source: [7])*

chips and discontinuous chips (see Fig. 10).

Continuous chips form when the material being cut flows away continuously from the machining point. The regions of deformed material undergo lamellar sliding but without exceeding the shear strength of the material.

If the work material being machined is of sufficient ductility, the chip formed will usually be continuous in form, provided that the cutting process is not impaired by the influence of external vibrations.

If the workpiece material is of lower ductility, if it has an inhomogeneous microstructure or if it is subjected to external vibrations, machining will result in the formation of continuous segmented (or serrated) chips. Compared with continuous chips, the upper surface of the chip in this case exhibits a pronounced sawtooth-like structure. Continuous segmented (or serrated) chips can form at high feed rates and at high cutting speeds.

Semi-continuous segmented (or serrated) chips, on the other hand, consist of chip sections that were completely separated in the shear zone. This type of chip forms when the degree of deformation in the shear zone exceeds the material's ductility. This applies not only to brittle materials, but also to materials in which the deformation induces brittleness in the microstructure. Semi-continuous segmented chips can also form at extremely low cutting speeds. Discontinuous chips typically form when brittle materials with an inhomogeneous microstructure are machined. These chips are not cut but rather torn from the surface of the work material, with the result that the workpiece surface is frequently damaged by these small chip fragments.

Machining highly ductile materials, such as Cu-ETP or Cu-DHP, at low cutting speeds can lead to the formation of a so-called built-up edge (BUE) on the tool's cutting edge and rake face. A built-up edge is made up of strain-hardened layers of the workpiece material that adhere around the cutting edge, giving the cutting edge an irregular shape and preventing the chip from coming into direct contact with the tool. Depending on the specific cutting conditions employed, the built-up edge may periodically break off and become deposited between the tool flank and the surface of the workpiece, or may become dislodged with the chip. As a result the quality of the workpiece surface deteriorates, tool wear increases, the dimensional accuracy of the machined workpiece worsens and the relative percentage of dynamic cutting forces rises.

The occurrence of built-up edges is temperature dependent. When copper and materials with a high copper content are machined, BUE formation always occurs in a specific range of the cutting speed v_c and the thickness of cut h. BUE formation also depends on the tool's angle of rake. To avoid the formation of a built-up edge, the machine operator can select a greater thickness of cut h, can raise the cutting speed v_c and/or can increase the rake angle γ. If that is not possible, v_c should be reduced to below the lower limit for BUE formation (e.g. in reaming, tapping). In the latter case, it is important to reduce friction at the cutting interface by achieving the best possible cooling lubrication of the tool.

3 Machinability

There is no unique or unambiguous definition of the term 'machinability'. It can be understood as summarizing those properties of a material that determine the ease or difficulty with which that material can be machined by various machining operations or techniques. The machinability of a material can vary very strongly depending on the geometry and material of the cutting tool, the machine tool and machining technique used and the machining conditions. The main goal of any machining operation is the fabrication of a workpiece of the desired geometry. In view of the complex relationships between the numerous factors involved, it is not possible to assess machining operations in terms of one single standardized machining criterion.

We will assess the machinability of copper and copper alloys in terms of the following four machining criteria: tool wear; chip formation; cutting forces and surface quality. Although these four quantities are mutually interdependent, the additional influence of factors such as the condition of the workpiece material, the cutting operation, the specifics of the machine tool and cutting tool used and the role of lubricants and cooling fluids, means that it is not possible to create a single unambiguous machinability criterion.

Tool wear is understood to mean the progressive loss of material from the surface of the cutting tool. The processes that cause tool wear during machining are abrasion, adhesion, scale from high-temperature oxidation, diffusion, thermal and mechanical stresses and surface fatigue.

Chip formation and chip shape play an extremely significant role in determining efficient chip removal, process safety and high productivity. This is particularly true for those machining operations in which the cutting zone is of limited size. This is the case for machining techniques with restricted chip flow, e.g. drilling, tapping, plunge cutting, broaching, grooving and all cutting and shaping operations on CNC machines. Long ribbon and tubular chips are harder to remove from the cutting zone than short spiral chips, chip curls or discontinuous chips. These longer chips can form tangled balls within the machine, resulting in the interruption of the machining process and damage to the workpiece and tool. They are also a safety hazard to the machine operator. In most cases, ribbon chips and tangled chips have to be removed manually from the workpiece or cutting tool, which introduces machine downtimes thus lowering productivity. As ribbon and continuous chips have a tendency to form snarled and tangled balls, their formation should, wherever possible, be avoided. But fine needle-like chips can also cause problems as they can block cutting fluid filters or get under the machine housing where they can cause increased wear.

The forces generated in metal cutting operations determine the power requirements and the structural rigidity of the machine tool. They have a considerable influence on tool wear and therefore on tool life. Generally speaking, the harder a material is to machine, the greater the forces that have to be applied. Cutting forces tend to decrease in magnitude with increasing cutting speed, because at higher cutting speeds, the cutting temperature is greater, which in turn results in a reduction in material strength (so-called thermal softening). The cutting force components increase proportionally with increasing depth of cut and also increase with feed though the rate of increase is less pronounced at higher feeds.

High dimensional accuracy and good surface quality are frequently required when machining copper and copper alloys. The resulting quality of the machined workpiece surface (roughness) is very often the most important machining criterion.

The relative weighting of the four main machinability criteria mentioned above will depend on the goal of the particular machining operation being used. For example, in rough machining work, the machinability criterion of greatest relevance is tool wear, followed by cutting forces, chip shape and chip formation. The emphasis in finishing work, in contrast, is primarily on the quality of the final surface, with chip shape and chip formation playing a secondary role. However, when machining on an automatic lathe, chip shape and chip formation may be the sole criterion used to assess the machinability of a workpiece material.

3.1 Tool life

The tool life T is defined as the time in minutes during which a cutting tool performs a machining operation under specified cutting conditions from the start of the cut to the point at which the tool has become unusable by reaching a predetermined tool-life criterion.

The tool life depends on numerous factors, including:

- the material to be machined,
- the tool material,
- the cutting speed, the feed and the depth of cut,
- the cutting tool geometry,
- the quality of the cutting edge ('tool finish'),
- the vibrations and motional accuracy of the workpiece, tool and machining equipment,
- the tool-life criterion, i.e. the threshold value of tool wear, typically expressed as the width of the flank wear land VB.

The cutting speed has the strongest influence on tool wear. The effect of feed on tool wear and thus on tool life is also significant. The depth of cut also influences tool wear, but the effect is very minor in comparison.

The dependence of the tool life on cutting speed can be represented in a tool-life graph. The tool-life graph is a log-log plot with cutting speed data v_c (in m/min) plotted on the abscissa and the corresponding tool life T (in min) plotted on the ordinate (see Fig. 11).

As can be seen in Fig. 11, the resulting curve can be approximated over a large part of the plot as a straight line with the standard straight line equation

$$y = m \cdot x + n \qquad (4)$$

As the plot is a log-log representation, this equations becomes:

$$\log T = \log C_v + k \cdot \log v_c \qquad (5)$$

Taking the antilogarithms to transform back to the original variables generates the so-called Taylor equation:

$$T = v_c^{\,k} \cdot C_v \qquad (6)$$

where:

T: Tool life in minutes

v_c: Cutting speed in metres per minute

k: Gradient of the straight line in the tool-life plot (k = tan α)

C_v: Tool life T for unit cutting speed (v_c = 1 m/min.)

The Taylor equation can be rearranged to yield:

$$v_c = T^{\frac{1}{k}} \cdot C_T \qquad (6a)$$

where

$$C_T = C^{-\frac{1}{k}} \cdot \qquad (7)$$

C_T, C_v and k are quantities that characterize the cutting conditions and that vary depending on the work material, the cutting tool geometry and the area of the undeformed (i.e. uncut) chip, which is itself determined by the chosen feed and depth of cut (cf. VDI Guideline 3321). The exponent k, which determines the slope of the tool life curve, is of particular relevance to practical applications as it expresses how the tool life T varies as a function of the cutting speed v_c. The steeper the gradient of the tool life plot, i.e. the smaller the angle of inclination α, the greater the dependence of tool life on cutting speed. At low cutting speeds, the relationship between log T and log v_c is no longer linear due to built-up edge formation at the cutting tool edge.

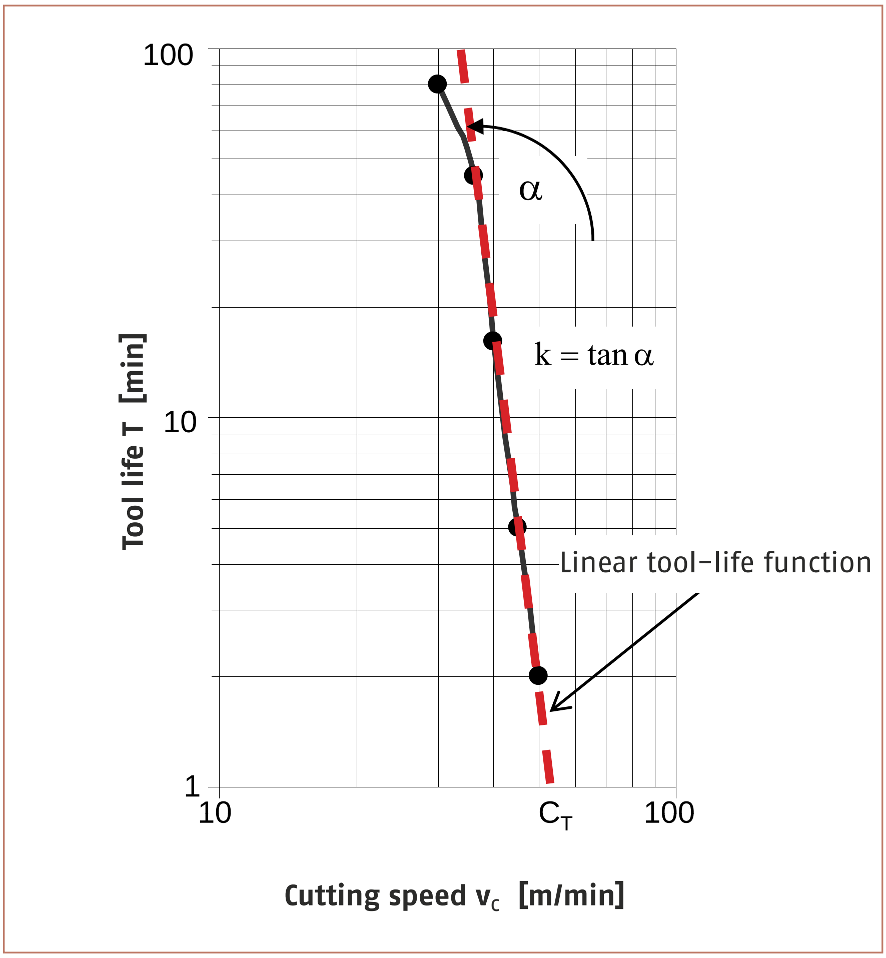


Fig. 11: *Taylor tool-life diagram (log-log plot of tool life against cutting speed)*

While the Taylor equation is completely adequate for most practical applications, this simple-to-use tool-life relationship does not have general validity. For example, milling operations tend to exhibit tool-life relationships that cannot usually be approximated by the Taylor expression.

To deal with these cases, so-called extended Taylor equations have been developed that take into account other variables that can influence tool life. One example is the extended Taylor equation that has been modified to account for the effects of feed and depth of cut:

$$T = \frac{C_1}{a_p^{\,c_a} \cdot f^{\,c_f} \cdot v_c^{-k}} \qquad (8)$$

where:

T	Tool life in minutes
v_c	Cutting speed in metres per minute
f	Feed in mm per revolution
a_p	Depth of cut in mm
k	Gradient of the straight line in the tool-life plot (k = tan α)
C_1	Dimensioned, empirically determined constant
C_a	Dimensionless constant: the exponent of the depth of cut
C_f	Dimensionless constant: the exponent of the feed

The size of the parameters k, C_a and C_f reflect the strength of their influence on tool life; the exponent -k is relatively large, whereas C_a and particularly C_f assume only small values. C_1 is a dimensioned constant that depends on the workpiece material, the tool material and the cutting operation.

3.2 Cutting force

The cutting force generated at the tool's cutting edge is a further parameter used to characterize the machinability of a material. An understanding of the cutting forces acting is fundamental to the design of machine tools, cutting tools and tool holders and workpiece holders. Knowledge of the cutting forces also enables machining jobs to be intelligently distributed among the available production machinery. To determine the drive power requirements or to dimension a tool holding system it is generally sufficient to make a rough estimate of the expected cutting forces.

As shown in Fig. 12, the total cutting force F can be resolved into three components: the cutting force F_c, the feed force F_f and the passive force (or back force) F_p. The symbols used here to designate the force components are those found in the DIN 6584 standard. The required drive power is determined primarily by the cutting force F_c. According to Kienzle and Victor, the cutting force F_c can be calculated as follows:

$$F_c = k_{c1.1} \cdot b \cdot h^{(1-m_c)} \qquad (9)$$

where:

F_c	Cutting force in N
b	Chip width in mm
h	Undeformed chip thickness in mm
m_c	Dimensionless index reflecting the increase of the specific cutting force
$1-m_c$	Gradient of the straight line $F_c' = f(h)$ in a log-log plot
$k_{c1.1}$	Specific cutting force in N/mm^2 for b = h = 1 mm

The term $h^{(1-m_c)}$ is expressed in mm. Corresponding equations can be defined for the other two force components F_f and F_p.

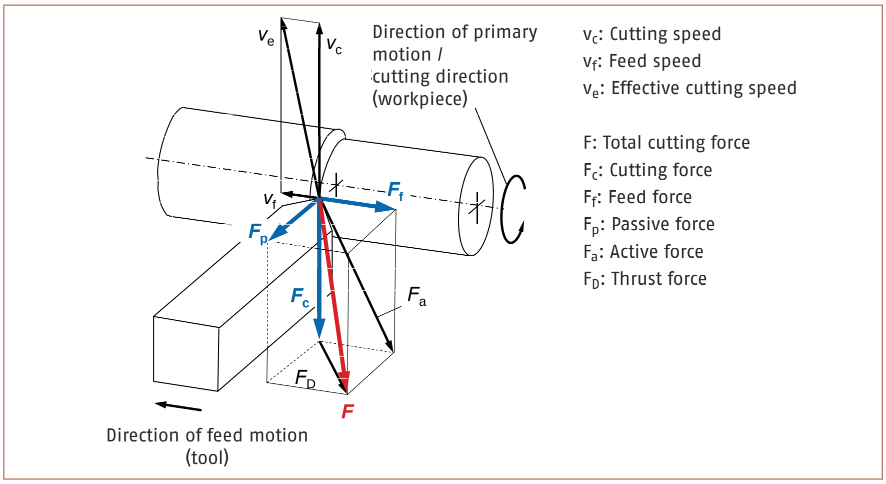


Fig. 12: *Total cutting force resolved into component forces (DIN 6584)*

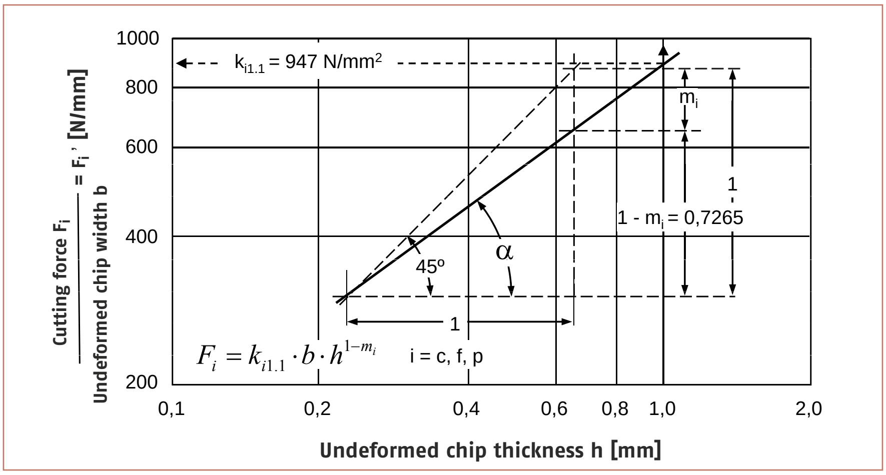


Fig. 13: *Graphical determination of the parameters $k_{i1.1}$ and $(1-m_c)$ with i = c, f or p [8]*

The graphical determination of the specific cutting force $k_{c1.1}$ or the material-dependent factors m_c or $(1-m_c)$ is illustrated in Fig. 13 and described in detail in the literature [8, 9, 10]. The cutting force expressions given above use only a limited set of parameters. Other factors that influence the cutting force, such as the angle of rake γ, the cutting velocity v_c, tool wear and workpiece shape were excluded for reasons of simplicity. Extended versions of the Victor-Kienzle equations are available in which these additional parameters are included as correction factors.

In turning operations using carbide tools, the only parameters in addition to the undeformed chip thickness h that have any practical influence the specific cutting force are the angle of rake γ, the angle of inclination λ_s and the degree of tool wear. It is generally the case that as the angle of rake γ increases, i.e. becomes more positive, the specific cutting force k_c decreases by 1.5 % for every one degree change in angle. This statement is valid for the range of angles given by ±10 % of the angle of rake originally measured. Tool wear plays a more significant role. However, in view of the numerous factors influencing the magnitude of the cutting force, it is only possible to make approximate, semi-quantitative statements about the increase in the cutting force with progressive tool wear. It has been

Machinability group	**Material**			**Principal value of specific cutting force $k_{c1.1}$ [N/mm²]**	**Gradient $1-m_c$**	**Notes on experimental conditions (see Table 2)**
	Designation	**EN number**	**UNS number**			
I	CuSP	CW114C	C14700	820	0,93	1)
	CuTeP	CW118C	C14500	910	0,88	1)
	CuTeP	CW118C	C14500	544	0,7755	8)
	CuZn35Pb2	CW601N	C34200	835	0,85	4)
	CuZn39Pb3	CW614N	C38500	450	0,68	1)
	CuZn39Pb3	CW614N	C38500	389	0,69	8)
	CuZn40Pb2	CW617N	C37700	500	0,68	1)
	CuSn4Zn4Pb4	CW456K	C54400	758	0,91	8)
	CuSn5Zn5Pb5-C	CC491K	C83600	756	0,86	6)
	CuSn7Zn4Pb7-C	CC493K	C93200	1400	0,76	7)
	CuSn5Zn5Pb2-C	CC499K	–	756	0,86	6)
	CuSn5Zn5Pb2-C	CC499K	–	724	0,82	8)
	CuNi7Zn39Pb3Mn2	CW400J	–	459	0,70	8)
II	CuNi18Zn19Pb1	CW408J	C76300	1120	0,94	1)
	CuZn35Ni3Mn2AlPb	CW710R	–	1030	0,82	1)
	CuZn37Mn3Al2PbSi	CW713R	–	470	0,53	3)
	CuZn38Mn1Al	CW716R	–	422	0,62	5)
	CuAl10Fe5Ni5-C	CC333G	C95500	1065	0,71	6)
	CuSn12Ni2-C	CC484K	C91700	940	0,71	6)
	CuZn33Pb2-C	CC750S	–	470	0,53	3)
	CuZn40	CW509L	C28000	802	0,80	8)
	CuAg0,10	CW013A	C11600	1100	0,61	2)
	CuNi1Pb1P	–	C19160	696	0,8095	8)
III	CuNi2Si	CW111C	C64700	1120	0,81	1)
	CuAl8Fe3	CW303G	C61400	970	0,82	1)
	CuAl10Ni5Fe4	CW307G	C63000	1300	0,88	1)
	CuSn8	CW453K	C52100	1180	0,90	1)
	CuSn8P	CW459K	–	1131	0,88	8)
	CuZn37	CW508L	C27400	1180	0,85	1)
	CuZn20Al2As	CW702R	C68700	470	0,53	3)
	CuMn20	–	–	1090	0,81	8)

The mechanical properties of the wrought alloys listed in the following tables refer mainly to rods and bars (as defined in EN 12164, EN 12163, EN 13601 and EN 12166, strip (as in EN 1652 and EN 1654) and tubes (as in EN 12449). The values for the cast alloys are from EN 1982. The order in which the alloy groups are presented follows CEN/TS 13388.

Table 1: *Specific cutting forces $k_{c1.1}$ and gradient factors $1-m_c$ for copper and copper alloys. (Note: data drawn from a variety of sources.)*

estimated that a flank wear land width (VB) of 0.5 mm indicates that the cutting force will have increased by about 20 %, the feed force by about 90 % and the passive force by approximately 100 %.

The cutting force Fc can be calculated using Equation 9 and the $k_{c1.1}$ values that are listed in Table 1 . If a material is not listed in Table 1, it is usually acceptable for rough calculations to estimate the $k_{c1.1}$ values by adopting the values listed for a comparable material.

Table 2 contains information on the experimental conditions.

Table 3 lists specific cutting forces in relation to the undeformed chip thickness h.

The data in the table have been drawn from numerous sources and cover a range of different test conditions.

In some cases, the two other force components, the feed force F_f and the passive force F_p (Fig. 12) may also be of interest.

The latter two forces are much smaller than the cutting force F_c. The passive force F_p does not do any work that would need to be supplied by machine power as it is orthogonal to the two main directions of motion (direction of primary motion and the direction of feed).

The ratio of the feed force F_f to the cutting force F_c depends on the tool cutting edge angle κ_r. Assuming that the effect of the nose radius rε can be ignored, a tool cutting edge angle of $\kappa_r = 90°$ means that the feed force F_f will be little more than 30 % of F_c.

As the forces acting when copper materials are machined are generally quite low, the following relationship is suitable for most approximate calculations:

$$F_f \approx 0{,}3\ F_c \quad (10)$$

When turning with cemented carbide tools at the now typical cutting speeds of v_c = 200 m/min or more, it is adequate for most approximate analyses to assume that F_p is of the same rough magnitude as F_f.

No.	**Machining operation**	**Tool material**	**Feed range or undeformed chip thickness f or h [mm]**	**Depth of cut or undeformed chip width a_p or b [mm]**	**Cutting speed v_c [m/min]**	**Cutting tool geometry**		**Notes**	**Source**
						Machinability group	**α-γ-λ-ε-κ; r [degrees; mm]**		
1	*Cylindrical turning*	*HM-K 10*	$f = 0{,}05-0{,}315$	$a_p = 2{,}5$	*180*	*I* *II* *III*	*6-0-0-ε-90/75/45; 0,5* *8-5-0-ε-90/75/45; 0,5* *10-20-0-ε-90/75/45; 0,5*	*Dry cutting*	*[7]*
2	*Cylindrical turning*	*HSS (M2-AISI)*	$h = 0{,}05-0{,}28$	$a_p = 2{,}54$	*15-90*	–	*α-20-λ-ε-90; r*	*Dry cutting*	*[11]*
3	*Turning*	*SS u. HM*	$f = 0{,}1-0{,}8$	$a_p :f = 2:1$ *bis* $10:1$	-	*I u. II SS* *HM* *III SS* *HM*	*8-0-0/8-90-45; 0,5/2* *5-6-0/8-90-45; 0,5/2* *8-14/18-0/8-90-45; 0,5/2*	*Dry cutting*	*[12]*
4	*Cylindrical turning*	*HM*	$h = 0{,}04-0{,}6$	$a_p = 2{,}5$	*200*	–	*5-15-λ-ε-90; r*	*Dry cutting*	*[13]*
5	*Fly cutting*	*HSS*	$f = 0{,}08-0{,}6$	$a_p = 8-9$ $b = 4-12$	*40*	–	*5-10-0-90-90; r*	-	*[14]*
6	*Cylindrical turning*	*HM-K 10*	$f = 0{,}08-0{,}32$	$a_p = 2{,}5$	*200*	–	*5-6-0-90-70; 0,4*	*Dry cutting*	*[15]*
7	*Cylindrical turning*	*HSS u. HM*	$f = 0{,}1-0{,}6$	$a_p = 1$ *u.* 2	*32*	*HSS* *HM*	*8-0-0/8-90-45; 0,5/2* *5-6-0/8-90-45; 0,5/2*	*Dry cutting*	*[16]*
8	*Cylindrical turning*	*HM*	$f = 0{,}05-0{,}14$	$a_p = 1$	*200*	*HM*	*8-10-0-84-96; 0,4*	*Oil*	*DKI*

Table 2: *Information on the experimental conditions relevant to the specific cutting forces listed in Table 1*

$$F_p \approx F_f \approx 0{,}3\ F_c \quad (11)$$

While the magnitude of these forces is of interest when dimensioning workpiece clamps, tool holders, etc., an approximate calculation of the cutting power is important in order to determine the power requirements of the machine tool performing the cutting operation, whereby the machine efficiency must also be taken into account.

According to the DIN 6584 standard, the effective cutting power is the product of the effective cutting force F_e and the resultant cutting velocity v_e and is also the sum of the cutting power P_c and the feed power P_f.

$$P_e = F_e \cdot v_e = P_c + P_f \quad (12)$$

$$P_c = F_c \cdot v_c \quad (13)$$

$$P_f = F_f \cdot v_f \quad (14)$$

As the tool feed velocity ('feed rate') is generally much lower than the cutting velocity and the feed force is also much smaller than the cutting force, the feed power can be neglected for most approximate calculations of overall cutting power. The net machine power can therefore be computed as follows:

$$P_e' = \frac{F_c \cdot v_c}{60000} \quad (15)$$

where:

$P_{e'}$	Net machine power in kW
F_c	Cutting force in N
v_c	Cutting speed in m/min
60000	Conversion factor in (N • m)/(kW • min)

Cutting tools with multiple active cutting edges generally work with smaller undeformed chip thicknesses h than single-point tools. The net machine power required when working with multipoint tools can be calculated from the stock removal rate V_w in cm^3/min (i.e. the volume of workpiece material removed per unit time) and a specific stock removal rate V_{wp} in cm^3 / (min • kW) (i.e. the volume of workpiece material removed per unit time and per unit of power supplied).

For multipoint tools, the following relationship applies:

$$P_e' = \frac{V_w}{V_{wp}} \quad (16)$$

$P_{e'}$	Net machine power in kW
V_w	Stock removal rate (volume of workpiece material removed per unit time in cm^3/min)
V_{wp}	Specific stock removal rate (volume of workpiece material removed per unit time and per unit of power supplied in cm^3/(min • kW))

The specific stock removal rate V_{wp} is directly proportional to the specific cutting force, as the following derivation shows:

$$V_{wp} = \frac{V_w}{P_c} = \frac{A \cdot v_c}{F_c \cdot v_c} = \frac{A \cdot v_c}{k_c \cdot A \cdot v_c} = \frac{1}{k_c} \quad (17)$$

Material			Undeformed chip thickness h [mm]														Notes on experi-mental condi-tions Table 2
Designation	**Num-ber (EN)**	**Num-ber (UNS)**	**0,08**	**0,1**	**0,125**	**0,16**	**0,20**	**0,25**	**0,315**	**0,4**	**0,5**	**0,63**	**0,8**	**1,0**	**1,25**	**1,6**	
Machinability group I / Type I alloys																	
CuSP	*CW114C*	*C14700*	*979*	*963*	*948*	*932*	*918*	*904*	*889*	*874*	*861*	*847*	*833*	*820*	*807*	*793*	*1)*
CuTeP	*CW118C*	*C14500*	*1232*	*1200*	*1168*	*1134*	*1104*	*1075*	*1045*	*1016*	*989*	*962*	*935*	*910*	*886*	*860*	*1)*
CuZn35Pb2	*CW601N*	*C34200*	*1349*	*1293*	*1240*	*1183*	*1134*	*1087*	*1040*	*994*	*953*	*912*	*871*	*835*	*800*	*764*	*4)*
CuZn39Pb3	*CW614N*	*C38500*	*1010*	*940*	*875*	*809*	*753*	*701*	*651*	*603*	*562*	*522*	*483*	*450*	*419*	*387*	*1)*
CuZn40Pb2	*CW617N*	*C37700*	*1122*	*1045*	*973*	*899*	*837*	*779*	*724*	*670*	*624*	*580*	*537*	*500*	*466*	*430*	*1)*
CuSn5Zn5Pb5-C)*	*CC491K*	*C83600*	*1114*	*1065*	*1019*	*969*	*927*	*887*	*847*	*807*	*772*	*737*	*703*	*672*	*643*	*612*	*7)*
CuSn7Zn4Pb7-C	*CC493K*	*C93200*	*2567*	*2433*	*2307*	*2173*	*2060*	*1953*	*1847*	*1744*	*1653*	*1564*	*1477*	*1400*	*1327*	*1251*	*7)*
CuSn5Zn5Pb2-C	*CC499K*	*C92220*	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Machinability group II / Type II alloys																	
CuNi18Zn19Pb1	*CW408J*	*C76300*	*1303*	*1286*	*1269*	*1250*	*1234*	*1217*	*1200*	*1183*	*1168*	*1151*	*1135*	*1120*	*1105*	*1089*	*1)*
CuZn35Ni3Mn2AlPb	*CW710R*	–	*1623*	*1559*	*1498*	*1433*	*1376*	*1322*	*1268*	*1215*	*1167*	*1119*	*1072*	*1030*	*989*	*946*	*1)*
CuZn37Mn3Al2PbSi	*CW713R*	–	*1542*	*1432*	*1330*	*1227*	*1140*	*1059*	*981*	*907*	*842*	*780*	*721*	*670*	*622*	*574*	*3)*
CuZn38Mn1Al	*CW716R*	–	*1102*	*1012*	*930*	*847*	*778*	*715*	*655*	*598*	*549*	*503*	*459*	*422*	*388*	*353*	*5)*
CuAl10Fe5Ni5-C	*CC333G*	–	*2215*	*2077*	*1946*	*1812*	*1698*	*1592*	*1489*	*1389*	*1302*	*1218*	*1136*	*1065*	*998*	*929*	*6)*
CuSn12Ni2-C	*CC484K*	*C95500*	*1955*	*1833*	*1718*	*1599*	*1499*	*1405*	*1314*	*1226*	*1149*	*1075*	*1003*	*940*	*881*	*820*	*6)*
CuZn33Pb2-C	*CC750S*	*C91700*	*1540*	*1387*	*1249*	*1112*	*1001*	*902*	*809*	*723*	*651*	*584*	*522*	*470*	*423*	*377*	*3)*
Machinability group III / Type III alloys																	
CuAg0,10	*CW013A*	*C11600*	*2946*	*2700*	*2475*	*2248*	*2061*	*1889*	*1726*	*1573*	*1441*	*1317*	*1200*	*1100*	*1008*	*916*	*2)*
CuNi2Si	*CW111C*	*C64700*	*1810*	*1735*	*1663*	*1586*	*1521*	*1458*	*1395*	*1333*	*1278*	*1223*	*1169*	*1120*	*1074*	*1024*	*1)*
CuAl8Fe3	*CW303G*	*C61400*	*1528*	*1468*	*1410*	*1349*	*1296*	*1245*	*1194*	*1144*	*1099*	*1054*	*1010*	*970*	*932*	*891*	*1)*
CuAl10Ni5Fe4	*CW307G*	*C63000*	*1760*	*1714*	*1668*	*1620*	*1577*	*1535*	*1493*	*1451*	*1413*	*1374*	*1335*	*1300*	*1266*	*1229*	*1)*
CuSn8	*CW453K*	*C52100*	*1519*	*1486*	*1453*	*1417*	*1386*	*1355*	*1325*	*1293*	*1265*	*1236*	*1207*	*1180*	*1154*	*1126*	*1)*
CuZn37	*CW508L*	*C27400*	*1907*	*1828*	*1752*	*1671*	*1602*	*1536*	*1470*	*1404*	*1346*	*1288*	*1231*	*1180*	*1131*	*1079*	*1)*
CuZn20Al2As	*CW702R*	*C68700*	*1540*	*1387*	*1249*	*1112*	*1001*	*902*	*809*	*723*	*651*	*584*	*522*	*470*	*423*	*377*	*3)*

**) The low value can be explained by the low cutting velocities (v_c = 32 m/min) used in the tests.*

Table 3: *Specific cutting force k_c in N/mm² as a function of the undeformed chip thickness h in mm for the materials listed in Table 1. (Note: data drawn from a variety of sources.) Please note that because of the differences in the experimental conditions used, data from different sources cannot be directly compared.*

Converting to units of cm³/(min · kW) yields:

$$V_{wp} = \frac{V_w}{P_c} = \frac{60000}{k_c} \quad (18)$$

V_{wp} Specific stock removal rate in cm³/(min · kW)

V_w Stock removal rate in cm³/min

P_c Cutting power in kW

k_c Specific cutting force in N/mm²

60000 Conversion factor in cm³ · N/(mm2 · min · kW) (= N · m/(kW · min))

Table 4 provides values of V_{wp} for the materials listed in Table 1 at undeformed chip thicknesses h in the range 0.08 to 0.315 mm that is typical when machining with multipoint tools.

3.3 Surface quality

As with other materials, finish-machining of copper or copper alloys should generally produce a machined workpiece surface of a predefined quality, i.e. the roughness of the surface must not exceed a certain level. Decorative surfaces are often required when turning components from free-cutting brass (e.g. CuZn39Pb3) and this frequently requires the part to be smoothed or precision finished. The achievable surface quality is therefore regarded as the most important machinability criterion when assessing the machinability of free-cutting alloys such as CuZn39Pb3, CuZn39Pb2, CuZn40Pb2, CuZn30Pb3, CuNi18Zn19Pb1, CuTeP, CuPb1P and CuSP.

Material			*Undeformed chip thickness h in [mm]*							*Notes on experimental conditions Table 2*
Designation	*Number (EN)*	*Number (UNS)*	*0,08*	*0,1*	*0,125*	*0,16*	*0,20*	*0,25*	*0,315*	
Machinability group I / Type I alloys										
CuSP	*CW114C*	*C14700*	*61,3*	*62,3*	*63,3*	*64,4*	*65,4*	*66,4*	*67,5*	*1)*
CuTeP	*CW118C*	*C14500*	*48,7*	*50,0*	*51,4*	*52,9*	*54,4*	*55,8*	*57,4*	*1)*
CuZn35Pb2	*CW601N*	*C34200*	*44,5*	*46,4*	*48,4*	*50,7*	*52,9*	*55,2*	*57,7*	*4)*
CuZn39Pb3	*CW614N*	*C38500*	*59,4*	*63,8*	*68,6*	*74,2*	*79,7*	*85,6*	*92,2*	*1)*
CuZn40Pb2	*CW617N*	*C37700*	*53,5*	*57,4*	*61,7*	*66,7*	*71,7*	*77,0*	*82,9*	*1)*
*CuSn5Zn5Pb5-C *)*	*CC491K*	*C83600*	*20,5*	*21,7*	*23,0*	*24,5*	*26,0*	*27,5*	*29,2*	*7)*
CuSn7Zn4Pb7-C	*CC493K*	*C93200*	*23,4*	*24,7*	*26,0*	*27,6*	*29,1*	*30,7*	*32,5*	*7)*
CuSn5Zn5Pb2-C	*CC499K*	*–*	*–*	*–*	*–*	*–*	*–*	*–*	*–*	*–*
Machinability group II / Type II alloys										
CuNi18Zn19Pb1	*CW408J*	*C76300*	*46,1*	*46,7*	*47,3*	*48,0*	*48,6*	*49,3*	*48,2*	*1)*
CuZn35Ni3Mn2AlPb	*CW710R*	*–*	*37,0*	*38,5*	*40,1*	*41,9*	*43,6*	*45,4*	*47,3*	*1)*
CuZn37Mn3Al2PbSi	*CW713R*	*–*	*65,9*	*71,9*	*78,4*	*86,3*	*94,2*	*102,7*	*112,4*	*3)*
CuZn38Mn1Al	*CW716R*	*–*	*54,5*	*59,3*	*65,4*	*70,8*	*77,1*	*83,9*	*91,6*	*5)*
CuAl10Fe5Ni5-C	*CC333G*	*–*	*27,1*	*28,9*	*30,8*	*33,1*	*35,3*	*37,7*	*40,3*	*6)*
CuSn12Ni2-C	*CC484K*	*C95500*	*30,7*	*32,7*	*34,9*	*37,5*	*40,0*	*42,7*	*45,7*	*6)*
CuZn33Pb2-C	*CC750S*	*C91700*	*39,0*	*43,3*	*48,0*	*54,0*	*59,9*	*66,5*	*74,2*	*3)*
Machinability group III / Type III alloys										
CuAg0,10	*CW013A*	*C11600*	*20,3*	*22,2*	*24,2*	*26,7*	*29,1*	*31,8*	*34,8*	*2)*
CuNi2Si	*CW111C*	*C64700*	*33,2*	*34,6*	*36,1*	*37,8*	*39,5*	*41,2*	*43,0*	*1)*
CuAl8Fe3	*CW303G*	*C61400*	*39,3*	*40,9*	*42,6*	*44,5*	*46,3*	*48,2*	*50,3*	*1)*
CuAl10Ni5Fe4	*CW307G*	*C63000*	*34,1*	*34,5*	*36,0*	*37,0*	*38,1*	*39,1*	*40,2*	*1)*
CuSn8	*CW453K*	*C52100*	*39,5*	*40,4*	*41,3*	*42,3*	*43,3*	*44,3*	*45,3*	*1)*
CuZn37	*CW508L*	*C27400*	*31,5*	*32,8*	*34,3*	*35,9*	*37,5*	*39,1*	*40,8*	*1)*
CuZn20Al2As	*CW702R*	*C68700*	*39,0*	*43,3*	*48,0*	*54,0*	*59,9*	*66,5*	*74,2*	*3)*

**) The low value can be explained by the low cutting velocities (v_c = 32 m/min) used in the tests.*

Table 4: *Specific stock removal rate V_{wp} in cm^3/(min·kW) as a function of the undeformed chip thickness h in mm for the materials listed in Table 1. (Note: data drawn from a variety of sources.)*

Surface roughness, which is usually measured in µm, is the property typically used to quantitatively assess the quality of a machined surface. The transverse roughness (kinematic roughness), which is measured in the direction of feed motion, is usually larger than the longitudinal roughness (cut surface roughness) measured in the direction of primary motion and is therefore of greater interest. The kinematic roughness is determined by the tool's nose radius and the relative motion of the tool and the workpiece.

The theoretically achievable peak-to-valley roughness $R_{t,th}$ with a single point operation such as turning can be calculated from the feed f and the nose radius r_ε (Fig. 14) by means of the following equation:

$$R_{t,th} = r_\varepsilon - \sqrt{r_\varepsilon^2 - \frac{f^2}{4}} \qquad (19)$$

This expression can be simplified by a Taylor series expansion, which yields the following approximation:

$$R_{t,th} \approx \frac{f^2}{8 \cdot r_\varepsilon} \qquad (20)$$

For most machining operations the required peak-to-valley surface roughness is usually specified, so that Eq. 20 can be used to determine the required feed for a given nose radius. The above expression can be rearranged to yield the feed:

$$f \approx \sqrt{8 \cdot r_\varepsilon \cdot R_{t,th}} \qquad (21)$$

The theoretically required feed f to produce a specified peak-to-valley roughness $R_{t,th}$ using a cutting tool with a given nose radius r_ε can be found by consulting Tab. 5. If the theoretically required feed cannot be set on the lathe, the next lower feed setting should be chosen.

However, in practical applications the peak-to-valley roughness achieved often deviates significantly from the theoretical value. This can be traced to the following three main causes:

- Finish machining, particularly when carried out with small feeds ($f < 0.1$ mm/rev), can lead to the formation of wear grooves in the vicinity of the minor cutting edge and the nose radius, resulting in a deviation from the theoretical profile of the machined surface.
- At higher feeds ($f > 0.1$ mm/rev), the continuous growth of flank wear, particularly at the nose radius, leads to a deterioration in the quality of the machined surface.
- As discussed earlier in Section 2.3, there is a range of cutting speeds in which built-up edge (BUE) formation is likely to occur. Periodic breakage of the BUE and displacement of these pieces of BUE often causes a significant deterioration in the quality of the machined surface. Built-up edges form when heavily strained workpiece material temporarily deposits on the cutting edge, giving the cutting edge an irregular shape. When the BUE breaks periodically, the bits of BUE can then become welded to the chip or the machined workpiece surface.

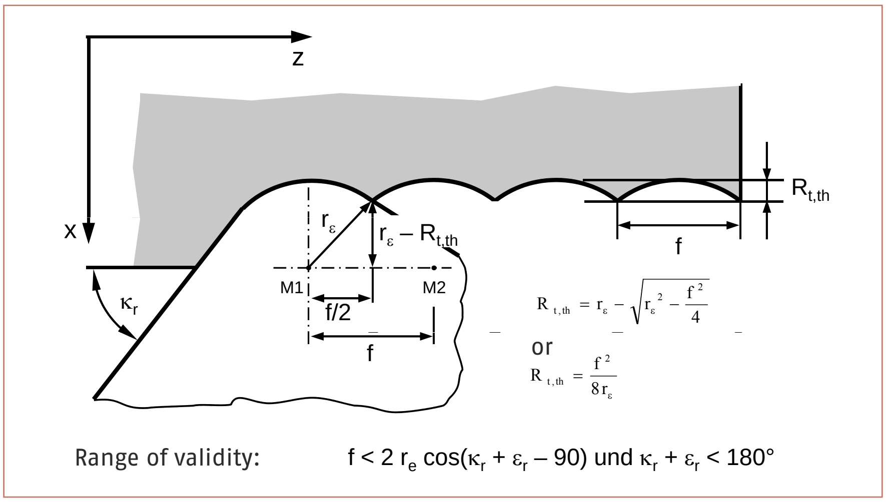


Fig. 14: *Geometric relationships when turning*

The transverse roughness of the workpiece surface that can be achieved also depends on the tool angles, particularly the rake angle. Increasing the rake angle improves work surface quality. The theoretically achievable value can be more closely approximated when machining copper and copper alloys than when machining other metals. However, increasing the rake angle reduces the wedge angle and thus reduces the tool life. As is the case with other metals, machining copper and copper alloys at high cutting speeds produces a better work surface quality than when machining at lower speeds.

The expressions (19), (20) and (21) are useful approximations when dealing with fine-grained materials; for more coarsely grained material, the actual peak-to-valley roughness R_t is significantly larger than the calculated value [17, 18]. When machining with a cutting tool of defined geometry (i.e. excluding operations such as grinding, lapping, honing, etc.), it can be roughly assumed that the grain size of the work material approximately represents the lowest degree of surface roughness achievable in practice. When high demands are placed upon the quality of the work surface finish, the use of diamond-tipped tools at high cutting speeds and low feeds is recommended. Such a configuration can produce mirror surface finishes.

When machining with multipoint tools (e.g. milling operations), a form error known as 'waviness' may be superimposed on the peak-to-valley height R_t of the surface. The 'wavelength' corresponds to the feed per revolution, the amplitude reflects the tool runout error if this is greater than about 10 µm. The

Nose radius r_ε [mm]	*Feed f in mm/rev = f (R_{th}, r_ε)*					
	Fine finishing		*Finishing*		*Rough cutting*	
	▽▽▽		▽▽		▽	
	$R_{t,th}$ 4 µm	*$R_{t,th}$ 6,3 µm*	*$R_{t,th}$ 16 µm*	*$R_{t,th}$ 25 µm*	*$R_{t,th}$ 63 µm*	*$R_{t,th}$ 100 µm*
0,5	*0,13*	*0,16*	*0,26*	*0,32*	*0,50*	*063*
1,0	*0,18*	*0,22*	*0,36*	*0,45*	*0,71*	*0,89*
1,5	*0,22*	*0,27*	*0,44*	*0,55*	*0,87*	*1,10*
2,0	*0,25*	*0,31*	*0,50*	*0,63*	*1,00*	*1,26*
3,0	*0,31*	*0,38*	*0,62*	*0,77*	*1,22*	*1,55*

Tab. 5: *Feed f in mm/rev as a function of the required theoretical roughness $R_{t,th}$ and the nose radius r_ε*

quality of the surface can be improved in face milling operations by using a milling cutter with indexable teeth inserts that have an 'active minor cutting edge', that is, the inserts have a chamfer on the minor cutting edge so that the chamfered edge lies parallel to the workpiece surface with a cutting edge angle of $\kappa_r = 0°$. The chamfer on the minor cutting edge may be up to several millimetres long. The feed per tooth should not exceed $^2/_3$ of the active chamfer length. If the minor cutting edge is larger than the feed per revolution, overlapping reduces the unavoidable runout error and improves the machined surface finish.

3.4 Chip shape

In addition to the type of chip formed, the shape of the chip is an important criterion for assessing the machinability of a material. A distinction is often made between materials that produce short chips and those that tend to form long chips. Short chips, with the exception perhaps of discontinuous and needle chips, tend to be more favourable with regard to chip flow and chip removal. Pure copper and solid-solution copper alloys with a high copper content belong to the group of materials that have a tendency to produce long continuous chips if the chip is allowed to form and flow in an uninterrupted manner. These materials are generally less easy to machine.

The assessment of whether a chip shape is unfavourable, acceptable or good (see Fig. 16) is made on the basis of the following criteria:

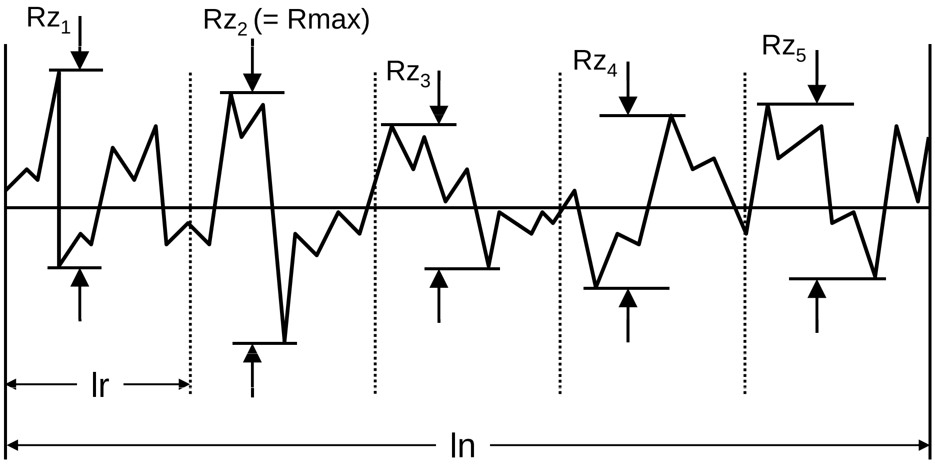
- Transportability: The chips should be of a shape that enables them to be removed easily from the machine's cutting zone and they should not be so small that they clog up the chip conveyor system or the cutting fluid filters.

- Injury hazard: Injury to operating personnel from sharp-edged tangled or corkscrew chips should be avoided.

- Risk of damage: The chips should not damage the workpiece, cutting tool or machine tool.

The first five chip shapes depicted in Figure 16: ribbon, tangled, corkscrew, conical helical and long cylindrical chips are not ideal as they make it difficult to eject the chip from the cutting zone. Corkscrew chips prefer to migrate over the flank of the tool causing damage to the tool holder and to those sections of the cutting edge outside the contact zone. Ribbon chips, tangled chips and discontinuous chips all present an injury hazard for persons near the machine. Fine needle chips can be formed when machining free-cutting brasses. Needle chips are undesirable as they tend to clog the chip conveyor systems and cutting fluid filters and increase the risk of injury to the machine operator.

Machining homogeneous copper materials, such as pure coppers and high copper copper-zinc alloys, tends to produce long flowing ribbon chips if the area of the uncut chip is large and the chip is allowed to develop unhindered. Tangled or snarled chips tend to form at low or medium feed rates, while corkscrew chips arise when machining with small nose radii, small



lr: Sampling length
ln: Evaluation length
Rz_i: Individual roughness depth (peak-to-valley)
Rz: Mean roughness depth ('ten-point height'): arithmetic mean of the individual roughness depths Rz_i measured for five consecutive sampling lengths
Rmax: Maximum roughness depth: largest peak-to-valley roughness value within the evaluation length

$$Rz_{(5)} = \frac{1}{5}\sum_{i=1}^{5} Rz_i$$

Fig. 15: Roughness parameters (according to Mahr and DIN EN ISO 4287)

depths of cut or large cutting edge angles. Corkscrew chips are particularly unfavourable because of the injury risk associated with their sharp edges. Conical helical chips can be expected to form when machining with small depths of cut and when only the nose radius of the tool engages with the workpiece. With increasing depth of cut, the chips become longer and tubular in appearance. This chip form is not desirable as its bulkiness chip makes it difficult to remove the chip from the cutting zone and convey it out of the machine.

The preferred chip forms are short-breaking chips such as short tubular chips, conical coiled chips and spiral chips. Arc chips, discontinuous chips and needle chips are also regarded as acceptable when machining free-cutting alloys such as free-cutting brasses, provided that the chips do not block the filters of the chip conveyor system.

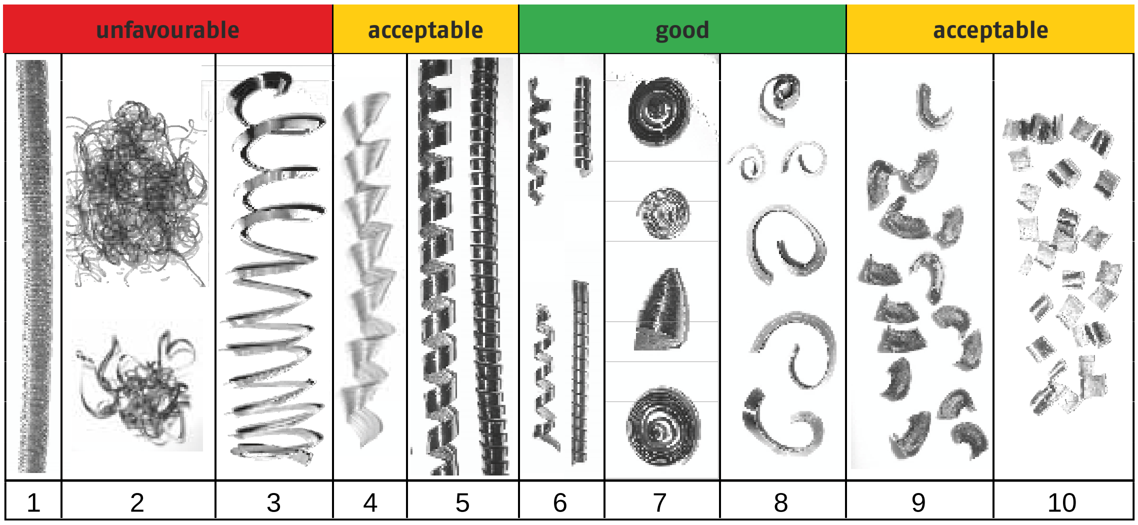
Factors influencing chip shape include: work material, tool material, machine tool characteristics, chip breaking, cooling lubricant, cutting conditions and tool geometry. The tool geometry recommendations provided do not address the shape of chip breakers.

Assuming that all other cutting conditions remain equal, short-breaking chips are generally more likely to form in workpiece materials of greater strength and with lower elongation. A coarse microstructure can also help to produce more favourable chip shapes when turning. This is the reason why cast alloys, particularly sanding-cast alloys, exhibit better chip formation properties than wrought alloys.

The cutting parameter with the greatest influence on chip formation is the feed. The larger the feed, the shorter the chip. A negative angle of rake leads to a greater degree of chip compression, which generally promotes the formation of more favourable chip shapes. In-creasing cutting speeds result in increasing cutting temperatures and the accompanying rise in the ductility of the work material favours the formation of ribbon and continuous chips.

It is often not possible to alter cutting conditions in order to modify the chip shape, as the cutting conditions have usually been set by other criteria. In such cases, chip shape formation can only be influenced by deploying chip breakers.

Generally speaking, chip formation is relatively unfavourable when machining pure copper and solid-solution high-copper copper alloys. The plastically deformed chip that is created during the shearing process still has a high elongation after fracture and therefore tends not to break – a fact that can cause problems for the machining operation. The addition of chip-breaking alloying elements such as lead, tellurium or sulphur can significantly improve the material's chip breaking properties (see Sec. 4.4).



1 Ribbon chips
2 Tangled (or snarled) chips
3 Corkscrew (or washer-type helical) chips
4 Conical helical chips
5 Long tubular chips
6 Short tubular chips
7 Conical coiled chips
8 Spiral chips
9 Arc chips (or chip curls or short comma chips)
10 Discontinuous (or elemental or short comma) chips

Fig. 16: *Classification of chip forms (Source: [19])*

4 Classification of copper-based materials into machinability groups

4.1 Standardization of copper materials

The EN standards provide information on the chemical composition, properties and main applications of copper alloys, with a distinction being made between standards for wrought alloys and standards for casting alloys. For each of these two main classes of alloy, the materials are further classified into alloy groups (see Table 6 and Table 7). Although the properties of copper materials are mainly determined by the composition of the alloy, this composition-based classification scheme is unsuitable for categorizing materials according to their machinability because alloys in the same alloy group often exhibit different machinability properties.

4.2 Machinability assessment criteria

As already discussed in Section 3, the machinability of a material is a highly complex property that cannot be described adequately by any one term or any single characteristic parameter, as is possible for properties such as mechanical strength or hardness. Any assessment of machinability has to take into account a number of different criteria. Which criteria are most important will depend on the particular machining operation being considered – a fact that makes it impossible to order machinability criteria into a single generally applicable system.

It is also not enough to simply consider one or two assessment criteria as

Designation	*Designation (non-standardized)*	*Further subdivisions*
Copper	*–*	*oxygen-containing; oxygen-free; non-deoxidized; silver-bearing oxygen-free; phosphorous deoxidized*
Low-alloyed copper alloys (alloying elements < 5 %)	*–*	*non age-hardenable age-hardenable*
Copper-aluminium alloys	*Aluminium bronze*	*binär (without other elements)*
	Multi-component aluminium bronzes	*with additional Fe, Mn, Ni*
Copper-nickel alloys	*–*	*–*
Copper-nickel-zinc alloys	*Nickel silver*	*without additional alloying elements with added lead to improve machinability*
Copper-tin alloys	*Tin bronze*	*binary alloy*
	Multi-component aluminium bronzes	*with additional zinc*
Copper-zinc alloys, binary alloys	*Brass*	*without other alloying elements*
	free-cutting brass	*with additional lead*
Copper-zinc alloys, multi-component alloys	*Special brass*	*with other alloying elements*

Table 6: *Wrought copper alloys (Classification as per CEN/TS 13388)*

Designation	*Designation (non-standardized)*
Copper	*unalloyed*
Copper-chromium casting alloys	*Copper-chromium*
Copper-zinc casting alloys	*Brass Special brass*
Copper-tin casting alloys	*Tin bronze*
Copper-tin-zinc-lead casting alloys	*Gunmetal*
Copper-aluminium casting alloys	*Aluminium bronze*
Copper-manganese-aluminium casting alloys	*–*
Copper-nickel casting alloys	*–*

Table 7: *Copper casting alloys (Classification as per EN 1982)*

complex relationships can exist between the various criteria. As discussed in Section 3, the main criteria used to assess machinability are tool wear, tool life, chip formation, cutting forces and surface quality.

Nevertheless, in order to provide practitioners with a basic overview of the machinability of the materials available, a machinability rating index for copper and copper alloys has become established in the literature and in the technical documentation published by copper producers. In Europe, the reference material used for comparison purposes is the lead-bearing free-cutting brass CuZn39Pb3, while in the USA it is the alloy CuZn36Pb3. These reference materials have been assigned a machinability index of 100. The rating index ranges from 100 for copper alloys with excellent machinability characteristics down to 20 for those that are very hard to machine.

The machinability index assigned to a particular copper alloy is made mainly on the basis of experience and data drawn from practical applications. These values have received support from a series of experimental studies. In 1977, the American standardization body ASTM developed a test that allows the machining performance of different steels to be compared under typical production conditions.
The Copper Development Association (CDA) subsequently applied the test to a variety of copper-based materials in order to assess their relative machinability and to compare them with steel and other alloys (see Fig. 1). The test – generally known as ASTM E618 – is based on the volume production of a standard part, see Fig. 17. The standard part itself is designed to be fabricated using the most common operations on automatic screw machines: rough turning, fine turning and drilling. The goal of the test is to determine the maximum number of standard parts that can be produced in eight hours. A number of test runs are performed to optimize the machining parameters such that the form tool only needs to be changed after eight hours. The assessment criteria used are dimensional accuracy and the surface finish of the machined part. The maximum number of parts produced is determined for each of the materials to be compared and the values are then ranked. The resulting machinability index is therefore a measure of the productivity level achievable during volume production operations using one material compared to when another material is used. However, as the test is very time-consuming and as significant quantities of material are required to perform the test, data are not currently available for all copper alloys.

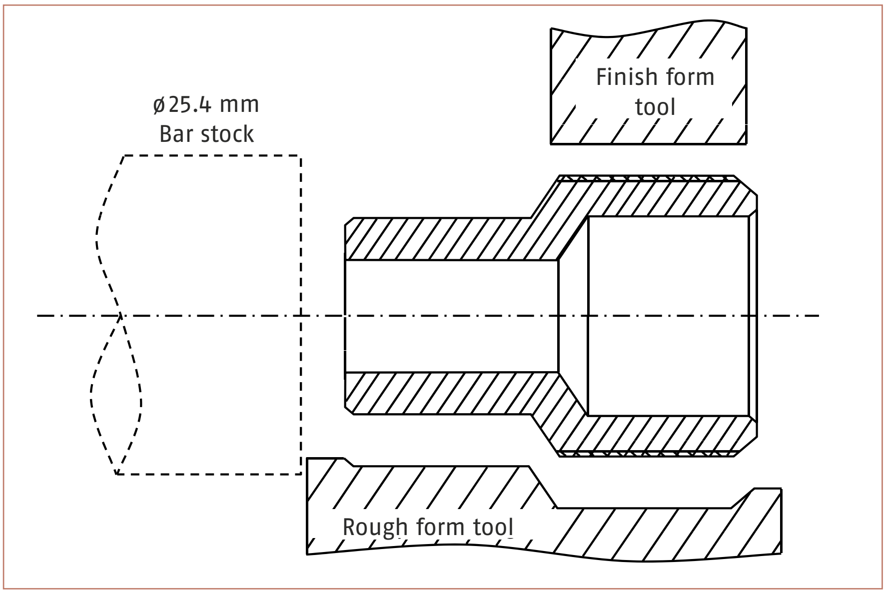


Fig. 17: *Standard part used in the ASTM E618 test and the position of the form tool. For the tests performed on copper alloys, the diameter of the bar stock was reduced to 19 mm and the geometry of the part adjusted accordingly. This is permitted under ASTM E618 if the modification is made for all the materials being compared. [1]*

In Europe, the copper alloy used for reference purposes is the free-cutting brass CuZn39Pb3; in the USA it is the alloy CuZn36Pb3. These materials are considered to exhibit optimum machinability and are therefore assigned a defined machinability rating of 100. Decreasing machinability is represented by reducing the machinability index in steps of 10 down to the minimum value of 20.

Machinability indices for copper alloys are provided by the German Copper Institute (DKI) in its material data sheets, by the American Copper Development Association and by copper producers. As a rule, machinability indices are not based on specific measured values. They provide a ranking system based primarily on tool wear and chip formation. A machinability index may therefore vary slightly in magnitude depending on source.

4.3 The effect of casting, cold forming and age hardening on machinability

When machining cast copper alloys, it is important to realize that the properties of the casting skin are significantly different to those of the core material. Generally speaking, the skin of the cast alloy is much stronger and harder than that of the bulk material. This has a detrimental effect on tool wear and can result in a substantial worsening of surface quality and dimensional accuracy.

The hardness and tensile strength of cast parts are generally lower than rolled or drawn products of the same composition, with elongation values varying within a broad band. If the casting skin is ignored, it is generally the case that casting alloys are more readily machinable than wrought alloys because of their microstructure.

Microstructure inhomogeneities, pores and non-metallic inclusions all create additional dynamic loads at the tool's cutting edge and this can cause edge chipping or frittering and significant reductions in tool life. Hard inclusions of aluminium oxide (corundum, spinel), silicon carbide, silicides, such as iron silicide, or quartz are particularly unwelcome when machining. Porosity, e.g. gas porosity caused by small cavities or voids, can also have a similarly negative impact on tool wear, but the effect is likely to be less pronounced than that due to repeatedly interrupted cutting.

The cold working of copper alloys leads to greater material hardness and tensile strength and a reduction in elongation. These changes in the mechanical properties have a favourable effect on machinability. In particular, these materials show better chip breaking characteristics than materials that have not been strain hardened through cold forming.

Cold forming of wrought alloys can produce strain within the material, as the forming process frequently only affects a portion of the material's crosssection. For instance, when cold drawing a rod, the outer layers of the material are subjected to tensile stresses while the bulk of the material is in compression. A similar situation is found in cold skin-rolled semi-finished stock. Completely removing the outer layers of the material, as occurs in turning, may in some cases result in a lengthening of the rod. Conversely, milling slots, grooves or keyways, or indeed performing any other machining operation that removes only a part of a material layer, can cause twisting or bending of the workpiece. Difficulties of this nature can also arise when processing non-circular tubing, e.g. in form turning, or when planing or milling cold-rolled sheet.

Deficiencies of this kind can, however, be eliminated by subjecting the machined parts to stress-relief annealing for about one hour. Copper can be treated at a temperature between 150 and 180°C, while copper-zinc alloys are treated between 250 and 300°C. This sort of heat treatment is equivalent to the procedure used to make copper-zinc alloys insensitive to stress corrosion cracking; improving the material's elastic properties without any reduction in strength.

Due to the relatively low modulus of elasticity of copper alloys, parts exhibiting high resilience after undergoing major cold forming should be processed in machines that operate without any play. If necessary, the workpiece has to be supported. In view of particularly pronounced strain hardening that copper-based materials undergo, they should, whenever possible, be machined in their hardened state. This is in fact one of the reasons why large differences in machinability are sometimes observed for the same material.

Machining of age hardenable (precipitation hardenable) copper alloys is best carried out on the cold-formed material prior to precipitation heat treatment, as cutting tool wear would be too great after hardening has occurred. The only operations favoured when the material is in its precipitation hardened state are grinding and polishing. To prevent material hardening due to high cutting temperatures, cutting fluids should be used to ensure adequate cooling and lubrication.

4.4 Alloying elements and their effect on machinability

Pure copper is difficult to machine because of its high ductility and high cold workability. Tool wear is very high and chip formation very poor. As chip compression is substantial, the cutting edge is subjected to large mechanical loads. The long tubular chips that form when pure copper is machined are difficult to handle and remove. As the cutting pressure remains uniform when machining pure copper, chatter marks tend not to form. There is however a risk of built-up edge formation when machining pure copper and this can lead to a poor machined finish. The tendency to form a built-up edge decreases with increasing cutting speed and greater feed rates.

As copper oxide does not dissolve in copper, the oxygen-bearing copper grades exhibit a certain degree of microstructural inhomogeneity, which to a small extent has a favourable effect on chip formation and a unfavourable influence on tool life. While the differences are not large, oxygen-free coppers tend to exhibit a greater degree of 'stickiness', making oxygen-bearing coppers generally preferable for machining purposes.

Chip formation can be improved by adding chip-breaking elements such as lead, sulphur, tellurium and selenium. The chips break into fine needle-like fragments that are ejected from the cutting zone. In Germany the preferred alloys are CuSP with 0.2–0.7 % S and CuTeP with 0.4–0.7 % Te, whereas internationally CuPb1P with 0.7–1.5 % lead has established itself as the alloy of choice. The addition of tellurium reduces the electrical conductivity only by about 5–8 %. These alloys are used for electrical engineering applications that require materials with both good electrical conductivity and good machinability.

As even traces of tellurium can substantially lower the hot forming properties of copper alloys, it is important to prevent chips of CuTeP mixing with other copper chips. The same applies to CuSP, as sulphur impurities have a detrimental effect on the cold forming capacity of copper alloys.

In terms of chip formation and tool life, alloys of copper with zinc, tin, nickel and aluminium show machining characteristics similar to those of pure copper, provided that the microstructures of these alloys are composed of homogeneous mixed crystals (solid solutions).

Quite different machining properties are shown by heterogeneous copper alloys that do not contain any chip-breaking elements. The group of heterogeneous copper alloys consists of copper-based alloys containing the elements zinc, tin, nickel or aluminium at concentrations so high that a second mixed crystal is formed. The second mixed crystal, which is usually harder and more brittle than the primary mixed crystal, causes an increase in the tensile strength and hardness of the alloy at the expense of its elongation and formability, particularly its cold workability. In this regard here, mention should also be made of the multi-component copper alloys that contain more than two alloying components.

The machinability of heterogeneous (i.e. two-phase or multiphase) copper alloys is significantly better than that of the homogeneous single-phase copper alloys. In alloys with low elongation, such as the cast copper-tin alloys, the chips break to form short spiral chips. In alloys exhibiting high elongation, such as CuZn40Mn2, the chips formed are either short spiral chips or long cylindrical chips depending on the feed rate deployed, with the latter being formed at low feeds.

The process of chip formation can lead to tool vibrations, which, if of large enough amplitude, can cause chatter marks on the workpiece. This can be counteracted by using tools and tool holders of maximum stiffness and minimizing tool overhang.

The machinability of heterogeneous two-phase copper alloys is reduced as a result of the presence of the second harder mixed crystal. Increasing tin content, e.g. in copper-tin casting alloys, causes a drop in cutting speed for the same tool life. Aluminium and larger quantities of iron and nickel also have a detrimental effect on the machinability of copper alloys. The machining properties of multi-component copper-aluminium alloys approach those of steel.

As already discussed for pure copper, chip-breaking additives can increase the machinability of copper alloys. The sole chip-breaking alloying element used in copper alloys is lead. Adding lead to the alloy has only a minor effect on the material's mechanical strength. However, the ability of the alloy to undergo cold forming and its ability to withstand impact and shock are both reduced significantly. For these reasons and particularly because the hot forming properties are impaired, lead is not added to high-strength and impact-resistant copper-aluminium alloys.

Lead-bearing copper alloys are only of limited applicability if the workpiece undergoes subsequent soldering or welding. The same applies to workpieces that, in addition to being machined, are also subjected to extensive cold forming operations.

Alloys containing chip-breaking additives form fine, needle-like chips or discontinuous chips. The manner in which chips are formed when machining leaded copper alloys makes them more susceptible to chatter marks than lead-free copper alloys of the same tensile strength. This can be counteracted by using machines that operate without any play and by using tools and tool holders of sufficient rigidity. On the other hand, the cutting forces that need to be applied when machining leaded copper alloys are low, as can be seen in Table 3. The excellent machinability of leaded copper alloys is attributable to the ease with which the material can be broken into tiny fragments. In addition to the low cutting forces, the service life of the cutting tools are also longer, being limited only by the average flank wear.

It should, however, also be recalled that fine needle-like chips can be disadvantageous as they can block the cutting fluid filters. Copper alloys that produce longer chips may also be preferable when drilling, as this chip form is easier to remove from the drilled hole.

In what follows, we shall take a closer look at the machinability of the individual groups of copper alloys in order to better understand why copper alloys are classified into three main machinability categories.

In the case of copper-zinc alloys (i.e. the brasses), a distinction is made between the single-phase solid-solution α-copper-zinc alloys (also known as 'alpha brasses' or 'cold working brasses'), which contain at least 63 % of copper, and the heterogeneous two-phase (α+β)-copper-zinc alloys ('alpha-beta brasses', 'duplex brasses' or 'hot working brasses') that contain between 54 and 63 % of copper. In their soft state, the single-phase α-brasses behave similarly to pure copper in terms of chip formation and tool life. The hardness and tensile strength of these materials increases with rising zinc content or through cold work hardening, leading to a slight improvement in machinability.

Better machinability is shown by heterogeneous copper-zinc alloys, such as CuZn40. The so-called special brasses, i.e. copper-zinc alloys that contain other elements except lead, also show somewhat better machining properties than the single-phase α-brasses. This is particularly true of chip formation, though tool life is effected negatively due to the presence of the harder components of the second mixed crystal (tin, aluminium, nickel, silicon, manganese).

Optimal machining properties in terms of chip formation (see Fig. 18c) and tool life are shown by the so-called leaded brasses, i.e. (α+β)-copper-zinc alloys that contain added lead. For turning operations, particularly those carried out on automatic screw machines, the alloys with the best machinability are CuZn39Pb3 and CuZn40Pb2.

Lead is practically insoluble in the copper-zinc alloy, and when finely dispersed it acts as an excellent chip breaker and in some cases even as a friction-reducing lubricant. A lead content greater than 3.5 % is uncommon, as it then becomes too difficult to achieve a highly dispersed distribution of the lead within the copper-zinc alloy. The small improvement in machinability that could be achieved if higher lead concentrations were used does not provide sufficient justification for accepting the associated deterioration in mechanical properties. For brasses that will not only be machined, but will also undergo cold or hot forming, the lead content is limited to about 1.5 %. Too high a concentration of lead also impairs polishability.

Further the European Directive 2000/53/EC restricts the use of automobile components containing heavy metals and the EU Directive 2002/95/EC rules the lead content in electrical and electronic equipment. However an exemption rule applies to copper-based materials that allow a maximum lead content of 4 percent by weight. The European Directive 98/83/EC states that plumbing materials must release no more than 25 µg of lead (Pb) per litre of drinking water, and as of 2013, no more than 10 µg Pb/l will be permitted.

Efforts to find a suitable element to replace lead as an additive in copper-based alloys led to the development of a lead-free silicon-bearing copper alloy for use in sanitary fittings. The machinability of this material is at a level comparable to that of the leaded brasses (Fig. 18b; machinability group I). The silicon-rich phases in the microstructure (kappa phases) act as chip breakers. Compared to lead, these phases are 'hard' chip breakers [20]. As the silicon increases the strength of the material and the κ-phase acts as an abrasive, tool wear is greater than when machining leaded alloys.

In copper-tin alloys (i.e. the 'tin bronzes') the boundary between homogeneous single-phase and heterogeneous two-phase alloys lies at around only 8 %. Nevertheless, the two-phase cast tin bronzes with higher tin content also tend to be less easy to machine when assessed in terms of tool wear and chip formation (Fig. 18a). And while cast tin bronzes are more machinable than single-phase wrought bronzes, the increase in tensile strength and hardness that accompanies increasing tin content tends to promote tool wear so that compared with other copper alloys the cutting speed has to be reduced.

The cast copper-tin-zinc alloys have a heterogeneous microstructure and those that contain added lead also exhibit good machinability. The same applies to the leaded cast copper-tin alloy CuSn11Pb2-C. These materials are solid lubricants to which the added lead content may significantly exceed 3 % in order to achieve the desired lubrication and casting properties.

Machinability that is as good or better is exhibited by the heterogeneous cast leaded tin bronzes that contain up to 26 % of added lead to improve lubrication properties.

The strengthening influence of nickel in heterogeneous but lead-free copper-nickel-zinc alloys (nickel silvers) also tends to reduce tool life.
In contrast, the machinability of leaded nickel silvers is almost as good as that of the free-cutting brasses. Tool lives, however, are significantly shorter due to the greater hardness of the nickel silvers.

The single-phase copper-nickel alloys are extremely difficult to machine due to their strong propensity to form burrs and very long, ductile chips.

Copper-aluminium alloys ('aluminium bronzes') exhibit a homogeneous single-phase micro-structure up to about 8 % aluminium. The microstructure of single-phase binary copper-aluminium alloys consists of relatively soft α-mixed crystals. Like other single-phase copper-based materials, these alloys are difficult to machine as they tend to produce long, ductile chips. Better machinability is exhibited by the two-phase aluminium bronzes and multi-component aluminium bronzes. However, because of their high tensile strength and hardness these materials cause substantial tool wear. Compared with cast copper-tin bronzes, an alloy such as CuAl10Fe5Ni5-C has to be machined at a much lower cutting speed to maintain the same tool life. Silicon-bearing copper-aluminium alloys, such as CuAl7Si, may contain hard inclusions of iron silicides as a result of contamination with iron. Carbide tools are therefore recommended when machining this type of material. The machinability of the heterogeneous two-phase aluminium bronzes is more like that of medium-hard steel grades than that of other copper-based materials.

CuSn8P
f=0,12 mm ap=1 mm

CuZn21Si3P
Mineral oil ISO VG 15

CuZn39Pb3

Fig. 18 *Chip forms*

4.5 Classification of copper and copper alloys into main machinability groups

Copper and copper alloys are conventionally classified into three main machinability groups, with each main group containing materials of similar machinability. The broad classification into the three main machinability groups is based on estimations of the assessment criteria discussed in Section 3. For copper and copper alloys, the main machinability criteria of relevance are chip form and wear. In addition to the attributes chip form and tool wear, micro-structure is also used to assist classification as it too has a significant influence on a material's machinability. Table Table 8 lists the attributes used to classify copper and copper alloys into the three main machinability groups.

Machinability group I
('Type I' or 'free-cutting' alloys)

This group includes copper-based materials containing added lead, tellurium or sulphur with a homogeneous or heterogeneous microstructure. The excellent machinability of the type I materials is due to the addition of these chip-breaking elements.

Machinability group II
('Type II' or 'short-chip' alloys)

Type II copper alloys are mostly lead-free and exhibit moderate to good machinability. They are generally harder than type I materials with a heterogeneous microstructure and are easier to cold form. The greater cold formability of type II copper alloys means that they generally produce longer chips than the type I alloys.

Machinability group III
('Type III' or 'long-chip' alloys)

This group contains those copper-based materials that are harder to machine than the alloys in groups I and II. The single-phase microstructures of these materials and their excellent cold workability result in higher cutting forces and long, ductile chips. The excellent cold forming properties of low-alloyed copper-based alloys seriously impair chip formation and result in accelerated tool wear. Homogeneous (i.e. single-phase, solid-solution) copper alloys containing zinc, tin, nickel or aluminium also exhibit poor chip forming qualities and low tool lives. Type III materials also include heterogeneous alloys such as the high-strength copper-aluminium alloys and the low-alloyed, strain-hardened copper alloys.

Tables Table 9, Table 10 and Table 11 present the conventional classification of standardized copper and copper alloy materials into the machinability groups I, II and III respectively. Classification was based primarily on expected chip formation, though for a number of hard-to-machine type III alloys, classification was based on the more pronounced tool wear.

As chip formation is strongly dependent on lead content, the machinability of a copper alloy with a lead content below the maximum permissible limit depends on the actual concentration of lead in the alloy. Under certain conditions, the lead content may justify reclassifying a type II copper alloy as type I or vice versa.

In each of the three main machinability groups a distinction is made between wrought and cast alloys. The machinability of the copper alloys can vary significantly, even between materials in the same machinability group. The tables have been supplemented by machinability ratings for the individual alloys (see earlier discussion). These ratings enable the materials within a main group to be distinguished more precisely. The machinability ratings of the alloys in group I range from 100 to 70, those in group II vary from 60 to 40, while the materials in group III exhibit machinability ratings from 30 to 20. The machinability rating is based partly on experimental evidence and partly on experience. It is important to realize that the machinability ratings listed were determined using a variety of different constraints and criteria. There is therefore a degree of uncertainty and imprecision associated with the quoted rating values and with their applicability to a particular machining situation. In turning work, the applicability of the rating figures is estimated to be around 70 %.

Attributes	*Machinability group*		
	I *(Type I Alloys)*	*II* *(Type II Alloys)*	*III* *(Type III Alloys)*
Microstructure	*homogeneous/heterogeneous structure with chip-breaking particles (Pb, S, Te)*	*Heterogeneous (coarse particulate phase) no Pb particles*	*a) homogeneous* *b) heterogeneous (finely dispersed deposits)*
Chip form	*short (discontinuous, brittle chips)*	*medium length (coiled cylindrical chips)*	*long and ductile (tightly coiled cylindrical, tangled or ribbon chips)*
Tool wear	*low*	*medium*	*high*
Cold workability of wrought materials	*generally poor*	*generally good*	*a) very good* *b) low*
Hot workability of wrought materials	*generally good*	*moderately good*	*a) moderately good* *b) good*

Table 8: *Conventional scheme for classifying the machinability of copper and copper alloys*

Alloy group I		Material			Tensile strength R_m [N/mm^2]	0,2% yield strength $R_{p0,2}$ [N/mm^2]	Elongation after fracture A [%]	Hardness [HB]	Tool geometry designator	Machinability rating
		Designation	Number (EN)	Number (UNS)						
Wrought copper alloys	Low-alloyed copper alloys – non-age-hardenable	CuPb1P	CW113C	C18700	250 – 360	200 – 320	5 – 7	90–110	–	80
		CuSP	CW114C	C14700					C*	80
		CuTeP	CW118C	C14500					C*	80
	Copper-nickel-zinc alloys	CuNi7Zn39Pb3Mn2	CW400J	–	510 – 680	400 -600	5 – 12	150 – 200	–	90
		CuNi10Zn42Pb2	CW402J	C79800	510 – 590	350 – 450	5 – 12	160 – 190	A / A*	80
		CuNi12Zn30Pb1	CW406J	C79300	420 – 650	280 – 600	8 – 20	130 – 180	A / A*	70
	Copper-tin-zinc alloys	CuSn4Zn4Pb4	CW456K	C54400	450 – 720	350 – 680	10	150 – 210	–	80
	Copper-tin alloy	CuSn5Pb1	CW458K	C53400	450 – 720	350 – 680	10	150 – 210	–	70
	Leaded binary copper-zinc alloys	CuZn35Pb2	CW601N	C34200	330 – 440	150 – 340	14 – 30	90 – 130	A	90
		CuZn36Pb2As	CW602N	C35330	280 – 430	120 – 200	15 – 30	80 – 110	–	80
		CuZn36Pb3	CW603N	C35600	340 – 550	160 – 450	8 – 20	90 – 150	A	100
		CuZn38Pb1	CW607N	C37000	360 – 550	150 – 420	8 – 25	90 – 150	A	80
		CuZn38Pb2	CW608N	C37700					A	90
		CuZn39Pb0,5	CW610N	C36500					A	70
		CuZn39Pb2	CW612N	–					A	90
		CuZn39Pb3	CW614N	C38500	360 – 550	150 – 420	8 – 20	90 – 150	A	100
		CuZn40Pb2	CW617N	C37700					–	90
		CuZn43Pb2Al	CW624N	–	as fabricated				–	80
	Multi-component copper-zinc alloys	CuZn40Mn1Pb	CW720R	–	390 – 560	200 – 500	10 – 20	110 – 160	A	60
		CuZn21Si3P	CW724R	C69300	530 – 700	300 – 450	10 – 20		–	80*
Copper casting alloys	Copper-tin casting alloy	CuSn11Pb2-C	CC482K	–	240 – 280	130 – 150	5	80 – 90	A	70
	Copper-tin and copper-tin-zinc casting alloys	CuSn3Zn8Pb5-C	CC490K	–	180 – 220	85 – 100	12 – 15	60 – 70	A	90
		CuSn3Zn9Pb7-C	–	C84400	200 – 234	–	16 – 26	55	–	90
		CuSn5Zn5Pb5-C	CC491K	C83600	180 – 220	85 – 100	12 – 15	60 – 70	A	90
		CuSn7Zn4Pb7-C	CC493K	C93200	230 – 260	120	12 – 15	60 – 70	A	90
		CuSn5Zn5Pb2-C	CC499K	–	200 – 250	90 – 110	6 – 13	60 – 65	–	90
	Copper-lead and copper-tin casting alloys	CuPb10Sn10-C	CC495K	C93700	180 – 220	80 – 110	3 – 8	60 – 70	A	90
		CuSn7Pb15-C	CC496K	CC93800	170 – 200	80 – 90	7 – 8	60 – 65	A	90
	Copper-zinc casting alloys	CuZn33Pb2-C	CC750S	–	180	70	12	45 – 50	A	80
		CuZn39Pb1Al-C	CC754S	–	220 – 350	80 – 250	4 – 15	65 – 110	–	80
		CuZn16Si4-C	CC761S	C87800	400 – 530	230 – 370	5 – 10	100 – 150	A*	70*

** the use of a cutting tool with a chip breaker is recommended*

Table 9: *Machinability classification of standardized copper-based materials*
Machinability group I: Copper-based materials with excellent machining properties

Alloy group II		Material			Tensile strength R_m [N/mm^2]	0,2% yield strength $R_{p0,2}$ [N/mm^2]	Elongation after fracture A [%]	Hardness [HB]	Tool geometry designator	Machinability rating
		Designation	Number (EN)	Number (UNS)						
Wrought copper alloys	Low-alloyed copper alloys, hardenable in cold-worked and precipitation-hardened state	CuNi2SiCr	–	C81540	–	–	–	–	–	40*
		CuNi3Si1	CW112C	C70250	700 - 800	630 - 780	10	180 - 200	A*	40*
	Copper-nickel-zinc alloys	CuNi18Zn19Pb1	CW408J	C76300	420 - 650	280 - 600	8 - 20	130 - 180	A / A*	60
	Binary copper-zinc alloys	CuZn40	CW509L	C28000	340	260	25	80	A*	40
	Leaded binary copper-zinc alloys	CuZn37Pb0,5	CW604N	C33500	300 - 440	200 - 320	10 - 45	55 - 115	A	60
	Multi-component copper-zinc alloys	CuZn31Si1	CW708R	C69800	460 - 530	250 - 330	12 - 22	115 - 145	A*	40
		CuZn35Ni3Mn2AlPb	CW710R	–	490 - 550	300 - 400	10 - 20	120 - 150	A*	50
		CuZn37Mn3Al2PbSi	CW713R	–	540 - 640	280 - 400	5 - 15	150 - 180	A / A*	50
		CuZn38Mn1Al	CW716R	–	210 - 280	–	10 - 18	120 - 150	A*	40
		CuZn39Sn1	CW719R	C46400	340 - 460	170 - 340	12 - 30	80 -145	A*	40
		CuZn40Mn2Fe1	CW723R	–	460 - 540	270 - 320	8 - 20	110 - 150	A*	50
Copper casting alloys	Copper-aluminium casting alloys	CuAl10Ni3Fe2-C	CC332G	–	500 - 600	180 - 250	18 - 20	100 - 130	C*	50
		CuAl10Fe5Ni5-C	CC333G	C95500	600 - 650	250 - 280	7 - 13	140 - 150	–	50
	Copper-tin casting alloys	CuSn12-C	CC483K	C90800	260 - 300	140 - 150	5 - 7	80 - 90	A*	50
		CuSn12Ni2-C	CC484K	C91700	280 - 300	160 - 180	8 - 12	85 - 95	A	40
	Copper-zinc casting alloys	CuZn32Al2Mn2Fe1-C	CC763S	–	430 - 440	150 - 330	3 - 10	100 - 130	A*	40*
		CuZn34Mn3Al2Fe1-C	CC764S	–	600 - 620	250 - 260	10 - 15	140 - 150	A*	40*
		CuZn37Al1-C	CC766S	–	450	170	25	105	A*	40
		CuZn38Al-C	CC767S	–	380	130	30	75	A*	40

** the use of a cutting tool with a chip breaker is recommended*

Table 10: *Machinability classification of standardized copper-based materials*
Machinability group II: Copper-based materials with good to moderate machining properties

Alloy group III		Material			Tensile strength R_m $[N/mm^2]$	0,2% Yield strength $R_{p0,2}$ $[N/mm^2]$	Elonga-tion after fracture A [%]	Hardness [HB]	Tool geo-metry desig-nator	Machi-nability rating
		Designation	Number (EN)	Number (UNS)						
Wrought copper alloys	Copper	Cu-OFE	CW009A	C10100	200 - 350	120 - 320	5 - 35	35 - 110	C*	20
		CuAg0,10	CW013A	C11600	200 - 350	120 - 320	5 - 35	35 – 100	C*	20
		CuAg0,1P	CW016A	–	260	220	–	12	C*	20
		Cu-HCP	CW021A	–					C*	20
		Cu-DHP	CW024A	C12200	200 - 350	80 - 330	5 - 35	35 - 110	C*	20
	Low-alloyed copper alloys, harde-nable, solution-annealed, cold-worked and precipitation-hardened	CuBe1,7	CW100C	C17000	–	–	–	–	A	20
		CuBe2	CW101C	C17200	1150 - 1300	1000 - 1150	2	320 - 350	A	30
		CuCo2Be	CW104C	C17500	700 - 800	630 - 730	5	200 - 220	A	30
		CuCr1Zr	CW106C	C18150	400 - 470	310 - 380	8 - 12	135 - 180	A*	30
		CuNi1Si	CW109C	–	500 - 590	420 - 570	10 - 12	140 - 160	A*	30
		CuNi2Be	CW110C	C17510	700 - 800	630 - 730	5	200 - 220	–	30
		CuNi2Si	CW111C	C64700	550 - 640	430 - 620	10	155 - 180	B*	30
		CuZr	CW120C	C15000	280 - 350	180 - 260	18 - 20	90 - 130	–	20
	Low-alloyed copper alloys, harde-nable, solution-annealed, cold-worked	CuBe2	CW101C	C17200	580 - 650	450 - 500	8 - 10	155 - 240	B / B*	20
		CuCo2Be	CW104C	C17500	400 - 500	330 - 430	8 - 10	110 - 175	B	30
		CuNi1Si	CW109C		300 - 410	210 - 320	9 - 16	85 - 150	B*	20
		CuNi2Si	CW111C	C64700	320 - 410	230 - 370	8 – 15	90 - 165	A*	30
		CuNi3Si1	CW112C	C70250	450 - 580	390 - 550	8 - 10	135 - 210	A	30
	Low-alloyed copper alloys, harde-nable, solution-annealed	CuCr1Zr	CW106C	C18150	200	60	30	65 - 90	B*	20
	Low-alloyed copper alloys – non-age-hardenable	CuSi3Mn1	CW116C	C65500	380 - 900	260 - 890	8 - 50	85 - 210	–	30
		CuSn0,15	CW117C	C14200	250 - 420	320 - 490	2 - 9	60 - 120	–	20
	Copper-aluminium alloys	CuAl10Fe3Mn2	CW306G	–	590 - 690	330 - 510	6 - 12	140 - 180	–	30
		CuAl10Ni5Fe4	CW307G	C63000	680 - 740	480 - 530	8 - 10	170 - 210	–	30
	Copper-nickel alloys	CuNi25	CW350H	C71300	290	100	–	70 - 100	–	20
		CuNi10Fe1Mn	CW352H	C70600	280 - 350	90 - 150	10 - 30	70 - 100	A / A*	20
		CuNi30Mn1Fe	CW354H	C71500	340 - 420	120 - 180	14 - 30	80 - 110	A / A*	20
	Copper-nickel-zinc alloys	CuNi12Zn24	CW403J	C75700	380 - 640	270 - 550	5 - 38	90 – 190	A / A*	20
		CuNi18Zn20	CW409J	–	400 - 650	280 - 580	11 - 35	100 - 210	A / A*	20
	Copper-tin alloys	CuSn4	CW450K	C51100	320 - 450	140 - 160	55	80 – 130	–	20
		CuSn5	CW451K	C51000	330 - 540	220 - 480	20 - 45	80 - 170	–	20
		CuSn6	CW452K	C51900	340 - 550	230 - 500	4 - 35	15 - 45	A*	20
		CuSn8	CW453K	C52100	390 - 620	260 - 550	15 - 45	90 – 190	A*	20
		CuSn8P	CW459K	–	390 - 620	260 - 550	15 - 45	90 – 190	A*	30
	Binary copper-zinc alloys	CuZn5	CW500L	C21000	240 - 350	60 - 310	15 - 30	55 – 115	A*	20
		CuZn10	CW501L	C22000	270 - 380	80 - 350	14 - 28	60 – 125	A*	20
		CuZn15	CW502L	C23000	290 - 430	100 - 390	12 - 27	75 - 135	A*	30
		CuZn20	CW503L	C24000	300 - 450	110 - 410	10 - 27	80 – 140	B*	30
		CuZn28	CW504L	–	310 - 460	120 - 420	10 - 27	85 – 145	B*	30
		CuZn30	CW505L	C26000					B*	30
		CuZn33	CW506L	C26800					B*	30
		CuZn36	CW507L	C27200	310 - 440	120 - 400	12 - 30	70 - 140	A / B*	30
		CuZn37	CW508L	C27400					A / B*	30
	Multi-component copper-zinc alloys	CuZn20Al2As	CW702R	C68700	340 – 390	120 - 150	40 - 45	65 - 95	A	30
		CuZn28Sn1AS	CW706R	C44300	320 - 360	100 - 140	45 - 55	60 - 110	A*	30
Copper casting alloys	Copper-aluminium casting alloys	CuAl10Fe2-C	CC331G	C95200	500 - 600	180 - 250	15 - 20	100 – 130	B*	20
	Copper-nickel casting alloys	CuNi10Fe1Mn1-C	CC380H	C96200	280	100 - 120	20 - 25	70	A*	20
		CuNi30Fe1Mn1NbSi-C	CC383H	C96400	440	230	18	115	A*	20
	Copper-zinc casting alloys	CuZn25Al5Mn4Fe3-C	CC762S	C86100	440	450 - 480	5 - 8	180 - 190	A*	30*

* the use of a cutting tool with a chip breaker is recommended

Table 11: Machinability classification of standardized copper-based materials
Machinability group III: Copper-based materials with moderate to poor machining properties

5 Cutting-tool materials

The principal tool materials used to machine copper-based materials are high-speed steels (HSS), cemented carbides and synthetic diamond. Plain carbon tool steels play no role in this field.

5.1 High-speed steel

High-speed steels (HSS) are highly alloyed tool steels. High-speed steels differ from other types of steel in that they contain a high concentration of carbides that gives these materials a relatively high resistance to wear and good hot hardness. The main alloying elements are tungsten, molybdenum, vanadium, cobalt and chromium. The hardness of the high-speed steels is influenced by both the hardness of the base material – the martensite – and the presence of the carbides. The tempering resistance of HSS is determined by the alloying elements dissolved in the matrix.

High-speed steels are designated in accordance with an established scheme: They are identified by the initials "HS" followed by the percentage content of tungsten, molybdenum, vanadium and cobalt. For example, the tool steel HS18-1-2-10 contains 18 % W, 1 % Mo, 2 % V and 10 % Co. Designations such as "HSS", "HSS-Co" or other manufacturer-specific designations are of little value unless the composition of the HSS grade is unambiguously stated.

The conventionally produced high-speed tool steels that are used for machining copper and copper alloys are divided into the high tungsten-alloyed steels, with tungsten concentrations of above 12 %:

	Designation in acc. with DIN EN ISO 4987	No.
a)	HS18-1-2-10	1.3265
b)	HS18-1-2-5	1.3255
c)	HS18-0-1	1.3355
d)	HS12-1-4-5	1.3202
e)	HS12-1-4	1.3302
f)	HS12-1-2	1.3318

and the molybdenum-alloyed steels:

g)	HS10-4-3-10	1.3207
h)	HS2-9-1-8	1.3247
i)	HS6-5-2-5	1.3243
j)	HS2-9-1	1.3346
k)	HS2-9-2	1.3348
l)	HS6-5-3	1.3344
m)	HS6-5-2C	1.3343

Cobalt (Co) is sometimes added to these steels to improve their hot hardness and their tempering resistance, while vanadium (V) is added to increase resistance to wear. A number of these steels, such as HS6-5-2C (material no. 1.3343) have a higher carbon content in order to lengthen tool life.

The high-speed steel HS10-4-3-0 (material no. 1.3207; see above list) can be recommended for many applications as it exhibits high hot hardness and good wear resistance and therefore prolonged tool life. However, a different HSS should be selected if the machining process or tool geometry requires a cutting-tool material of greater toughness. The toughest of the conventional high-speed steels is the alloy HS2-9-1 (material no. 1.3346), which is why small twist drills, end milling cutters, etc. are frequently manufactured from this or a similar HSS. Milling cutters and counterbores are produced primarily from HS6-5-2 (material no. 1.3243), reamers are generally made from HS6-5-3 (material no. 1.3344).

In addition to the high-speed steels produced by conventional metallurgical processes, HSS materials produced by powder metallurgy (PM) are also available commercially. Compared with conventionally produced HSS materials, those produced by PM generally exhibit a greater degree of alloying. Because of the much finer distribution of carbide particles within the microstructure, PM HSS alloys have a considerably better cuttingedge hardness than HSS types produced by conventional metallurgical techniques. They are also easier to grind due to their finer grain structure and the absence of segregation streaks. Both of these factors help to improve tool life when performing difficult machining operations, such as tapping, profile reaming, gear hobbing and gear shaping. The edge strength of the cutting material is an important factor in such operations as chip flow is often restricted or because the cutting edge engages very suddenly with the work material. For these applications, high-speed tool steels produced by powder metallurgical methods are preferred.

5.2 Carbides

Carbides are sintered composite materials comprising a metallic binder (typically cobalt) into which the carbides (WC, TiC, TaC, etc.) are embedded. The function of the binder is to bind the brittle carbide particles together to form a relatively strong solid. The function of the carbides is to create a material with a high hot hardness and wear resistance.

Copper alloys are machined using tools made from uncoated WC-Co cemented carbides or using coated carbide tools. Straight two-phase WC-Co carbides consist exclusively of hard grains of tungsten carbide (WC) embedded in the cobalt (Co) binder. In the alloyed WC-Co carbides part of the WC is replaced by vanadium carbide (VC), chromium carbide (Cr_3C_2) or tantalum/niobium carbide ((Ta,Nb)C). WC-Co carbides are characterized by high abrasion resistance. The various grades of WC-Co carbides available differ in the relative content of cobalt binder and the size of the tungsten carbide grains. With increasing cobalt content, the toughness of the cemented carbide rises at the expense of hardness and wear resistance. The uncoated carbides used for finishing and semi-roughing operations typically contain about 6 % w/w of cobalt (WC-6Co). Tougher cemented carbides with a higher cobalt content (e.g. WC-9Co) are used for roughing operations or interrupted cuts.

In terms of WC grain size, a distinction is made between the conventional fine grain carbides with an average grain size of 0.8–1.3 μm, the finest grain carbides (0.5–0.8 μm) and the ultrafine grain carbides (0.2–0.5 mm).
If the cobalt binder content remains constant, decreasing the WC grain size leads to an increase in hardness and transverse rupture strength. High-quality finest grain and ultrafine grain carbides exhibit superior hardness, edge strength and toughness compared with conventional fine grain carbides [21].

These high-performance carbides are typically used for the production of forming tools such as drills or end milling cutters. Cutting inserts for turning operations are usually made from fine grain carbide with a grain size greater than 0.8 mm.

According to the DIN ISO 513 standard, copper-based work materials are in main application group 'N' (see Fig. 19). Each of the main application groups (DIN ISO 513 distinguishes a total of six main groups) is further divided into application groups (see Fig. 19). The number after the letter 'N' indicates the toughness and wear resistance of the cutting-tool material. The higher this number is, the higher the toughness and therefore the lower the wear resistance of the cutting material. Carbide manufacturers assign their different carbide grades to one or more suitable application groups depending on the particular properties of the individual coated or uncoated carbide. Uncoated and coated carbides are given the letter code designations 'HW' and 'HC' respectively. Examples of such designations are: HW-N10 or HC-N20.

Carbides in application group N10 exhibit the broadest application range when machining copper-based materials. Carbides in the application groups N15–N20 are preferred if the machining operation requires a tool material with enhanced toughness, such as when turning with geometrically complex tools, or when the turning method produces an uncut chip of large area, or in uninterrupted cutting. Compared with the N10 carbides, the N15-N20 carbides have a higher cobalt content and are correspondingly tougher.

Coatings

The performance of (cemented carbide) cutting tools can be further improved by coating. Coatings make high-speed machining possible and can significantly extend tool life. Coated carbides were a milestone in the development of cutting tools that were both tough and wear-resistant. The most-important coating materials are titanium carbide (TiC), titanium nitride (TiN), titanium aluminium nitride (TiAlN), aluminium oxide (Al203), titanium carbonitride (TiCN), diamond-like carbon (DLC) and diamond. By varying the coating material, the structure of the coating layer, its thickness and the coating method used, the properties of the coated material can be adjusted to suit the requirements of a specific machining task.

Coated tools show reduced wear because of increased wear resistance and reduced interfacial adhesion. They also act as a diffusion barrier and improve the tool's thermal and chemical stability. The coatings used with the cutting materials in main group N include TiAlN, TiN, AlCrN, CrN, AlTiCrN, DLC (a-C:H, a-C:Me) and diamond coatings.

5.3 Diamond as a cutting material

Diamond is composed of pure carbon and is the hardest of all known materials. However, its extreme hardness makes it very brittle and therefore very sensitive to impact and thermal stress. These properties effectively define the areas in which diamond is applied as a cutting material. Both natural and synthetic diamonds are used in machining operations. Both monocrystalline (DIN ISO 513 code: DM) and polycrystalline diamond (DIN ISO 513 code: DP) are used. The abbreviation PCD is also frequently used when referring to tools manufactured from polycrystalline diamond.

Monocrystalline diamonds are particularly well-suited for precision machining operations and are widely applied in the field of ultra-precision machining.

Main application groups			Application groups			
Code letter	Colour code	Workpiece material	Hard cutting materials			
N	green	**Non-ferrous metals:** aluminium and other non-ferrous metals, non-metal materials	N01 N10 N20 N30	N05 N15 N25	↑	↓
↑	increasing cutting speed increasing wear resistance of tool material					
↓	increasing cutting speed increasing wear resistance of tool material					

Fig. 19: Main application group N of hard cutting materials (DIN ISO 513)

PCD tools are used both for precision machining and for roughing operations. In some applications the rough machining and finish machining steps can be combined into a single step [22].

5.4 Selecting the cutting material

The cost-effectiveness of a cutting material depends on several factors. If no restrictions are placed on the thickness of the uncut chip, the number of workpieces machined per unit time depends on the cutting material used and is given by the product $h \bullet v_c$, where h is the thickness of the uncut chip and v_c is the applicable cutting speed.

If larger amounts of stock are to be removed, depth of cut ap is another factor that directly influences tool productivity – though one that is only slightly dependent on the choice of tool material.

In nearly all practical cases, however, the depth of cut a_p is fixed by the stock allowance, while the thickness of the uncut chip h and/or the feed f are limited by the rigidity of the machine/workpiece/tool system or by certain specifications regarding the roughness of the machined surface, irrespective of the cutting material used. In such cases, the influence of the cutting material is restricted simply to its effect on the cutting speed v_c.

Another factor influencing the choice of cutting material is the cost per tool life, which according to the VDI Guidelines 3321 can be approximated by:

$$K_{WT} = \frac{K_{Wa}}{n_T} + K_{Ww} \cdot \left(+K_{Ws}\right) \qquad (22)$$

where:

K_{WT}	Tool costs per tool life in €
K_{Wa}	Purchase price of tool in €
n_T	Number of tool lives per tool (for solid shank tools or brazed inserts: n_T = number of regrinds; for indexable cutting inserts; n_T = number of cutting edges per insert)
K_{Ww}	Cost in € associated with changing the worn tool
K_{Ws}	Cost in € for regrinding the tool (not applicable if indexable inserts are used)

Equation 22 shows that the cost of purchasing the tool K_{Wa} typically represents only a small fraction of the total costs K_{WT} associated with the service life of the tool. The two other terms are generally larger.

The tool costs associated with the production of one part are therefore given by the following equation:

$$K_W = \frac{K_{WT}}{n_{WT}} \qquad (23)$$

where:

K_W	Tool costs in € for fabricating one part
n_{WT}	Number of parts machined in one tool life

The total cost of manufacturing one part is therefore given by:

$$K_1 = t_{h1} \cdot R + K_{fix} + K_W = K_{th1} + K_{fix} + K_W \quad (24)$$

where:

K_1	Total fabrication cost per unit product in €
t_{h1}	Machining time per part in minutes
K_{fix}	Fixed costs in € (independent of cutting speed v_c)
K_{th1}	Machining costs in €
R	Cost rate for operator and machine (excluding tool costs) in €/min

Choosing the right type of cutting-tool material is almost impossible without considerations of this kind. For instance, a tool with a high purchase price may be able to significantly reduce unit fabrication costs either because it can produce a larger number of parts during its service life (higher value of n_{WT}) or because it enables the same number of parts to be machined in a faster time.

Such considerations generally lead to the conclusion that cemented carbide cutting tools (typically, N10 grade carbide) are much more preferable than HSS tools. Indeed, carbide can remain the material of choice even when cutting speed restrictions mean that the number of parts produced per unit time is no greater than that achievable with a HSS tool. This is because the longer service life of a carbide tool allows a greater number of parts to be machined in one tool life, increasing the value of n_{WT} in Eq. 23. If indexable cutting inserts are used, K_{Ws}, the third term in Eq. 22, is zero, which reduces the unit production cost given by Eq. 24.

The factors limiting the application of carbide as a cutting material are usually related to tool geometry. Geometrically complex cutting tools typically have to be made from extremely tough cutting materials. Cemented carbides are often unable to meet these requirements or the cost of manufacturing a complex tool shape from carbide often proves prohibitively expensive. Tapping is an example of a cutting operation that places high demands on the toughness of the tool material, as at the end of the operation the tap has to be unscrewed from the hole. The resulting frictional forces can generate high tensile stresses at the tool's cutting edges. Taps are therefore typically produced in HSS.

6 Cutting-tool geometry

6.1 Rake and clearance angles

Due to the large variation in the machinability of copper alloys, the geometry of the cutting tool has to be adjusted to meet the specific characteristics of the work material being machined. Matching the tool geometry to the workpiece material is particularly advisable if favourable chip formation is to be achieved. Categorizing tool geometry based on the main machinability groups I–III is unsatisfactory, as it represents too great a simplification. In order to classify tool geometry, the three main groups are further divided into three groups with the letter codes A, B and C (see Table 12). For cutting tools with a more or less fixed cutting-edge geometry (e.g. milling cutters), the DIN 1836 standard distinguishes between the cutting teeth forms H, N und W. Tooth shape H corresponds approximately to class A, tooth shape N to class B and tooth form W to class C.

The tool geometry designators assigned to the copper-based materials are listed in tables Table 9 to Table 11. The machinability of a copper alloy can therefore be classified as in the following example:Material CuZn39Pb3 = I.A.100 (I: main machinability group / alloy type, A: tool geometry designator, 100: machinability rating).

Copper and cooper alloys have a pronounced tendency to form long ductile chips. The resulting ribbon and tangled chips can be hazardous to the machine operator and can disrupt the machining process. When performing continuous turning operations on these materials it is therefore frequently necessary to shape the chips into shorter coiled chips. This can be achieved by using chip breakers that force the flowing chip into a specific form as soon as the chip has achieved a minimum thickness of about 0.2–0.3 mm. The tool geometry codes for tools that possess a chip breaker are indicated by an asterisk * in Table 12 (A*, B*, C*). The table also lists the angle of the chip breaker back wall.

Chip breakers increase the extent of chip compression, which induces higher machining forces and reduces tool life. The tougher the chip material is or the greater the extent to which it is deformed, the more pronounced this effect becomes.

The degree of chip deformation depends on the width of the chip breaking element and on the angle between the effective rake face and the back wall of the chip breaker [23]: the deeper the chip breaking element and the steeper the back wall, the more the chip is compressed. As a general rule, a chip breaker height of 0.8 mm and an angle of 70° or 50° between the back wall and the tool's effective rake face are recommended. The fillet between the rake face of the cutting tool and the back wall of the chip breaking element should have a radius roughly in the range 0.3–0.5 mm. The width of the chip breaking element is determined primarily by the thickness of the uncut chip h, which is itself determined by the feed f and the tool cutting edge angle κr ($h = f \cdot \sin \kappa r$), and to a lesser extent by the width of the uncut chip b. A wide chip requires a wide chip breaker. The following approximate guidelines are generally valid [23]:

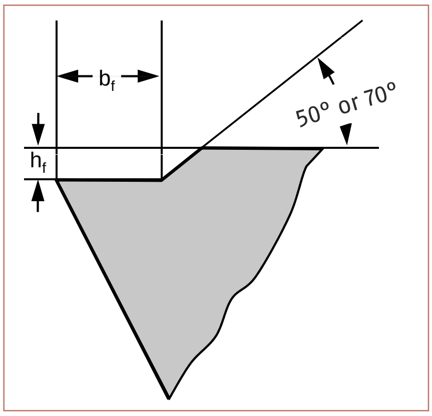


Fig. 20: *Cross-section through a chip breaking element ground into the tool*

Undeformed chip width b in mm	Width of chip breaker b_f in mm
0,4 … 1,5	5 • h
1,6 … 7	8 • h
7,5 … 12	12 • h

The chip breaker can also be aligned parallel to the tool's cutting edge or aligned so that it widens or narrows towards the tool's nose.

Chip breakers that run parallel to the cutting edge (alignment angle = 0°) do not tend to direct chip flow toward or away from the workpiece and therefore favour the formation of watch-spring-like spiral chips. If the width of the chip breaker decreases towards the nose of the tool (alignment angle > 0°), chip flow is directed away from the workpiece, favouring the creation of cylindrical chips.

If the chip breaker is designed to widen towards the tool's nose (alignment angle < 0°), the direction of chip flow is toward the workpiece surface, which

Tool geometry designator	*Carbide*		*HSS*		*Angle of back wall of chip breaker1)*
	γ (°)	α (°)	γ (°)	α (°)	(°)
A *A**	*0 - 8*	*6*	*5 - 10*	*8*	*50*
B *B**	*8 - 12*	*6*	*10 - 14*	*8*	*70*
C *C**	*20*	*6*	*25*	*8*	*50 -70*

*1) An asterisk * after the tool geometry designator indicates a tool with chip breaker.*

Note: The chip breaker data applies only to turning tools or indexable inserts for turning or drilling; they do not apply to milling cutters, drill tools, etc.

Table 12: *Tool geometry classification scheme*

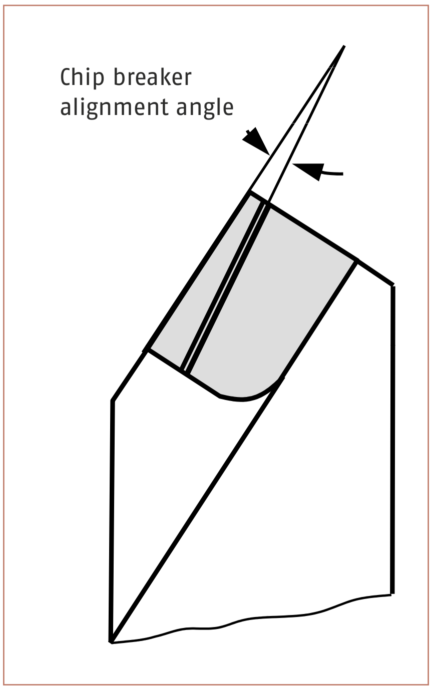


Fig. 21: *Alignment angle of chip breaker*

favours the formation of short chip curls, provided that the chip is not too ductile. There is, however, the risk that the chip can damage the newly machined work surface.

The effectiveness of a chip breaker is generally dependent on the ductility of the flowing chip, which itself is dependent on the properties of the work material and on the dimensions of the cut chip: the thinner the chip is, the harder it is to deform or break.

If some aspect of the machining operation, such as the roughness of the work surface or the weakness of the workpiece or tool, forces a thin chip to be produced, then chip form and flow cannot be controlled with any certainty. In such cases, machining ductile copper-based materials will almost inevitably lead to the formation of tangled chips. In order to limit the operational disruption caused by this type of chip, this stage of the machining process has to be carried out using a small depth of cut, as this lowers the strength of the cut chip by reducing its width.

Notwithstanding the above remarks, a chip breaker is unnecessary in situations in which it would be either useless (thickness of uncut chip is small) or superfluous because the machining operation involves interrupted cutting (as in, for example, milling), or because the chip is forced to flow in a specific direction dictated by the geometry of the cutting operation (as in drilling or tapping).

7 Cutting fluids

Some copper-based materials are machined dry whereas others are machined while applying a cutting fluid. On some machine tools, the use of a cutting fluid is essential as the cutting fluid also serves to lubricate parts of the machine.

During machining, the cutting fluid does not normally penetrate to the root of the chip so that there is no direct influence of the tool's cutting edge at the tool-work contact zone. However, the cutting fluid can have an indirect effect on processes at the contact zone as cooling the workpiece and the tool increases the temperature gradient that transports heat away from the work-tool interface. Additionally, the cutting fluid can quench the upper side of the chip and therefore facilitate the curvature and/or fracturing of the chip. Finally, the cutting fluid also flushes clean the machining area.

Whether a cutting fluid functions more as a coolant or as a lubricant depends on the machining operation being performed and the cutting tool used. As HSS tools only retain their hardness up to the tempering temperature of around 550–600 °C, cutting fluids are used primarily as coolants when machining with HSS. In contrast, carbide tools can maintain their hardness up to higher temperatures.

If, on the other hand, the tool has several regions that are in direct contact with the workpiece but that do not contribute to the material removal process (as is the case with reamers and taps), then the cutting fluid is more important as a lubricant than as a coolant.

If the machine tool manufacturer does not specify the cutting fluid to be used, emulsified oils are generally preferred when cooling is the predominant aim.

The favourable cooling properties of these oil-in-water emulsions are due to the high specific heat capacity of water. If, though, lubrication is the primary concern, cutting oils are preferred to emulsions. Low viscosity oils are favoured as they are easier to deliver and remove from the cutting zone.

Cutting oils with added sulphur can show a propensity to react with copper. Therefore, either a sulphur-free cutting oil should be used or the workpiece should be rinsed immediately after machining [24].

In cases in which normal cooling-lubrication by a stream of cutting fluid ('flooding') is not applicable, the fluid can be applied as a high-speed mist.

In mist application, the cutting fluid is carried in a pressurized air stream and deposited in the cutting zone. The expansion of the air stream is accompanied by a temperature drop that also aids cooling (e.g. when tapping threads using cutting oil on multistation machines, which are normally operated with emulsified oils).

Besides conventional flood-cooling, copper-based materials can also be subjected to neardry machining, in which a minimum quantity lubrication (MQL) system is used, or dry machining in which no cutting fluid is used [25]. Both approaches are technologically feasible for machining copper alloys.

Which cutting fluid is used in practice depends not only technological feasibility, but frequently also on factors determined by the machine tool set-up, such as chip removal, heat dissipation, lubrication of machine parts, and the possibility of influencing chip breakage.

8 Calculating machining costs

Cutting parameters can be optimized using purely computational methods provided that only one parameter is optimized at any time [26]. However, if, as is often the case in practice, several cutting parameters can be varied simultaneously, a purely mathematically based optimization is not usually possible.

Typically, the cutting parameters are determined and optimized by adopting a stepwise approach [26] that begins by identifying those parameters that can be regarded as fixed. Which parameters these are depends on the particular machining operation used. It could be the depth of cut ap, which is limited by the specified stock allowance, or, as is frequently the case, the cutting speed v_c, which is limited by the rotational speed range of the machine tool and the diameter of the part being machined. A further example of such a fixed parameter is the number of teeth on the milling cutter selected for use. These fixed value parameters are then adopted as such in the calculation.

Those parameters that are not predetermined are then arranged in order of increasing size of their exponents in the expanded Taylor tool life equation (Eq. 8).

$$T = \frac{C_1}{a_p^{e_a} \cdot f^{e_f} \cdot v_c^{-k}} \qquad (8)$$

This usually results in the following sequence of parameters: depth of cut ap; feed f (or thickness of the uncut chip h); and cutting speed v_c.

The depth of cut ap should initially be chosen to be as large as possible, provided, of course, that it was not identified as a fixed parameter (resulting, for example, from a specified stock allowance) in the first stage of the optimization process. Further adjustments to ap are then made in order to take account of the constraints set by the tool, work material and the machine tool. Selecting the largest possible depth of cut reduces the number of cuts required. Having determined the initial value of the depth of cut a_p, the feed f should then also be selected to be as large as possible. Here, too, the value selected will be limited by factors relating to the tool, work material and machine used.

The optimization of the cutting parameters has thus been reduced to determining the cutting speed v_c as a function of the specified tool life T. Generally speaking, the relationship between cutting speed and tool life can be expressed using the simple Taylor equation (Eq. 6):

$$T = C_v \cdot v_c^{\,k} \qquad (6)$$

In the range of cutting speeds typically used, the achievable tool life T decreases with increasing cutting speed v_c and vice versa. A higher value of v_c will also reduce the machining time t_h thus lowering the machining time costs per workpiece, but as it also reduces the tool life T, it causes an increase in the tool cost per workpiece K_W. As these two costs evolve in opposite directions, their sum per workpiece passes through a minimum at a certain cutting speed v_{oK}. Fig. 22 shows how the various cost components vary as a function of cutting speed and identifies the location of the cost-optimized cutting speed v_{oK}. Any deviation from this cost-optimized cutting speed voK will increase the unit cost of production as either the machining time or the tool costs will rise.

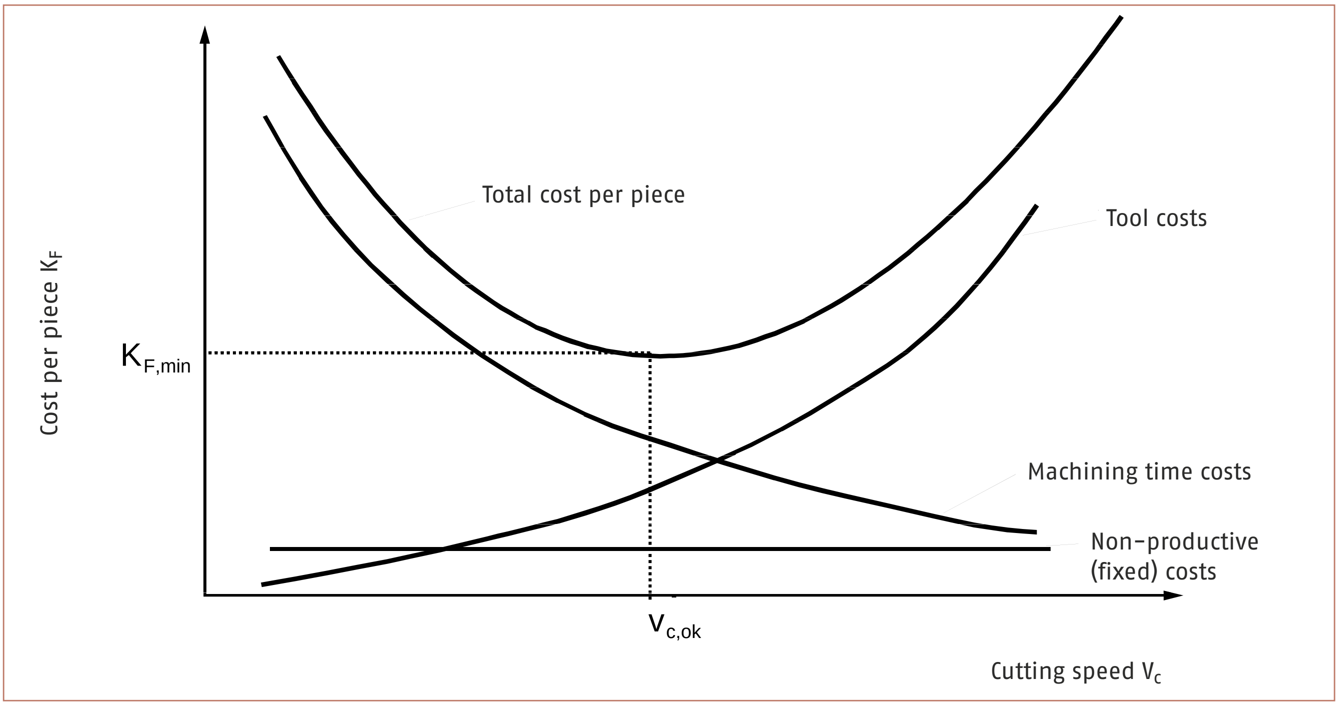


Fig. 22: Cost components plotted as a function of cutting speed (VDI 3321)

The cost-optimized tool life T_{ok} can be derived with the aid of equations 6 and 24. Differentiation and rearrangement yields Eq. 25:

$$T_{oK} = \frac{(-k-1) \cdot K_{WT}}{R} \quad (25)$$

where:

T_{oK} = Cost-optimized tool life in min

k = Gradient of straight line in tool-life plot

K_{WT} = Tool costs per tool life in € as defined in Eq. 22

K_{ML} = Cost rate for operator and machine + labour and machining overheads in €/h

t_w = Tool change time

Equation 25 shows how the cost-optimized tool life T_{oK} depends on the exponent -k, the tool costs per tool life K_{WT}, the cost rate for operator and machine (including labour and machining overheads) K_{ML} and the tool change time tw. The magnitude of the exponent -k depends on the work material/tool material pair and from the machining operation in use.

The exponent -k is large for HSS tools and/or work materials that are difficult to machine, but smaller for cemented carbide tools and/or work materials that are easy to machine. It therefore follows that, all other machining conditions being equal, a material that is difficult to machine will require a larger value of the cost-optimized tool life ToK. It is, however, not always possible to meet this requirement in practice.

If the calculated value of T_{oK}, and thus v_{oK}, lies outside the tool life range typically used in practice, the optimum value achievable under the given operating conditions is that value which comes closest to the ideal calculated value.

As a general rule, expensive tools should be used in combination with low values of the cutting parameters and on machine tools that are economical to run. On the other hand, low-cost tools can be used in combination with the maximum technically realizable cutting parameters and on machine tools that are more expensive to run.

Similar calculations can be carried out to determine the time-optimized cutting speed v_{ot}, i.e. the cutting speed that minimizes machining time per workpiece [26]. This will not be discussed further here as there is generally no significant difference between v_{oK} and v_{ot}.

If a number of (possibly different) tools are being used simultaneously to machine a part, Equation 25 has to be modified as K_{WT} now represents the sum of the tool costs for each of the cutting tools being used simultaneously. The value calculated for the cost-optimized tool life T_{oK} will therefore be greater than when a single tool is used [27, 28].

9 Ultra-precision machining of copper

Copper finds widespread use in optical systems. Ultra-precision machining of copper can produce optical components with high-quality mirror surfaces and high dimensional accuracy. In this chapter we briefly explain the basic principles of ultraprecision machining and some of its applications, followed by an examination of the quality levels achievable and the technical constraints of the technique.

9.1 Principles of ultra-precision machining

Ultra-precision machining (also commonly known as diamond turning) differs from conventional machining techniques in the cutting material used. Monocrystalline diamond enables tools to be fashioned with very precise cutting edge geometry and low wear. The nose radii of such tools are typically around 50 nm. When combined with ultra-precision machining technology, diamond cutting tools can be used to fabricate optical surfaces with a surface roughness (R_a) of only a few nanometres (see Fig. 23).

One advantage of copper alloys and other non-ferrous metals is that they are very easy to machine with monocrystalline diamond tools. Steel cannot be machined with these tools because of the chemical affinity of iron for carbon [21, 29, 30].

The key features of ultra-precision machine tools are the aerostatic or hydrostatic guide systems, air spindles and linear direct drives. To achieve a high level of thermal stability and good damping characteristics, granite is the preferred material for the base of the ultra-precision machine.

The two main ultra-precision machining techniques used with diamond cutting tools are turning and fly cutting. Turning enables a broad variety of geometries to be machined, and fast tool servo (FTS) systems now allow the fabrication of non-rotationally symmetric optical surfaces. Fly cutting can be thought of milling with a single-tooth milling cutter. The fly cutter typically has a single-point diamond cutting tool mounted on the periphery of a rotating disc. Fly cutting is used to produce flat surfaces or to create linear grooves. The geometry of the groove or slot is determined by the shape of the cutting tool (radius, facetted, v-form).

The quality of a surface produced by diamond cutting is slightly dependent on the cutting speed. Generally speaking, turning operations are performed at a constant spindle speed so that at the centre of the workpiece the cutting speed would be zero. Although the cutting forces exerted in ultra-precision machining are typically less than 1 N, machines of high rigidity are required in order to avoid vibrations and to achieve the required dimensional precision of less than 0.1 µm.

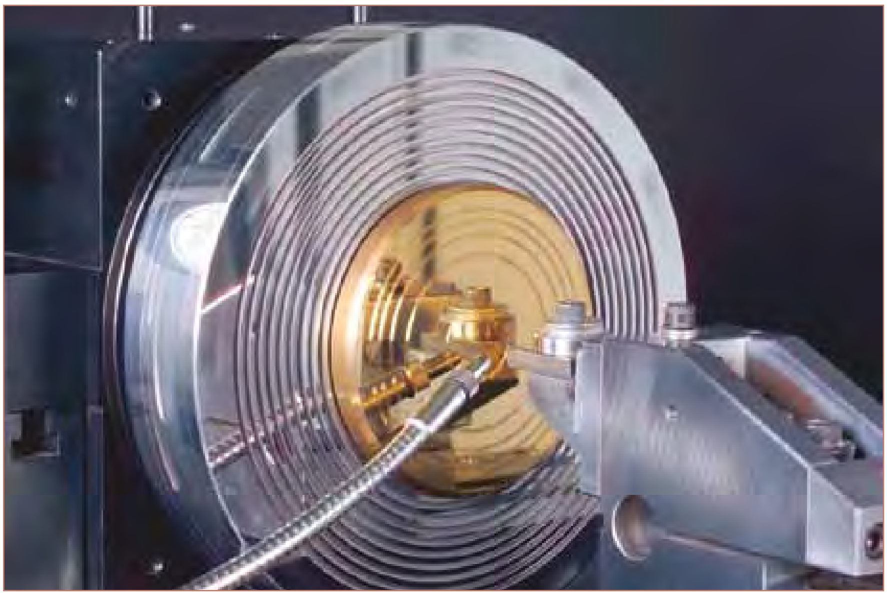


Fig. 23: Ultra-precision machining of a structured plane brass surface

The spindle speed chosen will depend on the diameter of the component being machined, the work material and the dynamics of the additional axes. Spindle speeds of up to 2500 rpm are typically used in the production of metal optics by ultra-precision machining. As in macro-scale machining, the feed is determined by the tool nose radius and the specified surface roughness. The depth of cut depends on the work material. For non-ferrous metals, recommended depths of cut for turning operations are 20–50 µm for roughing and about 3 µm for finish machining.

Ultra-precision machining lathes are generally equipped with a minimum quantity lubrication system. Isoparaffins are transported to the cutting zone in a pressurized air stream where they are atomized. In addition to lubricating, the MQL system also ensures that the chips are flushed from the cutting zone. The lubricants have a high heat of vaporization and do not therefore influence the cutting process by evaporative cooling [29].

9.2 Example applications involving copper alloys

Copper and copper alloys are used for different ultra-precision machining applications. Copper is widely used for fabricating optical components for laser systems. Copper is chosen not only because it permits fabrication of high-quality surfaces, but also, and importantly, because of its high heat capacity. Despite the high-quality surface finish and additional surface coatings, the mirror material can heat up thus deforming the shape of the mirror. To avoid such impermissible variations in form, the mirrors are cooled by means of internal cooling channels. In order to produce the best possible mirror surfaces, the copper that undergoes diamond turning should have the highest possible purity. The copper grade of choice is so-called OFHC (oxygen-free high-conductivity) copper. The mirrors produced are used not only to guide and focus the light beams, but also to shape the beams as well. By deploying FTS systems, non-rotationally symmetric surface structures can be created on the mirror surface. For example, multifaceted mirror surfaces can be created that act as beam homogenizers. In addition, the focus of the beam can be modified by using free-formed mirrors.

Besides being used for mirror optics, copper and copper alloys are also used to make the moulds for the injection moulding of polymeric optical components. Because of their greater hardness, copper-beryllium alloys are also used in such applications. However, according to the Restriction of Hazardous Substances Directive 2002/95/EC (RoHS), beryllium-containing components are subject to labelling requirements. Brass is used not only as a mould insert for the injection moulding of plastics, but also for the fabrication of micro-structured masters. Brass plate is the starting material for these structural masters, which can be up to one square metre in size. Replication masters of this kind are used, for example, in display applications where the grooved or pyramidal structures are machined by fly cutting.

9.3 Material properties and their influence on ultra-precision machining

The results of an ultra-precision machining operation depend not only on the cutting tool and the machine characteristics, but also on the properties of the work material. The copper and copper alloys used in engineering applications usually have a polycrystalline microstructure. This has to be taken into account when the required precision increases or when the dimensions of surface features decrease. A number of studies have been carried out on polycrystalline copper to examine the quality of the surface finish that can be achieved and the cutting forces that arise [29, 31]. The characteristics of the machined surface are strongly dependent on the material's grain structure and grain boundaries.
As a result of the so-called spring-back effect (compression of individual grains during the machining process), diamond cutting of a plane surface of OFHC copper can yield level differences of up to 40 nm between neighbouring crystals (see Fig. 24) [29].

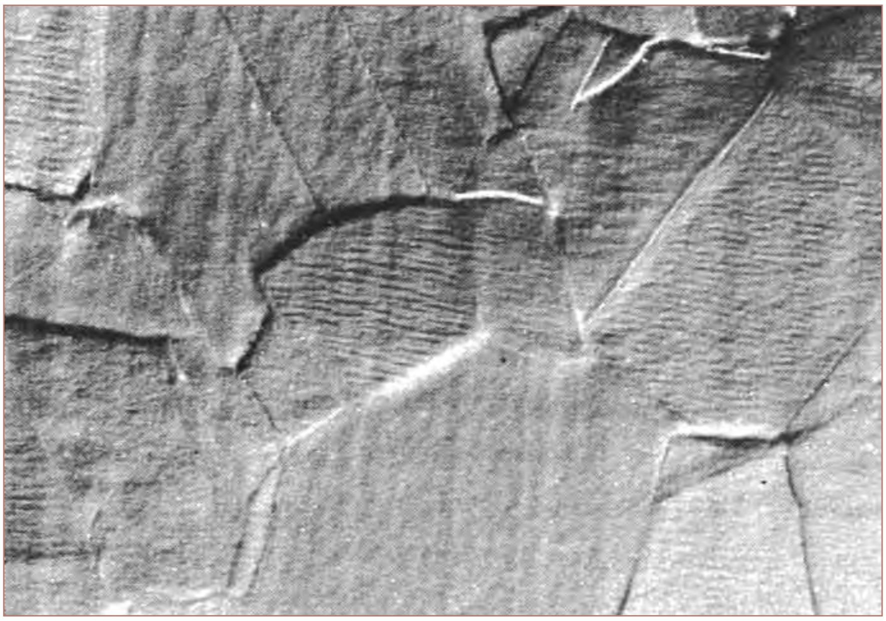


Fig. 24: Diamond cut surface of OFHC copper [29]

The formation of these surface structures is a result of the anisotropic behaviour of the work material. Due to the face-centred cubic (fcc) lattice structure of copper, the packing densities within the individual lattice planes differ, which results in elastic and plastic material properties that are strongly directionally dependent. For example, the modulus of elasticity of a copper single crystal varies between 68 and 190 kN/mm² depending on the load direction. In polycrystalline microstructures, these effects reinforce each other due to the different orientations of the grains in the microstructure. When a polycrystalline copper substrate is machined the individual grains in the microstructure therefore respond differently and this leads to the variation in levels described above.

The effects of grain structure are also apparent in the microstructuring of the substrate surface, particularly the formation of burrs along grooved structures. Figure 25 depicts V-shaped grooves with a depth of 7 µm that have been produced by plunge-cut turning in the surface of a piece of OFHC copper. The burr formation along the edges of the grooves varies with the grain structure of the copper, which has been made visible here by etching.

As the material properties change in the vicinity of the grain boundaries, machining conditions and therefore burr formation change accordingly. In the material shown here, the grain size is in the range 50–80 µm. The homogeneity of the microstructure can be improved by reducing the grain size. Microcrystalline copper materials can be produced by severe plastic deformation (SPD). One such SPD technique is the ECAP method (Equal Channel Angular Pressing) with which a high degree of deformation

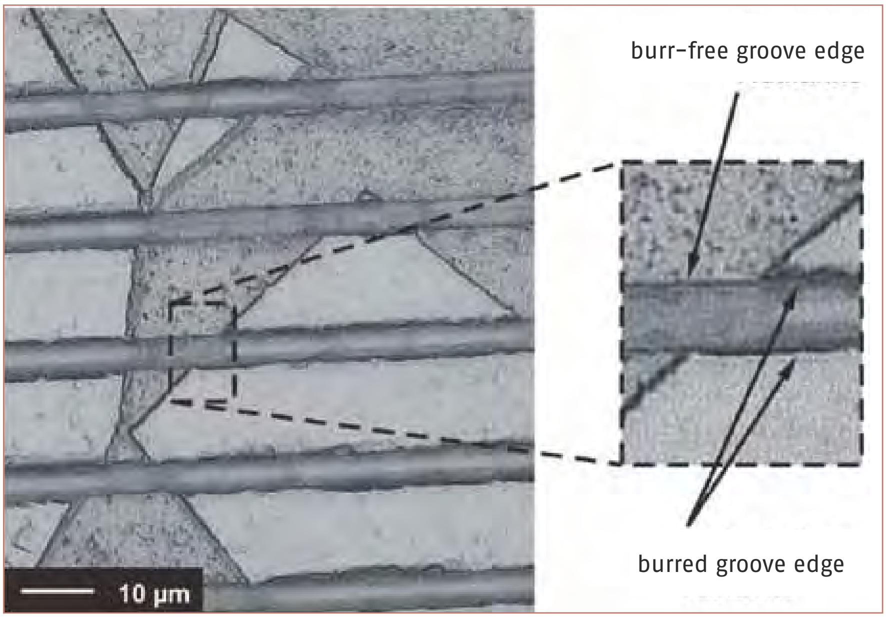


Fig. 25: *Grain-structure-dependent burr formation [32]*

can be achieved thus generating severe dislocations within the material. Samples of material produced by ECAP have already been successfully used in microstructuring tests [32]. Nevertheless, diamond cutting of OFHC copper can produce surfaces with a roughness parameter R_a down to 3 nm [29].

10 Recommended machining parameters for copper and copper alloys

The tables of recommended machining parameters list suggested cutting speeds for machining operations such as turning and milling as a function of the undeformed chip thickness. The following procedure can be used to identify the correct machining parameters:

If the material to be machined is standardized, locate the material in Tables Table 9 to Table 11 and note down its machinability rating and the tool geometry designator. If the material has not been standardized, select the most similar alternative material based on the main alloying components.

Use the material's machinability rating to determine the recommended machining parameters in Table 13 to Table 19 for the machining operation of interest.

Use the tool geometry designator to determine the recommended tool geometry from Table 12.

As machinability depends on the strength and hardness of the work material, tensile strength and Brinell hardness data are included in Table 9 to Table 11. If the material strength or hardness differs from the values given, the recommended machining parameter determined by the machinability index will need to be interpolated or extrapolated accordingly.

In the following sections we discuss and explain the recommended machining parameters for a variety of machining operations.

10.1 Turning of copper and copper alloys

The values quoted in Table 13 are estimated to be valid in about 70 % of cases. They are based on a flank wear land width of VB ≈ 0.6 mm at the end of the tool's life, and a tool life of T = 30–60 min for carbide cutting tools in group N10 (N20), or T = 45–90 min for HSS cutting tools (HS10-4-3-10).

If the tool life T is to be doubled, the value of v_c should be reduced by about 16 % for carbide tools and by about 10 % for HSS tools. However, in the case of ductile, high copper content materials, doubling the tool life T of a carbide tool requires a reduction in the cutting speed v_c of around 30 %.

If the tool life is defined as the cutting time to reach a flank wear land width of VB ≈ 0.4 mm, then to achieve the same tool life T as that based on a value of VB ≈ 0.6 mm, the cutting speed v_c would need to be reduced by about 35 % for carbide tools and by about 15 % for HSS tools.

Uninterrupted cutting has practically no effect on the service life of HSS tools; if carbide tools are used, a reduction in the cutting speed v_c of about 10 % is recommended.

When turning is performed on a cast part with a normal sand-textured skin, the cutting speed should be reduced by about 15 % when carbide cutting tools are used and by about 20 % for HSS tools.

When machining copper materials with a strain hardened skin, the machinability of the material is determined by the machinability of the skin, which is itself dependent on the hardness of the skin layer.

For turning operations in which chip flow is restricted, such as form turning, groove cutting, parting off and threading, the cutting speed vc should be lowered by about 40 % when carbide tools are used and by about 50 % when HSS turning tools are deployed.

If an HSS grade other than HS10-4-3-10 is used, the following correction factors apply:

HSS	**Faktor for v_c**
HS10-1-4-5	0,82
HS12-1-4	0,76
HS6-5-2	0,72
HS2-9-1	0,65

It is not uncommon that the recommended cutting speeds in Table 13 cannot be attained in practice due to constraints such as limits to the maximum achiev-

]Machinability rating	Undeformed chip thickness h [mm]					
	Carbides			HSS		
	0,1	0,32	0,8	0,1	0,32	0,63
100	1260	1000	800	154	85	60
90	1150	910	730	142	79	57
80	1030	800	660	130	74	53
70	910	730	580	117	68	50
60	800	630	510	105	62	46
50	680	540	430	93	57	43
40	570	440	360	81	51	39
30	450	360	284	68	46	36
20	220	160	120	36	28	22

Table 13: *Recommended machining parameters for turning copper and copper alloys*
Recommended cutting speeds v_c in m/min as a function of the undeformed chip thickness h in mm and the machinability rating

Machinability rating	*HSS*	*Solid carbide D = 3 - 20 [mm]*	*Carbide inserts*
	v_c [m/min]	*v_c [m/min]*	*v_c [m/min]*
100	80	250	400
90	74	239	373
80	69	228	345
70	63	216	318
60	58	205	290
50	52	194	263
40	46	183	235
30	41	171	208
20	35	160	180

Table 14: *Machining parameters for drilling copper and copper alloys*
Recommended cutting speeds v_c in m/min for HSS, solid carbide and index-able-insert drills as a function of the machinability rating

Diameter D [mm]						
		3 - 5	5 - 8	8 - 12	12 - 16	16 -20
Feed f [mm]	HSS	0,1 - 0,16	0,16 - 0,25	0,25 - 0,32	0,32 - 0,4	0,4 - 0,5
	Carbide	0,08 - 0,12	0,12 - 0,18	0,18 - 0,23	0,24 - 029	0,3 - 0,35

Table 15: *Feeds for drilling copper and copper alloys*
Recommended feed as a function of drill diameter

able spindle speed or when a workpiece with a very small diameter is being machined. In such cases, the machining parameters have to be adjusted to take account of the particular machining operation and the prevailing cutting conditions.

10.2 Drilling and counterboring of copper and copper alloys

Copper-based materials are generally drilled using HSS twist drills. These are supplemented by solid carbide drills, indexable-insert drills and (deep-hole) gun drills. Recommended cutting speeds for HSS, solid carbide and indexable-insert drills are listed in Table 14.

The feed rate to be used during a drilling operation depends on the work/tool material pairing, but primarily on the drill diameter. The required feed per revolution increases with increasing drill diameter. Recommended feed values are listed in Table 15 as a function of drill diameter and the tool material.

Because the properties of copper-based materials span such a broad range, the choice of drill type and/or cutting-edge geometry depends on the type of material to be drilled: Copper alloys that yield short, fragmented chips are drilled using type H drills (cf. DIN 1414, sheet 1 and 2), type N drills are chosen for materials producing longer curled chips, while type W drills are used for those materials that yield extremely long continuous chip forms. The removal of long tough chips is easier in type W HSS drills that have polished or chromeplated flutes.

Type H drills correspond to a class A cutting-edge geometry, type N drills to class B, and type W drills to class C (Table 12).

Commercially available carbide drills include drills with brazed carbide tips, solid carbide drills or drills with indexable carbide inserts.

Carbide indexable insert drills prove to be the most economical tools when drilling holes with diameters greater than about 18 mm (and lengths up to about 2.5 • d). Type N and type H drills can be used if the machine is sufficiently rigid and sufficiently powerful. Whether these drill types can be used to drill copper-based materials that produce long continuous tough chips depends on the availability of indexable inserts with chip breaker grooves.

Drills with internal cooling holes are recommended for drilling deep holes. The cutting fluid flows through the coolant hole and can therefore be delivered more easily to the drill's cutting edges as well as helping to flush the chips away from the cutting zone.

Gun drills are used to drill extremely deep holes (L > 10 • d) whenever high demands are placed on the dimensional tolerances, alignment and surface quality of the bore hole wall.

Other rules apply when drilling with gun drills but will not be discussed further here. Suffice to say that the geometry of the tool's cutting-edge and the feed rate depend primarily on achieving a chip form that can be easily removed from the cutting zone.

In drilling operations, the range of achievable cutting speeds is determined by the chip formation process. Within this range, the cutting speed v_c is selected primarily on the basis of the tool costs per tool life, K_{WT}, that itself depends on the type of drill used, its diameter and length. The cutting speed also depends on whether the margin of the drill rubs against the walls of a drill guide bushing, and on how easily the cutting fluid is able to reach the cutting tip. This is why when using a drill that does not have coolant channels the choice of cutting speed v_c depends not only on the position of the drill during drilling (horizontal or vertical), but also on the depth of the hole being drilled.

Finally, the choice of cutting speed is influenced by the work material. Despite higher initial purchase costs, a cutting tool material with a longer tool life can result in a significant reduction in the machining costs per hole.

In addition to the above criteria, the geometry of the hole to be produced must also be taken in to account when selecting v_c and f. When drilling through-holes, the outer corners of the drill tip are subject to increased wear during drill breakthrough. It is therefore advisable to reduce the cutting speed and the feed rate by about 5 %

Machinability rating	HSS		Hole diameter d [mm]					
	uncoated	coated	5	10	16	25	40	63
	v_c [m/min]		f [mm]					
100	14	19	0,15 – 0,2	0,2 – 0,3	0,25 – 0,35	0,4 – 0,5	0,4 – 0,5	0,6
90	13	18						
80	13	17						
70	12	16						
60	11	15						
50	10	14						
40	10	13						
30	9	12						
20	8	11						

Table 16: *Recommended machining parameters for reaming copper and copper alloys with HSS reamers*
Recommended cutting speeds v_c in m/min as a function of the machinability rating and recommended feeds f in mm as a function of the hole diameter

Machinability rating	Carbide		Hole diameter d [mm]				
	HC – N10	5	10	16	25	40	63
	v_c [m/min]	f [mm]					
100	30	0,2 – 0,3	0,3 – 0,4	0,35 – 0,45	0,4 – 0,5	05 – 0,6	0,6
90	27						
80	25						
70	22						
60	19						
50	16						
40	14						
30	11						
20	8						

Table 17: *Recommended machining parameters for reaming copper and copper alloys with solid carbide reamers*
Recommended cutting speeds v_c in m/min as a function of the machinability rating and recommended feeds f in mm as a function of the hole diameter

during exit; this restriction does not apply when drilling blind holes.

For countersinks and core drills (as detailed in DIN 343, 344, 222 and in DIN 8043, 8022), the machining data can be derived from the corresponding data for HSS drills: the cutting speed v_c should be reduced by 30 %, while the feed f should be increased by 100 %.

10.3 Reaming copper and copper alloys

The service life of a reaming tool depends more on the dimensional tolerances of the hole to be machined than on the work material. Under favourable conditions, the most cost-effective tool life T_{oK} can be achieved down to a tolerance grade of IT 8. If tolerances are tighter, it is generally not possible to achieve the optimum tool life.
The cost-optimized cutting speed v_{oK} for reaming operations is therefore significantly lower than the values that are typically recommended. Recommended values for reaming operations are listed in Table 16 and Table 17.

In contrast, quite high feeds f can be selected for reaming because the tool feed has only a relatively minor effect on the number of holes that can be reamed per tool life, on the conformity to prescribed tolerances and on the surface roughness of the hole wall.

The specified reaming allowance should not be too small and should be roughly equal to the allowance typically assumed in countersinking. A tool cutting edge angle κ_r of about 45° is generally selected for short-chip alloys, while an angle of approximately 30° is typical for long-chip materials. Smaller angles tend to cause the reamer to seize, reducing tool life without improving the quality of the surface finish. It is important that the reamer runs sufficiently true at the start of the cut and that the transition from the lip to the margin is slightly curved.

The end of the tool life should not be determined by the dimensional accuracy of the reamed hole, but rather by a flank wear land width of $VB \approx 0.3$ mm at the lip. Failure to adopt this wear criterion will result in a significant reduction in the number of regrinds possible, thereby substantially increasing the tool costs per piece.

The roundness of a hole produced by a multiflute reaming tool tends to adopt a multi-cornered polygonal profile with one 'corner' more than the number of cutting edges on the tool. Choosing a reamer with an odd number of cutting edges does not, however, eliminate this problem, though it can be reduced significantly by using reamers with very irregularly spaced flutes. When reaming ductile materials, or when reaming through-holes, the surface finish of the hole can be improved by using a tool in which the direction of the flute helix is opposite to that of the cut (e.g. left-hand helix, right-hand cut) as this ensures that the chips are pushed ahead of the tool as it progresses into the hole.

Cutting oils are recommended when performing reaming operations.

Tooling costs can be reduced if a reamer with an indexable cutting insert can be used instead of a solid multiflute reamer for the reaming operation of interest.

10.4 Tapping and thread milling copper and copper alloys

Selecting the right type of tap is crucial if a tapping operation is to be successful. The choice of tap depends on the work material and the geometry of the required thread. Recommended cutting speeds are listed in Table 18.

Straight-flute taps are generally used for short-chip alloys and spiral-point taps are usually chosen when tapping through-holes as they tend to eject the chip ahead of the tool. This is not possible when tapping blind holes, for which taps with bottoming style chamfers are used.

Straight-fluted, spiral-point taps with a pitch of up to about 2 mm are also used to cut threads in through-holes or relatively deep holes in long-chip materials. However, taps with a right-hand helix are used to cut (right-hand) threads in blind holes. Helix angles of about 15°, 35° and 45° are readily available commercially. The greater the L/d ratio and the tougher the chip formed, the larger the helix angle should be.

Besides tapping, internal threads can also be cut by thread-milling. Coated carbide thread mills can cut threads in brass at cutting speeds of 200–400 m/min. If uncoated tools are used, the cutting speeds should be reduced by 25 %. The feed per tooth fz is typically in the range 0.05 to 0.15 mm. The lower end of the range should be selected if machining long-chip brasses. Cutting speed and feed in

Machinability rating	Carbide N10	HSS	
		uncoated	coated
	v_c [m/min]		
100	40	20	30
90	39	19	29
80	38	19	28
70	36	18	26
60	35	17	25
50	34	17	24
40	33	16	23
30	32	15	22
20	30	15	20

Table 18 : *Recommended cutting speeds for tapping copper and copper alloys*

thread milling operations also depend on the diameter of the thread: the greater the thread diameter, the higher the cutting speed and the larger the feed per tooth that can be selected. If unalloyed copper is being machined, the cutting speeds can be increased by about 25 % and the feeds doubled.

10.5 Milling copper and copper alloys

In face milling, the machined surface is produced by the cutting edges on the end face. If the surface is produced by the cutting edges on the outside periphery of the cutter, the technique is known as peripheral milling. If the peripheral cutting edges are not straight, but profiled, the so-called form milling cutter generates a shaped surface determined by the form of the tool's peripheral cutting edges.

If both types of milling operation can be used for a particular job, face milling is generally more economical. In face milling an uncut chip thickness of zero does not usually arise. Very thin chip thicknesses at the start of the cut can cause rubbing between the cutting edges and the workpiece surface, spoiling surface quality and promoting tool wear. Furthermore, the minor cutting edges dull more quickly than the major cutting edges whose wear during face milling is not of primary importance in determining the roughness of the milled surface.

In contrast, peripheral milling has the advantage that it can produce geometrically complex shapes in a single pass. However, in peripheral milling the roughness of the machined surface is directly determined by the state of the major cutting edges.

We can distinguish two types of peripheral milling depending on the direction of rotation of the milling cutter. In 'up milling' the direction of motion of the cutter's teeth when they engage with the work is opposite to the feed. In 'down milling' or 'climb milling' the direction of motion of the teeth when they cut into the work is the same as the feed direction.

If the work material does not have a hard, wear-inducing skin, down milling is normally preferred to up milling as down milling results in less rubbing between the cutting teeth and the work surface, and the cutting forces are more favourably distributed. However, when copper and copper alloys are being machined, the resulting difference in tool life is not large.

The cutting materials typically used for milling copper-based materials are the

Machinability rating	*Face milling with indexable inserts*			
	HM – N10 uncoated		*DP – N05*	
	h_z in mm			
	0,1	*0,2*	*0,1*	*0,2*
100	580	540	1050	1000
90	554	516	1006	954
80	530	494	963	910
70	507	472	923	868
60	484	451	884	829
50	463	431	847	791
40	443	412	811	754
30	423	394	777	720
20	405	377	744	687

Table 19: *Machining parameters for face milling of copper-based materials using in-dexable teeth*
Recommended cutting speeds v_c in m/min as a function of the undeformed chip thickness h_z in mm and the machinability rating

Peripheral milling with an end milling cutter								
Machinability rating	Tool material				f_z in mm			
	HSS		solid carbide		Diameter of mill cutter in mm			
	uncoated	coated	uncoated	coated	1	6	12	20
100	45	80	140	280	Roughing			
90	41	73	120	230	0,004–0,006	0,01–0,02	0,04–0,5	0,05–0,07
80	38	67	110	210				
70	35	61	100	200				
60	32	56	96	190	Finishing			
50	29	52	92	180	0,004–0,006	0,01–0,02	0,04–0,5	0,05–0,07
40	27	47	87	175				
30	24	43	85	165				
20	22	40	80	160				

Table 20: *Machining parameters for peripheral milling of copper-based materials using end milling cutters*
Recommended cutting speeds v_c in m/min and feeds per tooth f_z in mm as a function of the diameter of the milling cutter and the machinability rating

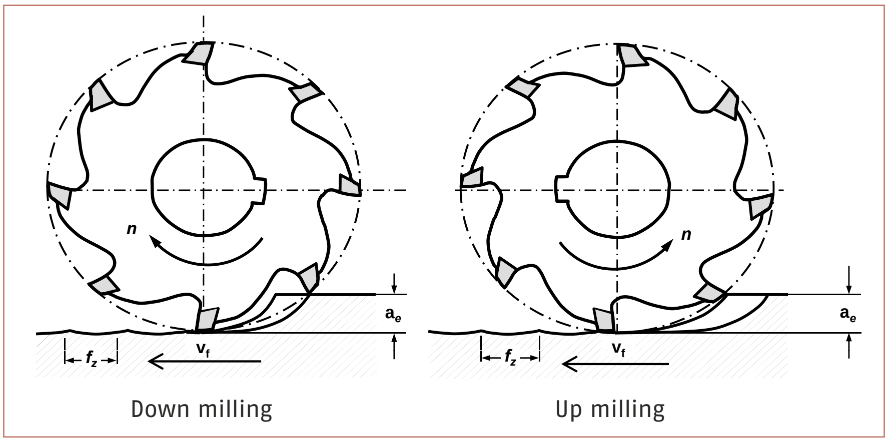
carbide application groups N10 and N20, and the HSS grades HS6-5-2, HS6-5-2-5, HS2-9-1-8 and HS12-1-4-5.
In milling operations, the undeformed chip thickness per tooth and per revolution h_m is typically in the range 0.1–0.35 mm. Face milling cutters and heavy cutting tools tend to be at the upper end of this range, while peripheral and weaker tools are located in the middle to lower region. The undeformed chip thickness in a face milling operation is determined by the feed per tooth and revolution f_z and the cutting edge angle κ as follows:

$$h_m = \frac{114{,}6°}{\varphi_s°} \cdot f_z \cdot \sin(\kappa) \frac{a_e}{D} \qquad (25)$$

In peripheral milling, the chip is curled somewhat like a comma with one of its ends having, in theory at least, zero thickness. The average thickness of the undeformed chip is given by the following equation:

$$h_m = \frac{114{,}6°}{\varphi_s°} \cdot f_z \cdot \frac{a_e}{D} \qquad (26)$$

where:
h_m = Undeformed chip thickness per tooth and revolution
f_z = Feed per tooth and revolution
κ_r = Tool cutting edge angle
φ_s = Angle of cutter engagement
h_m = Average thickness of undeformed chip
a_p = Depth of cut (feed)
a_e = Working engagement (radial depth of cut)
D = Diameter of milling cutter



Down milling
Up milling

Fig. 26: *The ‘down’ and ‘up’ forms of peripheral milling*

As milling cutters vary significantly in terms of the number of cutting teeth they have and the associated tool costs, the recommended cutting speeds v_c can provide only broad guidance. The values listed in Table 19 refer to face milling operations using indexable inserted tooth cutters made from uncoated carbide or polycrystalline diamond.

If the cutting speed v_c is reduced by about 10 %, the tool life can be effectively doubled; if the cutting speed is increased by 10 %, the tool life will be halved.

If milling a material with a typical sand-cast skin, the cutting speed of a carbide milling cutter should be reduced by about 15 %, that of a HSS tool should be lowered by around 20 %.

The recommended speeds are based on a flank wear land width of VB ≈ 0.6 mm at the end of the tool’s life (rough milling). If the tool life is defined to be the machining time to reach a flank wear land width of VB ≈ 0.4 mm, then to achieve the same tool life as that based on VB ≈ 0.6 mm, the tabulated values would need to be reduced by about 50 % for carbide tools and by about 30 % for HSS tools.

11 Appendix

11.1 Sample machining applications

Alloy group		Material			Machinability and processability	Typical applications	Machinability rating
		Designation	Number (EN)	Number (UNS)			
Wrought copper alloys	Low-alloyed copper alloys – non-age-hardenable	CuPb1P	CW113C	C18700	–	–	85 (no P)
		CuSP	CW114C	C14700	Good machinability; free-cutting copper	Screw-machine products, machine-turned parts; screws; nuts; nozzles for welding and cutting torches; valve seats for fittings	85
		CuTeP	CW118C	C14500	Good machinability; free-cutting copper	Nozzles for welding and cutting torches; screws	85
	Copper-nickel-zinc alloys	CuNi7Zn39Pb3Mn2	CW400J	–	–	–	–
		CuNi10Zn42Pb2	CW402J	C79800	–	–	–
		CuNi12Zn30Pb1	CW406J	C79300	–	–	–
		CuNi18Zn19Pb1	CW408J	C76300	–	–	–
	Copper-tin-zinc alloys	CuSn3Pb7Zn9		C84400	–	–	90
		CuSn4Zn4Pb4	CW456K	C54400	–	General plain bearings; electrical connectors; contacts; toggle lever bearings	80
	Leaded binary copper-zinc alloys	CuZn35Pb2	CW601N	C34200	–	–	90
		CuZn36Pb2As	CW602N	C35330	–	Sanitary fittings	(85)
		CuZn36Pb3	CW603N	C35600	Good machinability and cold workable; main alloy in USA for use on screw machines and machining centres	Screw-machine products, machine-turned parts; pins; precision machined parts for clocks, watches and optical applications	100
		CuZn37Pb0,5	CW604N	C33500	–	–	60
		CuZn39Pb0,5	CW610N	C36500	–	Contact pins	60
		CuZn38Pb1	CW607N	C37000	–	–	70
		CuZn38Pb2	CW608N	C37700	Good machinability and cold workable	Valve components, optical and precision machined parts	80 (90)
		CuZn39Pb2	CW612N	–	Excellent machinability and drilling/milling quality; good stamping/punching quality	Watch and clock movements; terminal strips; electrical connectors	(85)
		CuZn39Pb3	CW614N	C38500	Excellent machinability; main alloy in Europe for use on screw machines and machining centres; form turned parts	Form turned parts; precision machined parts; clock and watch components; electrical applications; ball pen tips	90 (100)
		CuZn40Pb2	CW617N	C37700	Excellent machinability; good hot workability; extruded sections	Form turned parts of all kinds; precision machined parts; clock and watch components	80 (95)
		CuZn43Pb2Al	CW624N	–	–	–	–
	Multi-component copper-zinc alloys	CuZn40Mn1Pb	CW720R	–	–	Roller bearing cages; screw-machine products	–
		CuZn21Si3P	CW724R	C69300	–	Lead-free machining alloy	–

Table 21 a: *Machinability classification of standardized copper-based materials*

Machinability group I: Copper alloys with excellent machining properties

Alloy group		*Material*			*Machinability and processability*	*Typical applications*	*Machinability rating*
		Designation	*Number (EN)*	*Number (UNS)*			
Copper casting alloys	*Copper-zinc casting alloys*	*CuZn33Pb2-C*	*CC750S*	–	–	*Gas and water valve bodies*	–
		CuZn39Pb1Al-C	*CC754S*	–	–	*Valves for gas, water and sanitary installations*	–
	Copper-tin and copper-tin-zinc casting alloys	*CuSn3Zn8Pb5-C*	*CC490K*	–	*Medium-hard structural material; good castability; corrosion-resistant to fresh water even at raised temperatures*	*Thin-walled valves (wall thickness up to 12 mm) suitable for applications up to 225 °C.*	*90*
		CuSn5Zn5Pb5-C	*CC491K*	*C83600*	*Structural material; good castability; good solderability, moderate brazeability; good corrosion resistance*	*Water and steam valve bodies for applications up to 225 °C; regular-duty pump housings; thin-walled castings of complex geometry*	*90*
		CuSn7Zn4Pb7-C	*CC493K*	*C93200*	*Medium-hard material with good anti-seizure properties*	*Moderate-duty plain bearings*	*70*
		CuSn5Zn5Pb2-C	*CC499K*	–	*Structural material; good castability; good solderability, moderate brazeability; good corrosion resistance*	*Fittings, valves and pump housings particularly for drinking water applications*	*90*
		CuPb10Sn10-C	*CC495K*	*C93700*	*Good self-lubricating properties*	*Plain bearings with high surface pressure*	*80*
	Copper-lead and copper-tin casting alloys	*CuSn7Pb15-C*	*CC496K*	*CC93800*	–	*Plain bearings; composite bearings*	*80*

Table 21b: *Machinability classification of standardized copper-based materials*

Machinability group I: Copper alloys with excellent machining properties

Alloy group		Material			Machinability and processability	Typical applications	Machinability rating
		Designation	Number (EN)	Number (UNS)			
Wrought copper alloys	Low-alloyed copper alloys (alloying elements < 5 %) – hardenable in cold-worked state	CuBe2	CW101C	C17200	–	High-strength parts	20
		CuCo2Be	CW104C	C17500	High-temperature stability	Resistance welding electrodes	40
		CuCr1Zr Standard does not define state for stamped, cold formed material	CW106C	C18150	High-temperature stability	Resistance welding electrodes; contact elements	20
		CuNi1Si	CW109C	–	–	Heavy-duty screws, nuts and bolts; roller bearing cages; spray nozzles; bearing bushes, applications for hardened states	–
		CuNi2Si	CW111C	C64700	High tensile strength	In hardened state	–
		CuNi3Si1	CW112C	C70250	High tensile strength	Mould inserts	–
	Low-alloyed copper alloys (alloying elements < 5 %) – non-age-hardenable	CuSi3Mn1	CW116C	C65500	–	–	30
	Copper-tin alloy	CuSn5Pb1	CW458K	C53400	–	–	70
	Binary copper-zinc alloys	CuZn36	CW507L	C27200	Main alloy for cold working	Deep-drawn parts	–
		CuZn37	CW508L	C27400	Good solderability, weldability and cold workability	Screws; hollow riveting	35
		CuZn40	CW509L	C28000	–	Clock and watch cases	40
	Multi-component copper-zinc alloys	CuZn31Si1	CW708R	C69800	For sliding loads	Bearing bushes; guides	–
		CuZn35Ni3Mn2AlPb	CW710R	–	–	Marine propeller shafts	–
		CuZn37Mn3Al2PbSi	CW713R	–	Structural material of high strength for sliding applications	Synchronizer rings; plain bearings; valve bearings; gear components; piston rings	–
		CuZn38Mn1Al	CW716R	–	Structural material of medium strength for sliding applications	Plain bearings; sliding elements	–
		CuZn39Sn1	CW719R	C46400	–	Tube plates for condensers; marine propeller shafts	30
		CuZn40Mn2Fe1	CW723R	–	–	Valves; damper bars	–

Table 22a: *Machinability classification of standardized copper-based materials*

Machinability group II: Copper-based materials with good to moderate machining properties

Alloy group		**Material**			**Machinability and processability**	**Typical applications**	**Machinability rating**
		Designation	**Number (EN)**	**Number (UNS)**			
Copper casting alloys	*Copper-zinc casting alloys*	*CuZn16Si4-C*	*CC761S*	*C87800*	*High-strength parts for electrical engineering applications*	*High-strength and thin-walled parts for electrical engineering applications*	*40*
		CuZn25Al5Mn4Fe3-C	*CC762S*	*C86100*	–	*Worm wheel rims; inner parts of high-pressure valves*	*30*
		CuZn32Al2Mn2Fe1-C	*CC763S*	–	–	–	–
		CuZn34Mn3Al2Fe1-C	*CC764S*	–	–	*Valve parts; control elements; taper plugs*	–
		CuZn37Al1-C	*CC766S*	–	–	*Permanent mould castings for precision engineering applications*	–
		CuZn38Al-C	*CC767S*	–	–	*Permanent mould castings for electrical and mechanical engineering applications*	–
	Copper-tin casting alloy	*CuSn11Pb2-C*	*CC482K*	–	*Good anti-seizure properties*	*Heavy-duty plain bearings (high permanent and impact loads)*	–

Table 22b: *Machinability classification of standardized copper-based materials*

Machinability group II: Copper-based materials with good to moderate machining properties

Alloy group		Material			Machinability and processability	Typical applications	Machinability rating
		Designation	Number (EN)	Number (UNS)			
Kupfer-Knetwerkstoffe	Copper	Cu-OFE	CW009A	C10100	Highest electrical conductivity	Vacuum and electronic applications	20
		Cu-HCP	CW021A	–	High electrical conductivity; good weldability and brazeability	Slip rings for electric motors	–
		Cu-DHP	CW024A	C12200	Good weldability and brazeability	Fuel and oil pipes	20
	Low-alloyed copper alloys – non-age-hardenable	CuAg0,10	CW013A	C11600	–	Contacts; commutator rings	20
		CuAg0,1P	CW016A	–	Good solderability, brazeability and weldability	Contacts; commutator rings	–
		CuSn0,15	CW117C	C14200	–	Connector pins	20
	Low-alloyed copper alloys (alloying ele-ments < 5 %) – hardenable in cold-worked and precipitation-hardened state Several states – variations as per the EN 12163 standard – see unhardened state	CuBe1,7	CW100C	C17000	–	–	20
		CuBe2	CW101C	C17200	–	High-strength springs	20
		CuCo2Be	CW104C	C17500	High-temperature stability	Resistance welding electrodes	40
		CuCr1Zr	CW106C	C18150	High-temperature stability	Resistance welding electrodes; continuous casting moulds	20
		CuNi1Si	CW109C		Medium tensile strength; good electrical conductivity	Identical to CuNi1Si	20
		CuNi2Be	CW110C	C17510	High tensile strength; good electrical conductivity	Current carrying components in overhead lines (screws, bearing bushings, contacts)	–
		CuNi2Si	CW111C	C64700	High tensile strength	Bolts	30
		CuNi2SiCr	–	–	–	Welding applications; die-cast aluminium and magnesium	40
		CuNi3Si1	CW112C	C70250	High tensile strength	Mould inserts	–
		CuZr	CW120C	C15000	–	–	20
	Copper-aluminium alloys	CuAl5As	CW300G	C60800	Particularly good corrosion resistance to salt solutions	–	20
		CuAl8Fe3	CW303G	C61400	Salt-water resistance; resistance to sulphuric and acetic acids; antimagnetic	Valve seats and combustion motors	20
		CuAl10Fe3Mn2	CW306G	–	Engine and gear parts subject to vibration and wear; scale-resistant, high-strength nuts and bolts, shafts, spindles, worm drives, gear wheels	Bearing bushings, mechanical engineering and process equipment applications	–
		CuAl10Ni5Fe4	CW307G	C63000	Hard; shock resistant; high load strength, good salt-water resistance	Toggle lever bearings; shafts; screws; wearing parts for combustion engines; mould making	20
		CuAl11Fe6Ni6	CW308G	–	High tensile strength	Journal bearings; valves; forming dies	–

Table 23a: *Machinability classification of standardized copper-based materials*

Machinability group III: Copper-based materials with moderate to poor machining properties

Alloy group		Material			Machinability and processability	Typical applications	Machinability rating
		Designation	Number (EN)	Number (UNS)			
Wrought copper alloys	Copper-nickel alloys	CuNi25	CW350H	C71300	Wear resistant; silver-white colour	–	–
		CuNi10Fe1Mn	CW352H	C70600	–	Brake pipes; intercoolers	20
		CuNi30Mn1Fe	CW354H	C71500	–	Electrical contacts	20
	Copper-nickel-zinc alloys	CuNi12Zn24	CW403J	C75700	Excellent formability	Optical and precision engineering components	20
		CuNi18Zn20	CW409J	–	–	Spectacle frame parts; membranes; connectors	–
	Copper-tin alloys	CuSn4	CW450K	C51100	–	Lead frames; connectors	20
		CuSn5	CW451K	C51000	–	Connecting rod bearings	20
		CuSn6	CW452K	C51900	–	Gear wheels; bushings; pump parts; clock/watch components; connectors; hose tubing; Bourdon tubes	20
		CuSn8	CW453K	C52100	–	Worm gears; gear wheels; bolts; screws; small-end bushings; rocker bearings; cotter pins	20
		CuSn8P	CW459K	–	–	Worm gear wheels; gear parts; heavy-duty plain bearings; toggle levers; valve guides in exhaust gas systems; small-end bushings, cam shaft bearings; rocker bearings; hydraulic cylinder bearings; pump components	30
	Binary copper-zinc alloys	CuZn5	CW500L	C21000	Excellent cold workability	Components for electrical installations; rotor bars; components for the watchmaking industry	20
		CuZn10	CW501L	C22000	Excellent cold workability	Watchmaking industry	20
		CuZn15	CW502L	C23000	Excellent cold workability	Flexible bellows	30
		CuZn20	CW503L	C24000	Excellent cold workability	Pressure gauges	30
		CuZn28	CW504L	–	Excellent cold workability	Bellows; musical instrument parts	–
		CuZn30	CW505L	C26000	Excellent cold workability	Connectors; radiator trim	30
		CuZn33	CW506L	C26800	Excellent cold workability	–	30
	Multi-component copper-zinc alloys	CuZn20Al2As	CW702R	C68700	–	Tubing condensers; heat exchangers	30
		CuZn28Sn1AS	CW706R	C44300	–	Heat exchanger tube sheets	30

Table 23b: *Machinability classification of standardized copper-based materials*

Machinability group III: Copper-based materials with moderate to poor machining properties

Alloy group		**Material**			**Machinability and processability**	**Typical applications**	**Machinability rating**
		Designation	**Number (EN)**	**Number (UNS)**			
Copper casting alloys	Copper casting alloys	CuCr1-C	CC140C	–	–	Welding electrode holders; contact connectors	–
	Copper-tin casting alloys	CuSn10-C	CC480K	C90700	Salt-water proof	Valve and pump bodies; stators, rotors and impellers for pumps and water turbines	20
		CuSn12-C	CC483K	C90800	Salt-water proof, wear resistant	Bearings for Cardan joints, couplers; ball-screw nuts for heavy loads; worm wheels and helical gear wheels	–
		CuSn12Ni2-C	CC484K	C91700	Salt-water proof, wear resistant	Bearings for Cardan joints, couplers; ball-screw nuts for heavy loads; worm wheels and helical gear wheels; bevel gear wheels; worm wheel rims	20
	Copper-aluminium casting alloys	CuAl10Fe2-C	CC331G	C95200	–	Bevel gear wheels, synchronizer rings; gear selector forks and gear selector parts	20
		CuAl10Ni3Fe2-C	CC332G		–	–	–
		CuAl10Fe5Ni5-C	CC333G	C95500	Good salt-water resistance	Heavy-duty crankshaft bearings and toggle lever bearings; heavy-duty worm and helical gear wheels; marine propeller components	50
	Copper-nickel casting alloys	CuNi10Fe1Mn1-C	CC380H	C96200	–	–	10
		CuNi30Fe1Mn1NbSi-C	CC383H	C96400	–	–	20

Table 23c: *Machinability classification of standardized copper-based materials*

Machinability group III: Copper-based materials with moderate to poor machining properties

12 Mathematical formula

12.1. Equations

In numerical equations, the dimensions of the quantities to be entered are given.

1) Geometrical relationship between the clearance, wedge and rake angles (tool-in-hand reference system):

$$\alpha o + \beta o + \gamma o = 90° \quad (1)$$

2) Chip thickness compression:

$$\frac{h_{ch}}{h} > 1 \quad (2)$$

3) Chip width compression:

$$\frac{b_{ch}}{b} > 1 \quad (3)$$

4) Equation of a straight line:

$$y = m \cdot x + n \quad (4)$$

5) Equation of Taylor tool-life plot (log-log plot of vc vs. T):

$$\log T = \log C_v + k \cdot \log v_c \quad (5)$$

6) Taylor function:

$$T = C_v \cdot v_c{}^{k} \quad (6)$$

where:

T: Tool life in minutes

v_c: Cutting speed in m/min

k: Gradient of the straight line in the tool-life plot (k = tan(α))

C_v: Tool life T for unit cutting speed (v_c = 1 m/min.)

The Taylor equation can be rearranged to yield:

$$v_c = T^{\frac{1}{k}} \cdot C_T \quad (6a)$$

7) C_T, C_v and k are quantities that characterize the cutting conditions:

$$C_T = C^{-\frac{1}{k}} \cdot \quad (7)$$

8) Extended Taylor equation:

$$T = \frac{C_1}{a^{c_a} \cdot f^{c_f} \cdot v_c^{-k}} \quad (8)$$

where:

T :	Tool life in minutes
v_c	Cutting speed in metres per minute
f	Feed in mm per revolution
a_p	Depth of cut in mm
k	Gradient of the straight line in the tool-life plot (k = tan α)
C_1	Dimensioned, empirically determined constant
C_a	Dimensionless constant: exponent of the depth of cut
C_f	Dimensionless constant: exponent of the feed

9) Cutting force formula (Kienzle/Victor):

$$F_c = b \cdot h^{(1-m_c)} k_{c1.1} \quad (9)$$

F_c	Cutting force in N
b	Chip width in mm
h	Undeformed chip thickness in mm
$1-m_c$	Dimensionless index reflecting the increase of the specific cutting force
$k_{c1.1}$	Specific cutting force in N/mm²

10) Approximate magnitude of feed force:

$$F_f \approx 0{,}3\ F_c \quad (10)$$

11) Approximate magnitude of feed and passive force:

$$F_p \approx F_f \approx 0{,}3\ F_c \quad (11)$$

12) Effective cutting power:

$$P_e = F_e \cdot v_e = P_c + P_f \quad (12)$$

13) Cutting power:

$$P_c = F_c \cdot v_c \quad (13)$$

14) Feed power:

$$P_f = F_f \cdot v_f \quad (14)$$

15) Net machine power:

$$P'_{è} = \frac{F_c \cdot v_c}{60000} \quad (15)$$

$P_{e'}$	Net machine power in kW
F_c	Cutting force in N
v_c	Cutting speed in metres per minute
60000	Conversion factor in (N • m)/(kW • min)

16) Approximate net machine power for multipoint tools:

$$P'_{è} = \frac{V_w}{V_{wp}} \quad (16)$$

$P_{e'}$	Net machine power in kW
V_w	Stock removal rate (volume of workpiece material removed per unit time in cm³/min)
V_{wp}	Specific stock removal rate • volume of workpiece material removed per unit time and per unit of power supplied in cm³/(min • kW))

17) Specific stock removal rate:

$$V_{wp} = \frac{V_w}{P_c} = \frac{A \cdot v_c}{F_c \cdot v_c} = \frac{A \cdot v_c}{k_c \cdot A \cdot v_c} = \frac{1}{k_c} \quad (17)$$

18) Numerical equation for specific stock removal rate:

$$V_{wp} = \frac{V_w}{P_c} = \frac{60000}{k_c} \quad (18)$$

V_{wp}	Specific stock removal rate in cm3/(min · kW)
V_w	Stock removal rate in cm³/min
P_c	Cutting power in kW
k_c	Specific cutting force in N/mm²

60000 Conversion factor in cm^3 • N/(mm^2 • min • kW) (= N • m/(kW • min))

19) Theoretically achievable peak-to-valley roughness:

$$R_{t,th} = r_\varepsilon - \sqrt{r_\varepsilon^{\,2} - \frac{f^2}{4}} \quad (19)$$

20) Approximate expression for theoretically achievable peak-to-valley roughness:

$$R_{t,th} \approx \frac{f^2}{8 \cdot r_\varepsilon} \quad (20)$$

21) Theoretical feed setting required for a specified peak-to-valley roughness and a given nose radius:

$$f \approx \sqrt{8 \cdot r_\varepsilon \cdot R_{t,th}} \quad (21)$$

22) Tool costs per tool life:

$$K_{WT} = \frac{K_{Wa}}{n_T} + K_{Ww} \quad \left(+ K_{Ws}\right) \quad (22)$$

where:

K_{WT}	Tool costs per tool life in €
K_{Wa}	Purchase price of tool in €
n_T	Number of tool lives per tool (for solid shank tools or brazed inserts: n_T = number of regrinds; for indexable cutting inserts; n_T = number of cutting edges per insert)
K_{Ww}	Cost in € associated with changing the worn tool
K_{Ws}	Cost in € for regrinding the tool (not applicable if indexable inserts are used)

23) Tool costs for fabricating one part:

$$K_{W1} = \frac{K_{WT}}{z_T} \quad (23)$$

where:

K_{W1}	Tool costs in € for fabricating one part
n_{WT}	Number of parts machined in one tool life

24) Total cost of manufacturing one part:

$$K_1 = t_{h1} \cdot R + K_{fix} + K_{W1} = K_{th1} + K_{fix} + K_{W1} \quad (24)$$

where:

K_1	Total fabrication cost per unit product in €
t_{h1}	Machining time per part in minutes
K_{fix}	Fixed costs in € (independent of cutting speed v_c)
K_{th1}	Machining costs in €
R	Cost rate for operator and machine (excluding tool costs) in €/min

25) Cost-optimized tool life:

$$T_{oK} = \frac{(-k-1) \cdot K_{WT}}{R} \quad (25)$$

where:

T_{oK} = Cost-optimized tool life in min

−k = Gradient of straight line in tool-life plot

K_{WT} = Tool costs per tool life in € as defined in Eq. (22)

R = Cost rate for operator and machine (excluding tool costs) in €/min

26) Undeformed chip thickness in face milling operations:

$$h_m = \frac{114{,}6°}{\varphi_s°} \cdot f_z \cdot \sin(\kappa) \frac{a_e}{D} \quad (26)$$

27) Undeformed chip thickness in peripheral milling operations:

$$h_m = \frac{114{,}6°}{\varphi_s°} \cdot f_z \cdot \frac{a_e}{D} \quad (27)$$

where:

h_z = Undeformed chip thickness per tooth and revolution

f_z = Feed per tooth and revolution

κ = Tool cutting edge angle

φ_s = Angle of cutter engagement

h_m = Average thickness of undeformed chip

a_p = Depth of cut (feed)

a = Working engagement (radial depth of cut)

D = Diameter of milling cutter

12.2 symbols and abbreviations

Symbol or abbreviation	Unit	Name/Description
a_p	mm	Depth of cut
a_e	mm	Working engagement (radial depth of cut)
A	mm^2	Area of uncut chip
ABS	–	Built-up edge
A_5	%	Elongation after fracture
b	mm	Undeformed chip width
b_{ch}	mm	Chip width
b_f	mm	Width of chip breaker
C_a	–	Constant in the extended Taylor equation: exponent of the depth of cut
C_f	min	Constant in the extended Taylor equation: exponent of the feed
C_T	m/min	Constant in the Taylor equation: $\wedge$ v_c when $T = 1$ min
C_v	min	Constant in the Taylor equation: $\wedge$ T when $v_c = 1$ m/min
C_1	dimensioned	Constant in the extended Taylor equation
d	mm	Diameter (of drill hole, drill, milling cutter etc.)
ε	%	Degree of deformation
E	N/mm^2	Modulus of eleasticity
f	mm/U	Feed per revolution
f_h	–	Correction factor that accounts for the influence of the uncut chip thickness on the cutting force
f_z	mm/tooth	Feed per tooth
F	N	Total cutting force
F_a	N	Active force
F_c	N	Cutting force
$F_{c,n}$	N	Perpendicular (normal) cutting force
F_e	N	Effective force
$F_{e,n}$	N	Perpendicular (normal) effective force
F_f	N	Feed force
$F_{f,n}$	N	Perpendicular (normal) feed force
F_n	N	Perpendicular (normal) force
F_p	N	Passive force
F_t	N	Tangential force
h	mm	Undeformed chip thickness
h_{ch}	mm	Chip thickness
$h_{c,1}$	mm	Normalized uncut chip thickness, $h_{c,1} = 1mm$
h_f	mm	Depth of chip breaker
h_m	mm	Average thickness of undeformed chip
h_{min}	mm	Minimum thickness of undeformed chip
h_z	mm/tooth	Uncut chip thickness per tooth
HB	–	Brinell hardness
HM	–	Carbide
HM-PCD	–	Carbide with polycrystalline diamond coating
HSS	–	High-speed steel

Symbol or abbreviation	Unit	Name/Description
HV	–	Vickers hardness
HRC	–	Rockwell hardness
k	–	Gradient of straight line in Taylor tool-life plot
k_c	N/mm^2	Specific cutting force
$k_{c1.1}$	N/mm^2	Principal value of the specific cutting force
K	–	Crater ratio
KB	mm	Crater width
KL	mm	Crater lip width
KM	mm	Distance of centre of crater from tool edge
KT	mm	Crater depth
K_{fix}	€	Fixed costs (independent of cutting speed)
K_M	dimensioned	Constant; dependent on type of drill, tool material and work material
K_{th1}	€	Machining time costs
K_{Wa}	€	Purchase price of tool
K_{Ws}	€	Tool regrinding costs
K_{WT}	€	Tool costs per tool life
K_{Ww}	€	Costs associated with changing the worn tool
K_{W1}	€	Tool costs per tool
K_1	€	Total fabrication costs per unit product
L	mm	Hole depth, length of drilled hole
M_D	Nm	Torque
n	rev./min	Spindle speed, rotational speed
n_T	–	Number of tool lives (for a solid tool $n_T = 1$; for an indexable cutting insert n_T = number of cutting edges)
p	bar	Pressure
P_c	kW	Cutting power
P_e	kW	Effective cutting power
$P_{e'}$	kW	Net machine power
P_f	kW	Feed power
r_e	mm	Nose radius of cutting tool
R	€/min	Cost rate for operator and machine
R_a	µm	Mean roughness depth
R_e	N/mm^2	Yield point
R_m	N/mm^2	Tensile strength
$R_{p0,2}$	N/mm^2	0.2 % yield strength
R_t	µm	Maximum roughness depth
$R_{t,th}$	µm	Theoretically achievable peak-to-valley roughness
SV	mm	Displacement of cutting edge
SV_α	mm	Flank-side displacement of cutting edge
SV_γ	mm	Face-side displacement of cutting edge
t	min	Cutting time
t_{h1}	min	Cutting time of tool per part

Symbol or abbreviation	Unit	Name/Description
T	min	Tool life
T_{oK}	min	Cost-optimized tool life
v_c	m/min	Cutting speed
v_e	m/min	Resultant cutting velocity
v_f	m/min	Feed velocity
v_{oK}	m/min	Cost-optimized cutting speed
v_{ot}	m/min	Time-optimized cutting speed
V	mm^3	Wear volume
VB	mm	Width of flank wear land
Q	cm^3/min	Material removal rate or stock removal rate (volume of work material removed per unit time)
V_{wP}	$cm^3/min \cdot kW$	Specific stock removal rate (material removal rate per unit of machine power)
W_c	$N \cdot m$	Cutting energy
x	mm	Height offset, height mismatch
z	–	Number of teeth on milling cutter
n_{WT}	–	Number of workpieces machined per tool life
α	degree	Helix angle of straight line
α_o	degree	Orthogonal clearance (or relief) angle
α_f	degree	Chamfer clearance (or relief) angle
α_n	degree	Minor flank clearance (or relief) angle
α_x	degree	Side clearance (or relief) angle
β_o	degree	Orthogonal wedge angle
β_f	degree	Chamfer wedge angle
β_x	degree	Side wedge angle
γ_o	degree	Orthogonal rake angle
γ_f	degree	Chamfer rake angle
γ_x	degree	Side rake angle
ε	degree	Tool included angle
ε_o	%	Degree of deformation in the shear plane
κ_r	degree	Cutting edge angle
κ_n	degree	Minor cutting edge angle
λ	degree	Cutting edge inclination
σ	degree	Drill point angle
τ	$da\ N/mm^2$	Shear strength
φ	degree	Angle of feed motion
φ	degree	Angle of approach of milling cutter teeth
φ_s	degree	Angle of cutter engagement
ψ	degree	Chisel edge angle
ω	1/s	Angular velocity

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