

Chapter 8

Cutting Materials

Cutting materials determine the economic viability of a cutting process to a great extent. The development of the cutting technology is therefore directly linked to the development of the cutting materials. Figure 8.1 shows the hour cutting speed. That is the cutting speed applicable for one hour of tool life, which has become possible due to new developments since the last turn of the century. Per decade, the possible cutting speed is approximately doubled.

In addition to the still often applied high speed steels the following hard cutting materials can be named, classified according to [DIN ISO 513](#):

- tungsten carbide
- cutting ceramics
- diamond
- boron nitride.

8.1 Requirements on Cutting Materials

Cutting materials have to be wear resistant (hard) and sufficiently tough to ensure a long tool life and high process reliability. Both requirements cannot be fulfilled simultaneously for the reason that hard materials are generally not tough and vice versa (Fig. 8.2). The loads and the wear mechanisms (see [Chap. 7](#)) require the following properties [[VIE70](#), [TÖN90](#)]: Hardness, hot hardness, toughness and chemical stability (Table 8.1).

Hardness: Hardness is a measure of the wear resistance of the cutting material. It counteracts abrasive and adhesive wear. Cutting materials can take their hardness from the base material, from hard particles incorporated in a binding matrix or exclusively by hard crystallites, which are directly connected by grain boundaries. The hard material content is accordingly different (Fig. 8.3).

Hot hardness: Even under high temperatures of the cutting wedge, the hardness has to be maintained to counteract abrasive wear and plastic deformations (Fig. 8.4).

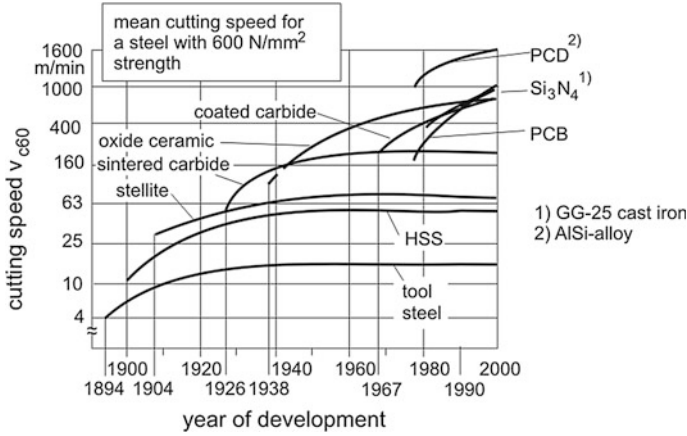


Fig. 8.1 Development of cutting materials

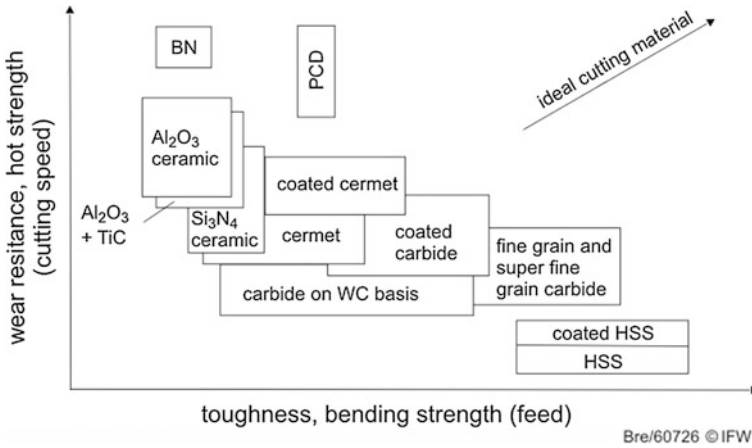


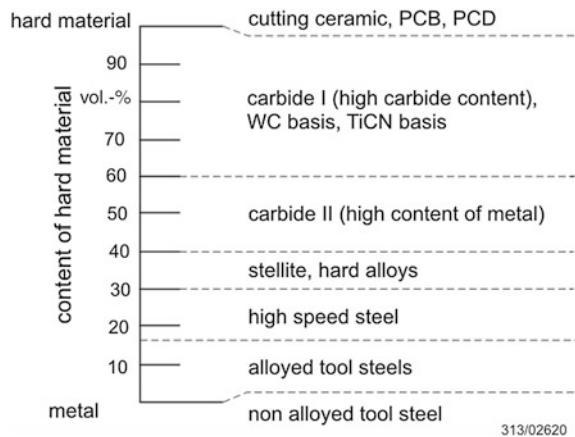
Fig. 8.2 Cutting materials and their wear resistance and toughness [KLO08]

Toughness: The ability of materials to withstand the propagation of cracks is called toughness. The fracture mechanics deliver a measure for the toughness by the stress intensity factor, the K_{Ic} -value (also called the fracture toughness). The K_{Ic} -value is determined with a technological test procedure with prescribed sample geometry after a numerical value equation. According to Fig. 8.5, a sample with defined initial fracture incipient crack (for instance a fatigue crack introduced by a tension pulsating stress) is loaded in a tension or 3-point bending test so far that the crack is unstable, i.e. abruptly propagating. The applied fracture stress is σ_b ; a is the length of the crack; Y is a calibrating factor, that takes the sample geometry into account.

Table 8.1 Properties of cutting materials

	Hardened steel	HSS	Carbide	Cutting ceramic	PCB	PCD
Density [g/cm ³]	7.8	8.0–8.8	6.0–15.0	3.8–7.0	3.4	3.5
Hardness HV 30	700–900	750–100	1,300–1,700	1,400–2,400	4,500	7,000
Young's modulus [GPa]	220	260–300	430–630	300–400	680	890
Melting point [°C]	1,200–1,400	1,300–1,400	~ 1,300	1,700–2,050	2,700	3,700
Temperature stability [°C]	200–300	600–800	800–1,200	1,300–1,800	1,500	600
Temperature expansion coeff. at room temperature [10 ⁻⁶ /K]	13–15	9–12	5–7.5	7.4–9	3.6	0.8
Compression strength [N/mm ²]	2,000–3,000	2,500–3,500	4,000–5,900	2,500–4,500	4,000	3,000
Bending strength [N/mm ²]	1,800–2,500	200–3,800	800–2,200	300–700	600	300

Fig. 8.3 Hard constituent in cutting materials



The stress intensity factor K_{Ic} of cutting materials lies between 13 and 30 MPa m^{1/2} for high speed steels, 8 and 18 MPa m^{1/2} for tungsten carbide and 2 and 7 MPa m^{1/2} for cutting ceramics.

For ceramics, which show brittle behavior, the bending fracture strength also gives an indication on the toughness. Its numerical value given in MPa is 100–200 times as much as the K_{Ic} -value. The toughness affects the fracture tendency of the cutting material and the wear resistance in transient mechanical and thermal loading. For instance, the latter loading is called thermo shock. The resistance against temperature change is called temperature change resistance or thermo-shock resistance.

Chemical stability: To counteract tribo-mechanical wear cutting materials should be inert against work materials and environmental agents such as air and cutting fluids. Chemical stability is a prerequisite for the use of a cutting material under high temperatures. A measure for the chemical stability is the bond

Fig. 8.4 Hot hardness of cutting materials

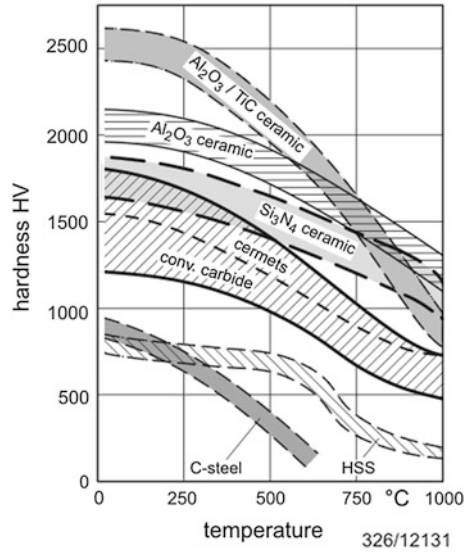
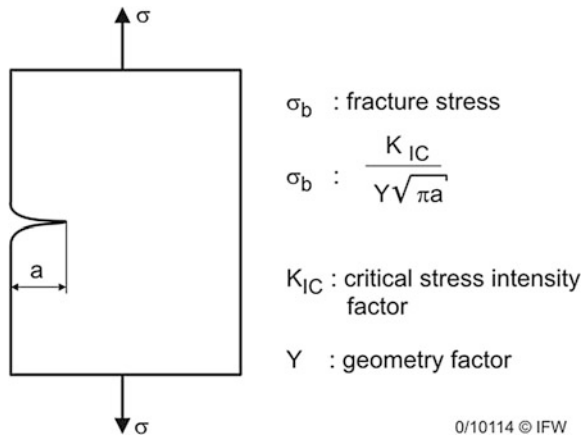


Fig. 8.5 Definition of fracture toughness



enthalpy. A large negative bond enthalpy of an alloy corresponds to high chemical stability, which means a large amount of heat energy has to be introduced to cause a chemical reaction.

There is no ideal cutting material, which fulfills all demands named above. For all cutting materials the fundamental dualism applies to be either hard and wear resistant or tough and resistant against transient loads.

8.2 Tool Steels

One distinguishes between unalloyed and alloyed tool steels. Unalloyed tool steels (Carbon steels) contain 0.6–1.3 % carbon. They get their hardness and wear resistance by hardening, which generates a martensitic structure. Alloyed tool steels for higher loads additionally contain up to 5 % shares of Cr, W, Mo and V. Compared to unalloyed tool steels they have an elevated wear resistance (additive of carbides generating elements) and a greater hardness (carbon passed into solution). Due to the limited hot hardness of tool steels (Fig. 8.4) only lower cutting speeds can be applied so that tool steels are hardly used on machine tools for the machining of metals. They are primarily applied for cutting manually-driven tools, for hand tools such as files and hand-reamers and for woodworking tools.

8.3 High Speed Steels

High speed steels (HSS) are ledeburitic, highly alloyed tool steels with alloy contents of up to 35 %. They are used as tools for drilling, milling, reaming, sawing and turning. In contrast to the tool steels mentioned above they have a higher annealing temperature and a hot hardness of up to 600 °C (Fig. 8.4).

The alloy elements bound as carbides do not determine the higher annealing stability, but therefore the alloy elements in the matrix do. The hardness and the high wear resistance also arise from the martensitic matrix as well as from the incorporated W, W-Mo, Cr, and V carbides.

The properties of high speed steel are primarily governed by the alloy elements W and Mo. The tungsten and molybdenum contents are therefore used to classify the high speed steels according to [DIN EN 10027-1] into four groups (Table 8.2).

Table 8.2 Alloy groups of high speed steels

Class	Name acc. [DIN EN 10027-1]	Fractions in %					Applications
		C	W	Mo	V	Co	
6 % W, 5 % Mo	HS6-5-2	0.85	6.5	5.0	2.0	-	- Drills - Taps
	HS6-5-3	0.85	6.5	5.0	2.8	-	- Milling cutters
	HS6-5-2-5	0.85	6.5	5.0	2.0	4.75	- Reamers
	HS10-4-3-10	1.25	10	4.0	3.25	10.0	- Tuning tools
2 % W, 10 % Mo	HS2-10-1-8	1.1	2.1	10	1.2	7.9	- End milling cutters
12 % W	HS12-1-4-5	1.45	12	0.8	3.75	4.75	- Turning tools - Turning tools
18 % W	HS18-1-2-5	0.80	18	0.8	1.5	4.75	- Planning tools - Milling cutters

They are marked by HS for high speed steel and the percentage contents of the alloying elements W-Mo-V-Co. The universal type HS6-5-2 covers more than 50 % of the totally manufactured high speed steel. The varieties mentioned in the 6 % W and 5 % Mo-classes cover approximately 90 % of the manufactured quantity [HAB88].

The alloying elements affect specific properties of the high speed steels:

- C Carbon is essential for the hardness and necessary for the formation of carbides.
- W Tungsten is a carbide former and increases the tempering resistance and the wear resistance.
- Mo Molybdenum increases the ability of through-hardening and the toughness; it can replace tungsten. Due to the half density lower mass contents are required compared to tungsten.
- V Vanadium, similar to tungsten, is a carbide former and increases the wear resistance.
- Co Cobalt is able to raise the hardening temperature. Thereby, more alloy contents of carbide formers can be solved, i.e. the hot hardness and the tempering resistance increase.

High speed steels are produced by melting processes. The hardening temperature (1,180–1,280 °C depending on alloy elements) and the immersion time during the tempering procedure are chosen so that the largest possible fraction of carbides is solved but no coarseness of grains is generated. The remaining part of austenite can be reduced by repeated annealing (540–580 °C). The precipitation of carbides works against the decrease of hardness by collapsing martensite connected with the annealing. The decrease of hardness, however, is connected with an increase of toughness.

In the melting process, the high speed steels tend to segregation during the solidification phase, which is detrimental on the wear resistance. To avoid these disadvantages, electro slag remelting processes (ESU) and powder metallurgy manufacturing (PM) are applied. Either method leads to a more uniform structure and finer grains. PM steels have better edge strength and cutting edge durability. They are used for threading and reaming tools. With higher carbide fractions they are better grindable than molten high speed steel. The higher manufacturing costs are detrimental.

Longer tool life and higher cutting speeds can be reached with high speed steel by coating with titanium nitride (TiN). The layers have a thickness of 2–7 µm. Friction between tool and work material and thus the adhesive wear can be reduced by TiN. The lower friction leads to a reduction of the necessary cutting power and the cutting forces by 10–20 %.

The rake face is heated by friction especially at higher cutting speeds. The greater part of the power transformation takes place in the chip formation zone (see Chap. 5), the shearing energy contributes but little to the temperature at the tool surface. Therefore, a reduction of the total power as a result of lower rake face friction has the following effect:

$$k_c = k_\Phi + k_\gamma \quad \text{without coating} \quad (8.1)$$

$$a \cdot k_c = k_\Phi + b \cdot k_\gamma \quad \text{with coating} \quad a, b < 1 \quad (8.2)$$

$$b = 1 + \frac{k_c}{k_\gamma} \cdot (a - 1) \quad (8.3)$$

The total specific energy k_c divides itself into the friction share on the rake face k_γ and the shearing share (plus the friction at the flank face) k_Φ . With a coating, the total energy decreases to $a \cdot k_c$ as a result of the lowered friction at the rake face to $b \cdot k_\gamma$. With the values from [Chap. 5](#) for the shearing and the friction energy and $a = 0.8$ (i.e. reduction of the cutting power to 80 %) follows $b = 0.2$ of the original value without coating. The temperatures in a high speed tool can be lowered significantly by a TiN coating, which results in a considerable gain in the possible cutting speed or the tool life respectively. In addition, the abrasive wear is reduced by the higher hardness of the TiN layer in the range of HV05 = 2,400 compared to the substrate with the hardness of HV05 = 900 at room temperature.

Due to the lower process temperatures during the vapor deposition of layers high speed steels are coated by physical vapor deposition (PVD). Typical coating temperatures in this process are lower than 500 °C. Thereby, hardly any annealing effects occur. For chemical vapor deposition (CVD) the process temperatures are 900–1,000 °C, which is far above the annealing temperature of high speed steel. CVD-coated tools therefore have to be post-hardened. Because of the connected risk of warpage this is achieved only for simple shapes such as cutting inserts. [Section 8.5](#) gives further explanations concerning the various vapor deposition methods.

Coated tools have a significantly longer tool life. Even reground tools still show a clear effect. The causes are the supporting and protecting effects by TiN-carryovers. Beside others, twist drills, milling cutters, hobs, taps, broaches and reaming tools are coated. They can then be used for partly decisively higher cutting and feed speeds. [Figure 8.6](#) shows the recommended cutting and feed speeds of differently coated twist drills of high speed steel and of solid tungsten carbide for a drill diameter of 6 mm.

8.4 Stellites

Stellites are cast hard alloys (not to be confused with hard metals, which are sintered). They are naturally hard so they need not be hardened. They were developed for the first time by E. Haynes in 1915. Stellites have the following composition: 42–53 % Co, 24–33 % Cr, 11–22 % W and 1.8–3 % C. Cr and W form carbides. Stellites have a hardness of HV0.5 = 700–750 at room temperature. At low cutting speeds they are inferior to high speed steel, at higher cutting speeds they are inferior to tungsten carbide materials ([Fig. 8.4](#)). The possibilities

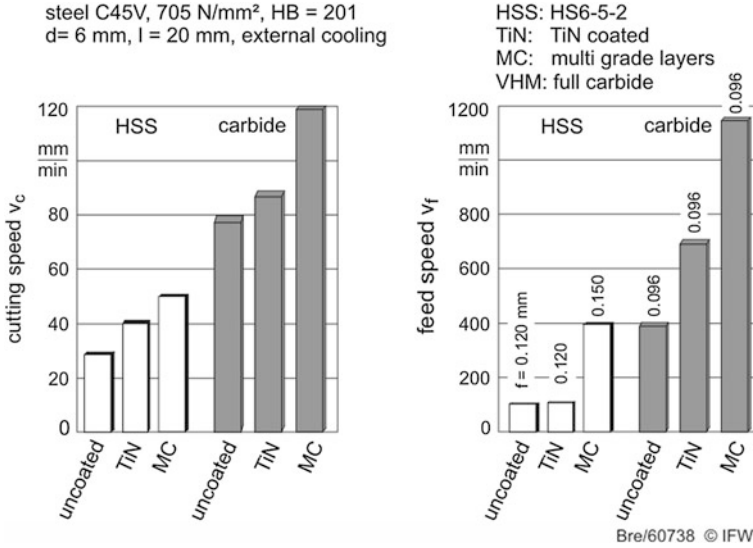


Fig. 8.6 Recommended cutting speeds and feed speeds of various coated twist drills (acc. to Guehring)

of shaping by casting can be beneficial for large profile tools. The high oxidation resistance of stellites can be of interest for materials, which tend strongly to oxidation wear.

8.5 Cemented Carbides

Cemented carbides are two- or multi-phase powder metallurgically produced alloys of a binding metal (β -phase) which determines the toughness -, and metal carbides or -carbonitrides as the hardness carrier [KIE53]. As hard materials, tungsten carbide (WC, called α -phase), titanium-, tantalum- or niobium-carbide (TiC, TaC, NbC, called γ -phase) or titanium carbonitride or other titanium mixed carbides are used. The first basic patent on a WC–Co cemented carbide was granted to K. Schroeter of the Osram-Studiengesellschaft in 1923. The beneficial combination of properties is due to the fact that tungsten carbide is very well wetted by cobalt (β -phase) and that cobalt is able to solubilize larger shares of tungsten carbide. The good wettability is such that tungsten carbide never breaks interfacially alongside the bonding metal-carbide boundaries. The solvent power causes high internal binding forces and a good edge strength of the carbide.

By variation of the α - and β -phase shares the cutting material can be tailored to a certain extent. Tough carbides contain up to 15 % Co, wear resisting in contrast only up to 5 % Co (Table 8.3). The diffusion tendency of WC carbide can be reduced by titanium carbide, which leads to better hot wear resistance of cemented

Table 8.3 Composition and properties of various cemented carbides

	WC	γ -phase	Co	HV30	Bending strength [MPa]	Application
P01	32	60	8	1,670	750	Fine turning
P10	55	36	9	1,600	1,300	Finishing (turning and milling)
P25	70	20	10	1,450	1,750	Milling
P40	74	12	14	1,350	1,900	Interrupted cut, turning and planning
K05	92	2	6	1,750	1,350	Finishing
K30	93	–	7	1,400	2,000	Milling, rough turning
M10	84	10	6	1,700	1,350	Turning

carbides in spite of the higher hot hardness of WC (HV05 = 1,800 at room temperature, HV05 = 800 at 1,000 °C) compared to TiC (HV05 = 3,000 at room temperature, HV05 = 400 at 1,000 °C). However, the binding capacity and hence the toughness and edge strength is reduced. Additions of TaC and NbC counteract this tendency by grain fining and thereby increase the toughness.

The most important new developments to increase the hardness of WC–Co carbides are the fine grain and the ultra-fine grain cemented carbides with a WC grain size of 0.5–0.8 μm and 0.2–0.5 μm respectively with a cobalt content of 6–16 % by mass. These fine powders have a nearly round grain shape in contrast to standard materials, which not only has a positive influence on the homogeneity of the microstructure generated by sintering but also on the reachable density.

A recent development in the field of carbides is a functional gradient set into the surface zones of cutting tools (FGH, functionally graded hard metal). Such a functional gradient is a precise, finely varying distribution of phases and/or composition of elements, which provides a resistant surface zone, able to withstand the interactions between workpiece and tool under high temperatures. So, for example, the Co content is increased in the surface area to selectively enhance the toughness and to reduce cutting edge breakages [BOE02].

According to [DIN ISO 513], the cemented carbides are classified into three groups. The so-called cutting application groups, P, K and M. The WC- (TiC, TaC-, NbC-) Co alloys in the P group (P for plastic) are used to machine long chips forming ferrous materials as steel. The TiC-/TaC- alloys, largely free of WC–Co, of the K group are applied for the machining of non-ferrous metals, ferrous cast iron materials, AlSi alloys, plastics and wood. The transition between the P and K groups form the cemented carbides of the M group, which are used for alloyed austenitic and ferritic steels respectively and for alloyed cast iron. Toughness and wear resistance are marked by appending digits within each application group. With increasing numbers the toughness increases and the wear resistance is reduced. Table 8.3 lists typical compositions and properties of cemented carbides.

The characteristic and at the same time limiting dualism for cutting materials, to have a high hardness and wear resistance on one hand and a high bending strength and toughness on the other, can be overcome largely by coatings of the substrate. This principle of functional separation combines wear resisting layers with tough

base material. Due to great temperature differences which occur in cutting tools, the control of temperature cracks as a result of different thermal expansion coefficients is a prerequisite for durable and crack free coatings.

Titanium carbide (TiC), titanium nitride (TiN), titanium carbonitride (TiCN) and titanium aluminium nitride (TiAlN) still have a large proportion of the coating materials. Selected properties of some of these materials compared to tungsten carbide are shown in Table 8.4. The properties of these hard materials are mainly determined by the kind of chemical bond. Good layer adhesion, for example, is best achieved by metallic bonding since it has the greatest adhesion forces. High hardness for optimal wear resistance is best achieved by covalent bonding. The also required chemical stability is predominantly due to ionic bonding. TiN holds shares of all three types of bonding. Therefore, it was successfully used as the first layer [BOB08].

New PVD layers consist of systems of TiN/TiAlN or hard-soft combinations such as TiAlN + WC/C in several folds or multiple fold layers. Nano-structured layers of TiSiN, TiAlN, TiAlSiN or TiAlBN have already been in use for several years. CrAlN, CrAlSiN or Al₂O₃ are components of multilayers coatings, which are successfully used for the machining of hard materials [BOB08].

Additionally in the CVD coating of multiple layers, coatings with oxide ceramic shares affect beneficially. Combinations of TiC, TiN, TiCN, and Al₂O₃ were advantageous. For the turning of steel and cast iron materials a layer package of TiN, TiCN, Al₂O₃ and ZrCN proved value. Improvements of performance of CVD coatings can be achieved by quaternary coating materials like (T,Zr)(C,N) or (Ti,Hf)(C,N) [DRE01].

Titanium carbonitride coatings can be built up on TiC with a monotonous transition of the shares up to pure TiN. TiN is chemically inert and therefore counteracts the wear by diffusion and oxidation. In addition, it has a low adhesion tendency and reduces the respected wear. Aluminum oxide is also inert. It serves as a protection against oxidation.

(Ti,Al)N benefits at high process temperatures and forms a thin, passive layer on the tool surface, which prevents fast growing wear by diffusion and oxidation. High ionization pulse processes allow the production of non-conducting nitride layers with a high content oxide forming components such as (Al,Ti)N super nitride layers with more than 65 mol % of aluminum nitride. This further development of tool coatings aims at an improved wear behavior. Figure 8.7 shows the basic structure of different layer concepts in principle.

The single or multi-layer coatings are 2–10 µm thick in total. They are generated by vapor deposition. Chemical vapor deposition (CVD) works with process temperatures of 900–1,000 °C. Figure 8.8 shows the process of the deposition of TiC layers according to the following reaction formula



Methane (CH₄) and titanium chloride (TiCl₄) are gaseously sent to a heated reactor, where metallic substrate plates of the highest pureness possible are

Table 8.4 Properties of coating materials

	WC	TiC	TiN	TiCN	(Ti,Al)N	Al ₂ O ₃
hardn. HV0.05 at RT	1800	3000	2400	3000	2800	2200
at 1000°C	800	400	450	790	1250	1100
thermal expansion coefficient 10 ⁻⁶ K ⁻¹	7.3	7.8	9.4	7-8	7.6	8.3
thermal conductivity W/mK	90	30	39	50-100	50-100	25
Young's modulus GPa	690	450	256	372	390	410
enthalpy of formation kJ/mol bei 1450°C	-54	-165	-335	-268	-210	-1670
flank face wear		+	0	+	+	0
crater wear		0	0	0	0	+
toughness		+	+	+	0	0
bonding capacity		+	+	+	+	0
friction coefficient		+	+	0	0	0
separation function		0	+	0	+	+

+ = ideally suited; 0 = adequate

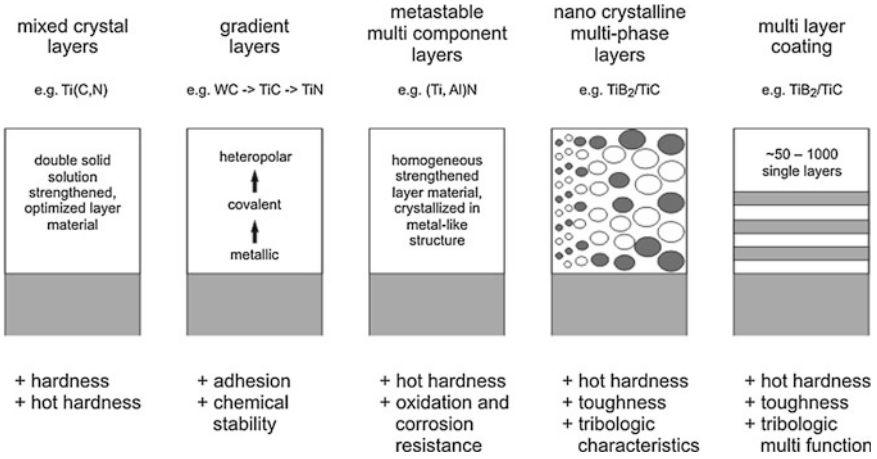


Fig. 8.7 Structure of different concepts of cover coating

located. At the heated surface of the substrate, the gases decompose into the respected solid material (TiC) and into volatile by-products (HCl). The layers grow up granularly (TiC, Al₂O₃) or fibrously (TiN). First, the growth of TiC occurs with a high coating rate. With a growing coating thickness the coating rate slows down, while the grain size of the layer increases. With CVD tensile stresses occur in the layers because of the different thermal expansion coefficients and because of the cooling down after coating. These stresses can exceed tensile strength and thus generate cracks.

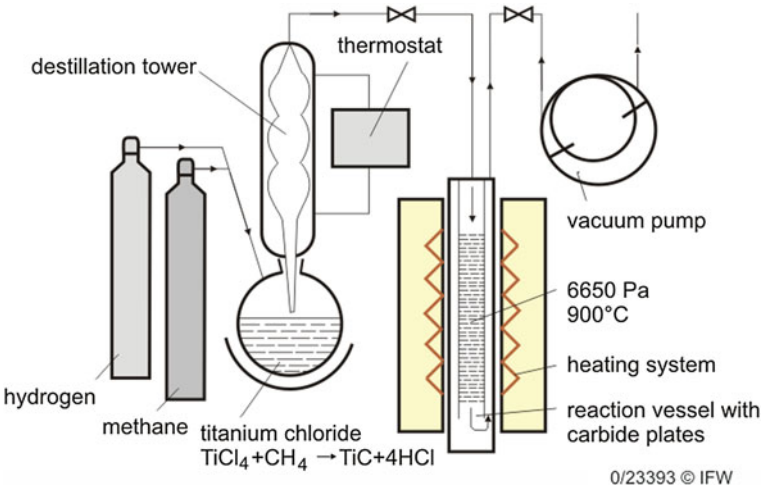


Fig. 8.8 Deposition of TiC coated carbide inserts by the CVD process

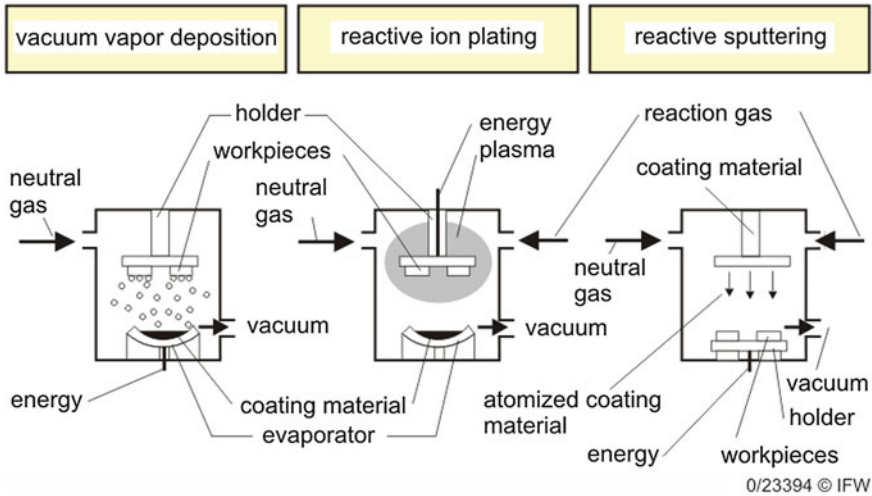


Fig. 8.9 PVD processes for coating

Physical vapor deposition (PVD) works at lower temperatures of about 500 °C. Ion plating or cathode sputtering is applied (see Fig. 8.9). The layers develop by the acceleration of loaded particles and by the bombardment of the substrate. Geometric limitations result, which can be partly neutralized by rotating the samples, because the faces to be coated have to be accessible. Residual stresses also develop in the coatings. However, they are hardly caused by the differences in thermal expansion, but rather by the ion bombardment. Compressive stresses are generated, which possibly benefits transient thermal loading, since the compressive residual stresses compensate the thermal stresses in the layers.

The plasma-CVD process avoids the limitations of the CVD and the PVD procedure (Fig. 8.10). The procedure no longer uses only thermal energy to activate the chemical reactions, but the process is activated by a plasma in the reactor. On the one hand, the plasma has a catalytic effect. On the other hand, its task is energy coupling. Thus, the reactions can occur at lower temperatures or only become due to them.

The PACVD can generate nitride, carbide or also carbonitride layers depending on the gas feeding. The coating according to the PACVD process implements substrate temperatures below 500 °C.

In contrast to the CVD coating diffusion actions, phase transforming and replacement reactions as well as the connected embrittlement effects between substrate and layer are therefore excluded. In contrast to layers generated by PVD, which are also superimposed under lower temperatures, the PACVD layers show high adhesion strengths and lower residual stresses as well as a smaller influence on the bending strength of the substrate. Furthermore, the adjusting and charging necessary with the PVD process to obtain a uniform layer thickness is omitted.

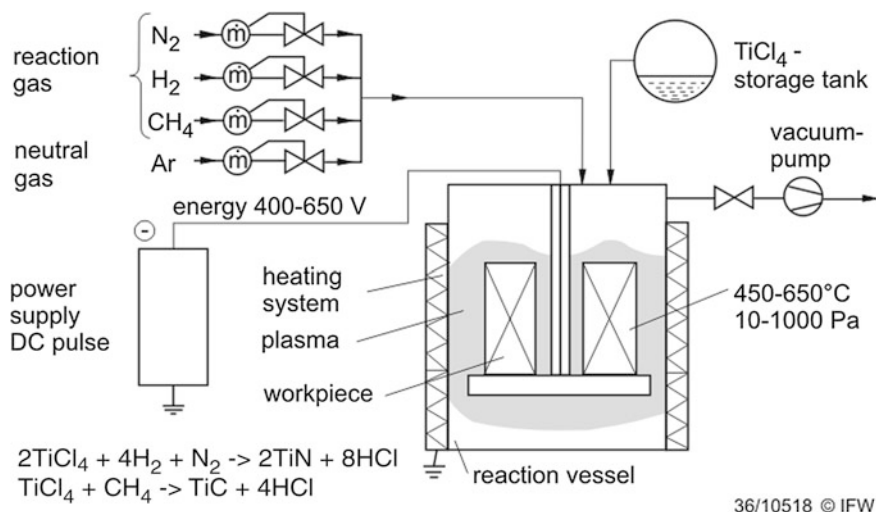


Fig. 8.10 Manufacturing of TiN-coated inserts by the PACVD process

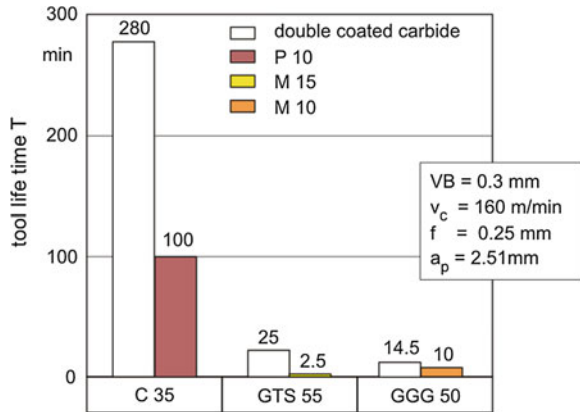
Very hard layers of diamond can be applied on cutting inserts and on shank tools by means of the CVD process. As substrate materials fine grained tungsten carbides or silicon based ceramics are suitable. The cobalt content is responsible for the strength of the CVD-diamond coated carbide tools [UHL04].

First successful trials with CBN coatings have also been documented [WIE07, UHL04]. Improvements to PVD coating techniques and plasma-assisted CVD resulted in CBN layers with more than 1 μm thickness deposited on carbide inserts. These layers are more than twice as hard as TiN layers and show more than a tenfold resistance to abrasive wear, where the coefficient of friction against steel is only half the size. Application attempts when turning steel, partially hardened and cast materials show the potential of the CBN layers but also the great amount of research to be done [UHL04].

Thin amorphous carbon layers were successfully synthesized 40 years ago, reminding of diamond as far as transparency, refraction index, insulation, hardness and chemical resistance is concerned. They are therefore called diamond-like carbon (DLC) [AIS71]. This material allows a wide variety of properties by means of the insertion of hydrogen, metallic or nonmetallic elements, which allows a significant determination of its properties. DLC coated tools are used to cut Al- and AlSi-alloys [SAN07, FUK04]. The tendency to build up edges is suppressed and the surface roughness of the workpiece is reduced.

Nowadays, 80 % of the carbide tools are PVD or CVD-coated [BOB08]. But they did not prove worthy for the machining of non-ferrous metals, highly nickel containing steels or nickel based alloys and austenitic and ferritic stainless steels. It also has to be noted that coated carbides have larger cutting edge radii by principle (equidistant, process necessary rounding). For very small undeformed chip thicknesses this leads to highly negative rake angles with the result that coated

Fig. 8.11 Comparison of tool life between cutting materials for cast iron and steel



tools are not usable for fine finishing operations. For the rest coated carbides are clearly superior to non-coated inserts as far as the wear behavior is concerned (Fig. 8.11). Besides, an economic reduction of grades is achievable due to the coating because a close adaptation to the machining conditions or to the machined material is no longer necessary.

Coated carbides wear slowly and show a characteristic wear development (Fig. 8.12). Even if the layer is penetrated, there is still a protective effect as can be seen in the moderate wear progress. It is explained by retain effects and a continuous plating by adhesion. After further use the typical steep wear occurs.

To assess the wear status of tools the crater depth KT can be applied beside the width of flank wear land. Figure 8.13 indicates the wear behavior of a TiC-Al₂O₃ carbide.

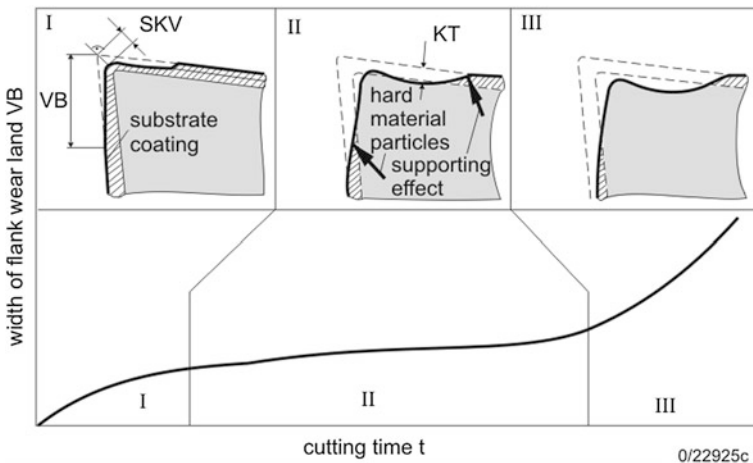


Fig. 8.12 Wear procedures in the case of coated carbides

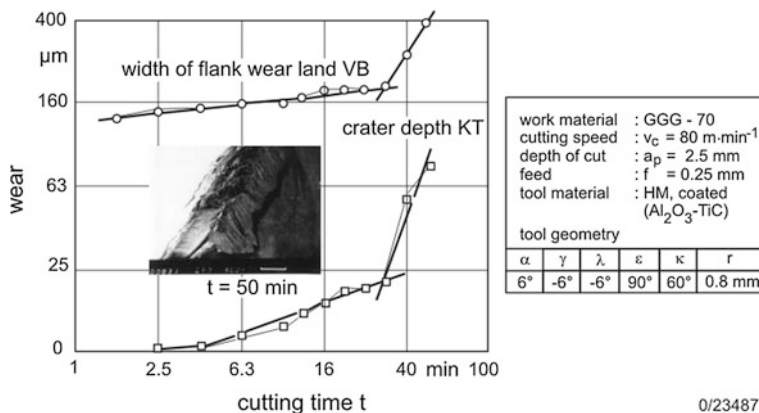


Fig. 8.13 Wear characteristic parameters of double-coated carbide when turning cast iron with globular graphite

A change of the properties of carbides, particularly of hardness, toughness and wear resistance is possible due to the change in the grain size and the shape of the carbides. This led to the development of ultra-fine grain hard metals. By using fine grain carbides (grain size $< 1 \mu\text{m}$) hardness, fracture toughness, compressive strength, wear resistance and edge strength are increased. Due to the small grain size and the material properties, particularly sharp and highly loadable cutting edges can be achieved with ultra-fine grain carbides. Accordingly, ultra-fine grain carbides are applied in finishing and fine finishing operations as well as for drills. Advantages exist for drill operations particularly when cutting with low cutting speeds ($v_c < 60 \text{ m/min}$). Here, the high toughness of the cutting material comes into play. So, clear tool life improvements have been achieved compared to conventional hard metals (Fig. 8.14).

8.6 Cermets

Hard metals without free tungsten carbide are called Cermets (from the word stem “ceramics” and “metals”) [ETT88]. They are multi-component hard metals based on titanium carbonitrides with tantalum, niobium and vanadium in the hard phase. The binder contains nickel and cobalt. Mixed crystal hardening can increase the wear resistance from the binder side, also by means of molybdenum, titanium, and aluminum. In contrast to tungsten carbides the cermets have a significantly higher chemical stability at high temperatures, i.e. less diffusion and oxidation wear. In addition, cermets offer a far higher edge stability. The sustainable cutting speeds are higher than those of coated tungsten carbides (Fig. 8.15).

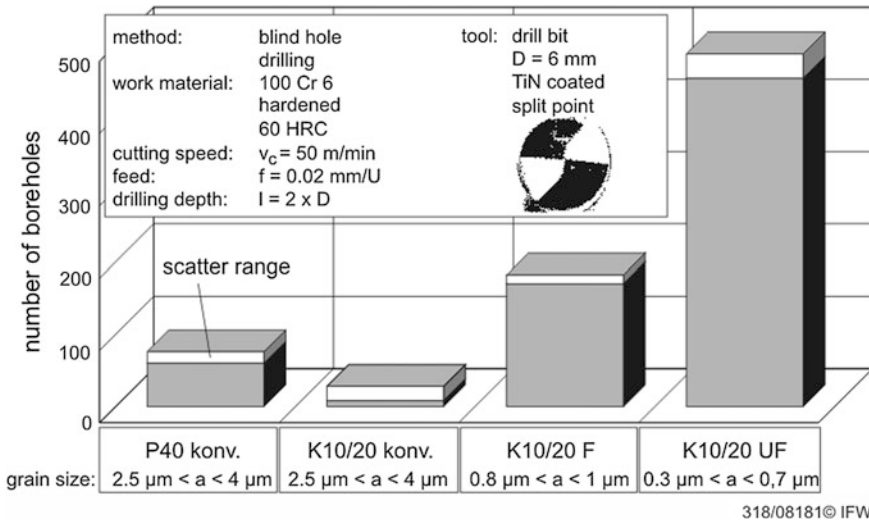


Fig. 8.14 Influence of carbide grade on the toll life behavior

The fracture toughness of cermets is lower (Table 8.4) than that of tough WC hard metal. Large differences exist in the thermal expansion coefficient and in the heat conductivity, which affects the application behavior in transient loading (see Chap. 7).

Cermets can be used for finish turning, thread turning and milling of steel and cast iron. The tendency of the batch production to use formed and molded parts with little allowance (near net shape technology) complies with the use of cermets.

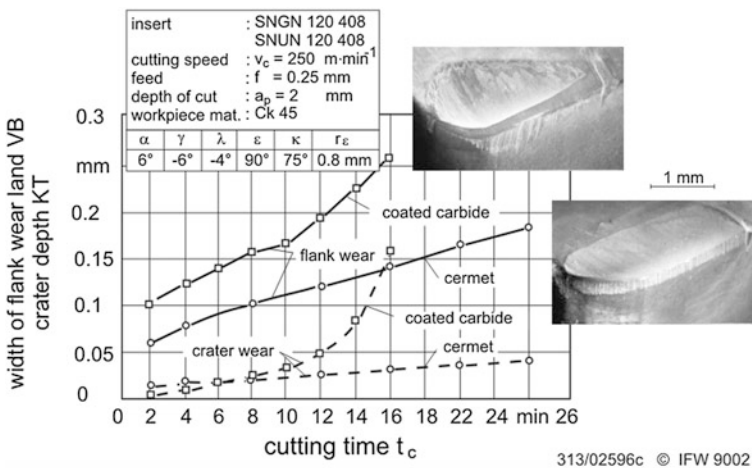
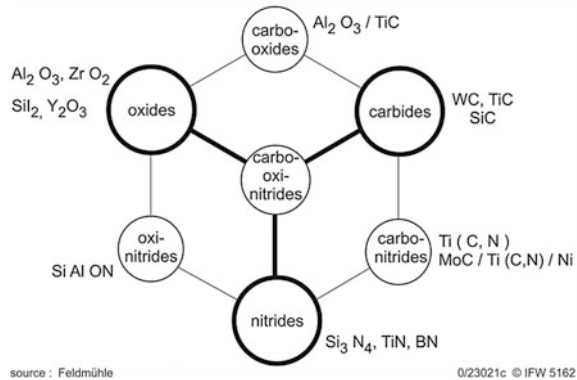


Fig. 8.15 Wear development of cermets and coated tungsten carbides over cutting speed

8.7 Ceramics

Cutting tools of ceramic materials are manufactured by sintering metal oxides, nitrides and carbides [FRI88, MOM93]. The ceramic base materials are divided into oxide and non-oxide ceramics. Aluminum and zirconium oxide belong to the most important oxide-ceramic cutting materials, silicon nitride, titanium carbide and nitride to the non-oxide ceramics (Fig. 8.16). Compounds and mixed crystals (for instance SiAlON) are used to combine the advantageous properties of various base materials.

Fig. 8.16 Base materials for ceramics

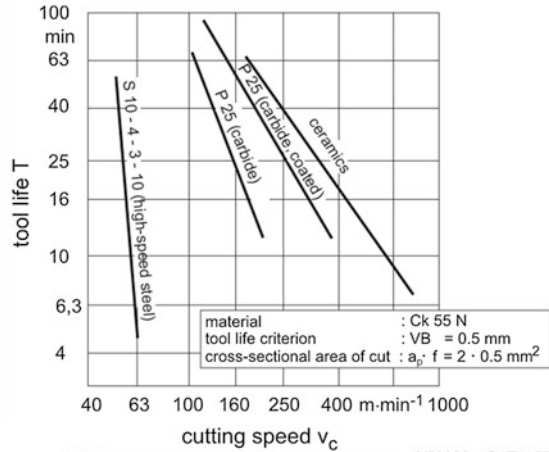


The most important properties of ceramics are their great hardness and their wear resistance. With increasing temperature the hardness of ceramics decreases more slowly than that of cemented carbide, whose hard particles are embedded into a metallic binder phase. Thus, ceramic cutting materials have a very good wear resistance even at high cutting speeds (Fig. 8.17). Their chemical inactivity reduces material adhesions and crater wear.

The toughness of ceramic cutting materials is limited. Ceramics break in a brittle way at mechanical overload, practically without any preceding plastic deformation. Compared to metals the expansion of a crack in ceramic materials requires only little energy. Therefore, ceramics are very sensitive towards external kerfs and internal material defects, where stress superelevations take place. The strength of a ceramic part is determined by the size of its biggest defect. Since the sizes of texture and surface defects are subject to statistic distributions, the fracture strength of ceramics varies in wide limits. It can be described by the Weibull distribution (Fig. 8.18). These relationships can affect the process reliability of applying ceramic cutting materials.

It was Osenberg who applied ceramic material for the first time as cutting tool in 1938. But he was unsuccessful, because he used pure aluminum oxide (alumina) which is a very brittle material [OSE38]. Enhanced oxide ceramic cutting

Fig. 8.17 Influence of cutting speed on tool life



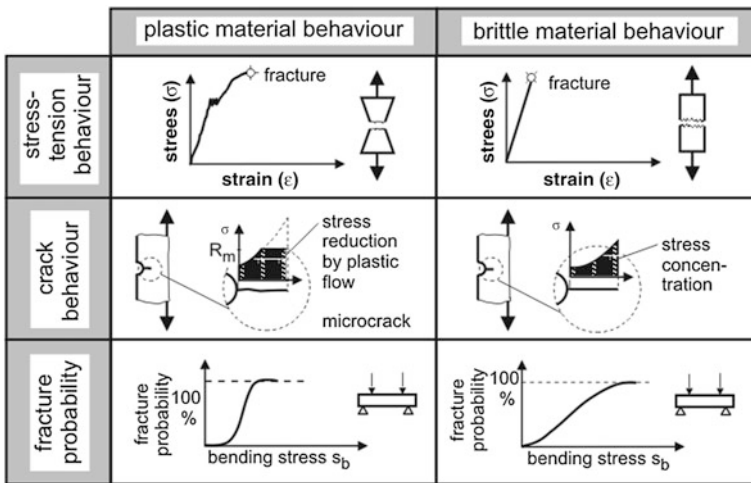
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materials have been available since the 1960s. They contain 5–15 % zirconium oxide or up to 40 % titanium carbide and nitride (“black” mixed ceramic) besides the 60–95 % of the hardness carrier alumina.

The addition of finely distributed zirconium oxide (ZrO_2) enhances the fracture toughness. This dispersion strengthening is based on three mechanisms: the stress inducing, the crack deflection and the crack furcation (Fig. 8.19).

Under mechanical load in the neighborhood of a crack from its metastable tetragonal high-temperature phase, the ZrO_2 converts into the monocline low-temperature phase. Since monocline ZrO_2 has a 4 % lower density than tetragonal ZrO_2 the particles tend to increase their volume. At this, they generate stress fields



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Fig. 8.18 Fracture behavior of metals and ceramics

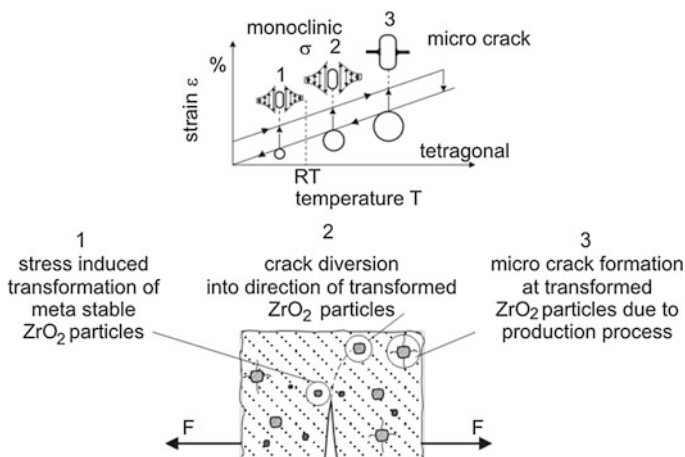


Fig. 8.19 Strengthening mechanisms of dispersion ceramics

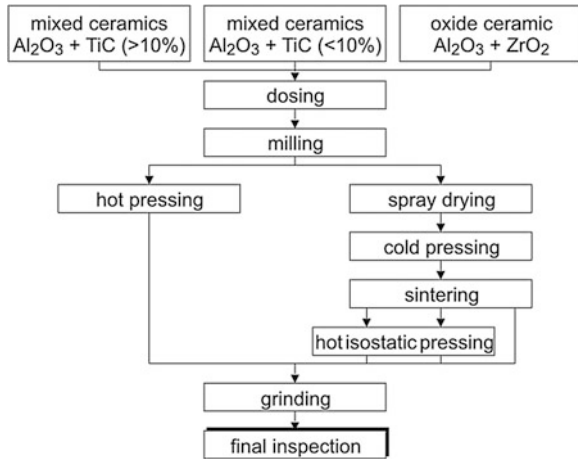
in the Al_2O_3 matrix. Cracks are deflected onto ZrO_2 particles and stop there (*crack deflection*). However, local stress fields are already generated in Al_2O_3 - ZrO_2 ceramic during the cooling of the sintering temperature. They are the result of the different thermal expansion coefficients of the two materials (*thermal misfit stresses*). These stresses can be adjusted by the grain size of the zirconium oxide in such a way so that they generate a great number of micro cracks (0.01 – $0.1 \mu\text{m}$) around the ZrO_2 particles. Because of their small size these cracks do not reduce the strength of the cutting ceramic. If an external crack encounters such a micro-crack network, its surface is greatly enlarged and the necessary energy to spread further increases correspondingly (*crack furcation*).

Dispersion-reinforced aluminum oxide ceramic is applied for the rough and finish turning of steel and cast iron up to a hardness of 48 HRC or 400 HV respectively. To cut aluminum alloys aluminum oxide ceramics are not suitable due to the chemical attack.

Titanium carbide and titanium nitride increase the hardness and abrasive wear resistance of the pure alumina. Their predominant covalent bondings give these materials a particularly high hot hardness compared to the predominant ionically-bonded alumina. This means that hardened steels up to 64 HRC can also be machined. The main application area of Al_2O_3 -TiC/TiN ceramic is finishing at high cutting speeds. The significantly elevated heat conductivity allows the use at rapidly varying thermal loads of interrupted cutting.

Silicon nitride (Si_3N_4) was introduced to machine cast iron and highly heat resistant materials at the beginning of the 1980s. The hardness of these non-oxide ceramics depends little on temperature. Due to beneficial thermal properties and a higher toughness, the silicon nitride ceramic is much less sensitive to thermal shock than pure oxide ceramic so that it can also be used in interrupted cutting. However, silicon nitride reacts at temperatures above $1,200^\circ\text{C}$ with iron forming

Fig. 8.20 Sintering of oxide ceramics



ferro-silicides. Therefore, it is not applicable for cutting steel, if such high temperatures are reached.

All cutting ceramics are produced by the sintering of fine powders. Thereby, the operational steps for cutting materials on the base of alumina and silicon nitride differ substantially. Figure 8.20 indicates the possible process steps for oxide ceramics. As precursors and in the form of powders, the intended basic materials and small shares of sintering additives are used, then weighed together in the required portions and finally subjected to a crushing and grinding procedure in a ball mill. This destroys the agglomerates of fine powder particles, which otherwise would lead to sintering defects. The grain size is set by the powder production (precipitation, gas phase reaction) and is generally not reduced any further here. The processed powder mixture can now be processed to solid ceramic bodies in different ways. The older procedure includes a compacting of the powder at room temperature and pressure of several hundred bar in a press form and then a non-pressure sintering of the semi-solid green body between 1,500 and 1,800 °C. These two process steps are combined in one single operation by means of the hot sintering mode. In both cases, the cutting insert is individually pressed and not cut from a larger sintered body. For particularly higher demands concerning pore free products and strength, the completed tools can be repressed isostatically at a high gas pressure and high temperatures. Prerequisite for this is an already closed porosity, at least at the surface. The sintered tools must finally be set to the required form and dimension by diamond grinding and polishing. The required high surface quality is also produced in this process step.

Figure 8.21 explains the cutting ceramic on the base of silicon nitride. Raw materials can be silicon nitride as well as silicon powders. The latter reacts only when sintering at the nitrogen atmosphere of the furnace to α - and β -silicon nitride (reaction bonded Si_3N_4). All silicon nitride ceramics must be sintered under high nitrogen pressure, because Si_3N_4 dissolves into its elementary constituents at

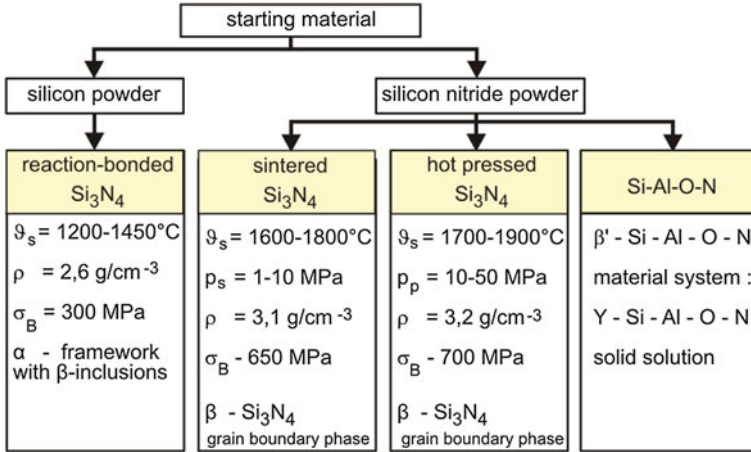


Fig. 8.21 Silicon nitride ceramic

normal pressure and high temperatures. Furthermore, sintering aids (yttrium-manganese- silicon-oxides) have to be added to build a silicate glass phase, which binds the needle-shaped silicon nitride crystals to a dense, pore-free structure. Because glasses have no fixed melting point but soften at elevated temperatures, the high temperature strength of silicon nitride cutting materials is reduced by the glass phase. The result is creeping, i.e. slow plastic deformation follows under mechanical load. The Si_3N_4 - crystals slip against each other alongside the grain boundaries. To increase the maximum applicable temperature of usage, the glass can be totally or partly crystallized out by subsequent tempering (aged at elevated temperature). Thus, between the Si_3N_4 -needles a matrix of garnet crystals is built with a high melting point temperature, which is far more creep-resistant.

Cutting inserts of hot pressed silicon nitride are sintered in the form of large plates and subsequently separated by laser. In contrast to oxide ceramic, laser cutting is unproblematic in this case as silicon nitride has no melting phase but sublimates at $1,900^\circ\text{C}$. To achieve form, dimension and surface-quality the silicon nitride inserts are also finished by diamond grinding. Due to the high hardness and the relatively high toughness, the grinding of ceramics is very expensive and causes a high partition of the total manufacturing cost of cutting tools.

The new developments of ceramic cutting materials aim towards an increase in process reliability. Therefore, the ceramics are strengthened by ceramic fibers, high strength fiber-shaped single crystals (whiskers) and platelets. They increase the bending strength and particularly the fracture toughness by means of crack deflection, crack bridging and thus stress reduction at the crack front. However, these measures complicate the grinding processes and increase the cost of the ceramic tools. In the case of whiskers there are health hazards in handling the powder, which is why the production was abandoned in Germany for the time being.

8.8 Diamond

Diamond and cubic crystalline boron nitride belong to the super hard cutting materials. Diamond is the hardest known substance. It consists of pure carbon. Elemental carbon co-exists in the stable modification, i.e. graphite and in the unstable high pressure modification, i.e. diamond. Diamond solidifies cubic crystalline, where each carbon atom is surrounded by four neighboring carbon atoms in the lattice. The C-atoms are tetrahedrally linked by covalent bonds. The high hardness of the diamond follows from the high binding energy of the atoms.

Diamonds are found and mined in nature. Since the 1950s [BUN55], diamonds are also being produced synthetically. Both modifications may exist as mono-crystalline or poly-crystalline diamonds.

8.8.1 Mono-Crystalline Diamond

Diamonds found in nature are mostly applied as single crystals, namely where cutting edges of highest sharpness and lowest chipping are required. Typical application domains are the ultra-precision cutting and the shine cutting of non-ferrous metals such as aluminum, copper and their alloys. Using the crystallographic orientation of the diamond, the crystal can be shaped by means of grinding and polishing to the minimum cutting edge radius $r_\beta \sim 1 \mu\text{m}$. The cutting edges are ground in a faceted way, i.e. with several major cutting edge angles and small minor cutting edges of $1^\circ\text{--}3^\circ$, or as arc edge (large radius r_e). The mono crystals are soldered or clamped in a holding element. Mono-crystalline diamond has strong direction-dependent physical properties (anisotropic material behavior), for instance hardness, strength, Young's modulus and heat conductivity. This anisotropy is used to modify diamond by cleaving, grinding and polishing. For its application as a tool it is orientated as far as possible into its hard, wear resistant directions. Basically, large mono-crystalline diamonds can also be produced synthetically. So far, however, due to the high cost of equipment and of tools for the production of large crystals for the application in geometric defined processes (for cutting in contrast to abrasive processes), natural diamonds as large mono-crystals are more economic.

8.8.2 Polycrystalline Diamond

The first diamond synthesis is said to have been successful in 1953 at ASEA, Sweden. In 1955, the synthesis was published in Nature by Bundy and others (General Electric, USA) [BUN55]. The first patents for industrial application were granted in 1960 [HAL60]. At that time, the production of smaller diamonds

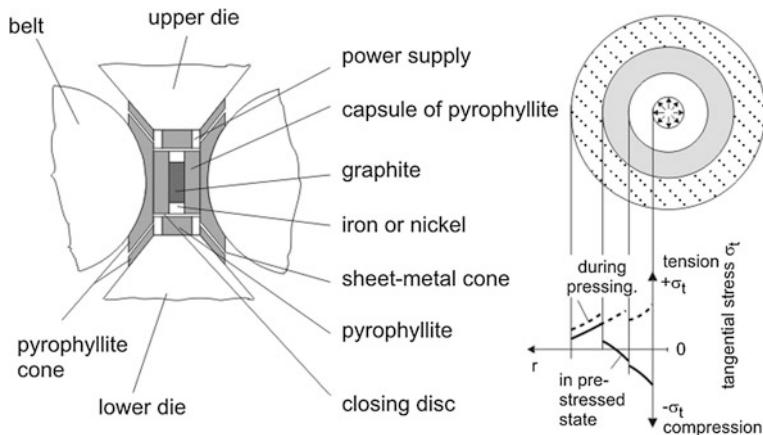


Fig. 8.22 Belt press for the production of synthetic diamonds [HAL60]

directly from graphite at high temperatures of 3,000 °C and high pressures of 10 GPa was initially successful. Adding solvents and catalysts (for instance cobalt, nickel, silicon, boron, beryllium and iron) can reduce the conditions of synthesis to 6 GPa and 1,500 °C. Cobalt, for example, has dissolving properties for carbon depending on pressure and temperature. Under conditions of synthesis in the metastable diamond-range cobalt is liquid. With increasing pressure and temperature the liquid solubility for carbon decreases, diamond is segregated. Repeated cyclic traversing of the synthesis range can enhance the conversion. This kind of synthesis generates single crystals, whose growth rate can be changed by systematical pressure and temperature control as well as by the quantity of seed crystals (density of nucleuses). The size of the crystallites can thus be influenced in a well-targeted way. To generate the necessary pressures for the diamond synthesis presses as shown in Fig. 8.22 are used.

Diamond synthesis generates grains in the range of 2–400 μm , which can be combined to a poly-crystalline matrix (PCD) after sorting in a further process by means of high-pressure-liquid-phase sintering. In this second process, the catalytic effect of the metallic companion is used again (Fig. 8.23). An adhesion enhancement can be achieved by means of a cobalt rich intermediate layer. If metallic phases are used as sintering aids, their liquidus line will lie below the sintering temperature even in the high pressure domain.

The properties of the poly-crystalline diamond layers can be controlled by the size of the applied grit and by the kind and quantity of the metallic phases. Grain sizes of 2–60 μm can be achieved in the final state, whereupon the grain size decreases during the sintering process. The Co-content after sintering decreases with the growing grain size of the base material [SIE91]. Consequently, it can be assumed that larger grits have higher shares of covalent bonds. That is the reason why PCD with coarser structures has the highest wear resistance but also the lower edge quality (possible sharpness).

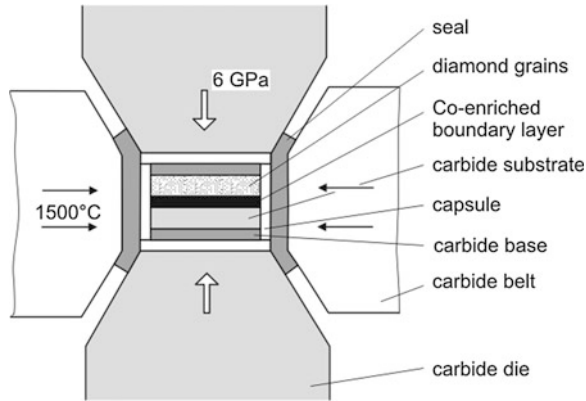


Fig. 8.23 High-pressure-liquid-phase sintering of PCD on substrate

Polycrystalline diamonds are largely isotropic because of the non-directed allocation they are composed of. They are, however, less hard than mono-crystals. They are much tougher than mono-crystals because of their isotropy, their grain boundaries and metallic inclusions.

Their application domain is the roughing-finishing machining of non-ferrous metals at set conditions, which no chemical wear and cutting wedge temperatures above 700 °C occur at. The tolerable temperature is not limited by the temperature of graphitizing at 900 °C but already at 650–800 °C. The reason is the enrichment of cobalt occurring in this temperature range resulting from the volume expansion of cobalt compared to diamond. However, this effect depends on the disposition time [SIE91]. Metallic materials such as aluminum, copper and their alloys, non-metals such as plastics, wood and graphite can be beneficially machined by PCD. PCD is particularly applied for highly abrasive material such as hypereutectic aluminum–silicon alloys (pistons, cylinder blocks), glass fiber reinforced plastics and wood-

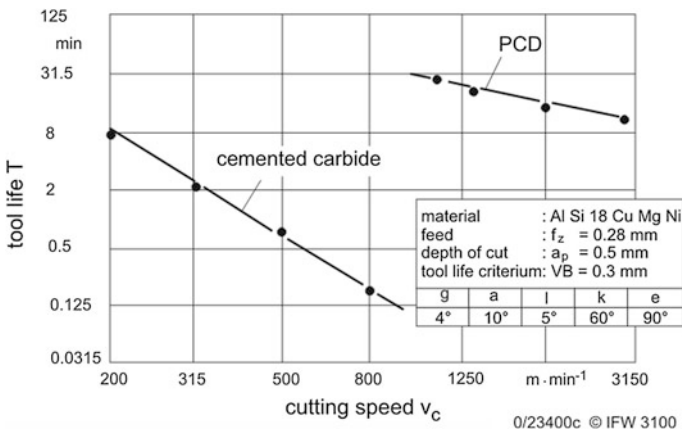


Fig. 8.24 Tool life for the milling of aluminum

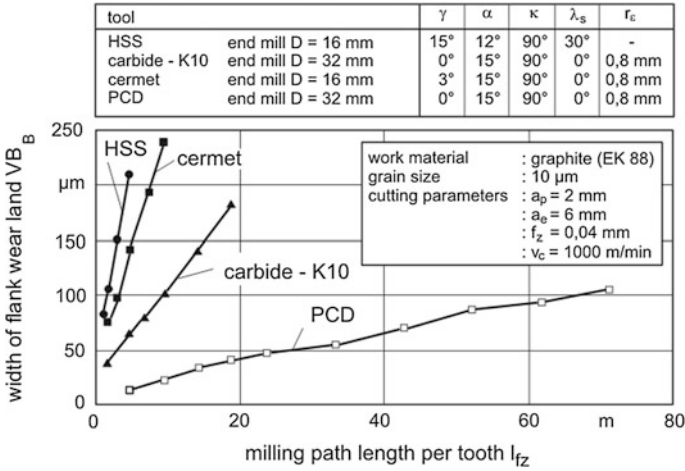


Fig. 8.25 Flank wear land for various cutting materials

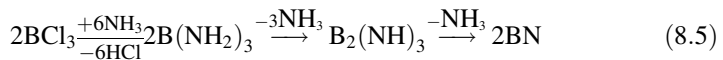
plastic-filling compound material seeing as very long tool lives can be reached in contrast to high speed steel, cemented carbides or ceramics (Figs. 8.24 and 8.25).

For soft materials declining to adhesion such as forgeable aluminum alloy, it may be of interest that adhesion and pseudo-chip building can be prevented or delayed by PCD because of its good cutting edge resistance (geometrical effect, delay of cutting edge rounding) and because of its low friction co-efficient (tribo-effect).

8.9 Boron Nitride

Cubic crystalline boron nitride (CBN) is the hardest cutting material beside diamond (Table 8.1). Unlike diamond, CBN is chemically resistant towards iron and other carbide building materials. It is stable up to temperatures of 1,400 °C. In the normal atmosphere, a protective layer of boron oxide (B₂O₃) prevents oxidation up to 1,300 °C. Therefore, CBN tools can be used to cut hardened steels, hard cast iron, nickel base alloys and to machine sputtered or welded hard layers.

Boron nitride naturally exists only in the hexagonal crystalline form, having a similar consistency as graphite. Boron and nitrogen are the elements directly next to carbon in the periodic system. Boron nitride can be transformed into the cubic crystalline modification as diamond through high-pressure- high-temperature synthesis. This kind of structure has a covalent binding. There is also a further lattice type of high hardness (but not as hard as the cubic type), the wurzite-modification. Hexagonal boron nitride is obtained by pyrolysis from boron-halogen compounds.



Boron nitride can be produced in various ways, differing in the number of process steps and in the use of additives. With the one-step process polycrystalline CBN is directly produced from the hexagonal modification and with the two-step process the CBN is first synthesized and in a subsequent sintering process the grit is treated to poly-crystalline material [KRE07].

For the pyrolysis metallic catalysts are mostly applied, where lithium is most frequently used, which leads to brown to black CBN. The further processing of the CBN grit produced in the pyrolysis to abrasive tools occurs in the same way as with the synthesized diamond.

Cubic boron nitride was first produced in 1957 [WEN57]. The synthesis requires the same arrangement as the synthesis of diamond. Pressures of 5–9 GPa and temperatures of 1,500–2,000 °C have to be applied [WEN61]. Alkali metals serve as catalysts, which allow the reduction of the synthesis temperature to the specified range.

Similar to diamond the CBN grit can be processed to thick poly-crystalline layers (layer thickness 0.5 mm) on cemented carbide or to solid CBN bodies by means of high-pressure-high temperature synthesis (Fig. 8.22). This poly-crystalline boron nitride (PCB) is available in two types of cutting material. One type being PCB with a high content of hard substance and strong penetration of the grains and the second type, with small content of hard substance and without grain penetration. The binder phase contains titanium carbide or titanium nitride. PCB with a lower hard substance content has a much lower heat conductivity ($\lambda = 40$ W/mK compared with 100–200 W/mK for the material with larger hard substance content).

PCB wears significantly less than cemented carbide (Fig. 8.26). Thus, higher cutting speeds can be reached for equal tool life by orders of magnitude [HER91]. When machining high strength materials with slender tools or workpieces of high compliance, it is of interest that lower cutting forces occur due to geometric (sharp cutting edges) and tribological (less friction) reasons (Fig. 8.27).

PCB is of great importance for the hard machining of steel, particularly under instable machining conditions or for interrupted cuts. For appropriate machining operations grinding can be replaced by turning, milling or drilling with PCB (see Chap. 10). Appropriate machining operations mean:

- small faces to be machined to keep form errors within limits
- limited demands on the dimensional and form accuracy
- compact, stiff workpieces, which are not inadmissibly deflectable by passive forces

If these conditions are met, considerable rationalization effects are achievable by means of higher material removal rates and shorter operation sequences.

8.10 Questions

1. Mention the types of loading on cutting tools.
2. What properties should cutting materials have?

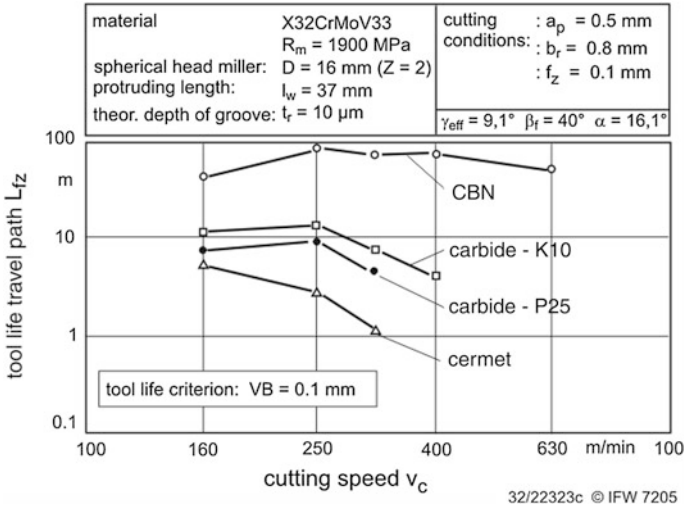


Fig. 8.26 Tool life travel of various cutting materials depending on cutting speed

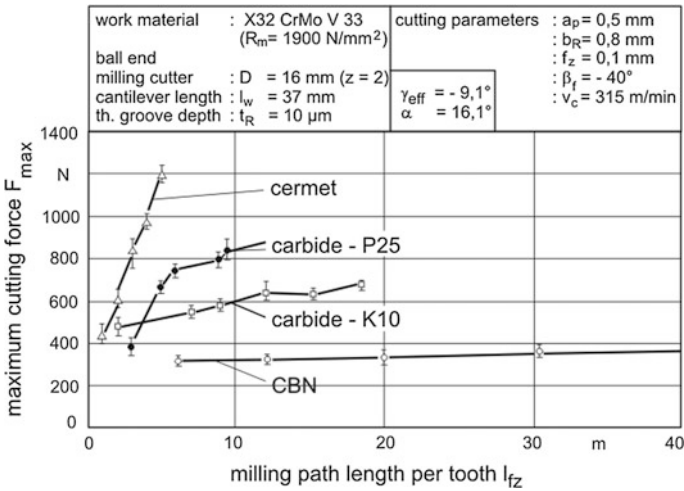


Fig. 8.27 Resultant force of various cutting materials

3. What cutting processes have special requirements concerning the mechanical and thermal fatigue strength?
4. What effect does the inclusion of hard substances into the cutting material matrix have?
5. Which classes of hard substances do you know? (4 classes)
6. Give one example for each class of hard substances.
7. Name at least 5 different cutting materials and order them by their wear resistance.
8. What is the carbon content of unalloyed tool steels?

9. Which main alloy elements form carbides?
10. What is the meaning of HS 10-4-3-10?
11. What does the marking HSS mean and what kind of tools is this cutting material preferably used for?
12. How are tungsten carbides produced and which main phases are they composed of?
13. Why are tools coated and what problems occur during coating? What ranges does the deposited layer thickness lie in?
14. Explain the differences between PVD, CVD and PACVD processes.
15. What benefit does one expect from TiC coated cemented carbides?
16. What are cermets?
17. How do cermets and WC containing carbides differ? What are the respective application domains?
18. What are the advantages and disadvantages of cutting inserts out of ceramics?
19. What is the essential difference between cemented carbides and ceramics regarding the composition? What sorts of ceramic are known to you?
20. What do you understand by the transformation strengthening of ceramics?
21. What is PCB and what properties does this material have?
22. What types of PCB exist and how do they differ?
23. Describe the process for the production of PCD.
24. What is the strengthening effect of a Belt-press?

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