Chapter 2
Advanced Cutting Tools

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In this chapter the basic design principles and the current state-of-the-art for cutting tools specially designed to be applied on difficult-to-cut materials are described. One by one, the main aspects involved in tool design and construction will be explained in depth over the following sections, completing a general view of the tool world, to provide easy comprehension of the whole book. Materials for the substrates, coatings, and geometry are explained, with special attention to recent developments. A section is devoted to new machining techniques such as high-feed and plunge milling, turn milling and trochoidal milling.

2.1 Materials for Cutting-tool Manufacture

Cutting tools must simultaneously withstand big mechanical loads and high temperatures. Temperature in the chip/tool interface reaches more than 700 °C in some

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cases. Additionally, the friction between tool and removed chip, on one hand, and tool against the new machined surface, on the other, is very severe. Bearing this in mind, the main factors for a good tool design and post-manufacturing are:

- Cutting-tool substrate material must be very stable chemically and physically at high temperatures.
- Material hardness must be kept to the high temperatures suffered at the chip/tool interface.
- Tool material has to present a low wear ratio, both for the abrasion and adhesion mechanisms.
- Tool material must present enough toughness to avoid fracture, especially when operation to perform implies interrupted or intermittent cutting.

In the following sections each of the main tool materials are going to be described, starting from the lowest hardness to the highest. These groups are:

- *High-speed steels* (HSS), including the new powder-sintered grades. However, this material family has not enough hardness for hard machining.
- Sintered carbides, usually known as *hardmetal*. They are a compound of submicron tungsten carbide grains with a binder (usually cobalt, 6–12%) This kind of material in the straight grade or in the coated grades (see an example in Figure 2.1) is the most used today for hard machining and high-speed machining.
- Ceramics based on alumina (Al_2O_3) or silicon nitride (Si_3N_4).
- Extra-hard materials, *i.e.,* polycrystalline diamond (PCD) and polycrystalline cubic boron nitride (PCBN), in different grades.

Before explaining the main aspects of each material, a mention of the company type involved in tool fabrication is an interesting point. Thus, in the current tool market two types of company are possible: firstly, the producers of basic tool materials, usually big international companies such as CeraTizit, Krupp, Sumitomo, General Electric, De Beers, Sandvik, Kennametal, Iscar and others, which also manufacture the complete cutting-tool systems including toolholders, inserts or integral cutting tools. Currently these companies represent the 80% of the total world market.

Figure 2.1   Milling tool for routing carbon-fibre-reinforced plastics, by Kendu®, made of sub-micrograin tungsten carbide (*top*), and with TiAlN coating applied by Metal Estalki® (*bottom*)
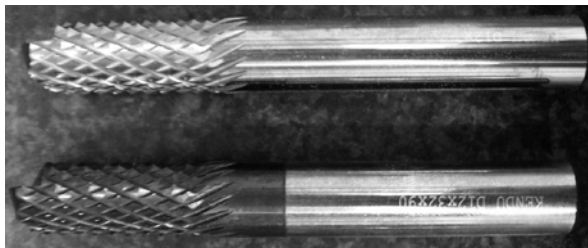
Secondly, there are small and medium companies that start from calibrated material rods, supplied by some of the former companies, and give form and geometry to cutting tools. This is the case of integral endmills, drilling tools and tailor-made tools. The natural markets for these companies are either very specific niches or special tailor-made tools built with user requirements.

2.1.1 High-speed Steel

This group of high-alloyed steels was developed at the early years of the 20th century. Basically they are high-content carbon steels with a high proportion of alloy elements such as tungsten, molybdenum, chromium, vanadium and cobalt. The mean hardness is 75 HRC.

The T series includes tungsten, the M series molybdenum, whereas vanadium produces the hardest of the carbides giving rise to the super-high-speed steels. The maximum working temperature of HSS is about 500 °C. Currently, HSS produced by powder metallurgy (HSS-PM) offers a higher content of alloy elements and a combination of unique properties: higher toughness, higher wear resistance, higher hardness and higher hot hardness. In Figure 2.2 a comparison of tool materials regarding hardness and bend strength is shown, in which the latter, directly related to toughness, is the main advantage of this type of tool material.

HSS and HSS-PM are excellent substrates for all coatings such as TiN, TiAlN, TiCN, solid lubricant coatings and multilayer coatings.

HSS-PM has many advantages in high-performance applications such as rouge milling, gear-cutting tools and broaching, and also in cases of difficult tapping, drilling and reaming operations. HSS-PM is used too in disc and bandsaws, knives, cold-work tooling, rolls, *etc*. However, for machining of tempered steels and very difficult-to-cut alloys HSS is not the first choice; tungsten carbide is a more recommended tool material (see Section 2.1.2).

Figure 2.2   Bend strength *versus* hardness for tool materials (HSS Forum [1])
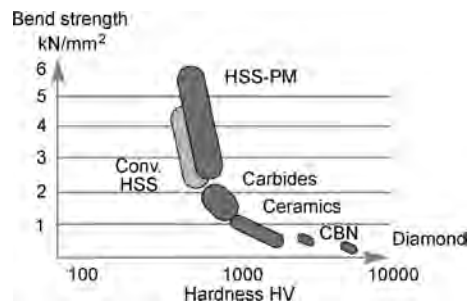
2.1.2 Sintered Carbide (Hardmetal)

Sintered carbide tools, also known as *hardmetal* tools or *cemented carbide* tools are made by a mixture of tungsten carbide micrograins with cobalt at high temperature and pressure. Tantalum, titanium or vanadium carbides can be also mixed in small proportions.

Therefore two main description factors define a hardmetal grade:

- The ratio of tungsten carbide and cobalt. The latter usually ranges from 6 to 12 % and it acts as binder. Cobalt has a high melting point (1493 °C) and forms a soluble phase with tungsten carbide grains at 1275 °C which helps to reduce porosity.
- The grain size, thus micrograin grades include particles smaller than 1 μm, and submicrograin are smaller than a half of a micron; the smaller the grain, the harder the hardmetal. Hardness increases with the reduction in binder content and tungsten carbide grain size, and *vice versa*, with values from 600 to 2100 HV.

Hardmetal tools are manufactured in two forms:

- Integral tools: they are manufactured by grinding a raw hardmetal rod, obtaining an endmill, a ball-endmill (Figure 2.3) or a drilling tool. The main advantage is the perfect balance of these rotary tools, but the main disadvantage is their high price, taking into account that only a little and very specific zone of the tool is worn by the cutting process. Several resharping of each tool are possible.
- Inserts: small pads with special geometry made with hardmetal, but they are fixed on toolholders made of steel. Turning tools and big milling discs use this configuration, which implies a rapid substitution of worn inserts.

Hardmetal grades are classified under the standard ISO 513 [2] into six groups, M, P, K, N, S and H, following a numerical scale for each of them. On the other hand, in the USA the C-x scale is used instead. The original concept of both classifications was to rate tungsten carbides according to the job that they had to do, and this led to a little clear scale in which no cobalt binder amount or grain size is specified. As consequence, tungsten carbide from different manufacturers may
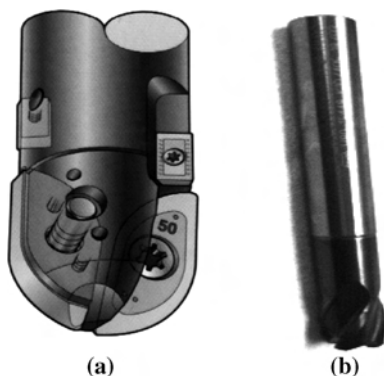
Figure 2.3 Ball-endmill with inserts (a), and integral bull-nose endmill (b)

(a)   **(b)**

have identical designation but may vary considerably in performance. In Table 2.1 hardmetal grades offered by the company Ceratizit® are shown.

The ISO group recommendations are:

- P, indicated for low- and medium-carbon steels, and light alloyed steels;
- M, composed of sintered carbides, suitable for the stainless steels machining;
- K, oriented to cast irons and alloyed steels, and harder than the P and M series;
- H, for tempered and hardened steels;
- S, for heat-resistant alloys and titanium alloys;
- N, for aluminium alloys.

The two-digit number after the letter, from 01 to 40 (50 in P group) defines the hardness and toughness of the grade. The lower numbers correspond to the harder grades, whereas the higher are the tougher of them. K10 to K30 are the most used today.

Regarding the American classification, C-1 to C-4 are general grades for cast iron, non-ferrous and non-metallic materials, C-5 to C-8 are suitable for steel and

Table 2.1 Ceratizit® hardmetal grades

Grade	ISO code	Code USA	Grain size	TiC Ta(Nb)C	Binder	Density	Hardness			Transverse rupture strength TRS		K_{IC}
					%	g/cm³	HV 10	HV 30	HRA	MPa	P.S.J.	MPa.m$^{1/2}$
TUNGSTEN CARBIDE COBALT GRADE												
TSF22	K10–K20	C-2	Ultrafine	–	8.2	14.55	1970	1930	93.7	4400	638,000	7.5
TSF44	K10–K30	C-2	Ultrafine	–	12.0	14.10	1760	1730	92.7	4600	667,000	7.8
MG 12	K05–K10	C-3	Submicron	–	6.0	14.80	1820	1790	93.0	3500	507,500	8.2
TSM20	K10–K30	C-3	Submicron	–	7.5	14.75	1750	1720	92.6	3500	507,500	8.6
TSM33	K20–K40	C-2	Submicron	–	10.0	14.50	1610	1590	91.9	3700	536,500	9.4
MG 18						14.45	1680	1660	92.3	3700	536,500	9.4
CTS18D	K20–K40	C-2	Submicron	–	9.0	14.55	1610	1590	91.9	3600	522,000	10.4
CTF12A	K15	C-2	Fine	–	6.0	15.00	1650	1630	92.1	2600	377,000	10.2
HC10	K10	C-3	Fine	–	5.6	14.95	1760	1730	92.7	2150	311,900	9.2
H20X	K15	C2	Fine	–	6.0	14.95	1670	1650	92.2	2200	333,500	9.9
WC-TiC/TaNbC – COBALT GRADE												
S4X7	P30–P35	C-5	Fine	12.0	11.0	14.95	1490	1470	91.0	2300	333,500	11.6
CERMET												
TCN54	HAT–P20	–	–	–	14.1		1650	1630	92.1	2000	290,000	8.5
SILICON NITRIDE GRADE												
SNC 1	CN–K20	–	–	–	9.0		1550	1530	91.5	1100	159,500	6.5

steel alloys because these grades resist pitting and deformation, C-9 to C-11 are indicated for high-wear applications, and C-12 to C-14 are for impact cases. A common misconception is that higher grades have less cobalt binder and therefore are harder and fragile, but that is not true. For this reason and others the ISO standard is currently increasing in use.

A tool material derived from hardmetal is the cermet (ceramic–metal) type, sintered tungsten carbide also including TiC (carbide with hardness 3200 HV) and in some cases TiCN, but they typically have a nickel–chrome binder. New grades with TaNbC and MoC increase the tool-edge strength against the cyclic impacts typical of milling.

Tungsten carbide is very stable regarding chemical and thermal aspects of machining, and is very hard as well. In most cases, cemented carbide degradation starts from the cobalt binder and the tungsten carbide–cobalt cohesion.
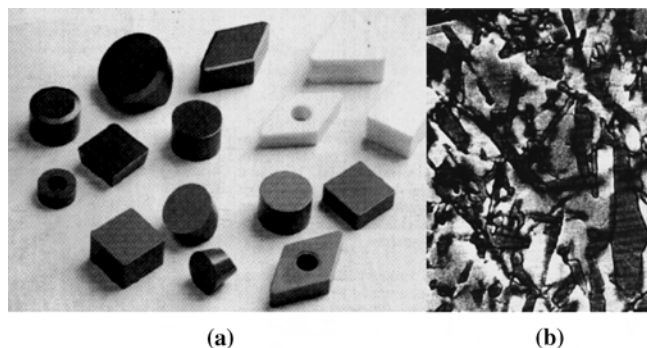
2.1.3 Ceramics

Ceramics are very hard and refractory materials, withstanding more than 1500 °C without chemical decomposition. These features recommend them to be used for the machining of metals at high cutting speeds and in dry machining conditions. Unfortunately they are fragile, and ceramics without any reinforcement are only indicated for turning of continuous shapes. In milling the continuous impact at each tooth entrance in the machined part implies a high risk of chipping and tool failure.

Ceramic materials are moulded from ceramic powders at pressures more than 25 MPa, to be later on sintered at approximately 1700 °C.

Ceramic tools are based primarily on alumina (Al_2O_3), silicon nitride (Si_3N_4) and sialon (a combination of Si, Al, O and N).

Alumina tools can contain additions of titanium, magnesium, chromium or zirconium oxides distributed homogeneously into the alumina matrix to improve toughness.

(a)   **(b)**

Figure 2.4   (a) Ceramic inserts: alumina (white), silicon nitride (grey), alumina with TiC (black), and (b) matrix of a reinforced ceramic (by Greenleaf®)

Silicon nitride ceramics present a higher resistance to thermal shock, with a higher toughness as well. These ceramics have a needle-like structure embedded in a grain boundary. This microstructure enhances fracture toughness. Their most typical application is the roughing of cast iron, even under unfavourable conditions such as heavily interrupted cuts. Silicon nitrides also are used to mill cast iron.

The ceramics reinforced by a non-homogeneous matrix of silicon carbide (SiC) whiskers ($Al_2O_3 + SiC_w$) are focused on the milling operation. Whiskers are fine-grained silicon carbide crystals similar to hairs. The whiskers form 20–40 % of the total ceramic, improving the tool toughness a lot, making them suitable for milling operations. Whisker-reinforced ceramics are successfully applied on hard ferrous materials and difficult-to-machine super alloys, especially in the case of the nickel-based alloy Inconel 718.

Ceramics are a very productive option in a lot of applications, but special care must be taken when machining is programmed. Tools must be kept hot throughout the operation (dry condition is the best) and shocks on tool edges at tool entrances and exits from the workpiece must be avoided. In turning, the *ramping* technique is highly recommended to reduce the notch wear in the cylindrical roughing of austenitic materials.

2.1.4   Extra-hard Materials

PCD and PCBN are extra-hard materials. There are several grades in the PCD and PCBN groups. As a rule of thumb, PCD is suitable for tools focused on machining abrasive non-ferrous metals, plastics and composites. Otherwise, PCBN finds applications in the machining of hardened tool steels and hard cast irons.

2.1.4.1   Diamond and Polycrystalline Diamond

PCD plates are obtained by a high temperature and pressure process where synthetic diamond grains are sintered with cobalt. Depending upon the machining operation, PCD is available in various grain sizes (Table 2.2). Thus, those grades with coarse grain sizes are used for making cutting tools with high wear resistance, but if very high surface finishing is required in the machined part, then ultra-micro grain sizes are preferred. Medium grain sizes are used for general-purpose cutting tools, since there is a balance between the high wear resistance of rough grain size and the good finish of ultra-micro grains.

Monocrystalline diamond (MCD) is natural diamond which enables the production of geometrically defined cutting edges with absolutely notch-free flutes. Natural diamonds often contain nitrogen which can produce varying hardness and thermal conductivity. This very expensive material is suitable for achieving very high surface finishes for mirror-bright surfaces, machining of non-ferrous materials, micromachining, dressing grinding wheels and machining of super alloys

Table 2.2 Some of the PCD grades by Sumitomo®

	Grade		
	DA90	DA150	DA200
Average diamond crystal size (μm)	50	5	0.5
Vickers hardness	10,000–12,000	10,000–12,000	8,000–10,000
Transverse rupture strength (kg/mm^2)	110	200	220
Product description	Coarse-grain diamond • Ultra-high abrasion resistance	Fine-grain diamond • High abrasion resistance • Excellent tool-edge sharpness	Ultra-fine-grain diamond • Superior tool-edge sharpness and toughness
Machining applications	• High-silicon aluminium • Graphite • Aluminium/grey iron bimetal • Ceramics • Tungsten carbide • Kevlar	• Low- and medium-silicon aluminium • Copper • Fibreglass • Carbon • Wood – plywood, fibreboard and hardwoods	• Plastics • Wood • Aluminium and copper applications where: – Low microfinish is required – Workpiece has severely interrupted surface

without burrs. Currently, the development of synthetic MCD in triangles and rectangles with an edge length of approximately 6–10 mm makes economically possible the use of this material for high-end applications.

2.1.4.2 Polycrystalline Cubic Boron Nitride

CBN is a polymorph boron-nitride-based material. Its high mechanical properties are due to its crystalline structure and its covalent link. It has been industrially produced since 1957, starting from hexagonal boron nitride put under high pressures (8 GPa) and temperatures (1500 °C). With a lower hardness (< 4500 HV) than diamond (> 9000 HV), CBN is the second-hardest synthetic material.

The CBN grains are sintered together with a binder to form a composite, PCBN. The size, shape and ratio of CBN/binder define the different PCBN grades (Table 2.3, Figure 2.5). The content of CBN crystals ranges from 40 to 95 %, whereas binder may be Co, W or ceramic. If interrupted cutting (milling) of iron castings is to be performed, high CBN content and Co matrix grade is recommended. Low CBN content and ceramic matrix can be used in finishing operations. PCBN is typically recommended in the turning, milling and drilling of pear-

Figure 2.5 Two grades of PCBN, Borazon™ by General Electric®
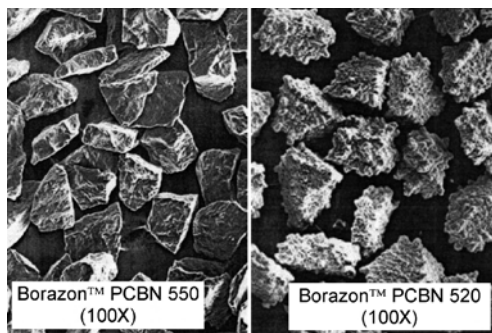
litic iron castings, both grey and ductile, but should not be used for ferritic iron castings. Ferrite is highly reactive, and produces the degradation of the CBN because of the diffusion of boron within the ferritic matrix.

Degradation of PCBN in the turning of thermal sprayed layers on turbine axles due to a complex chemical attack of coolant has also been reported [3].

Using PCBN, cutting conditions can be very high, for example $V_c = 1800$ m/min, $f_z = 0.31$ mm/z in the machining of lamellar grey iron casting (GG25) with tool life of 1200 m/tooth. In the case of martensitic (55 HRC) or white (55 HRC) iron castings, cutting speed within the range 100–200 m/min using feed rates of about 0.15 mm/z can be used [4]. Recommendations given by tool manufacturers are more conservative, with values of 300–900 in the case of grey irons and 100–300 m/min for ductile irons.

If cutting speeds over 1500 m/min are used, an aluminium oxide layer may appear on the cutting edge, resulting from the adhesion of aluminium inclusions from the iron casting. At lower cutting speeds that layer protects the edge from wear. However, over 1500 m/min the temperature at the edge becomes too high (around 1400 °C), which collaborates with a complex chemical reaction between the PCBN binder material and the silicon from the casting, giving rise to TiB2 and TiCN products.

As far as the tool geometry is concerned, in the case of endmills the best results have been obtained when a small helix angle was used (about 2°). Supposedly, the cutting is more stable when using low helix angles. In [5], endmills with helix angles of 2° and 30° are compared, both under severe machining conditions: $V_c = 1500$ m/min, $f_z = 0.02$ mm, $a_p = 18$ mm, $a_e = 0.05$ mm, tool diameter = 60 mm and no coolant. Before the end of the tool life was reached, the former could machine a length of 1800 m, whereas the length machined by the latter was 850 m.

PCBN commercial tools consist of a PCBN layer placed on a hardmetal tool body. Again, the tool/toolholder balance is a crucial factor when choosing integral rotary tools.

Usually, PCBN tools present a very simple geometry. However, the CBN300 chipbreaker (by SECO®) is designed with an increased rake angle. This leads to lower cutting forces and lower levels of transferred energy, resulting in a lower temperature levels in the cutting zone.

Table 2.3 Some of the PCBN grades by Sumitomo®

	Grade						
	BN100	BN250	BN300	BN500	BN600	BNX20 (US300)	BNX10
CBN content (%)	85	60	60	65	90	60	50
CBN crystal size (μm)	3	1	0.5	4	2	3	4
Primary binder material	Titanium nitride	Titanium nitride	Titanium nitride	Titanium carbide	Co–Al	Titanium nitride	Titanium nitride
Vickers hardness (HV)	3900–4200	3200–3400	3300–3500	3800–3500	3900–4200	3200–3400	2800–3000
TRS (kg/mm²)	85	105	115	105	105	105	85
Recommended for machining	• Grey cast iron • Powdered metal	• Light- & medium-interrupted hardened steel	• Severely interrupted hardened steel	• Nodular iron • Grey cast iron • Alloyed iron	• Grey cast iron • Powdered metal • Chilled cast iron • Ni/Co-based superalloys • Ni-hard iron	• High-speed continuous turning of hardened steel	• High-speed continuous hardened steel finishing

The use of PCBN depends of several factors to be taken into account. Thus, after several milling tests on hardened steels for mould making, these factors were gathered and evaluated (Table 2.4).

PCBN suits fine the turning of continuous surfaces, for example the turning of brake discs. In ball-endmilling the major problem to be solved is that cutting speed at the tool tip is zero, and as a result, the PCBN suffers high mechanical stresses. The best method to overcome this problem is the use of 3+2-axis machines, placing the tool at angles of 15–20° with respect to the surface to be machined.

A finishing test on hardened steels of a small mould of 85 mm side length is here selected as example. Before the introduction of PCBN and high-speed milling this piece was manufactured by electrodischarge machining because of its small radii and deep cavities. The applied parameters with PCBN were axial depth of cut $a_p = 0.2$ mm, radial depth of cut $a_e = 0.2$ mm, cutting speed $V_c = 1000$ m/min, feed per tooth $f_z = 0.15$ m/tooth and spindle speed $n = 24{,}000$ rev/min, producing the mould in less than 17 min. Lead time for this part was reduced by more than 500 %.

Table 2.4 Success factors for PCBN application of high-speed milling (HSM) on iron castings and tempered steels

Factors		Probability of success of HSM on dies and moulds with PCBN tools		
		High	Medium	Low
Material		Free ferrite lower than 5 %	→	Free ferrite higher than 10 %
Machine	Spindle speed	High-speed ma-chine (<15,000 rpm)	→	Machine with conventional speeds
	Number of axes	5 axes	→ 3 + 2 axes	→ 3 axes
Cutting fluid		Dry	→ Oil mist under high pressure	Coolant
Process	Trajectory	Continued	→	Interrupted
	Strategy	Inclination of the tool towards the feed direction and climb milling	→	Cutting with the top of the tool ($V_c = 0$)
	Computer-aided dsign/manufacture	CNC optimized	→	CNC without optimization
	Simulation and virtual optimizing	Control of the feed rate for a constant chip volume	→	Stepped feed motion
Geometry		Big surfaces of low complexity	→	Small surfaces with high com-plexity and cavities

2.2 Coatings

A tool coating is a layer with thickness ranging from 2 to 15 μm solidly deposited and bonded to the tool substrate to improve the cutting-tool performance (see Figure 2.6), and applied after the tool is shaped. Coatings provide a hard, chemically stable surface and thermal protection to tools, improving their performance during cutting.

2.2.1 Historical Introduction to Physical Vapour Deposition Coatings

Physical vapour deposition (PVD) coatings are ceramic materials usually applied in 1–15 μm thicknesses on tools made of steel and hardmetals. They were developed industrially in the 1970s to provide the ability of ceramics to withstand high
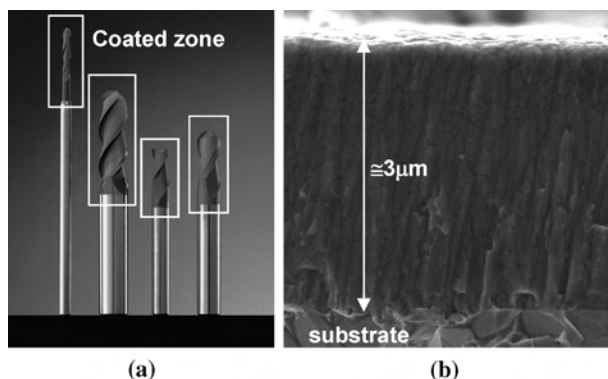
Figure 2.6 (a) PVD-coated hardmetal tools, and (b) cross-section of an AlTiN coating. Source: Oerlikon®

temperatures to substrates much tougher than ceramics such as HSS and hardmetals. This combination resulted in one of the most successful developments in the last 30 years in cutting-tool materials and since then a great improvement in cutting speeds and productivity has been achieved.

Chemical vapour deposition (CVD) coatings were already commercialized for carbide inserts in previous years but those based on PVD technology were the ones which resulted in the broadest market impact. This success was due to the possibility to process PVD coatings at much lower temperatures than CVD coatings, 400–500 °C against 900–1000 °C, which enabled the use of PVD coatings for HSS tools. But there was also a great difference which helped promote the use of PVD coatings: the ability to control thicknesses on the edges accurately. This latter property guaranteed a sharper coated edge coated with PVD compared to an edge coated by CVD. There were also other properties such as higher intrinsic hardness and compressive stresses which helped promote their use against CVD coatings; this latter property favours the inhibition of crack growth in tool edges which are exposed to impact. The freedom to coat by PVD without chemical interaction with the substrate was also a great advantage, contrary to CVD coatings which easily interact with the substrates, occasionally producing brittle carbides at the interfaces. Lastly, the ease of recoating and resharpening PVD-coated tools, against CVD-coated tools, opened a large industrial market highly sensitive to cost-reducing opportunities.

2.2.2 Industrial Evolution of Different Compositions

The first commercial coating was a titanium nitride, and since then most of the industrial coatings have been based on nitrides. It was 1979 when Oerlikon® (previouly Balzers) began the production of TiN coatings based on electron beam ion-

Table 2.5 Current tool coatings, Platit[®]

Coating	Colour	Nanohardness (GPa)	Thickness (μm)	Friction (fretting) coefficient	Max. usage temperature (°C)
TiN	Gold	24	1–7	0.55	600
TiCN-MP	Red-copper	32	1–4	0.20	400
TiCN	Blue-grey	37	1–4	0.20	400
CrN	Metal-silver	18	1–7	0.30	700
CBC	Grey	20	0.5	0.15	400
AlTiN	Black	38	1–4	0.70	900
μAlTiN	Black	38	1–4	0.30	900
TiAlCN	Burgundy-violet	33	1–4	0.30	500
Cromvic	Grey	20	1–10	0.15	400
Gradvic	Grey	20/33	1.5–5	0.15	400
cVic	Grey	20/37	1–5	0.15	400
ZrN	White-gold	20	1–4	0.40	550
AlCrN	Blue-grey	32	1–4	0.60	900
nACo	Violet-blue	45	1–4	0.45	1200
nACRo	Blue-grey	40	1–7	0.35	1100
nATCRo	Blue-grey	42	1–4	0.40	1150
nACo3	Violet-blue	45/34	1–5	0.45	1200/900
nACRo	Blue-grey	40/34	1–5	0.35	1100/900
nATCRo	Blue-grey	42/34	1–5	0.40	1150/900

plating technology and this conspicuous golden coating was to play the leading part in making PVD coatings very popular.

The next generation of industrial coatings was composed of chromium nitride (CrN) and titanium carbonitride (TiCN), the first of them focused on forming tools and cutting soft metals, broadening the application of PVD coatings. The other one focused on enhancing the hardness of TiN coatings from 2300 HV to 3200 HV, which resulted in an overall improvement of the performance of materials usually coated with TiN.

But it was not until the late 1990s when a major change arrived in coating technology with the production of TiAlN coatings. The addition of aluminium to the TiN-based composition provided not only a higher hardness such as 3300 HV but a remarkable improvement which was enhanced high-temperature behaviour. In order to explain the latter property it must be noted that during the use of a coating in a cutting process the edge must withstand temperatures of several hundred degrees Celsius. With both TiN and TiCN there is an unavoidable hardness reduction above 500 °C, therefore limiting their use in high-speed or dry conditions which result in higher temperatures at the cutting edge.

The effect of the aluminium alloying resulted not only in a greater hardness at temperatures of up to 900 °C, but also it provided a much better oxidation resistance up to that temperature. Both properties, hardness at high temperatures and oxidation resistance up to 900 °C, opened a new field of cutting conditions for the

most advanced tools, meaning higher cutting speeds and dry cutting with life-
times comparable to cutting tools coated with TiN working at moderate condi-
tions with lubrication. This was a great leap for cost saving in advanced manufac-
turing processes.

These coatings were commercialized by most of the leading coating technology
manufacturers: Platit® with Universal TiAlN, Oerlikon® with Balinit Futura and
Cemecon® with Tinalox.

On the other hand, several new coatings were developed for different cutting
materials and tool types, and also for forming tools. Table 2.5 summarizes some of
the coatings offered by Platit's technology.

2.2.3   Current Trends in Coatings for Hard Machining

The next stage in the evolution of TiAlN coatings came with those usually known
as AlTiN coatings, for their higher aluminium content. As noted by coating devel-
opers, higher aluminium content implies a better thermal resistance. The reason
for that behaviour was the nanostructuring of the coating into TiAlN crystallites in
a cubic AlN-based matrix. This nanostructure, which compared to the microcrys-
talline TiAlN was more stable at high temperatures, enabled a further increase in
lifetime of carbide endmills for high-speed cutting. The most remarkable example
of these successful coatings was their use on ball-nose endmills for cutting hard
tempered steels such as those employed for moulds made of tempered steels. The
coatings under this composition are Platit® AlTiN, with up to 67 % aluminium,
Oerlikon® Xceed and Cemecon® Hyperlox.

However, a new trend in high-temperature nanostructure control was set when
Hitachi® unveiled endmills coated with TiAlN–TiSiN coatings and soon after,
Platit® did so with AlTiSiN coatings with the nACo™ trademark. Figure 2.7
shows the wear behaviour of carbide ball-nose endmills coated with different
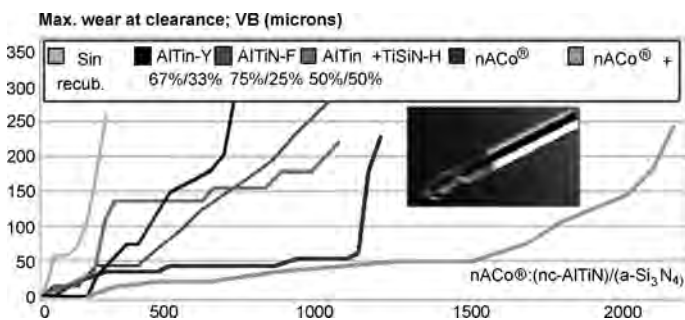
Figure 2.7   Results of wear measurements for solid carbide endmills ($z = 2$, $\varnothing = 10$ mm, rpm =
18500, $f_z = 0.18$ mm, $a_p = 0.25$ mm, $a_e = 0.6$ mm, minimum quantity of lubricant). Workpiece:
1.2343 tool steel (57 HRC). Source: Platit

coatings. The step increase in wear resistance from an AlTiN coating to a nACo™ AlTiSiN coating is remarkable. Also shown is the result for higher Si-content nACo™-coated endmills.

Silicon-containing coatings have been adopted by tool manufacturers and end users for improving more hard-machining conditions. The success of employing silicon alloying ensures that a fine nanostructure is maintained up to 1200 °C, therefore, the hardness loss at high temperature is minimized thanks to silicon in the coating, which surrounds TiAlN crystallites as a silicon nitride binder.

Another machining process requiring high-temperature hardness is titanium milling. It is well known that great heat is involved in the cutting operation of titanium. In this case, as shown in Figure 2.8, the addition of silicon in the nACo™ coating produces the best result.

The year after introduction of AlTiSiN coating to the market a new coating was presented by Oerlikon: Balinit Alcrona. This coating is an AlCrN coating intended for expanding the capabilities of TiAlN coatings especially where high oxidation resistance is required. The hardness of AlCrN coating is similar to that of TiAlN, but what makes this coating outstanding is its high oxidation resistance, up to 1200 °C. That is thanks to the growth of a stable $(Al,Cr)_2O_3$ oxide during cutting instead of the $TiO_2 + Al_2O_3$ oxides which grow in TiAlN coatings.

However, the main achievement of AlCrN coatings is limited to a lifetime extension of hardmetal tools under standard cutting conditions and its successful use for hardmetals is usually far from hard-machining conditions. In order to overcome this limitation Platit developed a new silicon-containing AlCrN coating: nACRo™. This last AlCrSiN-based coating has been successfully applied in hobbing, drilling and milling when both high temperature resistance and oxidation resistance of the coating are required.

Current trends in coating technology for hard machining can hardly be explained on a general basis as the coating applications are becoming more specialized than ever; for similar machining methods different approaches are found.
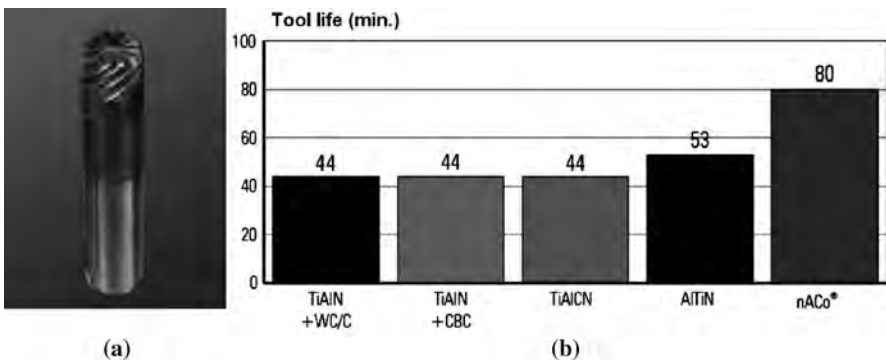
Figure 2.8 (a) Carbide mill, and (b) tool life for carbide mills ($z = 12$, bull-nose radius: 1.2–1.9 mm, $\varnothing = 20$ mm, $V_c = 250$ m/min, $f_z = 0.11$ mm, $a_p = 0.5$ mm, $a_e = 1.1$ mm). Workpiece: TiAl6V4. Source: Platit

From the material point of view, alloying of TiAlN coatings with different alloying elements opens endless possibilities: TiAlCrN, TiAlCrSiN and TiAlCrY-SiN compositions are reported by several researchers and even addition of Zr, V, B or O to coating compositions.

2.2.4   Coating Selection and Optimization for Hard Machining

One parameter for a fixed coating design is a proper selection of the thickness in order to provide a life long enough to the edge but avoiding the adhesion failure of the coating due to internal compressive stresses.

The selection of the proper coating structure involves combining the best properties of the following structures:

- Monobloc coating (monolayer of the same composition): used when there is no impact or when cutting forces are low.
- Bilayer coating for combining good properties of an inner layer near the substrate and upper layer; for example, when a hard coating is needed and top lubricant coating is needed for better chip flow.
- Multilayer coating to improve the shear strength of the coating, avoiding crack propagation between different layer materials.
- Adhesion layers: addition of a thin adhesion layer of 0.05–0.2 μm to increase the adhesion of the next layer.
- Triple coatings: a novel approach by Platit to optimize the coating structures, consisting of a good adhesion layer, a tough core layer and a hard and temperature-resistant top layer.

On the other hand, there is an even more important condition related to cutting-edge preparation before and after coating. One of the main obstacles to advanced coating success for hard-machining processes is the edge condition before coating. The more lifetime an advanced coating is able to provide the more sensitive it is to starting conditions in the edges. Therefore, along with the high-performance coating development a new approach has been required to stabilize the lifetime of the coated tool and new edge-finishing processes have been required. Figure 2.9 shows the great effect of the cutting edge radius on the lifetime of an endmill. As can be seen, there is a big difference between no radius and the optimum one.

But the coating surface can also be improved for better edge stability. Industrial PVD coatings are produced by arc technology, more economical and more suitable for providing stable quality to coatings. However, its main drawback is the presence of droplets in the coating surface, which originate from the target melting during the arc burning. These droplets are bonded to the coating surface and are responsible of most of the coating roughness. Coating roughness on the edge creates a deleterious effect on the lifetime stability, therefore droplet removal processes are usually performed for high-end tools. The effect of one of these processes is shown in Figure 2.10.

Figure 2.9 Tool life
for carbide mills nACRo
coated ($z = 4$, bull-nose
radius 1.2–1.9 mm,
$\varnothing = 10$ mm, $V_c = 150$ m/min,
$f_z = 0.05$ mm/z, $a_p = 1.5 \times \varnothing$,
$a_e = 0.25 \times \varnothing$). Workpiece:
1.2379. Source: Platit
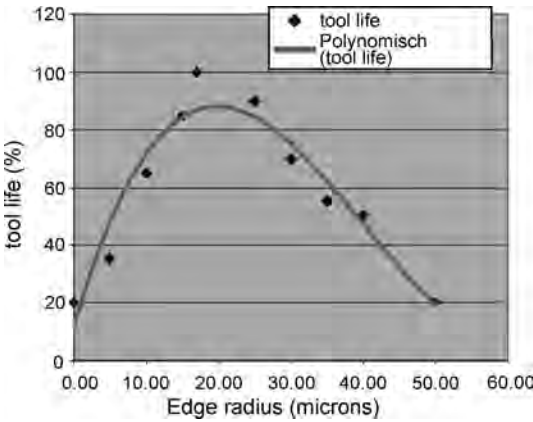
Figure 2.10 Images of AlTiN
coatings (a) before and (b) after
surface treatment for droplet re-
moval, by Platit®
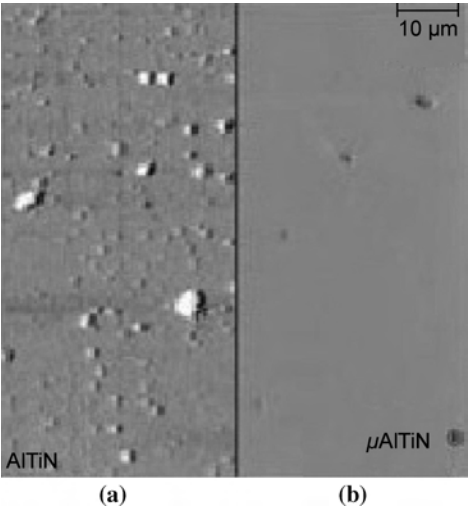
2.3 Tool Wear

Tool wear is caused by the continuous action of the chip removal process, and can
be located in two tool zones:

- wear on the rake face, which usually gives rise to a crater-like pattern;
- wear on the flank or clearance face, due to the high friction of tool edge with
  the fresh machined surface. It looks like a typical abrasion pattern.

All tool wear types are described in the corresponding ISO standards. In Fig-
ure 2.11 a turning tool is shown, where the main wear zones and the way to define
them is based on ISO 3685, *Tool-life testing with single-point turning tools* [6].

Figure 2.11 Wear on a turning tool, ISO 3685
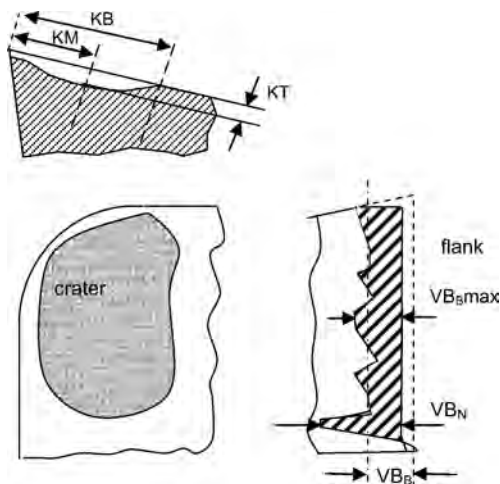
2.3.1 Tool Wear in Turning

Turning is a continuous operation with constant cutting force. However, tools undergo constant heating derived from the shear deformation energy and friction, which cause a high temperature at the tool/chip interface. The high temperature at the tool rake face is a principal wear factor in turning, being for austenitic steels, superalloys or titanium alloys even more than 600 °C.

Basically four wear mechanisms are possible in turning:

- *Crater wear:* a chemical/metallurgical wear due to de diffusion and adhesion of small particles of the tool rake surface on the fresh chip. A mechanical friction also collaborates in causing a scar-like shape on the rake face which usually is parallel to the major cutting edge. Crater wear is frequent in the turning of titanium alloys (see Figure 2.12) and other low thermal conductivity materials.
- *Notch wear:* a combination of flank and rake face wear which occurs just in the point where the major cutting edge intersects the work surface (it coincides with the depth of cut line). It is very typical in the turning of materials with
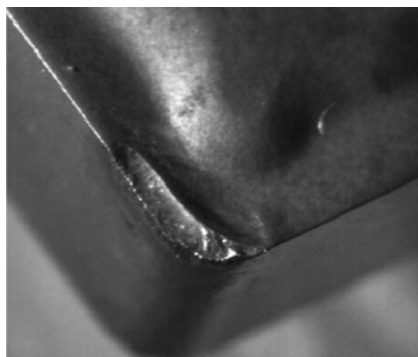
Figure 2.12 Crater wear in the turning of Ti6Al4 V, very close to the tool edge

tendency to surface hardening due to mechanical loads. Thus, previous tool passes rub the fresh machined surface increasing the hardness of the outer layer (this hardened skin is only few microns thick). Notch wear is common in the turning of austenitic stainless steels and nickel-based alloys.

- *Flank wear:* this type of wear is placed on the flank (relief) face (see Figure 2.13). Wear land formation is not always uniform along the major and minor cutting edges of the tool. It is the more common in the case of hard materials where no chemical affinity between tool and material exists, abrasion being the main wear mechanism.

- *Adhesion:* due to the high pressure and temperature, welding occurs between the fresh surface of the chip and tool rake face. This is a considerable welding if materials have metallurgical affinity and causes a thick adhesion layer, and a posterior tearing of the softer rubbing surface at high wear rate. Adhesion is usual in the case of aluminium alloys in dry or near-to-dry conditions, but it is not common in hard machining.

In most machining processes, flank wear is the type to control because it implies a significant variation of tool dimensions and therefore in the dimension of machined parts. Values of 0.3–0.5 mm are the maximum accepted, the former value for finishing and the latter for roughing.

Figure 2.14 illustrates a typical evolution of mean flank wear (VB_B) along time, for different cutting speeds. As occurs in all friction cases, the relative speed between the two contact surfaces is the leading factor of degradation. The *wear curve* is divided into three stages, similar to the friction wear of other mechanical components:

- The zone AB where the sharp new edge is worn rapidly. The initial wear size is $VB = 0.05$–0.1 mm.
- The zone BC, where wear rate is constant and slowly increases. This zone starts from 0.05 to 0.6 mm onwards.
- The zone CD, where wear ratio is very high. When this zone is reached a new tool must replace the worn one or resharpening must be performed before tool breakage.
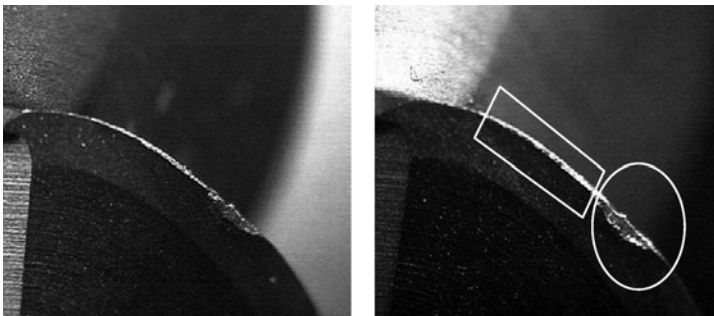
Figure 2.13   Flank at two times in ball-end milling in the finishing of a mould on 50 HRC steel. In the rectangle is the mean flank wear (*VB1*), and the circle indicates the maximum flank wear (*VB3*)

Figure 2.14 Flank wear evolution for
different cutting speeds
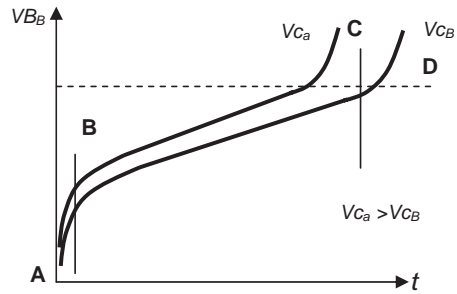
2.3.2   Tool Wear in Milling

On general lines, those aspects commented upon above for turning are also valid
for milling. The standard ISO 8688 [7] describes the main wear patterns and
localizations, shown in Figure 2.15.

- *Flank wear (VB):* the loss of particles along the cutting edge, that is, in the
  intersection of the clearance and rake faces, being observed and measured on
  the clearance face of endmilling tools. Three different measurements are pos-
  sible:
  - *Uniform flank wear* (*VB*1): the mean wear along the axial depth of cut.
  - *Non-uniform* flank wear (*VB*2): irregular wear in several zones of the cutting
    edge.
  - *Localized flank wear* (*VB*3): wear usually found in specific points. One type
    is that placed just in the depth of cut line, the notch wear (VB_N), typical of
    materials susceptible to mechanical hardening.
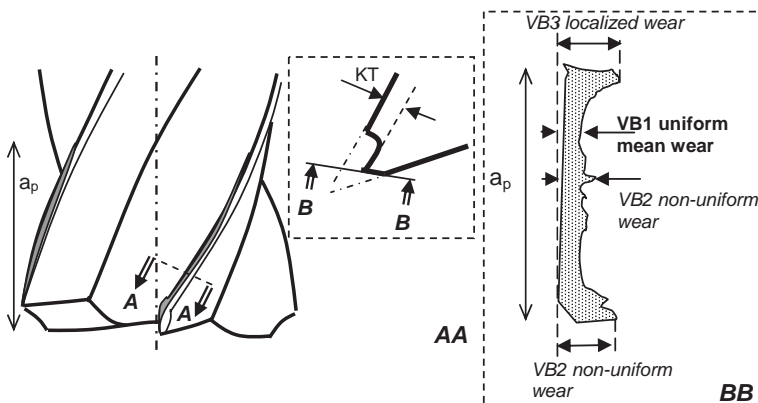
Figure 2.15   Wear of endmilling tools, from ISO 8688

- *Wear on the rake face (KT):* this is located on the internal flutes of endmills. The most typical is the crater wear (*KT*1), a progressive development of a crater oriented parallel to the major cutting edge.
- *Chipping (CH):* irregular flaking of the cutting edge, at random points (see Figures 2.16 and 2.17). It is very difficult to measure and prevent. It consists of small tool portions breaking away from the cutting edge due to the mechanical impact and transient thermal stresses due to cycled heating and cooling in interrupted machining operations.
- *Uniform chipping (CH1):* small edge breaks of approximately equal size along the cutting edge engaged on material.
- *Non-uniform chipping (CH2):* random chipping located at some points of the cutting edge, but with no consistency from one edge to another.
- *Flaking (FL):* loss of tool fragments, especially observed in the case of coated tools.
- *Catastrophic failure (CF):* rapid degradation of tool and breakage.

Mean flank wear size is the usual tool life criterion, due to it implying a significant variation of tool dimensions and therefore in the dimension of the machined part. Values of 0.3–0.5 mm are the maximum accepted, the former for finishing and the latter for roughing. Chipping greater than 0.5 mm is also a tool life criterion. In low machinability alloys several wear types appear simultaneously, adding and multiplying their negative effects [8] (see Figure 2.18).
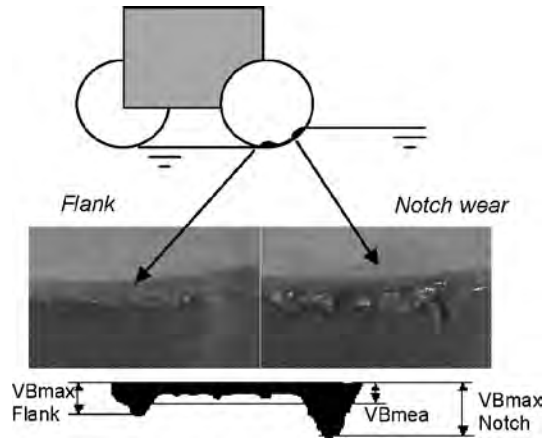

(a)   (b)
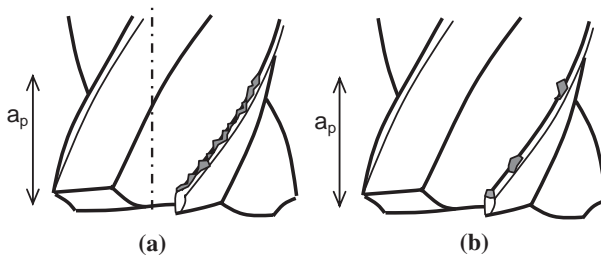
Figure 2.16 Chipping: (a) *CH1,* and (b) *CH2*
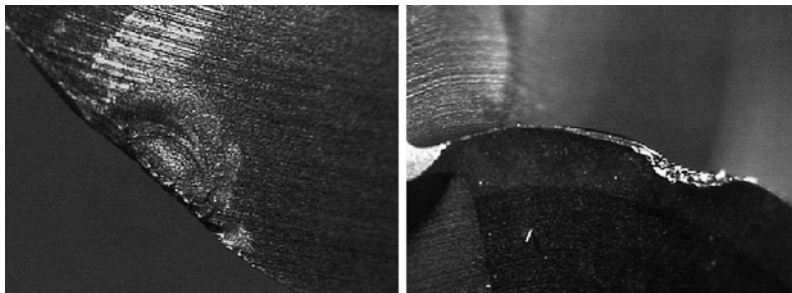
Figure 2.17 Chipping of a ball mill, after working on a tempered steel to 55 HRC

Figure 2.18 Two wear types
when milling Inconel 718
with round-type whisker
reinforced ceramics

2.3.3   Tool Life

Tool life is the time before a determined tool wear is reached. Since the first extensive experiments by Taylor in 1907, it has been known that cutting speed is the most influential parameter on tool life for a raw-material–tool couple. The so-called Taylor equation establishes that:

$$\frac{v_c}{v_r} = \left(\frac{T_r}{T}\right)^n \qquad v_c T^n = v_r T_r^n, \tag{2.1}$$

where:

n is an experimental constant for each tool–material couple;
v_c is the cutting speed;
T is the tool life;
v_r is the reference speed at which a known tool life T_r is reached.

There are some variations including other machining parameters affecting tool life, for example:

$$V_c \cdot f_z^{\,x} \cdot a_r^{\,y} \cdot T_{VB}^n = C_{VB} \cdot VB^m, \tag{2.2}$$

where f_z is the feed per tooth, a_r is the radial width of cut, T_{VB} is the time to reach a determined VB, C_{VB} is a constant from experimental tests, and VB varies with the criteria used in the reference experiments. The x, y, m are characteristic of each tool-material couple.

Taylor parameters are usually known for common steels and free-machining materials, but difficult to find for low-machinability alloys. This difference derives form the fact that the final value of components usually made in common steels depends a lot on manufacturing costs; therefore the maximum use of each tool is a very important aspect to be economically competitive. However, components usually made of special alloys or of tempered steels are high-end products, and the final value of the component depends more on the machine cost per hour or the

raw material itself. In this context the Taylor approach is not that interesting and thus few data about tool life appear in the literature.

Tool life is usually measured (a) in time, when constant machining parameters are used in a manufacturing process and the customer tries to compare similar tools from different suppliers, (b) in metal removal volume if roughing operations is being performed, or (c) in machined length if a finishing operation is considered. However, these three values are related by means of the machining parameters and process basic equations and they can be graphed in the same record (see Figure 2.19).

Some tool manufacturers make a special coating layer with a different colour on new inserts to make easy the measurement and detection of wear, such as that shown in Figure 2.20. The golden TiN coating applied to the inserts' clearance surfaces simplifies wear detection and thus avoids the unnecessary waste of unused cutting edges. The grey TiCN rake face minimizes negative tensile stress and improves adhesion and toughness.

mm (length)	0	273	546	819	1092	1365	1638
s (time)	0.00	16.85	33.70	50.56	67.41	84.26	101.1
cm^3 (volume)	0.00	3.47	6.93	10.40	13.87	17.34	20.80
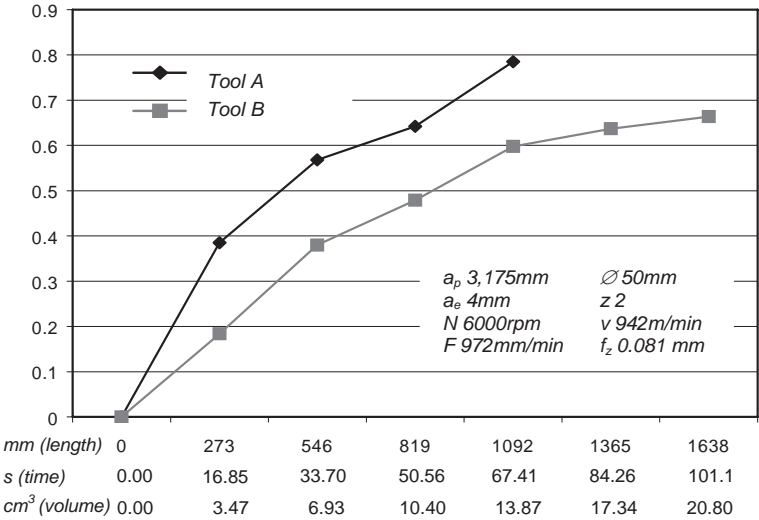
Figure 2.19 Typical tool life curves for two tools, flank wear *vs.* cut length, machining time and removed chip volume

Figure 2.20 Insert Tiger-Tec™ by Walter[®]

2.4 Cutting Fluids

Throughout a machining process, as much as 97 % of the mechanical energy is converted into thermal energy: 80 % of the heat is generated in the primary shear zone, 75 % of which is evacuated by the chip and 5 % goes to the machined part; 18 % of the total thermal energy is produced at the tool–chip interface, and 2 % comes from the tool-workpiece interface. These conditions of friction and temperature cause tool wear by different physical mechanisms explained in the previous section, giving in the result a poor surface finish and lack of precision. In Figure 2.21 the thermal field of a turning tool is shown, in the stationary thermal regime reached after several machining seconds.

Cutting fluids are used to reduce the negative effects of heat and friction on the tools and workpieces. The fluid produces three positive effects in cutting: (a) cooling, (b) lubrication between the chip and rake face of the tool, and (c) evacuation of chips towards the chip collecting system.

There are various types of cutting fluids, oils, oil–water emulsions, pastes, gels, mists and gases (liquid nitrogen and CO_2). They are obtained from petroleum distillates, plant oils or other raw ingredients.

For different reasons the reduction and even the total elimination of cutting fluids is advised. On the one hand, the cost of the life cycle of the cutting fluid (filtration, purification and elimination of residues) has a direct repercussion on the manufacture costs. On the other hand, the current environmental concern imposes heavy limitations on the use of hazardous substances (such as cutting fluids). Thus, in industrialized countries, strict regulations related to the use of cutting fluids are being developed. These regulations are increasingly restrictive with respect to the use of lubricants.

Because of the above-mentioned reasons dry machining would be of maximum interest, but this is somehow non-viable in aluminium and light alloys due to the tendency of these materials to adhere to the tool edges. Nor is it possible in the case of titanium, nickel or stainless steels due to the very high temperatures reached at the tool/chip interface. Therefore, taking into account the impossibility of dry machining, a technique involving minimal consumption of cutting oil called minimum quantity of lubricant (MQL) can be applied. This technique con-

Figure 2.21 Infrared measurement of cutting temperatures, at $V_c = 137$ m/min and $f_z = 0.08$ mm, in a common steel turning
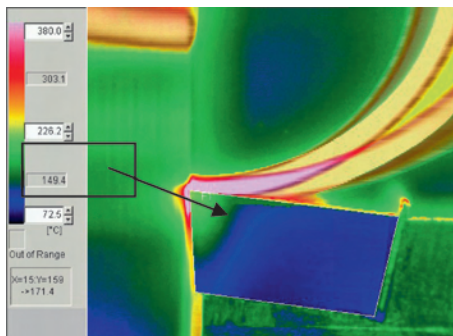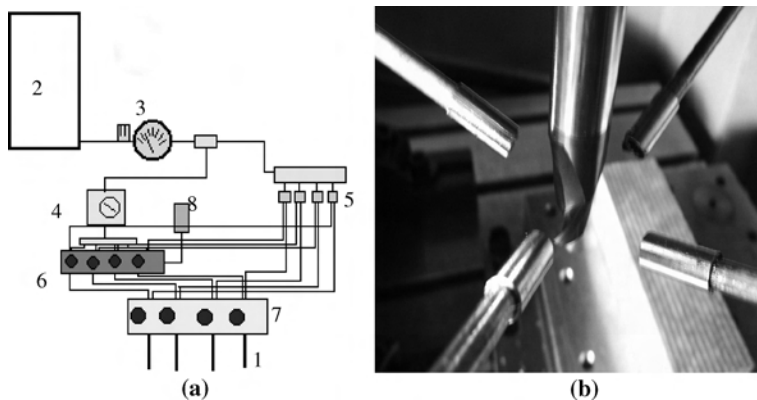
Figure 2.22   (a) Configuration of an MQL system, and (b) detail of the nozzles, four in this case

sists of the injection of a high-speed air jet with micro-drops of biodegradable oil in suspension.

A typical and modern MQL system is detailed in Figure 2.22. The system operates with pressurized air (10–12 bars). The pressurized air arrives to the system and it enters a maintenance unit (2); afterwards the air goes through a pressure regulator (3). Then, part of the air arrives to a subsystem where it produces the impulsion of the oil, regulated through a frequency meter (4) and several pumps (6) which provide the quantity of oil to be supplied by each nozzle at each instant. Oil is impelled up to the nozzle (1), where the mixture of oil with air is produced. The simultaneous effect of pressure and speed of the air in the exit nozzle sprays the oil. The obtained oil drops are below $2\,\mu$m diameter.

In the machining of hardened and tempered steels (more than 40 HRC in finishing conditions) dry or near to dry machining is a common option. In addition, the pressurized air injection is used to take away chips from the cutting zone. Cryogenic cooling by means of liquid nitrogen is now researched for titanium and nickel alloys [9]. However when difficult-to-cut alloys are machined the most common technique is the emulsion coolant, 5–10 % oil in water.

2.5 Tool Geometry

A cutting tool presents a main cutting edge and several faces. Many tools have another secondary cutting edge (minor edge). The shape of edges and angles between faces influence the machining performance greatly. In Figure 2.23 the basic geometry for a single-point cutting tool (that is, a turning tool) and for a multiple-point cutting tool (an endmilling tool in this case) are shown.

The definition of tool geometry is explained in the ISO 3002/1 [10]. Here two reference systems are described: *tool-in-hand* and *tool-in-use*.
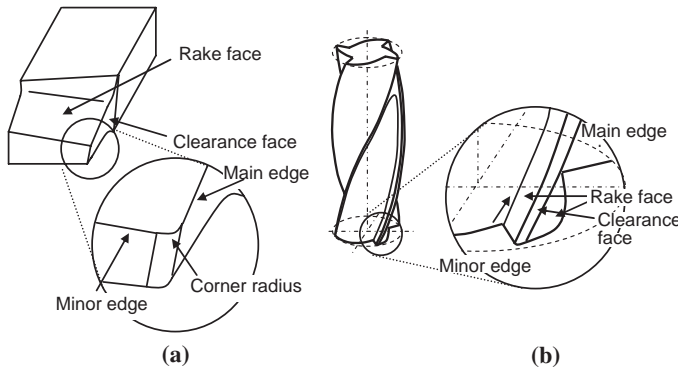
Figure 2.23 Basic geometry for (a) turning and (b) endmilling tools

In the tool-in-hand reference system three planes are defined:

- P_r: tool reference plane, parallel to the tool base or contains the axis of the rotational tool;
- P_f: assumed working plane, perpendicular to P_r and contains the feed direction;
- P_p: tool back plane, perpendicular to P_r and P_f;
- P_n: edge normal plane, perpendicular to the edge in each point.

In Figure 2.24, P_r, P_f and P_p for a turning and a milling tool are shown. Using these planes several angles are measured:

- κ_r: position edge angle (measured in P_r);
- κ'_r: position edge angle of the minor edge (measured in P_r);
- γ_n: normal rake angle (measured in P_n);
- α_n: normal clearance (measured in P_n);
- λ_s: edge inclination angle (measured in P_s).

Pr: Reference plane for the tool
Pf: Assumed working plane
Pp: Tool back plane
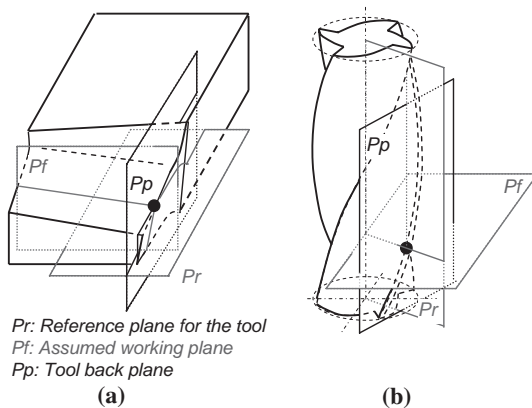
Figure 2.24 Tool-in-hand reference system for (a) turning and (b) milling tools

Figure 2.25 Tool-in-use reference system for a turning tool

Pr$_e$: Reference plane
Pf$_e$: Working plane
Pp$_e$: Tool back plane
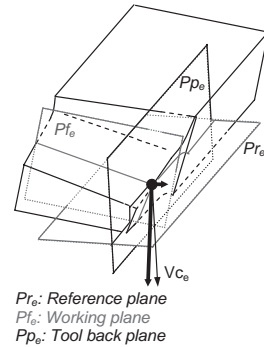
In Figures 2.27 and 2.28 the reference system is applied to and endmill and ball mill, respectively [11].

In the case of the tool-in-use reference system the main direction is given by the effective cutting speed (*i.e.*, the sum of the cutting speed and feed). Here three main planes are defined (see Figure 2.25):

- P_{re}: working reference plane, defined by the edge point and perpendicular to the effective cutting speed;
- P_{fe}: working plane, contains the cutting speed and feed vectors and is perpendicular to the reference plane;
- P_{pe}: tool back plane, perpendicular to P_{re} and P_{fe}.

2.5.1 Endmilling Tools

A main difference between endmills and ball-endmills is the helix angle variation along the cutting edge. Even though the possibility that the flutes of a ball-endmill may be with a constant helix angle, most of the tools in the market present constant lead, resulting in a variable helix angle. This is due to the usual grinding process applied for the fabrication of this kind of tool. Another consequence of the grinding process is that the normal rake and relief angles are made constant along the cutting edge.

Thus, the spatial generation of the edge is the result of projecting a cylindrical helix on a sphere perpendicularly to the axis of the tool direction. The resulting cutting-edge geometry is shown in detail in Figure 2.27. Here, cutting-edge angles have been measured following ISO nomenclature. The inclination angle, λ_s, is measured in the P_s plane (defined by cutting-edge discrete element AB and the cutting-speed vector V_c), and it is the angle formed by the cutting speed V_c and the cutting edge AB. Local helix angle, represented as i, is measured on the P_p plane (defined by V_c vector and Z-axis).

In cylindrical endmills (see Figure 2.26), the inclination angle of the edge coincides with the helix angle, since the tangent plane to the edge is always parallel to the tool axis.
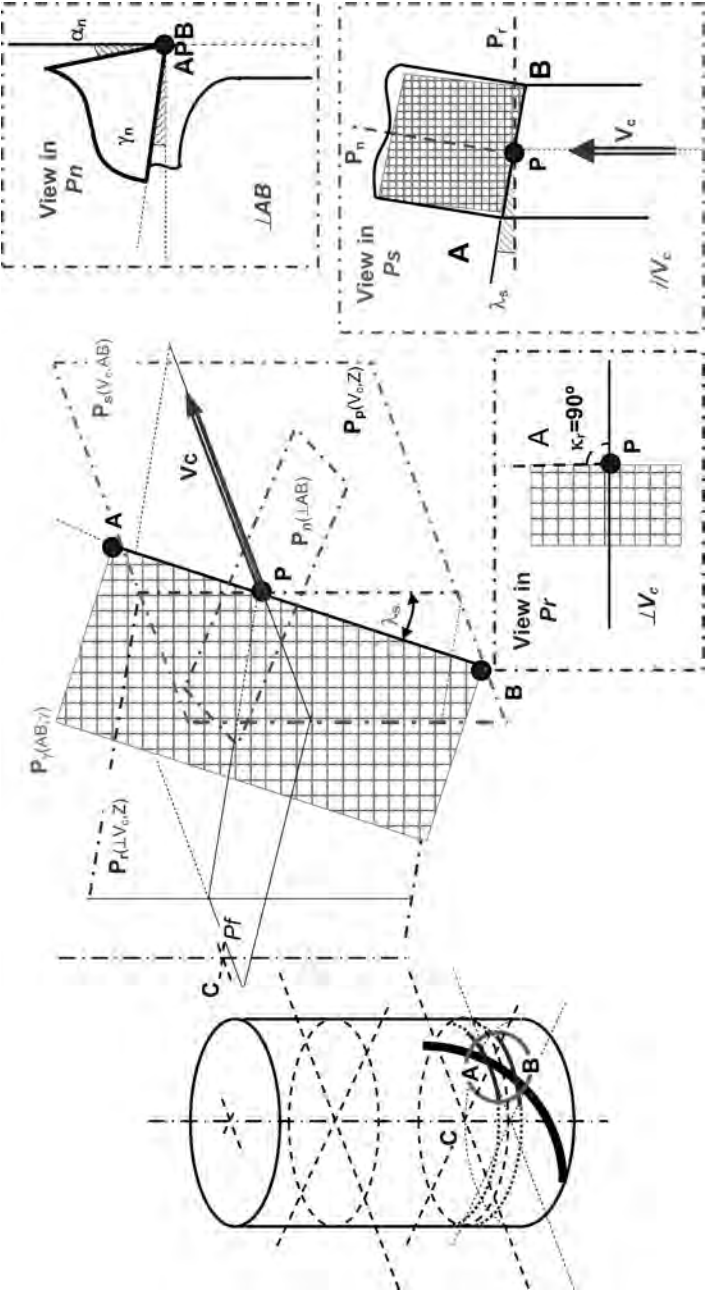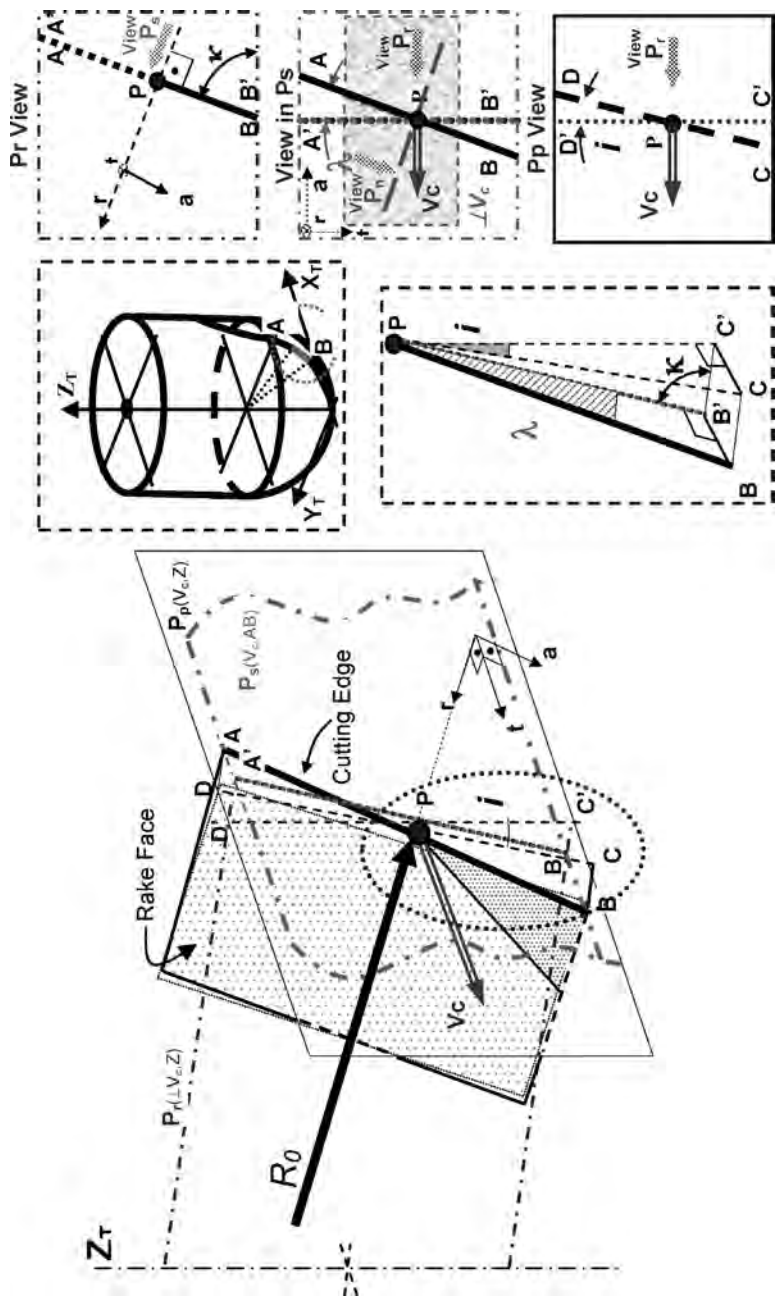
Figure 2.26   Geometry of an endmill

Figure 2.27 Geometry of a ball-endmill

2.5.2   The Rake and Clearance Angles

In oblique cutting, machining forces are composed of three components, instead of the two of orthogonal cutting. The geometry and angles of a cutting tool defines the values of each of the components, in addition to the characteristic shear angle Φ of the material and the inclination angle of the cutting edge with respect to the cutting speed, i. In Figure 2.28 the cutting-force components are described.

However, the most important concepts to evaluate in all the machining operations under a qualitative point of view are those presented in Figure 2.29: the clearance angle, the rake angle and the edge angle.

The rake angle shown in this figure is positive, the most common case, but in hard machining it could be negative, with the tool oriented towards the cutting-speed direction. Since clearance angle always must be positive to avoid rubbing on the part surface, a negative rake angle implies a very strong cutting edge, and therefore is recommended for very difficult-to-cut materials where cutting forces are much too high. Another aspect to bear in mind is the so-called edge radius, different from the corner radius (where the main and minor edges intersect). The edge radius is only few hundredths of a millimetre, and in some cases, as in PCBN inserts, a chamfer is produced instead of the rounded edge.

In milling tools both the mean and minor edges have a big influence on tool performance. Therefore the radial and axial rake and clearance angles must be considered. Several combinations could be used; in Figure 2.30 two of them are shown. The first situation in the figure is very aggressive, due to the both negative angles. The second situation is a good combination because the positive axial angle allows chip was evacuated out from the part surface, and the negative radial angle permits a very robust tool edge design.
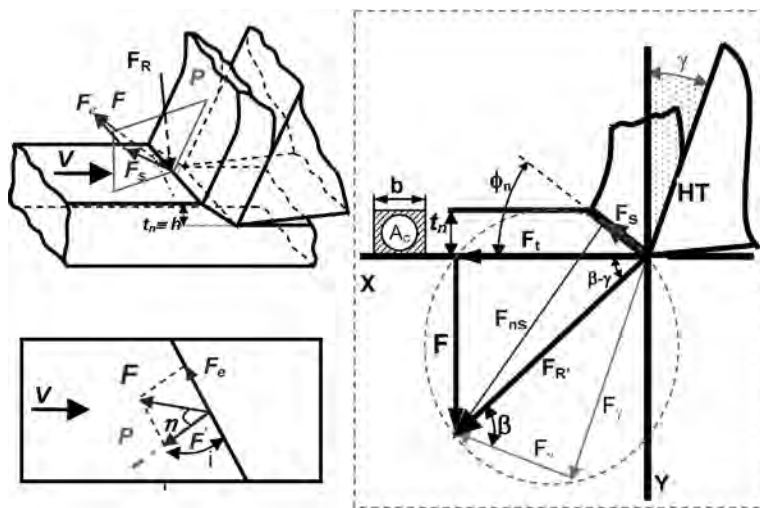
Figure 2.28   Geometry of the oblique cutting, with the decomposition of the cutting force in the main directions
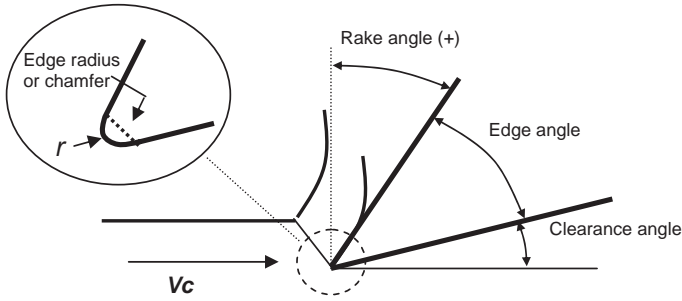
Figure 2.29   Basic angles for a rapid tool evaluation
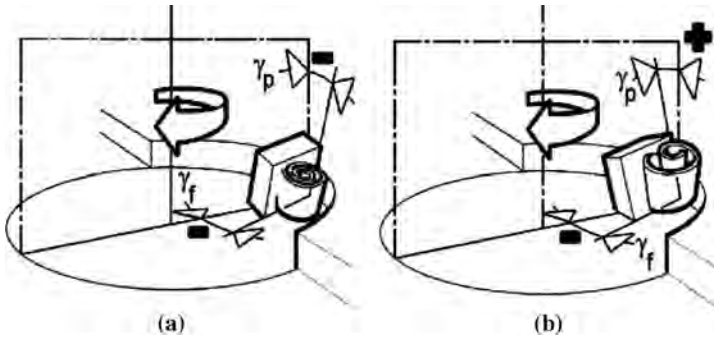
Figure 2.30   (a) Axial and (b) radial rake angles (courtesy of Sandvik Coromant)

2.5.3   *Position Angle*

The tool cutting-edge angle (κ_r) has a direct influence on chip thickness and therefore on the cutting-force components. At the same feed rate, decreasing the side cutting-edge angle increases the chip contact length and decreases chip thickness. As a result, the cutting force is dispersed on a longer cutting edge and tool life is prolonged.

Increasing the side cutting-edge angle increases chip width. Therefore, decreasing the position angle is recommended for:

- hard workpieces which produce high cutting temperature due to their high specific cutting forces;
- when roughing a large-diameter workpiece.

2.5.4   *Milling Tools for Several Applications*

Bearing in mind the geometry possibilities for milling tools and requirements derived from the workpiece hardness, shape and dimensions, big manufacturers of
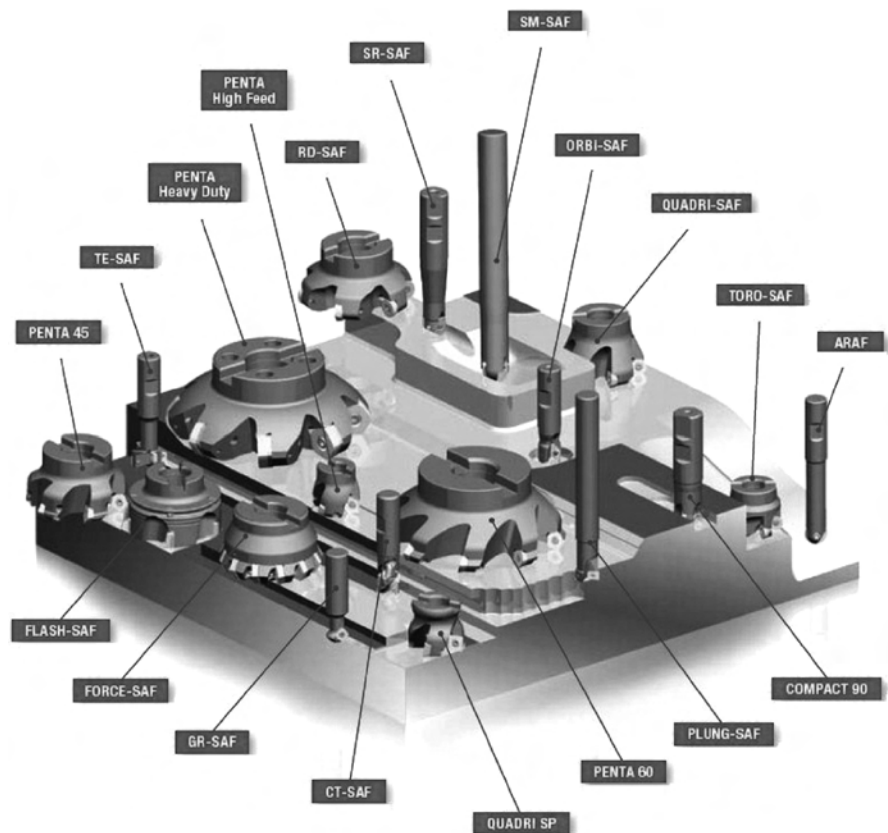
Figure 2.31   Milling tools supplied by Safety®

tools offer a complete catalogue of milling tools. In Figure 2.31 the milling options provided by the tool manufacturer Safety® are represented, including milling discs with inserts with different lead angles for facing, insert tools with lead angle 90° for slotting and shouldering, and ball-endmilling tools.

2.6   Hard Machining for Mould and Dies

Before the generalized use of high-speed milling, the usual technology employed in mould manufacture was a combination of conventional milling and electrodischarge machining [12, 13]. From 1997 to 1999 roughing and semi-finishing were usually carried out with conventional machines, with mould steel in a soft state before tempering. Subsequently, heat treatment was applied. After that, finishing was performed in high-speed machining centres. There were two reasons for such a sequence:

- Roughing, which is subject to few precision requirements, was done in machines which cost per hour one-fifth of high-speed machines. Moreover, tool wear was light because of the low hardness of the workpiece material.
- The most usual high-speed spindles available in those days were unable to deliver sufficient torque below 1500 rpm, making roughing impossible.

In 2000, technical variations made to high-speed spindles control resulted in an improved capacity to deliver enough torque even at low rotational speeds. In this manner, roughing in high-speed machines became possible, with a similar application practice to the conventional case. Therefore, a new procedure was defined starting directly from a block initially heat-treated, carrying out consecutively all operations in the same machine. The mean advantages of this simpler process was that less time was needed to launch a new mould, since between successive operations there was less time needed for set-up. At the same time, accuracy and reliability of workpiece also increased, due to the avoidance of workpiece zero setups between operations.

At present, the decision whether to use high-speed machines starting from tempered raw material, or conventional roughing of non-tempered steel followed by tempering and high-speed milling, depends on production costs and required lead times. But in all the cases finishing is performed by ball-end high-speed milling.

2.6.1 Ball-endmilling for Sculptured Surfaces

High-speed milling with ball-endmills is the basic technology for finishing complex surfaces, the final and high-added-value stage when complex forms are produced [12, 14–16].

In Figure 2.32 a typical ball-endmilling tool for finishing hard steels is shown. A four-flute geometry with a full cutting edge to the centre of the ball, in combination with an improved version of TiAlN coating (more than 3700 HV hardness) provides the necessary efficiency of cutting together with high heat and wear resistance.

This operation commonly involves the milling of a 0.3 mm allowance (as shown in Table 2.6), which is usually done using ball-endmills with diameter below 20 mm, due to the intricate shape details. Taking into account that slopes
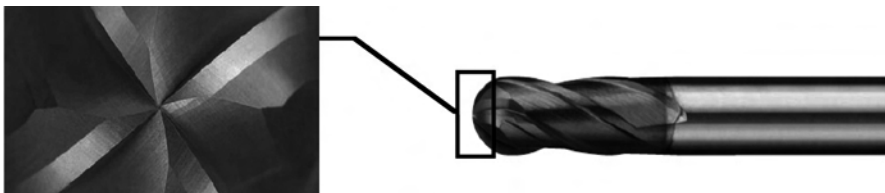

Figure 2.32 The VF4MB by Mitsubishi[®], 4 flute geometry with a full cutting edge to the centre of the ball

Table 2.6 Cutting conditions recommended by Mitsubishi® for the VF4MB

Work material	Hardened steel (55HRC) W.Nr. 1.2344(H13)					Hardened steel (55 62HRC) X210Cr12				
	%<15°		%>15°		Depth of cut (mm)	%<15°		%>15°		Depth of cut (mm)
R (mm)	Revolution (min⁻¹)	Feed rate (mm/min)	Revolution (min⁻¹)	Feed rate (mm/min)		Revolution (min⁻¹)	Feed rate (mm/min)	Revolution (min⁻¹)	Feed rate (mm/min)	
R0.5	40,000	10,400	40,000	4,200	0.050	40,000	7,300	40,000	3,100	0.040
R1	40,000	12,500	39,000	6,100	0.090	40,000	10,400	24,000	3,100	0.080
R1.5	40,000	15,600	27,000	5,600	0.100	32,000	10,000	16,000	2,900	0.100
R2	32,000	14,100	20,000	4,700	0.120	24,000	8,100	12,000	2,500	0.100
R2.5	25,000	11,700	16,000	3,700	0.160	19,000	6,900	9,600	2,200	0.120
R3	21,000	10,900	13,000	3,400	0.200	16,000	6,200	8,000	2,100	0.160
R4	16,000	8,300	10,000	2,600	0.240	12,000	4,700	6,000	1,600	0.160
R5	13,000	6,800	8,000	2,300	0.400	10,000	4,200	4,800	1,200	0.160
R6	9,000	4,700	6,000	1,700	0.400	7,000	2,900	3,600	940	0.240

commonly found in sculptured forms go from 0° to 90° and that effective cutting speed must be between 300 and 400 m/min – this is the maximum recommended for the current carbide tools coated with AlTiN – the spindle rotational speed must be over 15,000 rpm. This means that high-speed spindles must be used. Nowadays, the maximum rotational speed of industrial electrospindles is around 20,000–25,000 rpm, with power ranging from 14 to 20 KW.

On the other hand, for this rotational speed, and bearing in mind a recommended feed of around 0.07–0.1 mm/tooth, the maximum linear feed is 10–15 m/min. These values can be obtained by typical linear ball screws connected to synchro-
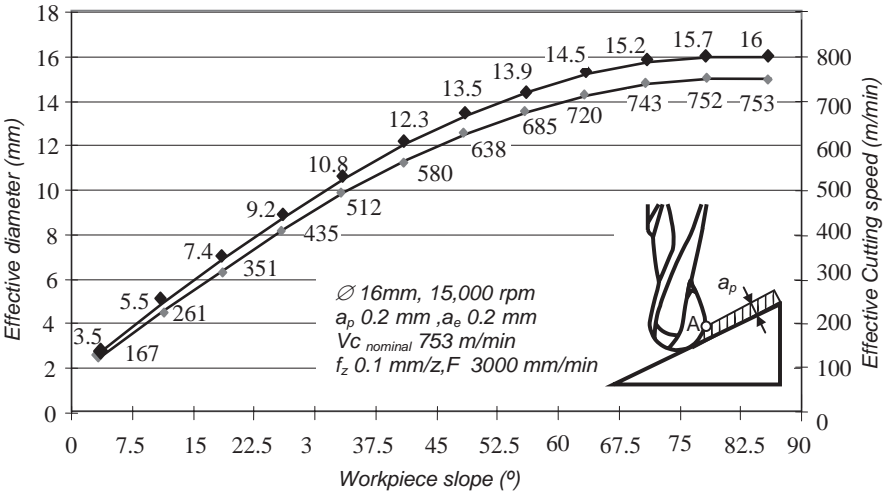
Figure 2.33 Effective tool diameter and cutting speed for different surface inclinations, using a ball-endmilling tool. *A* is the point of maximum cutting speed

nous motors, or by linear motors. The machine axis control at this feed is not a problem for current numerical controls.

In Figure 2.33 values of maximum cutting speed at the effective diameter are shown for a $\varnothing 16$ mm integral ball-endmilling tool. Integral carbide tools are more used than insert tools for finishing.

2.6.2 Five-axis Ball-endmilling

In five-axis ball-endmilling, two additional orientation axes added to the machine allow the machining of very complex parts, which cannot be machined using three-axis machines [17].

Otherwise, cutting speed is zero at tool tip, making the tool cutting very unfavourable. This is because when ceramics or PCBN tools are used, typical failure is the fragile breakage of the tool tip. With five axes, milling can be performed avoiding the tool tip cutting.

Moreover, tool overhang, necessarily large when deep cavities are machined, can be reduced using five-axis milling. Therefore, tool stiffness is higher, which increases machining precision and reduces the risk of tool breakage. Tool stiffness is directly related to the tool slenderness factor L^3/D^4 [15, 18], so a tool length (L) reduction dramatically reduces tool deflection and the lack of precision due to this effect.

2.7 Toolholders and Tool Clamping Systems

The assembly of tools in machining centres is a key factor for obtaining parts with high dimensional accuracy and surface quality. Moreover, the performance of a tool can be significantly influenced by the quality of the clamping system to the machine. In general, the use of clamping systems as rigid as possible is recommended in order to reduce the toolholder–tool deflection and provide a secure holding system for the tool for high-performance machining conditions. In addition, a rigid clamping system is the basis for an accurate and precise tool–toolholder–spindle assembly. However, on the other hand, it is necessary to provide a simple tool-change solution to obtain minimum chip-to-chip times. Currently more different tools, specifically designed for single operations, are used to carry out individual operations. Therefore, the number of tool changes required to machine a complete part is higher than traditional machining strategies. The answer of machine-tool builders to this requirement has been the development of new methods for a quicker and more precise tool change, with systems capable of managing hundreds of different tools and with chip-to-chip times even below 0.7 s.

In general, toolholders must achieve the following capabilities:

- assembly and disassembly must be simple;
- allow automatic tool change (ATC) commanded from the CNC;
- maximum coaxial accuracy on the tool–toolholder–spindle assembly;
- maximum stiffness of the complete system;
- maximum torque transmission from the spindle to the tool.

It is important to take into account that a finely designed tool clamping system would not improve the behaviour of the tool; however, an incorrect clamping system would reduce tool life significantly.

The most common solution is the introduction of an intermediate component which on one extreme holds the cutting tool and on the other is fixed to the machine-tool spindle or turret. Therefore, there are two mechanical interfaces between the tool tip and the machine-tool spindle: *tool–toolholder* clamping and *toolholder–spindle* (or turret for lathes) clamping.

2.7.1   Toolholders for Turning Operations

Tool holding systems for turning operations are relatively simple, since in lathes the tool is fixed to the machine turret rigidly. The most common system is the use of the standard DIN 69880 (VDI) clamping, which consists of bars of cylindrical section attached to the turret lathe, with a serrated shape. However, there are solutions that allow more flexibility and an easier assembly of different tools. These systems are based on a specially developed joint between tool and toolholder. The most extended system is the Capto®, originally developed by Sandvik Coromant™ but recently out of patent. Figure 2.34 shows both solutions: a toolholder based on the DIN 69880 standard and the Capto system. The former also presents the VDI serrated-shape interface of toolholders for indexable turrets.

(a)   (b)
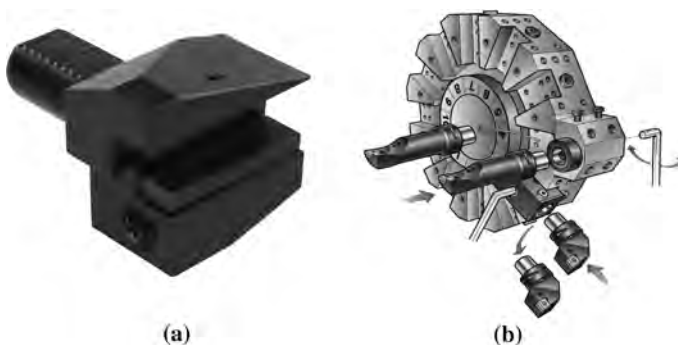
Figure 2.34   (a) DIN 69880 (VDI DIN69880) toolholder, and (b) Capto® system for turning tools
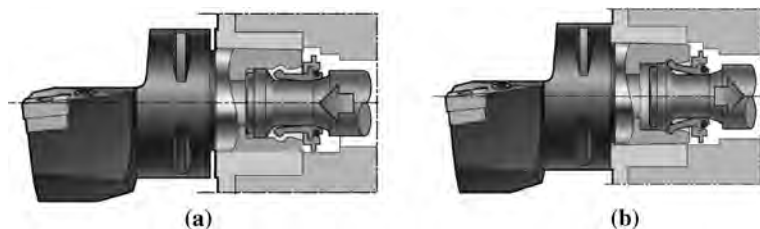
Figure 2.35 Capto system scheme: (a) unclamped position, and (b) clamped position (courtesy of Sandvik Coromant)

The Capto clamping system is based on the double interplay between tool and holder surfaces, both external and internal surfaces. While the external surfaces are based on a combination of polygonal and radius-shaped design and provide torque transmission, the internal clamping device allows easy clamping and unclamping of the tool. The system is based on a segmented expandable bushing (see Figure 2.35) in the clamping unit, and lips on the outer periphery of the segments lock into an inner groove on the cutting unit, clamping the two components together. In the unclamped position, the drawbar is in the forward position; the forward ends of the segmented bushing move towards the centre line of the coupling. The diameter is reduced and the lips on the outer edge of the bushings disconnect from the inner groove of the cutting unit. The drawbar pushes the cutting unit out. In the clamped position, the drawbar is in the retracted position; the forward ends of the segmented bushing are forced outwards away from the centre line of the coupling by the shoulder on the drawbar. The lips on the outer edge of the bushings lock into the inner groove of the cutting unit which is pulled into its working position.

In addition to turning, Capto is currently a solution for milling tools as well, being in use in multitasking operations (see last section of this chapter).

2.7.2 Toolholders for Milling Operations

The role of the toolholders in milling operations is similar to other machining operations, since high stiffness, holding reliability and tool position accuracy are required. However, today milling processes apply high spindle speeds (up to 40,000 rpm), which produce high centrifugal forces where the rotational system presents unbalanced elements. This fact has forced designers to rethink aspects such as the joint between toolholder and machine-tool spindle or the requirement for toolholder balance. Therefore, the conventional toolholders for milling operations, based on the single lateral contact face of the tapered shank, are being substituted by systems with a double contact face: lateral and perpendicular to tool axis (Figure 2.36).
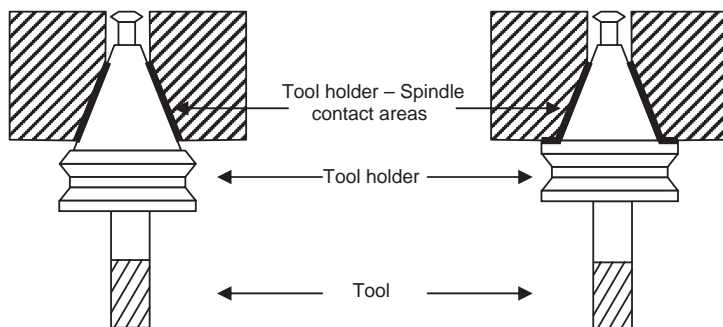
Figure 2.36 Toolholder for milling: single-contact system (*left*), and double-contact system (*right*)

Single-contact toolholders have been used since the development of ATC. The most common is the ISO-7388, which consists of a tapered toolholder to be inserted into the machine spindle. These toolholders, known simply as ISO tooling, can be used reliably up to 6,000–8,000 rpm. However, in the last 15 years the development of new tool materials, spindle technology (including electrospindles) and high-performance machine tools has allowed the emergence of HSM. In this technique, cutting speed is increased by more than five times the conventional speed. Therefore, the rotation speed of the milling tools has to be increased too, up to 40,000 rpm in some cases.

If rotation speed is higher than 8,000 rpm, centrifugal forces are relevant and the single-contact system loses joint stiffness rapidly. One of the main problems of the ISO toolholders comes from the clamping system. ISO toolholders are clamped by a mechanical system that pulls up the toolholder and it is released by an actuator (both hydraulic and pneumatic). If spindle speed increases, centrifugal force can cause lateral expansion of the spindle axis, while the clamping system continues pulling up the holder. Thus, the spindle is pulled inside the spindle nose, causing inaccuracies and it is even possible for it to be stuck in the spindle nose.

Moreover, the mass offsets of the rotating tool–toolholder system with respect to the rotation axis cause unbalancing forces, which depend on the square of the rotating speed. Therefore, the same tool–toolholder system (with the same unbalanced elements) rotating from 4,000 rpm to 20,000 rpm increases the unbalancing forces 25 times. As a consequence, new toolholders and balancing systems were introduced to reduce the centrifugal force effect and unbalancing problems.

In order to reduce these problems, other clamping systems have been developed, such as the HSK.

2.7.2.1 HSK Toolholders

HSK is the acronym of a new standard tooling interface for milling toolholders; it basically means "hollow shank tooling". It was developed in Germany in the late 1980s and rapidly became a standard in Europe. Actually it is widespread in Asia and the USA as well. The standard references for HSK tooling are DIN69893
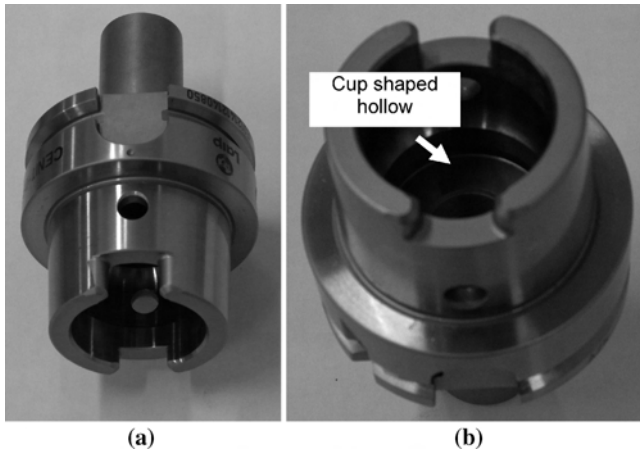
Figure 2.37 (a) Heat shrink holder HSK63A, and (b) detail of HSK63 A holder

and spindle receivers DIN69063. These standards were introduced as non-proprietary solutions and describe the specifications for HSK.

The HSK system presents some advantages with respect to the ISO system. One of the most relevant is that HSK present a double-face contact system. This difference is a key factor in high-speed machining operations since the reference surface for the toolholder is the spindle nose [19]. In addition, the dual contact systems achieve better repeatability on automatic tool changes.

Another important difference is the clamping system. HSK toolholders are fixed by a segmented expandable bushing driven by a drawbar. The segments are inserted in a cup-shaped (Figure 2.37) hollow machined in the toolholder. Therefore, if spindle speed increases, the centrifugal force expands the segments and consequently the clamping force is increased too. This capability allows for more aggressive cutting conditions; in addition it provides greater rigidity and accuracy than systems based on ISO holders.

Machines using ISO holders are also more sensitive to chatter than those using HSK because the junction between toolholder and spindle is not as rigid. The lower rigidity of this union drops the natural frequency of vibration and limits the material removal rate.

There are different types of HSK holders. They are defined by two or three digits and a letter, for example HSK-63 A (one of the most common in use). The figure gives the outer diameter of the plate that sits on the spindle nose. The letter indicates the type of holder depending on various factors such as length, guidance systems, *etc*. In general, the most usual types are:

- A: General type, in use in more than 95 % of machines.
- B: It has a larger flange than the A type. It is used for more aggressive cutting conditions.
- E and F: Same as A and B but without marks and guidance systems for enhanced balance.

As noted, HSK has great benefits, but there are some disadvantages with respect to the ISO clamping system. First, the HSK tooling is more complex and expensive. Second, HSK is very sensitive to the presence of particles such as chips or grease. Moreover, there can be chips in the hollow where segments guided by the drawbar have to fix the holder to the spindle. This sensitivity to impurities requires extreme care during tool changes, and the usual solution is to inject pressurized air into the spindle nose and the holder before each tool change.

2.7.2.2   Other Toolholder Systems

There are other types of holders widely used in milling and drilling operations. These systems are based on dual-flange holders and are either V-flange or BT-flange, depending on the precise flange configuration. V-flange toolholders are often referred to as CAT tooling (from Caterpillar), because the initial design was developed about 30 years ago by engineers at Caterpillar Tractor Co. working in conjunction with machine-tool builders. The design eventually became a national standard, and the majority of toolholders currently in use in the US are CAT style. Japanese and European applications, on the other hand, may use BT-flange holders, described in the Japanese standard JIS6399 (MAS-403). Both systems use single-contact surface systems, so similar problems with ISO systems have to be expected if spindle speeds increase over 8,000 rpm. BT holders actually present a version with double-contact for high-speed milling.

Another holder type is the BIG-PLUS® system, with simultaneous dual contact between the machine spindle nose and toolholder flange face. This system is based on the most currently available standards for JIS-BT, DIN69871 and the CAT-V flange tooling and actually is licensed by more than 100 machine-tool and spindle manufacturers.

2.7.3   Tool–Toolholder Clamping Systems

As mentioned above, there are two different joints between the machine spindle and the tool tip: first, the toolholder and machine tool spindle joint, which has been described in the previous section; second, the joint formed by the toolholder and tool. The connection between tool and toolholder has to satisfy the same requirements of accuracy, stiffness, torque transmission and interchangeability as the spindle-shank one. Therefore, different mechanical solutions have been developed to perform these specifications. Obviously, each solution presents advantages and disadvantages with respect to others and all of them are being used nowadays.

Basically there are three types of rotary tool clamping systems: collet chucks, hydraulic holders and shrink-fit holders.

2.7.3.1 Collet Chuck Tool Clamping Systems

It is the most common solution, based on introducing the tool into a segmented collet which is inserted into the holder (Figure 2.38). The clamp force is achieved by a nut that presses on the segments of the collet. The collet segments are designed to increase the flexibility of the collet and to obtain a uniform pressure on the contact surfaces between tool and collet, and collet and holder.

The collet system is valid for most of the high-speed machining operations and it is the most economical solution. Another advantage of this system is that it may have different collets for a single holder, so different diameter tools can be used in the same holder.

In terms of precision, high-quality collets can obtain a run-out near 7–8 μm at 25 mm from the spindle nose. These results can be achieved with high-quality mechanical holders and collets, manually adjusted.

However, some applications require lower run-out values. Moreover, the stiffness of the clamping system cannot be enough. In these cases, the holders should use hydraulic or shrink-fit tool clamping. Both systems provide more rigidity and precision.

2.7.3.2 Hydraulic-expansion Tool Clamping Systems

Hydraulic-expansion holders clamp the tool through a hydraulic system (Figure 2.39). There is a metallic membrane surrounding the tool shank. The membrane
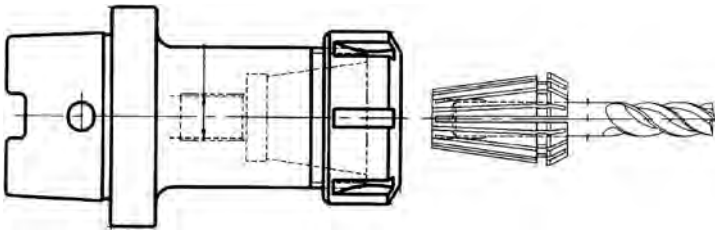

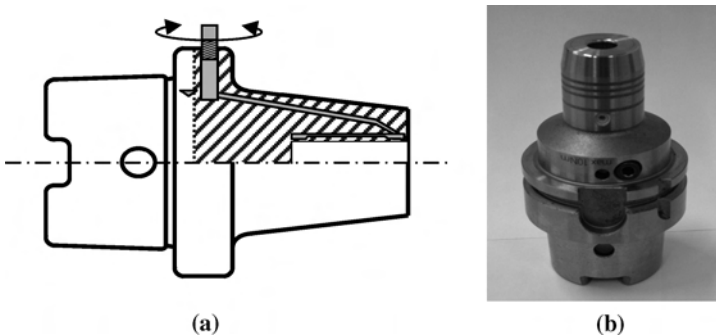**Figure 2.38**   Collet-based toolholder (courtesy of LAIP®)

Figure 2.39   (a) Hydraulic-holder scheme, and (b) hydraulic HSK63 A holder

is surrounded by a fluid deposit; the fluid pressure can be incremented by a screw, which moves as a piston. Therefore, the tool is clamped by the membrane, which transmits the pressure of the fluid to the toolholder uniformly. Since all the fluid is inside the holder, chips or cutting fluid do not affect the toolholder.

The main advantage of these systems is the high accuracy of the tool and tool-holder union. Some commercial suppliers guarantee run-out values below 2.7 μm measured 30 mm below the spindle nose on 12 mm diameter endmills. These run-out values make these holders suitable for ultra-high-speed machining operations (more than 30,000 rpm) and for high-accuracy operations with small endmills. Moreover, material removal rate can be increased since the tool is perfectly bal-anced and there is no misalignment between spindle and tool axes.

On the other hand, there are two major drawbacks. First, the cost of this type of tooling can be up to five times higher than conventional mechanical collet tooling. Second, each holder must be used only for a tool diameter, since the membrane is adapted for a specific shank diameter. Therefore, a different holder is needed for each tool shank. There are some solutions for this problem, usually based on using additional membranes that can be inserted in the holder. However, this solution increases the run-out values up to 1 μm for each additional membrane.

2.7.3.3 Heat-shrink Tool Clamping Systems

Heat-shrink toolholders provide high accuracy and minimum run-out at a reason-able cost. Unlike hydraulic ones, there are no internal systems to bring pressure to hold the tool. Instead, the holder consists of a monolithic element with a precision hole where the tool is inserted.

At room temperature, the hole is slightly smaller than tool diameter. Using an external heater, the cone is heated and the tool housing hole expands. The heater
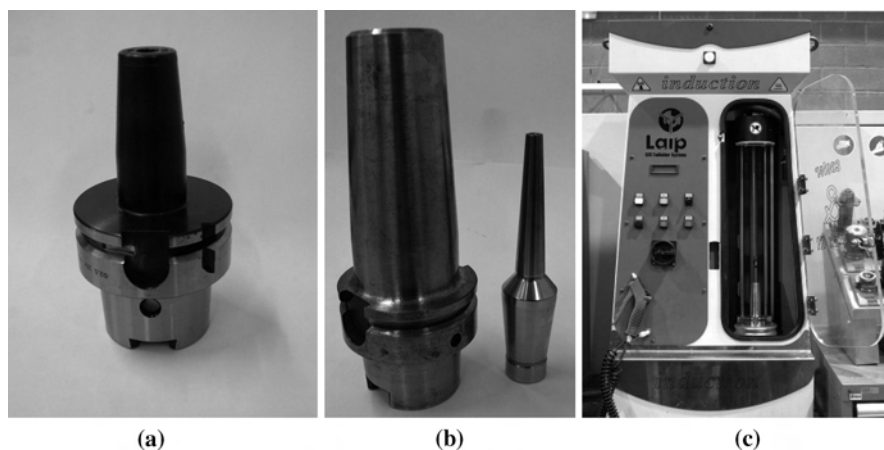
Figure 2.40 Thermal-shrink holders: (a) thermal-shrink HSK63 A holder, (b) thermal-shrink holder with tool extension for higher accessibility, and (c) induction heater

can be as cheap as a hot-air heater, but more sophisticated heaters based on induction are being used industrially (see Figure 2.40). Once the hole has expanded, the tool is introduced and the holder is cooled again to room temperature. When the holder recovers its original dimensions, tool is clamped strongly. This method provides excellent stiffness and minimum run-out (values are comparable to hydraulic holders). Furthermore, there are no additional items such as screws, nuts, *etc*. to hold the tool, so an excellent balancing is achieved.

On the other hand, it is necessary to have a holder for each different tool diameter, which may introduce an added cost.

2.7.3.4 Toolholder Balancing

As mentioned, the toolholder balancing is a key factor in high-speed machining. The unbalancing of a system depends on the unbalanced mass and the position of its centre of gravity about the rotation axis. Since it is impossible to get a perfectly balanced system, the objective is to reduce the unbalance to the minimum value.

The tool–toolholder–machine-tool spindle unbalancing can be originated by a combination of factors:

- asymmetric elements in the toolholder, such as screws, wedges, grooves, *etc*.;
- tools with asymmetric shapes (Weldon holder, drills with one cutting edge, *etc*.);
- imperfections in the holder, tools or collets.

Thus, balancing is defined as the amount of mass multiplied by the eccentricity of the mass. The problem is not the unbalance itself, but the combination of the unbalance with high spindle speeds. The force due to the unbalance can be calculated as:

$$F_{\mathrm{U}} = U\left(\frac{S}{9550}\right)^2$$

where F_{U} is the unbalance resultant force measured in newtons, U is the system unbalancing measured in gram-millimetres and S represents the spindle speed measured in revolutions per minute.

If the unbalance is about 6 to 8 g mm, the force due to unbalance at 18,000 rpm could be higher than the cutting force, especially in finishing operations. Therefore, in order to limit the unbalance effects, tooling manufacturers use ISO 1940-1 to establish the degree of admissible unbalance of the tooling. This standard establishes different *G classes*. The lower the G class, the better balanced is the tooling. Many manufacturers are producing tooling class G1.0 to G2.5. This G class gives the maximum allowed unbalance using the formula

$$U = \frac{9553mG}{S} \tag{2.3}$$

where U is the admissible balance measured in gram-millimetres, m is the total mass of the system measured in kilograms and G is the G class of the system following the ISO 1940-1 standard.

## 2.8   New Techniques for Hard Machining

The development of new tools, on one hand, and the new multitask machines, on the other, has allowed the proposal of new machining techniques for roughing, semi-finishing and finishing. The main purpose of them is to avoid machining vibrations and to take advantage of the stiffer direction of machining centres, that is, the spindle axis.

2.8.1   High-feed Milling

High-feed milling is a roughing technique that works with cutters and inserts designed specifically for the technique. Inserts typically feature large sweeping radii and positive rakes (see Figure 2.41). The high-feed method takes advantage of small setting angles (55° or less). This produces a minimal radial and a maximum axial cutting force. As a matter of fact, the cutting forces are directed towards the machine spindle in the axial direction. This is the stiffer direction of the machine, which reduces the risk for vibrations and stabilizes machining.

This allows for higher cutting parameters even when machining with a large overhang. Therefore, instead of cutting with greater depth, it does the opposite: it pairs shallow depth of cut with high feed per tooth, in some cases higher than 1.5 mm.

At the same time the axial depth of cut is very small, leading to a near-final shape in the case of complex surfaces. Consequently semi-finishing operation is eliminated. This greatly reduces the machining time in the case of moulds or dies.
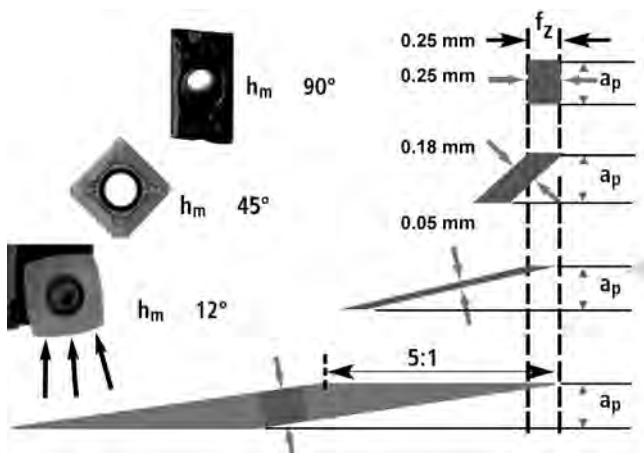
Figure 2.41   Effect of the tool position on the chip section, the basis of the high-feed milling technique (courtesy of Stellram®)

High-feed milling inserts can make facing, ramping, helical interpolation and plunging operations. The interpolation capability of modern CNC machines makes it possible for a small tool to mill out a much larger hole or pocket by ramping. The tool ramps from one level of passes to the next within the feature, or it follows a helical path at a continuous angle all the way down to the feature's depth. Ramping angle in penetration depends on the clearance between insert and part surface and therefore indirectly depends on the insert size, being higher for the smaller inserts.

Inserts can present three, four, five or six cutting edges. Thus, Safety uses pentagonal inserts having five cutting edges (see Figure 2.42 and Table 2.7). Inserts for use in the V556 tools encompass two geometries for roughing and finishing, respectively, and four grades, including VP5020 and VP5040 multilayer PVD TiAlN/TiN coated grades for general applications, a TiN/Al2O3/TiCN CVD VP5135 coated
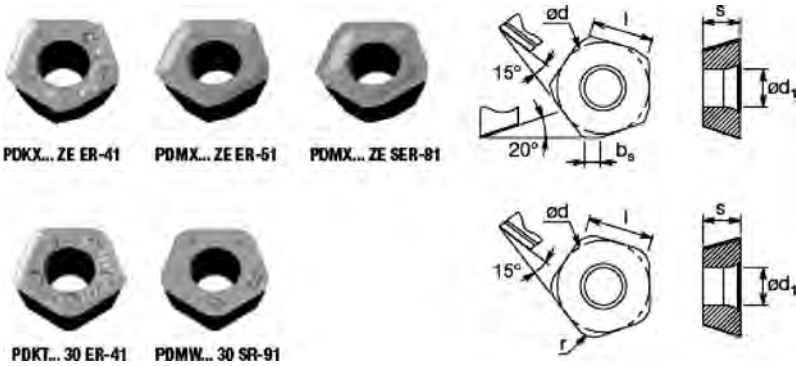

PDKX... ZE ER-41   PDMX... ZE ER-51   PDMX... ZE SER-81

PDKT... 30 ER-41   PDMW... 30 SR-91

Figure 2.42 The Penta-edge insert for high-feed milling of Safety®

Table 2.7 Recommended values for the Penta high-feed inserts by Safety® (for a tool life of 15 min)

Material		Hardness	Cutting speed v_c (m/min)		Tooth feed f_z (mm)			
					Face milling with $a_e = 0$ & $a_p = 1$ mm		Ramping with $a_e = 0$	
			Grades		Geometries		Geometries	
			5020	5040	51	81	51	81
P	Non-alloy steel	< 150HB	180 (130 - 220)	140 (100 - 160)	0.5 - 1.5	1.0 - 2.5	0.5	0.8
	Low-alloy steel	150 - 280 HB	140 (110 - 170)	110 (90 - 130)	0.5 - 1.0	0.8 - 2.0	0.5	0.8
	High alloy steel	180 - 280 HB	110 (90 - 130)	100 (80 - 120)	0.5 - 1.0	0.8 - 2.0	0.5	0.8
M	Stainless steel	< 270 HB	120 (100 - 140)	110 (90 - 130)	0.5 - 1.0	0.8 - 1.5	0.5	0.8
K	Grey cast iron	< 350 N/mm²	250 (200 - 300)	-	0.5 - 1.5	0.8 - 2.5	0.5	0.8
	Nodular cast iron	< 800 N/mm²	200 (200 - 250)	-	0.5 - 1.5	0.8 - 2.0	0.5	0.8
N	Non-ferrous metal	90 HB	1000 (700 - 2000)	-	1.0 - 3.0	-	1.0	-
S	Heat resistant alloys	-	40 (30 - 50)	-	0.5 - 1.0	-	0.5	-
	Titanium	350 HB	35 (25 - 45)	-	0.5 - 1.0	-	0.5	-
H	Pre-treated steel	30 - 45 HRc	120 (80 - 160)	100 (80 - 120)	0.5 - 1.0	-	0.5	-
	Hardened steel	45 - 55 HRc	70 (50 - 90)	60 (50 - 80)	-	-	-	-
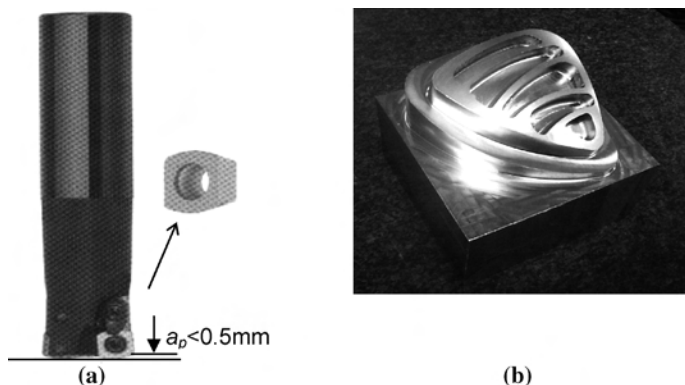
Figure 2.43   (a) Hitachi Alpha Plus tool, and (b) small mould made by high-feed milling and high-speed milling (tool $\varnothing = 25\,\text{mm}$, $f_z = 2.2\,\text{mm}/z$, $N = 1700\,\text{rpm}$, $a_\text{p} = 0.7\,\text{mm}$, $a_\text{e} = 18\,\text{mm}$)

grade for tough machining, and VP1120 abrasive-resistant grade ideal for grey and ductile cast irons.

Four-sided inserts produce a side wall that is close to a square profile, this being the main advantage of these inserts.

In Figure 2.43 a small mould in a 35 HRC steel is presented as an example, being machined from a initial raw block of $130 \times 90 \times 90\,\text{mm}$. In the high-feed roughing the feed per tooth was 2.2 mm, a_p 0.7 mm and a_e 18 mm with a Hitachi Alpha Plus™ tool of $\varnothing 25\,\text{mm}$. The component was finished in only 17 min in a roughing-finishing sequence. High-speed finishing was performed at 20,000 rpm with a ball-endmilling tool.
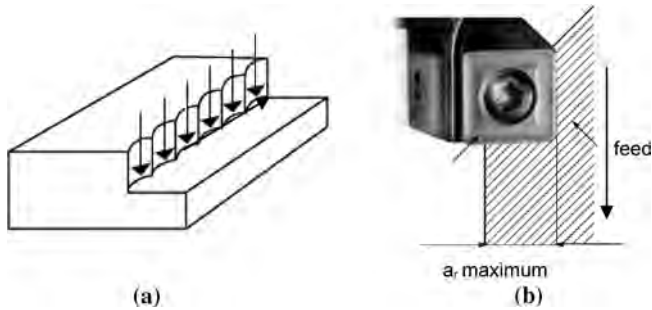
2.8.2   Plunge Milling

This is a high-performance roughing technique in which a milling tool is moved multiple times in succession in the direction of its tool axis or of its tool vector into the material area that is to be removed, forming plunge-milling bores. The bores are superposed to eliminate the material of a pocket or zone.

This technique is also referred to as *milling in the Z-axis*; it is more efficient than conventional endmilling for pocketing and slotting difficult-to-machine materials and applications with long overhangs.

The machining parameters depend on the insert size, the tool overhang and the tool diameter. When a tool overhang of $\varnothing 6\,\text{mm}$ is used, the usual step between two bores must be lower than $0.75 \varnothing$. The radial depth of cut is 1 mm less than the radial length of the insert edge. If overhang increases the step must be reduced.

The advantages of the plunge-milling technique are:

- reduction by half in the time needed to remove large volumes of material;
- reduced part distortion;

Figure 2.44   Plunge milling: (a) general procedure, and (b) maximum radial width of cut (courtesy of Stellram®)
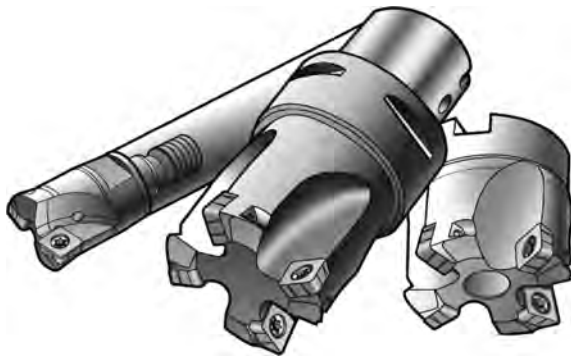
Figure 2.45   Sandvik® Coromill 210 is suitable for both high-feed and plunge milling

- lower radial stress on the milling machine, meaning spindles with worn bearings can be used to plunge mill;
- long reach, which is useful for milling deep pockets or deep side walls.

Plunge milling is recommended for jobs such as roughing cavities in moulds and dies. It is recommended for aerospace applications, especially in titanium and nickel alloys.

Inserts specifically for plunging are available for roughing and semi-finishing, but inserts suitable for high-feed milling can be also used for this technique. In Figure 2.44 the insert of system 7791VS by Stellram® is shown, specifically designed for this application. In Figure 2.45 some milling tools for both feed and plunge milling are shown.

2.8.3 *Turn Milling and Spinning Tool*

Two operations were recently developed for application in the new-generation multitask machines, face turn milling and the spinning tool.
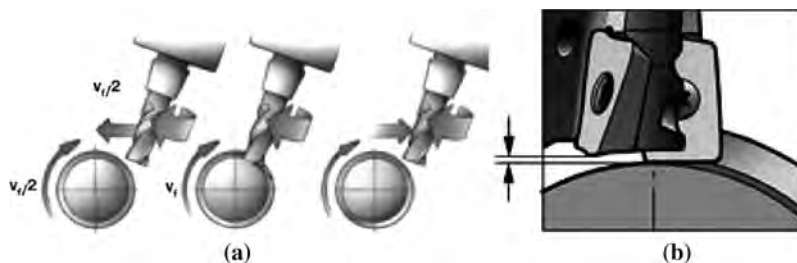
Figure 2.46 (a) Face turn milling (courtesy of Sandvik®), and (b) detail of the wiper insert

In face turn milling one wiper insert is used to generate the straight-line contact between the cutter and the machined surface in order to create the cylindrical part of the component. A wiper insert (see Figure 2.46) is one that follows along behind the cutting edge, extending just a little farther into the material to smooth out the freshly machined surface, avoiding the usual scallops of milling surface patterns.

The rotational speed of parts must be equal to the recommended feed per tooth. Basically it is a face-milling operation where feed is applied in a rotational way by the C-axis of the lathe. The basic parameters for milling can be directly applied to this practice.

As main advantage the chip control [20] offered by interrupted cutting can be highlighted in comparison with the long chips of turning. Other applications and advantages can be regarded:

- Turning tools tend not to do well in interrupted cutting, but a milling tool can fare much better. A milling cut is already an interrupted cut by definition. In the region of the workpiece where the cut becomes interrupted, it may make sense to switch from turning to turn milling.
- When the turned part is long, slender and not braced in the middle, turn milling may prevent it from deflecting.
- In a hard-to-machine metal, a single turning insert might not be able to deliver enough tool life to last to the end of the cut. A milling tool can cut longer, because it has multiple inserts to divide the load.

The radial (X-axis) motion of the milling cutter can be coordinated with the rotation of the workpiece to machine profiles other than perfect circles. Sandvik itself uses this technique to rough-machine the three-face, tapered shape of its Capto toolholders. The same principle, the milling cutter moving in and out while the workpiece turns, can also be used to generate off-centre features without having to change the setup. The off-centre pin on a crankshaft could be an example of this.

Y-axis motion is needed because the milling cutter has to do most of its cutting off-centre. The tool cannot machine the part to its final shape and dimensions when it is on-centre, that is, when the tool centre is located on the cylindrical part axis. In this case the endmill would cut with the centre point and not on its edges.
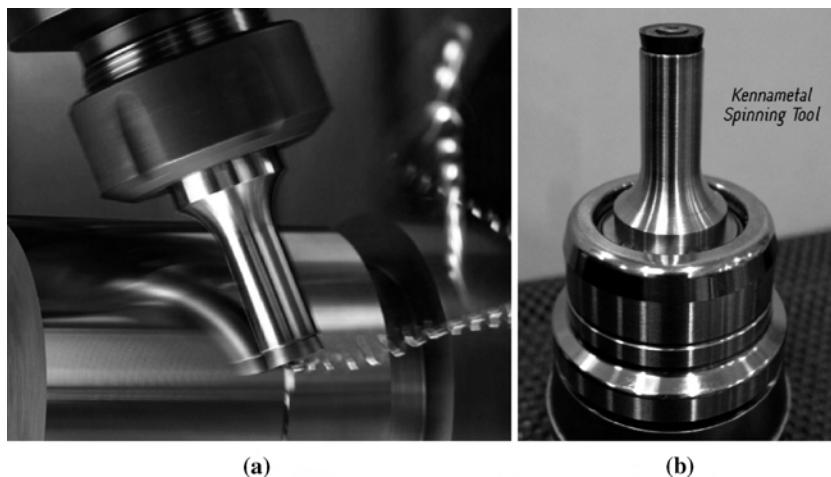
**Figure 2.47**   Spinning tool, developed by Mori Seiki® (a) and Kennametal® (b)

Therefore the tool centreline should be offset from the work's axis of rotation by a quarter of the cutter diameter to cut properly. Using this approach, the problem appears when the tool reaches a shoulder: a rounded corner is produced by the off-centred endmill. To achieve a sharp corner, the cutter must take a second pass. The offset is eliminated, so the tool moves back to the on-centre position in *Y*. This second pass cleans the corner material away.

Spinning tools are another approach, where the cutting speed is the sum of the rotational speed of the cylindrical part and the milling movement at high rotational speed. This new cutting technology uses a specialized insert – similar in design to a round, or full-radius insert – mounted at the bottom of a cylindrical tool shank (Figure 2.47). Designed to distribute heat and wear more effectively than a single-point lathe tool, the spinning-tool technology can increase productivity by up to 500 % and tool life by up to 2,000 %.

This approach competes technically against traditional turning with single-point tools where the cutting force produces a torque and bending on the tool and gives rise to vibrations. But in the case of the spinning tool, most of the cutting forces are directed axially into the spindle and hence significantly reduce vibrations. The spinning tool can also cut in a back-and-forth motion, and this capability was also demonstrated on taper and arc shapes.

2.8.4   *Trochoidal Milling*

A trochoidal toolpath is defined as the combination of a uniform circular motion with a uniform linear motion, *i.e.*, toolpath is a kinematics curve so-called trochoid (Figure 2.48). Light engagement conditions and high-speed milling are
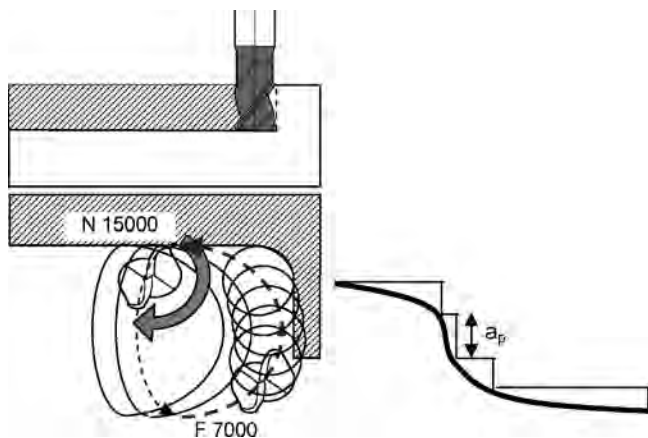
Figure 2.48   Trochoidal milling

applied, in addition to large axial depth of cut. In this way a large radial width of cut is avoided.

Slots wider than the cutting diameter of the tool can be machined, all with the same endmilling tool, usually an integral one. Since a small radial depth of cut is used, cutters with close pitch can be applied, leading to higher feed speed and cutting speed than with ordinary slot-milling applications.

A main drawback is that toolpath length is much higher compared to standard toolpaths such as zigzag because large tool movements are without engagement into the material. Moreover, in the case of sculptured surfaces, overlarge steps are produced on the surface, making very difficult the following semi-finishing operation. Therefore it is recommended for slotted shapes but not for free-form machining.

Currently all commercial computer-aided manufacturing (CAM) packages allow easy programming of this method.

2.9   Tools for Multitask Machining

Throughout the 2000s a new machine-tool concept called *multitasking machines* has been developed. This machine type is based on combining turning and milling operations in the same machine bed. Such solutions have been studied for over 20 years, mainly adapting turning centres equipped with a *C*-axis with mini-turrets for rotary tools. However, these machine tools were developed basically for turning operations, while milling operations were carried out with small tools with low power consumption (less than 1 kW). Moreover, the programming of these machines was a real challenge, as it was necessary to combine turning and milling cycles and it was necessary to program simultaneously four- or five-axis operations, with high collision probabilities.
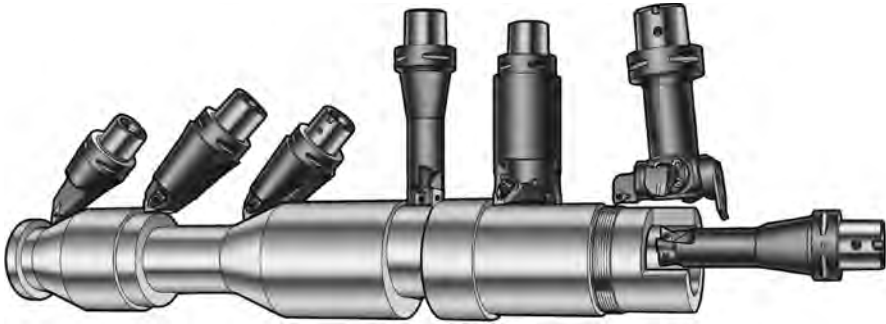
Figure 2.49 Tools specially designed for multitasking machining (Courtesy of Sandvik Coromant). The second from the right side is a mini-turret

These problems limited the development of these solutions until the 2000s, when a new series of machines were presented. The new multitasking machines are able to perform turning and milling operations without distinction and achieve the same power and accuracy of turning and machine centres. In short, multitasking machines include a spindle instead of a turret, in which a rotary tool (for milling, drilling, threading or hobbing) can be held, or a tuning head cab be locked. For more information on these machines the book about machine tools [21] is recommended.

The development of these solutions was also based on the use of latest-generation CNC and more reliable and powerful CAM programming systems. At present, multitasking machines are a reliable solution for the machining of complex parts, combining operations of turning, milling, drilling, boring, *etc*., with the main advantage of making only one set-up, and consequently this fact allows a big reduction in lead times, increasing the machining accuracy.

In order to improve the results of multitasking operations, specific tools have been developed. In particular, a new design is based on two, three or four different turning inserts around the same holder. As the spindle of these machine tools can index its position, the different inserts can be oriented to combine different machining operations with the same holder, being known as *mini-turrets* (Figure 2.49).

## 2.10   Conclusions, the Future of Tools for Hard Machining

Machining is now in a particular "golden age", where a lot of time, money and effort has been invested to define the best tool for each application. Today for each application the objective of large or small manufacturers is to supply a much optimized tool, in all the related aspects discussed in this chapter. One of the most important aspects for the success of the new cutting tools is the *application guide*, because each application needs special recommendations, and in some cases they are contradictory to others.

The economical impact of cutting and machining is increasing, although the near to net shape technologies imply a reduction of the amount of material to be removed in each part. But the demand for elaborate parts and high-end products exceeds all expectations. Consequently the improvement of productivity, tool life and workpiece precision is a main goal for a lot of companies, taking into account respect for the environment as well.

Micromilling is going to be a growing technology where hard milling is going to be applied [22], with special attention to medical devices. In Figure 2.50 a test part used to study micromilling is presented. Tool fabrication is another important issue for the application of micromilling technology. For industrial applications, micropowder (0.3 μm particle size) sintered tungsten carbide is used, making two flute endmills of 100 μm in diameter, with an edge radius of 1–2 μm. In any case, the commercial offer is limited and there are no different geometries for different materials, being an important problem because most of the tools are designed for steel machining. Commercial tools have a well-defined geometry with small tolerances. Tolerance indicated in the catalogues for the sum of geometrical error plus runout error is of ±10 μm. However, real errors are usually smaller (±5 μm), but even in the best case, the tolerance with respect to size of the form to be machined is poor if compared to conventional high-speed machining mills. Tool wear (see Figure 2.51) is rapid and has a considerable effect on the process performance. It actually affects accuracy, roughness, and generation of burrs and vibrations.
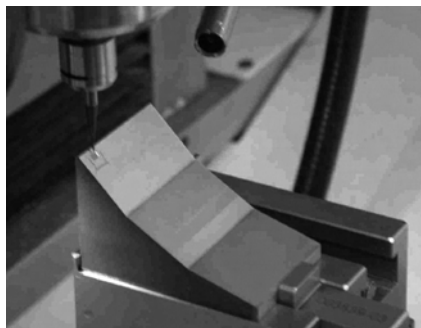
Figure 2.50   Micromilling of the test part made in 50 HRC hardened steel; two-tooth Ø 0.3 mm ball-endmill, 45,000 rpm, feed per tooth $f_z = 0.44$ μm/tooth, depth of cut $a_p = 8$ μm, radial penetration $a_e = 7.5$ μm
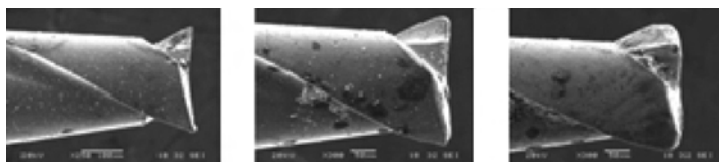
Figure 2.51   Tool wear evolution in micromilling (source: Tekniker)

On the other hand, materials with improved mechanical features are now in development, with more tensile strength and creep resistance. New alloys are usually very low-machinability alloys, asking for recommendation to be machined. Some examples are austempered ductile irons for car components and wind-energy gearboxes, gamma TiAl [23] for car components and aeronautical engines, high-silicon aluminium alloys, carbon-fibre-reinforced plastic composites [24], and others. Special tools will soon be on the market to solve the problems derived from the applications of these very difficult-to-cut materials.

References

[1]   HSS Smart Guide, 2010 available in www.hssforum.com
[2]   ISO 513: 2004 Classification and application of hard cutting materials for metal removal with defined cutting edges – designation of the main groups and groups of application
[3]   López de Lacalle LN, Lamikiz, A, Fernandes, M, Gutiérrez, A, Sánchez, J (2004) Turning of thick thermal spray coatings. J Thermal Spray Technol 10(2):249–254
[4]   López de Lacalle LN, Lamikiz A, Muñoa J, Salgado MA, Sánchez JA (2006) Improving the high-speed finishing of forming tools for advanced high-strength steels (AHSS). Int J Adv Manuf Technol 29:1–2
[5]   Schulz, H (1996) High-speed machining. Carl Hanser Verlag
[6]   ISO 3685-1993 Tool life testing with single point turning tools
[7]   ISO 8688-1-1989: Tool life testing in milling
[8]   López de Lacalle LN, Sánchez JA, Lamikiz A, Celaya A (2004) Plasma assisted milling of heat-resistant superalloys. J Manuf Sci Eng 126(2):274–289
[9]   Celaya A, López de Lacalle LN, Lamikiz A (2010) Assisted machining processes. In: Davim P (ed) Metal cutting: research advances. Nova Science Publishers, New York
[10] ISO 3002-1:1982, Basic quantities in cutting and grinding – Part 1: Geometry of the active part of cutting tools – General terms, reference systems, tool and working angles, chip breakers
[11] López de Lacalle LN, Lamikiz A, Sanchez JA, Salgado MA (2007) Toolpath selection based on the minimum deflection cutting forces in the programming of complex surfaces milling. Int J Mach Tools Manuf 47(2):388–400
[12] López de Lacalle LN, Lamikiz A (2008) Sculptured surface machining. In: Davim P (ed) Machining: fundamental and recent advances. Springer, London
[13] Lamikiz A, López de Lacalle LN, Sánchez JA, Salgado MA (2004) Cutting force estimation in sculptured surface milling. Int J Mach Tools Manuf 44:1519–1526
[14] López de Lacalle LN, Lamikiz A, Sánchez JA, Arana JL (2002) Improving the surface finish in high-speed milling of stamping dies, J Mater Process Technol 123(2):292–302
[15] Lamikiz A, López de Lacalle LN, Sánchez JA, Bravo U (2005) Calculation of the specific cutting coefficient and geometrical aspects in sculptured surface machining. Mach Sci Technol 9(3):411–436
[16] Lazoglu I (2003) Sculpture surface machining: a generalized model of ball-end milling force system. Int J Mach Tool Manuf 43:453–462

[17] StarragHeckert (2007) 4/5 axis machining for complex workpieces.
[18] Salgado M, López de Lacalle LN, Lamikiz A, Muñoa M, Sánchez JA (2005) Evaluation of the stiffness chain on the deflection of end-mills under cutting forces. Int J Mach Tool Manuf 45:727–739
[19] Aoyama T, Inasaki I (2001) Performances of HSK tool interfaces under high rotational speed. CIRP Ann Manuf Technol 50(1):281–284
[20] Zelinski P (2010) Applying turn milling, mmsonline, available at www.mmsonline.com
[21] Lopez de Lacalle LN, Lamikiz A (2008) Machine tools for high performance machining. Springer-Verlag
[22] Uriarte L, Herrero A, Zatarain M, Santiso G , López de Lacalle LN, Lamikiz A, Albizuri A (2007) Error budget and stiffness chain assessment in a micromilling machine equipped with tools less than 0.3 mm in diameter. Precis Eng 31:1–12
[23] Beranoagirre A, López de Lacalle LN, (2009) Milling of gamma TiAl intermetallic alloys. AIP Conf Proc 1181:43–50
[24] López de Lacalle LN, Lamikiz A, Campa FJ, Fernández Valdivielso A, Etxeberria I (2009) Design and test of a multitooth tool for CFRP milling. J Compos Mater 43:3275–3290