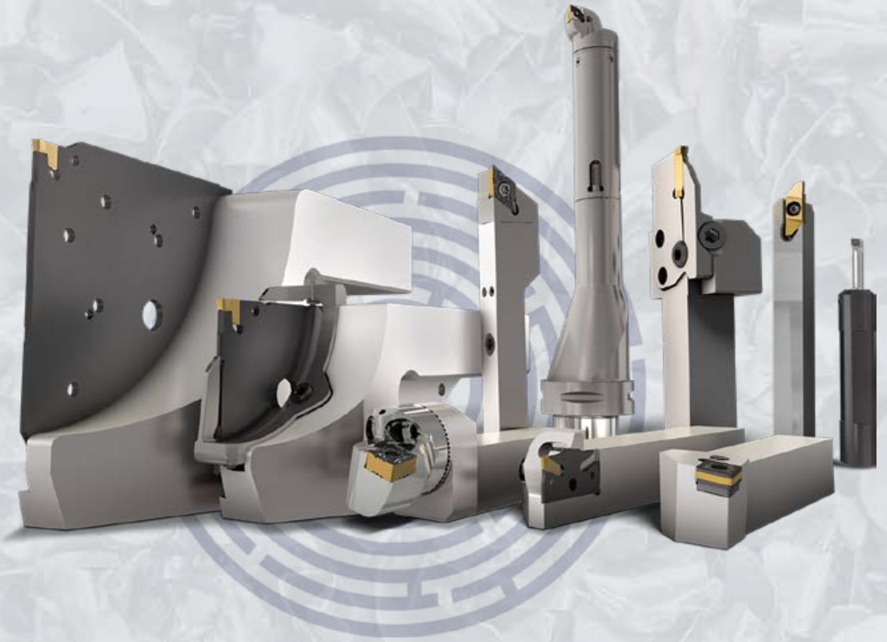
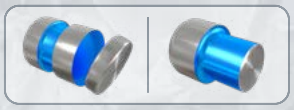
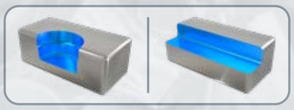
Get to Know Cutting Tools

ISCAR's Reference Guide







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With repsect to the metal cutting communities

PREFACE

There are a lot of books, manuals, handbooks, and guides on cutting tools. They differ in the subject methodology, treatment of themes, style, details, and language. And now one more edition is in front of you. What news can it bring? Will it be interesting? Why is it being published?

In **ISCAR**, we make cutting tools. These are our products, and together we developed, creating our history.

Our experience has shown that a small book, which introduces the reader to cutting tools concisely, in a common form, would be quite useful. Such a book would not act as a textbook or a brief, but as a comprehensive reference guide.

The metric system is used in this guide, followed by the US customary system in brackets.

Contents

Symbols and units*

A — cross—section area of cut layer, mm^2 (in^2)

a — depth of cross—section of removed material layer, mm (in)

a_e — width (radial depth) of cut, mm (in)

a_p — (axial) depth of cut, mm (in)

$a_{p\ max}$ — maximum axial depth of cut, mm (in)

b — width of cross—section of removed material layer, mm (in)

C — empirical constant in Taylor's tool life formula

c — ratio of width of cut a_e to nominal tool diameter d

D — diameter of machined surface, mm (in)

D_1 — diameter of unmachined surface, mm (in)

d — nominal tool diameter, mm (in)

d_1 — diameter of tool shank, mm (in)

F — resultant (total) cutting force, N (lbf)

F_a — axial cutting force, N (lbf)

F_b — bending force, N (lbf)

F_r — radial cutting force, N (lbf)

F_t — tangential cutting force, N (lbf)

f, f_r — feed, feed per revolution, mm/rev (IPR, ipr, inches per revolution

f_s — feed per double stroke, mm/double stroke (inches per double stroke, IPS)

f_z — feed per tooth, mm/tooth (IPT, ipt, inches per tooth)

h — equivalent chip thickness in modified Taylor's tool life formulas, mm (in)

K — cutting edge form factor (K—factor); also, can refer to unit power factor, kW per 1 cm^3/min (hp per 1 in^3/min)

K_m and $K_{m\%}$ — a material machinability index (factor, rating, ratio) in terms of numbers or percentage,

k_c — actual specific cutting force, N/mm^2 (ksi)

k_{c1} — specific cutting force to remove a material chip area of 1 mm^2 (.0016 in^2) with 1 mm (.004 in) thickness, N/mm^2 (ksi)

n — rotational velocity (spindle speed), rpm (RPM, rpm)

m — empirical constant in Taylor's tool life formula

mc — chip thickness factor in the equation for finding actual chip thickness k_c

P — cutting power consumption, kW (hp)

P_n — cutting edge normal plane

P_r — tool reference plane

P_s — tool cutting edge plane

Q — material removal rate (MRR), cm^3/min (in^3/min)

r — corner radius, mm (in)

S_α — width of honed cutting edge measured on flank

S_γ — width of honed cutting edge measured on rake face

T — tool life

VB — flank wear width

v_c — cutting speed, m/min (SFM, sfm)

v_{cm} — cutting speed, at which tool life T is observed, m/min (SFM, sfm)

v_{cr} — cutting speed for machining a material, chosen as a reference, for the tool life T, m/min (SFM, sfm)

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* in the metric system
(units in the US customary system are given in brackets)

v_f — feed speed (feed rate), mm/min (IPM, ipm, inch per minute)
z — number of teeth (flutes)
α — clearance (clearance angle, relief angle)
β — wedge angle
γ — rake (rake angle)
γa, γp — axial rake
γr, γf — radial rake
κr — cutting edge angle
λs — flute helix angle
δ — machining allowance (stock to be removed) per pass, mm (in)
ψ — lead angle
ω — angular velocity, s^{-1}

Abbreviation list

AISI — American Iron and Steel Institute
ANSI — American National Standards Institute
ASME — American Society of Mechanical Engineers
BN — boron nitride
BUE — build-up edge
CAE — computer-aided engineering
CAD — computer-aided design
CAM — computer-aided manufacturing
CBN, cBN — cubic boron nitride
CNC — computer numerical control
CVD — chemical vapor deposition
Dia. — diametr
DOC — depth of cut
FEM — finite element method
FF — fast feed*
HSK — “Hohlshafte Kegel” (“hollow shank taper” in German)
HFM — high feed milling
HPC — high pressure coolant
HSM — high speed milling, high speed machining
HSS — high-speed steel
HSS-E, HSSE — cobalt-type high-speed steel
HTSA — high-temperature superalloys
IOT — Internet of Things
ISO — International Organization for Standardization
MRR — metal removal rate
PCBN, PcBN — polycrystalline cubic boron nitride
PCD — polycrystalline diamond
PM — powder metallurgy
PVD — physical vapor deposition
R&D — research and development
SCEM — solid carbide endmills
SEM — scanning electron microscope
VDI — Verein Deutscher Ingenieure (German) - Association of German Engineers

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* fast feed is synonymic with high feed

Cutting Tool Types and Main Elements

Cutting tools are the tools for shaping workpieces by chip removal (or machining) processes.

The most distinctive features that classify cutting tools are:

1 According to a machining process, for which a tool is intended:

- turning tools
- milling tools
- drilling tools
- counterboring tools
- broaching tools
- planing tools
- gear chamfering tools and so on

A more detailed classification divides the mentioned tools into specific groups. For example, turning tools comprise tools for longitudinal turning, facing, grooving etc., while milling tools are intended for milling faces, shoulders, slots, and so forth.

When speaking about a whole class of cutting tools for machining specific shapes, in many cases the appropriate tools are considered in a broader context, for example:

- hole making tools (that include drilling, reaming, boring, countersinking, and other tools)
- gear-making tools (for milling, gear hobbing, power skiving, gear shaving tools etc.)

Usually, turning, milling, and drilling tools are considered general-purpose cutting tools.

2 According to primary motion: rotating and non-rotating tools.

It should be noted that some tools, which relate to non-rotating, may look like rotating and vice versa. A typical example is a non-rotating drill that is clamped in a lathe tailstock for producing holes in rotating workpieces.

Motions in Machining: Primary Motion

This is a rectilinear or rotational motion of a cutting tool or a workpiece that provides the tool advance toward the workpiece to ensure chip removal. In a machining process, the primary motion features the maximum speed when compared to all other motions. The primary motion in turning, for example, is the rotation of a workpiece, while in milling, the primary motion is the rotation of a mill. Most of the energy, which is required for machining, is directed to provide the primary motion.

3 According to the number of cutting edges:

- single-point tools that have only one cutting edge
- multi-point tools with more than one cutting edge while the edges are placed in series in the primary motion direction

Sometimes, the tools with two cutting edges are considered double-point tools.

4 According to the design concept:

- solid (one-piece) tools that are made from one piece of material
- assembled tools with detachable connected tool elements
- assembled tools where the tool elements are directly joined (i.e., brazing)

5 According to the mounting method:

- bore-type tools
- shank-type tools

6 According to adjustment capability:

- adjustable
- non-adjustable

7 According to description:

- standard
- special (tailor-made)

If everything is simple enough with special tools – they are customized and produced in accordance with a customer specification and the definition "standard" has a certain duality. On the one hand, it may mean that a tool meets the requirements of some national or international standard. On the other hand, cutting tool manufacturers use this definition to specify their in-stock product range of standard delivery. Obviously, in many cases an in-stock product may be in full concordance with an acting standard.

When classifying cutting tools, a key feature for classification should be determined.

ISCAR's Cutting Tool Range

ISCAR produces both assembled and solid cutting tools, traditionally divided into rotating and non-rotating. Following are the main product lines in the standard tool range:

- turning tools for external and internal turning, grooving, and parting (cutting-off)
- milling tools
- holemaking tools including drilling, reaming, and countersinking
- threading tools, containing a mix of rotating and non-rotating tools
- Other standard range products including tools intended for broaching, milling gears, splines and serrations, and grooving.

ISCAR also produces a wide variety of toolholding products such as tool blocks, holders, adapters, chucks, arbors, collets etc.

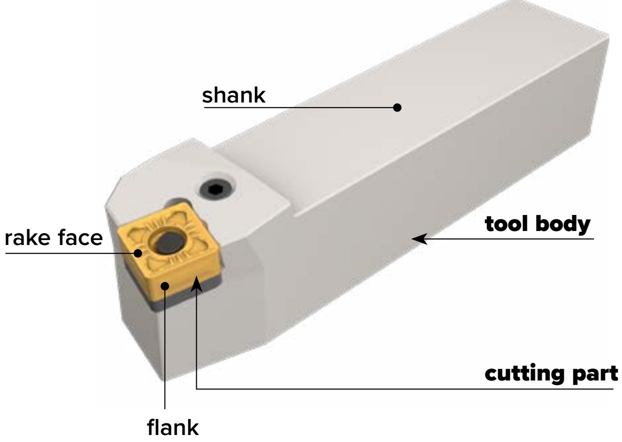
Cutting Tool Elements

A cutting tool (Fig. 1.1-1.4) features a cutting part and a body.

The cutting part is the main functional part of a tool that is necessary for cutting action.

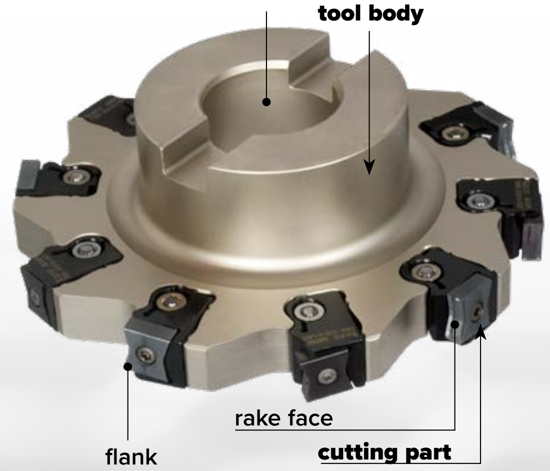
In assembled tools, a cutting part is mounted on a tool body, while in solid tools, the body has a specially shaped area that forms the cutting part.

Fig. 1.1.



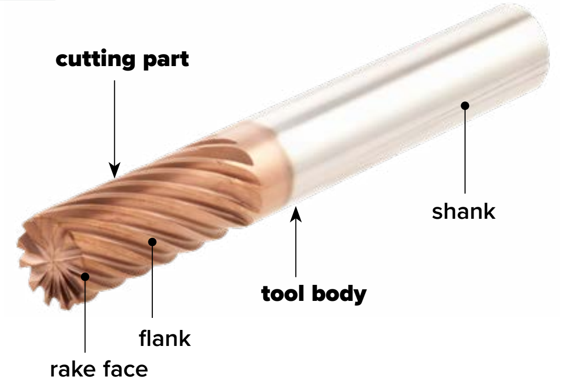
a turning tool (non-rotating, single-point, assembled, shank-type, non-adjustable

Fig. 1.2.



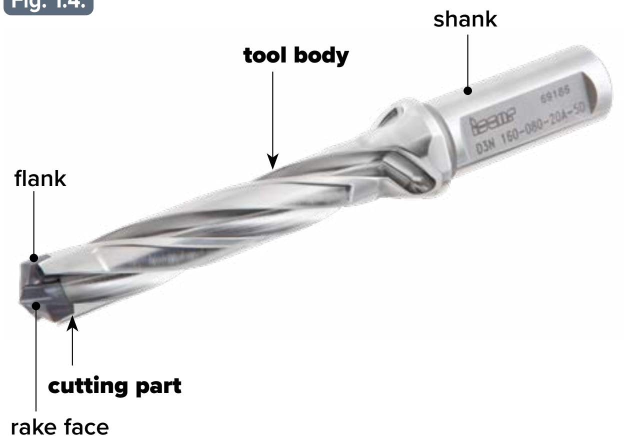
a milling tool (rotating, multi-point, assembled, bore-type, adjustable)

Fig. 1.3.



a milling tool (rotating, multi-point, solid, shank-type, non-adjustable)

Fig. 1.4.



a drilling tool (rotating, double-point, assambled, shank-type, non-adjustable)

Along with it, a body comprises a mounting part, which is needed for mounting a tool in a machine or a tool holder to perform a tool motion relative to a machined workpiece. In rotating tools, with the use of the mounting part, the power that is required for machining, is transmitted from a machine tool to the cutting part. The mounting part can be external (male) or internal (female). The external mounting part is known as a shank, and the internal part is known as a bore.

To ensure cutting action, the cutting part of a tool must have an appropriate shape and be made from a proper material. The shape is associated with cutting geometry, while the material relates to cutting (tool) material.

Cutting Tool or Metal Cutting Tool?

Historically, metals were the main materials to produce machined parts. Even now, when the use of various composites and ceramics has risen exponentially, metals still dominate among engineering materials. Formerly, cutting tools were intended primarily for machining metals, metal cutting, and this determined their name. Today the term "metal cutting tool" is rare enough, while simply "cutting tool" is much more common; and these two definitions have become synonyms.

Cutting Geometry

The portion of a cutting part that removes material directly has a wedge-shape profile, which is formed by two surfaces. The first, the rake face or simply the face, is the surface on which the chips flow when cutting – the chip-flowing surface. The second, the flank (also referred to as a relief surface or a clearance surface), is the surface that fronts on the machined surface of a workpiece. In a cutting process, the flank defends the machined surface from galling due to friction. Both the rake face and the flank may be complex surfaces that incorporate several ones. In such cases, the sections of the surfaces are designated separately: for example, main relief, secondary relief etc.

The area between the rake face and the flank features a wedge (a cutting wedge – not to be confused with a wedge as a clamping element that secures a cutting insert on the body of an assembled tool). The intersection of the rake face and the flank produces a cutting edge. The cutting edge contains a major cutting edge removing the largest side of a chip cross-section, and a minor cutting edge that, consequently, removes the rest.

To determine the cutting geometry in terms of quantity, specific angles are used. Strict definitions of these angles relate to the corresponding choices related to the reference systems of planes:

- the tool-in-hand system to specify the angles for design, manufacturing and measuring of a tool
- the tool-in-use system to specify the angles for a working tool
- the machine system to check the angles after mounting a tool in a machine

Motions in Machining: Feed Motion and Resultant Cutting Motion

The feed motion is a rectilinear or rotational motion of a cutting tool, which adds the primary motion to complete cutting action. This motion features significantly less speed when compared to the speed of a primary motion.
The resultant motion of a primary and a feed motion is known as a resultant cutting motion.

The reference systems are rectangular coordinate systems with the origin in a selected point on the cutting edge of a tool. The tool-in-hand system relates to the element of a tool, which is chosen a base (a datum); the tool-in-use system is aligned with the resultant cutting motion in a machining operation; and the machine system uses as reference the direction of a primary motion. The machine reference system may be considered as a transition between the two other systems.

When the angles are defined in the tool-in-hand system, the prefix “tool” precedes the name of an angle, while for the angles in the tool-in-use system, word “working” is added before the angle name. The angles in the tool-in-use system are also known as “effective”.

To explain the angle specification, let’s consider the tool-in-hand reference system. The angle definitions require introducing appropriate reference planes, and the tool reference plane is the basic from them.

The tool reference plane (Pr) is a coordinate plane going through a particular point of a cutting edge when the plane orientation depends on a specific type of cutting tool. For example, for a turning tool with square shank Pr is parallel to the shank base (Fig. 1.5), while for a milling cutter Pr includes the cutter axis. One more plane, the cutting edge normal plane (Pn), is a plane normal to the cutting edge in the edge point. And an additional coordinate plane, which is tangential to the cutting edge in the chosen point and normal to the tool reference plane, is the tool cutting edge plane (Ps). There are other planes, however, for simplified angle definitions, the mentioned two can be enough.

The tool rake γ, also known as the rake angle is the angle between the rake face and the tool reference plane Pr. If the rake is measured in the cutting edge normal plane, it is specified as the tool normal rake and designated with subscript "n": γn. Accordingly, if the rake measuring relates to other planes of a reference system, the appropriate prefixes, such as "orthogonal", "side" etc., and corresponding subscripts is used. In rotating tools, for example, the rake, which is measured in a plane normal to the tool axis, is known as the radial rake γr. In everyday language, however, the prefix are often omitted because in professional conversation participants clearly understand the specific theme of discussion.

Angles in the Reference Systems of Planes

The difference in angle values, which are specified in the tool-in-hand, the tool-in-use and the machine reference systems of planes depends on the type of a tool. For some tools, the difference is small but for others it can be significant.

The clearance α, which is also referred to as the clearance angle and the relief angle, is the angle between the flank and the tool cutting edge plane Ps. Using subscripts and prefixes in the clearance designation depends on a measured plane similarly to the above case with the tool rake.

The tool angles predetermine the orientation of the rake face and the flank relative to a machined surface, and this has a direct impact on the tool cutting capability. The rake γ is a key for a chip forming mechanism, and mechanical and heat load that follow a machining process. Therefore, the rake is critical for a cutting action. At another point, the clearance α is the dominating factor for smoothening friction between the tool flank and the machined surface to reduce the abrasive wear of a tool. The preferable values of the rake and the clearance depend on a range of factors such as machined material, the material from, which a tool is made, cutting conditions etc. These values are based on experience, however, today's computer modeling capabilities provide additional options for optimizing the values.

The rake and clearance can be positive or negative (Fig. 1.8). The angle between a face and a flank, which is measured in an appropriate plane, is a wedge angle β. This angle reflects the strength of the wedge-shaped cutting profile.

It is not too difficult to see that

$$\alpha+\beta+\gamma=90^\circ \qquad (1.1)$$

In addition to the angles that determine the orientation of a face and a flank, there are angles which describe the position of a cutting edge. In the tool-in-hand system such angles are the tool cutting edge angle, the tool lead angle and the tool cutting edge inclination. To keep it simple, these angles may be specified as follows (Fig. 1.9).

The tool cutting edge angle κr is the angle between a cutting edge and the direction of a linear feed motion. Sometimes, the cutting edge angle is designated as an entering angle or entrance angle.

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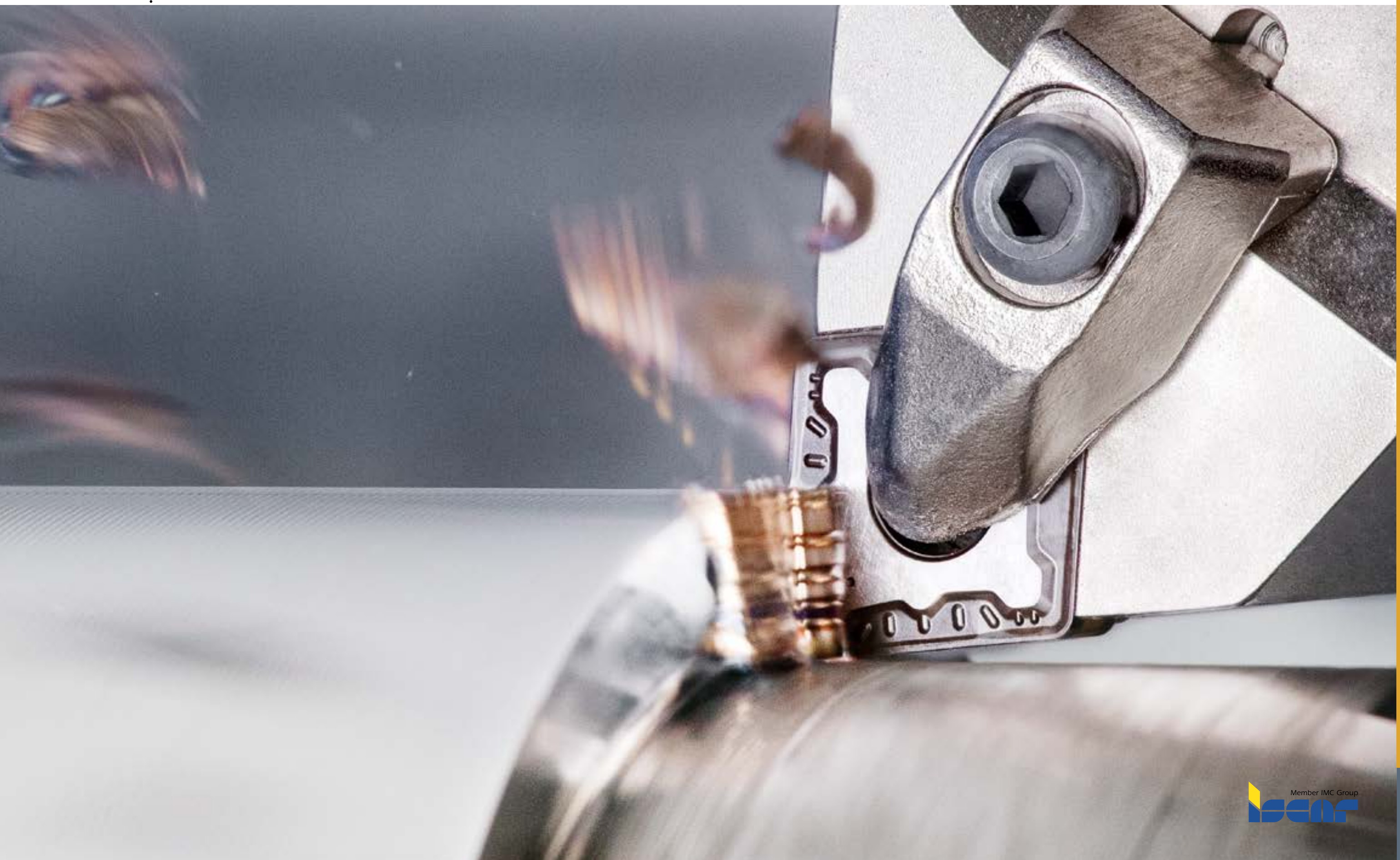
The tool lead angle ψ, also referred to as the tool approach angle, is the angle complementary to the tool cutting edge angle, i.e., the sum of both these angles is equal to 90°. For example, for a typical face milling cutter the cutting angle is the angle between the cutting edge and the plane, which the cutter generates. If this angle is 60°, then the lead angle will be 30°.

The cutting edge angle (and its implicit definition by the lead angle) is a principal factor for chip thickness.

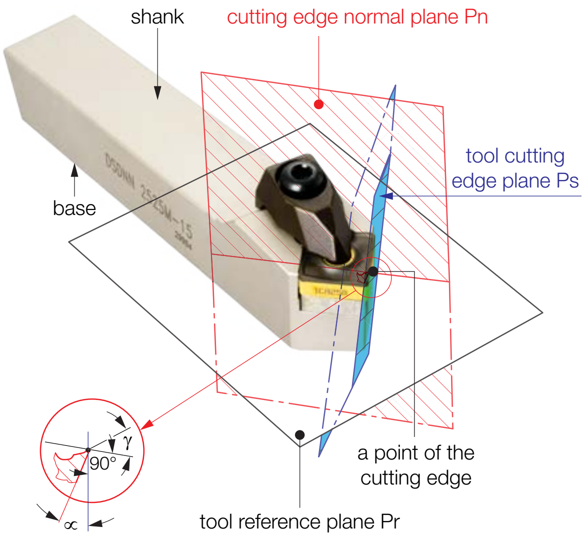
The tool cutting edge inclination λ is the angle between the tool cutting edge and the tool reference plane Pr. The cutting edge inclination has direction; hence, it can be both positive and negative. The cutting edge inclination has an impact on a chip flow direction. In rotating tools, the inclination of the cutting edge with reference to the tool axis is designated as the tool axial rake γa.



Whittling Wood by a Jackknife (1)

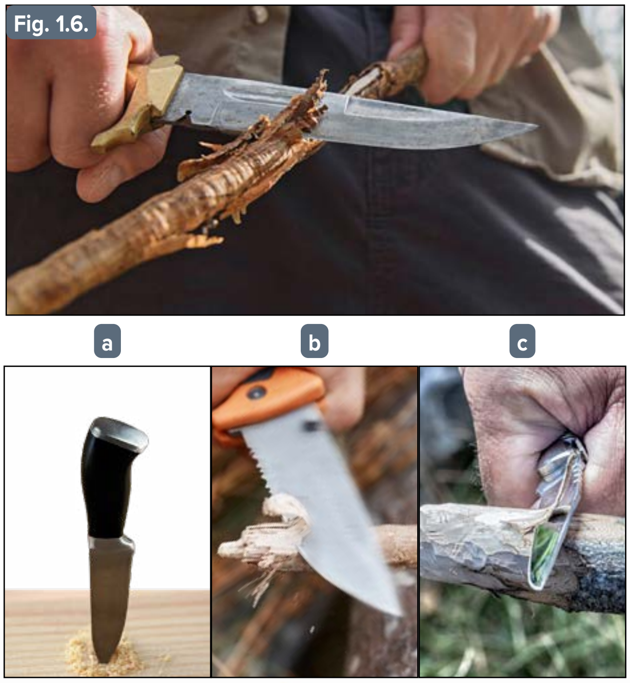
As a child, you used a penknife to carve boats from bark of a pine tree or to pare a thick tree branch for making a fishing rod. Let's imagine that we are going to whittle a piece of wood with a Jackknife. The orientation of the knife relative to the cut wood is especially important (Fig. 1.6). Depending on the knife orientation, the results of our work will be different. In one case, (a, Fig. 1.6) we will apply a scraping motion that requires additional physical efforts to remove the wood layer of the required thickness. In the second case (b), the lack of clearance between the knife and wood produces another difficulty: unstable cutting by the dragging knife, which constantly bounces off the wood, will result in inferior quality of the formed surface. In both cases the knife becomes dull quickly. However, the correct knife orientation (c), will provide the intended effect. Everyone who has ever carved with a knife remembers, how, already after the first cut, he has oriented the knife in the right position relative to a piece of wood to continue working successfully. This simple example relates directly to our brief description of cutting geometry. The technological meaning of the correct knife orientation by hand is the proper setting of rake and clearance angles for effective whittling, i.e., the angles in the tool-in-use reference system – the working rake γe and the working clearance αe. The designer of the knife – our "tool design engineer" – transforms them in the appropriate angles in the tool-in-hand system (γo and αe), which is referenced to a base such the bottom plane of the knife handle (Fig. 1.7). Interestingly, the difference between the angles in our two systems, is substantial.

Fig. 1.5.



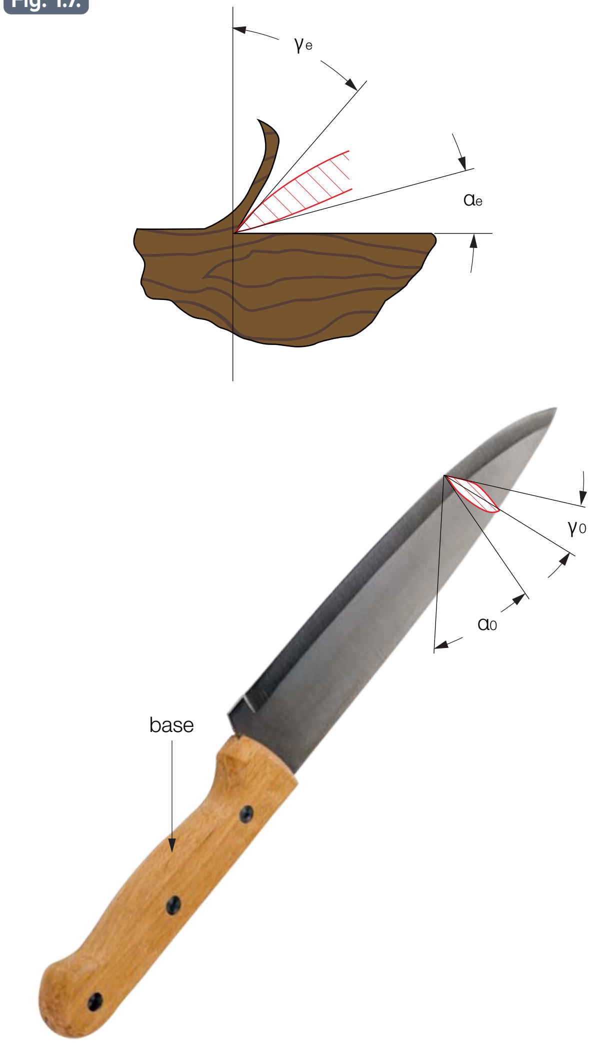
tool planes and angles

Fig. 1.6.



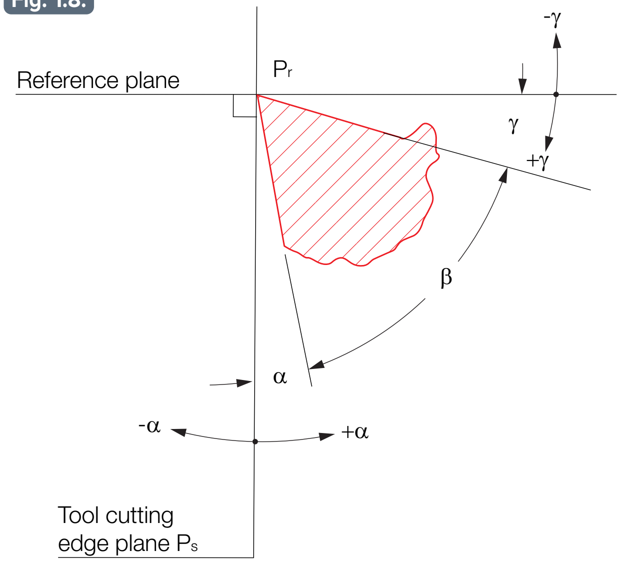
whittling wood

Fig. 1.7.



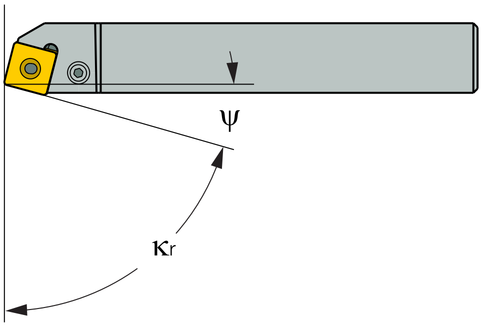
working angles of a knife whittling wood and the knife tool angles

Fig. 1.8.

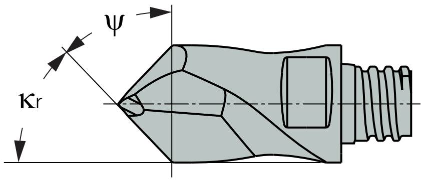


angle directions

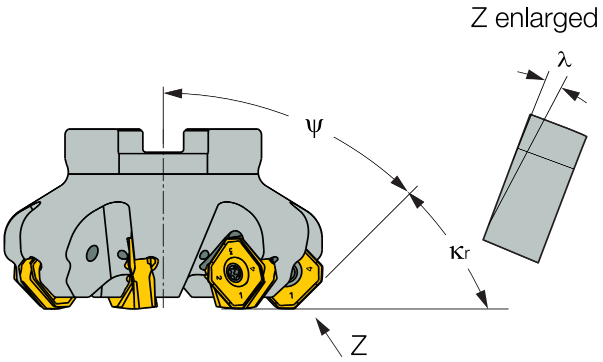
Fig. 1.9.



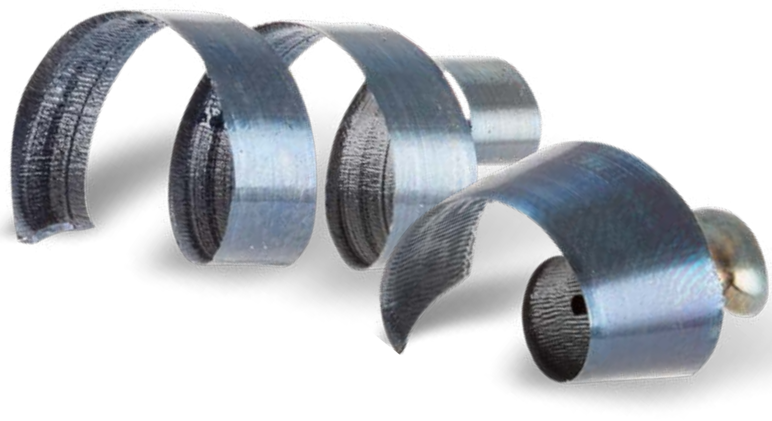
assembled turning tool with an indexable insert



exchangable solid drilling head



assembled milling cutter with indexable inserts
angles of cutting edge orientation
for different cutting tools.



Cutting Materials

To ensure correct cutting action the tool cutting part should be made from the appropriate material. In machining, the wedge-shaped profile of the cutting part is under considerable mechanical and thermal loads that cause wearing of the flank and the face of a tool. Therefore, the cutting part material, referred to as the cutting material or tool material must meet specific requirements such as:

- harder when compared to machined material
- have the required hot hardness to ensure necessary hardness at elevated temperatures that feature cutting
- provide high strength
- facilitate wear resistance

In addition, cutting material should be machinable to enable producing the necessary cutting shape by existing technological processes.

The common cutting materials are:

- high speed tool steel (HSS)
- cemented carbides
- cermets
- ceramics
- cubic boron nitride
- cubic boron nitride and diamond

Cubic boron nitride and diamond are often referenced to as super hard, ultra-hard, or extra hard cutting materials.

Whittling Wood by a Jackknife (2)

Let's get back to carving boats with a penknife. Imagine that somebody would like to try a letter opener knife instead of the penknife. If the letter opener is made from wood or plastic, the result will be negative: the opener simply will not cut. On the other hand, applying a letter opener from steel will not provide desired result due to difficulties in carving. Both cases illustrate a wrong tool choice. In the first case the knife materials were not hard enough to ensure proper cutting action, in the second case despite acceptable tool material the cutting geometry failed to meet the requirements of the operation.

High Speed Tool Steel (HSS)

When compared to the other cutting materials, HSS has the highest transverse strength. Heat treatment processes enable increasing the HSS hardness (commonly around HRC 65 at room temperature), however, it is lower in comparison with the other cutting materials. The primary HSS advantage is good machinability. Therefore, high speed steel is a popular material for various complex-shape tools and standard tools, especially those intended for reuse after regrinding.

Hard Cutting Materials

Cemented carbides, cermets, ceramics, boron nitride, and diamond relate to hard cutting materials – their hardness is significantly higher when compared to HSS.

HSS retains its high hardness when heated up to 650°C (1200°F). This limits the cutting speed because if the temperature of a tool cutting edge exceeds the above value, the HSS hardness diminishes, and the edge loses cutting capabilities. Typical cutting speeds for HSS tools rarely exceed 60 m/min (200 sfm).

In fact, HSS is a high alloy steel. According to the major alloying element, AISI (the American Iron and Steel Institute) specifies two main types of HSS: molybdenum-type (the M-series) and tungsten-type (the T-series).

In cutting tools, the M-series is more common. Also, there is a third type of high speed steel that contains cobalt. The addition of cobalt increases hardness up to HRC 70 but reduces toughness.

Cobalt-type HSS can be both the M- and the T-series. These steels have designations “HSS-E” or “HSSE” (in truth, the designation was originally related to M35 steel) or by letters “HSSE Co” with a following number that shows the cobalt percentage.

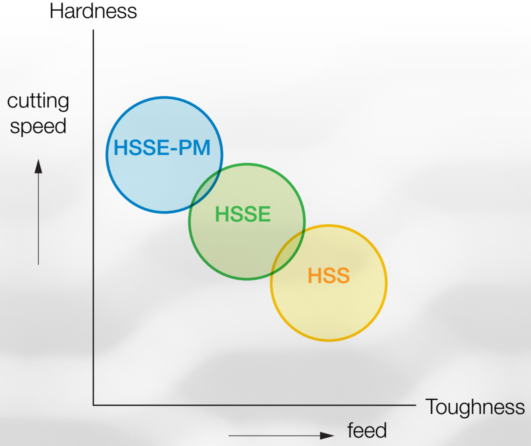
Cobalt Steel

In the past, the term “cobalt steel” was related to AISI M35 high speed tool steel but now this term is a common name for various HSS grades containing cobalt.

Modern methods of powder metallurgy (PM) enable producing high-strength and hard grades of sintered high speed steel. The letters “PM” after the HSS grade designation, for example, “HSSE-PM”, highlight that the steel grade is manufactured by powder metallurgy technology. To improve performance, wear-resistant coatings are applied to HSS tools.

Fig. 2.1 shows a general location of high speed steels according to hardness-toughness coordinates.

Fig. 2.1.



High speed steel capabilities

Cemented Carbides

Today cemented carbides or hard metals are the most common cutting materials. These are sintered alloys containing carbides of wolfram (WC) that are bonded (“cemented”) mainly by cobalt (Co). Due to wolfram having another name, tungsten, which is even more popular in metalworking, WC is also referred to as tungsten carbide.

Cemented carbides comprising only WC and Co as a binder relate to simple or plain hard metals. They have the designation “WC-Co”. Adding carbides of titanium (TiC), tantalum (TaC) and other alloying components improves mechanical properties of the hard metals and their resistance to wear. In such cases the cemented carbides are designated by “WC-TiC-Co”, “WC-TiC-TaC-Co” etc.

“Cemented Carbide”, “Tungsten Carbide”, “Wolfram Carbide”, “Hard Metal” or “Hardmetal”?

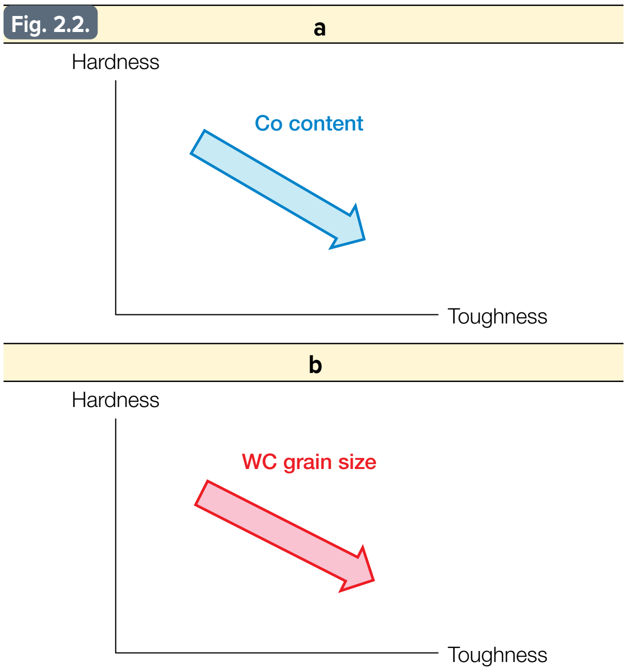
“Tungsten” is another name for the chemical element Wolfram (incidentally, the word origin is Swedish, meaning “heavy stone”). Although “tungsten carbide” relates to simple (plain) hard metals that consist merely of wolfram carbide and cobalt, today all these terms usually refer to cemented carbides and not only to the simple ones. In the field of cutting tool manufacturing, the terms “cemented carbide”, “tungsten carbide” and “hard metal” (or the appropriate abbreviation “HM”) are common.

The key features of cemented carbides are hardness and strength. These features depend heavily on the two following factors:

- the content of cobalt
- the size of tungsten carbide grains. Increasing the content of cobalt makes cemented carbides tougher but less hard. The same tendency features growing the grain size of WC (Fig. 2.2)

Alloying the cemented carbide by transition metals, such as ruthenium (Ru), osmium (Os) and rhenium (Re) improves hardness and strength but, on the other hand, increases production costs.

Fig. 2.2.



Mechanical properties of tungsten carbides as a function of:
a) Cobalt (Co) content
b) Grain size

Toughness of Cemented Carbides

Toughness of cemented carbides is determined by laboratory tests of the sample for transverse rupture strength (TRS).

The size of the grains is associated by specifying a cemented carbide as “fine”, “coarse”, “submicron” etc. Each of these definitions may slightly differ for various standards and norms of carbide product manufacturers, but usually they refer to the following:

fine grade	1 - 1.4 µm (40 - 55 µin) grain size
submicron grade	0.7 - 0.9 µm (27.5 - 35 µin) grain size
ultra-fine grade	0.2 - 0.6 µm (8 - 24 µin) grain size.

In addition, depending on the grain size, there are medium, coarse, extra coarse, and even nano carbide grades (Table 2.1).

The last, for example, features extremely small grain sizes: less than 0.2 µm or 8 µin. In hard metal cutting tools, most used tungsten carbides feature 6-12% cobalt content and 0.3-4 µm (12-160 µin) grain size range.

Table 2.1

Grade Type	Units	Grain Size, µm (µin) From	Grain Size, µm (µin) Up To
Extra Coarse	µm	more than 5 µm	
	µin	more than 197 µm	
Coarse	µm	3.5	5
	µin	137.8	197
Medium Coarse	µm	2.1	3.4
	µin	82.7	134
Medium	µm	1.5	2
	µin	60	80
Fine	µm	1	1.4
	µin	40	55
Submicron	µm	0.7	0.9
	µin	27.5	35
Ultra-Fine	µm	0.2	0.6
	µin	8	24
Nano	µm	less than 0.2 µm	
	µin	less than 8 µin	

typical specification of cemented carbides depending on grain size

According to the grain size, the cemented carbides, which are used for producing cutting tools, mainly relate to medium, fine, submicron and ultra-fine grade types.

Coated Carbides

Coating of cemented carbides significantly improves resistance to wear and ensures higher cutting speed and feed providing better productivity. As a result of coating, a cemented carbide is covered by a protective thin layer of extremely hard material, mainly ceramic, that in ideal conditions features high strength, chemical resistance, and heat insulation. Also, coating should decrease friction between a tool face and produced chip. This is expected from a film of several-micron thickness! Understandably, not all ideal coating characteristics can be fulfilled. To find an acceptable balance, coating technology is a subject of continuous scientific research and production improvement.

Coating Layers

In single-layer coatings, the uniform layer of a specific coating material covers a hard metal substrate. In multilayer coatings, the layers of different coating materials are applied to a substrate. The layers have their own specific key function: providing thermal isolation, increasing resistance to abrasion and adhesion wear, ect. And, again, all of this in a film of several-micron thickness!

Most cemented carbides, which are used for producing cutting tools, integrate wear-resistant coatings. In coated hard metals, a carbide is a substrate that is coated by one or several specific materials. These materials differ in physical properties such as hardness, resistance to abrasion, oxidation temperature, lubricity etc. Typical coating materials for hardmetals are ceramics like titanium nitride (TiN), titanium carbide (TiC), titanium carbon nitride (TiCN), titanium aluminum nitride (TiAIN) and aluminum oxide or alumina (Al_2O_3). Due to synergism, multiple coating, which combines different materials, often enables substantial changing of coating features when compared to single-layer coating. In the last years coating cutting tools by materials such as aluminum titanium chromium nitride (AITiCrN) and titanium diboride (TiB_2) has become common enough.

Principally, there are two main coating methods: chemical vapor deposition (CVD) and physical vapor deposition (PVD). They differ in the deposition nature, as it follows from a method designation, the deposition temperature, the coating thickness, the characteristics of coating stresses, dimensional uniformity etc. When applied to cutting tools, each method has its advantages and disadvantages.

CVD utilizes chemical reactions in a gas environment at temperatures of about 900-1000°C (1650-1830°F) that facilitate high coating adhesion. This process is well suited for multiple coating by different coating material. CVD forms a relatively thick coating that increases wear resistance and high-temperature strength of a coated cemented carbide. At the same time, the process requires strict thermal control because the high environmental temperature may affect the carbide microstructure and thus diminish the cutting performance.

Historical Notes: Introduction of Coatings

Despite the CVD coating that was applied to cemented carbide tools in the 1960s, most hard metal tools continue to be uncoated for quite some time.

To make cemented carbides more universal and applicable to machining various engineering materials, tool manufacturers invented hard metals that contained various additives. The progress in CVD processes and the adoption of PVD coating method for cutting tools in the 1980s dramatically changed the world of machining; now most cemented carbides are coated. The addition of this new technology permitted the cemented carbides to focus on cutting specific material groups.

The substrates contained fewer additives; therefore, their structures became more uniform and stable, which further improved control during production.

The temperature of the PVD method, based on vacuum deposition processes such as sputtering, evaporation, cathodic arc deposition and others, is approximately twice as low when compared to CVD.

This eliminates changes in the metallurgical properties of a carbide substrate. Compared with CVD, PVD coatings are thinner, and therefore perfect for tools that require sharp cutting edges, such as solid carbide endmills or threading tools. However, a line-of-sight character of common PVD techniques can lead to variations in coating thickness. To overcome this problem, the coated tools are mounted on specially designed movable parts of PVD coating equipment. On the other hand, the areas of cutting tools that do not require coating (the shank of a solid drill, for instance) can be masked when PVD methods are applied, while for CVD technology this is problematic.

Combining Coating Methods

Modern technology allows both methods – CVD and PVD – to be combined for coatings of replaceable cutting inserts, as a means of controlling coating properties. **ISCAR**'s carbide grade DT7150 features a tough substrate and a dual MT CVD and TiAlN PVD coating. This was originally developed to improve the productive machining of special-purpose hard cast iron.

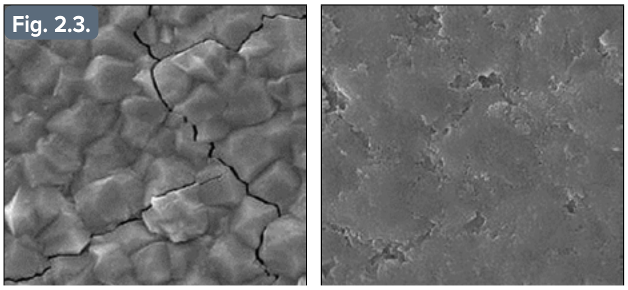
Reducing the risk of negatively affecting the carbide microstructure changes with CVD method – MT CVD ("MT" stands for medium or moderate temperature). It utilizes lower temperatures – around 800°C (1470° F).

Post-Coating Treatment

Smoothing a coated face decreases the coefficient of friction improving the anti-friction properties of a coating. This diminishes adhesive wear of a cutting tool that is caused by welding of removed material to the face due to high temperature in the cutting zone. Therefore, the smoothing action that prolongs tool life is a direct effect of the post-coating treatment.

PVD coatings show a tendency to compression stresses that improve cracking resistance. On the other hand, in CVD coatings, due to different thermal-expansion coefficients of coating layer materials and a carbide substrate, tensile stresses, which contribute to crack formation, take place. Post-coating treatments are focused on overcoming this problem. Initially, applying mechanochemical post coating treatment methods, which are based on blasting and brushing, has resulted in significantly reduced tensile stresses to decrease fracturing (Fig. 2.3). The advance in post-coating treatment technology has made the treatment process more controllable and has even enabled producing compression stresses instead the tensile stresses.

Fig. 2.3.



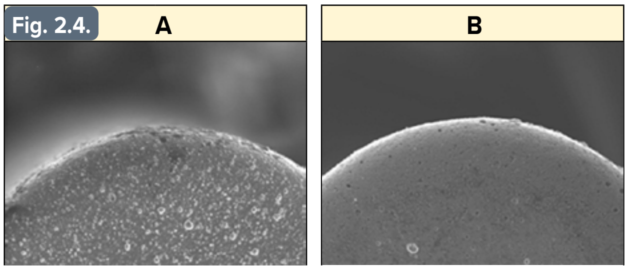
SEM image of ISCAR's CVD coating surface before (left) and after (right) a post-coating treatment.

The microgeometry of a PVD arc coated surface features droplets that are built in a coating layer. The droplets negatively affect surface quality and increase the coating friction ratio. When cutting, a chip flow draws the droplets out producing dimples, which reduce coating thermal insulating capabilities shortening tool life. Post-coating treatments that smoothen a coating surface make the surface uniform to reduce the negative impact of droplets (Fig. 2.4).

Droplets

For a better understanding of the droplet phenomenon, let's imagine common spray painting using an aerosol can. The process can produce a few droplets here and there on a painted surface.

Fig. 2.4.



The effect of ISCAR's post-coating treatment on a PVD coated surface: A – untreated surface, B – treated surface (SEM image).

Hence, applying post-coating technologies considerably reduces and even removes unwanted defects and results in increased tool life of a coated hard metal and greater productivity.

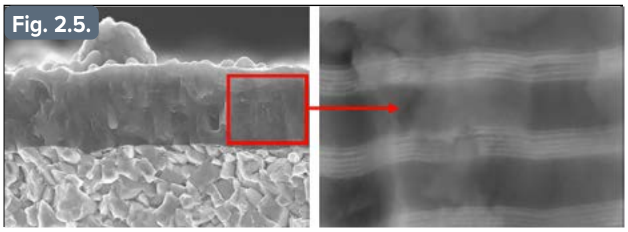
SUMOTEC

SUMOTEC is a post-coating technology, which was developed by **ISCAR** in the early 21st century. Introducing SUMO TEC has resulted in considerably improved tool life for both CVD- and PVD-coated carbide inserts.

Nanolayered Coatings

PVD coatings, which were introduced in the late 1980s, performed a gigantic step in overcoming the complex problems that prevented progress within the field of nanotechnology. PVD coatings brought a new class of wear-resistant nanolayered coatings. Such coatings (Fig. 2.5) that are a combination of layers having a thickness of up to 50 nanometers (2 microinch), demonstrate significant increases in the strength of the coating compared to conventional methods.

Fig. 2.5.



PVD coating of ISCAR's carbide grade IC807 features a nanolayered structure – SEM image.

Carbide Grade

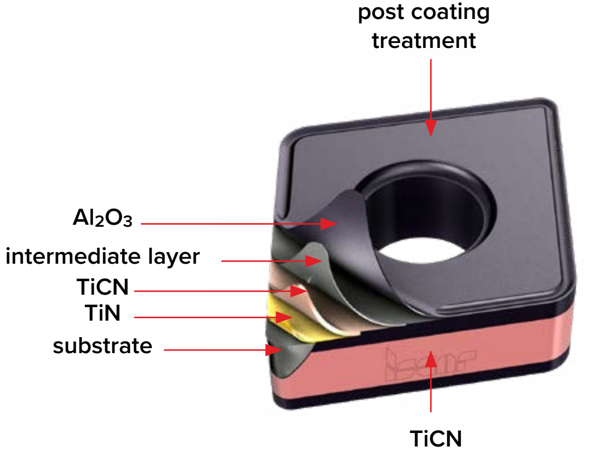
A combination of cemented carbide, coating and post-coating treatment produces a carbide grade. Only one of these components - the cemented carbide, a composite material comprising hard carbide particles that are cemented by binding metal - is the necessary element of the grade. The others are optional. Therefore, the term "cemented carbide" can refer to both the substrate of a coated grade and to an uncoated grade.

Coating Bottom Line

Coating materials have higher microhardness than tungsten carbide. In cutting tools, introducing coatings has changed a natural relation between hardness and toughness of hard metals. When coated, a tungsten carbide demonstrates higher wear resistance when compared to the uncoated carbide of the same toughness level. Hence, coating facilitates changing physical and mechanical parameters of tungsten carbide, which determine performance data. In addition, coating technology has enabled optimizing cutting capabilities of hard metals to machine specific groups of engineering materials by, for example, improving resistance to abrasion, diffusion, or oxidation. This has resulted in considerable increases in both cutting speed and productivity.

Wear resistant coatings have found use in not only carbide tools but other cutting materials. For instance, PVD coated HSS tools are common today.

Fig. 2.6.



ISCAR's carbide grade IC6025, which is intended for indexable turning inserts, features multilayer MT CVD coating and post-coating treatment.

Cermets

The word "cermet" implies made from "ceramic" and "metal". It designates an artificial composite material usually manufactured by powder metallurgy technology. Introducing cermets in cutting tool manufacturing advances economical alternatives to tungsten and cobalt in typical hard metals. Cutting tool cermet, a ceramic with a metal binder, is a type of cemented carbide where hard particles are composed mainly by titanium-based compounds, such as titanium nitride (TiN), titanium carbon nitride (TiCN), titanium carbide (TiC) instead of the tungsten carbides commonly used in cutting tools. The binder metals are usually nickel, molybdenum, and cobalt. Cermets, as well as tungsten carbides, may integrate wear-resistant coatings. When compared with tungsten carbides, cermet has higher resistance to abrasive and oxidation wear, but its toughness is considerably less. In addition, cermet is very sensitive to thermal load. In contrast with cemented carbides, the application field of cermets is not so broad. Cermets are used mainly for obtaining good surface quality.

Ceramics

When compared with cemented carbides, ceramics possess considerably higher hot hardness and chemical inertness. This means that ceramics ensure much greater cutting speeds and eliminate diffusion wear. Ceramics have lower crack resistance – this feature emphasizes the importance of cutting-edge preparation as a factor of successful machining.

There are two main types of ceramics:

- based on aluminum oxide or alumina (Al_2O_3)
- based on silicon nitride (Si_3N_4)

Aluminum oxide based ceramics include pure ("oxide" or "white"), mixed ("black"), and reinforced ceramics.

Pure ceramics are represented by alumina usually with a small addition of zirconia oxide (ZrO_2) to improve toughness.

Ceramic Whiskers

In metalworking shop talk, whisker-reinforced ceramics are often referred to as "whiskers".

In mixed ceramics, adding titanium carbide (TiC) or titanium nitride (TiN) to alumina increases ceramic hardness and improves resistance to thermal shock. The ceramic color becomes black or dark brown.

Whisker-reinforced or "whisker" ceramics are aluminum oxide based ceramics that are reinforced by uniformly dispersed silicon carbide (SiC) whiskers. Whisker ceramics have higher hardness and strength compared to unreinforced alumina based ceramics, and this improves cutting performance.

Cutting Ceramics

As cutting materials, ceramics lie between cemented carbides and super hard materials such as polycrystalline diamond (PCD) and cubic boron nitride (CBN), according to their toughness-hardness characteristics.

Silicon nitride-based ceramics (silicon-nitride ceramics) can be divided into several types, according to content, mechanical properties, and production technology. As contrasted with aluminum oxide based ceramics, silicon nitride based ceramics are tougher and feature increased resistance to thermal shock. However, Si_3N_4-based ceramics are sensitive enough to diffusion wear when compared with Al_2O_3-ceramics. Therefore, applying silicon-nitride ceramics to cutting some materials, such as steel, is limited.

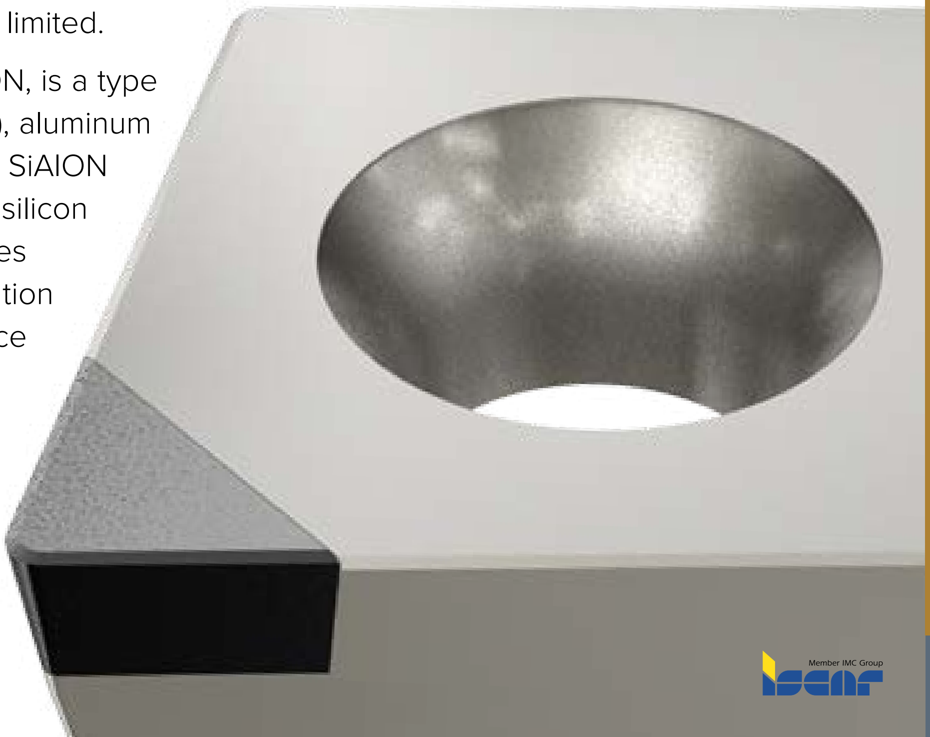
Sialon or, more accurately, SiAlON, is a type of ceramic comprising silicon (Si), aluminum (Al), oxygen (O) and nitrogen (N). SiAlON may be considered as a type of silicon nitride based ceramic but features less toughness and higher oxidation resistance. It is simpler to produce SiAlON than to produce other silicon nitride based ceramics.

Cubic Boron Nitride (CBN, cBN)

Cubic boron nitride (CBN, cBN), a man-made synthesized material, is second only to diamond in hardness but features high thermal shock resistance and high chemical resistance. An important functional advantage of CBN as a cutting material is its low friction ratio.

CBN or PCBN

Both CBN and PCBN relate to Boron Nitride (BN) - a polymorph material formed by two chemical elements. Boron Nitride exists in different crystal structures. One is cubic and the BN in this structure is Cubic Boron Nitride (CBN, cBN).
As a cutting tool material, CBN is used as a polycrystalline compound, where CBN particles and an added binder are sintered together. The material produced is "Polycrystalline CBN" or simply "PCBN" ("PcBN"). The percentage of CBN can vary in different PCBN grades. In the context of cutting tools, the commonly used abbreviations "CBN" and "PCBN" may be considered as synonyms.



CBN grades differ in grain size, structure, and additions. Depending on the CBN percentage there are grades with a high (85% and more) and low (around 55%) content of cubic boron nitride. The other additions in a grade composition are hard ceramic components such as titanium nitride (TiN) and titanium carbide (TiC). The growth of the CBN percentage in a grade increases thermal conductivity. High- and low CBN content grades differ in cutting capabilities and therefore, in applications according to the type of machined materials. In CBN tools, optimized cutting edge preparation depending on the machined material type is extremely important for effective cutting action.

Diamond

Diamond, the hardest known material, is one of the forms of carbon. In cutting tools, both forms of diamond, natural and synthetic (man-made), are used. Despite the high hardness (4-5 times more when compared to tungsten carbide), diamond has significantly less toughness. Therefore, diamond is suitable for fine cuts with small mechanical load. Excellent abrasion resistance, high heat conductivity and low friction ratio provide high-grade surface finish and ultimate tool life. However, diamond is not suitable for machining ferrous metals because the chemical reactions with iron at high temperatures, which occur in such a case, result in loss of cutting capability.

Diamond- and Diamond-Like Carbon Coatings

Diamond is not only the hardest cutting material but also a coating element. Everyone, who has ever been a locksmith, will surely remember a diamond file, a hand tool that enables filing very hard materials such as hard steel, ceramics, or glass. A common nail file for shaping nails – the usual attribute of a manicure set – is a diamond file.

Similarly, there are tools with the cutting part from cemented carbide, which is CVD coated by a film of diamond particles.

In diamond-like carbon (DLC) coating, the cutting part of a tool is coated by amorphous carbon, which features some properties of diamond. DLC coating is also referred to as hard carbon coating.

Most cutting tools utilize synthetic polycrystalline diamond (PCD), which is sintered at high temperatures and high pressure. If natural diamond is a monocrystal, PCD consists of particles of many ferruminated diamond crystals. PCD grades are divided into fine, medium, and coarse according to grain size. Decreasing the grain size results in rather higher wear resistance, while the size growth slightly increases impact strength. The hardness of PCD is very close to that of natural diamond.

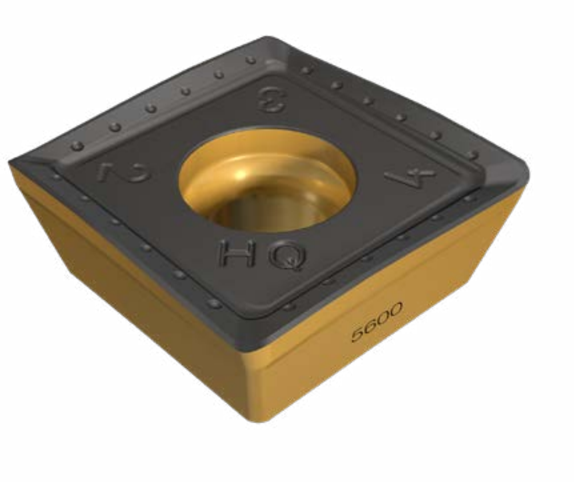
The monocrystalline structure of natural diamond provides a perfect cutting edge contour without any junction points. Such a feature is a serious advantage to ensure an extremely high, "mirror like" surface finish that is required in some applications, for example, when machining crucial parts of optic equipment. In contrast, a PCD cutting edge is formed by various crystals. This produces appropriate junctions on the edge, and every junction produces its own trace on a machined surface.

Cutting Material Grade Designation

Tool manufacturers use their own code systems for designating cutting material grades. Usually, a grade designation contains a combination of letters and numbers. The letters are often associated with the manufacturer or the main group of application, and the numbers may relate to a production version, a grade characteristic (the grain size, for example), etc.

By way of illustration, the letters in **ISCAR**'s system of designating cutting material grades indicate the following material group:
IB – cubic boron nitride (CBN),
IC – cemented carbide and cermet,
ID – polycrystalline diamond (PCD),
IS – ceramics,
DT – cemented carbide with
dual (CVD+PVD) coating.

Fig. 2.7.



A cutting material grade designation or its details are usually marked on tool elements. In the picture: numbers "5600" of ISCAR's IC5600 carbide grade are printed on the side surface of an indexable insert while letters "IC" are omitted

Cutting Edge Conditions

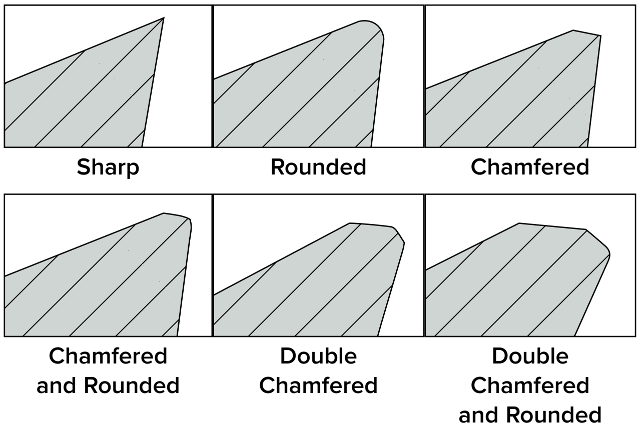
The shape of the rake face, the rake and the clearance angles are key elements of the cutting edge macro geometry. There is one more factor, which has significant impact on a cutting action. This is a cutting edge micro geometry: a microscopic-scale condition of the edge. This cutting edge condition is also referred to as cutting edge preparation cutting edge condition is also referred to as a cutting edge preparation.

An optimized edge preparation depends on the cutting material, the cutting geometry, the material to be machined, and the type of machining. Cutting materials are hard and brittle. Therefore, their sharp edge tends to chip, and appropriate edge preparation significantly reduces this phenomenon. Also, in many cases edge preparation is necessary to eliminate cutting edge flaws because of tool manufacturing technology. For example, a ground cutting edge may feature numerous flakes - very small chips that are viewed under magnification – that should be removed or reduced by edge preparation processes.

Principally, from a micro geometry point of view, a cutting edge may be rounded, chamfered, combined of the mentioned, and sharp. The cutting edge conditions are specified by various standards, for example, ISO 1832 (Fig. 3.1).

A rounded edge is also referred to as "honed edge" and edge rounding – "honing". A chamfer on the cutting edge provides an appropriate rake angle in the chamfer area. If this angle is negative, the chamfer is called "T-land" a or "negative land". T-land reinforces a cutting edge that improves the edge resistance to impact load, however, on the other hand, the T-land increases cutting forces.

Fig. 3.1.



Sharp | **Rounded** | **Chamfered**

Chamfered and Rounded | **Double Chamfered** | **Double Chamfered and Rounded**

Cutting edge conditions according to ISO 1832 standard.

Avoid Misunderstanding: Honing

In cutting tools, a rounded cutting edge is referred to as a "honed edge", and edge rounding to as "honing". Not to be confused with the honing – a fine machining process that is performed with the use of a special abrasive tool called "hone"!

The cutting edge microgeometry is essential for cutting performance and tool life, thus optimal cutting edge conditions is an area of serious scientific research and technological improvements. One example is a honed edge. Common honing values are in the range of 0.02-0.08 mm (.0008-.003") but if needed, they may exceed these limits. However, the final form of edge rounding depends on the mutual arrangement of honed sections on the rake face and flank of a tool. These sections are determined by measurable parameters $S\gamma$ and $S\alpha$ accordingly, and their ratio can specify the rounding shape. The ratio is referred to as the cutting edge form factor or K-factor, which reflects rounding symmetricalness:

$$K = S\gamma / S\alpha \tag{3.1}$$

Depending on the ratio value the honed edge tends to the rake or the flank (Fig. 3.2). K=1 characterizes a honed cutting edge wholly rounded by radius that relates to the symmetrical micro geometry. For K≠1 the edge features an oval-shaped profile, and this asymmetrical edge micro geometry can be represented by two types:

- waterfall with K<1
- trumpet (reverse waterfall) with K>1

Avoid Misunderstanding: K-Factor

K-factor may also be referred to as "specific power factor" (or "power unit factor"). Usually, this is the power (in kW, hp etc.), which is needed to remove a unit volume of a specific material (in cm^3, in^3 for example) by cutting. However, in some sources such a factor is determined in the opposite way, and means the material volume that is removed by cutting when a unit power is applied.

Like finding optimal cutting edge conditions, choosing a more suitable form for a honed edge is a function of various factors. Limitations of available technological equipment in combination with the complexity of a tool shape can be a serious obstacle to ensure the optimal shape of an edge practically. Also, it should be noted that, in general, a waterfall-shape edge is prone to face wear on the tool rake, while an edge with trumpet shape is predisposed to flank wear. To summarize, a decision regarding the type of honed edge requires considering quite a few aspects. The symmetrical and the waterfall shapes are the most common today.

In addition to functional performance, cutting edge rounding is directly relevant to tool manufacturing because edge honing intersects with coating processes. Coating materials are prone to accumulate on a sharp edge, forming a sort of buildup. Consequently, edge honing, which guards against this undesirable factor, is considered as a necessary operation prior to coating.

To provide required micro geometry, various mechanical and thermal technology methods such as drag finishing, brushing, dry and wet micro blasting, diamond brush polishing, grinding, electro erosion etc. are applied.

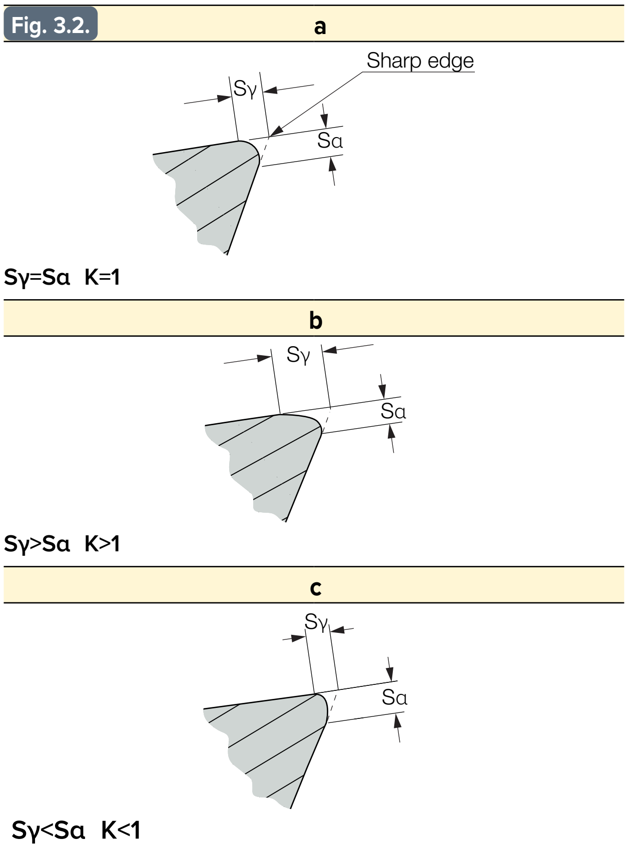


Fig. 3.2.

a) **$S\gamma = S\alpha$ $K=1$**

b) **$S\gamma > S\alpha$ $K>1$**

c) **$S\gamma < S\alpha$ $K<1$**

Honed cutting edge types and K-factor:
a) symmetrical honing, edge rounded by radius,
b) asymmetrical honing, trumpet-shape edge,
c) asymmetrical honing, waterfall-shape edge

Tool Wear

When speaking about product wear, damage, change in sizes, form or mass of the product are implied. Understandably, wear affects the performance and the value of the product. The same approach to wear is true for cutting tools.
Various standards (for example, ISO 3685-1 or ISO 8688-1) interpret tool wear as the change of the cutting part of a tool, which is caused by the gradual loss of cutting material or deformation during machining. Tool wear results from the following factors:

- friction
- mechanical load
- thermal load
- chemical inter actionin cutting, these factors often combine with each other that lead to a synergistic effect.

There are several main mechanisms of tool wear.

Abrasive wear leads to abrasion of tool surface. The major reason for this wear is the heterogeneous (nonuniform) metallurgical structure of a workpiece material, featuring particles of different hardness. As a result, a cutting tool is exposed to impact like abrasive machining (a kind of “grinding” or “filing”), which causes the removal of cutting material from the tool.

Mechanical wear occurs due to excessive mechanical loading (both static and dynamic) that can lead to destruction of a cutting edge. The cutting edge strength has a natural limit, and as soon as the stresses arising in the edge exceed a permissible value, the destruction begins. Interrupted cutting increases the impact load, and accelerates the destruction.

At certain values of cutting speed and temperature, tool areas have a tendency of welding together with particles of the material, removed by cutting. As a result, a build-up edge (BUE) appears on the tool surfaces of the cutting wedge. This adhesion wear mechanism formed foreign reinforced material, which becomes the cutting edge with changed cutting geometry.

In cutting, when the temperature in the cutting zone is high, the oxygen, which is in the air, reacts with the upper layer of cutting material. The oxidation process is intensified in the area that determines the width of chips - i.e., at the distance of cutting depth from the tip of the edge where the cutting edge and the machined material are separated. Oxidation wear is often evident as a notch on the cutting edge.

High temperature cutting zone contributes to a mutual diffusion of material particles of the tool, the machined workpiece, and the formed chips. This changes the composition and metallurgical properties of the surface layers of a cutting material and diminishes cutting capabilities. The intensity of this diffusion wear process mainly depends on the chemical constitution of the cutting- and the workpiece materials. Generally, diffusion wear and oxidation wear relate to chemical wear.

The characteristics of a machining operation stipulate tool wear mechanisms. The main from them are:

- cutting material and workpiece material
- cutting data (cutting speed, feed, depth of cut, width of cut)
- cutting geometry
- coolant and cooling method

Tool Wear - Types of Tool Deterioration

Tool wear, which reflects the wear mechanisms, appears in various forms on different elements of a cutting part. Understanding these forms, their analysis and appropriate conclusions are crucial components to optimize a tool application, control cutting data and prolong tool life. Ensuring machining conditions provide ideal wear development is an important factor for effective cutting tool performance. The types of tool deterioration are well described and classified in technical literature and various standards and norms.

Flank Wear

Based on the name, this wear (Fig. 4.1) develops on the flank of a tool.

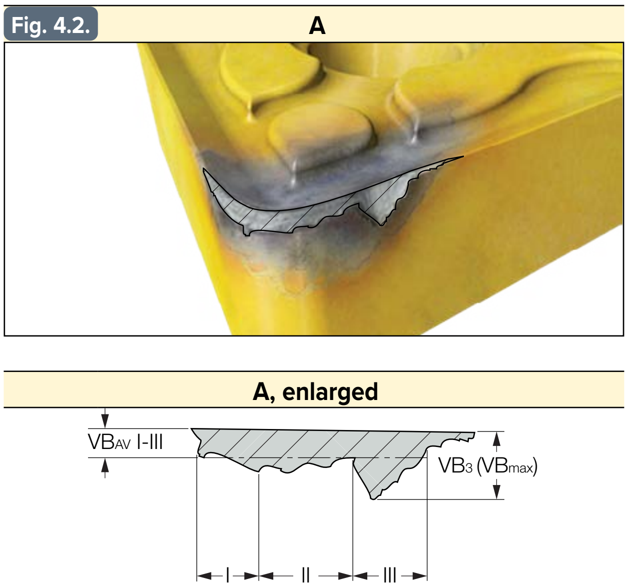
Fig. 4.1.

Flank wear

Flank wear is measured by the wear width – the width of wear marks on a flank, usually designated as VB. The number after letters "VB" indicates a flank area that relates to the measured width. Depending on the mark profile, flank wear can be specified as uniform, non-uniform, and localized (areas I, II, and III in Fig. 4.2 correspondingly). When specifying a wear width, often the average value for different flank areas is used (VB_{AV} I-III in Fig. 4.2).

Normally, flank wear is considered "natural" and ideal if it is uniform, which is always preferred when designing a tool. The major reason for uniform and non-uniform flank wear is abrasion. Studying of flank wear results in important forecasting: the prediction of tool life and determining the change interval for a worn tool or cutting edge.

Fig. 4.2.



Flank wear types

Localized flank wear, which is known as notch wear, appears as a notch or groove (the red oval in Fig. 4.3). This wear mode is caused by adhesive and oxidation wear mechanisms.

Fig. 4.3.

Local flank (notch) wear

Tool Language Studies Indicating Wear Parameters

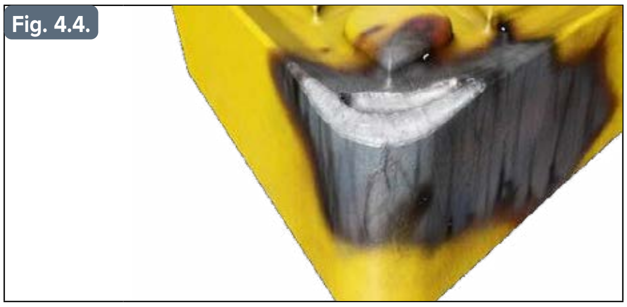
In cutting tool terminology, letters VB designate a flank wear width. Everything seems to suggest that their origin is from a German word "Verschleißmarkenbreite", which means "the width of a wear mark". Also, the parameter VG specifies a maximum wear that relates to "Verschleißgrenze" or "wear limit".

Face Wear

Face wear is connected mainly with abrasive and diffusion wear mechanisms. The chip, which is formed during a cutting process, contacts the rake face of a tool, and causes fretting of the face.

Typically, face wear appears as crater wear (Fig. 4.4) that features a crater, which is formed from the tool cutting edge.

Fig. 4.4.



Face wear in the form of crater wear

If the crater breaks through the wall separating it from the edge and opens on the tool flank, then this type of face wear is defined as stair-formed wear.

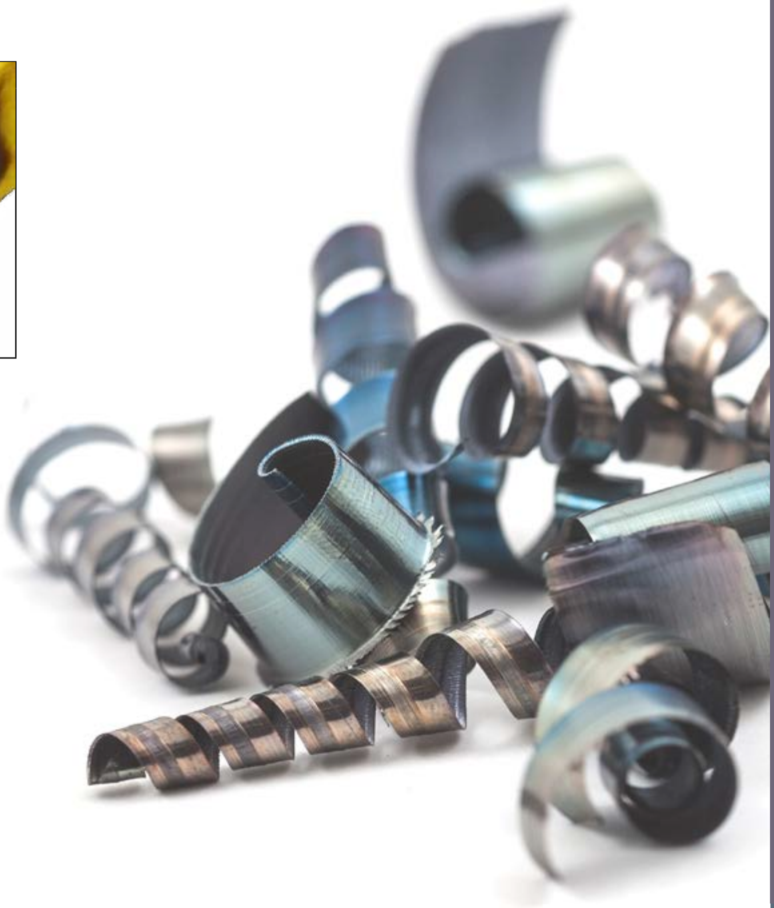
Cutting Edge Chipping

As a result of fatigue action due to intensive mechanical loading, a cutting edge may begin to chip (Fig. 4.5). In fact, the destruction of the edge begins before its wear. Interrupted cutting intensifies the edge tendency to chip. Further increase in load can lead to brittle fracture of the edge and loss of cutting ability.

Like flank wear, chipping of the cutting edge is divided into uniform, non-uniform, and localized.

Fig. 4.5.

Chipping of the cutting edge



Cracks

Cracks indicate cutting material fatigue. However, there are multiple types of fatigue wear to consider, as cracks vary in their types and, accordingly, shapes. The cracks, which are formed on both the face and the flank of a tool almost perpendicular to the cutting edge, indicate the result of variable thermal loading while the cracks on the face or the flank that are roughly parallel to the cutting edge point to fatigue failure due to mechanical loading. Thermal cracks are often named comb cracks (Fig. 4.6).

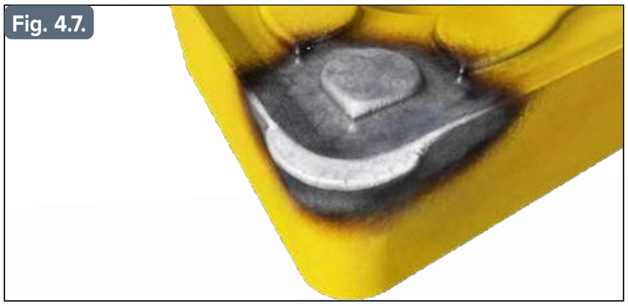
Fig. 4.6.

Comb cracks

Plastic Deformation

Plastic deformation is a result of combined mechanical and thermal loads on the tool cutting edge. This type of tool deterioration features changing the tool cutting part profile without loss of the tool material.

Fig. 4.7.



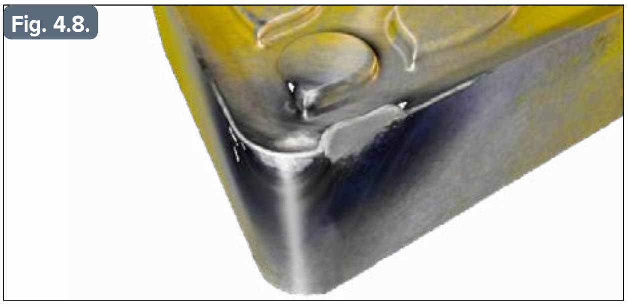
Plastic deformation

The tool characteristics such as cutting geometry and cutting material largely determine the resistance to plastic deformation.

Build-Up Edge (BUE)

Build-up edge (BUE) appears under certain cutting conditions, and machined material sticks to the tool face (Fig. 4.8). The hardness of BUE is much higher than the hardness of the workpiece material, and therefore becomes a part of the tool's cutting edge. Obviously, this edge transformation changes cutting geometry and affects performance. During machining, chip flow can remove a particular part of the build-up edge, while the other part can penetrate the workpiece material. These processes lead to spalling of the cutting edge, and further BUE development may cause failure.

Fig. 4.8.



Build-up edge (BUE)

Catastrophic Failure

Catastrophic failure of a cutting edge (Fig. 4.9) means the complete edge fault.

Fig. 4.9.

Catastrophic failure (fracture) of cutting edge

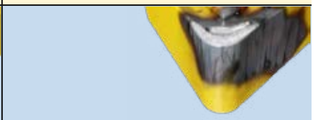
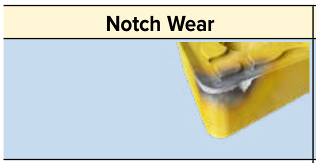
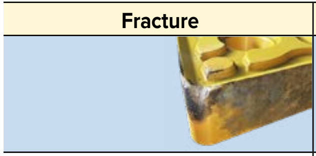
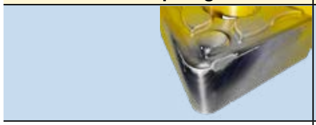
Table 4.1 summarizes the main types of tool deterioration and wear mechanisms, and Fig. 4.10 provides guidelines for possible remedy.

Table 4.1.

Tool Deterioration		Main Wear Mechanism Types
flank wear	uniform	abrasive
	non-uniform	
	localized (notch)	adhesive and oxidation
face wear	crater	abrasive and diffusion
	stair-formed	
chipping fo the cutting edge	unimorm	mechanical
	non-uniform	
	localized	
cracks	thermal (comb)	fatigue due to variable thermal loading
	mechanical	fatigue due to mechanical loading
build-up edge (BUE)		adhesive

Tool deterioration and wear mechanisms

Fig. 4.10.

Flank Wear	Crater Wear
	
Possible Causes: • Cutting speed too high • Heat development too high • Carbide grade too low-wear	**Possible Causes:** • Cutting speed too high • Heat development too high • Feed too low
Possible Remedy: • Reduce cutting speed • Harder carbide grade • Smaller lead angle	**Possible Remedy:** • Reduce cutting speed • Harder carbide grade • Increase feed
Notch Wear	**Chipping**
	
Possible Causes: • Cutting speed too high • Carbide grade too low-wear	**Possible Causes:** • Carbide grade too wear-resistant • Cutting edge too positive • Formation of edge
Possible Remedy: • Reduce cutting speed • Harder carbide grade • Vary cutting depth	**Possible Remedy:** • Tougher carbide grade • Higher cutting speed • Choice of more stable cutting edge
Fracture	**Comb Cracks**
	
Possible Causes: • Cutting edge too positive • Carbide grade too rigid • Vibrations	**Possible Causes:** • Heat alternating voltage • Strongly interrupted cut • Thermal shock through coolant
Possible Remedy: • Reduce cutting depth • Lower feed • More stable cutting wedge	**Possible Remedy:** • Choice of tougher carbide grade • Improved coolant supply • Dry machining for interrupted cuts
Build-Up Edge	**Plastic Deformation**
	
Possible Causes: • Low cutting speed • Feed too low • Cutting edge too negative	**Possible Causes:** • Feed too high • Cutting speed too high • Carbide grade too tough
Possible Remedy: • High cutting speed • Increase feed • Smooth, positive cutting edge	**Possible Remedy:** • Reduce cutting speed • Reduce feed • Choice of harder carbide grade

Tool wear and possible remedy

Control and regulation of tool wear

There are various standards, norms, company instructions and other technical documents that specify wear types and their codes, acceptable deteriorations, maximum wear parameters and required equipment for wear measuring and inspection, as an example, requirements of ISO 3685 and ISO 8688 standards.

Setting Tool Wear Standards and Norms; Tool Wear Value Examples

Tool wear values are specified with respect to the wear type. They may be expressed by maximum numbers of a flank wear or crater dimensions, distance between cracks, number of flakes per unit of a cutting edge and so on. Some forms of deteriorations are regarded as not suitable for determining tool life and may be used only in extraordinary circumstances.

Numerical values of maximum tool wear depend on a cutting tool type and a deterioration mode. Moreover, the magnitudes may vary as a function of specific machining conditions.

For example, in laboratory testing of milling cutters carrying indexable carbide inserts, maximal non-uniform flank wear is generally considered as 0.3-0.8 mm (.012-.0315″) depending on the cutter diameter. However, on the shop floor cutters are used with wear values of up to 1.5 mm and even more.

Local flank wear, the measured wear parameter VB_3 in test milling does not exceed 1.2-1.5 mm (.047-.06″).

Maximum wear definition is crucial for determining tool life and cutting time after which a tool cannot be used.

Fig. 4.11 shows wear development in normal cutting conditions.
Several stages can be associated with a wear development process:

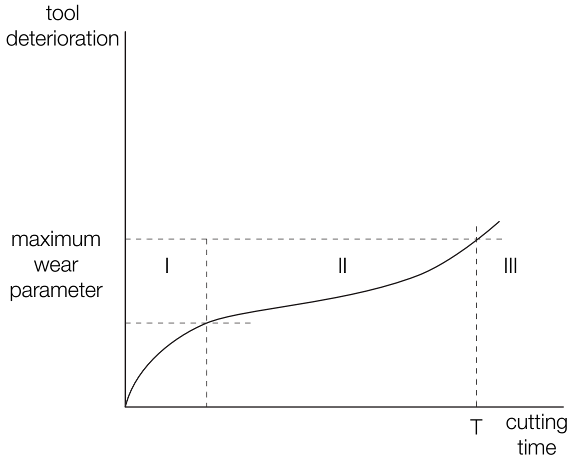
I – initial wear that features rapid wear development

II – uniform increase in wear until the critical value of a deterioration is reached

III - sharp increase in wear resulting in failure.

The critical value of a deterioration, which characterizes maximum wear, corresponds to the tool life. A few factors have an impact on tool life, and among them the most important are cutting conditions and machinability of a workpiece material.

Fig. 4.11.



Stages of tool wear development

There are direct and indirect methods for measuring and inspection of tool wear.

Direct methods use microscopes, coordinate measuring machines, digital image processing etc.

Indirect methods are based on analyzing end machining results (such as surface finish or accuracy) and operation characteristics (power consumption, cutting force, vibration etc.). In addition, these methods also include visual inspection; appearing noise; checking a cutting edge by a fingernail, which, despite safety requirements, is still common and even total tool failure.

Fig. 4.12.

Checking tool wear by use of computerized microscope in ISCAR's Technical Center

Wear Detection by ... Coating

In multi-layer coating of indexable inserts, the top coating layer, in addition to the layer function in wear protection, can play one more important role – wear detection. Modern coating technologies utilize a colored wear-indicator top coating layer. During cutting operations, distinct visible trails remain on the layer, and this greatly contributes to early wear detection.

Engineering Materials

Machinability, Cutting Tool Material Applicability

Cutting tools are intended for machining engineering materials – the materials which are used for producing numerous structures and their elements, machine parts and other components. Engineering materials include ferrous and non-ferrous metals, composites and plastics, ceramics etc. The materials vary in their physical and mechanical properties . Some materials are easier to cut, others are more difficult. Machinability of a material is the material property that reflects how easily this material can be machined, the ability of the material to be cut under set machining data. There are various factors that impact material machinability, such as the material chemistry, hardness, fabrication methods etc. Machinability can be represented through the machinability index (factor, rating, ratio). This parameter shows how easy (or hard) a material is cut when compared to a basic material. Today, the machinability index is determined for most engineering materials. Finding the index relates to a myriad of test data and its analysis.

Assume that we chose a material and will machine it by a tool of suitable cutting geometry to define the cutting speed, which provides predetermined tool life and ensures acceptable surface finish. Let's agree to consider this material as a reference, and the machinability index of the reference material as 100% (or 1).

Then, we will repeat the same test for another material, and will find the appropriate cutting speed that facilitates the same tool life. The machinability index for the tested material will be the ratio of the found cutting speed to the cutting speed of the reference material:

$$K_m = v_{cm}/v_{cr}$$

in terms of numbers, (5.1a)

or

$$K_m\% = v_{cm}/v_{cr} \times 100\%$$

in percentage terms (5.1b)

where

K_m and $K_m\%$ – a material machinability index (factor, rating, ratio) in terms of numbers or percentage

v_{cr} – the cutting speed for machining a material, chosen as a reference, for the tool life T

v_{cm} – the cutting speed, at which the same tool life T is observed.

Using this method, the machinability of different engineering materials can be estimated. For example, if considering machinability of free cutting steel as 100%, the averaged machinability rating for some groups of engineering materials is assumed to be equivalent to the data in Table 5.1.

Table 5.1

Material	Machinability %
non-alloy free cutting steel	100
low alloy steel, annealedl	60
high alloy steel, annealedl	50
austenitic stainless steel, annealedl	40
commercially pure titanium	43
titatium Ti-6Al-4V, annealedl	25

Machinability rating of some material groups

Smaller values of K_m feature materials with worse machinability, because cutting these materials is more difficult.

Free Cutting Steel

Free cutting (or free machining) steel is a collective name for carbon steels that feature the increased content of Sulphur as contrast with common carbon steels with similar Carbon percentage. Such increasing results for better machinability and chip control.

The rating values in Table 5.1 is too general and is suitable for common data rather than practical analysis, which requires more detailed specification. There are sources of machinability rating information that consider various materials according to their designation and delivery condition.

According to AISI, the reference material for rating is free cutting steel 1212 (~DIN W.-Nr. 1.0711 with HB 160 hardness. The machinability index K_m% of this steel is accepted as 100% (K_m=1). The results of numerous tests that are performed for materials on one-to-one basis enable evaluating material machinability rating when compared to AISI 1212 steel. The received index values form rating databases that are open to the public. In metal cutting, machinability rating is a material characteristic that has a great practical value.

Example: When machining steel AISI 1212, HB 160, by an indexable milling cutter in a testing laboratory at cutting speed of 190 m/min (625 sfm), a 40-min. tool life per cutting edge is observed.

Estimate the cutting speed for milling low alloy steel AISI 5120 (~DIN W.-Nr. 1.7027) with HB 170...190 hardness by the same cutter, which is needed for the equal tool life if the machinability index of steel AISI 5120 is 0.72.

v_{cr}=190 m/min.

Due to both steels having similar hardness

$v_{c\ 5120} = v_{cr} \times K_m = 190 \times 0.72$
=137 (m/min) [450 sfm]

Engineering Materials and Cutting Tool Material Application

Generally, cutting materials are harder than the material of a machined workpiece. Hence, a cutting material grade is principally suitable for machining various engineering materials. However, in some cases grade usage is beneficial while in others – ineffective. Therefore, a cutting material grade is characterized by a sphere of material application that reflects the type of engineering material to which a tool that is produced from a specific grade, can be applied. Under the ISO 513 standard a sphere of application is referred to as the main group of applications.
According to the standard, each group corresponds to machined materials, and it has its own identification letter and color. For example, group P (blue color) relates to machining steel, M (yellow) – austenitic and duplex stainless steel, K (red) – cast iron etc.

In addition, the standard divides the main group of application into groups of applications, which define the location of a specific cutting material grade in an arbitrary hardness-toughness scale. The location is specified by numbers. Higher numbers indicate an increase in grade toughness, while lower numbers indicate an increase in grade hardness. From a practical standpoint, higher numbers speak about increasing cutting speed, and the lower ones – increasing feed.

This approach enables classifying cutting material grades according to their reasonable applicability to provide appropriate data for grade consumers. Cutting tool manufacturers along with their own designation of the material grade indicate its groups of application, as follows (P10-P25), (M10-M20), or main application groups, if the place for such indicating is limited (Fig. 5.1 and 5.2, highlighted by red oval).

Fig. 5.1.

Grade : IC810

A SUMOTEC PVD coated grade. Optimal choice for milling nodular cast iron at medium to high cutting speeds.

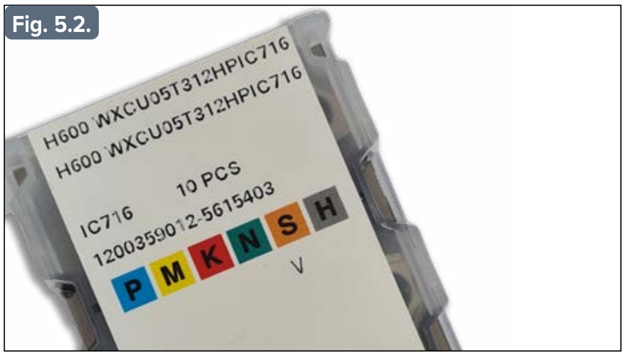
ISO Range - P/M/K	(P15-P30)(K15-K35)
ISO Range - N/S/H	

Grade or Coating Type	PVD
Coating Layers	AlTiCrN+TiN

Find group of specific workpiece material (opens in a new window)

Indicating groups of application for IC810 carbide grades in ISCAR's e-catalog

Fig. 5.2.



Information about the main group of application groups for IC716 carbide grade on an insert packaging box

Tool Language Studies: Identification of Main Groups of Application

ISO adopted the material classification principles that were developed in Germany, and therefore, the origin of the identification letters is in German. For example, the letter "K" relates to the German word «Kurzspanend» (produced short chips), and "H" to "Hart" (hard), just to name a few.

Classification of Engineering Materials

According to the ISO 513 standard, the engineering materials can be divided into groups that referenced to cutting tool applicability. However, the classification, by which materials with different machinability will be collected within a given group, is problematic. Let's go back to Table 5.1. According to the table, the average machinability of different steels varies significantly: machinability of high alloy steel is twice as low when compared to machinability of free cutting steel. From a machinability stand point, defining these steel materials with one group is not sufficienct. Obviously, more detailed material grouping is required.

Cutting tool manufacturers have developed their own systems of engineering material classification to provide the customer with appropriate information about tool application and appropriate cutting data that relate to a specific type of material. Due to modern industrial demands and trends to unify data representation, such systems are getting closer.

ISCAR's approach to classifying engineering materials is based on ISO 513 and VDI 3323 standards. In line with the approach, main groups of applications, which specify classes of machined materials, are divided into material subgroups (Fig. 5.3).

Within the range of a main application group, the subgroups represent the group materials that have different machinability. In the particular case of machining specific materials, assigning the material to any subgroup within the range of an appropriate main group of application enables determining cutting data more precisely.

Non-ISO Applications

ISO 513 standard operates with six main groups of applications that correspond to certain classes of machined materials. At the same time, modern industry has adopted additional engineering materials, which are not mentioned in the standard but are commonly used such as various composite, graphite etc. The new version of VDI 3323 standard group materials, designate 'O' ("other"). Cutting tool manufacturers often maintain the same principle of classification defining "O"- or similar groups as "non-ISO" applications or "non-ISO materials".

Fig. 5.3.

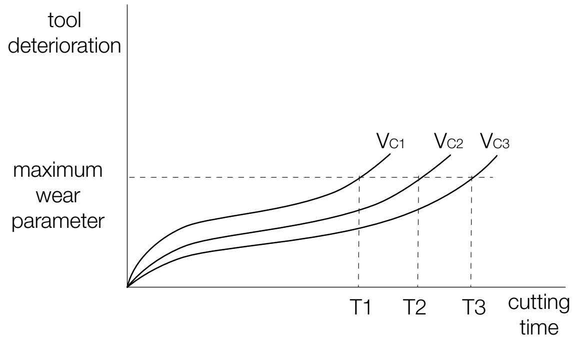
ISO 513		ISCAR Materials Groups, Based on VDI 3323						
Identification Letter	Materials to be Machined	Material Subgroup Description	Structure/ Composition	Application Subgroup (old)	Application Subgroup (new)	Condition	Tensile Strength $[N/mm^2]$	Hardness HB
P	**Steel: All Kinds of Steel and Cast Steel Except Stainless Steel With an Austenitic Structure**	non-alloy steel, free cutting steel	<0.15% C	1	**P1**	annealed	420	125
			<0.45% C	2	**P2**	annealed	650	190
			<0.45% C	3	**P3**	quenched and tempered	850	250
			<0.75% C	4	**P4**	annealed	750	220
			<0.75% C	5	**P5**	quenched and tempered	1000	300
		low alloy and cast steel		6	**P6**	annealed	600	200
				7	**P7**	quenched and tempered	930	275
				8	**P8**		1000	300
				9	**P9**		1200	350
		high alloyed steel, cast steel and tool steel		10	**P10**	annealed	680	200
				11	**P11**	quenched and tempered	1100	325
		bainitic steel, ultra-high-carbon steel			**P12**	baintic tempered	1300	380
		sintered (powder metallurgy) steel			**P13**	HIP product	950	280 (250-340)
		stainless steel and cast steel	ferritic / martensitic	12	**P14**	tempered	680	200
			martensitic	13	**P15**	tempered	820	240
			martensitic		**P16**	precipitation hardened (PH)	1200	350

ISCAR's material group classification (fragment)

Estimating Tool Life

Let's turn again to Fig. 4.11. The graph in the figure reflects a typical wear development when machining material at specific cutting data. Increasing cutting speed, while the other cutting parameters remain the same, intensifies wear growth (Fig. 6.1).

Fig. 6.1.



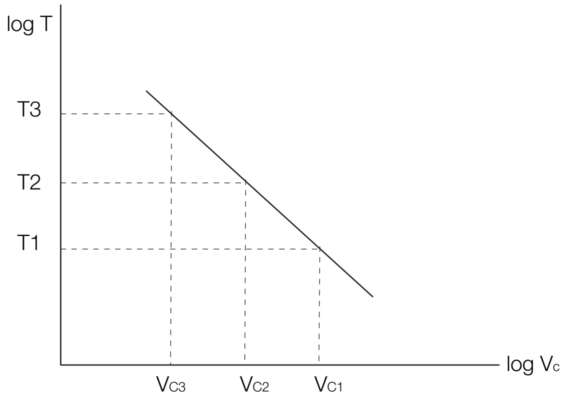
$V_{c1} > V_{c2} > V_{c3}$

tool wear development as function of cutting speed

As mentioned, an acceptable maximum wear parameter relates to tool life - the cutting time after which a tool cannot be used.

In Fig. 6.1, machining at cutting speeds v_{c1}, v_{c2} and v_{c3} provides tool life T1, T2, and T3 correspondingly. The graphic representation of the related tool life-cutting speed in logarithmic coordinates known as vT diagram (Fig. 6.2) illustrates this better.

Fig. 6.2.



vT diagram in logarithmic coordinates

Wear development analysis to predict tool life has started from empirical study. A myriad of tests has enabled creating the curves of wear development for different types of controlled tool deterioration and various cutting speeds.

The first empirical formula for calculating tool life was proposed by F.W. Taylor in the 1900s after numerous tests over many years. Taylor's research launched the beginning for serious studies of tool wear phenomenon and tool life determination. During the tests, Taylor appeared to be the first who distilled a pattern of the wear development and divided into three stages: tool wear increases rapidly, when cutting starts, later its development stabilizes at a further machining phase, and then sharply increases at its third stage until critical wear is reached (Fig. 4.11). Taylor's tool life formula is conveyed as below:

$$v_c \times T^m = C \quad (6.1)$$

where C and m are empirical constants, which depend on cutting and workpiece materials.

Historical Notes: Frederick Winslow Taylor

Frederick Winslow Taylor came down in history as a talented mechanical engineer, a brilliant inventor, the founder of scientific management, and the president of American Society of Mechanical Engineers (ASME). In 1906, F.W. Taylor derived an equation that enabled estimating tool life for varying cutting speed. The derivation of this equation was preceded by 12 years of countless turning tests and analyses of the test results.

Turning in the mentioned stages of wear development, Taylor's formula relates to the second stage, when the wear increases uniformly and gradually. This formula reflects a case of abrasive wear that is observed when machining at cutting speeds within a reasonable range, while the other cutting parameters, such as feed, depth of cut, width of cut, remain unchanged. Also, the formula does not consider the factor of cutting geometry.

Subsequent studies and modelling the wear mechanism led to extended and modified tool life equations that operate varying parameters, empirical coefficients, constants, and exponents. These equations are complicated enough and therefore, more suitable for computerized systems than for quick calculations on the shop floor. An example of the equations, is as follows:

$$v_c \times h^p \times T^m = C \quad (6.2)$$

From Taylor's formula, the equation shows an additional term: equivalent chip thickness h to the power of p. If p is a constant, the equivalent thickness represents a function of feed, depth of cut, and cutting geometry characteristics.

The advance in applied sciences and technology has improved the estimation of tool life to other levels.
Realizing various models in combination with complex calculations on modern computers enables considering various factors, which can affect tool life, and can affect tool life, and substantially improve the accuracy of tool life estimations. At the same time, depending on the specific features of a machining operation, the results of estimation as contrasted with real values shows that some models provide more accurate data, others less. Therefore, precise evaluation of tool life continues to be a central part of ongoing research.

When considering Taylor's formula from today's standpoint, its incompleteness, of course, is beyond doubt. However, this formula served as a starting point for the subsequent searches of equations, which mathematically express the tool life as a function of machining data and tool parameters. Moreover, in some cases, this formula is quite suitable for various calculations even now.

Example: In milling martensitic stainless steel AISI 420 (DIN W.-Nr. 1.4021) at cutting speeds of 150 m/min (492 sfm), the carbide insert tool life is about 40 min per cutting edge. How will tool life change, if the cutting speed will be increased up to 200 m/min (656 sfm)? The other cutting data remains the same.

According to equation (6.1)

$v_{c1}/ v_{c2} = (T_2 / T_1)^m$, and $T_2=T_1\times (v_{c1}/ v_{c2})^{1/m}$.

Constant m for cutting steel by carbide tools is 0.2...0.4. Assume m=0.3.

Hence, $T_2=40\times(150/ 200)^{1/0.3}=15.3$ (min).

For m=0.4 $T_2=40\times(150/ 200)^{1/0.4}=19.5$ (min).

The case study shows that in the milling operation, increasing the cutting speed by 33% reduces tool life approximately 50%.

Cutting Data and Cutting Conditions

Generally, cutting data relates to quantitative variables that determine running a cutting process numerically. Cutting data can also be referred to as cutting parameters. Cutting data consists of:

- cutting speed
- feed
- depth of cut
- width of cut
- machining allowance (stock)
- number of passes
- tool overhang

and additional parameters that depend on specific features of a particular machining operation. For example, these parameters include the spindle speed that characterizes a rotating workpiece or tool in cutting with rotational primary motion; stepover and stepdown, which define a tool displacement in radial and axial directions after every pass in milling.

Even though cutting data is often identified with cutting conditions, its actual value is questionable. Cutting conditions typically include machining factors that are difficult to quantify. For instance, unfavorable cutting conditions relate to a whole set of reasons:

- workpiece with skin (siliceous or slag, for example)
- significantly variable machining allowance that leads to changing the depth of cut
- considerable impact load due to non-uniform machined surface
- surface with high-abrasive inclusions

Unfavorable and Unstable Cutting Conditions

Principally, these two terms are not interchangeable. However, despite the gap in definitions, the conditions are a cause-and-effect relationship and therefore, in some instances, used as synonyms.

In another case, unstable cutting conditions refer to the low stability of a complete machining system (machine tool, workpiece holding fixture, cutting tool, workpiece) due to:

- poor tool and workpiece holding
- high tool overhang
- non-rigid machine tools
- thin-walled workpiece

In characterizing cutting conditions, the terms "heavy" and "heavy-duty" machining are improperly used. Moreover, sometimes these terms are considered mistakenly as synonyms. In principle, “heavy machining" relates to machining large-sized and heavy-weight workpieces on powerful machine tools and refers more to the dimensions and mass of a workpiece. “Heavy-duty” specifies a degree of tool loading and mainly characterizes a mode of machining.

One "Golden Rule" for Manufacturing Engineer, Process Planner and Machinist

"Avoid heavy-duty machining in unfavorable conditions especially if your technological system is unstable!"

To summarize, a general description of cutting conditions depends on various aspects that are difficult to define. In many cases finding cutting data for a specific machining operation is relied upon the user's estimation of cutting conditions related to light, normal and hard.

In primary motion, the points of a tool cutting edge move with appropriate velocities. The maximum velocity is the cutting speed v_c. For example, in drilling a hole by a drill rotating with rotation velocity n, the cutting speed is the circumferential velocity of the point farthest from the drill axis (Fig. 7.1). In fact, the cutting speed is the relative linear speed between the cutting tool and the machined surface of a workpiece.

For a rotary body of diameter R, the circumferential velocity v is defined by the following equation:

$$v=\omega\times R \tag{7.1}$$

where ω - angular velocity in radians per second (s^{-1}).

In machining, rotation velocity in revolutions per minute (RPM, rpm) is used instead of angular velocity in radian per second. The cutting speed is measured in meters per minute (m/min) in metric units and surface feet per minute (SFM, sfm) in US customary and imperial systems, v_c can be calculated as below:

$$v_c=\pi\times d\times n/1000 \text{ m/min} \tag{7.2a}$$

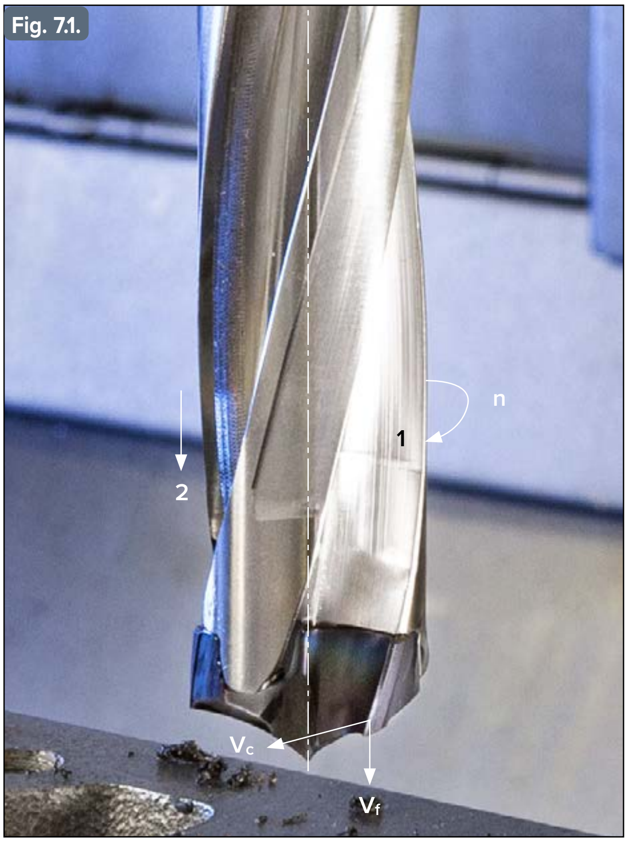
and

$$v_c=\pi\times d\times n/12\approx d\times n/3.82 \text{ sfm} \tag{7.2b}$$

d is the diameter of a rotating tool (in milling, drilling etc.) or workpiece (in turning) that is expressed in mm in equation (7.2a) and in inches in equation (7.2b) .

Because both the rotating tool and the workpiece are mounted on a machine tool spindle – a part intended to transmit torque – rotation velocity n is often referred to as spindle speed.

Fig. 7.1.



Motions and motion velocities in drilling.

1 – primary motion (rotation of the drill with angular velocity n),

2 – feed motion (rectilinear movement of the drill along the drill axis),

v_c – cutting speed, v_f - feed speed.

Another velocity - feed speed v_f – determines a feed motion. In fact, this is the speed at which the tool advances into the workpiece. There is a difference between feed speed and feed. The feed f is determined by the distance, which the point of a cutting edge travels along its path in the feed motion, to the appropriate number of cycles of another cutting motion. One revolution of a tool in milling or a workpiece in turning, stroke in shaping – these are the examples of such a cycle. In the above case of drilling, the cycle is one revolution of a drill.

If the feed corresponds to one revolution of a tool or a workpiece, it is known as feed per revolution and designated also as f or, more rarely, fr. Feed per revolution is a common characteristic for machining processes like turning, drilling, countersinking etc.

Advance in Terminology

In North American countries the term "feed rate" is often used instead of the ISO definition "feed speed". The less common term "advance" is a synonym for "feed": "advance per tooth" and "advance per minute" mean the same as "feed per tooth" and "feed speed" Manufacturers can refer to "feed speed" as "table feed". The original term refers to a classical machine, especially from previous generations, where feed motion was created by movements of the machine table.

In processes like shaping, planing, and slotting, feed motion features double strokes that comprise forward (cutting) and backward (return) strokes. These processes are specified by feed per double stroke (sometimes simply feed per stroke if word "double" is omitted) fs. In many cases, however, feed per double stroke is denoted also by f.

In multi-point (multi-edge) cutting tools having teeth or flutes, feed per tooth f_z is used. This is the feed that corresponds to rotation by one angular pitch of the tool teeth (flutes).

It is easily seen that

$$f=f_z \times z \tag{7.3}$$

where z is the number of tool teeth (flutes).

Further to this

$$v_f=f \times n \tag{7.4}$$

and

$$v_f= f_z \times z \times n \tag{7.5}$$

Example: A reamer carrying exchangeable eight-flute solid carbide heads is applied to reaming a through hole Ø32H7 mm (Ø1.2500H7) in a steel workpiece, which has a hardness value of HRC 51...53. The reamer manufacturer recommends the following initial cutting data: v_c=40 m/min (131 sfm), f_z=0.1 mm/tooth (.004 ipt).
Find spindle speed and feed speed.

Metric system. From equations (7.2a) and (7.5)

$n=1000\times v_c/(\pi /d)= 1000\times 40/(\pi /32)$
$=398$ (rpm). $v_f=f_z\times z\times n$
$= 0.1\times 8\times 398=318.4$ (mm/min)

US customary (imperial) system.
From equations (7.2b) and (7.5)

$n=12\times v_c/(\pi /d)= 12\times 131/(\pi /1.25)=400$ (rpm).
$v_f=f_z\times z\times n= 0.004\times 8\times 400=12.8$ (ipt)

Chip Load or Feed?

In milling, the term "chip load" is commonly considered as a synonym for the term "feed per tooth". This term is more typical for the North American market. However, the correct synonym for "chip load" is "chip thickness". In shop talk "chip load" relates usually to maximum chip thickness.

Depth of cut a_p, one more cutting data parameter, is the distance between machined and unmachined surfaces of a workpiece. This distance is measured towards a normal to the machined surface (Fig. 7.2). Practically, this is the distance that the cutting edge extends into the workpiece material. Depth of cut is often referred to as abbreviature DOC.

Fig. 7.2.

Depth of cut in turning

If D and D1 are diameters of machined and unmachined surfaces accordingly, a_p in external longitudinal turning can be determined as below:

$a_p = (D_1 - D)/2$ **(7.6a)**

In boring (internal turning), the diameter of a machined hole greater than the diameter of an unmachined hole, and the previous equation takes the following form:

$a_p = (D - D_1)/2$ **(7.6b)**

In parting (cut-off), the depth of cut is the same as the cutting edge width.

In grooving, the depth of cut corresponds to the width of the slot, performed by the grooving tool in one pass. If the groove width is equal to the width of a tool cutting edge, and the groove is generated by one pass only, the depth of cut, is the cutting edge width.

In counterboring and reaming (Fig. 7.3), the depth of cut is calculated using the following equation:

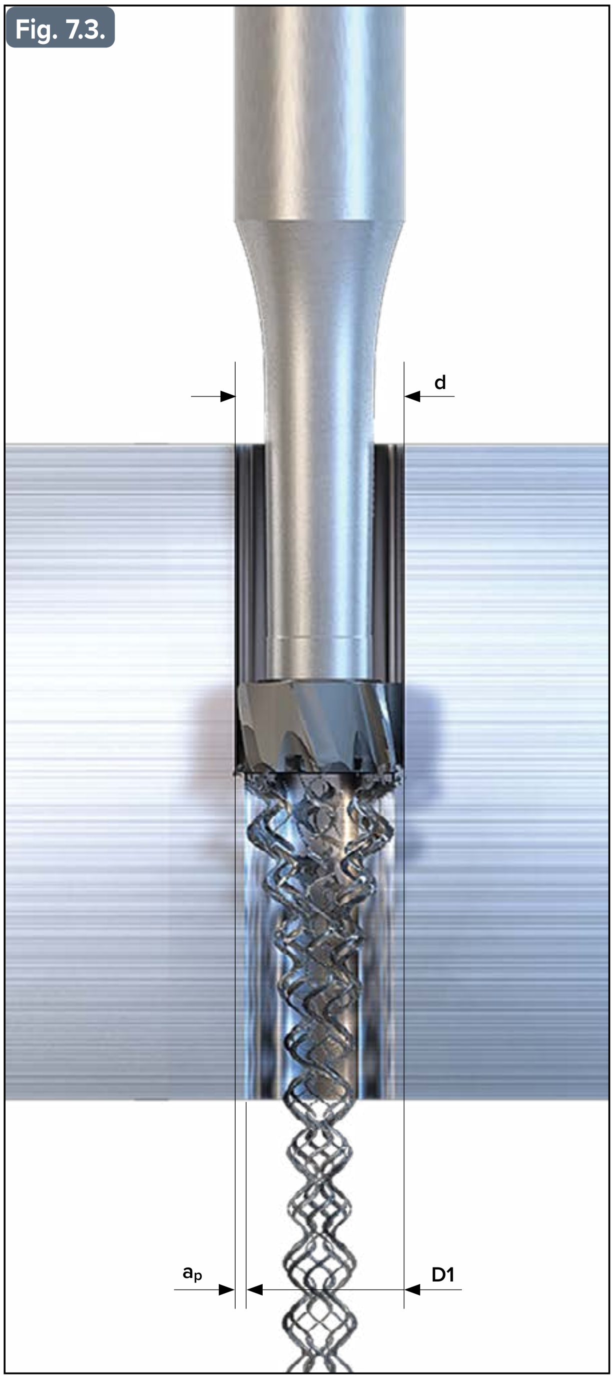
$a_p = (d - D_1)/2$ **(7.6c)**

d is the tool diameter.

A typical milling cutter removes material with two of its surfaces at once: the periphery and the face. Therefore, in milling, the depth of cut relates to two process parameters that are measured in two different directions:

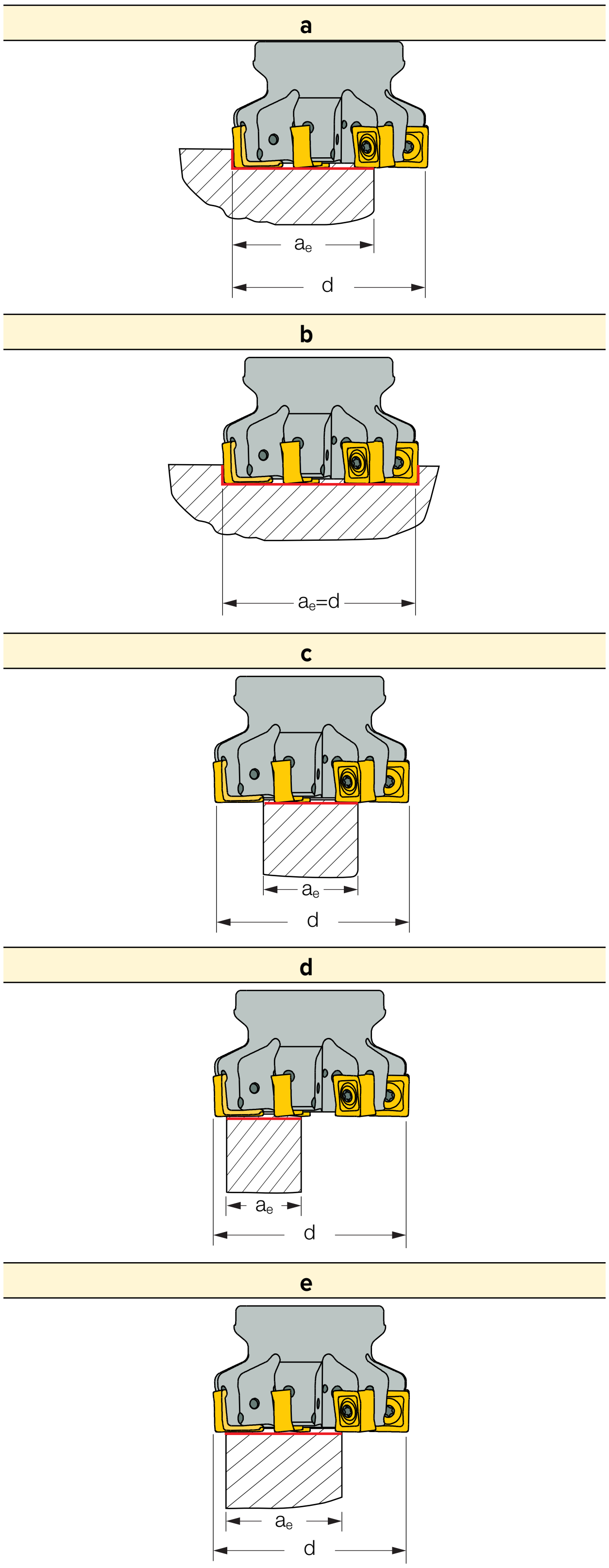
- axial depth of cut a_p that is measured along the mill axis
- radial depth of cut a_e, which is measured radially when milling faces, shoulders, and slots. The radial depth of cut is more known as width of cut – the width of a material layer that is removed by a mill in one pass (Fig. 7.4).

Fig. 7.3.



Depth of cut in reaming

Fig. 7.4.



Depth and width of cut in milling

Stepover and Stepdown

Stepover and stepdown are often identified with depth of cut and width of cut. In multi-pass machining, "stepover" and "stepdown" refer to the distance between two adjacent passes. "Stepover" relates to this distance when, after finishing a pass, a tool moves sideward and then performs the next pass. By contrast, if at the end of a pass the tool moves downward to start the next part, the distance is called "stepdown". Sometimes "stepover" and "stepdown" are referred to as "sidestep" and "downstep" although this is less common.

Machining allowance (machining stock, stock allowance) is the thickness of material layer, which should be removed when machining. There are total allowance and process allowance. If process allowance specifies allowance for a particular machining process such turning, milling etc., the total allowance relates to all material that is removed during the production of a part. The total allowance incorporates allowances for all machining processes that are required for the part manufacturing. Process allowance can be divided into allowances for certain process operations, for example: rough turning, semi finish turning, and finish turning. These operations may be performed by one tool or by different ones.

Process Planning

Allowance determination is one of the important tasks of machining process planning – a field of manufacturing engineering, for specifying machining processes and their operations to ensure efficient manufacturing of a part based on the best technological capabilities such as machines, fixtures, cutting tools, CAD/CAM systems etc.

Machining allowance refers to applying a specific cutting tool, with a given allowance for an application. Depending on the requirements of accuracy and surface finish, possible tool limitations (for instance, the maximum depth of cut provided by the tool, is less than the allowance), the material removal can be done with just one tool pass or requires multiple passes.

When defining cutting data for machining a workpiece from a specific material on machinery equipment, the following principles should be followed. In rough machining, the cutting depth is set to the largest possible, preferably to be equal to the operation allowance or its greater part. The same approach is applied to specifying the feed: the feed should be as high as possible in the light of existing technological limitations such as machine power, cutting condition, tool strength etc.

In finish machining, the key factors for determining depths of cut and feeds are the required parameters of accuracy and surface finish, and surface quality provided by the previous operation. Cutting speed depends on the characteristics of the tool cutting material, cutting conditions, type of machining, and prescribed tool life.

The evolution of accurate metal shaping, such as precision investment casting, precision forging, and 3D printing, are all capable of shaping a part very close to its final profile, significantly diminishes traditional chip-removal processes. As a result, the requirements for machining operations in engineering processes tend to change. The role of productive and accurate cutting with a small allowance at high speeds and feeds is expected to grow substantially, and metalworking industries will require a wide range of tools that are more precise and durable.

Cutting Data As a Function of Cutting Conditions

Cutting conditions have a direct impact on specifying cutting data. Generally, the relationship of these machining characteristics is quite simple: harder cutting conditions equal smaller cutting parameters.

Machining Calculations

Material Removal Rate, Cutting Forces, And Power Consumption

Material removal rate (MRR) Q is a key indicator of machining productivity. The higher Q, the more productive the machining. Material removal rate is the volume of material that is removed by tool per unit of time during machining operation. Calculating MRR depends on the machining process.

MRR: “material” or “metal”?

Since metals have historically been the main engineering material, material removal rate is often referred to as “metal removal rate”.

For example, in turning

$$Q=v_c \times a_p \times f \qquad (8.1)$$

While in milling

$$Q=a_p \times a_e \times v_f \qquad (8.2)$$

The MRR units are mm^3/min or cm^3/min in the metric system and in^3/min in the US customary (imperial) system.

In drilling

$$Q=v_c \times a_p \times f_z \qquad (8.3)$$

Due to $a_p=d/2$ and $f_z=f/z$ (refer to the previous section)

$Q=v_c \times a_p \times f_z = \pi \times d \times n \times d/2 \times f/z = \pi \times d^2/(2 \times z) \times n \times f = \pi \times d^2/(2 \times z) \times v_f$

For typical two-flute drills z=2, and

$$Q= \pi \times d^2/4 \times v_f \qquad (8.3a)$$

Machining Calculations: Conformity of Units

When calculating, you should pay attention to the corresponding units of measurement for the variables in the equations. Mixing unsuitable units is not allowed, and it leads to wrong results. For example, in finding MRR using the values of depth and width of cut in mm (inches) together with cutting speed given in m/min (sfm) will cause serious error.

Example: Find MRR for milling performed with a face milling cutter according to the data below:

- depth of cut 5 mm
- width of cut 180 mm
- cutting speed 120 m/min
- feed 0.25 mm/tooth

From equations (7.5) and (7.2a) $v_f=f_z \times z \times n$ and $n=1000 \times v_c/(\pi \times d)$.

$n=1000 \times 120/(\pi \times 250) =153$ (rpm)

$v_f=0.25 \times 10 \times 153=382.5$ (mm/min)

Using equation (8.2)

$Q=a_p \times a_e \times v_f= 5 \times 180 \times 382.5 =344250\ (mm^3) =344.25\ cm^3$

Example: A turning operation for 2.5″ in Dia. bar is specified by 1000 rpm spindle speed, 0.006 ipr feed and 0.08″ depth of cut. Find MRR.

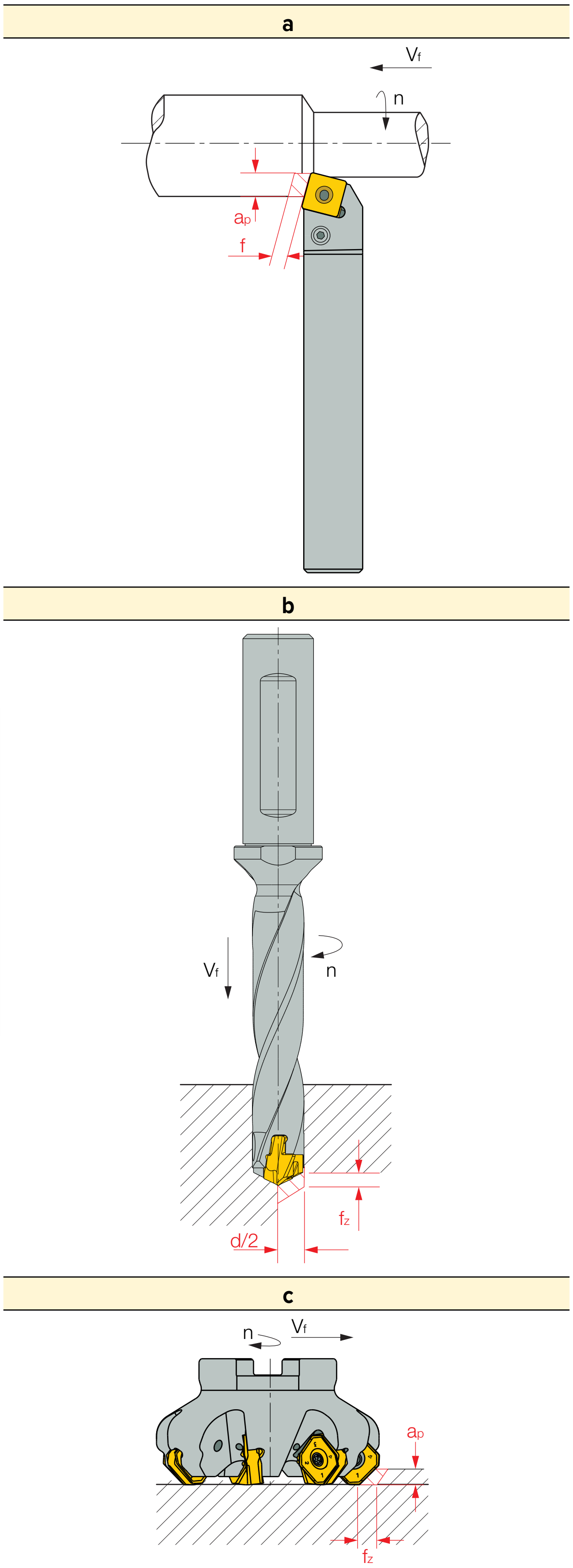
From equation (7.2b) $v_c=\pi \times d \times n/12=\pi \times 2.5 \times 1000/12= 654.5$ sfm.

One foot comprises 12 inches,
and therefore, v_c=7854 ipm

NB. For calculating cutting speed in ipm, equation (7.2b) transforms to $v_c=\pi\times d\times n$, i.e. in this case there is no need to divide by 12.

According to equation (8.1)
$Q=v_c\times a_p\times f=7854\times 0.08\times 0.006=3.77$ (in^3)
The product a_p by f_z defines the area of a cut material layer, Fig. 8.1, in which the area and its dimensions are highlighted by a red color. This is a good example for calculating the material removal rate.

Fig. 8.1.



Area of cut material layer in turning (a), drilling (b) and milling (c).

So, metal removal rate is an important machining characteristic that reflects cutting productivity. However, MRR cannot be considered isolated from other process parameters. One of them is tool life. There is no point in machining at such a high material removal rate causing the tool to break as soon as it starts cutting because of heavy loading caused by extreme cutting speeds and feeds. Another parameter relates to cutting power consumption.

In cutting, the tool, which penetrates the material of a machined workpiece, is loaded by the material resistance force. This force is known as a resultant or total cutting force. The magnitude and the direction of this force depend on a machining process, the material machinability, cutting data, cutting conditions, and the tool cutting geometry. In the rectangular coordinate reference systems, a resultant (total) cutting force F can be resolved by three components:

- tangential cutting force F_t
- radial cutting force F_r
- axial cutting force F_a

The word "cutting" in the description of cutting force components is often omitted.

Sometimes, the tangential, radial, and axial cutting forces are designated also as F_z, F_y, and F_x correspondingly.

$$F = \sqrt{F_t^2+F_r^2+F_a^2} \quad (8.4)$$

Depending on the type of machining, the effect of the forces on the tool is different, and the magnitudes of these forces are in varying ratios with respect to each other.

In machining with rotational mode of primary motion, tangential force F_t is the largest when compared to the other components. This force is considered the main cutting force component, and determines the torque and power consumption required for cutting action.

In turning (Fig. 8.2), radial force F_r, which is directed radially from the axis of rotation of a workpiece, pushes a turning tool away from the workpiece. The resulting pushing effect may be a source of vibrations that affect machining accuracy and surface finish. Axial force F_a that is directed longitudinally, parallel to the axis of rotation, acts against feed motion. In terms of turning, this force is also referred to as "longitudinal" force.

Fig. 8.2.

Cutting forces in turning

In milling (Fig. 8.3), radial force F_r, like in turning, pushes a milling cutter away from a workpiece. The resultant force F_b of F_r and F_t, which is called "bending force", causes bends cutter. The projection of this resultant force on the axis of feed motion forms the reaction force caused by a machine fee drive. Axial force F_a, acting along the cutter axis, loads the spindle unit bearings.

Fig. 8.3.

Cutting forces in milling

In drilling (Fig. 8.4), axial force F_a corresponds to the main cutting edges (lips) of a drill. This force compresses a drill along the drill axis, and, together with force Fch acting on the drill chisel edge, and determines the power consumption of a feed drive.

Fig. 8.4.

Cutting forces in drilling

Determining cutting forces is a key parameter in the design of machine tool units, work- and toolholding device, static and dynamic behavior of the cutting tool itself, and stiffness analysis of the entire technological system comprising machine, tool, fixtures, and the workpiece.

The cutting forces are calculated by use of empirical equations. The more factors are taken into consideration in the equations, the more complicated these equations are. Another approach is based on the relationship between the cutting forces. As a function of the machining process, the cutting forces are related by a ratio to each other. The ratio looks like:

$$F_t:F_a:F_r=1:x:y \qquad (8.5)$$

Coefficients x and y depend on machining operations, machined material, cutting geometry and cutting material etc. In practice, using averaged values of x and y enables quite acceptable results. Therefore, after calculating tangential force F_t, the main component of the total cutting force, the other components can be easily found from equation (8.5).

In estimating tangential force F_t, a method that is based on specific cutting force values is reasonable. The actual specific cutting force k_c is the force that is needed to remove the material chip area of 1 mm^2 (.0016 in^2), which has an average chip thickness referred to as hm.

$$k_c = k_{c1} \times hm^{-mc} \qquad (8.6)$$

where k_{c1} is the specific cutting force to remove the material chip area of 1 mm^2 (.0016 in^2) with 1 mm (.004 in) thickness.

mc is the chip thickness factor that reflects the dependence of k_c on k_{c1} with changing the actual chip thickness when compared to 1 mm^2 (.0016 in^2).

k_{c1} and mc are characteristics of the machined material based on test results. The analysis of empirical data has enabled specifying these characteristics as averaged values for all groups of engineering materials. In various sources of machining data, k_{c1} relates to cutting material with a tool bearing a zero rake angle ($\gamma=0°$). If the actual tool rake significantly differs from zero, the above equation may be corrected in the following way:

$$k_c = k_{c1} \times hm^{-mc} \times (1-\gamma/100) \qquad (8.7)$$

Knowing the specific force and the cross-section area of the cut material layer A, one can easily determine the tangential force.

Example: A 90-degree milling cutter machines a square shoulder that has cross-sectional dimensions 4 mm×9.5 mm (.16″×.38″). The workpiece material is annealed high alloyed steel AISI H13 (DIN W.-Nr. 1.2344). The rake angle of the cutter is 10°. We need to find the tangential cutting force if 0.1 mm average chip thickness (.004″ chip load) is maintained.

According to the Materials and Grade section in **ISCAR**'s Milling Line Catalog, the machined material relates to a material group, which features k_{c1} =2450 N/mm^2 (355 ksi) and mc=0.23.

From equation (8.7) actual cutting force $k_c = 2450 \times 0.1^{-0.23} \times (1-0.1) = 3745$ N/mm^2 (543166 psi or ~543 ksi).

Tangential cutting force $F_t' = 3745 \times 4 \times 9.5 = 142310$ N= 142.3 kN, and $F_t'' = 543166 \times 0.16 \times 0.3\ 8 = 33024$ lbf (~33 klbf).

Avoid Misunderstandings: Specific Cutting Force

In technical literature, the actual specific cutting force may be designated by k_{c1}, and specific cutting force to remove a material chip area of 1 mm^2 (.0016 in^2) with .1 mm (.004 in) thickness by $k_c1.1$. The number "1" that follows index "c" relates to 1 mm^2 (.0016 in^2) chip area, and addition "1.1" highlights "1 mm^2 (.0016 in^2) chip area with .1 mm (.004 in) thickness". Not to be confused!

Determining the tangential cutting force enables finding cutting power consumption P and, consequently, the estimated power, required at the main drive of a machine tool.

$$P=F_t\times v_f=A\times k_c\times v_f \qquad (8.9)$$

If a and b are the depth and the width of a cut layer cross-section A, then consider the following unit conversion:

- in metric system

$$P=(a\times b\times k_c\times v_f)\ /\ (6\times 10^7)\ \text{kW} \qquad (8.10a)$$

where a and b in mm, k_c in N/mm^2 and v_f in mm/min

- in the US customary (imperial) system

$$P=(a\times b\times k_c\times v_f)\ /\ (12\times 33000) =(a\times b\times k_c\times v_f)/396000\ \text{hp} \qquad (8.10b)$$

where a and b in inches, k_c in psi and v_f in ipm

If k_c is given in ksi, the numerical coefficient of unit conversion in the denominator of the above equation is reduced one thousand times:

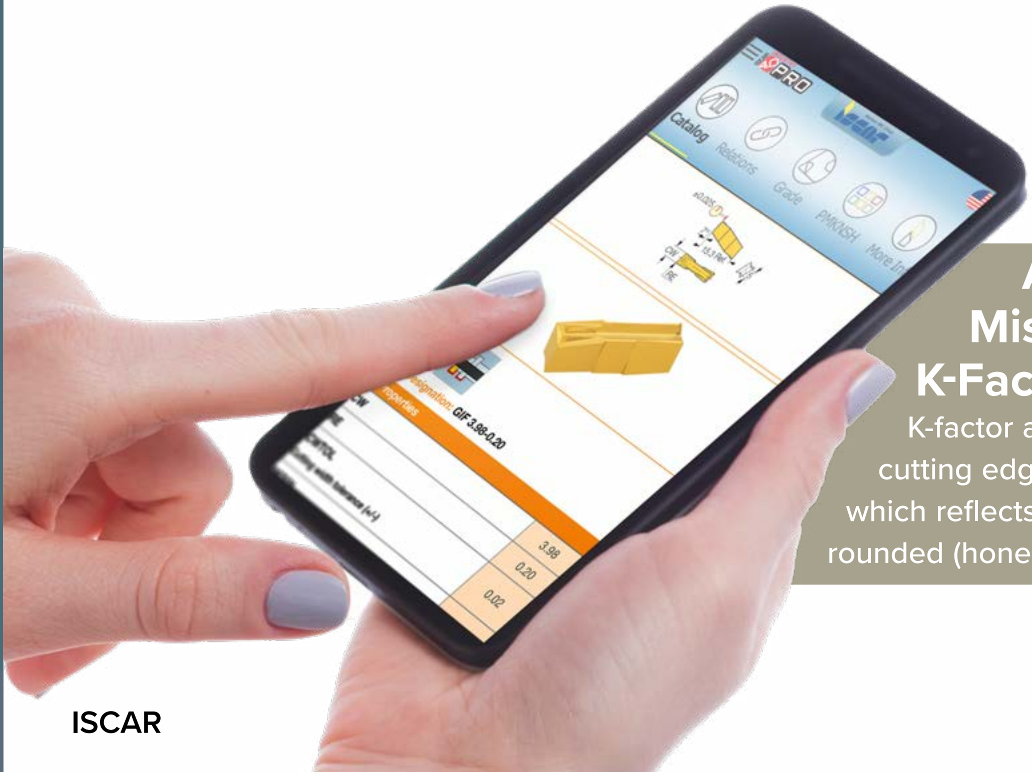
$$P=(a\times b\times k_c\times v_f)\ /\ (12\times 33) = (a\times b\times k_c\times v_f)/396\ \text{hp} \qquad (8.10c)$$

Example: Let's go back to the previous Example: Find the cutting power consumption if the cutter has 4 flutes and 16 mm (.625″) diameter, and the machining features a cutting speed of 120 mm/min (394 sfm) and a feed per tooth 0.1 mm/tooth (.004 ipt).

A 90-degree milling cutter machines a square shoulder that has cross-sectional dimensions of 4 mm×9.5 mm (.16″×.38″). The workpiece material is annealed high alloyed steel AISI H13 (DIN W.-Nr. 1.2344). The rake angle of the cutter is 10°. To find the tangential cutting force if 0.1 mm average chip thickness (.004″ chip load) is maintained:
Equation (7.2a) and (7.2b),
to calculate spindle speed:
$n'=(1000\times 120)/(\pi\times 16)=2387$ (rpm) and
$n''=(12\times 394)/(\pi\times 0.625)=2408$ (rpm).

Equation (7.5) feed speed:
$v_f'=0.1\times 4\times 2387=954.8$ (mm/min)
$v_f''=0.004\times 4\times 2408=38.53$ (ipm)

According to equation (8.10a) and (8.10c):
$P'=(142310\times 954.8)\ /\ (6\times 107)=2.26$ (kW)
$P''=(0.16\times 0.38\times 543\times 38.53)\ /\ 396=3.21$ (hp)



Avoid Misunderstanding: K-Factor

K-factor also refers to the cutting edge form factor, which reflects the symmetry of a rounded (honed) cutting edge.

In addition, cutting power consumption can be estimated with the use of power unit factor (specific power factor) K – a reference data that, when machining a specific material, defines power, required for maintaining the material rate of one volume unit per minute, such as 1 cm^3/min, 1 in^3/min etc.:

$$P=Q\times K \qquad (8.11)$$

where Q is material removal rate in cm^3/min (in^3/min) and K – power unit factor in kW/ cm^3/min (hp/ in^3/min)

Example: Turn to the above examples again. A reference handbook recommends using K=0.042 kW/ cm^3/min (0.92 hp/ in^3/min) for steel with hardness HB 280...320.

Using equation (8.2)

$Q'=a_p\times a_e\times v_f=4\times 9.5\times 954.8=36282$ (mm^3/min) $=36.28$ cm^3/min

$Q'=a_p\times a_e\times v_f=0.16\times 0.38\times 38.53=2.34$ (in^3/min)

By equation (8.11)

$P'=Q'\times K=36.28\times 0.042=1.52$ (kW)

$P''=Q''\times K=2.34\times 0.92=2.15$ (hp)

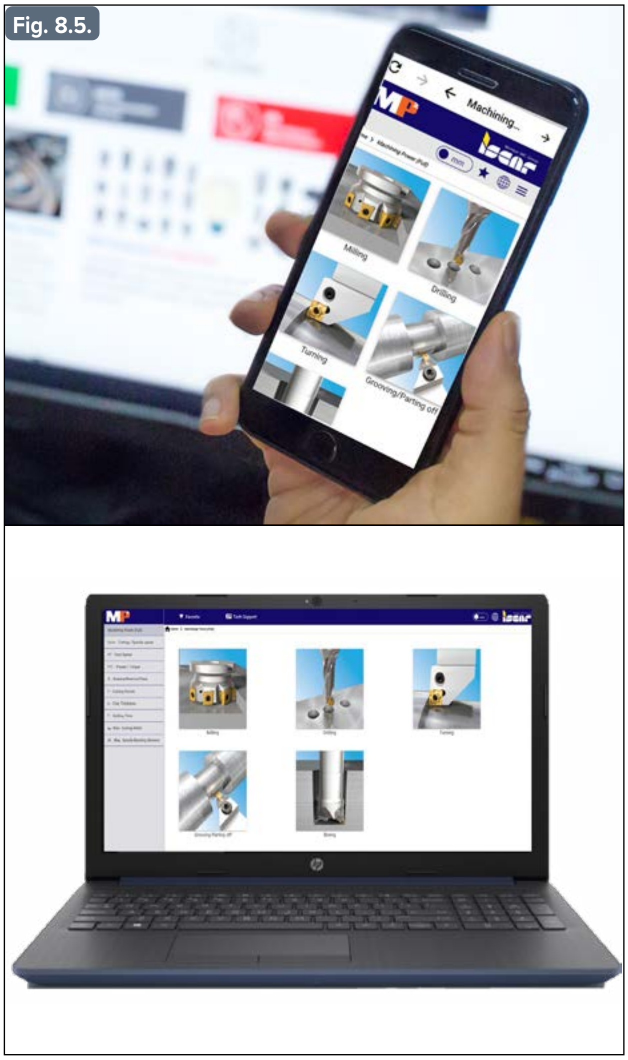
Calculating Accuracy

The last two examples show the results of finding cutting power consumption, which are received by use of different calculation methods, that vary notably: the difference is around 30%. This highlights one important rule: The detailed engineering materials are divided according to cutting forces or specific power factor depending on their content and mechanical properties in reference with data sources, to achieve accurate results.

ISCAR's Machining Power Calculator

Computerization of metal cutting has opened new prospects for accurate engineering calculations. Advanced software enables realizing complicated empirical models which emerge new levels of calculations. ISCAR's Machining Power Calculator estimates power consumption, cutting forces, bending moment, load time variations, plot charts and other important parameters during machining. The Calculator is available for PC and mobile applications.

Fig. 8.5.



The Machine Power Calculator is available in PC and mobile app versions

Indexable Inserts

Industries started using cemented carbides for machining in the 1930s. Since that time carbides have become by far the most popular material to produce cutting tools. While some tools that feature relatively small sizes are wholly produced from carbide, others use carbide in the cutting area only. Originally the cutting area consisted of a carbide tip that was brazed or soldered to a tool body. However, in the 1940s cutting tool manufacturers began to produce cutting tools with the advantage of replaceable carbide segments that were mechanically mounted on to the tool body.

This clever innovation and the use of mechanical clamping, which provides much greater strength compared with the previously brazed connections, are now recognized as memorable milestones, not only in tool manufacturing, but also in advancing the efficiency of all metalworking industries.

This major development led to impressive improvements in productivity within the area of machining operations. It was immediately possible to increase the load on the tool and to intensify operational material removal rates. In addition to this cost-effective method ensuring simple and economical replacement of the cutting element when worn or in case of breakage, it allowed the manufacturing of cutting segments and the tool bodies to be divided. Depending on the shape of the inserts used, they could be quickly indexed ensuring the rapid change of a worn cutting corner by several methods, such as rotating the insert on its axis or by flipping it upside down. Initially the new cutting segments were known by several names, such as throwaway tips, interchangeable inserts, replaceable inserts, however, since the 1960s the more widespread, generic term indexable inserts is used.

Indexable inserts (Fig. 9.1), which vary in their overall dimensions and accuracy, can be classified according to different features such as:

- cutting material
- shape
- cross-sectional profile
- with hole and without
- one- and two-sided

and others.

Fig. 9.1.

Indexable inserts features a rich variety of shapes and sizes

Cutting material

Most indexable inserts are produced from cemented carbide grades. At the same time, a fair number of inserts are made from ceramics, cermet, and cubic boron nitride (CBN). When polycrystalline diamond (PCD) is used as cutting material, a carbide insert functions as a base, which is tipped by high-priced PCD (Fig. 9.2). Also, due to the same reasons, there are CBN-tipped inserts made with cubic boron nitride.

Fig. 9.2.

PCD-tipped indexable inserts

Insert shape

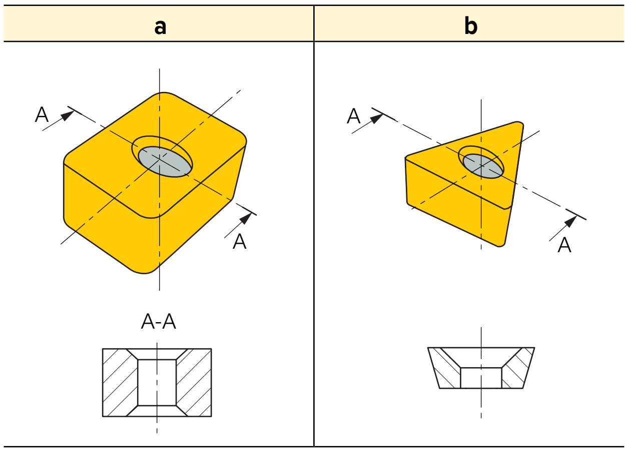
An insert comprises top, bottom, and side (peripheral) surfaces referred to as top, bottom, and side. At least one of the top and bottom surfaces intersect with the side surfaces, forming cutting edges. The top plane view reflects the top surface, bound by the insert contour with the cutting edges. This view determines the insert shape. The world of inserts includes many geometrical shapes. There are polygonal, round, and complex insert profiles.

The shape of an insert depends on various considerations as a basis of the insert design concept that compromises between different factors such as requirements of machining process, providing optimal cutting geometry, maximizing the number of indexable cutting edges, efficient utilization of cutting materials, clamping principle etc.

Cross-section profile

According to the cross-section profile of an insert, positive and negative inserts are distinguished repectivley (Fig. 9.3). In positive inserts, the side is inclined with respect to the acceptable insert bottom, while in negative inserts, the generator of the side surface is parallel. Therefore, in positive inserts, the bottom is smaller than the top, and in the negative inserts, these surfaces have the same area. The angle of the mentioned inclination is known as the normal clearance of an insert, or simply insert clearance.

Fig. 9.3.



Negative (a) and positive (b) insert shapes

Every shape has its advantages and disadvantages. For example, the negative shape enables producing cutting edges from both top and bottom surfaces to increase the number of cutting edges and utilize the insert more effectively (Fig. 9.4). On the other side, the positive shape provides more options for optimizing cutting geometry to ensure a tool positive rake in normal and axial directions.

Fig. 9.4.

ONHU 0806 double-sided negative insert has 16 cutting edges

Fig. 9.5.

HM390 TDKT 1907 one-sided insert features positive shape

Avoid Misunderstanding: Positive Insert

The term "positive insert" that has originally related to the cross-sectional profile of an insert has also one more meaning. This term is often used for specifying the inserts with top surface that is substantially inclined with respect to the insert cutting edge. When being mounted on a tool, such an insert forms positive tool rake angle. Advances in powder metallurgy have resulted in the production of inserts, in which this inclination is more "aggressive".
This causes a significant increase in the positive rakes of a tool carrying the inserts. The term - "high positive insert" emphasize the mentioned feature. Important to note that this definition reflects the current state of the art. As the production of tools with cemented carbide inserts does not deplete on its own resources, we may assume that the "high positive" of today will be considered as the "normal" tomorrow.

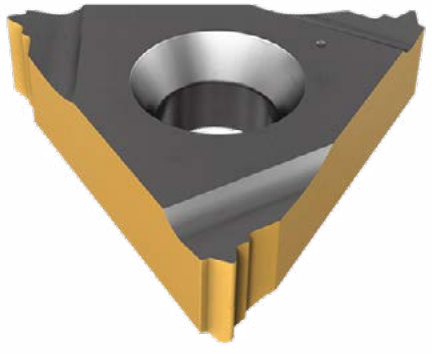
Central hole

There are indexable insert designs both with and without a central hole. The hole is used for fixing an insert by screw, lever, or another clamping device when the insert is mounted on a tool. In most cases, this is a through-hole, but some inserts have blind a hole. Through-holes are divided into cylindrical (Fig. 9.6) and partly cylindrical. The partly cylindrical holes feature countersunk one (Fig. 9.7) or two hole sides. Normally, countersunk angles are within the range of 40...90°.

Fig. 9.6.

Insert with wholly cylindrical hole

Fig. 9.7.



Insert with countersunk hole

One- and double-sided inserts

In one-sided inserts, only the top surface has cutting edges (Fig. 9.5). Double-sided inserts, which have a negative shape, facilitate cutting edges on both top and bottom surfaces (Fig. 9.4). In double-sided inserts, a worn cutting edge is replaced with a new one not only by indexing but by turning inserts upside down. Therefore, double-sided inserts are also known as "reversible".

Insert mounting

In a cutting tool body, an indexable insert is mounted in a specially produced cavity that is called “insert pocket” (Fig. 9.8). This cavity comprises a base and walls that bound the base of the insert.

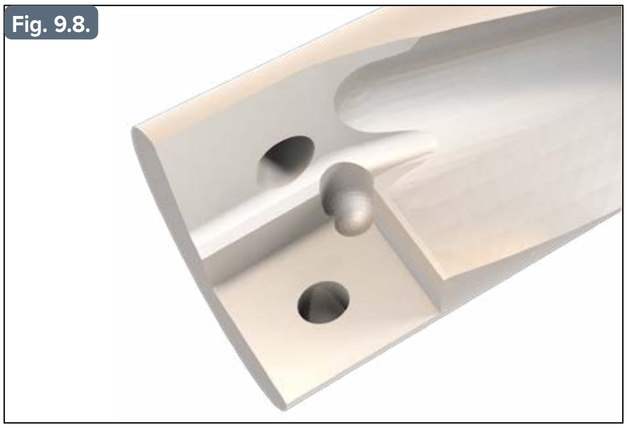
Cutting Edge or Cutting Corner?

Historically, the cutting edges of turning insert’s were synonymous with the insert cutting corners. Even today, cutting edges are sometimes referred to as “cutting corners”. However, such terminology is not acceptable. Moreover, a cutting edge usually includes a corner as a cutting or transition element.

The base has the largest contact area when compared to the contact surfaces of the walls. The most common way of insert mounting utilizes the insert location placed on the bottom surface, which adjoins the pocket base, and the main component of the clamping force which acts along the pocket base. In rotating tools, the inserts mounted in this way are known as radially clamped inserts (Fig. 9.9a).

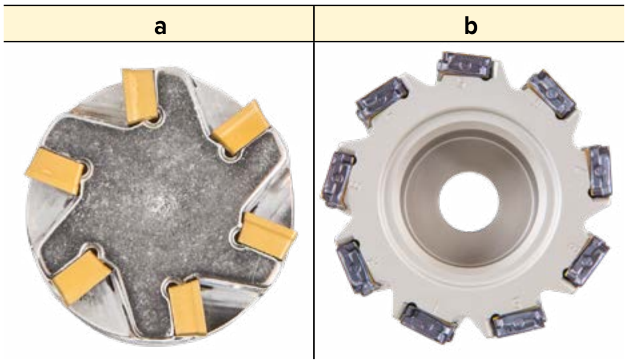
Alternatively, the tangential method of insert fixing stipulates changing the pocket location and placing inserts upright (Fig. 9.9b). The main advantage of this method is the effective orientation of the insert cross-section with respect to external load, caused by tangential cutting force F_t (Fig. 9.10). Similar design considerations have brought the changed pocket location to non-rotating tools (Fig. 9.12), where the term "tangential clamping" and its derivatives is now common.

Fig. 9.8.



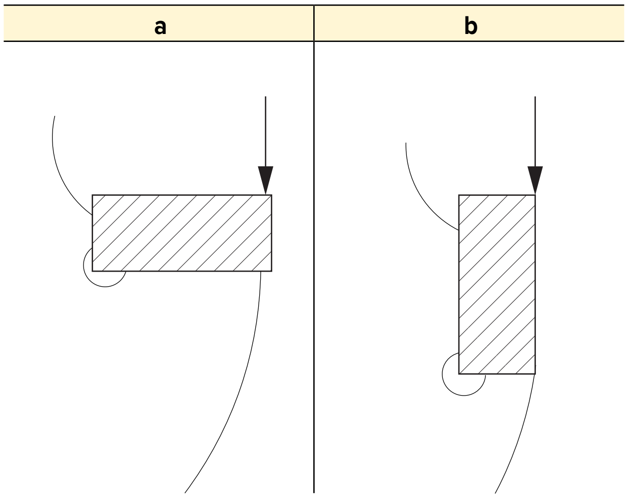
Insert pocket

Fig. 9.9.



Milling tool with radially (a) and tangentially (b) clamped inserts

Fig. 9.10.

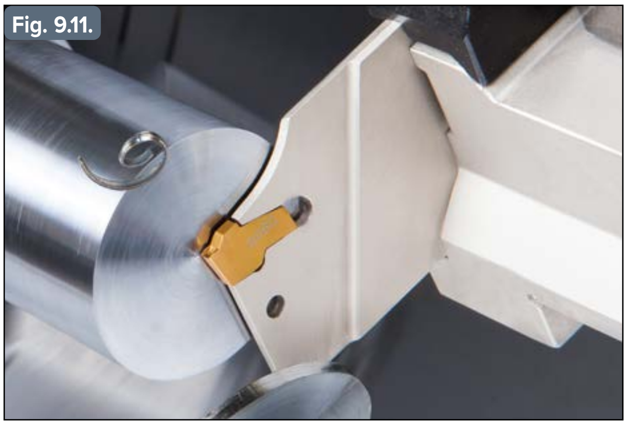


Radial (a) and tangential (b) insert mounting

Self-Clamping Insert Concept

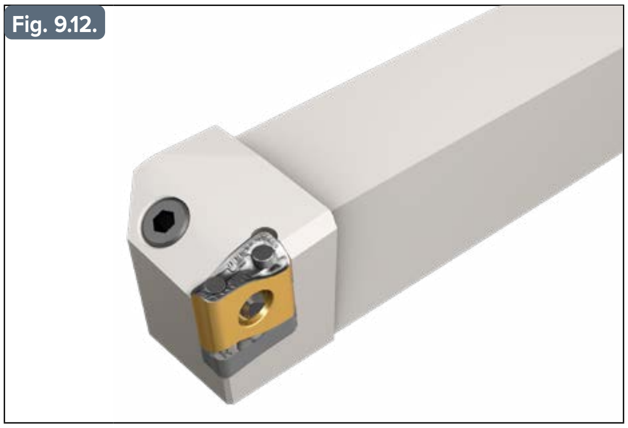
Indexable inserts are fixed in the insert pockets mainly by mechanical parts such as screws, levers, clamps etc. Back in the seventies, **ISCAR** introduced **SELF-GRIP**, the brand name of the original blockbuster parting tool design concept. According to the design concept of the **SELF-GRIP** tool (Fig. 9.11), a pressed carbide insert was clamped into a tool blade using the blade's elastic forces without the need for mechanical securing elements. At that time, other manufacturers also attempted to clamp inserts into a parting tool using the same principle. However, it was **ISCAR** that invented a reliable, truly workable concept that set the benchmark for parting applications and created the game changer in parting.

Fig. 9.11.



SELF-GRIP parting tool. The insert is fixed in the pocket without mechanical element

Fig. 9.12.



Turning tool with tangentially clamped insert

Clamping Torque

Proper insert fixing by a clamping screw, or any other screw-down element requires applying an appropriate tightening torque (clamping moment). Cutting tool manufacturers provide the appropriate torque values in technical data sources. In addition, the values are usually marked on a tool body directly marking details.

The design of various keys or wrenches, delivered by the manufacturers as accessories, ensure the necessary torque. Alternatively, there are dynamometric keys with adjustable or fixed torque (Fig. 9.13.) that provide a good option for applying correct torque. A clamping screw, which is the smallest and weakest element of a tool as a system, has a great impact on the system's reliability. The over-tightening of screws often results in fatigue failure of the screw or difficulties in releasing the screw after machining, and dynamometric keys are highly recommended for reliable insert clamping.

Fig. 9.13.

An example of a key with fixed tightening torque. The torque value is printed on an exchangeable blade and a handle, and, highlighted by use of a color: the color of the handle's cap should match the color of the sleeve on the key blade

Clamping Screw

An insert clamping screw requires thorough visual examination before its use. The threads and head of the screw, as well as the socket for a key, should all be in good operating condition, and therefore, demand special attention. If these screw elements are damaged, or the screw is bent, the screw must be replaced immediately. When tightening a screw, apply the correct tightening torque and use the right key to prolong the wear life of the screw. Don't forget recommendations for the application of an anti-seize lubricant when replacing an insert. Following these guidelines will increase the screw life.

Insert Manufacturing

The technology used in the manufacturing of indexable carbide inserts is based on powder metallurgy, comprised of several manufacturing processes as follows:

- preparing carbide powder (mixing)
- pressing the powder (compacting)
- sintering compact
- post-sintering processing
- coating

In principle these stages have remained unchanged over many decades. Progress in science and technology has significantly impacted the manufacturing process of inserts.

In the past, inserts were produced using manual machines. The application of various complex powder metallurgical processes was very difficult or even impossible to perform. The introduction of more progressive industrial equipment, that features advanced automation and computer control, made the technological processes more stable, controllable, and reliable. Consequently, the mechanical properties of manufactured inserts became more uniform, predictable, and repeatable. These factors allowed dramatic improvements in terms of the accuracy of sintered inserts by reducing production tolerances.

Today, a typical insert production press is a highly engineered device that is computer controlled. A moveable punch can be made from several “sub punches”, each operated separately. Some press designs encompass multi-axial pressing options. The remarkable progress in press technology enables the production of complex shaped inserts that are characterized by variable corner heights (Fig. 9.14). This capability enables the realization of optimal cutting geometry, which guarantees not only smooth and stable machining but also the increased accuracy of a machined surface.

Additionally, the advantages provided by applying modern CAD/CAM systems make it possible to improve the design and the shape-generating parts of pressing die sets. The ability to simulate the pressing processes related to new sintered products, when they are at the beginning of their design stages, allows further design amendments and enhancements to be made.

Fig. 9.14.

Insert H690 TNKX 1005 features pronounced different corner heights

Insert Accuracy

Indexable inserts provide the exchangeable cutting part of a tool, and insert accuracy has a direct impact on the tool accuracy. The inserts vary in their accuracy. Functionally, required accuracy depends on the insert application, while obtainable accuracy relies on the technology of insert manufacturing. The inserts are made of sintered powder metallurgy products. Therefore, the capabilities of pressing and sintering processes largely determine insert accuracy. Reflecting today's state of the art, wholly sintered inserts ensure the satisfactory level of accuracy. For better accuracy, grinding operations are required. It is enough to grind only the side surface of an insert but for highest precision, top surface (for one-sided inserts, and top and bottom surface (for double-sided inserts) are ground as well.

To assure proper insert locations, appropriate flat insert surfaces are often lapped. Applying lapping – a type of abrasive machining process - is not an evidence of high insert accuracy in this case.

Insert and Chip Formation

When mounted in a tool, the upper surface of an insert turns to the tool rake face. Therefore, the top and the bottom surface for double-sided inserts are often referred to as the insert rake face. Designing the rake face of an indexable insert requires engineering skill: knowledge of metal cutting theory, the chip formation process, understanding specific features of machining different materials, knowing principles of powder metallurgy and limitations of manufacturing sintered products, experience, and appropriate training in tool design. The rake face determines the cutting geometry of a tool - its total cuttability (cutting capability); and forming the rake face in an optimal way as a key element of the insert design.

Over the years, technological options for cutting tool manufactures have largely dictated the shape of the rake face. For example, in the earliest days of indexable tooling the inserts featured flat faces. Breaking a long chip with turning tools carrying these inserts often required using additional cover parts that were mounted in the tools above the inserts. In certain tool designs, even an upper clamp, which secured the insert, acted as a chipbreaker. Another common solution for flat-face turning inserts was to produce a chip breaking dimple by use of grinding. The dimple promoted curling the chip in a spiral and breaking it into smaller segments. Both these methods were far from perfect.

The chip breaking cover part produced a natural obstacle for the chip flow. The chips caused intensive abrasion of the part and significantly reduced its tool life. The shape and dimensions of the dimple strongly depended on a grinding wheel that reduced possible dimple forms. But the main problem was the necessity of long-term tests to develop a chipbreaker that would ensure stable performance when machining different types of material. To some extent, chipbreaker design was more like a path of trial and error.

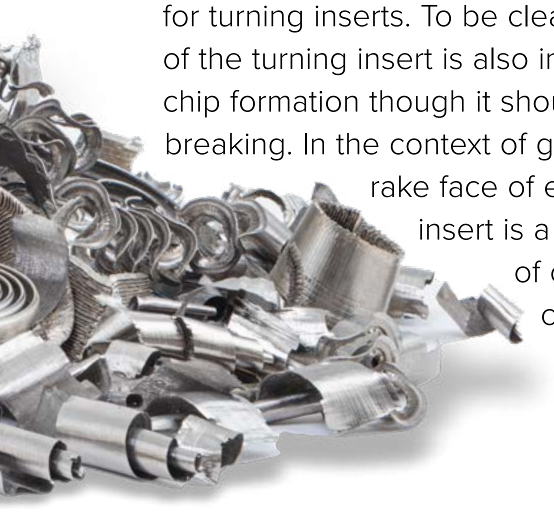
Advances in powder metallurgy changed the situation dramatically, bringing new machines and computer-based control that substantially improved stability and reliability in a wide range of processes. The technology of sintered carbide products facilitated the shaping of insert rake faces in various forms and broke the dependence of the chip breaking surface on the dimple or the cover part. The rake face received a look of combined concave and convex portions, local protrusions etc. - this complex geometry was designed to provide the necessary chip formation and effective chip control. The rake faces of today's indexable inserts feature the same surface texture.

CAD Impact

Introducing computer aided design (CAD) systems into the research and development (R&D) of cutting tools had a significant impact on shaping the rake face. CAD provides tool designers with a powerful tool for complicated 3D modelling, engineering calculations and analyzing possible limitations of a designed insert and its rake face. The combination of state-of-the-art sintered product technology, advanced CAD systems and up-to-date CNC machines marked a quantum leap in the cutting tool industry. It not only allowed producing a wide variety of inserts with geometrically complex faces but substantially shortened the design process.

The totally new level of cutting tool design and technology reduced testing needs significantly. However, the time required for studying cutting capabilities of a new insert geometry by use of machining trials remained considerable.

This holds for the design of all indexable inserts, not only turning. In the case of milling inserts, the rake face shape is considered mainly from the point of view of chip forming only - milling is a process of interrupted cutting and therefore chip breaking creates no difficulties. In milling inserts, the rake face is called a chipformer and not a chipbreaker as it is characterized for turning inserts. To be clear, the rake face of the turning insert is also intended for chip formation though it should enable chip breaking. In the context of geometry, the rake face of every indexable insert is a combination of concave and convex areas.

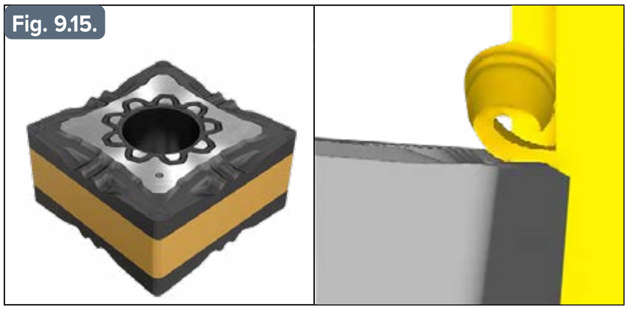


Effect of 3D Modelling

Scientific research, numerous tests, and the analysis of accumulated information in the field of metal cutting, combined with significant advances in computer technology, have provided the cutting tool industry with a new powerful design tool - three-dimensional modelling of chip formation. The first simplified models of chip formation were found on empirical and calculated data and suffered from serious inaccuracies. Further development, based on the finite element method (FEM), raised cutting action modelling systems to a whole new level. Today, cutting tool designers utilize advanced software that enables simulation of chip formation processes with a sufficient approximation to reality. Even though the software cannot replace machining tests, it contributes greatly to effective design of indexable inserts and most of all, their rake faces.

Example: When designing **ISCAR**'s CNMG 120404-F3P turning insert, it was found that simulating cutting action was useful for shaping the insert's top surface (Fig. 9.15). The fancy patterning was not devised to reflect the virtuosity of an R&D team, and in fact modelling proved to be an extremely valuable tool in realizing the team's objective of ensuring the best cutting capabilities.

Fig. 9.15.

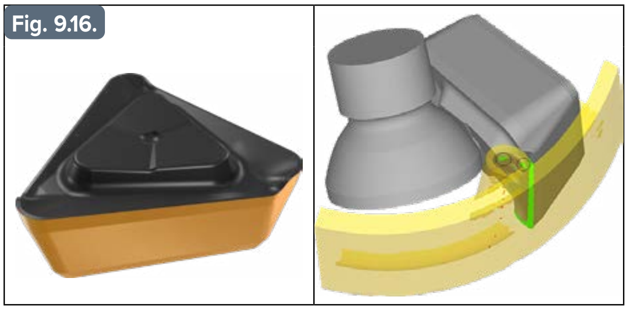


Modelling chip formation has significantly contributed to optimizing the rake face of CNMG 120404-F3P

Example: NAN-MILL is a family of indexable mills in the small-diameter range (up to 10 mm or .375"). Although this range is traditionally considered as more suitable for solid carbide tools, these indexable mills represent an attractive and cost-beneficial alternative especially in rough machining operations.

The mills of the family integrate an original design concept: they feature a clamping screw located above the insert and a screw head that functions as a wedge. However, to prevent any contact between the screw head and the chips produced (a potential consequence of this design), the insert chipformer required additional adaption. Modelling the chip formation process was an important factor in successfully solving the problem (Fig. 9.16).

Fig. 9.16.



Chip formation modelling has resulted in appropriate shaping of the insert rake face assuring required chip flow

Chip forming simulation has already become a valuable tool in shaping the insert rake face efficiently. Further progress in modelling cutting action should bring tool designers closer to achieving optimal chip forming geometries and will significantly improve the quality of the designed tool.

Insert Designation

Tool manufacturers provide their own systems of insert designation. This results in difficulties for insert identification and often requires referring to a manufacturer catalogue to clarify details. At the same time, international and national standard organizations (such as ISO, ANSI) have developed appropriate standards to make insert identification uniform and easy. ISO 1832 standard Indexable inserts for cutting tool – is a system for insert designation that enables quick and simple understanding of the main parameters of an insert such as its shape, dimensions, accuracy etc. The inserts that meet the requirements of this standard are known as ISO standardized-, ISO standard-, or even simply ISO inserts. ISO 1832 standard covers the designation of inserts from various cutting materials including tipped inserts as well. Most ISO inserts relate to turning.

According ISO 1832 standard, the designation of an insert comprises a set of symbols that are letters and numbers. Some of the designation symbols – first seven for solid indexable inserts and first twelve for tipped ones – are mandatory, while others are used if necessary.

The first symbol is a letter that specifies the insert shape: A, B and K – parallelogram that has different smallest included angles (85, 82° and 55° correspondingly),
H – hexagonal, O – octagonal,
W – trigon etc.

The second symbol is a letter to designate the normal clearance of an insert, for example: A – 3°, D – 15°, P – 11° and so forth.

The third symbol is a letter describing the insert accuracy - the tolerance class for the following critical dimensions: the insert width (the diameter of inscribed circle), the insert thickness, and the dimension, which depending on the insert shape, determines the insert height directly or indirectly.

The fourth symbol points to the shape of the insert rake face (with a chip breaker or without, on one insert face or on both faces), and characterizes the central hole for insert fixing (with hole or without, cylindrical or countersunk etc.).

Avoid Misunderstanding: IC

The abbreviation "IC" (or "ic") means "inscribed circle". At the same time, "IC" may refer to another abbreviation, "**ISCAR**'s carbide", that is used in designating **ISCAR**'s cemented carbide grades.

The fifth symbol is a number that denotes the insert size. Depending on the insert shape, the size is the round-off whole value of the parameters like the length of the main cutting edge, the nominal diameter etc.

The sixth symbol is a round-off whole number, which describes the insert thickness.

The seventh symbol may be a number or a letter to describe the configuration of the insert corner.

Example: The designation of ISO insert CNMG 120404 that it is a rhombic insert with an 80°-included angle (C) of negative type i.e., with zero clearance (N); tolerance class M; the insert has a cylindrical hole through and chip breakers on both top and bottom surfaces. The insert size is 12.7 mm, (12), the thickness is 4.76 mm (04), and the insert features a 0.4 mm corner radius (04).

ISCAR's Designation System for Indexable Inserts

The ISO system for designating indexable inserts has notably contributed to insert standardization and unification. However, along with the undeniable advantages, this system is not free from disadvantages. The first relates to the characteristics of the insert rake face: The ISO system relates to the presence of a chip breaker or its absence. The second point relates to the insert shape. The advance of powder metallurgy technology has enabled producing inserts of complex shapes with a formed side surface. Identifying such inserts by use of the ISO system is complex In designating indexable inserts, **ISCAR**, uses the following ISO system yet in many cases designations of original **ISCAR** inserts contain additional symbols and prefixes. Let's get back to already mentioned turning insert CNMG 120404-F3P. The first seven symbols of the insert designation wholly meet the ISO 1832 standard. The other symbols – "F3P" – imply:

F – the chipbreaker is designed mainly for finish operations,

3 – a relative application range according to insert loading ("3" stands for normal load),

P – the insert is intended mostly for machining steel (ISO P main group of application).

One more example relates to milling inserts. Prefix "T490" in the designation of insert T490 LNHT 1306PNTR means that this is a tangentially clamped insert (T) with 4 indexable cutting edges (4) that is mounted on 90-degree milling cutters (90).

Solid Tools

Historically, solid tools are the origin of all cutting tools. In solid tools, the tool material is the cutting material. This material changed according to state of the art: carbon steel, high speed steel (HSS), cemented carbide... Today's industrial solid tools (Fig. 9.17-9.20) utilize mainly carbide and HSS structures in various tool designs: turning tools, taps, drills, mills etc. HSS tools have become a classic, and when relating to solid tools, the focus is typically on carbide tools, while emphasis is often placed on rotating solid tools that are commonly known as round tools.

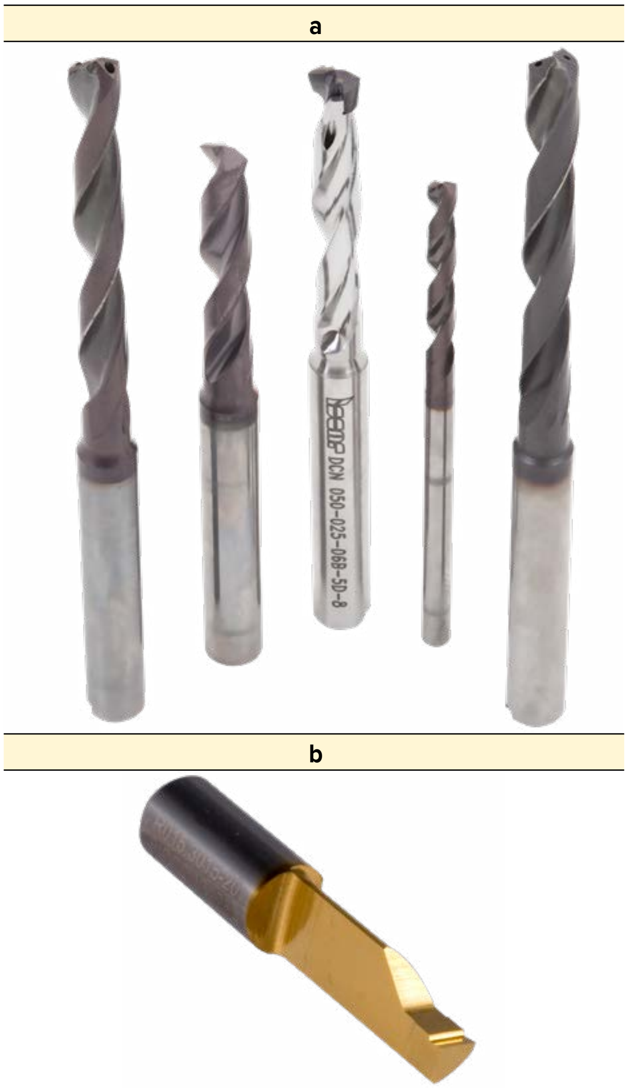
Round tools are produced from round workpieces – cylindrical carbide rods – by grinding. Modern CAD systems and advanced CNC tool grinding machines have ensured a complete rethink of the tool design and manufacturing by providing leeway to 3D modelling to optimize complex cutting geometry (Fig. 9.21) and the actual geometry by use of significantly advanced machine capabilities.

Within arm's reach, round tools of the same type, such as drills or endmills, and sizes look similar, even identical. However, this likeness is ostensible, and finding optimal geometry for a solid tool is a challenging task for tool designers. The design component in creating cutting-edge round tools is highly topical now because progressive CNC grinding machines enable producing tools of common geometries in accordance with tool parameters and machine monitoring by use of embedded software functions.

Another element which contributes to the success of round tools relates to strict technology compliance and shop-floor discipline, thus high process quality has a direct impact on tool performance and tool life. In addition, the quality of carbide rods as a third factor to produce effective tools, cannot be discounted.

That is why round tools that are so similar at first glance differ in their cutting capabilities and price.

Fig. 9.17.



Solid carbide tools: twist drills (a) and miniature grooving tool (b).

Fig. 9.18.

Solid carbide endmills features a rich variety of cutting geometries

Fig. 9.19.

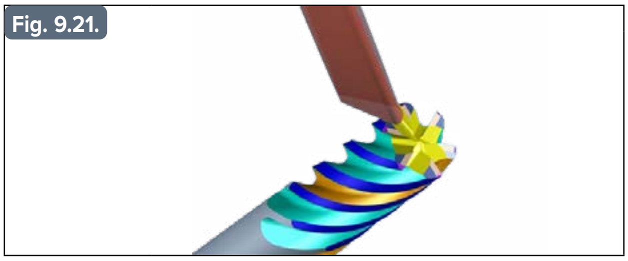
Threading solid tools: HSS taps (a) and carbide threading endmills (b)

Fig. 9.20.

Solid carbide reamer

The most important advantage of solid tools is attributed to their high obtainable accuracy. A tool does not comprise assembled elements, it is produced from monolithic material and has the malleable profile of a cutting edge, formed by machined surfaces. For example, under average cutting conditions, the accuracy of produced holes is estimated as ISO tolerance grade IT12 for drills carrying indexable carbide inserts in comparison with IT10-IT9 and in some cases even IT8 for solid carbide drills.

Fig. 9.21.



Simulation of grinding process already at the design stage is a powerful tool to reach optimal cutting geometry and minimize production costs.

Most worn-out round tools can be reground (resharpened), allowing accurate restoration of cutting geometry, and recoating The regrindable concept enables efficient and sustainable utilization of cutting material. If the regrinding of a tool is required the tool cutting geometry must be designed accordingly.

Regrinding Solid Tools

Usually, reground tools have shorter tool life due to uncoated areas or problematic recoating. However, the main reason for the loss of efficiency results from the reduction of the tool diameter due to the decreasing rake angles and flute depth which source from regrinding the tool relief surfaces. Therefore, the tool cuts harder, and its chip handling properties decrease. In solid carbide endmills, on average, every 1% decrease of the tool diameter results in a decline of the tool performance by 2%-3%, and from the definite reduction value the tool performance drops dramatically. Following the tool manufacturer's instructions for regrinding is very important to avoid the negative sides of this operation.

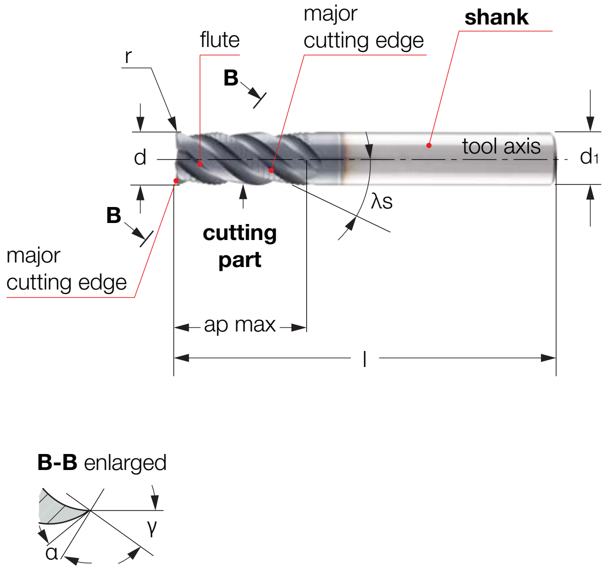
The solid tool concept has one more important advantage. In addition to higher accuracy, rotating solid tools feature better axial symmetry when compared with indexable cutters. Typically, solid tools are less in diameter and naturally require higher rotational velocity even for the same cutting speed.

This explains why most tools, which are intended for high speed machining (HSM), are solid.

In round tools, the tool cutting edge is generated as the line of intersection of two complex surfaces: the rake face and the periphery or flank. These surfaces are generated by machining operations, usually, by grinding. The rake face is a section of the tool element that is known as the flute - a groove, mostly helical, in the tool. The flute not only forms the tool cutting edge but ensures the evacuation of chips produced during cutting. In tool grinding, the generated flute shape is a direct result of appropriate motions of a tool grinding machine in combination with the profile of an applied grinding wheel. Optimizing the flute profile to provide both the required rake angles and effective chip evacuation is an essential design task that largely determines the tool performance. This highlights again the importance of simulating the grinding surface by use of advanced CAD/CAM systems.

Fig. 9.22 shows typical elements of solid endmills. The flute is determined by flute helix angle λs. The number of flutes is the number of tool cutting edges or teeth. Another tooth characteristic is the angular pitch - the distance between two identical points of two adjacent teeth, which is measured along an arc with the center on the tool axis. The pitch can be equal (even, regular) and unequal (uneven, irregular). For example, an endmill with five teeth and an equal pitch shows the distance as 72°. The same five-toothed endmill with an unequal pitch can be represented by various pitch combinations, such as 73°-71°-72°-73°-71° or 74°-72°-70°-71°-73°.

Fig. 9.22.



Main elements of a solid endmill

Normally, the overhang-to-diameter ratio for solid endmills, particularly for carbide ones, is greater when compared with indexable tools. Such a feature, in combination with a flute shape that weakens a tool cross-section, demands specific attention to the vibration strength of an endmill. To improve dynamic stability, tool design engineers often make a tooth angular pitch unequal, and a flute helix variable. This violates the principle of axial symmetry and may give a reverse result. Therefore, an optimal, intelligent design for solid endmills requires engineering ingenuity and compromising.

Variable Helix

The term "variable helix" refers to the helix angle in vibration-free designs of solid endmills, found in **ISCAR**'s CHATTERFREE solid carbide endmills (SCEM) that are based on the pitch control principle. A typical SCEM features helical teeth, and the helix angle determines the cutting edge inclination of a tooth. In traditionally designed endmills, the helix angle is the same for all flutes, yet varies in vibration-free configurations. The term "variable helix" is commonly understood to represent two design features:

1. The helix angle varies along the flute.
2. Combining flutes with unequal helix angles where the angles are constant along every flute.

However, the term "variable helix" is more correct only in relation to design feature 1, and the terms "different helix" or "variable pitch angle" should be used to specify design feature 2.

Solid roughing endmills are intended for rough machining with high stock removal rates. These endmills bear a chip-splitting design that features serrated, "grooved", cutting edge (Fig. 9.23). Due to the chip splitting action, a wide chip is divided into small segments that improves chip evacuation and chip handling. Also, chip splitting action strengthens vibration dampening of a cutter.

Fig. 9.23.

Roughing endmill with serrated cutting edges

Two in One

ISCAR FINISHRED endmills have four flutes, two serrated teeth and two continuous teeth. This facilitates the integration of two cutting geometries into a single tool: rough (serrated teeth with chip splitting action) and finish (continuous teeth), providing the “two in one” advantage. By running at rough machining parameters, semi-finish or even finish surface quality can be achieved.
This type of tool can replace two rough and finish endmills, reducing cutting time and power consumption while increasing productivity.

Fig. 9.24.

FINISHRED “two-in-one” endmill

Helix angle λs establishes the inclination of a cutting edge. This angle determines the direction of the total cutting force, controls chip flow, and has an impact on the gradualness of entering the endmill into the material. Depending on the helix direction, λs shows a - positive or negative. The helix angle is considered positive for a right-hand helix (as shown in Fig. 9.22), and negative for a left-hand one. If the flutes are straight, the endmill has zero helix angle. Most solid endmill designs have a right-hand helix, while a left-hand helix is more common for solid reamer designs (Fig. 9.20). There are also endmills that combine both helix directions (for example, those that are intended for machining composite materials, Fig. 9.25). In right-hand tools, the helix angle factors in the axial force that acts on the endmill and can possibly extract the tool from the spindle. Therefore, λs is an important element of the endmill vibration strength.

The helix angle is a function of the type of machining and machined material.

When designing solid endmills, choosing the helix angle compromizes between performance and the application field.

In contrast with indexable milling cutters, solid carbide endmills (SCEM) can provide more teeth for the same nominal diameter. At the same time, growing the tool diameter requires more carbide material, and this increases costs. Starting from given diameter values, SCEM price becomes so high that the solid tool design does not provide a cost effective solution. Most of the solid carbide endmills have diameters of up to 25 mm (1.00″).

Fig. 9.25.

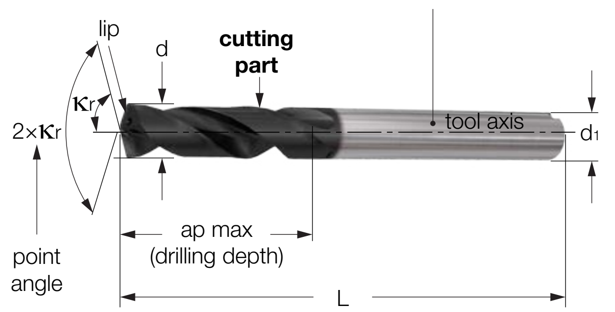
Solid carbide endmill with right- and left-hand helix for machining composite materials

A similar situation is observed in holemaking tools. In solid carbide twist drills, the drill diameter does not exceed 20 mm (.75″). The drills have two flutes, and greater diameters lead to an unjustified increase for the removed cutting material and production costs.

Modern technology enables producing solid carbide drills with internal spiral channels for coolant supply to the cutting zone, and this greatly contributes to improving performance.

Main parameters of solid carbide twist drills (Fig. 9.26) are drill diameter d and its tolerance, point angle, cutting geometry, shank diameter d1, and drilling-depth-to-diameter ratio. It is easy to see that the point angle is equal to twice the tool cutting edge angle κr (refer to previous section – cutting tool types and main elements). The point angle and other parameters of cutting geometry depends on the type of machined material. Like in the case of solid endmills, to provide a wide range of applications for twist drills, the drill designers resort to solutions regarding the point angle, flute helix angle etc. For example, the 140° point angle is common for general-use drills, made from carbide, and 118° for HSS type.

Fig. 9.26.



Elements of solid carbide twist drill

Slot Drill

"Slot drill" is the name of an endmill that cuts straight down. Slot drills have at least one center cutting tooth and are used mainly to form key slots. Slot drills are typically two-flute mills, but they can have three and even four flutes.

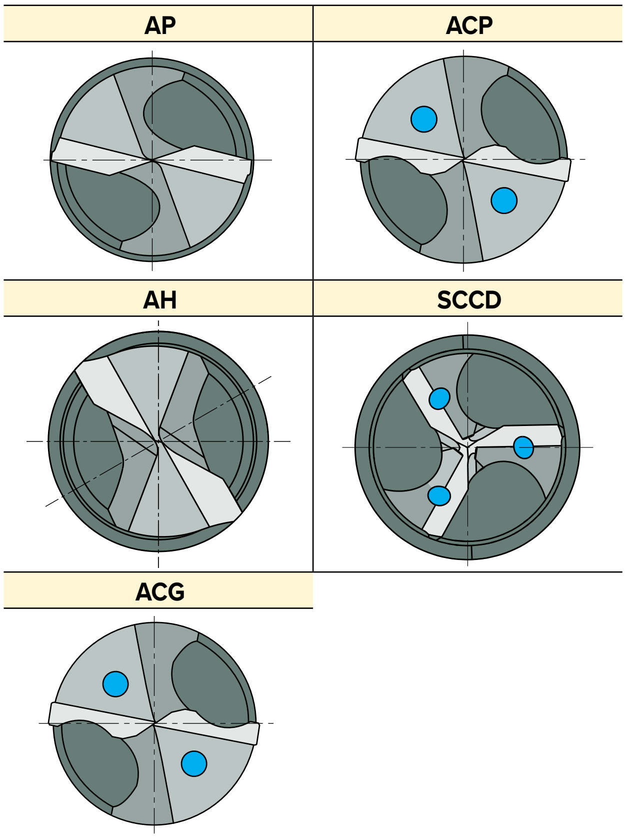
Typically, twist drills feature a two-flute design but there are also drills with three flutes (Fig. 9.27) to increase productivity, particularly when drilling materials, producing small chips like cast iron.

Fig. 9.27.

Two-flute solid carbide drill with internal coolant channels

Solid drills vary in cutting edge configurations. Some of configurations are very common and are considered as a type of standard solution. By way of illustration, the configurations of **ISCAR**'s typical solid drill are shown in Fig. 9.28.

Fig. 9.28.



Cutting edge configurations

Length Series

Solid round tools of the same type and the same diameter often vary in overall length within a family. According to the length gradation, there are short, medium, and long series types. Additional series such as extra-short or extra-long can also be applied. As a rule, short-length tools ensure highest strength and rigidity whereas extra-long solid carbide endmills are intended for long-reach applications.

Brazed Tools

We're all acquainted with carbide tipped drills for drilling holes in concrete, for household use. This drill gives a good example of a brazed tool. This tool has a steel body and a carbide cutting tip that is brazed onto the body.

The "golden age" of brazed tools in metalworking (Fig. 10.1) ended when cemented carbides (hard metals) were introduced featuring indexable carbide inserts.

Fig. 10.1.

Typical brazed tools. These tools prevailed in the carbide tool design for a long time.

When compared to solid carbide tool designs, the brazed tool concept, much like tools with indexable carbide inserts, enables the effective utilization of cemented carbides - expensive cutting material. In addition, this concept ensures high accuracy because the tool cutting edge is formed by grinding. A worn tool can be reground. These are the main advantages of brazed tools. At the same time, there are disadvantages that eventually lead to limited use of the brazed tool concept.

Brazed or Soldered?

Principally, brazing and soldering relate to the same process: joining various materials together using a molten metal (filler) between these parts, while the filler has a lower melting point than the joined materials. The main difference between brazing and soldering is the process operating temperature, which is lesser for soldering, and the type of a metal filler. A brazed joint usually features higher strength when compared with a soldered connection. When related to cutting tools, using the term "brazed" is more correct.

The weakest point of the concept is the brazing process itself. This process requires heating the parts that are intended to be joined by use of the brazing process. The thermal-expansion coefficient of cemented carbides is substantially lower when compared to steel. This difference results in considerable tension stresses in the carbide tip's, and poses risk of breakage.

Grinding plane surfaces with short carbide tips of a brazed tool creates no problems but generating a complex tip surface by grinding faces difficulties. This limits an effective chip former on the top section in comparison with indexable inserts.

Manufacturing brazed tools is a complex and time-consuming process which demands special equipment. Despite the undoubted progress in brazing technology, a brazed connection requires thorough post-brazing inspection and strength tests.

Fig. 10.2.

Single tube deep drilling head with brazed tips

Fig. 10.3.

CBN- tipped indexable turning inserts

Brazed tools are regrindable which is not a cheap process. After regrinding the position of the tool's cutting edge is changed, which demands setup changes. In indexable tools, replacing a worn cutting edge is performed by insert indexing or mounting a new insert. A worn brazed tool is removed from a machine and then sent for regrinding. Therefore, a new tool should be mounted on the machine to continue cutting. With this approach in mind, most companies using brazed tools stock redundant tooling.

Nevertheless, the brazed tool concept remains common (Fig. 10.2) especially if the tools are large-sized. In addition, brazing technology is used for fixing tips of expensive ultra-hard cutting material such as cubic boron nitride (CBN) or polycrystalline diamond (PCD) on indexable inserts or solid tools (Fig. 10.3 and 10.4)

Fig. 10.4.

Solid drills with PCD wafer (left) and PCD nib (right) for drilling composite materials

Exchangeable Solid Heads

Assembled tools with exchangeable cutting heads are found in between indexable and solid tool concepts. Of special interest are heads that are made of hard metals, which build a bridge connecting these concepts. As it may sound paradoxical, the definition “indexable solid carbide tools” is well suited for various families of assembled tools with carbide heads.

A good example of such families is the **MULTI-MASTER** indexable solid carbide heads (Fig. 11.1).
The three-principles of the **MULTI-MASTER** concept are based on the face contact between a carbide head and shank, centering the head by use of a short taper, and securing the head by a threaded connection. The face contact ensures the head overhang within strict tolerance limits, resulting in high dimensional repeatability of the assembly. Taper centering provides a high accuracy level. The thread connection makes replacing the heads simple and operator-friendly.

MULTI-MASTER tools meet the requirements of the important “no-setup time” principle, as replacing a worn head does not require additional setup operations. The head can be changed without removing a tool from a machine, which significantly decreases downtime. The **MULTI-MASTER** unified thread connection allows the tool bodies, called “shanks”, which carry different cutting heads and vice versa, converting the shank to a universal holder consequently reducing both tool inventory and storage.

MULTI-MASTER covers a broad-spectrum of applications in milling, hole making, engraving, and gearing. In milling operations, these include square shoulder, faces, 3D surfaces, chamfers, cavities and pockets, slots and grooves, threads, and machining by high-speed- (HSM) and high-feed (HF_M) milling methods. In holemaking operations, center and spot drilling, countersinking, etc.

Fig. 11.1.

MULTI-MASTER products

The **MULTI-MASTER** tool family features a wide variety of integral shanks with different types of adaptation such as the HSK taper (DIN 69893, Form A), **CAMFIX** polygonal taper (ISO 26623-1) or a taper for direct clamping in ER collet chucks.

This expands mounting options by ensuring rigid and secured axial and rotational movement that minimize the tool overhang. These features contribute to highly effective machining, particularly for serial and large-volume production related to small parts on multi-tasking machines and driven-tool lathes. In addition, the wide choice of extensions and reducers ensures tool configuration for machining hard-to-reach part areas.

Material of the MULTI-MASTER Shanks

The shanks – the **MULTI-MASTER** tool bodies - are produced from the following materials: steel, tungsten carbide and heavy metal (an alloy containing 90% and more of tungsten).

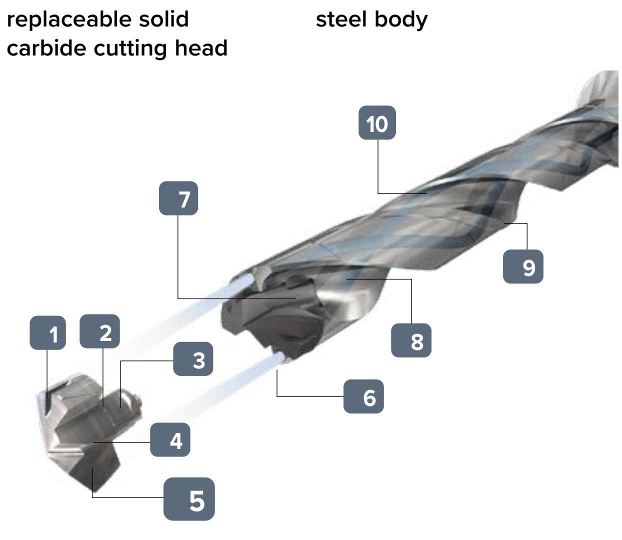
In the context of functionality, a steel shank is the most versatile. Due to the stiffness of tungsten carbide, a carbide shank is intended primarily for finishing and semi-finishing, machining at high overhangs and milling internal circumferential grooves. In case of unstable cutting, applying a heavy metal shank provides good results due to the vibration-proof properties of heavy metal. However, heavy metal shanks are not recommended for heavy-duty machining.

MULTI-MASTER heads provide a good illustration to “bridge” between the indexable and solid tool concept. Combining two head types complements two design approaches: fully ground heads made from solid blanks, and heads made from pre-shaped sintered inserts. Having a wide variety of heads, shanks, adaptors, and reducers makes it much easier when choosing the correct tool configuration for a variety of metal cutting operations. Apart from that, the line and its products are ideal for tailor-made products, which makes tool customization much easier.

All of this turns the robust **MULTI-MASTER** line into an effective tool product that successfully combines the advantages of indexable and solid designs.

Twist drills with exchangeable carbide heads are another Example: In the **SUMO-CHAM** drill family (Fig. 11.2), the replaceable heads are mounted on steel bodies by a self-clamping mechanism that is based on the elastic properties of a tool body. The exchangeable head concept enables mounting the same head on bodies with different drilling depths (Fig. 11.3). Also, a body can carry the heads with different cutting geometries that are intended for machining specific material groups or drilling flat-bottom holes.

Fig. 11.2.



1. grooved for clamping key
2. precise centering surtace
3. axial stopper
4. radial stopper
5. flute specifically desinged for effective chip formation
6. frontal coolant
7. advanced pocket design
8. twisted coolant channel
9. high-strength steel grade
10. polished specially shaped flute

The structure of a SUMOCHAM drill

A **SUMO-CHAM** head has a common two-lip drill design, and a drill body features two flutes accordingly. To increase productivity, especially when drilling materials that produce short chips, the **SUMO-CHAM**'s younger sister the **QUICK-3-CHAM** family of drills with exchangeable heads, utilizes another tool assembly, a three-lip head mounted on a three-flute body.

Self-Clamping Breaks New Grounds

SUMOCHAM and its drill families are based on the self-clamping design principle being an exchangeable cutting head secured in a drill body by the tool body's elastic forces. In the 1970s, the manifestation of this principle in the **SELF-GRIP** parting tools resulted in a big breakthrough for parting and grooving. With the appropriate level of technology, a new round of self-clamping - applying the **SELF-GRIP** heritage to drilling – has proved again the great potential of this principle and has opened new promising prospects.

Fig. 11.3.

SUMOCHAM drills of different depth series

In both the families, the complex shape of heads is a combination of two tool technologies: indexable and solid. The shape is pre-formed by powder metallurgy methods, and then only specific surfaces that require high precision are ground.

Continuing the topic of holemaking, one more example of the exchangeable head concept can be given: a high speed reamer. In a typical high speed reamer of the **BAYO-T-REAM** family (Fig. 11.4), a multi-flute carbide head is mounted on a body with the use of a quick-change bayonet mechanism. Depending on the type of machined hole (through or blind), the body can carry heads with different flute directions.

Fig. 11.4.

BAYO T-REAM high speed reamer

The main advantages of tools with exchangeable heads are as follows:

1. Versatility – a tool body can carry different heads, suitable for mounting on different bodies.
2. Easy-to-use – The head is replaced in a quick and simple way.
3. The “No-setup time” principle, featured in some tool family designs, enables replacing a worn head when a tool is clamped directly in a machine without additional setup operations.

Round Tool Concepts

Indexable, Solid, or Both

In this section, we summarize the aforesaid to examine the following subject: indexable or solid - which design concept of the rotating cutting tool is better? As in many subjects related to technology, there is no absolute answer to this question. However, a definite answer does exist if the advantages and disadvantages of both concepts are considered according to specific conditions.

An assembled tool carrying removable indexable inserts, a concept that has become common in the industry since the 1960's, requires cutting capabilities from one of its components – the insert. The cutter body acts as a holder for inserts of a specific shape produced from different hard-to-machine tool materials (for example, cemented carbide grades, cubic boron nitride (CBN), cermet etc.), while the body itself is made of steel.

Fig. 11.5.

Modern technology of powder metallurgy enables producing indexable inserts for complex shapes.

The inserts differ in their chip forming surface, to generate the necessary cutting geometry. Clamping the insert, which features the geometry and material suitable for cutting the workpiece, results in an optimal cutting tool for the workpiece. The insert possesses several cutting edges. If one edge is worn, it can be replaced by indexing the insert by means of rotation or reversable action. The indexable principle ensures cost-beneficial utilization of the tool material.

The insert is formed by powder metallurgy technology to create the unique shape of the chip forming surfaces, whereas obtaining this shape by other technology methods is extremely difficult to form exceptionally strong cutting edges capable of withstanding heavy work loads.

At the same time, an indexable tool has definite disadvantages. Firstly, its accuracy is lower compared to a solid cutter. Secondly, the tool diameter cannot be small (for example, less than 8-10 mm or .315-.375 inches). Reducing the diameter leads to diminishing the size of all assembly components, including the insert and its clamping elements (usually a screw), which have a natural dimensional barrier.
In addition, the insert cutting edge is strong but not as sharp as that of a solid tool.
For machining soft materials, like copper, commercially pure titanium, or aluminum, which require a sharp edge, additional edge grinding needs to be performed.

Fig. 11.6.

Solid endmill from ceramic cutting material

The main advantage of a ground solid tool is its high precision: being higher than that of an indexable cutter. A solid tool cannot be indexed but is suitable for regrinding.

Like an indexable cutter, a solid tool also has dimensional limitations that relate to the tool cost. As opposed to the indexable concept, the solid tool cannot be large in diameter, usually the diameter of the solid tool does not exceed 25 mm or 1.000 inches - or in overall length. This type of tool demands significantly more tool material, and takes more time to manufacture by grinding. These constraints lead to a substantially higher tool cost. By contrast to the indexable tool, the cutting edge of the solid tool is sharper but less strong.

Fig. 11.7.

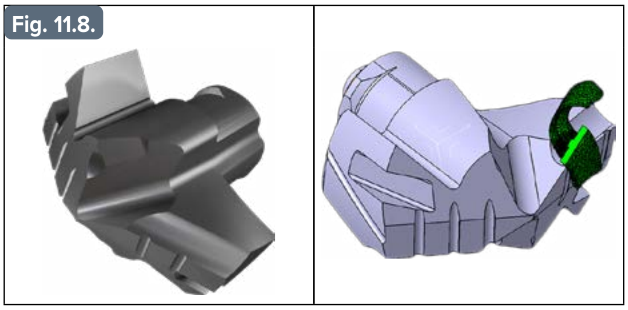
Drills: solid carbide drills and a drill with exchangeable carbide heads (in the center)

The machined surface dimensions may dictate which concept should be applied to an operation. For example, for drilling a hole of 3 mm (.12 inches) in diameter a solid drill will be used. Aside from this dimensional aspect, the following principles characterize correct tool selection.

For heavy cuts (usually rough or semi rough), featuring significant cutting forces and power consumption, imply that an indexable tool is the preferred solution. If an operation features light cuts and demands high accuracy and surface finish, a solid tool is required.

The past few years have seen a dramatic change in this traditional concept. The search for new solutions to improve productivity, combined with advances in machine tool engineering, has created efficient cutting strategies and appropriate machines. A significant number of modern machines have less power but far higher speed drives and advanced computer numerical control units for high speed machining, performed by small-diameter tools moving at optimal trajectories for constant tool loading. This step, together with progress in regrinding and recoating technologies, represented a second wind for solid tool use by opening new options in rough machining. Advances in tool materials have increased the hardness level of machine workpieces. Today, solid carbide endmills, operated by high speed milling techniques, are capable of successfully cutting hard steel up to HRC 65.

Fig. 11.8.



Chip flow modelling is an important factor in designing chip forming surfaces of a SUMOCHAM drilling head

Tool manufacturers recognized the advantages of combining both solid and indexable concepts into a single design to meet the latest developments. Tools with exchangeable heads made from solid carbide, such as **ISCAR**'s **MULTI-MASTER** and **SUMO-CHAM** tool families, represent this beneficial combination. In these families, a cutting head can be mounted on different bodies, and a body can carry different heads. This "indexable solid" principle enables a myriad of options for a tool configuration.

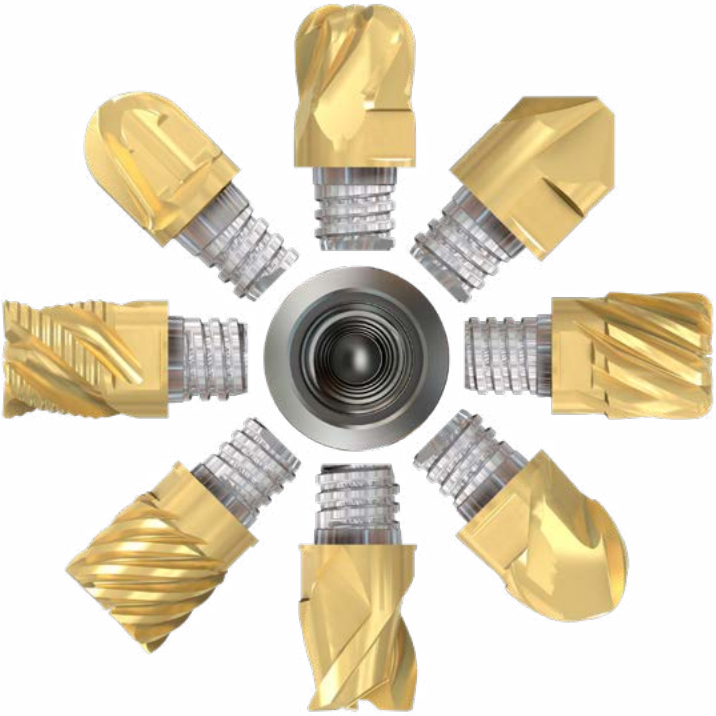
So, which concept is better? Industry requires both types of cutting tool, depending on processes of technology. The ratio of indexable tools to solid and "indexable solid" tools in today's market is estimated at 1:1, which indicates how cutting tool development is progressing in both directions. But technological advances and improvements in processing will make tool requirements, whether solid or indexable, more demanding.

Modular Tools

Modular systems have succeeded in finding their way into the lives of many people, from LEGO construction toys to IKEA's modular furniture.

In metalworking, typical examples of these systems are unit-built machines and modular fixtures. As for cutting tools, modular structures have proven their efficiency in this area as well, and various tool manufacturers have developed their own modular products, which are popular with their customers.

The main benefits of modularity are versatility and time-savings. A modular concept facilitates the quick and easy building of an optimally customized cutting tool using an assembly of standardized elements. If a tool is required for immediate production, a suitable solution is close at hand. This concept contributes to reducing warehouse stock and diminishing inventory lists that cut manufacturing costs.



However, the modular tool concept is not free of disadvantages. The main disadvantage is the reduction of rigidity; an assembly of several elements is not as stiff as an integral product and the assembled structure may lose accuracy compared to a one-piece design.

When deciding on a particular tool, both advantages and disadvantages of the modular concept need to be considered. The customer decides which is the best tool for his needs based on production strategy, current production demands, or an immediate need for a tool. The cutting tool manufacturer should provide the customer with the means to make the correct choice and at the same time continue to develop modular products that achieve greater adaptability, rigidity, and accuracy. A glance at some of modular cutting tools makes it possible to showcase the design features of a product.

FLEX-FIT family of tools (Fig. 12.1) is **ISCAR**'s oldest modular line. The **FLEX-FIT** adaptation principle is based on using a cylindrical connection for centering and general-purpose

Fig. 12.1.

FLEXFIT modular tool family for various assembled milling cutters

standard metric thread (M8...M16) intended for securing. Simplicity and maintainability have made this rotating tool system very popular in the market. Today, **FLEX-FIT** has a wide variety of shanks, adapters, and heads with indexable inserts, which are mostly used in milling operations, such as machining complex 3D surfaces, slots, and grooves. The shanks are made from steel and cemented carbide. The carbide shanks increase rigidity, which substantially reduces vibrations especially in long overhang applications.

Fig. 12.2 shows some elements of a modular turning tool system that comprises round bars, exchangeable heads with indexable inserts, and housing adapters. The system was initially intended for boring, although when selecting a boring bar, the ratio of a required bar overhang to the bar diameter strongly influenced the choice of the right tool.

Fig. 12.2.

Elements of a modular turning tool system with anti-vibration round bars.

There are three types of bars to cover the complete range of boring applications for overhang-to-diameter ratios of up to 10. Steel bars enable machining with ratios of up to 4. Cemented carbide bars facilitate boring with ratios up to 7. However, when machining where a higher overhang is required, the use of a stiffened carbide shank can be limited.

For the ratios of ratios 7 to 10, the system provides an anti-vibration bar that significantly reduces and eliminates vibrations when cutting. The key component of this bar is the damping mechanism that comprises a heavy mass supported by spring elements. The success of the bars with exchangeable heads in the boring line led to the introduction of this design concept in various applications such as turning, grooving, and threading. A housing adapter enables mounting standard prismatic turning tool holders for machining relatively big diameters. In addition, there are polygonal taper shanks to increase the application field of the system.

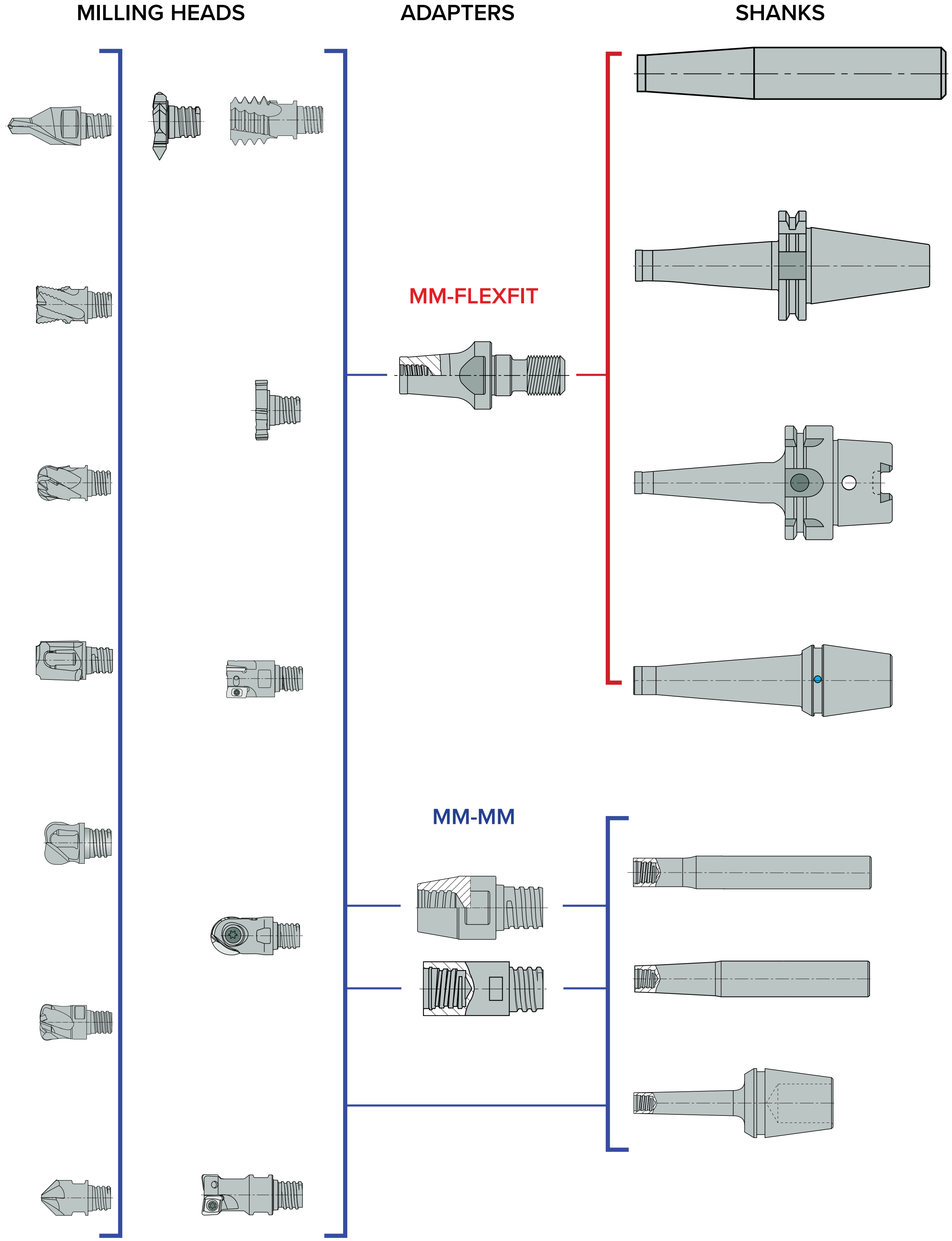
The **MULTI-MASTER** - family of rotating tools with exchangeable heads consist of a wide range of shanks, extensions, adapters, and reducers and can be considered as a modular tool system. (Fig. 12.3).

The original **MULTI-MASTER** design focused only on solid carbide heads. Within a very short time the family expanded with various heads carrying indexable inserts. Specially designed **MULTI-MASTER** adapters and **FLEX-FIT** mutual connections substantially expand the application range for both families.

Modular cutting tools are more common in the metalworking sector and feature a wide range of products for the success of small-to-medium run production in die and mold making.

A flexible modular concept ensures the ability to quickly find effective tool solutions when a product program is constantly changing. The impact of a smaller tool inventory attracts large manufacturers. Consequently, new developments focusing on reliable, accurate, and digital modular tools to meet industrial needs will remain relevant.

Fig. 12.3.



The MULTI-MASTER as a modular tool system

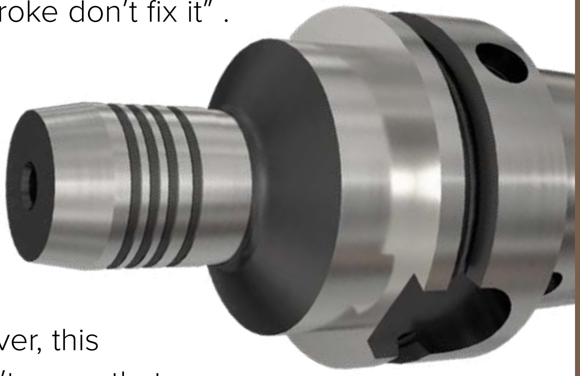
Trends in Toolholding

A toolholder is a device for mounting a cutting tool on a machine tool. One of the toolholder ends carries the cutting tool while the other end is clamped to the machine tool. Therefore, the toolholder acts as an interface between the machine tool and the cutting tool. Toolholders ensure proper clamping of the cutting tool in the spindle or tool changer magazine in a machine tool. They also facilitate the torque transmission from a machine spindle to a rotating tool. The metalworking industry has compulsory standards that specify the matching surfaces for both these purposes. These standards define a wide range of toolholding systems to meet different manufacturer requirements. The standards include simple holders for manual (by hand) tool changing on conventional machines, all the way through precise high grade – balanced – tool holders/adapters for high-speed machining applications. This variety of tool holding provides the manufacturer with effective tool holding solutions, depending on production targets and available machinery. Established tool clamping principles require wide interchangeability and unification, and normalized designs of machine tool adaptations have resulted in well-defined standards that specify detailed tool holder parameters. Fig. 13.1 and 13.2 are examples of toolholding systems for non-rotating and rotating tools.

Tool Language Studies: HSK

The abbreviation "HSK" has German origin, and it refers to "Hohlshafte Kegel" or "hollow shank taper" in German.

In general, toolholding equipment has not undergone dramatic shifts for a long time. Although there have been some notable advances such as the introduction of quick-change tooling in the 1970's and the appearance of modular systems using polygon taper coupling (specified as the ISO 26623 standard) and systems based on HSK adaptation for high rotational speeds in the 1990's, tooling development can be regarded according to the old saying: "if it ain't broke don't fix it" .



However, this doesn't mean that new innovations and development are over. Time puts new demands on machining, which has transformed to new requirements for machine tools, and consequently to cutting tools and toolholders – both elements of a chain that enable recognition of machine tool capabilities when machining parts of a surface. The toolholder relates to the most "conservative" link of the chain and has undergone fewer revolutionary changes for the noted reasons.

Industry digitizing and the INDUSTRY 4.0 philosophy, have had a serious impact on toolholding. Smart manufacturing of tomorrow demands intelligent toolholders to exchange data in the world of the Internet of Things (IOT). This will lead to creating new information capabilities of toolholders by adding more and more electronic units. Even today, built-in chips provide various data about a toolholder that communicates with machine tools, industrial robots, storage devices, and more.

Adding a new data function is no doubt an extremely important direction in toolholding development. However, R&D, and seeking improvements to toolholders as a mechanical system are far from being extinct.

Engineered Balance

Engineered balance is a general name for design methods to make the mass distribution of a rotary body theoretically symmetrical with the body axis.

Using these methods, engineers tried to ensure required balance parameters in the design stage before production.

3D modelling in a CAD system environment significantly expands the engineered balance possibilities.

As the engineered balance relates to virtual objects, it cannot replace a "physical" balancing of real parts. However, an engineered balance design substantially diminishes the mass unbalance of a future product and makes "physical" balancing much easier.

Engineered balance principles are a necessary feature for the skillful design of rotary tool holders.

Recent improvements in toolholder designs are distinctly seen in the following areas.

1 **Heat Shrink Chucks**
High-speed machining (HSM) methods have brought tool balancing requirements to new heights. In HSM, the dynamic characteristics of tool cannot be separated from a toolholder, and a particular focus should be given to the assembly of the tool and the toolholder. Minimizing the unbalance of an assembly is one of the challenges that tool developers face. They have tried to guarantee the required balance parameters at the design stage before production. This engineered balance design cannot replace the "physical" balancing of a real assembly, and substantially diminishes the mass unbalance of a future product that makes "physical" balancing much easier. Axisymmetric heat-shrink chucks optimally meet the requirements of a balanced toolholder for HSM at the design stage. This explains why the advance of heat-shrink chucks is of priority.

2 **Coolant Supply**
Pinpointed coolant supply through the tool body, when a coolant flow is directed to a cutting zone, significantly improves machining performance. The industry requires more advanced toolholders with inner supply options, especially for machining with high pressure cooling (HPC).

3 **Modular Quick Change Tooling**
A modular design principle considerably simplifies finding the optimal configuration of a tool assembly and diminishes requests for special tools.

4 **Long Reach Applications**
Long-reach machining applications, which require high overhang of a tool assembly, feature poor stability. Increasing vibration strength of the assembly is one more trend of toolholder development.

5 **Polygonal Taper Connection**
The ISO-standardized polygonal taper adaptation has proven itself common in multitasking machines and turning centers.

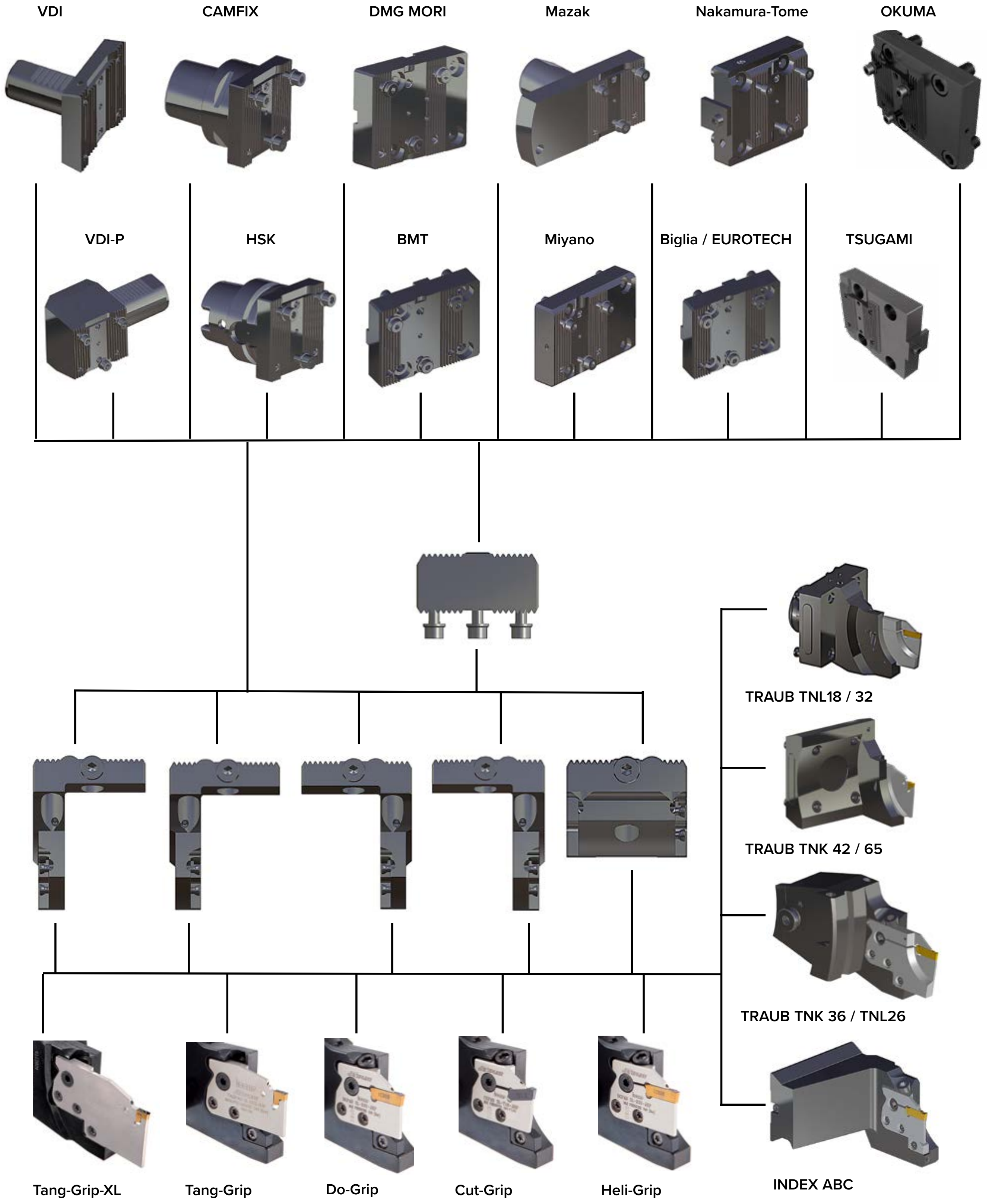
Toolholding and Tooling: Are They Synonymous?

"Toolholding" usually relates to tool holding systems that comprise various toolholders, such as arbors, chucks or adaptors, and their accessories (extensions, reducers, rings, sleeves. "Tooling" is a much broader definition. "Tooling" can refer to cutting tools together with tool- and work holding arrangements that are intended for a machine tool. "Tooling" relates sometimes to tool management and in certain circumstances it refers to toolholding systems.

These are only a few of the high-profile directions for developing toolholders. The others are focused on high-torque transmission, preventing tool pull-out because of the high axial component of the cutting force, increasing accuracy and more ergonomic solutions. The conclusion of a seemingly stagnated mechanical design of toolholders is incorrect.

Fig. 13.1.

System Overview



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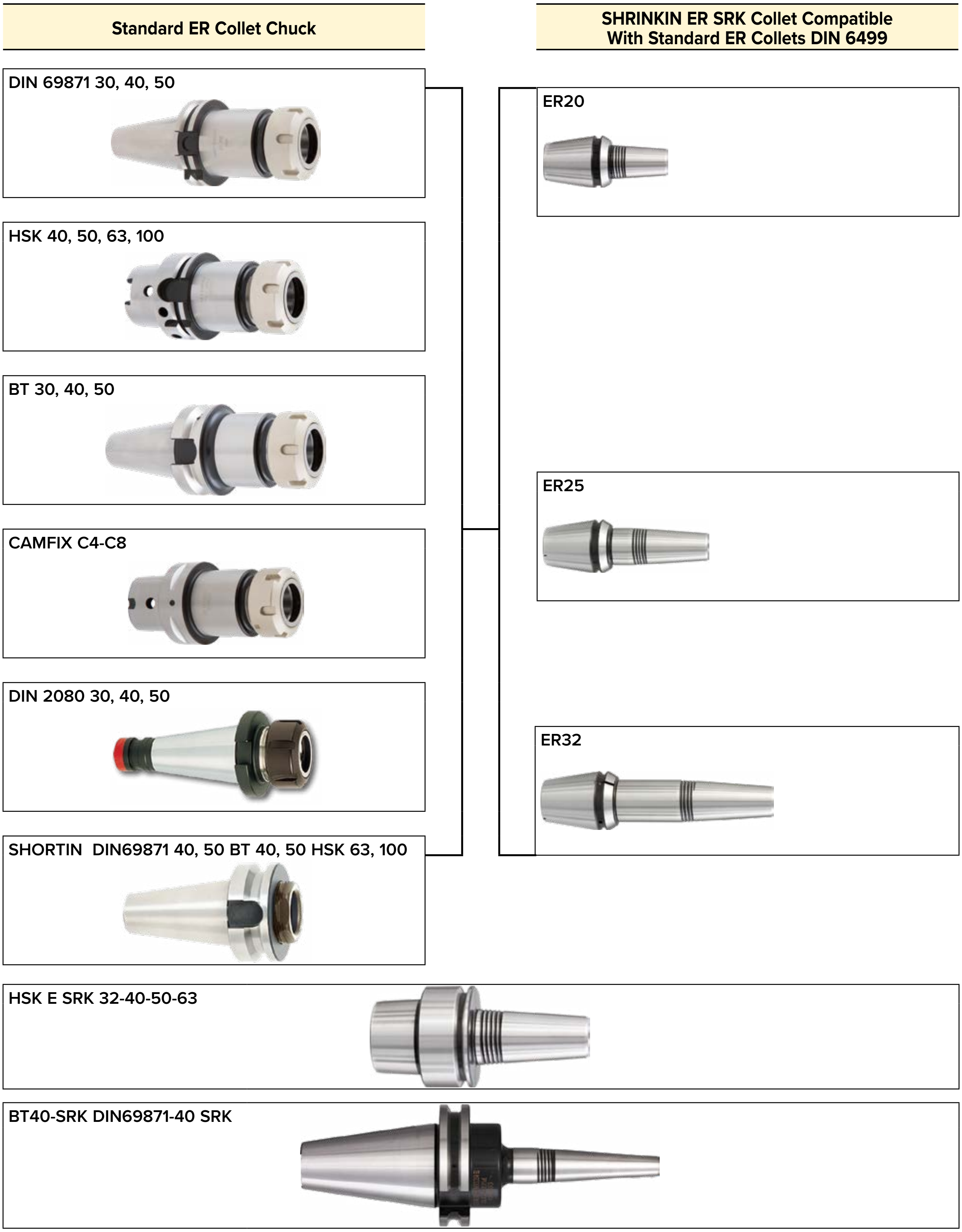
ISCAR modular toolholding system for turning lathes

Fig. 13.2.



ISCAR thermal shrink chuck toolholding systems

Tools Inseparable Digital Companion

Rows of CNC machine tools sharing their workspace with industrial robots that transport machined parts, accompanied by a minimal number of machine operators, are already a common scenario that depict modern metalworking plants and shops. CNC machines are the catalyst which created progressive computer data engineering to enable this new reality. Advanced multi-axis machines facilitate the production of very complicated shapes with minimal setups. Advanced milling and turning capabilities, coupled in multitasking machines, open new opportunities for effective process planning. Innovative CNC metal cutting systems are on the verge of a one-set full part production – the ultimate dream of every manufacturer. A quantum leap in CNC technology enables the practical understanding of machining methods that have been theoretical for a long time, such as power skiving.

The progress in the world of computerized numerical control is impressive. It has impacted related spheres such as work and tool holding, and the diverse world of cutting tools.

Industry 4.0

The term "Industry 4.0," can mean different things to different people and there is often some confusion about the meaning of the words.
Originally, "Industry 4.0" ("Industrie 4.0") was the title of a German governmental strategic initiative for impactful digitizing of national manufacturing industries for the next 10-15 years. A source of irresistible inspiration to even the most cynical industry players, the Industry 4.0 concept has brought. The ideas of complex computerization and production automation, information exchange between industrial process systems, and decision-making processes to new and formerly unattainable levels.

What are the expectations of machine tool producers from the cutting tool producers? What are the requirements that modern cutting tools must meet? How should tool manufacturers be driven when planning their production program for the near future? The answer is simple... The next generation of tools must be better! To cut faster, to provide longer tool life, to ensure better surface finish and more. These are obvious and undoubted demands which every tool manufacturer needs to contend with to assure its future. However, the progress in CNC technology has highlighted one more feature in tool design being the digital component. This virtual element has turned into an integral part of tomorrow's cutting tool.

The contemporary evolution of smart manufacturing is based on network technologies. In a smart factory, CNC machines perform under the conditions of real-time and combine mutual information exchange from an environmental context that blends both real and virtual worlds. The systems interact with the context via the Internet of Things referred to as IOT. For example, the real world shows the position of a cutting tool and acting cutting forces, while the virtual world specifies 3D tool paths during an operation combined with predetermined machine stock allowance. Subsequently, the real and virtual worlds find themselves in a cutting tool where they complement each other.

A digital tool component possesses vast amounts of information or data. Its elements are comprised of 3D and 2D models, estimated tool life, accumulated cutting time, possible limitations such as maximum rotational speed, optimal machining data and additional essential information. Tomorrow the gate of a smart factory will be closed for tools without such components, consequently cutting tool manufacturers have started to prepare and adapt for these changes. The virtual element is now focusing on the development of new tools and tooling solutions.

For centuries, technical drawings were considered a common language for defining tool features. Computer aided engineering (CAE) and CNC systems require another means for data exchange. Cooperative efforts of world specialists from various engineering and scientific fields have resulted in the creation of the ISO 13399 standard, which specifies computer representations of information related to cutting tools, their holder which the lexicon base of the language. Adherence to this standard means that the tool digital component's platform remains independent, and computerized systems can utilize the data seamlessly. This new standard is only the first sign.

The smart factory will require additional smarter manufacturing systems and smarter tools for these systems. Information about tool properties, such as the remainder of its tool life period, specific tool identification, service limitations necessitates uniform rules for specifying the information and its computer representation – like the ISO 13399 standard, yet more comprehensive. These will require the intensive cooperation of companies and governmental institutions.

Fig. 14.1.

Modern cutting-edge tool manufacturing is unthinkable without advanced CNC machines

Today, cutting tool customers expect to receive not only a tool as the physical product, but also quick access to accompanying information such as virtual assembly options for collision checks, finding the optimal tool configuration, clear machining data, and learning how changing cutting parameters will reflect on tool life. This has already formed the virtual tool component, and its significance will only grow.

Information has constantly accompanied cutting tools even before the distinct digitizing of metalworking and INDUSTRY 4.0. catalog data, tool drawings, and recommendations regarding applications which were provided in printed formats and later as electronic formats and continue to be essential for metalworking. Computerization has affected customer support by providing expanded capabilities in the form of data. Various software applications have enabled selecting optimal tools and estimating tool life under specific machining conditions. For example, **ISCAR**'s Machining Power Calculator applications enables quick calculation of cutting forces, bending load, and power consumption. Customers can easily access data and related information by use of computers and mobile devices. Notwithstanding, advancements in network communications have introduced the world of metal cutting to the virtual electronic world.

Digital representation (digital twin) technologies complement manufacturing processes. Machining modelling, collision checking, process optimizing to find the best cutting strategies are only some examples. In a smart factory, the digital twin is the most significant brick of the foundation. Understandably, only a tool having its digital twin is acceptable for the smart factory's toolroom.

The progress of CNC technology leads to new demands for cutting tools. A tool producer is expected to be a provider of a product that ideally combines a tool as a material object, its real-time digital twin, and an appropriate software environment. This allows the seamless incorporation of the tool data in CAD/CAM and virtual manufacturing, direct transmitting by Internet of Things (IoT) networks - tool packages and virtual assemblies.

Fig. 14.2.

3D Representation

○ Light ● Detailed

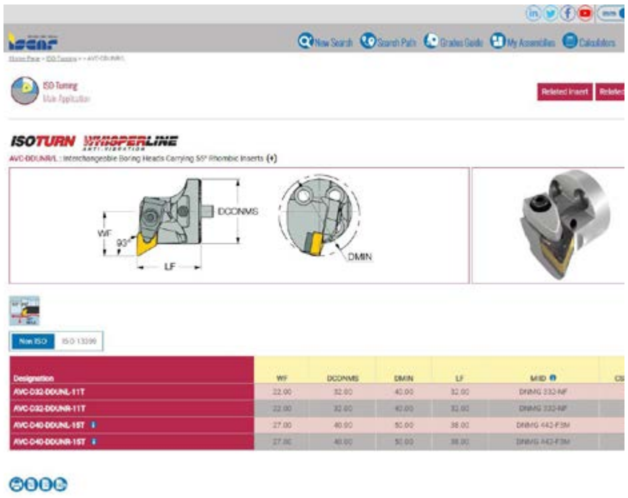
In process planning, virtual assmbly options enable finding an optimal tool configuration and simulating the tool path

ISCAR's Digital Tool Component

Today **ISCAR**'s digital tool component, which is based on the ISO 13399 standard, includes the following characteristics:

- E-catalogue with various search functions, updated promotion information and reference data.
- The .p21 file (a STEP file) comprising a product identification class for a comprehensive tool data representation and exchange.
- 3D tool representation for computer modelling and CNC programming in accordance with the ISO 10303 standard (STEP).
- A 2D tool representation in DXF format for a planned process documentation, drawings, tool layouts and setup sheets.
- Virtual tool assembly options for turning, milling and holemaking tools intended for generated digital assembly twins in both 3D and 2D representations.
- NEOITA – **ISCAR** Tool Adviser, an expert system that recommends optimal tooling solutions for a specific application.
- The machining calculator and the cutting material grade optimizer software applications.

Fig. 14.3.



AVC-DDUNR/L : Interchangeable Boring Heads Carrying 55° Rhombic Inserts (+)

Designation	WF	DCONMS	DMIN	LF	MIID
AVC-D32-DDUNL-11T	22.00	32.00	40.00	32.00	DNMG 332-NF
AVC-D32-DDUNR-11T	22.00	32.00	40.00	32.00	DNMG 332-NF
AVC-D40-DDUNL-15T	27.00	40.00	50.00	38.00	DNMG 442-F3M
AVC-D40-DDUNR-15T	27.00	40.00	50.00	38.00	DNMG 442-F3M

p.21 files, 3D and 2D tool representations, and other virtual products for advanced CNC technology, form ISCAR's digital tool package

Looking for the Optimum Tool

How are the manufacturer's expectations from cutting tool producers defined? Cutting tool producers are expected to provide optimal cutting tool solutions for a given application. So, how is an optimal cutting tool defined for a specific application? It is obvious that standards must be set to achieve a formidable solution. Cutting tool standards are also defined by principles to enable choosing the best possible tool for a given application. Technical literature often states one tool or another as being optimal for an application. Therefore, a clear definition of the optimal standard is essential.

The criteria for finding the optimal cutting tool depends on various factors. The type of manufacturing (short-run, large-scale, mass), product range, machined materials, machinery used, cutting strategies and more have a direct impact on the manufacturer's selection of the most effective tool. The manufacturer is interested in a tool that guarantees the highest performance levels. This can be achieved by optimizing the tool geometry and producing the tool from the most relevant cutting material grade. But the chosen geometry and grade are tool key elements associated with the type of machined material. So, what is the ideal tool for cutting? An example of an effective tool for machining cast iron, will likely not be the best solution for machining heat-resistant superalloys.

Manufacturers are faced with constant dilemmas for machining vast choices of workpieces of different shapes and dimensions. The profile of a given application may dictate a long-reach tool, whereas in other cases the large overhang of the tool will have forced limitations that decrease machining stability which inevitably affects performance.

Selecting the optimal tool is one segment of many that relate to the core of the problem critical for all machining processes, which no doubt maximizes how to machine profitability. To reach this goal, various interdepended factors are considered such as the effective use of machine tools, competent process planning, available work-holding fixtures, and tool stock management among others. All factors are subject to optimization and finding the appropriate tool may prove to be an integral link to accomplishing the task.

Modern production abilities feature highly engineered CNC machine tools with advanced capabilities. New age premium machines are costly and reduce machining cycle time which in turn diminishes production costs.

An ideal cutting tool should provide maximum productivity in combination with reasonable and stable tool life. To determine the appropriate solution, tool manufacturers develop advanced cutting geometries and new cutting material grades that enable reliable cutting at high metal removal rates (MRR) for diverse types of machining data. As the tool is expected to enable effective machining of different engineering materials, the geometry and the grades should be optimized accordingly.

Decreasing machine downtime is one more way to reduce production costs. The appropriate waymarks, which relate to tool attributes such as ensuring tool availability and minimizing setup time, can greatly contribute to the solution. Tool delivery is crucial for replacing "suitable" with "optimal".

By saying, "the best tool is the one you have on hand", one can understand important metalworking principles, making the ideal tool readily accessible.

In a perfect world, the ideal tool facilitates machining various workpiece shapes on long- or short-reach applications without loss of performance. Tool customizing is an additional parameter for finding the optimal solution.

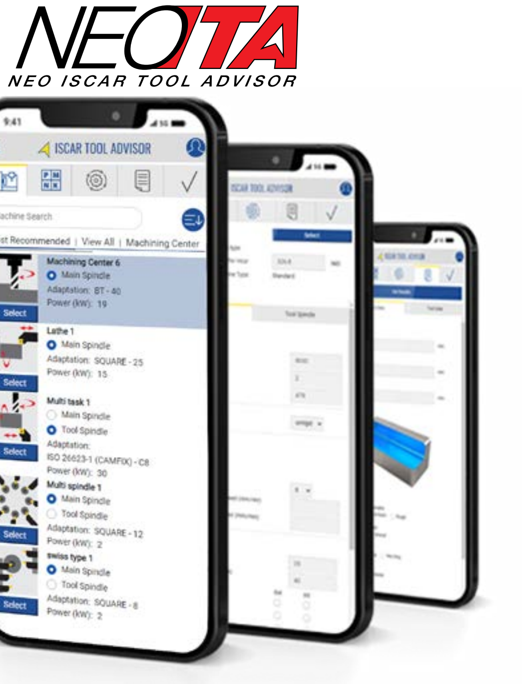
Advanced machines are expected to integrate optimal machining strategies. These strategies are planned, programmed, checked, and verified in a virtual environment of computer-assisted engineering (CAE) systems well before the process begins on a CNC machine. Therefore, the right tool should have an appropriate virtual component, a digital twin, to be embedded in CAE systems.

NEOITA – ISCAR's Tool Advisor

ISCAR's Tool Advisor, known as NEOITA, is a parametric search engine that "thinks" like a process engineer and allows finding the right tool based on the accumulated knowledge of best practice worldwide. This system enables searching for an optimal tool intended for a specific machining operation. With the use of engineering analysis and expert knowledge, NEOITA generates a set of more efficient solutions with suitable cutting data, calculates metal removal rate (MRR), machining power, facilitates direct access to the e-Catalog, insert wear detection, and more.

A responsive design application has brought NEOITA to handheld devices. Through cloud-based technology, the NEOITA is available 24/7 and in multiple languages

Fig. 15.1.



Machining Center 6
● Main Spindle
Adaptation: BT - 40
Power (kW): 19

Lathe 1
● Main Spindle
Adaptation: SQUARE - 25
Power (kW): 15

Multi task 1
○ Main Spindle
● Tool Spindle
Adaptation:
ISO 26623-1 (CAMFIX) - C8
Power (kW): 30

Multi spindle 1
● Main Spindle
○ Tool Spindle
Adaptation: SQUARE - 12
Power (kW): 2

swiss type 1
● Main Spindle
○ Tool Spindle
Adaptation: SQUARE - 8
Power (kW): 2

NEOITA, the ISCAR Tool Advisor expert system available for mobile phone use

Instead of Afterwords

Cutting Tool Value and the Logic of Cutting Tool Development

Cutting Tool Value

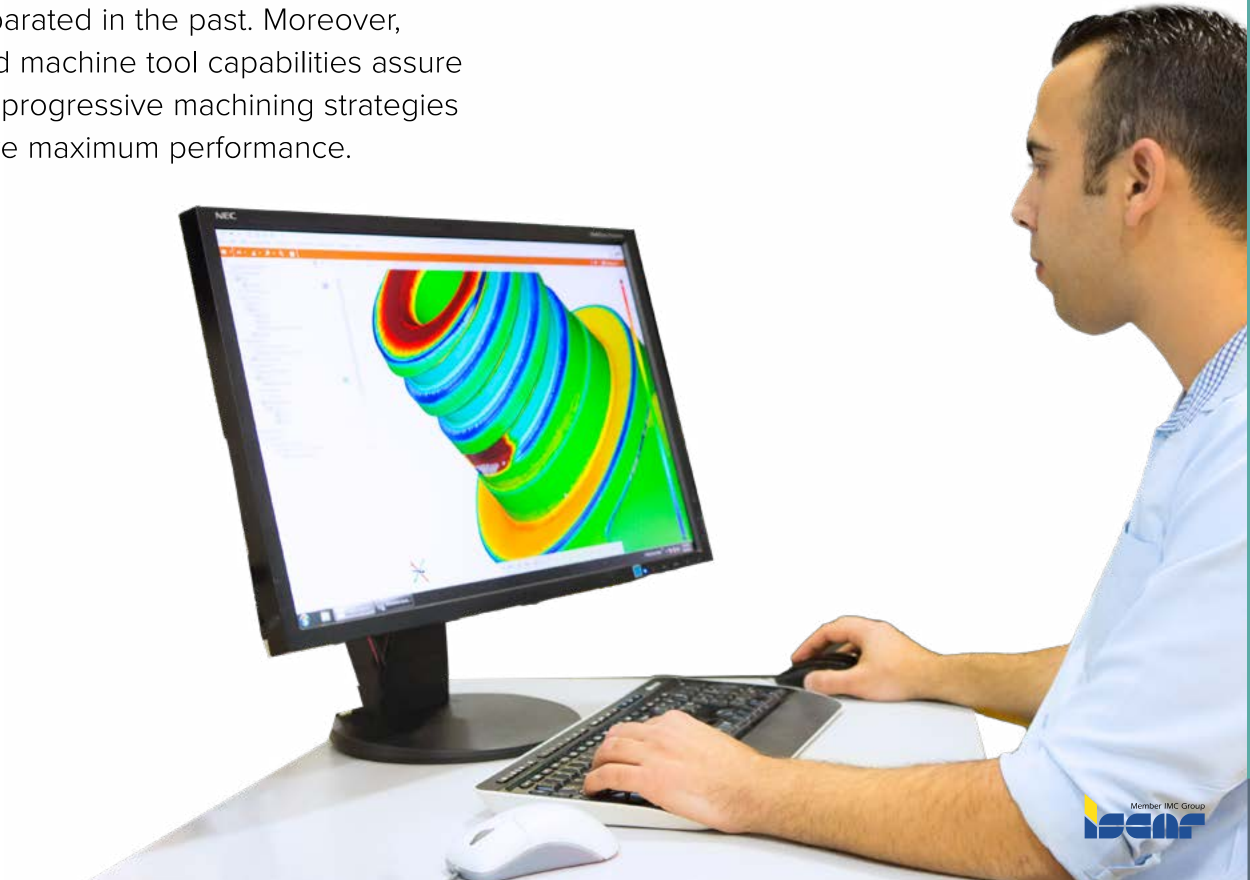
Let's imagine the shop floor of a modern metalworking plant. Innovative highly engineered CNC machine tools produce complex parts from workpieces that are clamped in sophisticated fixtures.

A cutting tool that forms the parts cannot be seen due to its position inside the machine. In machining, cutting tools shape parts by means of material removal.

The system comprises a machine tool, a workholding fixture and a tool holding device. Shaping a part is performed by various machining processes that use different cutting strategies. The progress made in machine tools resulted in modern machines that enable combined and whole process operations; processes that were separated in the past. Moreover, advanced machine tool capabilities assure applying progressive machining strategies to achieve maximum performance.

A cutting tool is generally the smallest and least expensive element of the technological system.

However, the true value of a tool to the system is much greater and the tool has a direct impact on the system's performance. What is the use of a high speed machine if the tool cannot work at those speeds? Stopping the machine randomly during the macining process is not an economical solution. Our goal is to cut faster to increase productivity and reduce machine downtime. This is way to decrease production cost. The tool is our way to overcome the productivity barrier and realize the full potential of an advanced machine.



A cutting tool, is the smallest element of the technological system that connects the part directly and provides the link between the machine and material. Realizing the advantages of high-tech machine tools and productive machining strategies, the cutting tool must meet appropriate requirements. Finding the answer to these requirements and in order to respond to the ever-growing demands of modern metalworking is the basis for new developments cutting metals.

The metalworking industry must deal with different engineering materials. Progress in material science and metallurgy brought new exotic materials and provided technologies to create materials with pre-defined properties. Producing components from such materials has significantly improved the working parameters of the parts, but machining has become more difficult. In many cases, the root of successful machining was connected only with cutting tool limitations.

Progress in technology has not stopped. Metalworking is at the door of changes, and the manufacturer should be ready to adopt them. The forthcoming changes cannot bypass cutting tool production - one of the more important links in the metalworking chain. Therefore, to have a clear understanding of the direction of industrial progress and the results of new requirements for the cutting tools of tomorrow is a cornerstone to assure the success of a tool manufacturer. This is the key to new tool developments and the demand for a wide range of products.

There are different directions for the development of cutting tools. The “traditional” way is to make the tools stronger, more productive, and cost-effective. Other directions of development are related to advanced manufacturing technologies embedded in the metalworking industry.

The Course of Nature

The traditional direction of development considers improving tool performance by introducing innovative cutting geometry, advanced tool material grades, progressive tool body designs to assure higher rigidity and durability. It may seem that this direction has almost depleted its resources and does not promise true revolutionary changes. However, cutting tool manufacturers have managed to surprise the metalworking world with substantially new products that provide significant benefits despite the traditional approach to the product design. An important success factor was the significant growth in scientific and technological levels of tool production, new achievements in powder metallurgy, coating technology, and the introduction of modern systems for inspection and quality control. The considerably increased capabilities of tool design itself, CAD/CAM systems, and 3D modeling, provide challenging innovative ideas.

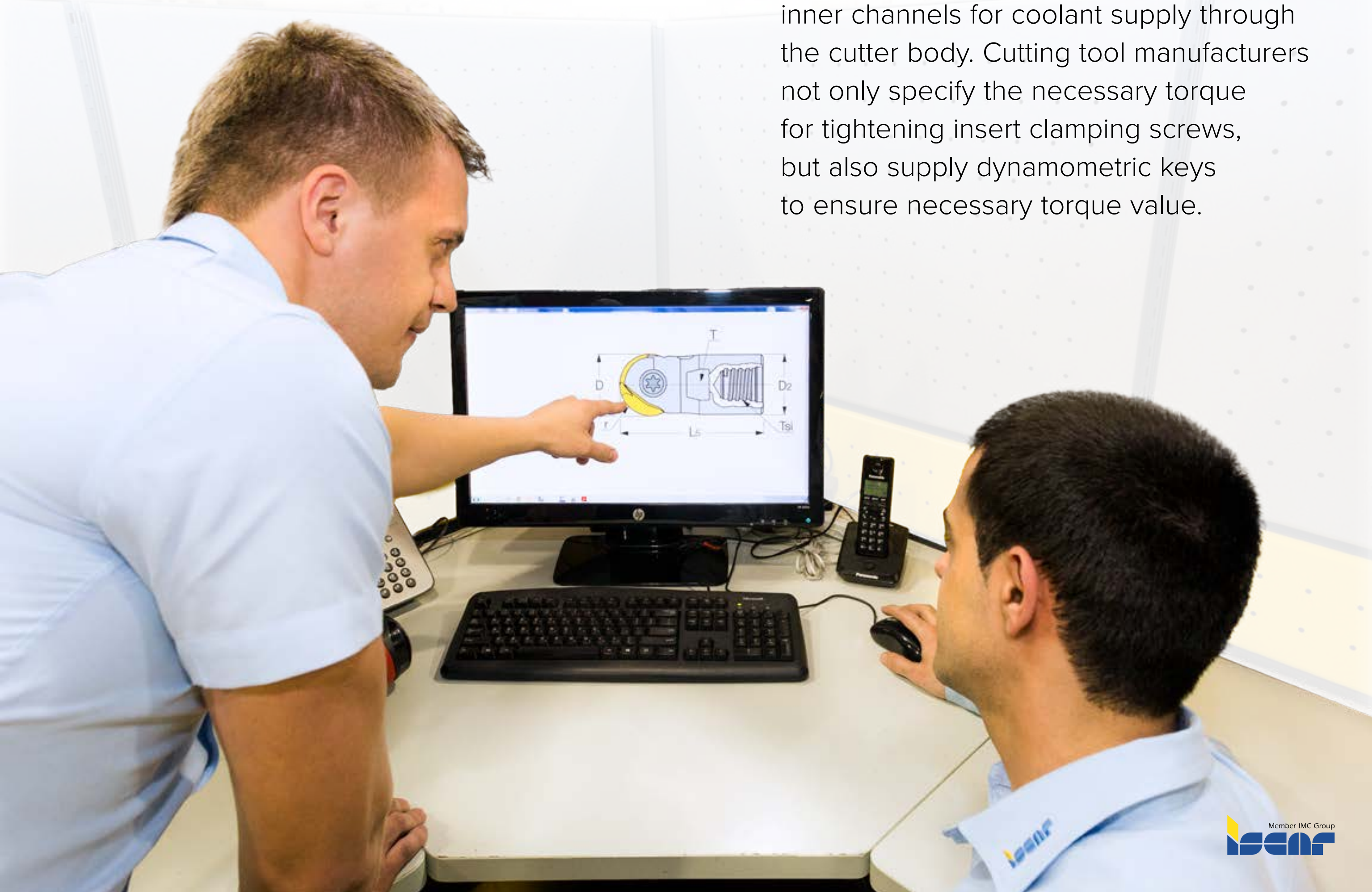
Technological developments have evolved new machining methods which require tools to meet new stringent demands. These tools should have the ability to cut hard metals while eliminating the need for grinding operations. The new age tools can contend with extremely high feeds (HFM) at high machining speeds (HSM) with the use of high-pressure coolant (HPC).

The design of such tools differs from general-duty tools as they require specific features that characterize the above-mentioned methods and strategies.

Advancements in machine tool engineering have pushed the metalworking industry closer to achieving one-setup production. Impressive capabilities of the latest multi-axis- and multi-tasking machine tools and hybrid manufacturing systems, which combine material removal and 3D printing technologies, give evidence of a quantum leap toward one-setup production. Driven-tool option features more and more turning centers by expanding their capabilities. Understandably, this progress leads to cutting tool and tool holder advancements that provide improved multifunctionality, tool life, and time-to-failure characteristics.

The attempts to find a cost-effective alternative to solid carbide tools provide a new impulse to designs with exchangeable carbide heads. Moreover, some of these designs provide a substantial advantage for high repeatability of the head overhang with respect to the tool. As a result, there is no need for additional adjustment after replacing a worn head, which can be quickly changed without removing the tool from a machine spindle. The “no-setup” benefit opened a source for decreasing machine downtime, in combination with economical advantages, promising prospects for the exchangeable solid-head concept as a direction of cutting tool development.

The metalworking industry has tightened its requirements for the versatility and maintainability of cutting tools. These changes have led to a good response from the tool manufacturer. For example, a typical cutter with indexable inserts features inner channels for coolant supply through the cutter body. Cutting tool manufacturers not only specify the necessary torque for tightening insert clamping screws, but also supply dynamometric keys to ensure necessary torque value.



Emerging Trends and New Challenges

In the metalworking industry, there are enduring trends that place the cutting tool manufacturer before new challenges.

The significantly increased use of composites and sintered materials requires specific cutters, customized in many cases.

Precise metal forming and 3D printing trends upward, leading to the growth of workpieces that are produced very close to the final shape of a part. This causes a considerable reduction of stock, removed by machining operations. Therefore, productive and accurate low power cutting on high-power machine tools is rising substantially. Advanced multi-axis machines are capable of precisely generating complicated shapes by cutting methods.

The machining of difficult-to-cut ISO S materials, especially β- and near- β- titanium grades and high-temperature superalloys (HTSA) feature low cutting speeds. Growing demands for the components from these materials require the respective increase in output by speeding up machining operations. As it turns out, the smallest element of the technological system – the cutting tool - becomes the main obstacle to productivity improvements.

It seems that the ultimate solution is connected with design, and manufacturing.

At the same time, the changes taking place in the industry have presented the toolmaker with tasks of a completely different kind.

Confident steps of industry digitization have turned the tool manufacturer to the virtual world. They have demanded to supplement the cutting tool – a material product - with a corresponding digital twin and a developed set of information services. This will be a necessary pass to the smart factory of tomorrow. Without the pass, the tool manufacturer will remain at the factory gate.

The customer of tomorrow is waiting for active virtual design options that are needed for process modelling, tool assembly integration, concept design of customized tools, and more.

Online marketing will play a key role in helping manufacturing companies make this change. The COVID-19 pandemic has accelerated the influence of online marketing, and the growing demand for online pre-sales services and post-sales support will be expected as a whole spectrum of services by the tool manufacturer.

Consequently, an "All-in-One" digital system for online marketing, tool data, access to various information, generating twin models, engineering and economic calculations, tool life analysis, immediate service, advice, knowledge, and competence, will all be an integral part of the product range for the cutting tool manufacturer.

The logic of industrial development demands tool manufacturer to adhere to new high-performance cutters with a developed informational integrant. The organic whole and balance between material and virtual worlds will be recognized very soon in the cutting tool industry and will define the intelligence of a cutting tool and its incorporation into advanced manufacturing systems.

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Quality Standard

ISCAR has been certified by the prestigious Standards Institution, as being in full compliance to ensure delivery of the finest quality goods. Quality control facilities include the metallurgical laboratory, raw metal testing, an online testing procedure and a machining center for tool performance testing and final product inspection. Only the finest products are packaged for entry into ISCAR's inventory.

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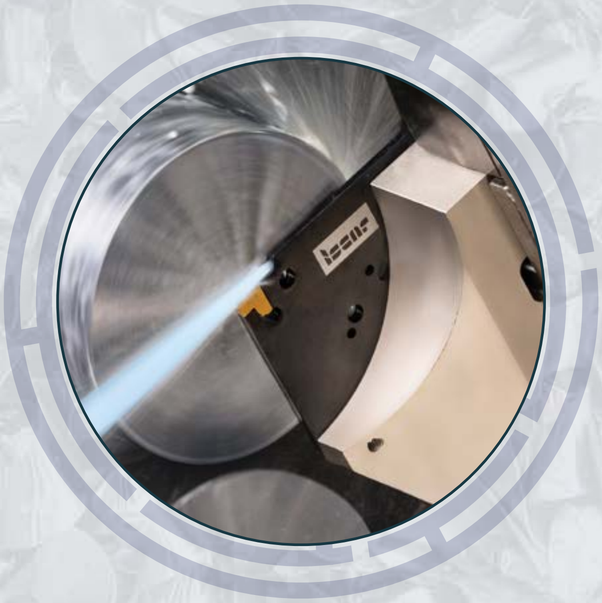

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