Modern Machining Technology
A practical guide

Edited By J. Paulo Davim
Modern machining technology
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Modern machining technology

A practical guide

EDITED BY
J. PAULO DAVIM

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Preface

Nowadays, machining technology is of great interest to several important industries such as the automotive, aeronautics, aerospace, renewable energy, moulds and dies, biomedical industries, etc. Machining covers all the manufacturing processes in which parts are shaped by removal of unwanted material. This term covers several processes, which are usually divided into the following categories: cutting (involving single point or multipoint cutting tools); abrasive processes, such as grinding; and thermal advanced machining processes, such as LBM (laser-beam machining), WEDM (wire electrical discharge machining), and PAC (plasma cutting), etc. Interest in this subject has increased over the past ten years, with rapid advances in materials science, automation and control, micro-technology and computer technology. Recently, machining of micro-components has become increasingly important for the development of new products for modern industry.

This book aims to provide practical information on modern machining technology for industry with an emphasis on the processes commonly used. The first three chapters of the book provide the fundamentals and applications of traditional cutting processes: turning, drilling and milling. Chapter 4 is dedicated to grinding and finishing processes. The final chapter is dedicated to thermal advanced machining processes: LBM (laser-beam machining) WEDM (wire electrical discharge machining), and PAC (plasma cutting), etc.
The book can be used as a text book for final undergraduate engineering courses or as a unit on machining technology at the postgraduate level. Also, this book can serve as a useful reference for academics, manufacturing researchers, mechanical, materials and manufacturing engineers, professionals in machining and related industries. The relevance of this book to many important centres of research, laboratories and universities throughout the world is evident. Therefore it is hoped that this book will inspire and enthuse other researchers in this field.

The Editor thanks Woodhead for this opportunity and for their enthusiastic and professional support. Finally, I would like to thank all the contributors for their availability for this work.

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Turning

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Abstract: Turning is the most common machining operation carried out in any machine shop, thus, knowledge of how to improve this is beneficial in a wide variety of practical applications. This chapter presents the most essential features of turning in order to help shop engineers and specialists to select the right tool, to adjust the machining regime, to avoid vibrations, and to improve the machining quality. For reasons of space, this chapter presents only those basics of turning needed to serve the stated objectives while the relevant references are provided for the well-known and thus widely available information on the matter.

Key words: chatter, cutting regime, surface roughness, tool geometry, turning.

1.1 Introduction

Many industrial seminars, promotion materials, industrial drives and even papers in scientific journals concentrate on advanced turning techniques, such as high-speed turning, hard turning, minimum quantity lubricant or near dry
turning, or ultra-precision turning of advanced work materials. Thus it seems that all the problems with traditional turning techniques have been solved and no further research and development will be necessary. Many colorful catalogs of leading tool manufacturers with high-quality realistic pictures enhance this notion even further, creating an impression that all one has to do is select the best tool and machining conditions for a given application, and just follow a few very simple well-defined steps.

In this author’s opinion, nothing could be further from the truth. It is true that the permissible turning speeds and feeds have almost doubled over the past decade. This became possible due to significant improvements in the manufacturing quality of the tools, including the quality of their components (carbides, coatings, etc.), the implementation of better turning machines equipped with advanced controllers as well as their proper maintenance, the application of better coolants, the improved training of engineers and operators, and many other factors. However, actual tool performance and process efficiency (the cost per part) vary significantly from one application to another, from one manufacturing plant to the next, depending on an overwhelming number of variables. Optimum performance in turning is achieved when the combination of the cutting speed (rpm), feed, tool geometry, carbide grade, including its coating, and coolant parameters, have been properly selected, depending upon the work material (its hardness, composition and metallurgical structure), the machine conditions, and the quality requirements of the machined parts. To get the most out of a turning job, one must consider the complete machining system, which includes everything related to the operation. Such consideration is known as the system engineering approach, according to which the machining system should be distinguished and analyzed for the coherence of its components.
This chapter aims to present the most essential features of turning in order to help shop engineers and specialists select the right tool, adjust the machining regime, avoid vibrations, and improve the machining quality. To keep the text within a reasonable limit, this chapter presents only those basics of turning needed to serve the stated objectives while the relevant references are provided for the well-known and thus widely available information on the matter.

1.2 Basic motions

To perform machining operations, relative motion is required between the tool and the workpiece. This relative motion is achieved in most machining operations and is a combined motion consisting of several elementary motions, such as the primary motion, called the cutting speed, and the secondary motion, called the cutting feed. The tool geometry and tool setting relative to the workpiece, combined with these motions, produce the desired shape of the machined surface.

Turning is a general term for a group of machining operations in which the workpiece carries out the prime rotary motion while the tool performs the feed motion. This combination of motions is used for the external and internal turning of surfaces. The basic motions required by turning are provided by a machine tool known as a lathe. The earliest illustration of a lathe is from a well-known Egyptian wall relief carved in stone in the tomb of Petosiris, dating from 300 BC. That is why the lathe is considered the oldest machine tool. The design of the lathe has evolved over centuries. Modern CNC lathes, equipped with powerful motors and high-precision drives, are controlled electronically via a computer menu style interface, the program may be
modified and displayed on the machine, along with a simulated view of the process.

Turning is used for machining cylindrical surfaces. The basic motions of turning are shown in Figure 1.1. They are:

- The primary motion is the rotary motion of the workpiece around the turning axis.
- The secondary motion is the translational motion of the tool, known as the feed motion.

Basic turning operations shown in Figure 1.1 differ by the direction of the feed motion with respect to the turning axis and the shape of the tool. In parallel turning (also known as longitudinal turning), the feed direction is parallel to the turning axis. In facing and parting, the feed direction is perpendicular to the turning axis. In tapering, the feed direction is at a specific angle to the turning axis. Figure 1.2 shows a variety of turning operations performed on the modern CNC lathe.
Internal turning known as boring is used to increase the inside diameter of an existing hole made with a drill, or it may be a cored hole in a casting. The basic motions of boring are the same as in turning, as shown in Figure 1.3.

Boring achieves three basic objectives:

- **Sizing**: Boring makes the hole the proper size and gives the correct surface finish.
- **Straightness**: Boring straightens the original drilled or cast (core) hole.
- **Concentricity**: Boring makes the hole concentric with the axis of rotation.

Most of the turning operations that occur with external turning are also to be found in boring, as shown in Figure 1.4. With external turning, the length of the workpiece does not affect
the tool overhang and the size of the toolholder. However, with internal turning, or boring, the choice of tool is very much restricted by the workpiece’s hole diameter and its length.

A general rule, which applies to all machining, is to minimize the tool overhang to obtain the best possible stability and thereby accuracy. With boring, the depth of the
The stability is increased when a larger tool diameter is used, but even then the possibilities are limited since the space allowed by the diameter of the hole in the workpiece must be taken into consideration for chip evacuation and radial movements.

### 1.3 The turning regime

Figure 1.5 illustrates the basic components of the machining regime in turning.

#### 1.3.1 Workpiece surfaces

The three basic surfaces of the workpiece are normally considered in turning as shown in Figure 1.5: (1) the work surface is the surface of the workpiece to be removed by machining; (2) the machined surface is the surface produced after the cutting tool passes; and (3) the transient surface is the surface being cut by the major cutting edge. Note that
the transient surface is always found between the work surface and machined surface. In most machining operations, the cutting edge does not form the machined surface. As clearly seen in Figure 1.5, the machined surface is formed by the tool nose and minor cutting edge. Unfortunately, not much attention is paid to these two important components of the tool geometry although their parameters directly affect the integrity of the machined surface, including the surface finish and machining residual stresses. Misunderstanding of this matter causes a great mismatch in the results of the known modeling of the cutting process and reality.

1.3.2 Cutting speed in turning and boring

In any machining operation, the cutting speed is the rate at which the workpiece surface is passed by the cutting edge. It is measured in meters per minute or feet per minute (often referred to as surface feet per minute or sfm). This definition is universal, and thus holds, no matter what the arrangements are (spatial location, motions, velocities, etc.) of the components of a particular cutting system. Note that when both the tool and the workpiece move (rotate, for example), the cutting speed is the relative speed of the tool and the workpiece according to this definition.

In metric units of measure (the SI system), the cutting speed is calculated as:

\[ v = \pi \frac{D_w n}{1000} \text{ (m/min)} \]  

where \( \pi = 3.141 \), \( D_w \) is diameter of the workpiece in millimeters, \( n \) is the rotational speed in rpm or rev/min.

For example, \( D_w = 76.2 \text{ mm} \) and \( n = 670 \text{ rpm} \), then

\[ v = \pi \frac{D_w n}{1000} = 3.141 \cdot 76.2 \cdot 670/1000 = 160.4 \text{ m/min}. \]
In the Imperial units of measure, the cutting speed is calculated

\[ v = \frac{\pi D_w n}{12} \text{ (sfm or ft/min)} \quad [1.2] \]

where \( \pi = 3.141 \), \( D_w \) is diameter of the workpiece in inches, \( n \) is the rotational speed in rpm. or rev/min. For example, \( D_w = 3 \text{ in (76.2 mm)} \) and \( n = 670 \text{ rpm} \), then

\[ v = \pi D_w n/12 = 3.141 \cdot 3 \cdot 670/12 = 526.1 \text{ sfm}. \]

Normally in the practice of machining, the cutting speed \( v \) is selected for a given tool design, tool material, work material and particularities of a given operation. Then the spindle rotational speed should be calculated using Eq. [1.1] and the given diameter of the workpiece as:

\[ n = \frac{1000v}{\pi D_w} \quad [1.3] \]

### 1.3.3 Feed and feed rate

The feed motion is provided to the tool or the workpiece, and when added to the primary motion, leads to a repeated or continuous chip removal and the formation of the desired machined surface. The cutting feed, \( f \), is the distance in the direction of feed motion at which the cutting tool advances into the workpiece per one revolution, thus the feed is measured in millimeters per revolution (inches per revolution). The feed rate, \( v_f \), is the velocity of the tool in the feed direction. It is measured in millimeters per minute (mm/min) or inches per minute (ipm) and is calculated as

\[ v_f = f \cdot n \quad [1.4] \]
1.3.4 Depth of cut

In turning and boring, the depth of the cut (sometimes called the back engagement) is calculated as

\[ a_p = \frac{D_w - D_{w1}}{2} \]  \[1.5\]

where \( D_{w1} \) is the diameter of the machined surface as shown in Figure 1.5.

1.3.5 Material removal rate

The material removal rate, known as MRR, in mm\(^3\)/min in turning and boring is given by
\[ MRR = 1000 fva_p \]  \[1.6\]
where \( v \) is in m/min, \( f \) is in mm/rev, \( a_p \) is in mm.

It directly follows from Eq. [1.6] that to increase MRR, one has to increase the cutting speed, feed and depth of cut under given constraints on tool life, surface finish, dimensional accuracy, available power of the machine tool, efficiency of machining, etc.

### 1.4 Cutting force and power

#### 1.4.1 Cutting force and its components

While cutting, the tool applies a certain force to the layer being removed, and thus to the workpiece. This force, known as the resultant cutting force \( \mathbf{R} \), is a 3D vector considered in the machine reference system (Standard ISO 841) set out in Figure 1.6(a). The origin of this coordinate system is always placed at a point of the cutting edge. The y-axis is always in the direction of the prime motion while the z-axis is in the direction of the feed motion. The x-axis is perpendicular to the y- and z-axes to form a right-hand Cartesian coordinate system.

For convenience, the cutting force is normally resolved into three components along the axis of the tool coordinate system. The main or power component of the resultant force, \( F_c \) (known also as the tangential force) is along the y-axis. It is normally the greatest component. The force in the feed direction, which is the z-direction, is known as the feed or axial force \( F_f \). The component along the x-axis \( F_p \) is known as the radial component as it acts along the radial direction of the workpiece. The equal and opposite force \( \mathbf{R} \) is applied to the cutting tool as a reaction force of the workpiece as shown in Figure 1.6(b). This force is also resolved into three
orthogonal components along the coordinate axis as shown in Figure 1.6(b). The additional component $F_{xz}$ that acts in the xz coordinate plane is also considered as it is essential for machining accuracy considerations.

### 1.4.2 Cutting power

As is well known (Usachev, 1915; Zorev, 1966; Shaw, 2004), power is calculated as the product of the resultant force and the velocity in the direction of this force. In metal cutting, however, the magnitudes of the force components and the corresponding velocities have to be considered. As the velocity in the direction of the radial force $F_p$ is zero, this component does not participate in power considerations. The axial force
Turning

$F_t$ is normally much smaller than the tangential force $F_c$. As discussed above, the velocity in the axial direction (the speed of feed) is negligibly smaller than the cutting speed. As a result, the contribution of the power due to the axial force $F_t$ to the total cutting power is small. The greatest force component that acts in the direction of the cutting speed is $F_c$. Therefore, the cutting power is normally calculated as

$$P_c = F_c \cdot v \ (W) \quad [1.7]$$

where $F_c$ is in newtons (N), $v$ is in m/s. That is why in the professional literature $F_c$ is often referred to as the power component or the cutting force.

If the $P_c$ is divided by the volume of material removed per unit time, i.e., by MRR defined by Eq. [1.6], then the power required to remove a unit volume per unit time (e.g. mm$^3$/s) is obtained. This is termed as the specific cutting power, $P_{c-c}$ defined as

$$P_{c-c} = \frac{F_z v}{MRR} = \frac{F_z v}{f v a_p} = \frac{F_z}{f a_p} \left(\frac{W}{\text{mm}^3}\right) \quad [1.8]$$

where the cutting feed, $f$ in mm/rev and the depth of cut, $a_p$ is in mm.

It is important to discuss here the common misconceptions associated with Eq. [1.8]. As seen, the proper dimension of $P_{c-c}$ is $W$/mm$^3$. Unfortunately, many specialists in the field do not realize the physical essence of this equation so they see only its second part where its formal dimension can be thought of as N/mm$^2$. As a result, $P_{c-c}$ is often called the specific cutting pressure (DeVries, 1992; Anselmetti et al., 1995; Altintas, 2000; Sreejith and Ngoi, 2000; Boothroyd and Knight, 2006) or even specific cutting force (symbol $k_c$) (Konig et al., 1972; Chang and Wysk, 1984; Yoon and Kim, 2004). It reality, it is not a true pressure or stress item.
Moreover, it is claimed that the ‘specific cutting pressure’ is a kind of property of the work material that can characterize its machinability (Stenphenson and Agapiou, 1996) and can be used to calculate the cutting force. The whole idea of the so-called mechanistic approach in metal cutting is based on this false perception. In such an approach, however, the role of tool geometry as the major contributor to the state of stress in the machining zone is totally ignored (Astakhov, 2010a).

1.4.3 Practical assessment of the cutting force and power

For most of the history of turning, the cutting power and force calculations/assessments/measurements were almost the central part and were often the objective of studies because of the lack of power available on the machine. Nowadays, modern lathes and tuning centers are provided with powerful motors, massive rigid drives and spindles so that the cutting power and forces are not of prime concern. However, forces are of importance in the consideration of the accuracy of machining, and the design of work- and tool holding fixtures, i.e. lathe chuck, steady rests, tool shanks, etc. Moreover, the power required by the cutting system determines the tool life, and the cutting force determines the contact stresses at the tool–chip and tool–workpiece interfaces (Astakhov, 2006). Therefore, these two are still important parameters in the optimization of turning operations.

It was shown that the existing notions of the theoretical determination of the cutting force are fruitless as they cannot pass a simple reality check (Astakhov, 2006). When it comes to experimental determination of the cutting force, there are at least two problems; the first and foremost of which is that
the cutting force cannot be measured with reasonable accuracy. Even if extreme care is taken, a 50% variation is still the case (Ivester, 2004). Many tool and cutting inserts manufacturers (not to mention manufacturing companies), do not have adequate dynamometric equipment to measure the cutting force. Many dynamometers used in the field are not properly calibrated because the known literature sources did not have the proper experimental methodology for cutting force measurements using piezoelectric dynamometers (Astakhov and Shvets, 2001).

Therefore, to make practical calculations of the cutting force and thus the energy spent in machining, another approach has to be found.

The advanced methodology (Astakhov and Xiao, 2008) is based on the definition of the metal cutting process proposed by Astakhov (Astakhov, 1998/1999) and on the model of energy partition in the metal cutting system developed using this definition (Fig 2.1 in Astakhov, 2006). According to this model, the power balance in the cutting system can be written as

\[ P_c = F_c v = P_{pd} + P_{pf} + P_{fF} + P_{ch} \]  \[1.9\]

from whence the cutting force is calculated as

\[ F_c = \frac{P_{pd} + P_{pf} + P_{fF} + P_{ch}}{v} \]  \[1.10\]

where \( P_{pd} \) is the power spent on the plastic deformation of the layer being removed, \( P_{pf} \) is the power spent at the tool–chip interface, \( P_{fF} \) is the power spent at the tool–workpiece interface, and \( P_{ch} \) is the power spent in the formation of new surfaces.
Practical determination of these powers, and thus the cutting force, was presented by Astakhov (Astakhov and Outeiro, 2008; Astakhov and Xiao, 2008; Astakhov, 2010b). Table 1.1 shows an example of the results of calculations using the proposed practical methodology as well as the total power required by the cutting system $P_c$. Figure 1.7 shows the relative impact of the discussed energies on the cutting force in the machining of steel 52100 and aluminum 2024 obtained using the discussed methodology of the cutting force assessment. The major advantage of the proposed methodology is that it allows not only the total power and

<table>
<thead>
<tr>
<th>Cutting Speed (m/s)</th>
<th>Feed (mm/rev)</th>
<th>Depth of cut (mm)</th>
<th>$P_{pd}$ (KW)</th>
<th>$P_{fr}$ (KW)</th>
<th>$P_{pd} + P_{fr}$ (KW)</th>
<th>$P_c$ (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.45</td>
<td>4</td>
<td>1.242</td>
<td>0.284</td>
<td>1.526</td>
<td>1.596</td>
</tr>
<tr>
<td>3</td>
<td>0.45</td>
<td>4</td>
<td>1.702</td>
<td>0.539</td>
<td>2.241</td>
<td>2.595</td>
</tr>
<tr>
<td>5</td>
<td>0.45</td>
<td>4</td>
<td>1.954</td>
<td>0.746</td>
<td>2.700</td>
<td>3.270</td>
</tr>
<tr>
<td>7</td>
<td>0.45</td>
<td>4</td>
<td>1.716</td>
<td>0.889</td>
<td>2.605</td>
<td>3.458</td>
</tr>
<tr>
<td>3</td>
<td>0.75</td>
<td>4</td>
<td>2.093</td>
<td>0.758</td>
<td>2.851</td>
<td>3.544</td>
</tr>
<tr>
<td>3</td>
<td>0.50</td>
<td>3</td>
<td>1.397</td>
<td>0.439</td>
<td>1.836</td>
<td>2.290</td>
</tr>
<tr>
<td>3</td>
<td>0.50</td>
<td>2</td>
<td>0.940</td>
<td>0.291</td>
<td>1.231</td>
<td>1.539</td>
</tr>
<tr>
<td>3</td>
<td>0.30</td>
<td>4</td>
<td>1.169</td>
<td>0.366</td>
<td>1.535</td>
<td>1.984</td>
</tr>
</tbody>
</table>

Note: Work materials – Aluminum alloy 2024 T6 (90.7–94.7%Al, 3.8–4.8%Cu, 1.2–1.8%Mg, 0.3–0.9%Mn), Hardness HB125; Tensile strength, ultimate – 185 MPa, Tensile strength, yield – 86 MPa, elongation at break – 5%, Shear strength 125 MPa, $K = 0.220$ GPa, $n = 0.16$; Tool – standard inserts SNMG 432-MF2 TP2500 Materials Group 4 (SECO Tools) installed into a tool holder 453-120141 R1-1 (Sandvik). The tool-in-machine tool geometry parameters are: the tool cutting edge angle = 45°, tool minor cutting edge angle = 45°, nose radius = 1 mm, radius of the cutting edge = 0.3 mm, normal flank angle = 7°, the normal rake angle = −7°.
thus the cutting force to be calculated, but also provides a valuable possibility to analyze the energy partition in the cutting system.

The results obtained using the discussed methodology are valid for new tools (a fresh cutting edge of a cutting insert). Tool wear significantly increases the cutting force. For steel E52100, \( VB_h = 0.45 \) mm causes 2.0–2.5 times an increase in the cutting force when no plastic lowering of the cutting edge (Astakhov, 2004) occurs (for cutting speeds 1 and 1.5 m/s) and 3.0–3.5 increase when plastic lowering is the case (for cutting speeds 3 and 4 m/s).

The results show that the power required for the plastic deformation of the layer being removed in its transformation into the chip is the greatest. Therefore, the major aim in any optimization of the turning regime and tool geometry is to reduce this power, thus ensuring cutting with minimum plastic deformation of the layer being removed. This results in increased tool life and improved integrity of the machined surface.
1.5 Uncut (undeformed) chip thickness, equivalent cutting edge, chip flow direction, and true chip cross-section parameters

1.5.1 Uncut (undeformed) chip thickness

Uncut (undeformed) chip thickness (known also as the chip load) is one of the most important characteristics in any metal cutting process as it defines many other important parameters, such as, for example, contact stresses on the tool–chip interface, amount of plastic deformation of the layer being removed, tool life, cutting force and power (Astakhov, 2006; 2010a).

Figure 1.8(a) shows the sense of the uncut chip thickness and its correlation with the parameters of the machining regime in turning. It follows from Figure 1.8(b) that the uncut chip thickness is calculated as:

\[ t_1 = \bar{f} \sin \kappa_r \quad [1.11] \]

Uncut (undeformed) chip width is

\[ b_1 = a_p / \sin \kappa_r \quad [1.12] \]

Figure 1.8 Sense of the uncut (undeformed) chip thickness

(a) Uncut chip (undeformed) chip thickness

(b) Uncut chip cross-section
Uncut (undeformed) chip cross-sectional area is

\[ A_1 = t_1 b_1 \]  

[1.13]

Substituting Eqs [1.11] and [1.12] into Eq. [1.13], one can obtain

\[ A_1 = a_p f \]  

[1.14]

Earlier, this author presented equations to calculate the uncut chip thickness, width and cross-sectional area for all possible configurations of the major and minor cutting edges (Astakhov, 2010a).

The tool cutting edge angle \( \kappa_r \) is probably the most important angle of the tool geometry as it has a multi-faced influence on practically all aspects of the metal cutting process and greatly affects the outcomes of a turning operation. This is because it defines the magnitudes of the radial, \( F_p \) and feed, \( F_f \) forces (Figure 1.8(a)) and, for a given feed and cutting depth, it defines the uncut chip thickness, the width of cut, and thus tool life. The physical background of this phenomenon can be explained as follows: when \( \kappa_r \) decreases, the chip width increases correspondingly because the active part of the cutting edge increases. The latter results in improved heat removal from the tool and hence tool life increases. For example, in rough turning of carbon steels, the change of \( \kappa_r \) from 45° to 30° leads sometimes to a fivefold increase in tool life (Astakhov, 2010a).

The reduction of \( \kappa_r \), however, has its drawbacks. One of them is the corresponding increase of the radial force because, as follows from Figure 1.8(a),

\[ \frac{F_f}{F_p} = \tan \kappa_r \]  

[1.15]
This increased radial force may cause bending of the workpiece, and thus barreling of the machined surface. The second significant drawback of decreasing $\kappa_r$ is the corresponding increase of the active length of the major cutting edge that can bring on chatter in turning.

### 1.5.2 Equivalent cutting edge and chip flow direction

Because in turning at least two, namely major and minor, cutting edges are involved in cutting, there have been a number of attempts to account for the inter-influence of the neighboring cutting edges in determining the direction of chip flow. They are well summarized in (Oxley, 1989). Klushin (Klushin, 1958), and Stabler (Stabler, 1964) suggested determining the true uncut chip thickness in the plane perpendicular to the direction of chip flow while the true uncut chip width is determined in the perpendicular direction and equal to the length of the segment CB, which joins the ends of the major and minor cutting edges engaged in cutting, as shown in Figure 1.9. In Figure 1.9, the directions AC and AB are orthogonal chip flow directions of the major and minor cutting edges, respectively, and direction BC is the resultant chip flow direction. The angle between AC and BC is referred to as the chip flow angle $\eta_{ch}$. The segment CB is often referred to as the equivalent cutting edge as suggested by Colwell (Colwell, 1954).

Figure 1.10 shows a model for determining the chip flow direction for one of the common configurations in turning where the tool has the inclination angle $\lambda_s \approx 0^\circ$ and the normal rake angle $\gamma_n \approx 0^\circ$. In this case, the chip flow direction is determined as

$$\eta_{ch} = \kappa_r - \eta'_{ch}$$

[1.16]
Figure 1.9 Chip flow direction

Figure 1.10 Model to determine the chip flow direction for a common configuration in turning
where:

\[
\eta'_{cb} = \begin{cases} 
\arctan \left[ \frac{c_n}{1 - a_n (1 - \cos \kappa_r) \cot \kappa_r + a_n (\sin \kappa_r + b_n)} \right] \\
\arctan \left[ \frac{c_n}{\sqrt{2a_n - 1 + a_n \cdot b_n}} \right]
\end{cases}
\]

if \( a_p \geq r_n (1 - \cos \kappa_r) \) and \( f \leq 2r_n \sin \kappa_{r_1} \)

\[
\text{if } a_p < r_n (1 - \cos \kappa_r) \text{ and } f \leq 2r_n \sin \kappa_{r_1}
\]

\[1.17\]

where:

\[
a_n = \frac{r_n}{a_p}, \quad b_n = \frac{a_p}{2r_n}, \quad c_n = 1 - a_n \left(1 - \sqrt{1 - b_n}\right)
\]

\[1.18\]

Although the cutting edge inclination angle \( \lambda \) may affect the direction of chip flow as discussed by this author earlier, its influence in practical turning operations is small because the inclination angles are rather small for standard single point turning tools (hereafter, SPTTs) (Astakhov, 2010a).

### 1.5.3 True chip cross-section parameters

The concepts of the equivalent cutting edge and chip flow direction introduce the concept of the true chip cross-section parameters. Figure 1.11 shows how the theoretical chip cross-section (shown in Figure 1.8(b)) transforms into the true chip cross-section in the direction of chip flow. In Figure 1.11, \( a_{1T} \) and \( b_{1T} \) are the true chip thickness and width, respectively. Geometrical considerations of the model shown in Figure 1.11 derive a simple equation for \( b_{1T} \)

\[
b_{1T} = \sqrt{a_p^2 + (a_p \cot \kappa_{r_1} + f)^2}
\]

\[1.19\]
Figure 1.12 shows that the experimentally obtained, $b_{ex}$ and calculated $b_{cl}$ (using Eq. 1.19) chip thicknesses obtained for different cutting feeds are the same.
1.6 Design of a turning operation

Although the design of each turning operation should follow its unique path depending on given practical conditions, the basic common features of this design are the same. As an example, Figure 1.13 shows a block diagram or flowchart for the turning operation design for the most general case. In reality, however, some steps can be omitted for given conditions where some parameters of the turning operations are known.

As can be seen in Figure 1.13, the design begins (Block 1) with the analysis of the part drawing where the part configuration, part material and its metallurgical state, diametric and shape tolerances as well as the requirements to surface integrity are shown. It is critically important for the following steps to know how many parts are to be machined, i.e., following an annual program because this defines the number of important technical and economic decisions to be made. The outcome of Block 1 is a turning manufacturing process.

![Flowchart for the turning operation design](image)
drawing made using the part drawing. This is because the part drawing, in general, includes not only the turning operation so that the requirements of the finished part are indicated in this drawing. For example, for a shaft shoulder, it indicates the surface finish, shape tolerance, hardness, etc. obtained after finish grinding. The turning manufacturing drawing reveals the features of the part obtained only in the turning operation.

Block 2 represents the part blank selection stage. Depending on the annual program, availability, requirements and the existing practice, it ranges from a simple bar stock where a lot of work material is normally to be removed by turning, to a complicated die casting, having a near net shape configuration where a small amount of work material is to be removed to fulfill the requirements of the turning manufacturing drawing. The final decision on the blank is made based upon a techno-economic analysis which compares various alternatives.

Most of the sub-steps in Block 2 are well covered in the literature on manufacturing technology (for example, Kalpakjian and Schmid, 2001; DeGarmo et al., 2007). However, a number of common mistakes are made in the selection of the blank metallurgical state as, unfortunately, it has seldom been considered an important issue (Astakhov, 2006).

Blocks 3, 4, and 5 constitute the very core of the turning operation design because a number of important decisions have to be made at these stages that affect the process efficiency and reliability. To start with, a tool layout for the whole turning operation should be designed. Usually the tool layout is the handover document transferred from engineering to the shop floor. A tool layout captures the tool information in the language of engineering, consisting of drawings, a bill of materials and parameter lists. A turning tool layout refers
to a single tool assembly for a certain operation performed with a specific spindle on a specific machine tool. Therefore, to design the tool layout which is actually a set of layouts for each cutting tool used in the operation, an important decision about the number of tools and their types has to be made.

To understand the essence of this decision, one should understand that a turning operation, in general, consists of a number of sub-operations performed at the same part location and clamping in the machine. Figure 1.14 shows a typical part to be machined in a turning operation. As can be seen, a number of various turning tools are required to accomplish a turning operation on this part.

Normally, catalogs of leading turning tool manufacturers are very useful in making such a selection. For example, Sandvik Coromant, in its catalogs and turning application manuals, shows detailed tool layouts for typical turning parts similar to that shown in Figure 1.15. In the case considered here, Tool 1 is equipped with an insert for the case hardened shoulder; Tool 2 is supplied with a standard T-MAX P cutting insert; Tool 3 is a grooving tool; and Tool 4 is for machining a curved profile with a Coro Turn 107 insert.

**Figure 1.14** Typical part to be machined
For any turning operation, there is both a minimum and an optimum number of turning tools to accomplish this operation. The optimum number of turning tools is the number that assures the lowest cost per machined part. Naturally, this number depends on the annual program (the size of the production lot) so that is an economic rather than a technical decision. The minimum number of tools is used when one tries to keep down the inventory of tools and inserts in the shop environment.

When ‘the group layout’ similar to that shown in Figure 1.15 is constricted, i.e., the number of the tools involved as well as their types (general geometry and configuration) are selected, tool layouts for each tool involved in the turning operation have to be designed. Such layouts include:

- tool starting and end positions that define: (1) the turning length, and (2) the length of the working path;
- the configuration of the tool cutting edge (its length and tool cutting edge angle);
- the machining regime in terms of the cutting speed and feed. As the development of a tool layout is an iterative
process, the initial assignment of these two regime parameters is normally based upon: (1) the cycle time available for the operation; (2) the data available in the company’s tooling database (for similar applications); and (3) the recommendation of the leading tool manufacturers available in their online catalogs. The selected cutting speed and feed then can be changed several times in the process of final revision of the turning operation.

- the tool holder, which depends on the machine available for the operation;
- the cycle diagram of the turning operation that allows the machining cycle time (the time needed for machining part) to be calculated. When one adds this time to the time needed for loading and unloading a part, the turning cycle time is obtained.

The type of tool selected by this layout gives a general idea of what kind of tool is needed for the sub-operation. Later on, the particular tool parameters (geometry, design, particular grade of tool material, coating, etc.) are selected.

Leading tool manufacturers provide a system of grades, geometries and application guidelines to help an operation designer to make important decisions on optimal solutions. Using these guidelines, it is relatively easy to determine which chip-control cutting tool will work best for the given work material and application conditions. However, before making any selection, a general idea about tool materials as well as the associated cutting speeds can be very helpful. There are a great number of publications available on properties and selection of tool materials (for example, Astakhov and Davim, 2008). Figure 1.16 summarizes the result to help the process designer figure out what type of tool material to use in a given application. Of the tool materials shown in Figure 1.16, carbides are the most widely
used in turning operations. The International Organization for Standardization (ISO) provides a classification of carbides (Table 1.2) in three general categories: P, M, and K. As shown in Table 1.2, each category has a number of individual grades, although many tool companies normally ignore such grades, and classify their carbides only by the categories and their own sub-categories, depending upon their own classification of the work materials and their properties.

As an example of tool selection, consider the Kenna Perfect Insert Selection System (by Kennametal) which consists of one pre-step and three steps. Let’s assume that the design of the tool layout results in the following information: (1) the work material is ANSI 1020 steel; (2) the operation is
semi-finishing with light interruptions; (3) the depth of the cut is 1.0 mm; (4) the desirable cutting feed is 0.4 mm/rev. At the pre-step, the group of tool material is selected according to Kennametal designation as shown in Figure 1.17 (P-group according to Table 1.2) based upon the work material.

The essence of Step 1 is shown in Figure 1.18. Based upon the known depth of cut, type of operation, and desirable
feed, the insert geometry is selected. In the considered case, an insert MN is selected. Note that even in the methodological material of one of the leading tool manufacturers like Kennametal, the cutting feed is wrongly termed the feed rate and measured in millimeters. As discussed in Section 1.3.3,
the feed rate is measured in mm/min, when the cutting feed is measured in mm/rev.

The boundaries of the polygon MN in Figure 1.18 are determined by its chip breaking ability by the selected insert (its chip breaker). This issue is well explained by Sandvik Coromant in its catalog. Figure 1.19 provides a self-evident explanation. As can be seen, the boundaries of the polygon are defined by the acceptable chip shape.

The essence of Step 2 is shown in Figure 1.20. In this step, a particular grade of the tool materials is selected for the given cutting condition. As can be seen in Figure 1.20, KC9125 grade is selected.
In Step 3, the cutting speed is selected depending upon the grade of the work material as shown in Figure 1.21. As can be seen, the cutting speed should be selected from the allowable range depending upon a particular machining system. The better the machining system, the higher the cutting speed that can be selected from the permissible range. In the case considered, \( v = 280 \text{ m/min} \) is selected.

Although only Kennametal methodology is discussed in this chapter, other methodologies offered by leading turning tool manufacturers are very similar. Moreover, catalogs of leading turning tool suppliers often contain the approximate values of the cutting force and cutting power. Therefore, the impression is given that there should be no problems selecting the proper turning tool (the geometry of the cutting insert), the grade of tool material (including its coating), and the machining regime (the cutting feed based upon chip control and the cutting speed based upon the grade of the work material).

Real life, however, proves otherwise. Despite the fact that they are multi-volume, the catalogs cannot account for the great variety of practical machining conditions and ensure that the selected parameters should be considered good on the first approximation. The catalogs do not discuss tool geometry parameters related to the tool performance or a good starting point. This is particularly true if one recalls that the same insert can be mounted in various tool holders so that its actual geometry can vary within a wide range (Astakhov, 2010b). The recommended cutting speed should be selected from a rather wide range. For example, Figure 1.21 shows that the recommended range of cutting speeds for the considered example is 140–340 m/min. It is not clear how to select the optimal cutting speed within this range. Moreover, it is not clear what one should do if chatter occurs in turning – reduce/increase speed/ feed?, alter the tool geometry?, select a different grade of the tool material, etc.?
### 3rd Step – Select the Cutting Speed

**Low-Carbon (<0.3% C) and Free-Machining Steel**

AISI: 1008, 1010, 1018, 1020, 1026, 10L18, 10L45, 10L50, 10L80, 1117, 1141, 1151, 11L44, 1200 series, and 12L14

<table>
<thead>
<tr>
<th>KENNA PERFECT Material Group</th>
<th>grade</th>
<th>Speed - sfm (m/min)</th>
<th>Starting Conditions</th>
<th>sfm</th>
<th>m/min</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>450  (135)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>600  (180)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>750  (225)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>900  (275)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1050 (320)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1200 (360)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1350 (410)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1500 (455)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P1</td>
<td>KT315</td>
<td></td>
<td></td>
<td>1450</td>
<td>440</td>
</tr>
<tr>
<td></td>
<td>KC9110/KC9315</td>
<td></td>
<td></td>
<td>1320</td>
<td>400</td>
</tr>
<tr>
<td></td>
<td>KC9125/KC9225/KC5010</td>
<td></td>
<td></td>
<td>925</td>
<td>280</td>
</tr>
<tr>
<td></td>
<td>KC9040*/KC9240/KC8050</td>
<td></td>
<td></td>
<td>700</td>
<td>215</td>
</tr>
</tbody>
</table>
The following sections provide advice on some important practical problems commonly found in turning.

Block 6 in Figure 1.13 represents the metrological part of the turning operation design. All the previous blocks are meant to achieve the required quality of the machined part according to the turning manufacturing drawing. Block 6 is to assure that the quality parameters (i.e., the required diametric accuracy) are measured using the in-process and post-process gages. Thus, Block 6 deals with industrial metrology which concerns the application of measurement science to manufacturing processes, ensuring the suitability of measurement instruments, their calibration and the quality control of measurements. The basic steps of this block are well covered in the literature on industrial metrology (for example, Smith, 2002; Dotson, 2006).

Block 7 in Figure 1.13 is the verification stage. It consists of two sub-stages:

1. **Digital verification of the tool path.** The generated tool path may create errors that could ruin the part being machined, damage the fixture, break the cutting tool, or crash the machine. Thus verification of the tool path is required. The CNC tool path verification is a powerful visual inspection module permitting the user to visualize the motion of the cutting tool. It simulates what will exactly happen on the shop floor. It highlights fast feed errors, gouges, and potential crashes or collisions. It might be possible to modify the tool path by finding out the cause of the inaccuracy and thus virtually eliminate most of the CNC program mistakes. There are a number of industrial software packages that provide a great help in digital verification not only of the tool path but also of cutting conditions (for example, VERICAT by CGTech, Irvine, California, USA).
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2. *Actual verification of the turning operation.* At this sub-step, a number of actual parts are machined and the indented accuracy, productivity, and other essentials of the designed operation are verified.

Often, the errors and irregularities that occurred in the verification stage are corrected as feedback information is sent to the previous block for correction. Normally, two or three iterations are sufficient to correct all errors.

1.7 Particularities of the geometry of cutting tool with indexable inserts

1.7.1 Tool geometry standards

The cutting tool geometry is of prime importance because it directly affects (Astakhov, 2010a): (1) chip control (chip flow direction, shape, breakability, etc.); (2) productivity of machining; (3) tool life; (4) the direction and magnitude of the cutting force, and thus its components; and (5) the quality (surface integrity and machining residual stress) of the machining. Nowadays, however, the assigning of the proper geometry parameter of a SPTT turns into the selection of the geometry of indexable cutting inserts and suitable tool holder rather than grinding the desired geometry on a brazed SPTT.

The economic indexable solid carbide tips overcome the skyrocketing price of solid carbide tooling by replacing only the used portion of the tool. The shank can be used over and over again. However, proper tool performance is achieved if the inserts and tool holder are properly selected.

There are two established tool geometry standards, namely the ISO Standard (1982) and the ANSI Standard (1975 (reaffirmed 1993)). A simple comparison of these standards shows that the ISO Standard is much more advanced as it
contains much clearer and more functional definitions. Moreover, the basic notions of the ISO Standard are well explained and shown with multiple examples as applied to various cutting tools while the ANSI Standard concentrates only on single-point cutting tools. The ISO Standard (1982) is widely used worldwide while the ANSI standard (1975 (reaffirmed 1993)) is used in parallel with the ISO Standard in North America. The definitions of various parameters of tool geometry and their impact on tool performance were discussed earlier (Astakhov and Davim, 2008a; Astakhov, 2010b).

The ANSI Code

The current ANSI Code consists of up to 10 positions; each position defines a characteristic of the insert in the following order: 1 shape; 2 clearance; 3 tolerance class; 4 type; 5 size; 6 thickness; 7 cutting-point configuration; 8 edge preparation; 9 hand; 10 facet size. Figure 1.22 shows an example of the ANSI indexable insert code. Of these parameters, the shape (Figure 1.23) and size (Figure 1.24) are of prime importance in the selection procedure.

The ISO Code

According to ISO 1832: 2004/2005, the designation code comprises nine symbols to designate the dimensions and other characteristics; the first seven symbols (symbols (1) to (7)) shall be used in every designation. Symbols (8) and (9)

![Figure 1.22 Example of the ANSI code for an indexable insert](image-url)
### Shapes of cutting inserts (ANSI)

<table>
<thead>
<tr>
<th>SHAPE</th>
<th>SHAPE</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>E</td>
</tr>
<tr>
<td>Parallelogram</td>
<td>Diamond</td>
</tr>
<tr>
<td>B</td>
<td>H</td>
</tr>
<tr>
<td>Parallelogram</td>
<td>Hexagon</td>
</tr>
<tr>
<td>C</td>
<td>K</td>
</tr>
<tr>
<td>Diamond</td>
<td>Parallelogram</td>
</tr>
<tr>
<td>D</td>
<td>L</td>
</tr>
<tr>
<td>Diamond</td>
<td>Rectangle</td>
</tr>
</tbody>
</table>

### Sizes of cutting inserts (ANSI)

**SIZE (I.C.)**

Examples:

- $1/8" = 1$
- $5/32" = 1.2$
- $3/16" = 1.5$
- $7/32" = 1.8$
- $1/4" = 2$
- $5/16" = 2.5$
- $3/8" = 3$
- $1/2" = 4$
- $5/8" = 5$
- $3/4" = 6$
- $7/8" = 7$
- $1" = 8$
- $1-1/4" = 10$

For equal sided inserts this indicates the inscribed circle (I.C.) in 1/8 of an inch.

For rectangles and parallelograms two digits are necessary:

1st digit = number of 1/8" in width

2nd digit = number of 1/4" in length
may be used when necessary. For tipped inserts in accordance with ISO 16462 and ISO 16463, the designation code comprises 12 symbols to designate the dimensions and other characteristics; symbols (1) to (7) as well as (11) and (12) shall be used in every designation. Symbols (8), (9), and (10) may be used when necessary. Symbols (11) and (12) shall be separated from symbols by a dash. In addition to the standardized designation for indexable inserts and for tipped inserts, a supplementary symbol (13), consisting of one or two characters, may be added by the manufacturer for a better description of his product (e.g., different chip breakers), provided that this symbol is separated from the standardized designations by a dash and that it does not contain the letter specific to reference symbols (8), (9), and (10).

Examples of metric and inch designation are shown in Figure 1.25. Each symbol defines a characteristic of insert according to Table 1.3.

Symbols for insert shape and size are shown in Tables 1.4 and 1.5, respectively.

1.7.2 Cutting insert holders

Systems of consideration of the tool geometry

Both the above-mentioned tool geometry standards discuss two systems of consideration of the cutting tool geometry, namely, the tool-in-hand and tool-in-use systems (hereafter, T-hand-S and T-use-S, respectively). The former relates to the so-called static geometry while the latter is based on consideration of the tool motions with respect to the workpiece. In this author’s opinion, however, these two systems are insufficient for a proper consideration of the cutting tool geometry of SPTT with indexable inserts. Another two systems, namely, the tool-in-holder (hereafter,
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**Figure 1.25** Examples of the ISO code for indexable inserts

<table>
<thead>
<tr>
<th>Metric designation</th>
<th>Inch designation</th>
</tr>
</thead>
<tbody>
<tr>
<td>TPGN 1234</td>
<td>TPGN 3224</td>
</tr>
<tr>
<td>160308EN</td>
<td>322EN</td>
</tr>
<tr>
<td></td>
<td>13</td>
</tr>
</tbody>
</table>

**Table 1.3** Significance of the symbols constituting the ISO designation

<table>
<thead>
<tr>
<th></th>
<th>Significance</th>
<th>Compulsory symbols for indexable inserts</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Letter symbol identifying</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Letter symbol identifying</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Letter symbol identifying</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Letter symbol identifying</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Number symbol identifying</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Number symbol identifying</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Letter or Number symbol identifying</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Letter symbol identifying</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Letter symbol identifying</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Number symbol identifying</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Letter symbol identifying</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Letter or number symbol identifying</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Manufacturer’s symbol or cutting material designation in accordance with ISO 513</td>
<td>Compulsory symbols for tipped inserts in accordance with ISO 16462 and ISO 16463, except as noted</td>
</tr>
<tr>
<td>Type</td>
<td>Letter symbol</td>
<td>Description of shape</td>
</tr>
<tr>
<td>-------------------------------</td>
<td>---------------</td>
<td>----------------------</td>
</tr>
<tr>
<td>I Equilateral and equiangular inserts</td>
<td>H</td>
<td>Hexagonal inserts</td>
</tr>
<tr>
<td></td>
<td>O</td>
<td>Octagonal inserts</td>
</tr>
<tr>
<td></td>
<td>P</td>
<td>Pentagonal inserts</td>
</tr>
<tr>
<td></td>
<td>S</td>
<td>Square inserts</td>
</tr>
<tr>
<td></td>
<td>T</td>
<td>Triangle inserts</td>
</tr>
<tr>
<td>II Equilateral but not equiangular inserts</td>
<td>C</td>
<td>Rhombic inserts</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td></td>
</tr>
<tr>
<td></td>
<td>E</td>
<td></td>
</tr>
<tr>
<td></td>
<td>M</td>
<td></td>
</tr>
<tr>
<td></td>
<td>V</td>
<td></td>
</tr>
<tr>
<td></td>
<td>W</td>
<td>Trigon inserts</td>
</tr>
<tr>
<td>III Non-equilateral but equiangular inserts</td>
<td>L</td>
<td>Rectangular inserts</td>
</tr>
<tr>
<td>IV Non-equilateral and non-equiangular inserts</td>
<td>A</td>
<td>Parallelogram-shaped inserts</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td></td>
</tr>
<tr>
<td></td>
<td>K</td>
<td></td>
</tr>
<tr>
<td>V Round inserts</td>
<td>R</td>
<td>Round inserts</td>
</tr>
</tbody>
</table>

*a The included angle considered is always the smaller angle*
### Table 1.5 Symbols for insert size (ISO)

<table>
<thead>
<tr>
<th>Type</th>
<th>Number symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>I–II Equilateral inserts</td>
<td></td>
</tr>
<tr>
<td>In countries using the metric system, choose the values of the side length as the symbol of designation and disregard any decimals. If the resulting symbol has only one digit, it shall be preceded by a zero.</td>
<td></td>
</tr>
<tr>
<td>EXAMPLE</td>
<td></td>
</tr>
<tr>
<td>Edge length</td>
<td>15.5 mm</td>
</tr>
<tr>
<td>Symbol of designation</td>
<td>15</td>
</tr>
<tr>
<td>Edge length</td>
<td>9.525</td>
</tr>
<tr>
<td>Symbol of designation</td>
<td>09</td>
</tr>
</tbody>
</table>

In countries using the Imperial (inch) system, choose the value of the inscribed circle as the symbol of designation. The symbol is the numerator of the fraction measure in 1/8 in. It is a one-digit symbol when the numerator is a whole number.

EXAMPLE Diameter of inscribed circle 1/2 in
Symbol of designation 4 (1/2 = 4/8)

It is a two-digit symbol when the numerator is not a whole number.

EXAMPLE Diameter of inscribed circle 5/16 in
Symbol of designation 2.5 (5/16 = 2.5/8)

| III–IV Non-equilateral inserts |               |
| In countries using the metric system, the symbol of designation is the length, disregarding any decimals. |
| EXAMPLE                        |               |
| Length of the main edge        | 19.5 mm       |
| Symbol of designation          | 19            |

In countries using the Imperial (inch) system, the symbol of designation is the numerator of the fraction for the value in ¼ in.

EXAMPLE Length of the main edge 3/4 in
Symbol of designation 3

| V Round inserts   |               |
| In countries using the metric system, choose the values of the diameter as the symbol of designation and disregard any decimals. |
| EXAMPLE           |               |
| Insert diameter   | 15.575 mm     |
| Symbol of designation | 15           |

For inserts having rounded metric diameter, the same rule is valid, combined with a special symbol at reference (7).

In countries using the Imperial (inch) system, proceed as for equilateral inserts (types I–II).
T-hold-S) and the tool-in-machine system (Astakhov, 1998/1999) (hereafter, T-mach-S) should also be considered.

Introduction of two additional systems of consideration might be thought of as overcomplicating the cutting tool geometry and its practical applications as this is suitable only for ivory tower academicians and has little practical value on the shop floor. In this author’s opinion, the opposite is actually the case. Namely, misunderstanding the tool geometry in the above-mentioned systems leads to improper selection of the tool geometry parameters and prevents the optimization of practical machining operations. Moreover, tool life and quality of the machined surface are often not as good as they could be if the tool geometry were selected properly. In other words, the proposed consideration does not complicate but rather simplifies analysis of the tool geometry.

The cutting tool geometry includes a number of angles measured in different planes. Although the definitions of the standard planes for consideration of the tool geometry are the same for all four above-mentioned systems of consideration, these planes are not the same in these systems (Astakhov, 2010b). The choice of a particular system and/or their combinations depends on the tool and toolholder design, tool post and tool fixing in the machine, direction of the tool motion with respect to the workpiece or axis of rotation, and other factors. In the case of a cutting tool with indexable inserts, the aim is to select the proper inserts and the available tool holder to assure the tool geometry required by the optimal performance of the machining operation. Therefore, the starting point of tool design (selection) is the optimum cutting geometry and the finishing point is the tool grinding geometry or specifically selected tool holders and inserts to assure the optimal cutting geometry. To do this, a tool designer (and tool layout, tool application and tool optimization specialists, manufacturing and process
engineers) should know the basic definitions and parameters of the tool geometry, the above-mentioned three systems of consideration of the tool geometry as well as the correlations between these systems (Astakhov, 2010b).

Despite being simple, logical and straightforward, the above-stated representation of the tool geometry is not common but has been indirectly used for years in various books and research papers. To demonstrate the necessity of the T-hold-S and the T-mach-S additional systems, the geometry of a common cutting insert shown in Figure 1.26 is considered as an example. The geometry of this insert is as follows: rake angle is 20°, flank angle is 3°, and assumed tool cutting edge angle is 0°. These angles, together with some other parameters (for example, the nose radius), may be considered the T-hand-S tool geometry of this insert.

Obviously this insert can be placed in various available standard and special tool holders (Figure 1.27) Often, the tool holder changes the rake and flank angles of the insert. If the insert shown in Figure 1.26 is used with a Seco Tool MSRNR-20-5D tool holder, then the tool cutting edge angle would be 75°, the normal rake angle would

**Figure 1.26** A square indexable insert
be 15°, while the normal flank angle would be 5°. If this insert is used with a MSRNR-20-6D tool holder, then the tool cutting edge angle would be 45°, the normal rake angle would be 17°, while the normal flank angle would be 4°. Thus, the tool geometry in the T-hold-S is not the same as that in the T-hand-S.

The position of the tool holder in the machine can change the T-hold-S geometry. In modern CNC machines, the direction of the feed motion may vary with the tool path, depending upon the configuration of the machined part so that the cutting tool angles change according to the actual direction of the cutting feed, as shown in Figure 1.28.

Besides the considered case of CNC machining, the T-mach-S (known also as the setting system) is used when the tool is set in the machine or a cartridge set in the tool body (the milling cutter, boring bar) so that the tool geometry established in the T-hold-S is altered, i.e. one or more important tool angles are changed. Although there can be a great number of various scenarios, the two commonest are:
- Tool re-positioning in the reference plane that changes the tool cutting edge angle $\kappa_r$.
- Tool re-positioning in the back plane that changes the rake and the flank angles.

Experience shows that all other cases are combinations of these two basic cases.

Figure 1.29(a) shows the case where the geometrical axis of the cutter is perpendicular to the axis of rotation of the workpiece. Obviously, the cutting edge angles $\kappa_r$ and $\kappa_{r1}$ of the major and minor cutting edges are as in the T-hold-S. Figures 1.29 (b) and (c) show two cases where the tool, installed in the machine, is rotated by an angle $\omega$, in the clockwise and counterclockwise directions. When the former is the case, then the cutting edge angles in the T-mach-S are calculated as:

$$
\kappa_{ro} = \kappa_r - \omega_r \quad \text{and} \quad \kappa_{r1o} = \kappa_{r1} + \omega_r \quad [1.20]
$$

and when the latter is the case, then

$$
\kappa_{ro} = \kappa_r + \omega_1 \quad \text{and} \quad \kappa_{r1o} = \kappa_{r1} - \omega_1 \quad [1.21]
$$

Because the cutting edge angles $\kappa_r$ and $\kappa_{r1}$ of the major and minor cutting edges have a profound influence on the SPTT.
performance, these should be always considered in the T-mach-S.

**Designation of holders**

Standard ISO 5608:1995 Turning and copying tool holders and cartridges for indexable inserts – Designation defines the designation and dimensions of tool holders. The designation code comprises 10 symbols for the designation of dimensions and other characteristics of the tool and the insert, of which the first 9 symbols shall be used in any designation. The last symbol may be used when necessary. In addition to the standardized designation (symbols in positions (1) to (10)), a supplementary symbol consisting of a maximum of three letters and/or numbers may be added by the manufacturer for a better description of his products, on condition that this symbol is separated from the standardized designation by a dash and that it does not contain letters specified for position (10).

No addition to or extension of the code specified in this International Standard can be made without consulting the
Technical Committee ISO/TC 29 and obtaining its agreement. Rather than adding symbols not provided for in this system, it is preferable to add to the designation conforming to this International Standard all necessary explanations in detailed sketches or specifications.

The meaning of the nine compulsory symbols and one optional symbol constituting the code is as follows:

1. Letter symbol identifying the method of holding the insert.
2. Letter symbol identifying insert shape.
3. Letter symbol identifying tool style.
4. Letter symbol identifying insert normal clearance.
5. Letter symbol identifying hand of tool.
6. Number symbol identifying tool height (shank height of tool holders and height of cutting edge).
7. Number symbol identifying tool holder shank width or, for cartridges, the letter C followed by a letter symbol identifying the cartridge type.
8. Letter symbol identifying tool length.
9. Number symbol identifying indexable insert size.
10. Letter symbol indicating special tolerances.

Figure 1.30 shows an example of a tool holder code for an ISO indexable insert.

Although the various tool manufacturers should use the same structure of the designation code for tool holders, the meaning of the letters and numbers included are not the same as defined by Standards ISO 5608:1995. Moreover, the designations codes are often different for ANSI and ISO inserts and the differences are more than simple in/mm conversions. These codes as presented in the catalogs of leading tool manufacturers are not clear, so some experience is required to understand the real meaning of such codes.
1.7.3 Selection of proper insert size and shape

Two practical issues are always of concern in the selection of the cutting insert shape and size for SPTT. As discussed in Section 1.7.1, the interpretation of the size of the cutting insert is not the same according to the ISO and ANSI Standards, so some practical help should be given to a process/tool designer to simplify the process of selection of proper insert size. To select the proper size, the maximum depth of cut $a_p$ and effective length of the cutting edge $l_a$ (Figure 1.31) required by the operation should be known to determine the length of the cutting edge $l_c$, and thus to select the proper insert size. It follows from the previous consideration that $l_a$ depends on the tool cutting edge angle $\kappa_r$. Table 1.6 gives recommendations on the selection of $l_a$.

The insert shape is selected based on the tool layout (Figure 1.15). One should be aware that the maximum allowable active length of the cutting edge depends on the insert shape, as shown in Figure 1.32. Therefore, not only the tool layout (the tool cutting edge angle), but also the maximum depth of cut and the tool holder are factors involved in the selection of the insert shape.
Figure 1.31  Active length of the cutting edge

Table 1.6  Effective length of cutting inserts

<table>
<thead>
<tr>
<th>Tool cutting edge angle, $\kappa_r$ (°)</th>
<th>Depth of cut, $a_p$ (mm)</th>
<th>Required effective length, $l_a$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>90</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>105</td>
<td>1.1</td>
<td>2.1</td>
</tr>
<tr>
<td>120</td>
<td>1.2</td>
<td>2.3</td>
</tr>
<tr>
<td>135</td>
<td>1.4</td>
<td>2.9</td>
</tr>
<tr>
<td>150</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>165</td>
<td>4</td>
<td>8</td>
</tr>
</tbody>
</table>

Figure 1.32  Maximum allowable active length $l_a$ for various inserts shapes

...
The selection of the insert shape also depends on other factors particular to a given turning operation. Figure 1.33 shows what has to be additionally considered in such a selection. To maximize the strength of the insert, the angle between the major and the minor cutting edge should be selected as large as the tool layout permits. When instability of the turning operation is of concern, the insert versatility is sacrificed to increase its strength. When a tapered surface is to be machined (Figure 1.28), the insert shape is selected so that the tool cutting edge angle of the minor cutting edge $\kappa_{r1}$ is not less than 5º.

### 1.8 Cutting feed and surface finish in turning

The nose radius of the tool defines: (1) the strength of the insert in roughing turning operations; and (2) the surface finish in finishing turning operations.

#### 1.8.1 Roughing operations

In roughing turning operations, the nose radius should be selected as large as is permissible by the tool layout because:
Modern machining technology

(1) it increases the strength of the insert; and (2) inserts with a larger radius permit working with higher cutting feeds. However, the nose radius is limited not only by the tool layout but also by vibrations. The maximum cutting feed in roughing operations should be selected according to the data shown in Table 1.7.

<table>
<thead>
<tr>
<th>Nose radius, ( r_n ) (mm)</th>
<th>0.4</th>
<th>0.8</th>
<th>1.2</th>
<th>1.6</th>
<th>2.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum cutting feed, ( f ) (mm/rev)</td>
<td>0.25–0.35</td>
<td>0.4–0.7</td>
<td>0.5–1.0</td>
<td>0.7–1.3</td>
<td>1.0–1.8</td>
</tr>
</tbody>
</table>

Often in roughing turning operations, cutting inserts having a nose radius 1.2 to 1.6 mm are used. Although Table 1.7 recommends that the maximum cutting feed should not exceed two-thirds of the nose radius, the larger cutting feeds can be used for the insert with the angle between the major and minor cutting edges of more than 60º and for work materials of good machinability when moderated cutting speeds are used.

### 1.8.2 Finishing turning operations

In finishing turning operations, the integrity of the machined surface is of prime concern. Therefore, the insert shape and its nose radius are selected to achieve the desired surface roughness.

Surface integrity in the engineering sense can be defined as a set of various properties (both superficial and in-depth) of an engineering surface that affect the performance of this surface in service. These properties primarily include surface finish, texture and profile; fatigue corrosion and wear resistance; adhesion and diffusion properties (Astakhov, 2010c). Of these
properties of the machined surface, surface finish is the most common characteristic/requirement which is included in a turning manufacturing drawing. Therefore, it is important to know the influence of various parameters involved in turning on the surface finish of machined parts. This section aims to provide some basic guidelines on the matter.

Surface roughness is a measure of the texture of a surface. It is measured by the vertical deviations of a real surface from its ideal form. If these deviations are large, the surface is rough; if they are small, the surface is smooth. Surface roughness plays an important role in determining how a machine interacts with its environment. Rough surfaces usually wear faster and their contact is characterized by higher friction coefficients than smooth surfaces. Therefore, surface roughness is a common parameter of surface integrity specified by the part drawing. Although roughness is usually undesirable, decreasing the roughness of a machined surface will usually exponentially increase its manufacturing costs. This often results in a trade-off between the manufacturing cost of a component and its performance in application.

There are many different roughness parameters in use, but $R_a$ – the arithmetic mean roughness – is by far the most common. Other common parameters include: $R_z$ – ten points mean roughness, and $R_t$ is the maximum height of the surface profile measured according to Standard ISO 468:1982: Surface roughness – Parameters, their values and general rules for specifying requirements.

Theoretical and actual surface roughness in turning

Of the many parameters of tool geometry, the influence of the cutting edge angles $\kappa_r$ and $\kappa_r1$ on the surface roughness of the machined parts is most profound (Shaw, 1984). To
explain this influence, consider the simplest case when the nose radius is zero as shown in Figure 1.34. As can be seen, the tool advancement due to the cutting feed $f$ results in the formation of surface roughness represented by triangle ABC. The sides of this triangle are as follows: side AC is equal to the cutting feed per revolution (i.e., if $f = 0.4$ mm/rev, then $AC = 0.4$ mm), side BC is parallel to the major cutting edge AD, and side AB is parallel to (coincides with) the minor cutting edge AE.

Figure 1.35(a) shows the sense of the so-called theoretical or geometrical surface roughness. The height $R_t$ and profile of this roughness (theoretical resulting from the feed marks) depend on the cutting feed and tool cutting edge angles $\kappa_r$ and $\kappa_{r1}$. For the tool with no nose radius (Figure 1.35(a)), this roughness can easily be computed in terms of maximum peak-to-valley distance as:

$$R_t = \frac{f \sin \kappa_r \sin \kappa_{r1}}{\sin (\kappa_r + \kappa_{r1})}$$  \[1.22\]
Turning

When a full-radius cutting insert is used (Figure 1.35(b)), the discussed roughness can be calculated as:

$$R_t = \frac{f^2}{8r_n}$$  \[1.23\]

**Example**

**Problem**
Determine the maximum peak-to-valley distance (theoretical surface roughness) in turning using the single point tool with a small nose radius (Figure 1.35(a)), the cutting feed $f = 0.25$ mm/rev and depth of cut $d_w = 3$ mm. A standard diamond-shaped insert CEJN 2525M is mounted in a tool holder with $\kappa_r = 95^\circ$ and $\kappa_{r_1} = 7.5^\circ$.

How would this distance change if a standard RCMX 1204M0 round insert having a diameter of 16 mm is used instead?
A logical question to be answered is: How far is the geometrical (theoretical) roughness of the machined surface from that obtained in the real cutting? As discussed by Astakhov (Astakhov, 2006), if the cutting process takes place at the optimal cutting temperature, the built-up edge does not form at all, so it does not have any effect on the surface finish. Figure 1.36 exemplifies this statement. As seen, the built-up edge affects the surface finish only when working with low cutting speeds when the cutting temperature is below the optimal cutting temperature (1.36(a)). When the cutting temperature is close or equal to the optimal cutting temperature, the built-up edge does not form at all so the surface roughness is practically equal to the so-called theoretical surface roughness determined by tool geometry and the cutting feed as seen in Figure 1.36(b) (Astakhov, 2006).

Figure 1.37 shows the comparison of the surface finish calculated through the tool geometry and the cutting feed
Figure 1.36  Surface finish in longitudinal turning

Note: Work material – ANSI 1045 steel, tool material – Carbide P10 (14%TiC,8%Co), rake angle $\gamma_n = 7^\circ$, flank angle $\alpha_n = 9^\circ$, tool cutting edge angle $\kappa_r = 93^\circ$, tool cutting minor cutting edge angle $\kappa_{r1} = 27^\circ$, tool nose radius $r_n = 1$ mm, depth of cut $d_w = 0.3$ mm at different cutting conditions: (a) cutting speed $v = 12$ m/min, feed $f = 0.38$ mm/rev, and (b) $v = 250$ m/min, $f = 0.45$ mm/rev

Figure 1.37  Calculated and actual surface roughness at two different cutting speeds (the cutting tool and work material are the same as those identified in the legend of Figure 1.36)
with that obtained experimentally at two different cutting speeds. As can be seen, when the cutting speed is selected so that the cutting temperature is close to the optimal cutting temperature (depending upon the particular cutting feed as it also affects the cutting temperature), the actual and the calculated surface roughnesses are close to each other. When the combination of the cutting speed and feed results in the optimal cutting temperature, they are the same. This actually can be a simple but objective indicator of turning operation ‘optimality’. Moreover, such an indicator can be used on the shop floor to assess a turning operation.

**Wiper geometry**

To improve the surface finish at high cutting feed, a tool geometry with a cleaning cutting edge which has $\kappa_{r1} = 0$ (Figure 1.35(d)) was introduced in the mid-1950s. Although its use resulted in significant improvements in surface finish, two drawbacks immediately became evident. First, the use of such geometry often resulted in the onset of severe vibrations (chatter), and, second, it was found that the results were highly sensitive to the location of the minor cutting edge which theoretically should be exactly parallel to the axis of rotation of the workpiece. Old, not sufficiently rigid machines and not sufficiently accurate tool posts and tools limited the wide use of the cleaning cutting edge.

Times have changed. Rigid, high-power machines and indexable close-tolerance cutting inserts have been introduced. As a result, the cutting feed can be increased to meet today’s requirement for high-penetration rate, high efficiency machining operations. However, as discussed above, in finish turning, the cutting feed has always been limited. It is a simple matter of geometry because, as shown in Figure 1.35(a), the cutting tool actually cuts a ‘thread’ on
the machining surface (Figure 1.36). Such a ‘thread’ can be tolerated in a roughing turning operation while, when finish turning, machinists must reduce feed rates to avoid leaving a pattern on the machined surface. Sometimes, even a slow feed rate and a light depth of cut cannot produce a surface finish good enough to meet part specifications. In these cases, the shop must rely on a finish-grinding step.

Theoretically, a machinist can use a tool with a larger nose radius to increase the feed rate and still obtain a smooth surface finish, according to Eq. [1.23]. The larger radius presents a broader cutting edge to the workpiece, so the tool can move further per workpiece revolution and still overlap the cut made in the previous revolution. But increasing the nose radius to achieve a larger feed rate has its limits, too. Tools with larger nose radii are more likely to begin vibrating in the cut. A larger nose radius also inhibits a tool’s ability to break chips and may require a greater depth of cut to engage the cutting edge properly that is not desirable for finishing as other parameters of the machined surface integrity may suffer (Astakhov, 2010c).

To overcome the problem, tool manufacturers re-visited the tool geometry with a cleaning insert, as shown in Figure 1.35(d). Modern machines are normally rigid, and thus the second problem with the cleaning edge position with respect to the axis of rotation has been addressed. It was addressed with the introduction of the so-called wiper insert geometry which does not differ significantly from the cleaning edge geometry. A standard insert, regardless of its nose radius $r_n$, has a smoothly curved tip, with a line that curves around at a consistent radius. As shown in Figure 1.38(a), it leaves a certain theoretical roughness (characterized by $R_t$) on the machined surface. By contrast, a wiper insert’s nose is slightly flattened and as shown in Figure 1.38(b). Manufacturers describe this geometry as a combination or a blend of radii ($r_1$ and $r_2$ in Figure 1.38(b)). The blended radii knock off the sharp points
created due to the cutting feed that provides a smoother finish without utilizing a larger nose radius or slower feeds.

The modern wiper geometry inserts are designed so that one can reduce $R_t$ approximately double compared to a standard insert or double the cutting feed while keeping the same $R_t$. In certain operations, the use of the wiper geometry eliminates the grinding stage in part production.

In studying the performance of their wiper inserts, the leading toolmakers claim to have discovered some side benefits, besides higher feed rates and better surface finishes. First, it was found that wiper inserts last longer than conventional inserts, even though they were not necessarily designed for extended wear. Second, the wiper geometry adds strength to cutting inserts so that they can handle severe interrupted cuts and cut with shocks (for example, machining of a workpiece with a hexagonal cross-section). Third, the higher cutting feeds possible with wiper inserts reduce the length of the overall tool path to machine a workpiece, as well as reducing the amount of time on the tool. Therefore, there is less time for the operation to generate heat and less distance to wear on the inserts’ flank face.

Despite these advantages, the limitations mentioned when describing the cleaning edge remain. Moreover, the grades of
wiper inserts available are similar to the standard insert grades toolmakers offer. The toolmakers do not produce inserts in as wide a selection as their standard inserts. However, Sandvik, for instance, only offers a few chip breaker styles, ISKAR has a limited selection due to the relatively small market for these inserts at present.

1.9 Tool wear of SPTT

As a SPTT works, its cutting portion wears and tool wear leads to tool failure. Normally, tool wear is a progressive process. In roughing operations, a tool failure criterion is set to limit the amount of tool wear, and thus prevent its breakage. In a finishing operation, a tool wear criterion is commonly based upon the maximum allowable surface roughness of the machined surface and/or the dimensional accuracy of the machined parts while other criteria of surface integrity (Astakhov, 2010c) can also be used.

1.9.1 Tool wear types and common tool wear evaluation characteristics

Standard ISO 3685:1993 Tool-life testing with single-point turning tools defines tool wear on the flank and rake faces of the cutting tool. Figure 1.39 shows the basic characteristics of tool wear occurring on the rake and flank faces.

The wear of the rake face is known as crater wear. The chip flows across the rake face, resulting in severe friction between the chip and rake face, and leaves a scar on the rake face which usually parallels the major cutting edge. The crater wear can increase the working rake angle and reduce the cutting force, but it will also weaken the strength of the cutting edge. The parameters used to measure the crater wear
are shown in Figure 1.39. The crater depth $KT$ is the most commonly used parameter in evaluating the rake face wear.

Wear on the flank (relief) face is called flank wear and results in the formation of a wear land. Wear land formation is not always uniform along the major and minor cutting edges of the tool. That is why, for wear measurements, the major cutting edge is considered to be divided into four regions, as shown in Figure 1.39: (1) Region C is the curved part of the cutting edge at the tool corner; (2) Region B is the remaining straight part of the cutting edge in zone C; and (3) Region N is the quarter of the worn cutting edge length $b$ farthest away from the tool corner.

Normally in tool testing, the width of the flank wear land $VB_B$ is measured in zone B as shown in Figure 1.39. In some
special cases, nose wear $VB_C$, maximum flank wear $VB_{\text{max}}$, or notch wear $VB_N$ are measured.

1.9.2 Tool life curves

Tool wear curves illustrate the relationship between the amount of flank (rake) wear and the cutting time ($\tau_m$) or the overall length of the cutting path ($L$). These curves are represented in linear coordinate systems using the results of cutting tests, where flank wear $VB_B$ is measured after certain time periods (Figure 1.40(a)) or after a certain length of the cutting path (Figure 1.40(b)). Normally, there are three distinct regions that can be observed on such curves. The first region (I in Figure 1.40(b)) is the region of preliminary or initial wear. Relatively high wear rate (an increase of tool wear per unit time or length of the cutting path) in this region is explained by accelerated wear of the tool layers damaged during its manufacturing or re-sharpening. The second region (II in Figure 1.40(b)) is the region of steady-state wear. This is the normal operating region for the cutting tool. The third region (III in Figure 1.40(b)) is

![Figure 1.40](image-url)

**Figure 1.40** Typical tool rate curves for flank wear: (a) as a function of time and (b) as a function of cutting path.
known as the tertiary or accelerated wear region. Accelerated tool wear in this region is usually accompanied by high cutting forces, temperatures and severe tool vibrations. Normally, the tool should not be used in this region.

Tool wear depends not only on the cutting time or the length of the cutting path but also on the parameters of the tool geometry (rake, flank, inclination angles, radius of the cutting edge, etc.), cutting regimes (cutting speed, feed, depth of cut), properties of the work material (hardness, toughness, structure, etc.), presence and properties of the cutting fluid and many other parameters of the machining system. In practice, however, the cutting speed is of prime concern in the consideration of tool wear. As such, tool wear curves are constructed for different cutting speeds while keeping other machining parameters invariable. In Figure 1.41, three characteristic tool wear curves (mean values) are shown for three different cutting speeds, \( v_1 \), \( v_2 \) and \( v_3 \). Because \( v_3 \) is greater than the other two, it corresponds to the fastest wear.
rate. When the amount of wear reaches the permissible tool wear $V_{B_{C}}$, the tool is said to be worn out.

The criteria recommended by ISO 3685:1993 to define the effective tool life for cemented carbide tools, and those with high-speed steels (HSS) and ceramics are:

**Cemented carbides**

1. $V_B = 0.3$ mm, or
2. $V_{B_{\text{max}}} = 0.6$ mm, if the flank is irregularly worn, or;
3. $K_T = 0.06 + 0.3f$, where $f$ is the feed.

**HSS and ceramics**

1. $V_B = 0.3$ mm, if the flank is regularly in region B; or
2. $V_{B_{\text{max}}} = 0.6$ mm, if the flank is irregularly in region B.

In practice, however, $V_{B_{C}}$ is selected from the range (0.15–1.00 mm) depending upon the type of machining operation, condition of the machine tool and quality requirements for the operation. It is often selected on the ground of process efficiency and often called the criterion of tool life. In Figure 1.41, $T_1$ is tool life when the cutting speed $v_1$ is used, $T_2$ when $v_2$, and $T_3$ when $v_3$ is the case. When the integrity of the machined surface permits, the curve of maximum wear instead of the line of equal wear should be used (Figure 1.41). As such, the spread in tool life between the lower and higher cutting speeds becomes less significant. As a result, a higher productivity rate can be achieved which is particularly important when high-speed CNC machines are used.

Although the tool wear assessments based on the above-discussed wear curves as well as the use of Taylor’s formula that correlated the tool life and the cutting speed (Astakhov, 2006) are standard, they are now outdated, and thus not really suitable in tool life assessment in modern manufacturing, particularly when different tool designs/tool materials/coatings are to be compared. For example, the use of operating time as per
Figure 1.40(a) to compare the performance of two tools can be wrong because one tool can permit the machining of a much larger area or removal of a much greater volume of the work material during this time. If the cutting path (Figure 1.40(b)) is used to compare two tools but one tool allows double the cutting feet, then a false result on the tools’ comparison occurs.

As shown by this author earlier (Astakhov, 2006), among the suitable characteristics for tool wear assessment, the volumetric or mass tool wear is very versatile because it does not depend on tool geometry and design. This parameter can be measured directly. As such, the volume of lost tool material \( V_w \) is obtained from the comparison of the 3D topography of the cutting wedge with that of the new tool (presumably stored in the memory of the image processing system). As such, the mass of worn material \( m_w \) is calculated as

\[
m_w = \rho_{ct} V_w
\]

where \( \rho_{ct} \) is the density of the tool material.

Figure 1.40 shows wear curves when \( m_w \) is used.

Volumetric or mass tool wear can also be calculated using the results of linear measurements and parameters of tool geometry (Astakhov, 2006). Moreover, other tool wear assessment indexes for fast and reliable tool wear tests and comparisons of tools having different designs, tool materials, optimum operating conditions (the cutting speed, feed, depth of cut, etc.) are offered: the dimension wear rate, surface wear rate, and the specific dimension tool life. Of these indexes, the surface wear rate is the most objective and easy to measure in practice.

The surface wear rate is the radial \( h_r \) wear per 1000 \( \text{sm}^2 \) of the machined area \( A_m \)

\[
h_s = \frac{dh_r}{dA_m} = \frac{100h_r}{Lf} \left( \mu\text{m}/10^3\text{sm}^2 \right)
\]

[1.25]
where $h_r$ is the radial wear and $L$ is the total length of the tool path.

As follows from Eq. [1.25], the surface wear rate is in reverse proportion to the overall machined area and, in contrast to it, does not depend on the selected wear criterion.

It is possible to use the width of the wear land at the tool point (nose) $VB_C$ instead of the radial wear to calculate the surface wear rate, i.e.

$$h_s = \frac{100VB_C}{Lf} \left( \text{um} / 10^3 \text{sm}^2 \right) \quad [1.26]$$

### 1.10 How to deal with vibrations in turning

Vibration is often referred to as chatter in metal cutting and is familiar to every machine tool operator. This phenomenon occurs in many machining operations such as turning, boring, milling, drilling, etc. The most common way in practice to deal with the phenomenon is to reduce the process parameters as, for example, the cutting speed. However, this is not always acceptable. Current machining in today’s manufacturing market is extremely competitive. One way to achieve a leading edge over competitors is to improve machining conditions by intelligently selecting the proper parameters of the machining operation to eliminate unwanted conditions such as chatter. By doing so, substantial savings in machining are achieved because chatter is the most problematic and limiting factor of machining, especially with high spindle speeds, non-rigid workpieces and long reach cutters. Although chatter may occur at standard conventional speeds, it is more distinct and destructive in the so-called high-speed machining.

The literature on machine tool dynamics primarily considers one parameter that affects chatter conditions,
namely the spindle rotational speed (rpm); it also happens to be the quickest and easiest parameter to fix or change to maximize the machining operation. Actually, one can program the best rpm of a machining operation before even taking a cut if the right equipment is used or it can be adjusted during a cut. There also are chatter control devices that work directly with machine controllers to detect chatter during the machining operation; they automatically adjust the rpm to the desired speed and begin cutting again. These items are required to effectively machine at maximum potential, but understanding chatter is the first thing to know in order to use any of these kinds of equipment or methods properly.

Two types of vibration that can occur in a machining operation are forced vibration and self-excited vibration. Forced vibrations are produced by a periodic force acting on the system. A harmonic force has a single frequency $f_v$ and it excites vibration with exactly the same frequency. It has a deterministic, steady vibration as well as an unbalanced shaft or rotor. It can be a problem, but it is limited due to the high stiffness of machine set-ups. In machine tools, forced vibration is excited by unbalanced rotating masses (shaft, gears, toolholders and tools), by pulsating oil pressure from gear pumps, etc. This type of vibration can easily be detected either by using an advanced machine controller or by placing a simple accelerometer on the cutting tool. As shown in Figure 1.42, the single (dominant) frequency $f_v$ of such a vibration is always equal to the rotating frequency or its first few harmonics. Once this vibration is detected, its cause can be eliminated or its severity can be reduced to an acceptable level.

Self-excited vibration, often referred to as chatter, involves a steady input of energy modulated into vibration. It arises in all machining operations if there is enough gain in the feedback process and if the chip width exceeds a limit value dependent upon the dynamics of the machine. Figure 1.43
shows character chatter marks left on the machined surface due to self-excited vibrations. When it occurs in machining, it is inevitably violent, destructive and difficult to eliminate, as the speeds and power increase. Chatter is the main limitation on the usable metal removal rate.
In the literature on chatter, it is believed to occur due to regeneration of waviness on the cut surface. Although hundreds of millions of dollars have been spent by various governmental bodies and leading machine tool manufacturers to study the phenomenon, nothing more than the so-called stability lobe diagrams have been produced.

An example of such a diagram is shown in Figure 1.44. In general, stability lobe diagrams have been developed by selecting the cutting parameters, which include the process-dependent specific cutting energy coefficients, radial immersion, and system dynamics (often selected as the tool point frequency response, although the workpiece dynamics must also be considered in some instances), then carrying out the selected simulation algorithm. In this case, the system dynamics are considered to be fixed and a new set of stability calculations must be completed if the system changes (e.g., a new tool is selected). It makes such a diagram highly impractical because the selected and experimentally determined parameters will alter with any change in machining conditions or even with tool position with respect to the workpiece. It can clearly be seen in Figure 1.43 that
chatter took place and then was reduced when the cutting tool changed its position.

To understand the nature of self-excited vibration, one needs to know the following facts. Self-excited systems begin to vibrate of their own accord spontaneously, the amplitude increasing until some nonlinear effect limits any further increase of its amplitude. The energy needed to sustain these vibrations is obtained from a source of power associated with the vibrating system which, due to some mechanism inherent in the system, gives rise to oscillating forces. The higher the rigidity of the system, the greater the forces (energy) needed to cause self-exciting vibration, the greater the system stability. This fact is accounted for in the design of modern turning centers of high rigidity (stiffness) that allow machining at greater cutting speeds and feeds with no vibration. Self-excited vibrations are characterized by the presence of a mechanism whereby a system will vibrate at its own natural frequency or critical frequency, essentially independent of the frequency of any external stimulus.

The foregoing consideration suggests that the use of rigid machining systems is the best way to avoid chatter. The tool overhangs should be minimized, the tool holder should be rigid, the length and clamping of the workpiece should be optimized. Unfortunately, this is not always possible in many practical cases so one needs to know how to deal with chatter.

The following discussion developed by this author should be clearly understood by everyone dealing with machining chatter – from high-level researchers, who are trying to develop new machine tools and cutting tools, to shop operators who are trying to eliminate chatter while keeping up the high productivity of machining:

1. For chatter to be sustainable, a certain amount of energy is required. This energy comes from the cutting process
itself. Therefore, an understanding of the cutting process is paramount in studying machining chatter. Unfortunately, this is not always the case as the specialists dealing with machining dynamics do not understand, and thus do not consider, the physics of the cutting process.

2. The energy that sustains machining chatter is due to the cyclic nature of this process and due to friction on the tool–chip and tool–workpiece interfaces. The amount of this energy is directly proportional to the variable part of the total work of plastic deformation in metal cutting.

This discussion introduces some simple basic rules to combat machining chatter:

Rule #1: Limit the energy that sustains machining chatter.
Rule #2: Limit the amplitude of the chatter.
Rule #3: Decrease the variable part of the energy of the plastic deformation of the work material.
Rule #4: Counterbalance the machining chatter.

Figure 1.45 presents a simple practical guide to deal with machining chatter where Rules # 1, 2 and 3 are implemented. If chatter occurs, the first measure to deal with it is the reduction of the active length of the cutting edge (Rule #1). It can be accomplished by:

- Switching from a round cutting inset to one with straight cutting edges (position 1 in Figure 1.45).
- Increasing the tool cutting edge angle (position 1 in Figure 1.45). Note that this measure is effective in dealing with chatter, its implementation increases the tool wear rate.
- Reducing the corner radii of the cutting insert (position 2 in Figure 1.45). The rule of thumb is not to use the depth of cut equal to or less than the nose radius.
### Figure 1.45 Vibration troubleshooting guide

<table>
<thead>
<tr>
<th>Cause of vibrations</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>The active length of the cutting edge, ( l_a ) is too long. Reduce the active length of the cutting edge by changing the insert shape or increasing the tool cutting edge angle.</td>
</tr>
<tr>
<td>2</td>
<td>( r_n &gt; 0.6 ) mm Too large tool nose radius. ( r_n = 0.2...0.4 ) mm Reduce tool nose radius.</td>
</tr>
<tr>
<td>3</td>
<td>( \gamma_n &lt; 0^\circ ), ( \alpha_n &gt; 6^\circ ) The normal flank angle is too large, while the normal rake angle is small. Decrease the normal flank angle, increase the normal rake angle.</td>
</tr>
<tr>
<td>4</td>
<td>Small tool minor cutting edge angle ( \kappa_r ). Increase the tool minor cutting edge angle ( \kappa_r ) by selecting a different insert.</td>
</tr>
<tr>
<td>5</td>
<td>The cutting edge is too sharp (small radius of the cutting edge ( \rho_{ce} )). Increase the radius of the cutting edge ( \rho_{ce} ). Use edge preparation.</td>
</tr>
<tr>
<td>6</td>
<td>The cutting feed ( f ) is too small. Increase the cutting feed ( f ).</td>
</tr>
<tr>
<td>7</td>
<td>All the above did not help. Reduce the depth of cut ( a_p ).</td>
</tr>
</tbody>
</table>

- Increasing the tool cutting edge angle of the minor cutting edge that reduces the length of the active part of the minor cutting edge and the amount of the work materials cut by this edge (position 4 in Figure 1.45) (Astakhov, 2010b). The wiper cutting insert should not be used if chatter occurs.
Reducing the depth of cut (position 1 in Figure 1.45). This is the last resort because it reduces the material removal rate, and thus affects the productivity of the turning.

Rule #2 is realized in positions 3 and 5 of Figure 1.45. As discussed, increasing the amplitude until some nonlinear effect limits any further increase. The simplest way to introduce such an effect is to reduce the penetration ability of the cutting edge into the workpiece. This can be accomplished by reducing the flank angle and by rounding a sharp cutting edge. These measures, however, may not be sufficient in certain situations when a workpiece of great length is being machined, particularly when steady rests are used. In this case, special geometry of an SPTT may be required to deal with chatter.

Examples of such an SPTT geometry are shown in Figure 1.46. Figure 1.46(a) shows a general purpose geometry to be used in the machining of extra-long workpieces. The normal rake angle is selected as follows: for machining low carbon mild steels, $\gamma_n$ is selected to be 20–25°, while for machining difficult materials this angle should be selected from the range of 4–10°. The normal flank angle, $\alpha_n$ should be 6–10°.

![Figure 1.46](image_url) Special SPTT geometry to deal with chatter according to Rule #2: (a) general purpose, and (b) when the depth of cut is less than 1 mm
Figure 1.46(b) shows the tool geometry when the depth of cut is less than 1 mm. The presence of a small chafer between the rake and the flank faces with a negative flank angle restricts the amplitude of chatter due to the non-linear elastoplasticity of the work material.

Rule #3 is realized in position 6 of Figure 1.45. As is known (Astakhov, 2010b), the relative plastic deformation reduces with an increase in the cutting feed. This leads to the reduction of the impact of the variable part of the energy due to plastic deformation to the total energy, and thus force. At high cutting feeds, the cutting system is more stable.

Rule #4: Counterbalance of machining chatter means altering vibrations. To do this, various tuned tooling systems (TTS) were introduced. When tuned correctly, longer tooling with greater length-to-diameter ratios can perform without undesirable vibration. A TTS may be applied to both rotating and stationary tools. A TTS combines dynamically tunable tools with a tuner system. The tunable tools include many commercially available damped tools and custom-made tools designed specifically for tight-tolerance applications. They do not include self-balancing, inertial disk, or rattler-type tools. The tools incorporate an internal mechanism that provides a controlled means of adjusting their dynamic characteristics. The mechanism forms a tunable damper that passively (i.e. using no internal electronics, measurement device, or active control) counteracts the tool vibration.

For maximum effect, the tunable damper should be located as close as possible to the area that vibrates the most. The damper is usually built-in near the tool tip. Alternatively, a tunable damper may be placed in the cutting tool head, the toolholder or extension, or a modular toolholder section. Tunable dampers may also be designed to accommodate through-coolant tooling. The internal tuned damping system is adjusted via a tuning screw, which alters the stiffness (and,
therefore, the vibration frequency) and damping of the mechanism. This allows the damper to counteract the tool’s most flexible mode of vibration.

**1.11 References**


Astakhov, V.P. and Xiao, X. (2008d) ‘A methodology for practical cutting force evaluation based on the energy spent in the cutting system’, *Machining Science and Technology* 12: 325–47.


