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TECHNOLOGY of MECHANICAL ENGINEERING

Part 1

Textbook

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This textbook is devoted to fixing of accuracy in mechanical engineering and bases of the theory of cutting tools.

The textbook is prepared at the Department of Mechanical Engineering of Tomsk Polytechnic University. It is recommended for foreign students following the Bachelor Degree Program in Mechanical Engineering at Tomsk Polytechnic University.

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PREFACE

The discipline "Technology of Mechanical Engineering" is a finishing rate in preparation of the experts under the program "Mechanical Engineering". For its study the knowledge of disciplines "Processing of materials", "Strength of materials" is required.

Fundamentals of the discipline "Technology of mechanical engineering" is studied on the senior rate for the bachelor level in 6, 7 and 8 semesters and is divided into 3 parts. The part "**Metrology, Standardization and Certification”** is studied in the sixth semester (3 credits) and contains **course project**. At the end of 6-th semester the **examination** and defense of **course project** is stipulated.

The part second "**Cutting and Cutting Tools**" is studied in the **sixth**, **seventh** and **eighth** semesters (4 + 4 + 4 = 12 credits) and contains **course project** in the **8** semester. **Credit test**, **examination,** and defense of **course project** are stipulated correspondently.

The part third "**Fundamentals of Mechanical Engineering**" is studied in the **sixth** semester (6 credits). At the end of semester the **examination** is stipulated.

The discipline "**Technology of Mechanical Engineering**" is continued in the **seventh** and **eighth** semesters (6 + 2= 8 credits). **Examination, examination** and defense of **course project** are stipulated correspondently.

This textbook provides the most comprehensive introduction to technology of mechanical engineering. Measurements throughout the textbook are given according to the SI Metric system of measurement. The content is generously illustrated, and the language used is simple and direct.

This text book is written on the basis of the book of Victor E. Repp and Willard J. McCarthy “Machine Tool Technology”. The author of this textbook expresses gratitude to the authors of the book for the given opportunity to use its material.

Suggestions on improvements of future editions of the textbook are welcome.

Cutting and Cutting Tools

The part second "**Cutting and Cutting Tools**" is studied in the **sixth**, **seventh** and **eighth** semesters (4 + 4 + 4 = 12 credits) and contains **course project** in the **8** semester. **Credit test**, **examination,** and defense of **course project** are stipulated correspondently.

Chapter 14. Cutting Tools

The cutting tool is a part of machine which removes the metal. Careful attention should be given to cutting tools in any machining operation. If either faulty or incorrect cutting tools are used, the cost is higher and the quality of work is poor.

Cutting tools, used for various metal-cutting operations include quite a wide range of shapes and may appear to have nothing in common but all metal-cutting tools in general conform to certain fundamental principles in so far as the cutting action is concerned. The cutting of metals, as applied under practical conditions, is based upon the principle that an edged tool will cut or shear off metal, provided:

1. The tool is harder than the metal.
2. The tool is so shaped that its edge can be effective in cutting or shearing off the metal.
3. The tool is strong or rigid enough to resist the cutting pressure but keen enough to sever the metal.
4. There is movement of the tool relative to the material, or vice versa, so as to make cutting action possible.

14.1. Classification of Tools

The number and types of cutting tools used is known to be very large. There are turning tools, milling cutters, drills, planer, slotter, and shaper tools, broaches and abrasives, the type of cutter depending upon the machine which employs it.

Tools may also be classified as being roughing tools or finishing tools according as they are designed to take heavy roughing cuts or light finishing cuts.

Both single and multiple-edged cutting tools are used to cut metals.

The single-point (or single-edged) cutting tool is the most universally used and can be defined as a tool that has one effective cutting edge and removes excess material from the workpiece along the cutting edge. A single-point cutting tool is also referred to as a tool bit. Ordinary lathe or boring mill tools that do turning, facing, or boring operations and have only one effective cutting edge are examples of single-point cutting tools. Tools that remove excess material on two or more cutting edges simultaneously are known as multiple-point (or multiple-edged) cutting tools.

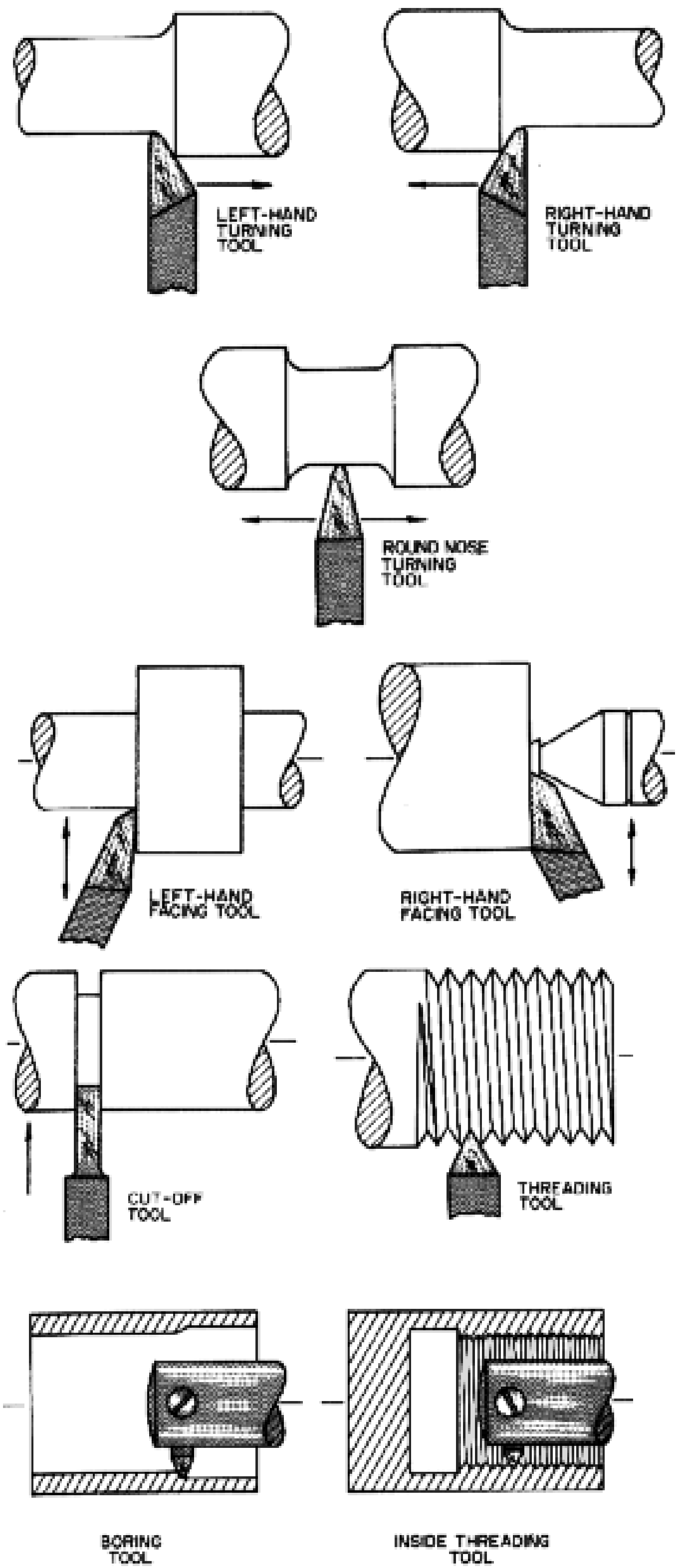


Fig. 14-1. Commonly used lathe tool bits and their applications.

The tools are usually shaped from tool steel bars of square or rectangular section on tool-grinding machines designed for the purpose.

A general grouping of the single-point tools in common use gives the types: a) a solid or forged tool having the same material throughout; b) a solid type having the cutting portion of high alloy steel, but welded on to a tough steel shank; c) a solid type of tool, but having the cutting edge in the form of a tip which is brazed or soldered on to the shank; d) a inserted type where a small piece of the cutting material (high alloy steels, or various carbides) is held in a bar or tool holder by means of a screw or wedge, etc., and ground to the basic shapes of common employment.

Inserted tools (indexable throwaway inserts) are widely used for large-volume production, or for machines of a difficult nature, when it is particularly desirable to maintain tool life between regrinds for as long a time as possible. Standard shapes for indexable throwaway inserts are made of carbide, ceramic, cermet, or diamond. Throwaway inserts are made so precisely that after the initial cutting edge has dulled, the tool may be unclamped, rotated to the next cutting edge, reclamped, and cutting continued without any change in the position of the toolhoder. Regrinding of these tools is generally more costly than replacing them. Thus, they are discarded after all cutting edges have been dulled.

Some of the most popular types and shapes of lathe cutting tools are shown in Fig. 14-1. These tool shapes are typically ground on tool blanks made of high-speed steel or cast alloy. Note that the types of tool bits include right- and left-hand turning tools, facing tools, cutoff tools, and threading tools.

The turning tools have a round nose with a comparatively large nose radius. This type of tool is designed primarily for finish turning.

14.2. Cutting Tool Geometry

The basic principle of design employed in making single-point and other types of cutting tools is the **wedge** which can be modified in accordance with requirements. The differences between the various types of metal-cutting tools are, firstly, differences in shape and, secondly, differences in the angles to which the surfaces of the tools are ground. In order to meet specific conditions of the job in process, the shape of the cutting tools used may be modified as required. The elements of a right-cut single-point tool that is used for turning and planing operations are shown in Fig. 14-2.

The term **tool bit** commonly is applied to relatively small pieces of cutting tool material which are inserted in a toolholder or tool shank in a manner that permits easy removal for regrinding or replacement. A lathe **tool bit** is designated right-hand or left-hand, depending on the direction in which it cuts; see Fig. 14-1. A **right-hand** tool has its cutting edge on the left, and it cuts from right toward left. A **left-hand** tool has its cutting edge on the right and it cuts from left toward right.

The **shank** is the body portion of the tool. The **point** of the tool includes all of that portion of the tool which is shaped to produce the face and the cutting edges.The **base** of a single-point tool is that side of the shank which bears against the supporting toolholder or tool block taking the tangential pressure of the cut. The **heel** is the forward end of the base immediately below and supporting the face. The **cutting edge** is the part of the tool bit that does the actual cutting.

The **face** is the top surface of the tool upon which the chips bear as they are removed from the workpiece and slide away. This surface is made by grinding **back** and **side rake** to form a **slope** that will assist in the shearing action that produces chips, and it helps the chips to flow over the face of the tool away from the point where they are produced to the place where they are disposed of. To help in accomplishing these effects, back rake is most important on a tool that cuts side-ways. The **true rake** angle of a tool is the combination of its back and side rake angles, and varies with the setting of the tool and with the feed and depth of cut.

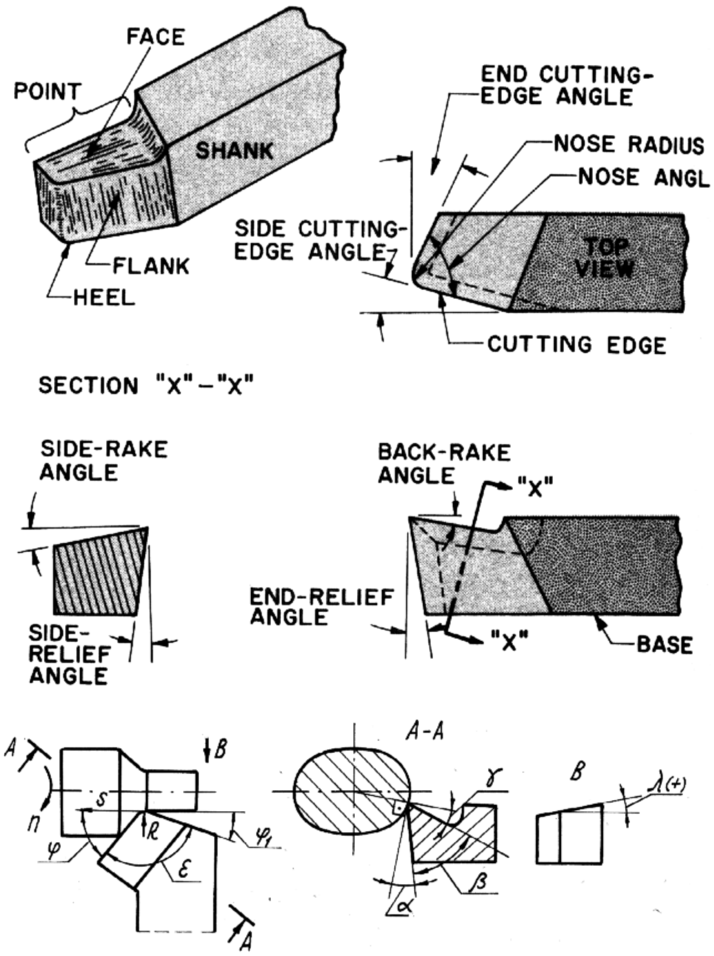


Fig. 14-2. Cutting-tool angles.

The **flank** of the tool is the surface adjacent to and just below the cutting edge. The **nose** is the corner or arc which joins the side cutting edge and the end cutting edge. The **nose radius** is the dimension of the round arc which forms the nose of the tool bit. For rough turning, a small nose radius (usually about 0.4 mm) is used but sometimes a large nose radius about 2.5 mm is preferable. For finish turning, a radius from 0.1 mm to 1.6 mm is used, depending on the rigid of the work and the size of the tool . A turning tool with a nose radius of 0.8 mm will produce a satisfactory finish for general rough or finish turning.

Clearance angles are provided on many single-point tools to reduce the amount of grinding that is necessary to sharpen them, and on multiple-edged tools to provide chip space.

The **toolholder angle** is measured between the bottom of the tool bit slot and the base of the toolholder shank. Toolholders are designed to hold tool bits at either fixed or variable angles. A standard 16.5° toolholder angle commonly used for high-speed steel bits is shown in Fig. 14-3. A zero-degree toolholder commonly used for cast-alloy and cemented-carbide tool bits is shown in Fig. 14-2. Shaper and planer toolholders usually support the tool at a zero-degree angle, that is, parallel to the base of the toolholder. The angle at which the tool bit is held in the toolholder must be considered before grinding a tool bit.

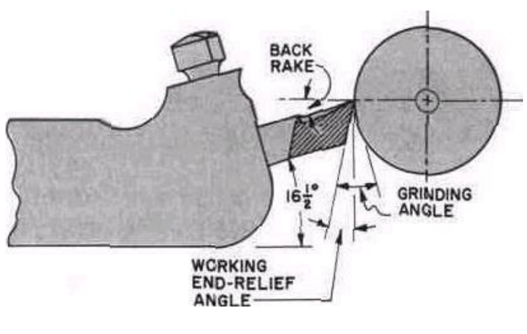


Fig. 14-3. Cutting edge set on center with 16.5° toolholder.

The **side-relief angle** is ground into the flank below the cutting edge. The angle is measured between the ground flank and a line passing through the cutting edge perpendicular to the base of the tool or the toolholder, Fig. 14-2. The side-relief angle allows the cutting edge to penetrate into the metal and promotes free cutting by preventing the side flank of the tool from rubbing against the work.

In acordance with Russian terminology the **main back** (but it corresponds to some extent to the side-relief angle for the English terminology) angle α is measured between the flank of the tool bit and a line passing perpendicular to the line passing through the axis of rotation of a part and active cutting edge in the plane passing perpendicular to the cutting edge and the base plane, Fig. 14-2.

The **end-relief** angle is ground below the nose of the tool. It is measured between this surface and a line passing through the nose cutting edge perpendicular to the base of the tool bit or the toolholder, Figs. 14-2 and 14-3. The end-relief angle permits free cutting by preventing the flank below the nose cutting edge from rubbing against the work.

Working angles are located between the tool and the work. In addition to the shape of the tool, these angles depend upon the location of the tool in relation to the work. The **working relief angle** is the angle formed between the ground flank of the tool and a line passing through the active cutting edge tangent to the machined surface, Fig. 14-2.

Comparison of the end-relief angle measured at the tool bit (grinding angle) and the working end-relief angle in Fig. 14-3 makes their differences apparent. The **grinding angle** is the angle which must be ground on the tool bit in order to produce the proper **working** end-relief angle.

When a tool bit is placed in a zero-degree tool-holder in a lathe, and when the tool is mounted on the center line of the work (Fig. 14-2), the end-relief angle, the **working** end-relief angle, and the grinding angle are equal. This also is true for shaper and planer tool bits which are mounted with the base of the tool bit parallel to the base of the toolholder.

The purpose of the end- and side-relief angles is to permit free cutting by preventing the flanks below the cutting edge from rubbing against the work. For different metals, the working relief angles vary from about 3^o to 15^o. The amount of relief angle depends on the following factors:

1. Kind of material being cut.
2. Hardness of the material being cut.
3. Kind of cutting-tool material.
4. Position of the tool in relation to the work.
5. The nature of the cut.

Only the required amount of end or side relief should be used. Excess relief angle reduces the support under the cutting edge and weakens the tool, thus reducing tool life. Hard materials such as high-carbon steel or hard cast iron require smaller relief angles than soft and more ductile materials. Also, smaller relief angles are used with the harder and more brittle cast-alloy or tungsten-carbide tools than with the tougher high-speed steel tools. Since the working relief angle is reduced when a lathe tool is positioned above the center line of the work, an increased end-relief grinding angle is required in order to provide adequate clearance.

Table 14-1. Average tool angles for single-point high-speed steel tools

Material	Side[1] Relief	End[2] Relief	Side[3] Rake	True back[4] rake
Free-machining steel	10°	10°	10°-22°	16°
Low-carbon steel (,05%-.30%)	10°	10°	10°-14°	16°
Medium-carbon steel (.30%-	10°	10°	10°-14°	12°
High-carbon tool steel (.60-	8°	8°	8°-12°	8°
Tough alloy steel	8°	8°	8°-12°	8°
Stainless steel	8°	8°	5°-10^0	8°
Stainless steel, free-machining	10°	10°	5°-10°	16°
Cast iron, soft	8°	8°	10°	8°
Cast iron, hard	8°	8°	8°	5°
Cast iron, malleable	8°	8°	10°	8°
Aluminum	10°	10°	10°-20°	35°
Copper	10°	10°	10°-20°	16°
Brass	10°	8°	0°	0°
Bronze	10°	8°	0°	0°
Molded plastics	10°	12°	0°	0°
Plastics, acrylics	15°	15°	0°	0°
Fiber	15°	15°	0°	0°

[1]End- and side-relief angles from 3° to 5° generally are recommended for shaper and planer tools.
[2]End-relief and side-relief angles averaging 8° to 10° are fairly standard for turning most metals. For general machining operations, both side- and end-relief angles often are equal.
[3]Use the lower angle when no chip breaker is used. Use the higher angle with a chip breaker.
[4]Rake angles are true angles measured from horizontal and vertical planes.

Relief angles of 5° are suitable for rough-turning and planing operations and 7° for finish-turning most metals. However, relief angles of 3° to 5° are employed with cemented carbide tools as a means of strengthening them. The nature of the cut also determines the amount of end and side relief used. For interrupted cuts, such as those required for turning shafts with keyways or irregularly shaped objects, small relief angles are used. Shaper and planer tools, therefore, should be provided with end- and side-relief angles of 3° to 5°.

The suggested working end-relief and side-relief angles for single-point, high-speed steel cutting tools for average uses are given in Table 14-1. End- and side-relief angles from 8° to 10° are fairly standard for turning many common metals with high-speed steel tools. In many shops, it is the practice to grind both the end and side relief at the same angle. Table 14-2 gives recommended angles for carbide tools.

For general-purpose turning applications, the following working end- and side-relief angles may be used: 10° for high-speed steel, 7° for cast alloy, and 7° for tungsten-carbide tools.

The **back-rake** angle is measured between the face of the tool bit and a line perpendicular to the work at the cutting edge, Figs. 14-2 and 14-3. This angle depends largely on the position at which the tool is held. In the case of a tool bit held in a zero-degree toolholder, with the tool parallel to the base of the holder, the back-rake angle is measured between the face of the tool and a line parallel to the top of the tool.

A tool is said to have **positive** rake when the face slopes away from the cutting edge and downward toward the back or side. It is said to have **negative** rake when it slopes upward toward the back or side. Some tools that are made of material which have a low transverse rupture strength are given negative rake as a means of adding metal to the cutting edge or lip to strengthen it, and tools for cutting brass are given zero or slight negative rake to avoid the tendency to dig into the work that is shown by tools which have a positive rake.

A large positive rake angle will help a tool to cut freely, but it weakens and shortens the life of the tool because it reduces the amount of metal in the lip. In designing a tool, therefore, a compromise must usually be reached between the ability to cut freely and economical tool life.

When the tool is in an angular toolholder, such as a 16.2^0 toolholder, the back rake is established largely by the toolholder. The back rake then is measured between the face of the tool and a line perpendicular to the work at the cutting edge.

An increase in rake angle increases the shear angle at the chip, thereby reducing the cutting force and power required. However, the increase in rake also reduces the cutting angle of the tool and thereby reduces the amount of material which supports the cutting edge.

Generally, small rake angles are used for machining hard materials, while steeper rake angles are used for more ductile materials. Exceptions to this rule include tools for brass, bronze, certain plastics and nonmetals.

Back-rake angles may vary from 0° to 35° for various applications. Suggested rake angles for single-point, high-speed steel tool bits are included in Table 14-1.

Side rake is the angle ground **across** the top of the tool face and is measured between the tool face and a line which represents the top of the unground tool as it is viewed from the end, Fig. 14-2. By providing a shearing action for chip removal, this angle enables the tool to cut more freely.

For side-cutting tools, the side-rake angle is much more important than the back-rake angle. It weakens the tool less than a steep back-rake angle. The side-rake angle largely determines the type of chip produced and the direction at which the chip leaves the tool face.

A steep side-rake angle causes long wire-like chips on ductile materials. **This type of chip is a safety hazard.** A decreased side-rake angle causes the chip to curl up and break off more readily. Side-rake angles vary from 0° to 22° or more for different applications. Suggested averages for machining various materials with high-speed tools are shown in Table 14-1.

These side-rake angles are listed within a range, such as 10° to 22° for free-machining steel. For steels of highest machinability, the ideal angle in this case would approach 22°. However, with the steeper angle, a chip breaker generally is required to cause the chips to curl up and break off readily. (Chip breakers are described later in this unit.) If a chip breaker is not used, the lower angle (in this case 10°) generally should be used.

In accordance with Russian terminology the **main front** (but it correspondents to some extent to the side-rake angle for the English terminology) angle γ is measured between the face of the tool bit and a line passing through the axis of rotation of a part and active cutting edge in the plane passing perpendicular to the cutting edge and the base plane, Fig. 14-2.

The **angle of keenness** is the included angle of the tool between the face of the tool and the ground flank adjacent to the side-cutting edge, Fig. 14-2.

The **side cutting-edge** angle is formed by the straight side cutting edge and a line representing the side of the tool shank before grinding. This angle may vary from 0° to 30° for machining various materials. Angles of more than 30° tend to cause tool chatter. An angle of 15° generally is used for rough turning, while one of 20° produces good results for general machining applications.

Table 14-2. Recommended angles for single-point carbide tools.

Material	Normal side-relief	Normal end-relief	Normal back-rake	Normal side-rake
Aluminium and magnesium alloys	6° to 10°	6° to 10°	0° to 10°	10° to 20°
Copper	6° to 8°	6° to 8°	0° to 4°	15° to 20°
Brass and bronze	6° to 8°	6° to 8°	0° to -5°	+8° to -5°
Cast iron	5° to 8°	5° to 8°	0° to -7°	+6° to -7°
Low-carbone steels up to SAE 1020	5° to 10°	5° to 10°	0° to -7°	+6° to -7°
Carbone steels SAE 1025 and above	5° to 8°	5° to 8°	0° to -7°	+6° to -7°
Ally steels	5° to 8°	5° to 8°	0° to -7°	+6° to -7°
Free-machining steels SAE 1100 and 1300 series	5° to 10°	5° to 10°	0° to -7°	+6° to -7°
Stainless steel, austenitic	5° to 10°	5° to 10°	0° to -7°	+6° to -7°
Stainless steel, hardenable	5° to 8°	5° to 8°	0° to -7°	+6° to -7°
High-nickel alloys (Monel, Inconel, etc.)	5° to 10°	5° to 10°	0° to -3°	+6° to +10°
Titanium alloys	5° to 8°	5° to 8°	0° to -5°	+6° to -5°

In accordance with Russian terminology the **main angle in the plan φ** is measured between a line passing in direction of feed and active cutting edge on the top view, Fig. 14-2.

The **end cutting-edge** angle, Fig. 14-2, is formed by the end cutting edge of the tool and a line at right angles to the straight side of the tool shank. This angle may vary from 7° to 30°. A large side cutting-edge angle or a large nose radius will give a long tool life. Either one alone or both in combination, however, will tend to cause chatter, that is, a vibration in the workpiece, cutting tool, and machine-tool that accelerates wear on the cutting tool and produces a poor finish on the workpiece. A side cutting-edge angle of 15° and a nose radius of about 1/3 the depth of cut are recommended for general work.

In accordance with Russian terminology the **auxiliary angle in the plan** φ_1 is measured between a line passing in direction of the feed and the end (auxiliary) cutting edge on the top view.

The **nose angle** is the included angle between the side cutting edge and the end cutting edge of the tool bit. See Fig. 14-2.

14.3. Chip Breakers

When relatively steep side-rake angles are used on single-point cutting tools, ductile materials are cut more freely. However, as previously mentioned, with the steep angles, long continuous chips are formed. This type of chip is a **safety hazard** to the machine operator, and the chips are more difficult to remove from the machining area.

A chip breaker causes the chip to coil up tightly and break off readily, thus removing the safety hazard. The short, broken chips occupy less space, and also permit better flow of cutting fluid to the tool point.

Three common types of chip breakers used on cutting tools are shown in Fig. 14-4. In order to grind chip breakers of this type accurately, a tool and cutter grinder are used. A surface grinder with a special compound-angle tool-holding fixture also may be used for this purpose.

With the **angular-shoulder chip breaker** shown at B in Fig. 14-4, the angle Y may vary from about 5° to 15°, with 7° or 8° being the average. The width W and depth D depend on the feed, speed, depth of cut, and kind of material. The width W at the end of the tool usually varies from 1.6 mm to 4.8 mm, and the depth, from 0.4 mm to 1.6 mm. Tools with a large nose radius have a secondary angle. The width Z should be about one-and-one-half times the nose radius.

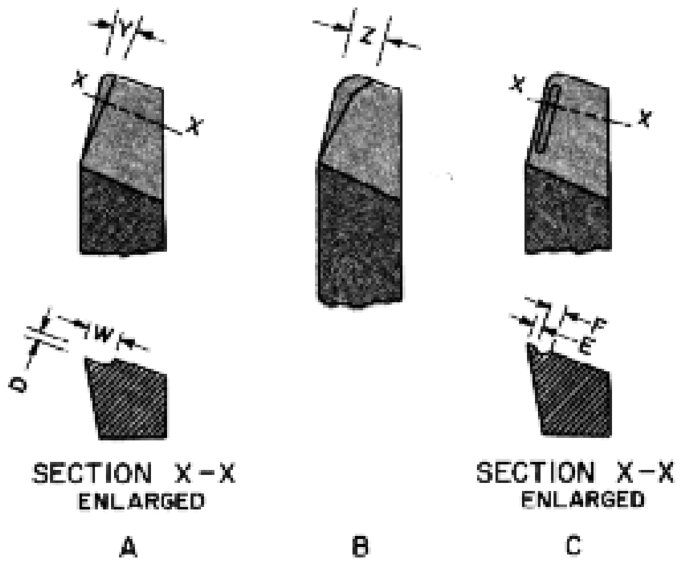


Fig. 14-4. Common types of chip breakers.

The **groove chip breaker** (A, Fig. 14-4) has a groove ground parallel to the side-cutting edge of the tool. For average applications, the following dimensions may be used: E= 0.8 mm; F= 1.6 mm; and depth of groove, 0.8 mm.

A removable **tungsten-carbide chip breaker** with a beveled edge is clamped above the cutting face of the tungsten-carbide throwaway insert.

The height at which a lathe tool should be set depends upon the metal to be turned and, to some extent, upon the operation being performed. As a general rule, the point of a highspeed steel tool bit may be set up to about 5° above center, except when turning brass or copper or when turning a taper, cutting a thread, boring or cutting off stock. In all of these cases, the point of the tool should be at exactly the same level as the axis of the work.

When turning steel or cast iron of small diameter, the point of the tool should be set on or only very slightly above the axis of the work. For turning aluminum, a tool especially ground and sharpened for that purpose is recommended, with the point of the tool set considerably higher above the axis of the work than when turning steel.

The point of cast-alloy tools or cemented-carbide tools should be set exactly at the height of the center line of the work.

The shapes of cutting tools other than the single-point tool are known to be essentially the same as previously described. For instance, revolving tools, such as milling cutters, have several cutting edges, giving the cutter the advantage of cutting more rapidly than would be possible with a single-point tool. Each blade of the milling cutter is basically a single-point cutter and must be provided with proper rake and clearance angles. Broaching tools have a cutting action similar to the action of a series of single-point planer tools, and the same is true of cutting-tools such as drills, reamers, hobs, etc.

Chapter 15. Cutting Tool Materials

15.1. Properties of Cutting Tools

Cutting tools must be made of materials which possess a variety of different properties in order to cut the many different metals and materials under varying conditions of severity. To meet these demands, tools have been produced from a variety of materials. In order to select the proper cutting tool for a given application, one must understand the basic properties required of cutting tools and the basic properties of each of the significant cutting-tool materials.The most important properties of cutting tools are hardness at high temperatures, wear resistance, and impact strength.

Hardness at High Temperatures. As a tool cuts, high heat is developed as a result of compression and friction at the cutting edge of the tool. All metal cutting tools begin to lose hardness when heated to sufficiently high temperatures. As the tool softens due to heat, it wears and breaks down at the cutting edge or face. Various cutting materials have different degrees of initial hardness, and they begin to lose their hardness at different temperatures. Hence, the hardness of the tool and the degree to which it retains its hardness at high temperatures are important in the selection of a cutting-tool material.

Wear Resistance. A cutting tool is wear-resistant if it resists abrasion at the cutting edge and along the tool face. Wear resistance improves as cutting tool hardness increases. Increased wear resistance is also obtained by using correct tool geometry, rigid tool mountings, correct speeds and feeds, and cutting fluids. As indicated previously, wear resistance is also related to heat. When the temperature level is attained at which the tool starts to lose its hardness significantly, the metal rapidly looses its wear resistance.

Strength. Cutting tools must also have high strength in order to be vibration- and impact-resistant. Strength in cutting-tool materials is not always proportional to hardness. Some of the hardest tool materials lack strength because they are too brittle.

15.2. Materials Used in Cutting Tools

The various materials from which most metal cutting tools are made can be classified under the following principal headings: carbon tool steel, high-speed steels, cast alloys, cemented carbides, ceramics and diamonds.

Carbon-Tool-Steel Cutting Tools. Many cutting tools are made from high-carbon tool steel. Some common examples include drills, reamers, center drills, forged boring bars, hand taps, and threading dies. In accordance with Russian terminology high-carbon tool steels are designed as У8, У10, У12, У10А; where figure is the amount of carbon in tenth of percentage portion. The chief advantage of carbon tool steel is its low cost. A principal disadvantage is its loss of hardness at relatively low temperatures. It begins to soften at 200°C to 260°C. This temperature range is indicated by the heat-color range from brown to purple. When this range is exceeded, a blue or dark gray color appears, and the tool softens and wears rapidly.

Keen cutting edges can be produced on carbon steel tools, and they possess good shock resistance. Carbon-steel tools should be operated at one-third to one-half the cutting speeds recommended for high-speed steels. With lower cutting speeds, less heat is generated, and tool life is prolonged.

High-Speed Steel Cutting Tools. The principal advantage of high-speed steel (HSS) in comparison with high-carbon steel is its retention of hardness up through a dull red heat, ranging from approximately 540°C to 625°C. HSS tools begin to soften due to tempering in this range, but they do not soften significantly until heated above this range. The property of tool steels to retain hardness at high heat or red heat is called **hot-hardness or red-hardness.**

Tools which very frequently are made of highspeed steel are: drills, reamers, end mills, center drills, counter bores, milling cutters, taps, lathe cut-of tools and lathe centers. High-speed steel also is widely used for tool bits used on lathes, shapers, and planers. High-speed steel cutting tools generally will stay sharp for a much longer period of use than tools made of carbon tool steel.

The high-speed tool steels are the most heavily alloyed of all the steels. Their principal elements are tungsten and molybdenum. Other elements which also are alloyed with these steels in significant amounts are cobalt, vanadium, and chromium. Each of these elements imparts particular properties to the steel. Tungsten, molybdenum, chromium, and vanadium are carbide-forming elements; that is they combine with carbon to form carbides. The carbides cause the steel to resist softening at higher temperatures. They also impart high wear resistance to the steel. Cobalt is not a carbide former, but it combines with the iron in steel in a manner which increases the red-hardness of high-speed steels.

There are several different types of high-speed tool steels. The most common types may be classified in the following manner:

1. Tungsten base steels. This type of steel commonly is accepted as the standard for use in comparing the properties of other types of HSS. One of the most commonly used steels of this type is the 18-4-1 steel (type **T1**). It is composed of 18% tungsten, 4% chromium, and 1% vanadium. Other tungsten steels with varying amounts of these elements are available.

2. Molybdenum base steels. One of the common steels of this type is 8% molybdenum, 4% chromium, and 2% vanadium (type **M10**). It has performance properties generally comparable to 18-4-1 tungsten steel.

3. Tungsten-molybdenum base steels. Steels of this class are similar to the tungsten steels, except that some of the tungsten is replaced with molybdenum. A common steel of this type is 5% molybdenum, 6% tungsten, 4% chromium, and 2% vanadium (type **M2**). It has performance properties similar to 18-4-1 tungsten steels.

4. Cobalt steels. Cobalt in amounts from 5% to 12% may be added to any of the above highspeed steels. The cobalt increases the red-hardness of the steel significantly. High-speed steel which includes a large percentage of cobalt is sometimes called **super HSS.** The super HSS frequently is used for tool bits or as tips on cutting tools. When the cobalt content is high, the hardness and wear resistance also are increased, but the impact toughness or resistance to shock generally is decreased.

In accordance with Russian terminology high-speed steels are designed as P6M5, P6M5K5, etc. A common steel of this type P6M5K5 is 6% tungsten (P), 5% molybdenum (M), 5% cobalt (K), carbon about 1%.

Coated High-Speed Steel Tools. Cutting tools of high-speed steel are now available with coatings of several kinds. A thin metallic layer of **hard chromium** can double the life of cutting edges on taps. Coatings of **titanium carbide, titanium nitride,** and **aluminum oxide** provide even greater tool life. These coatings are formed by a chemical reaction between highspeed steel and the vapor of the coating material at 954-1054°C. The thickness of these coatings averages 0.0076 mm. Experience with these coatings shows that tool life can be increased from three to over six times, depending on the kind of tool.

Certain cutting tools are available in several types of high-speed steel, and with different coatings. When in doubt, follow the manufacturer's recommendations in making selections. Production efficiency is improved and tool costs are lowered through proper selection of cutting tools for each application.

Cast-Alloy Cutting Tools. A number of cast alloys have been developed for use as cutting-tool materials. Some common brand names are **Stellite, Rexalloy, Armaloy,** and **Tantung.** The cast alloys are used as brazed tips on tool shanks, as removable tool bits, as inserts in toolholders, and as inserts in milling cutters. The cast alloys are nonferrous materials with a cobalt base. They do not contain iron, except that which is present in the form of an impurity in the raw materials used. Cast alloys used as cutting tools may contain various combinations of the following principal elements: cobalt 35% to 55%, chromium 25% to 35%, tungsten 10% to 20%, nickel 0% to 5%, and carbon 1.5% to 3%. Very small amounts of other elements sometimes are added. The cast alloys are cast slightly oversize and are ground to shape. They cannot be forged or machined successfully.

The principal advantage of the cast alloys, in comparison with high-speed steels, is their high red-hardness. Because of this property, higher cutting speeds may be used, and tool life is maintained at the resultant higher cutting temperature. Although cast alloys begin to soften slightly at temperatures from 650° C to 815° C, they are not seriously affected by temperatures below 815° C. Any loss of hardness at these high temperatures is regained upon cooling. High-speed steels are slightly harder than the cast alloys at temperatures below 593° C. Above this temperature, the cast alloys are harder and retain their hardness up to 815° C. Thus, the cast alloys perform better for machining applications where temperatures ranging from 593° C to 815° C are developed. These applications usually will occur at cutting speeds which exist between the highest cutting speeds for high-speed steels and the lowest practical speeds for carbide tools. The cast-alloy tools generally perform best at high speeds. They may be operated at cutting speeds approximately 50% to 75% faster than the maximum for high-speed steel tools.

Most cast alloys are more brittle and generally will not stand the heavy shock or impact pressures which carbon tool steels or high-speed steels will stand. They must, therefore, be well supported in a tool shank or toolholder.

Aluminum-oxide abrasive wheels are recommended for grinding or sharpening the cast alloys. They may be ground wet or dry, but they should not be quenched after grinding dry.

Cemented-Carbide Cutting Tools. Cemented-carbide cutting tools are used widely in production machining. Their principal advantages are high initial hardness, retention of hardness at red heats up through about 926° C and increased cutting speeds. Carbide cutting tools may be operated at speeds from two to four times the cutting speeds used for high-speed steel cutting tools.

The principal ingredients of the cemented carbides used for cutting tools are tungsten carbide and cobalt. Certain types of cemented carbides have titanium and tantalum carbides included to obtain specific properties. The carbide-tool materials are called **cemented carbides** because the carbide grains are cemented together during the manufacturing process with a binder, usually cobalt. Carbide tools are cast to shape and are very hard in the **as cast** condition. They do not require any further heat treatment. Carbides can only be shaped by grinding.

Fig. 15-1. A carbide throwaway-insert tool bit mounted in a lathe toolholder.

Carbide cutting tools frequently are used in the form of cutting tips brazed on the tool shank or on the body of a cutting tool. Carbide cutting tools are also used as tool inserts of the disposable type which may be rotated for use on each of the cutting edges or corners before they are thrown away. Carbide inserts are made in many standard shapes. Carbides are also used for disposable chip breakers on shank toolholders. Smaller cutting tools such as drills, reamers, center drills, and end mills are available in solid carbide form. Carbides also may be used as inserts on lathe or grinder centers.

There are two basic groups of carbide materials used in cutting tools. **Group C** carbide is composed principally of tungsten carbide and cobalt, and it is used for machining cast iron and the nonferrous metals. In accordance with Russian terminology carbide materials of this group are designed as BK4, BK6, BK8, BK6OM, etc. A common used material of this type BK8 is 8% of cobalt (K) and the rest (92%) - tungsten carbide (B). Letters OM are designed as particularly (O) fine grain (M). When the cobalt content is high, the impact toughness or resistance to shock generally increase, but the hardness and wear resistance decrease.

Group S is composed principally of tungsten carbide, tantalum carbide, titanium carbide, and cobalt. It is used for machining the various steels. If Group C is used for machining steel, wear craters appear rapidly on the face of the tool. The titanium and tantalum carbide ingredients in Group S carbides improve the wear-resistance qualities. In accordance with Russian terminology carbide materials of this group are designed as T5K10, T15K6, T30K4, TT7K12, etc. A commonly used material of this type T15K6 is 6% of cobalt (K), 15% of titanium carbide (T) and the rest (79%) - tungsten carbide. Letters OM are designed as particularly (O) fine grain (M). When the tungsten carbide content is high, the impact toughness or resistance to shock generally increase, but the hardness and wear resistance decrease.

The amount of cobalt in either of the two groups of carbide affects the hardness of the cutting tool. As the amount of cobalt is decreased, the tool becomes harder. With increased hardness, the carbide has increased wear resistance and tool life, together with decreased shock resistance due to brittleness. With decreased hardness, there is a decrease in wear resistance, but there also is a corresponding increase in shock resistance or impact toughness.

A second factor which influences the hardness, wear resistance, and impact toughness of the carbides is the grain structure. A fine grain structure increases hardness, while a coarse grain structure decreases hardness. The manufacturer can, therefore, control the hardness and toughness of carbides through control of the ingredients and the grain structure.

There are many different machining applications for which carbide cutting tools are used. These vary from roughing cuts to light finishing cuts for materials which may be very hard or soft. Different **grades** of carbide materials have been developed by tool manufacturers to meet the conditions demanded. Some grades of carbide are recommended for use for very specific applications, while others may be used for a broad range of general applications. Attention should be given to the selection of the right grade for the particular job or machining application.

The Carbide Industry Classification System may be used as an aid both in classifying machining applications and in selecting the proper grade of carbide cutting tools. Many carbide tool manufacturers recognize this classification system. Each manufacturer recommends one or more specific grades of carbide for use in each machining application. In some cases, one carbide grade may be selected which will produce satisfactory results on several different machining applications. The following eight classifications are used in grouping machining applications for cemented-carbide cutting tools according to the Carbide Industry Classification System:

Cast iron and nonferrous materials -

C-1: Finishing to medium roughing cuts

C-2: Roughing cuts

C-3: High-impact dies

Steel and steel alloys -

C-4: Light high-speed finishing cuts

C-5: Medium cuts at medium speeds

C-6: Roughing cuts

C-7: Light finishing cuts

C-8: General purpose and heavy roughing cuts.

Included in this system are six additional classifications concerned with **wear applications** and **impact applications.** However, these are not within the scope of this unit.

In selecting a specific grade of carbide tool for one or more of the above machining classifications, the manufacturer's recommendations should be consulted. Such recommendations are available in tool supply catalogs and manufacturers' bulletins.

Each manufacturing company has its own numbering or identification system for each carbide grade. There also may be variations in the properties and performance of the carbide grades recommended by several different carbide tool manufacturers for a particular machining application.

Coated Carbides. Coated carbides are conventional or slightly modified carbide grades that are coated with a thin layer - from 0.005 mm to 0.010 mm - of a very hard heat-resistant material. The most commonly used coatings are titanium carbide, titanium nitride, hafnium nitride, aluminum oxide, and combinations of these materials. Coated carbides offer substantially greater tool life or higher cutting speeds but are somewhat less thermal- and shock-resistant than uncoated carbides of similar grade. Over 50% of the carbide cutting tools now being used are coated carbides. When carefully matched to the machining task, coated carbides offer substantial savings in machining time over uncoated carbides. Recommendations for coated carbide applications may be obtained from any carbide tool manufacturer.

Precautions in Use. Because of the special properties of carbide materials, particularly their hardness and brittleness, certain precautions should be observed with their use. Carbide tools must be rigidly supported in the toolholder or holding device. The machine and the work setup should be rigid and free from vibration. Interrupted cuts should be avoided when possible. The machine should not be stopped during a cut. Because of the pressure-welding characteristics of carbide tools at low speeds, they should be operated at the recommended cutting speeds, usually two to four times higher than those for high-speed steel tools. Proper cutting fluids also should be used.

Cermet Cutting Tools. Cermet cutting tools are blends of ceramic and metal powders which are formed into shape by pressing and sintering. One type which is commonly available is composed of 70 - 80% titanium carbide blended with a small percentage of molybdenum carbide, and with nickel as a binder. In accordance with Russian terminology cermet materials of this group are designed as tungstenless: THM-20, THM-25, THM-30, KTHM-30, KXH-10, KXH-40, etc.

Cermets are more brittle than carbides, which generally limits their use to light finishing cuts. Their hardness, however, is superior to carbides, which provides significantly greater tool life at the same or better cutting speeds. In turn, cermets are significantly outperformed by ceramic cutting tools.Cermet cutting tools are available as throw-away inserts.

Ceramic Cutting Tools. Ceramic cutting tools are made of metal oxide powders which are formed into shape either by cold pressing and sintering, or by hot pressing. Hot pressed blanks are slightly stronger, but the strength of both types is lower than that of carbides. Most "straight" ceramic tools are made of aluminum oxide, although silicon and magnesium oxide are also used, either separately or in combination with aluminum oxide. Small percentages of metallic binders are added to improve impact strength. In accordance with Russian terminology ceramic materials are designed as ЦМ-332, etc.

Ceramic cutting tools, like cemented-carbide cutting tools, are used in the form of inserts or tool bits held in a toolholder mechanically. However, unlike carbide tools, they cannot be brazed. Ceramic tool materials rank between sapphire and diamond in hardness; they are harder than cemented-carbide tools. They have a crystalline structure and are hard and brittle, and high in wear resistance, but they shatter quite easily because of low impact resistance or low rupture strength.

The hardness of ceramic tool materials is affected little by heat. Hot metal chips do not weld readily to the cutting tool when operated at the proper cutting speeds; therefore, cutting fluids generally are not needed. However, when coolants are needed to prevent distortion, the fluids should flow liberally over the cutting tool. A liberal flow will prevent intermittent cooling which may cause the tool to crack or shatter.

The principal advantages of ceramic cutting tools are increased cutting speeds and increased tool life per cutting edge. These tools also may be used for certain machining applications where it is necessary to cut heat-treated or very hard steel. Ceramic cutting tools may be operated at cutting speeds two to four times higher than for cemented-carbide tools. However, because of their low impact resistance, they generally should be used for fairly light finishing cuts at high speed. The high cutting speeds usually result in improved surface finish, which often eliminates the need for a ground finish.

A new type of ceramic tool material is made by blending aluminum oxide with about 30% titanium carbide. In accordance with Russian terminology ceramic materials of this type are designed as ВОК-60, ВОК-63, ВШ-75, etc.

This new tool material is only slightly harder than the straight oxide tools, but it has higher thermal and shock resistance. This improved strength allows their use for milling steels as well as cast iron. They perform well at cutting speeds of 600 mpm for face milling gray iron, and are capable of many turning operations which cause straight oxide tools to fail.

Cubic boron nitride (CBN) is a new ceramic material that is nearly as hard as diamond. It can maintain its high hardness at nearly 1370°C, and it oxidizes less rapidly than diamond. Cutting tools of CBN have reduced cutting times on tough nickel alloys as much as 500%. However, CBN tools are too brittle to use on interrupted cuts, and vibration will shatter the cutting edge.

Diamond Cutting Tools. Diamond is the hardest material known. This property, together with extreme heat resistance, permits cutting speeds up to 3048 mpm. Low strength and shock resistance, however, limit their use to machining soft, low strength, or highly abrasive materials such as graphite, plastics, ceramics, and certain aluminum and copper alloys.

Diamonds used for cutting tools are either natural diamonds of industrial quality or manufactured diamonds. Until recently, diamond cutting tools were available only as a single crystal or a cluster of crystals attached to a tool shank by brazing. A disadvantage of these tools is that their strength, hardness, and wear resistance varies with the orientation of the crystal, making their performance somewhat unpredictable.

Sintered **polycrystalline diamond** tools are now available which eliminate the orientation problem. The tools are made up of fine crystals of diamond bonded together to form solid tool shapes. Random orientation of the diamond crystals provides uniform cutting behavior in all directions, and with a marked improvement in toughness over single-diamond crystal tools. Polycrystalline diamond tools are available as brazed tips on various tool shanks, as tips bonded to carbide tool inserts, or as solid inserts. Wear resistance of diamond tools is excellent, outlasting carbides anywhere from 10:1 to as much as 450:1.

Comparative Cutting Speeds. There is no definite rule which can be used in recommending cutting speeds for cutting tools made from different materials. Recommended speeds will vary according to the following factors: the kind and hardness of material being cut, the rate of feed, the depth of cut, the finish desired, the rigidness of the machine, the rigidness of the work setup, the type of cutting tool, and the type of cutting fluid used. In the absence of specific recommendations for each machining application, the following general rules may be used as a guide in selecting cutting speeds for cutting tools made of different materials.

1. High-speed steel cutting tools may be operated at speeds about twice those recommended for carbon-steel tools.
2. Cast-alloy cutting tools generally may be operated at speeds approximately 50% to 75% greater than the maximum speed recommended for high-speed steel tools; these speeds are approximately three times greater than those for carbon-steel tools.
3. Cemented-carbide cutting tools may be operated at cutting speeds from two to four times faster than those recommended for high-speed steel tools. Cutting fluids generally are required at the high end of this speed range.
4. Cermets are capable of operating at cutting speeds between 10% and 100% higher than cemented-carbide cutting tools, depending on cutting conditions.
5. Ceramic cutting tools may be operated on certain light machining operations at speeds from two to four times greater than those recommended for the same application with carbide cutting tools.
6. Diamond tools may be operated in the same range of cutting speeds as carbide and ceramic tools, or at vastly higher speeds depending on cutting conditions.

General recommendations concerning cutting speeds for drilling, lathe work, shaper work, and milling are included in the sections of this book concerned with these machines and their operation. More specific recommendations for cutting speeds and feeds for various applications may be found in standard handbooks for machinists.

Chapter 16. Cutting Action of the Cutting Tool

Cutting Speed, Cutting Feed, and Depth of Cut. These three variables are inseparable in practice since they depend upon one another.

In machining operations, the movement of the tool relative to the work is of great importance. The distance that the tool is set into the work for cutting operations is referred to as the depth of cut.

Cutting speed V is the term used to express the velocity of the cutting tool over the surface of the work. It is expressed in meters per minute (mpm), meters per seconds (mps) or feets per minute (fpm). When the work is rotating and the tool is fixed as on a lathe, the cutting speed varies directly as the revolutions of the work n and the diameter of the work D. When the tool is rotating and the work is fixed, as in a milling operation, the cutting speed varies directly with the revolutions of the tool, this being also true of drilling and boring operations. The maximum limit of cutting speed is that speed which when exceeded will cause the tool to fail by losing its temper. This maximum cutting speed cannot be expressed in general, since it is not constant but varies under different conditions.

Cutting feed S in machine-tool work expresses the distance the tool moves along for each revolution of the work in lathe work and drilling and the rate of movement of the table toward the cutter in milling-machine work. Shaper and planer feed is the sideward movement of the tool per stroke. In lathe and drilling operations the feed S_r is expressed as hundredths or tenths of millimeters per revolution (mpr) of drill or work. Milling-machine feed is usually expressed in millimeters of table movement per minute (mpm) - S_m. It may also be expressed as hundredths or tenths of a millimeters per tooth for one revolution of tool - S_z. $S_m = S_z \times z \times n$, where: z is a number of cutting teeth; n is a number of revolutions per minute (rpm) of a cutting tool.

For general machining work it is customary to use coarse feeds ($S>0.5$ mpr) for roughing cuts and finer feeds ($S<0.1$ mpr) for finishing cuts. Coarse feeds remove the greatest amount of stock in the least time to make for economical production.

16.1. Cutting Action

All metals in the solid state have a characteristic crystalline structure, frequently referred to as the grain structure. The crystals or grains may vary in size from very fine to very coarse, depending on the type of metal and whether or not it has been heat-treated. Each crystal is composed of groups of atoms or molecules clustered together. The crystals of a pure metal such as pure copper are composed of large clusters of atoms. The crystals of an alloy such as steel, which may be composed of several metallic or nonmetallie elements, have large clusters of either atoms or molecules.

Figure 16-1 is a diagram of a cutting tool, such as a shaper tool bit, forming a chip on a metal workpiece. As the tool advances against the workpiece, great forces are exerted on the crystalline metallic grains in front of the tool face. These grains, in turn, exert similar pressures on the grains ahead of them, in the direction of the cut. As the tool continues to advance, the material at point **A** is sheared by the cutting edge of the tool, or it may be torn loose by the action of the bending chip which is being formed. As the tool advances, maximum stress is exerted along line **AB**, which is called the **shear plane**. This plane is approximately perpendicular to the cutting face of the tool. The angle between the shear plane and the direction of the movement of the tool (cutting speed **V**) is called the **shear angle Φ**. When the force of the tool exceeds the strength of the material at the shear plane, rupture or slippage of the crystalline grain structure occurs, thus forming the metal chip (or chips). The cutting edge of the tool tends to scrape or smooth the machined surface. This cycle is rapidly repeated as the tool advances along the workpiece.

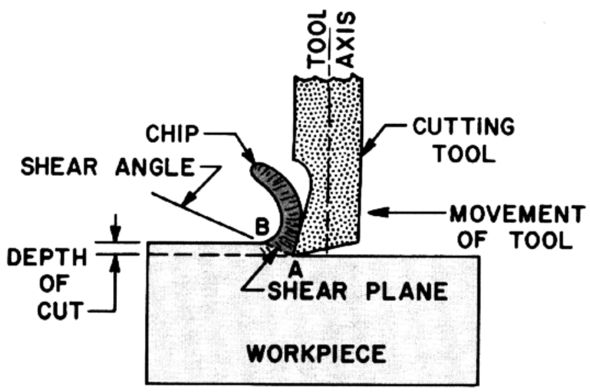


Fig. 16-1. Action of cutting tool forming a continuous chip.

When a tool cuts metal a force is exerted on its face by the material pushed ahead, and a friction force is set up along the face of the tool by a sliding chip. These forces have a resultant, and an equal and opposite force must be applied to the tool to make it cut. The driving force on the tool may be resolved into two components for convenience. One is perpendicular to the movement of the tool V (in the most cases one is parallel to the axis of the tool) (P_y,) and the other acts in the direction of the movement of the tool (P_z). The second alone determines the power required because it is in line with the tool movement.

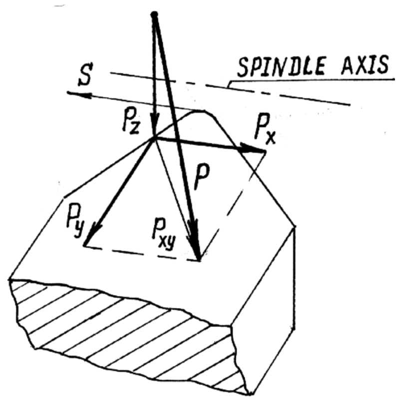


Fig. 16-2. Components of the cutting force P.

The force driving a lathe tool has three principal components, Fig. 16-2. One is called the **vertical** or **tangential** component $\mathbf{P_z}$ because it acts vertically, tangent to the workpiece. The second is the **longitudinal** or **traversing** component $\mathbf{P_x}$ and acts parallel to the axis of the workpiece in the direction the tool is moved (in the direction of the feed **S**.) The third is called the **radial** or **normal** component $\mathbf{P_y}$ and acts radially on the workpiece and normal to the finished surface in a horizontal plane. Both the vertical and longitudinal forces affect the power required to make the cut but the velocity **V** of the work surface is much greater than the traverse of feed rate **S** of the tool, and most of the power is related to the vertical force: $W=P_z \times V$, where: W is the cutting power, watt (W); P_z is the tangential component of cutting force, newton (N); V is the cutting speed, meter per second (mps).

Cutting tools produce metal chips of various kinds and shapes. Some chips are broken into small pieces, some are continuous coils, and some are short, bent parts of a coil. The type of chip formation is a factor in determining how rapidly metal may be removed from the work-piece, and it influences the texture of the machined surface.

16.2. Types of Chips

Cutting tools form three basic types of chips, depending on the type of material being cut and the shape of the cutting tool: **continuous chip, discontinuous chip** and, intermediate between them, **joint chip.** The type of chip influences the amount of tool wear and determines the quality of surface finish.

The **continuous chip** is formed when ductile metals such as aluminum or free-machining steel are machined, Fig. 16-1. The chip has the form of a continuous coiled ribbon.

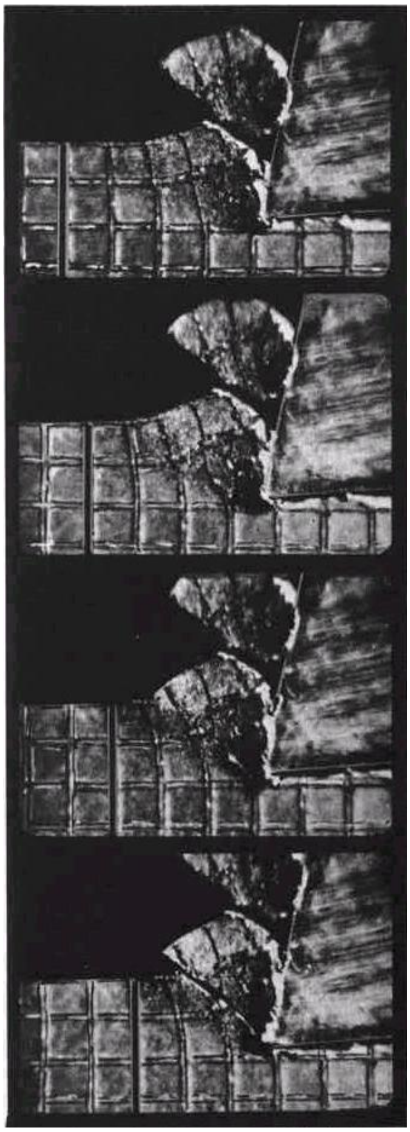


Fig. 16-3. Formation of typical discontinuous chip magnified about five times.

Ductile metals usually have a larger grain size and good plasticity, thus enabling the grains to withstand considerable distortion without fracture. As the tool advances, the metal ahead of the cutting edge is compressed. This compressed metal becomes work-hardened as it starts to form a chip. The hardened chip resists further compression and escapes along the tool face in the form of a continuous chip. This cycle rapidly repeats itself as the tool proceeds with the cut. The tool edge tends to smooth the surface which remains relatively soft.

The continuous chip is the ideal way of machining metal. It produces a good finish, causes less friction, and requires less power to remove a given amount of metal. Factors which tend to cause continuous chips on ductile materials are large rake angles on the tool, high cutting speeds, a sharp cutting edge with a highly polished tool face, and the use of a good cutting oil to reduce friction. Continuous chips can be hazardous to machine operators. They also tend to clog automatic turning machines. For these reasons, it has become common practice to employ chip breakers which effectively break up the continuous chip into small curls in the shape of figure 9's.

The crystalline grains of tough, ductile metals usually are moderate in size and are held together with a strong bond. As the tool compresses the metal ahead of the cutting edge, the metallic grains become work-hardened, resist further compression and start to escape along the tool face in the form of a chip. However, some of the tough, highly-compressed metal thoroughly cleans the tool face and forms a weld-like bond along the cutting edge and on the tool face. The metal bonded to the tool is called a **built-up edge** (Fig. 16-4). As the chips slide over the tool face, the built-up edge slides off, and the cycle repeats itself. The continuous chip with a built-up edge frequently is formed on tough metals such as medium-carbon steels, tool steels, and alloy steels.

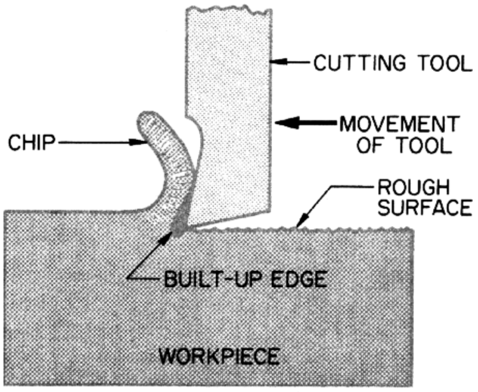


Fig. 16-4. Continuous chip with a built-up edge.

Some of the metal immediately ahead of the tool, and ahead of the built-up edge on the tool, tends to fracture or tear apart at the shear plane. It then slides under the cutting edge of the tool, thus causing a rough surface which often is considerably work-hardened. This type of chip causes the increased friction and increased heat, and it requires much more power for removal of a given amount of metal.

Factors which tend to minimize the formation of chips with a built-up edge are: proper rake angles on the tool, a sharp cutting edge, a polished tool face, the correct cutting speed and feed, and the use of a good cutting fluid.

When a brittle metal such as cast iron or bronze is machined, the chips are broken up in the form of flakes along the shear plane and ahead of the cutting edge of the tool. This type of chip is called a **discontinuous chip** or **segmental chip** (Fig. 16-3). Brittle metals have small, irregularly-shaped grains which are held together with a brittle glass-like bond. Since the grains are so hard, pressure from the tool transfers easily from one grain to another ahead of the tool. This causes the metal to fracture into short chips, which escape freely along the tool face and clear the cutting zone easily. This type of chip, however, causes considerable tool wear and rounding of the cutting edge.

Factors which contribute to the formation of discontinuous type chips are: a small rake angle on the cutting tool, low cutting speeds, thick chips, and vibration of the cutting tool.

The **joint chip** is the intermediate between continuous chip and discontinuous chips when elements of chip are jointed between each themselves.

16.3. Influence of a Built-up Edge on Cutting Forces

The degree of plastic deformation of a cutted layer can be characterized by **shortening** of a chip. **Shortening of length** or **length factor** is a ratio of length of a cutted layer (l) to length of a chip (l_1): $K_l = l/l_1$. It is always more than 1 because of forces of friction on a face of the cutting tool. **Thickness factor** of a chip K_a is a ratio of thickness of a chip (a_1) to thickness of a cutted layer (a): $K_a = a_1/a$. It is always more than 1. **Width factor** is a ratio of width of a chip (b_1) to width of a cutted layer (b): $K_b = b_1/b$. It is always more than 1. **Shortening** of a chip is $\zeta = K_l = K_a \times K_b$.

Than more plastic deformation, than more K_l and a cutting force. The cutting force depends on many factors of a processable material, modes of cutting (depth of cutting, feed and speed of cutting), geometry and material of the cutting tool, cutting fluids, etc.

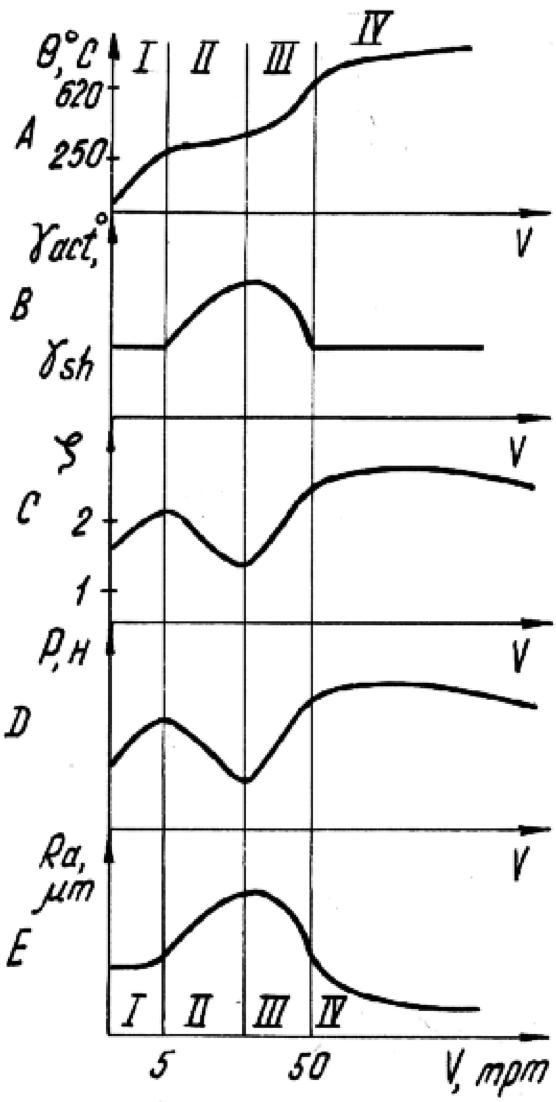


Fig. 16-5. Influence of a built-up edge on cutting force and roughness of the processed surface.

The increase of cutting speed V results in the increase of a cutting temperature θ (Fig. 16-5A, sectors I-II.) When the cutting temperature reaches a definite level, specific for each processable material, adherence of chip begins on the face surface of the cutting tool. High pressures and the resultant friction at the edge of the tool cause the freshly cut metal to adhere or pressure-weld to the tool face. The adhered material has a slightly higher hardness than a material in the initial condition. The increase of hardness occurs because of hardening in result of plastic deformation in the zone of cutting (directly ahead of the cutter and at the contact with it.) This adhered material is called a built-up end. The built-up end increases an **actual main front** (or side-rake) **angle** γ_a (Fig. 16-5B, sector II.) The branch of a shaving occurs more easily, therefore ζ (degree of plastic deformation) (Fig. 16-5C, sector II) and a cutting force P becomes less (Fig. 16-5D, sector II.) But the built-up end increases a roughness Ra of a processed surface on the workpiece (Fig. 16-5E, sector II) because of the instability, roughness of the form and periodic breaking of the built-up end.

The further increase of speed V results in the increase of temperature θ (Fig. 16-5A, sector III), that results in the reduction of durability and hardness of the built-up end. It causes reduction of its size. The reduction of the actual main front angle γ_a (Fig. 16-5B, sector III) results in the increase of ζ (Fig. 16-5C, sector III) and the cutting force P (Fig. 16-5D, sector III), reduction of a roughness Ra (Fig. 16-5E, sector III.)

The built-up end is absent at a temperature of cutting more 650^o C (approximately V>50 mpm), that reduces a roughness (Fig. 16-5E, sector IV.) This sector is recommended for accuracy cutting (V>150 mpm.)

16.4. Calculation of Cutting Speed

Use of correct cutting speeds is important to a good tool life and efficient machining. Excessively high cutting speeds will cause overheating of the tool and a premature cutting edge failure. Use of cutting speeds that are too slow will reduce a productivity and increase the manufacturing costs.

Cutting speed V refers to the rate in meters per minute (mpm) at which the surface of the workpiece moves past the cutting tool. Conditions that affect a cutting speed include: kind of material being cut, kind of material the cutting tool is made of, shape of the cutting tool being used, rigidity of the workpiece, rigidity of the machine, and kind of cutting fluid being used.

Table 16-1 gives cutting speed recommendations for cutting common metals with high speed steel, cast alloy, and carbide cutting tools. Further data on cutting speeds for specific alloys and for specific machining applications are included in standard handbooks for machinists.

The usual problem facing a machine operator or numerical control programmer is to find the correct **revolution per minute (rpm) n** to run the tool or workpiece. The tool or workpiece diameter, kind of material to be cut, and the kind of cutting tool material to be used are usually known. Obtaining the recommended cutting speed from a table or chart completes the data needed to calculate the correct rpm:

$$n = 1000V/\pi D, \qquad (16.1)$$

where: n – a number of revolutions per minute (rpm); V - cutting speed, mpm; D - workpiece diameter or cutting tool (when tool is revolved), mm; $\pi \approx 3.14$.

The cutting speed can be calculated with the help of empirical formulas for each kind of processing. Generally it looks as:

$$V = \frac{C_V}{T^m \cdot t^x \cdot s^y} \cdot K_V \ , \qquad (16.2)$$

where: V - cutting speed, mpm; C_V – a factor depending on the kind of material being cut, the kind of processing, the material of a cutting tool, the range of cutting feed; T - value of tool life, operating time between regrindings or replacements, minutes; t - depth of cut, mm; s - cutting feed, mpr; m, x, y - powers which are taking into account the kind of material being cut, the kind of processing, the material of a cutting tool, the range of cutting feed; K_V - product of factors which take into account the influence of the material being cut, the condition of a surface, the material of the cutting tool, angles of the tool and the nose radius. The value of a tool life is multiplyed by factors taking into account multiple-tool processing and multiple-machine service.

The further information concerning the factors and powers is included in standard handbooks for machinists.

Table 16-1. Cutting Speeds

Material	Cutting tool material	Heavy cut, mpm	Finishing cut, mpm
Free-machining steels	H.S.S.	35	90
	cast alloy	75	150
	carbide	120	200
Low-carbon steels	H.S.S.	30	80
	cast alloy	60	130
	carbide	100	190
Medium-carbon steels	H.S.S.	30	70
	cast alloy	60	100
	carbide	90	150
High-carbon steels	H.S.S.	25	60
	cast alloy	50	90
	carbide	75	140
Cast iron, soft gray	H.S.S.	25	40
	cast alloy	40	75
	carbide	70	120
Brass and bronze free machining	H.S.S.	50	100
	cast alloy	100	170
	carbide	170	270
Aluminum	H.S.S.	40	90
	cast alloy	50	110
	carbide	75	180
Plastics	H.S.S.	30	75
	cast alloy	45	115
	carbide	60	150

16.5. Calculation of Cutting Force

The cutting force can be calculated with the help of empirical formulas for each kind of processing. Generally it looks as:

$$P_{z,y,x} = 10 \cdot C_P \cdot t^x \cdot s^y \cdot V^n \cdot K_P \ , \qquad (16.2)$$

where: P_z, P_y, P_x – the components of a cutting force, N; C_P – a factor taking into account the kind of material being cut, the kind of processing, the material of the cutting tool; t - a depth of cut; s - a cutting feed; V - a cutting speed, mpm; x, y, n – powers which take into account the kind of material being cut, the kind of processing, the material of the cutting tool; K_P – the product of factors which take into account the influence of a material being cut, the condition of a surface, the material of the cutting tool, angles of the tool and the nose radius.

Further information concerning the factors and powers is included in standard handbooks for machinists.

16.6. Wear and Cutting Tool Life

The wear of a cutting tool reduces the cutting tool life – the time between regrinding or replacement of tool or cutting edge. The wear of cutting tool takes place: 1) on the face near the cutting edge , 2) on the cutting edge, 3) on the flank (Fig. 16-6).

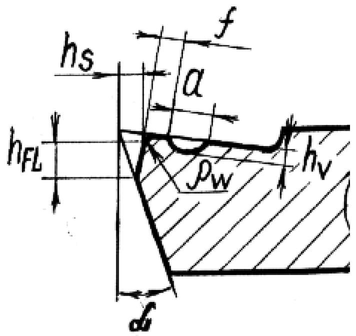


Fig. 16-6. Cutting tool wear.

A wear groove with a length **a** and a depth $\mathbf{h_v}$ (Fig. 16-6) on the face of tool causes the chip to coil up tightly and break off readily but the wear extends the groove and can cause the destruction of cutting edge. Generally a wear groove is not dangerous and even reduces cutting force.

The wear on a cutting edge causes the roundness $\boldsymbol{\rho_W}$ of the cutting edge and increases the cutting force which results in the increase of heat and leads to the destruction of the cutting edge. The wear on the flank $\mathbf{h_{FL}}$ results in the same but it increases faster than the wear of the cutting edge and that is why it is more dangerous (Fig. 16-8A). Generally the wear on the flank is estimated by the length of wear h_{FL} and limits the wear for cemented carbide tool is about 0.25 mm for a finishing cut and 0.75 mm for a heavy cut.

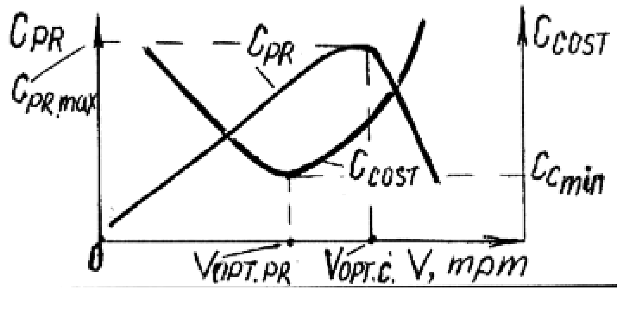
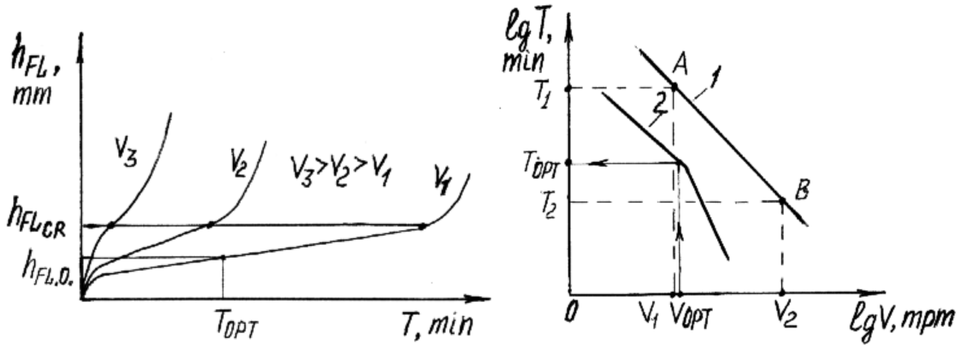


Fig. 16-7. Influence of the cutting speed V on a productivity C_{PR} and a cost price C_{COST}.

The causes of wear can be classified as: 1) abrasive, 2) adhesion, 3) chemical.

The **abrasive wear** has a greater influence at rather low cutting speeds especially when cutting materials contain carbides, or forged and cast preparations are cut. The firm particles scratch surfaces of the tool, leaving characteristic scratches. This kind of destruction occurs also on large cutting speeds, but chemical and adherence wears prevail because of the large temperatures of cutting.



A B

Fig. 16-8. Influence of the cutting speed V on the tool life T.

The **adhesion wear** occurs in connection with welding: high pressures and the resultant friction on tool surfaces cause the freshly cut metal to adhere or pressure-weld to the tool surfaces. It causes the destruction of particles of the tool as a result of the low transverse rupture strength of the tool material. This process is accelerated at the increase of cutting temperature and cutting speed, for large contact loads on the surfaces of the tool.

The **chemical wear** occurs because of chemical reactions on surfaces of a tool. In the main this is the oxidation of a tool material on its surfaces. The material loses its hardness and durability, its particles come off and leave together with the chip, opening a new layer. Microcracks and defects of the tool material accelerate these processes.

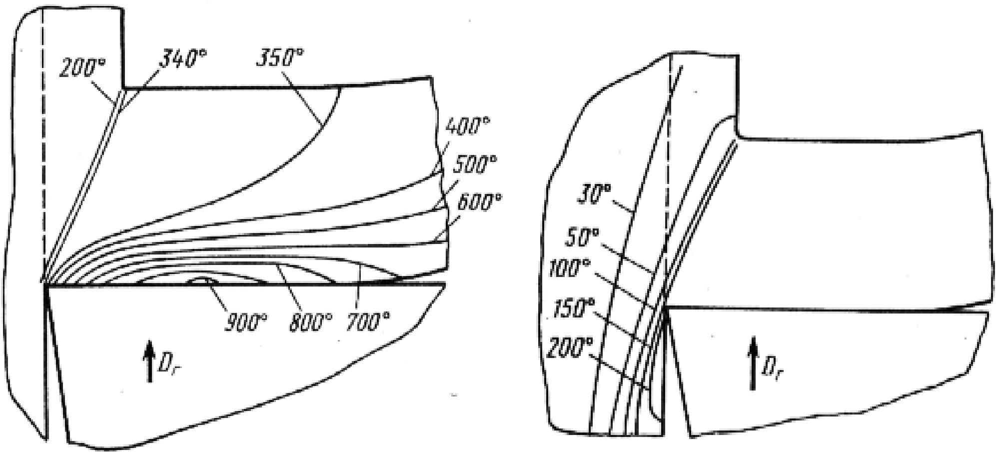
The cutting temperature causes the basic influence on the wear. Even a small increase of the cutting temperature leads to a great increase of wear. Especially it is characteristic for high cutting speeds used in an industry, as the increase of wear results in the even greater increase of cutting temperature. The necessity of regrinding or replacement is determined: wear length on the flank is too large; a roughness has more allowable level; loss of accuracy; occurrence of vibration or singing; change colour of a chip because of increase of temperature in connection with wear; change of chip kind. If the worn out tool is not replaced, the destruction of the tool will take place.

The equation for the dependence of a tool life on the cutting speed T= f(V) has a power form, that is the diagram represents not a straight line. But this diagram is a straight line in the logarithmic coordinates and it is enough to have two points to draw it (Fig. 16-8B). For any given tool life the cutting speed can be determined. The optimum cutting speed is calculated taking into account the maximal productivity or the minimal cost price of processing (Fig. 16-7). Usually a tool life is nominated equal to 30 minutes for finishing cut and 60 minutes for heavy cut or for multiple-tool processing. The tool life is nominated 300 minutes and more for automatic transfer lines, where frequent replacing are inadmissible.

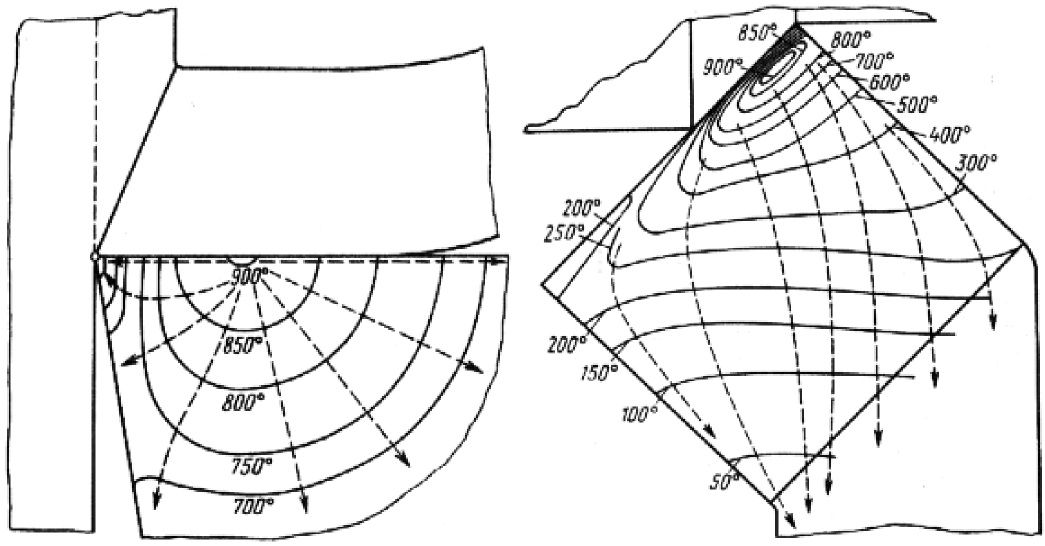
Chapter 17. Cutting Fluids

17.1. Principal Functions of Cutting Fluids

In addition to the proper feed, cutting speed, and shape of a cutting tool, a careful attention should be paid to the selection and use of a proper cutting fluid. Cutting fluids prolong the tool life, increase the rate of metal removal, aid in producing a finer finish, and enable machining with closer tolerances.



A. Distribution of temperature into chip. B. Distribution of temperature into work



C. Distribution of temperature into cutting main cross section.

D. Distribution of temperature on tool in cutting tool face.

Fig. 17-1. Temperature distribution when steel 45 is cut. T15K6, V=150 mpm, S=0.3 mmpr, $\gamma=0^{o}$, $\alpha=10^{o}$, $\varphi=45^{o}$.

The term cutting fluid includes **straight cutting oils**, **water soluble cutting oils**, and **chemical** or **synthetic cutting fluids** which are not oils. Each of the basic cutting fluids is developed for certain machining applications.

The principal functions of cutting fluids include **cooling** the cutting tool and the work (Fig. 17-1), **lubricating** the face of the tool and the chip, and preventing the chip from welding to the cutting edge. In addition to these functions, cutting fluids should also provide a flushing action for chip removal, leave no stain or discoloration on the work, leave minimum sediment deposit on the machine, prevent or inhibit rusting of the machine and the work, resist smoking and fogging over the work, resist bacterial growth, and resist the development of an unpleasant odor as the fluid ages or becomes contaminated.

Approximately 90% of the energy used in metal cutting is converted into heat. Heat results from the compression and friction generated as the metal chip is formed and escapes over the face of the cutting tool. When the cutting speed and depth of cut are increased, the amount of heat developed also increases. When heavy cuts are made at high speeds, a cutting fluid with good coolant properties is essential for cooling the workpiece and cutting tool.

A cutting fluid with good lubricating properties is an aid in the prevention of a built-up edge on the cutting tool. Such an edge frequently is developed when tough, ductile materials are machined at a cutting speed that is too low. High pressures and the resultant friction at the edge of the tool cause the freshly cut metal to adhere or pressure-weld to the tool face. As the metal is piled up, it slides off along the tool face, and the cycle repeats itself again and again. The work-hardened chip, while forming the built-up edge of the tool, leaves a rough surface on the workpiece. A heavy duty cutting fluid with extreme pressure additives retards this development.

High cutting speeds with increased friction and heat result in rapid wear at the cutting edge of the tool. In some cases, complete tool breakdown results. The work-hardened chip moves over the face of the tool too rapidly to weld to the tool face. High heat causes the tool to soften and wear.

The following tool materials begin to soften in the indicated heat ranges: carbon tool steel at 204° to 260° C; high-speed steel at 540° to 590° C; cast alloys at 550° to 815.6° C; and cemented carbides at 810° to 920° C. Therefore, the principal purposes of a cutting fluid at high speeds are to cool the tool and the work, to lubricate the tool face and the chip, and to resist the formation of a built-up edge on the tool.

Cutting fluids also are used for many grinding operations. A fluid with good cooling properties is necessary to prevent distortion of the work due to heat developed with heavy grinding. On light grinding, proper lubrication prevents wheel clogging and improves the smoothness of the finish. Cutting fluids also increase the life of the grinding wheel by reducing the frequency of wheel dressing.

17.2. Classification of Cutting Fluids

Numerous cutting fluids are available under different trade names. However, most of the commercial cutting fluids can be classified in three groups: the straight cutting oils, the emulsifiable oils, and the chemical or synthetic cutting fluids.

Straight Cutting Oils. Lard oil, derived from animal fats, is a good cutting oil for many machining applications at lower cutting speeds. However, it is relatively expensive when used undiluted in large quantities. Mineral oil may be added, and, when so diluted, it commonly is classified as mineral-lard oil - one of the basic straight mineral cutting oils.

There are several basic mineral cutting oils. Each type acquires its special characteristics or properties through additives, including fatty oils, fatty acids, sulfur, chlorine, phosphorous, and certain other chemicals. The basic ingredient, petroleum mineral oil, provides for the cooling property of the oil. It also provides for some lubrication of the cutting tool and the chip.

Lubrication properties are improved when fatty oils or fatty acids are added to mineral oil. The fatty oils include such oils as lard oil, sperm oil, or fish oil. These improve the wet-ability or oiliness of the cutting fluid, by enabling the oil to disperse evenly and cling to the cutting tool.

Under the heat and pressure developed while cutting, the fatty oils combine to form a metallic soap between the cutting tool and the chip, thus reducing friction. Reduced friction results in improved tool wear, reduction in power, and improved surface finish.

Antiweld properties of mineral cutting oils are provided through the addition of sulfur, chlorine, or both sulfur and chlorine. When a clean metal chip, under the heat of friction, is coated with a cutting fluid containing sulfur (or chlorine), a chemical reaction takes place between the surface of the tool and the chip, forming a sulfide (or chloride) film. This film has a lower shear strength than the metal being cut, thus reducing friction at the cutting edge of the tool. The film also aids in preventing the formation of a built-up edge on the tool. The chemical additives provide for antiweld properties at a higher temperature than can be provided for with the addition of fatty oils alone. The chemical reaction of the chlorine takes place at temperatures lower than that required for the sulfur reaction. Therefore, sulfur additives in cutting oils usually are recommended for heavy-duty machining operations where high heats are developed. Through various combinations of additives, a wide variety of cutting oils are produced for use in machining different metals under different conditions.

Active and Inactive Cutting Oils. The two basic types of mineral cutting oils are active and inactive. The **active** oils usually are recommended for use with ferrous metals on heavy-duty operations requiring extreme pressures. They cause discoloration of many copper alloys, including bronze bearings, due to the chemical reaction of additives, mainly sulfur.

The **inactive** cutting oils do not cause any discoloration of metal, and so can be used with machines which have bronze bearings or bushings. They are recommended for machining the nonferrous metals.

Both the active and the inactive types are available as **transparent** oils. Certain inactive, transparent cutting oils have been developed which are "tri-purpose" oils. That is, they can be used as a cutting fluid, as a lubricant for the machine, and in the hydraulic system of the machine. Hence, there is no problem of one oil contaminating the other where leaks or other forms of mixing occur.

Emulsifiable Oils. The emulsifiable oils also are known widely as water soluble oils. However, they are not really soluble, since oil does not dissolve in water. Because of an emulsifying base, usually in the form of a soap, the oil is dispersed in fine droplets throughout the water. These oils are mixed in various proportions according to the machinability of the metal and the severity of the operation. The mixtures vary from 10:1 (10 parts of water to 1 part of oil) for severe operations on metals of low machinability, to 50:1 or more for grinding operations. When mixed, the fluids usually are cloudy or milky white.

The emulsified oil solutions have better coolant properties than the cutting oils. Actually, water is one of the best coolants known. However, water has little lubrication value, and it reacts readily with the work surfaces and machine surfaces causing rust. Therefore, rust inhibitors are compounded with the oil for prevention of such corrosion.

Other additives are compounded with emulsifiable oils to develop desired properties. Lubrication properties are developed through the addition of fatty oils or fatty acids. Antiweld properties are provided for through the addition of sulfur, chlorine, or both, depending on the characteristics desired.

Emulsified oil solutions have limited working life. They should be replaced periodically, and the machine should be thoroughly cleaned before the new solution is used. Emulsifiable oils are sterile as manufactured, and they frequently have germicidal substances compounded in the oil to combat bacterial growth. However, with age and heavy use, they become rancid and develop an unpleasant odor. The solution should then be replaced.

When emulsified oil solutions are mixed, the oil always should be added to the water (rather than water to oil) in order to form a proper solution. Soft water should be used when possible. If unavailable, an emulsifiable oil specially prepared for use in hard water should be used.

The proportion of oil mixed with water in preparing an emulsified oil solution varies according to the machinability of the metal and the severity of the operation.

When oil manufacturer's recommendations are available, they should be followed. In their absence, however, the following general recommendations may be used as a guide.

The emulsifiable oil solutions are the most widely used of all the cutting fluids. They have wide application and may be used on most metals for all except the most severe operations. These oils usually are the most economical cutting fluids for use where they are recommended.

Dermatitis is an inflammation of the skin. Some people acquire dermatitis when in contact with emulsifiable cutting oils, particularly when the skin is dirty or contaminated. Therefore, hands should be kept clean by thorough washing with soap and warm water before and after working with cutting oils. Clothing also should be kept clean and free of cutting oil.

A third group of cutting fluids are the **chemical** (or **synthetic**) cutting fluids. These fluids are diluted solutions of water and water-soluble chemical compounds. There are two principal types: (1) true solutions, and (2) surface-active types. The true solutions consist of inorganic and/or organic materials dissolved in water, mainly to inhibit rust. They have little lubricating value and thus serve mainly as coolants. These fluids are transparent and are usually dyed pleasing colors for identification purposes.

The surface-active type is a water solution which contains additives for lowering the surface tension of the water, and also for imparting lubricating qualities. To provide improved lubricating and extreme pressure qualities, sulfur, chlorine, or phosphorous compounds are added.

Chemical cutting fluids are replacing straight and emulsifiable cutting oils for many applications. For best results, the chemical concentrates must be mixed in correct proportions with deionized water. In all cases, the manufacturer's recommendations should be closely followed. When properly mixed and maintained, chemical cutting fluids can often provide longer life at less cost than oil base cutting fluids.

Other Cutting Fluids and Coolants. Several other types of cutting fluids may be used in machining metals:

Kerosene may be used on aluminum, aluminum alloys, and brass for machining operations of low severity. It has satisfactory cooling properties, and some lubricant properties for chip removal. It also may be mixed with lard oil as a cutting fluid for more severe applications on these materials. Nevertheless, the other cutting fluids usually are considered superior to kerosene and also present less of a fire hazard.

Compressed air sometimes is used as a coolant and for the purpose of removing chips when machining cast iron. Cast iron contains graphite, which tends to serve as a lubricant at the edge and face of the cutting tool. For this reason, cast iron may be machined dry, but cutting rates and tool life may be improved with the use of soluble oil or chemical cutting fluids.

Cutting wax fluids have been developed for use as cutting compounds. However, certain types also may be used as additives to be compounded with other cutting fluids, such as petroleum-based mineral cutting oils or emulsified oil solutions. The manufacturer's recommendations should be followed in mixing or using cutting waxes.

17. 3. Selection of Cutting Fluids

There is no set rule which can be followed in the selection of a cutting fluid for a particular machining operation. However, three principal factors can be used as a guide in selecting a cutting fluid for a particular application: (1) the machinability rating of the metal, (2) the severity of the operation being performed, and (3) the operating conditions.

Machinability is a difficult word to define because its meaning is dependent on many factors, and not all authorities agree on its exact definition. In general, however, the term machinability means the ease with which a metal may be machined. A metal with a high machinability rating frequently machines with comparatively low power consumption, has a high rate of metal removal, produces a good surface finish, and causes minimum tool wear.

For the purpose of selecting proper cutting fluids, most of the commonly used metals have been classified in six groups according to their approximate machinability ratings. The machinability rating is expressed as a percentage, in comparison with A1S1 1112 cold-drawn steel, which has a rating of 100 percent. Metals which are more difficult to machine have a machinability rating of less than 100%. Metals which machine more easily have a rating of more than 100%.

In most machining applications, as the machinability rating of the metal increases, cutting speeds may be increased. With metals having low machinability ratings, the use of an active cutting oil with heavy-duty lubricant and anti-weld properties generally is recommended.

The **severity** of the machining operation being performed is a significant factor in the selection of a cutting fluid. Various metal-cutting operations are rated according to numbers 1 through 10. Broaching (rated number 1) is the most severe, while sawing and grinding (rated number 10) are the least severe. The heaviest-duty cutting fluids generally are recommended for the most severe machining operations.

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