8

Machining

Machining refers to cutting operations that are based on the removal of material from an originally rough-shaped workpiece, for example via casting or forging. Thus, in the literature, such operations have been often called metal cutting, material removal, and chip removal techniques. Herein the term machining is used as an all-encompassing term that includes the fabrication of metal as well as nonmetal parts.

Machining operations are considered to be the most versatile manufacturing techniques for the production of highly accurate part geometries. They can be utilized for the fabrication of one-of-a-kind products as well as for mass production. Recently, Tlusty estimated that the annual value of machining operations in the U.S.A. is above \$160 billion based on the existence of almost 1.87 million machine tools.

Machining operations can be classified according to the geometry of the object's profile—rotational versus prismatic, as well as to the sizes of the object features. External and internal rotational object profiles can be achieved through turning and boring operations, respectively, carried out on lathes and/or boring machines. Prismatic profiles can be fabricated through milling operations carried out on a variety of milling machines. All these techniques would yield acceptable surface quality for the majority of the machined parts. However, for higher surface finish quality, there exist a variety of abrasive techniques, such as grinding, lapping, and polishing.

Parts with small dimensions that cannot be machined on conventional material removal machines have to be fabricated on nonconventional machines, such as electrochemical, electrical discharge and laser beam cutting machines (Chap. 9). As we move towards nanoscale technologies, other modern technologies, such as electron beam–based material removal techniques, are expected to be utilized in pertinent manufacturing fields.

Machine tools for material removal have probably been in existence for two millennia. Turning operations carried out on lathes operated by cords attached to flexible wood sticks, for turning workpieces back and forth, can be traced to the Middle Ages in Europe. However, as discussed in Chap. 1, the development of industrial machine tools for commercial metal cutting purposes took place first in England and then in the U.S.A. during the period 1750 to 1900. The primary motivation for the development of these early machine tools was to be able to fabricate parts with higher accuracies than those producible by casting and forging and also to machine better dies for use by these net shape techniques.

Innovations in the past century focused on the following primary issues: high-speed machining for cost reduction, harder tools for enlarging the class of materials that can be machined, better mathematical modeling of the mechanics of cutting for increased product quality (via reduced vibrations) and for longer tool life (via lower cutting forces), and automation. Except for the last issue, automation through numerical control (to be discussed in Part III of this book), all other issues will be addressed in this chapter.

In Sec. 8.1 below, several representative nonabrasive machining techniques will be reviewed and critical material removal rate variables such as cutting velocity and feed rate will be introduced. Economics of machining, which attempts to minimize costs, utilizes these variables in the derivation of the necessary optimization models. Thus in Secs. 8.2 and 8.3 of this chapter we will address the relationship of cutting tool wear to machining process parameters. We will conclude the chapter with a discussion of representative abrasive machining methods in Sec. 8.4.

8.1 NONABRASIVE MACHINING

Numerous conventional nonabrasive fabrication techniques have been utilized in the past two centuries for the machining of parts with highly complex geometries. These operations have been typically classified as single-point or multipoint machining: the latter type utilizes multipoint cutting tools (such as drills, reamers and milling cutters). These operations have also been referred to as continuous versus intermittent machining: in continuous cutting, the tool is in continuous contact with the workpiece until the end of the pass; in intermittent cutting, since the tool has multiple (discontinued) cutting points, every point remains in contact with the workpiece only for a part of the tool-holder's rotation, i.e., it cuts the workpiece intermittently, where overall continuity is achieved due to the existence of many cutting points.

8.1.1 Turning

In one-dimensional turning, a (single-point) cutting tool mounted on a carriage travels parallel to the axis of rotation of the workpiece, normally held by a chuck and a tailstock (for longer parts) (Figs. 1a, 1b). This feed motion of the tool reduces the radius of the rotational workpiece by an amount equal to the depth of the cut in a direction normal to the feed motion axis (in the same plane). In two-dimensional turning, the tool travels and cuts into the workpiece in the feed direction as well as in the perpendicular depth-of-cut direction, thus yielding workpiece profiles with a variable diameter (Fig. 1c). Both one-dimensional and two-dimensional turning operations can be carried out on manual or on automatically controlled lathes.

The major process variables in turning are the feed rate, f, the cutting velocity, V, and the depth of cut, a. The feed rate of turning is equal to the travel rate of the tool in the feed direction, normally defined in the units of mm/rev (or inches/rev)—i.e., distance traveled by the tool per each revolution of the spindle/workpiece. The cutting velocity of turning refers to the linear velocity of the workpiece at the point of contact with the tool:

$$V = \pi N \left(\frac{d_1 + d_2}{2} \right) \tag{8.1}$$

where N is the spindle's (i.e., workpiece's) rotational speed, defined in the units of revolutions per minute (rpm), d_1 and d_2 refer to the initial and post-cutting diameters of the workpiece, respectively, defined in the units of meters or feet, together, yielding the units of m/min (or ft/min) for V. (For example, we could machine a stainless steel workpiece with a TiN-coated cutting tool at up to $f = 0.75$ mm/rev and $V = 200$ m/min for $a = 0.5$ mm.)

Turning of a workpiece is normally carried in several passes: in the first pass (or several initial passes), the objective is removal of material at increased rates (achieved by selecting a high feed rate) at the expense of surface finish quality; and in the last fine-turning pass the objective is meeting dimensional integrity and surface quality requirements using a reduced feed rate for the same cutting velocity, so that for each rotation of the spindle, the distance that the tool travels in the feed direction is considerably shortened, thus providing maximum continuity on the workpiece's surface.

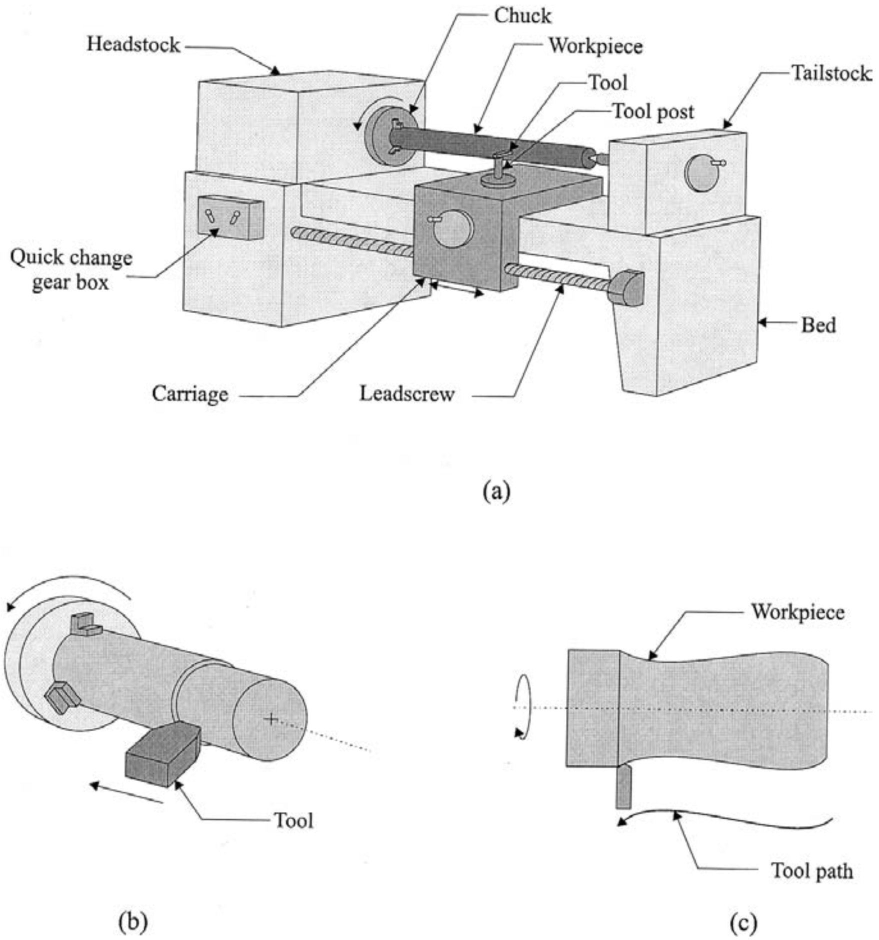


FIGURE 1 (a) An engine lathe; (b) one-dimensional turning; (c) two-dimensional turning.

As mentioned above, turning operations are carried out on lathes (Fig. 1a). The workpiece is held in a three- or four-jawed chuck that is normally manually tightened or power actuated. (For small-diameter cylindrical parts, one may choose to utilize collets, instead of multijawed chucks, for increased tightness.) Most lathes are of the bench type (mounted on a frame with cabinets for tool storage) and are commonly referred to as engine lathes—a term given to the first lathes, which were operated using belts attached to external engines. Today, lathes have built-in electric motors and provide spindle speeds up to 10,000 rpm (for smaller workpiece diameters). Most lathes are capable of performing a number of different cutting operations on rotational workpieces beyond turning—drilling, boring, and thread cutting. Furthermore, some, like turret lathes, can (sequentially) carry out several operations on the same workpiece utilizing a multitool turret, often under the control of an on-board microprocessor based controller.

8.1.2 Boring

The boring operation is the internal turning of workpieces-namely, enlargement of a hole through material removal (Fig. 2). Thus issues discussed above for turning normally apply to boring as well. Boring can be carried out on a lathe if the workpiece size allows it. Otherwise, there exist horizontal and vertical boring machines especially designed for the fabrication of large-diameter internal holes with high accuracies (Fig. 3). Unlike in turning, however, moderate cutting speeds and feed rates are utilized (for small depths of cut) to achieve these accuracies.

The vertical boring machine is reserved for the machining of large workpieces (above 1 m in diameter, up to 5 to 10 m). Multiple tools can be mounted on the overhead tool holders that engage the workpiece fixtured on a turning worktable. On horizontal boring machines the option of having the tool or the workpiece rotate exists. In the former, the workpiece is fed into the cutting tool.

8.1.3 Drilling

Drilling is the most common (multipoint) cutting technique targeted for the production of small-diameter holes; but the complexity of its tool geometry makes it difficult to model mathematically. Normally a rotating tool

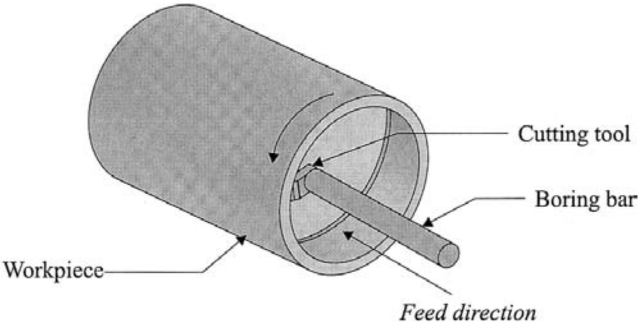


FIGURE 2 Boring on a lathe.

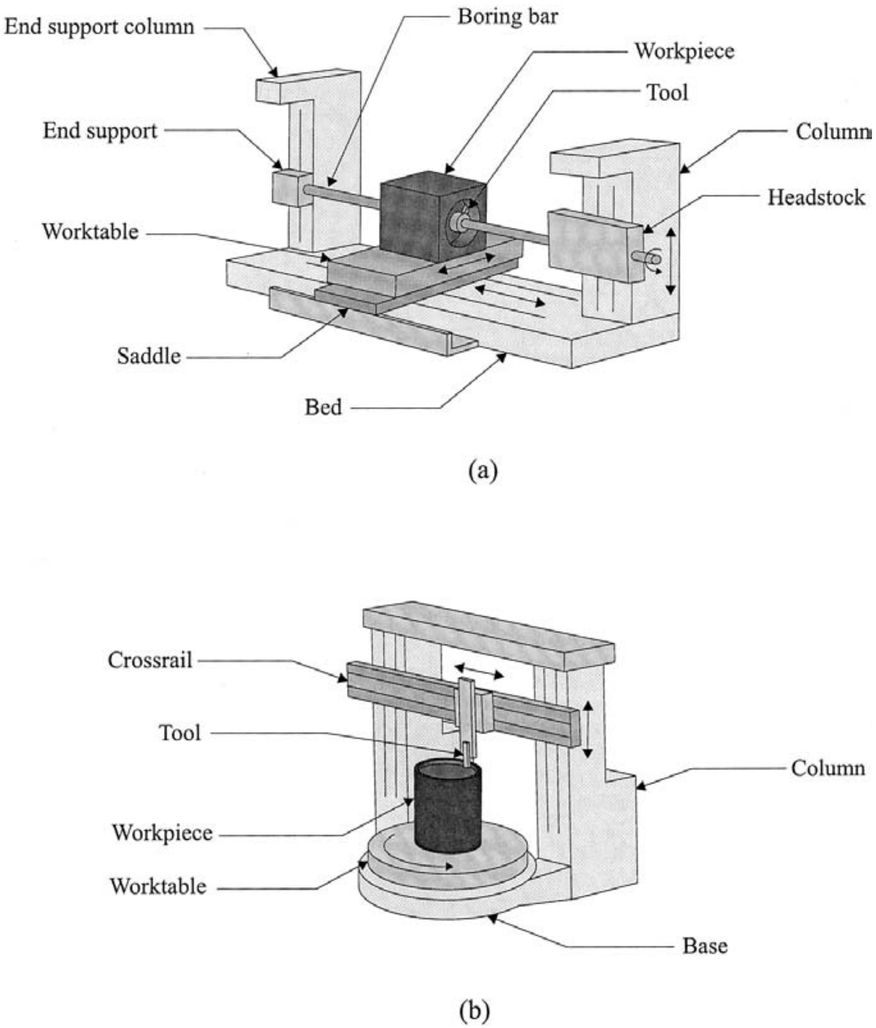


FIGURE 3 (a) Horizontal boring machine; (b) vertical boring machine.

mounted on a spindle is fed into a fixtured stationary workpiece (Fig. 4). Occasionally, drilling can be carried out on a lathe, where a rotating part is fed into a stationary drilling tool held in a turret or a tailstock.

The major process parameters in drilling are the diameter of the drill (or the hole to be machined), d, the feed rate, f, and the cutting velocity, V. The feed rate of drilling is equal to the travel rate of the tool into the

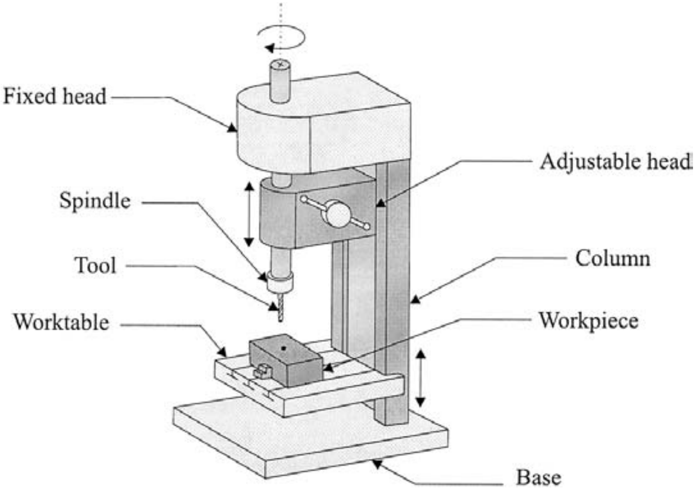


FIGURE 4 Drilling.

workpiece, defined in the units of mm/rev. The cutting velocity of drilling refers to the linear velocity of the tool at the point of contact with the workpiece:

$$V = \pi N d \tag{8.2}$$

where N is the spindle's (i.e., the tool's) rotational speed (rpm). The effective feed rate, f_e, and the depth of cut, a, for drilling are defined per tooth: For a 2-flute drill, $f_e = f/2$, and $a = d/2$, unless the drilling operation is an enlargement of a diameter from d_1 to d_2 —then, $a = (d_2-d_1)/2$.

In drilling a new hole (in a solid workpiece), the drill with its chisel edge yields a very rough cut under the axial point contact of the tool with the workpiece. The surface of interest, however, is the side wall of the hole, which is burnished by the rubbing action of the ''twisted'' flutes of the drill and the material that escapes outward. If one considers this an unacceptable machining operation, a reaming tool can be used for improving significantly the side-wall's surface quality. A reaming tool is also a multipoint cutter, but due to its geometry with ''straight'' flutes, it acts like a boring tool and yields excellent surface finish. (The depth of cut during reaming is, generally, between 0.25 to 0.70 mm).

Drill presses can be utilized for drilling holes and their subsequent potential tapping (threading) or reaming. Most drill presses are of the bench type and may allow for drilling holes at angles different from the vertical. There also exist turret-type press drills with turrets that hold many cutting tools (drills, reamers, etc.) for a set of sequential operations on a workpiece fixtured on an X–Y table. Such drill presses would be utilized for fast and accurate relative positioning of the tool with respect to the fixed drilling location of the workpiece.

8.1.4 Milling

Milling is a material removal process for nonrotational objects: it uses a multipoint tool that rotates about a fixed axis while the prismatic workpiece is fed into the tool according to a prespecified travel path (Fig. 5). This intermittent cutting process is commonly classified as face (or end) milling versus peripheral (or plain) milling (Figs. 5a, 5b, respectively).

In two-dimensional end milling, the axis of rotation of the cutter remains orthogonal to the travel plane of the workpiece while a desired profile is machined. Once the planar cutting operation is completed, the workpiece can be elevated in the vertical direction (to the machining plane) for the next planar profiling operation. This stop-and-go milling operation is normally referred to as 2 and one half dimensional machining, since the workpiece only moves incrementally in the third direction (yielding a staircase effect for curved surfaces). Milling operations, however, can be carried out as up to five-axis, three-dimensional machining, where the position of the workpiece is continuously varied in all three orthogonal Cartesian axes while the tool's axis is rotated simultaneously with respect to two orthogonal axes (Fig. 6). Such coordinated and synchronized motions of the tool and the workpiece can yield highly accurate spherical surfaces (or any other three-dimensional surface) with improved surface finish.

The cutting process parameters in milling are similar to those in single-point turning: the thickness of the material removed is considered to be the

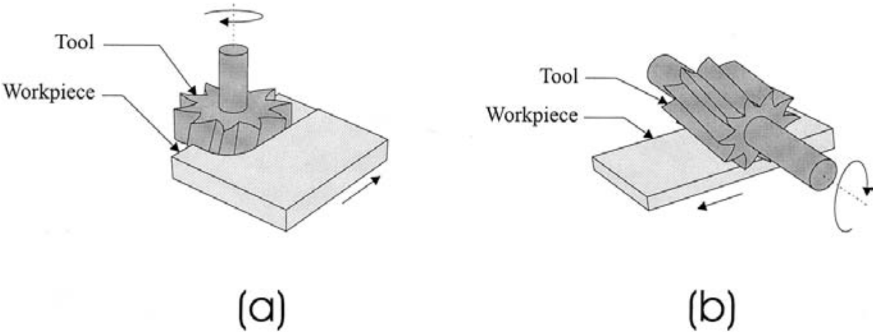


FIGURE 5 (a) Face/end milling; (b) peripheral/plain milling.

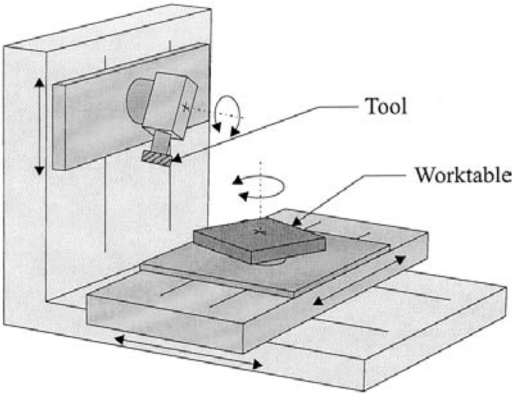


FIGURE 6 Five-axis milling.

depth of cut (the travel of the workpiece along the orthogonal direction to the planar motion of cutting), while the effective feed rate per tooth is given as the travel rate (feed rate) of the tool holder, *f*, along the desired profile divided by the number of teeth. As in drilling, the cutting velocity is the (relative) linear velocity of the tool tip as it engages the workpiece. If one assumes that the velocity of the tool is much greater the velocity of the workpiece (i.e., the feed rate) at the instant of engagement, then in a simplified form,

$$V = \pi N d \tag{8.3}$$

where N is the rotational speed of the fixed-axis tool (or spindle) in the units of rpm and d is the diameter of the tool in the units of mm (or inches). (For example, in milling a stainless steel workpiece with a coated TiN cutting tool, a feed rate of up to 0.4 mm/tooth can be achieved for a cutting velocity of up to 500 m/min.)

As in turning, the surface finish of a workpiece in milling is a function of the depth of cut (thickness layer) as well as the feed rate. Most applications would require numerous rough cuts carried out at high feed rates and large depths of cut, as would be allowed by the tool characteristics and the milling machine power, for a maximum material removal rate (i.e., minimum cost). A subsequent fine cut would be carried out at much lower values of both process variables (especially the effective feed rate, f_e).

The most common milling machine is the knee-and-column milling machine (Fig. 7), which can have a spindle configuration either for peripheral (horizontal) or for face (vertical) milling. The column provides necessary rigidity to the cutting tool and normally houses the electric motor that

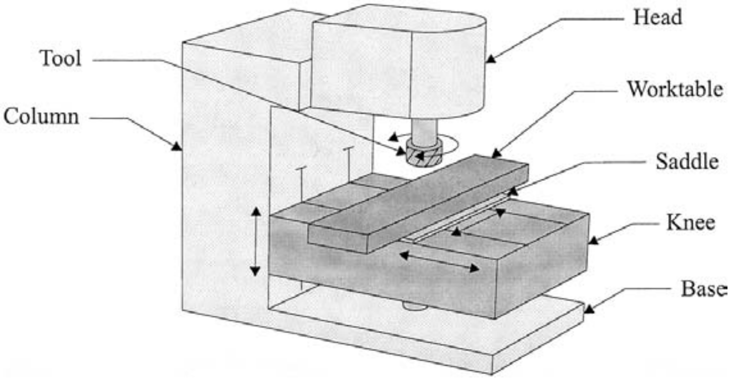


FIGURE 7 Knee-and-column milling machine.

drives it; the knee supports the worktable (and its actuators) capable of motion in three orthogonal directions. Other machining operations that can be carried out on milling machines include gear-machining, planing, and broaching (though frequently the latter operations are carried out on special purpose planing/shaping and broaching machines).

8.1.5 Design for Machining

A large number of part geometry and machining process parameters affect the quality and cost of parts manufactured through machining operations. The impact of process parameters on part quality and cost will be discussed in Sec. 8.2 in the context of tool wear and surface finish. In this section, our primary focus will be on part geometry requirements.

Machining, though very versatile, is an expensive technique for the fabrication of parts when compared to net shape techniques, some of which were presented in Chaps. 6 and 7. Thus machining should be used sparingly and in an optimized manner. From a part geometry point of view, engineers must choose the most suitable process/machine and be aware of the technical difficulties in the fabrication of intricate features. Furthermore, the initial stock part geometry should be selected for minimal material removal—i.e., with dimensions as close as possible to the final part dimensions. In regard to achievable tolerances, users should consult existing handbooks and specifications for the machines on the factory floor. For example, turning and boring yield different tolerance levels for different hole radii (e.g., ±0.01 to ±0.1 mm tolerance for radii of 20 to 1000 mm). Drilled holes' radial dimensional tolerances can be improved using reaming from ±0.05–0.20 mm to ±0.025–0.125 mm. As will be discussed later in this chapter, all these tolerance levels can of course be further improved using abrasive surface finishing techniques.

Setup times add considerable cost to the machining of parts. Thus parts should be designed to require minimum setup changes as well as cutting tool changes. Undercuts, for example, though feasible to manufacture, are significantly cost adding features. Furthermore, long and narrow parts, large and flat parts, and thin walled parts are not easily machinable.

Sharp corners, tapers, and major variations in profiles should be avoided in turning. Tool travel along the external part profile for turning and along the internal profile for boring should be as much as possible free of interruptions (which would require the tool to disengage and reengage somewhere along the profile, as opposed to an easy engagement at the start of the profile). Through holes are preferable to blind holes in both boring and drilling operations. (Through holes are easier to ream; for blind holes, the hole should be drilled deeper than necessary if reaming is to follow.) Furthermore, holes are easier to drill on flat surfaces perpendicular to the tool's motion axis.

In milling operations, external intersections of surfaces should be chamfered, if necessary, instead of honed with a small radius of curvature. For internal cavities (through or blind), one must be aware of the minimum radius of curvature of the vertical edges, which would be determined as a function of the depth of the cavity (the deeper the cavity, the longer the cutting tool necessary, the larger its diameter for rigidity).

Some design issues for rotational and prismatic object geometries are shown in Fig. 8.

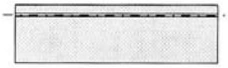
8.2 MECHANICS OF CUTTING—SINGLE-POINT TOOLS

The objective of this section is to address two important factors that affect machining productivity in terms of cost and quality: tool wear and chatter. A number of process parameters and tool- and workpiece-material properties impact these factors, most notably, cutting forces and chip formation. The mechanics of cutting in terms of cutting forces will be addressed first in Sec. 8.2.1, which will be followed by a discussion on chip formation and control in Sec. 8.2.2.

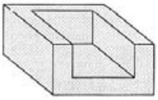
8.2.1 Cutting Forces

The study of the mechanics of cutting can be traced to the mid-1880s in Europe, to the works of French scientists Cocquilhat and Joessel, who reported on cutting forces and their relationship to tool geometry. At the start of the 1900s, we note the work Reuleaux on chip formation and the

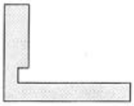
Hole with large L/D ratio.



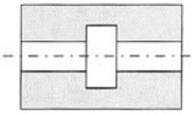
Sharp corners.



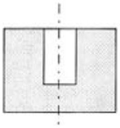
Undercut.



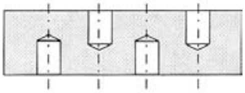
Internal recesses.



Difficult blind hole.



Requires two setups.



Unmachinable screw threads.

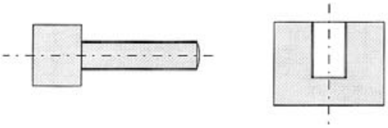


FIGURE 8 Design features to avoid in machining.

work of Taylor on tool life. In the more modern history of metal cutting (1940–1970), the primary contributors were Ernst (chip formation), Merchant (chip geometry), Kronenberg (tool geometry), Armarego (mechanics of cutting), and Tlusty (vibrations and chatter).

As addressed by the above and other researchers, it is commonly accepted that machining through material removal is a plastic flow process. Material (chip) removed from the workpiece at the tool contact point flows over the tool's surface and eventually breaks away. The mechanics of this process has been often studied through single-point cutting-edge models and extrapolated to multipoint cutting. These models have been classified as orthogonal cutting and oblique cutting operations (Fig. 9). The former is the

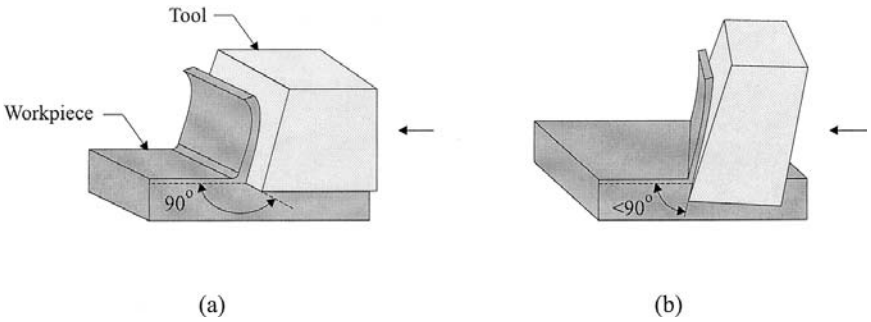


FIGURE 9 (a) Orthogonal cutting; (b) oblique cutting.

simpler case that assumes the cutting edge is orthogonal to the cutting velocity direction. The latter one assumes a nonzero inclination of the tool's cutting edge.

Figures 10a and 10b define the cutting geometrical parameters and the primary forces acting on the tool, respectively. The cutting force F_c is in the same direction as the cutting velocity, V, the thrust (feed) force, F_t, is in the direction the tool is forced into the material (feed direction):

$$F_c = \frac{F_s \cos(\beta - \alpha)}{\cos(\phi + \beta - \alpha)} \tag{8.4}$$

$$F_t = \frac{F_s \sin(\beta - \alpha)}{\cos(\phi + \beta - \alpha)} \tag{8.5}$$

where F_s is the shear force that causes the chip to deform at a ϕ angle to the direction of cutting, α is the tool rake angle, and β is the angle between the

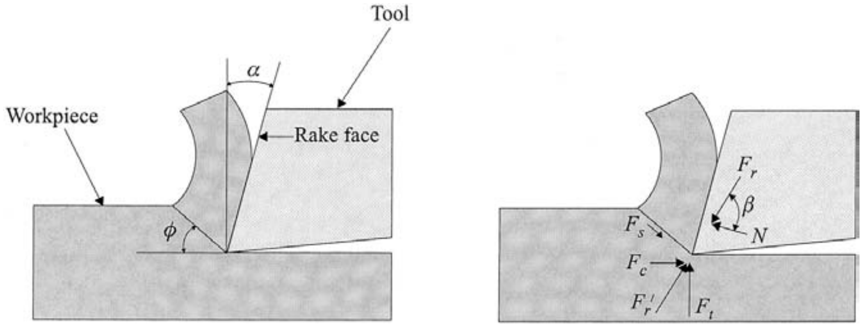


FIGURE 10 (a) Orthogonal cutting geometry; (b) forces.

resultant force F_r and the normal to the rake surface of the cutting tool, N. Merchant's equation states that $2\phi = 90^\circ + \alpha - \beta$.

As noted above, the primary machining forces (F_c and F_t) are directly affected by the tool's geometry, as well as by the workpiece material properties, which in turn impact on the choice of power requirements and cutting tool materials. For example, decreasing the rake angle, α, increases machining forces, which in turn indirectly contributes to faster tool wear rates, and vice versa.

It has been common practice to measure machining forces through dynamometers. These sensors are normally placed under the tool carrier, in turning, and underneath the workpiece, or between the tool and the spindle, in milling. The primary objective of monitoring machining forces is to monitor indirectly the tool wear and adjust the cutting parameters such as feed rate, when necessary.

8.2.2 Chip Formation and Control

Chip formation is a plastic flow (shear) phenomenon initiated along the shear angle—the primary shear zone (Fig. 11). As the chip moves along the tool's surface, fracture contributes to its breakage. There are large number of different chip geometries that can be produced during machining based on the workpiece material, cutting conditions, and possible chip breakers employed.

The three classes of chips are

Continuous chips: The formation of continuous chips is most common to ductile materials (copper, aluminum, mild steel, etc.) machined at high cutting speeds and/or with high rake angles. Although such chip formation yields good surface finish, in practice, long chip strips would cause entanglement with the cutting tool and be detrimental to the safety of machine operators and even damage the surface of the workpiece. Continuous chips can be broken, however, at appropriate lengths, through the use of chip breakers, while maintaining good surface finish.

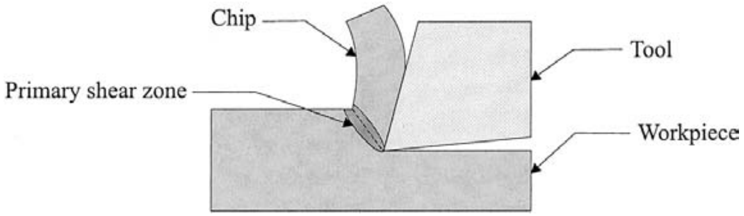


FIGURE 11 Shear zone in orthogonal cutting.

Continuous chips with built-up edges (BUE): At lower cutting speeds and lower rake angles, edges (of workpiece material) can build up between the tool and the under surface of the chip. Such BUE can weld to the chip as well as to the workpiece and get fractured away as machining progresses, while causing surface imperfections as well as contributing to rapid tool wear. They can be avoided using effective coolant liquids and increased rake angles.

Discontinuous chips: Material brittleness, low rake angles, and large depths of cut contribute to the formation of discontinuous chips (not necessarily separated but fractured). This intermittent phenomenon may cause the tool to vibrate (chatter), which will in turn adversely affect the quality of the object's surface and potentially cause increased tool wear.

Friction in Metal Cutting

In metal cutting, the area of contact between the tool and the chip experiences very high cutting forces and temperatures. This phenomenon is further complicated by the fact that the chip's under surface moving along the rake face of the tool is chemically clean. The combination of these factors leads to high values of the coefficient of friction and potentially to a stick-and-slip type of relative motion of the chip. That is, for a large portion of the contact length, the workpiece material adheres to the tool's rake face. This motion of the chip is characterized as plastic flow. An appropriate increase in the rake angle could significantly reduce the normal force on the rake face and subsequently reduce the coefficient of friction, thus indirectly prolonging the tool's life.

Chip Flow Control

Chip flow control refers to the breaking of continuous chips in a controlled manner. There are two common methods of achieving chip breakage: the obstruction type (commonly used in turning operations) and the groove type (incorporated into almost all modern tool inserts). In obstruction-type chip breakers, an obstruction of optimal height that is placed a short distance from the cutting edge interrupts the flow of the continuous chip and forces it to curl (Fig. 12a). In groove-type chip breaking, an optimal geometry groove is built into the tool (at the time of its fabrication) for curling the chip and causing it to break directly, or act as a guide to curl the chip and push it against an obstruction for its breakage (Fig. 12b). In drilling, chip breakage and improved removal can be achieved through suitable flute profile design (e.g., by incorporating chip breaking groove features into the flute or flank profile).

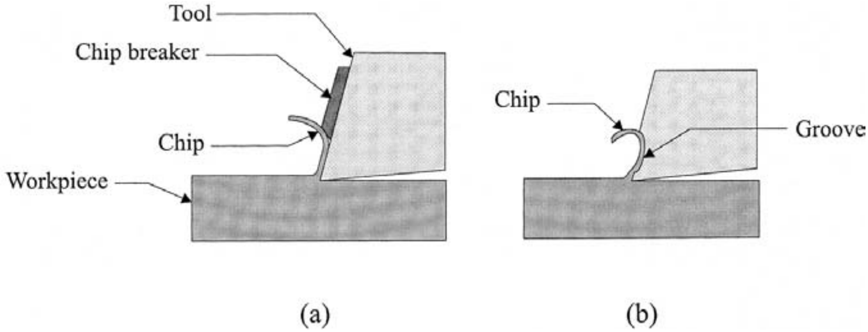


FIGURE 12 (a) Obstruction; (b) groove breaking.

8.2.3 Vibrations in Machining

Cutting tool and workpiece vibrations during machining can be quite detrimental to tool wear and negatively affect the dimensional accuracy and surface finish of the workpiece. Machine tool vibrations have been investigated by many academic and industrial researchers, most notably by Tlusty's group since 1963. The objective has been to model and predict vibrations through analytical and finite element modeling–based numerical works in order (1) to design the optimal machine tool configuration and (2) to determine (off-line) the best cutting process parameters (velocity, feed rate, and depth of cut). The overall conclusion has been that, no matter how rigid the machine tool structure is, cutting vibrations are inevitable. They should be managed through passive vibration isolation techniques or active (real-time) control methods.

Machine tools commonly experience three types of vibrations:

Free vibrations: These occur owing to an impulse force applied on the machine tool, such as a sudden reversal of the milling table's direction of motion. These vibrations are considered to be transient and rapidly decay. A suitable vibration isolation system would effectively damp free vibrations.

Forced vibrations: These occur owing to a (normally periodic) dynamic force applied on the machine tool, such as intermittent cutting forces in milling, periodic variations in depth of cut, and imbalances in the drive system of the machine tool. Their impact is the greatest when the existing frequency is near one of the natural frequencies of the machining operation, potentially leading to the very undesirable instability of the system. Forced vibrations can be managed most effectively by varying the cutting process parameters and the cutting geometry (i.e., adjusting the amplitude and direction of the cutting forces and therefore the amplitude and frequency of vibrations).

Self-excited vibrations: These vibrations, also known as ‘‘chatter,’’ are primarily due to variations in the cutting conditions, while machining under specific (constant) process parameters. Chatter is undesirable and difficult to predict because of the combinatoric nature of machining parameters (e.g., workpiece material, tool material, cutting geometry, velocity, feed rate, and even cutting fluid used). Machining while chatter is present yields unacceptable surface finish and leads to rapid tool failure, including catastrophic cutting edge failure.

There are two main mechanisms to self-excited tool vibrations: mode coupling, which occurs when the tool vibrates in at least two directions in the plane of cutting (that includes the cutting velocity vector) with the same frequency and a phase shift normally due to nonoverlapping passes of cut; and regenerative instability, which is due to a relative periodic vibration between the tool and the workpiece, since surface waviness in successive cuts would never overlap (statistical impossibility) and thus cause variations in chip width (Fig. 13). This continuous regeneration of surface waviness causes periodic variations in cutting forces that lead to self-excited vibration. The most effective way of dealing with chatter is its (often experimental) prediction (i.e., of the possible instability) and adjustment of the cutting parameters for its avoidance.

Stability of machining dynamics can be achieved by coping with all sources of vibration—free, forced, and self-excited. As mentioned above, machine configuration optimization by utilizing vibration isolation mechanisms and high-quality components (e.g., radial bearings) will significantly contribute to this objective. Selecting optimum cutting conditions and tool geometries will also reduce vibrations (especially chatter). In milling, for example, one can use cutters that have variable tooth spacing to break the regular waviness of the surface, when chatter becomes a difficult problem.

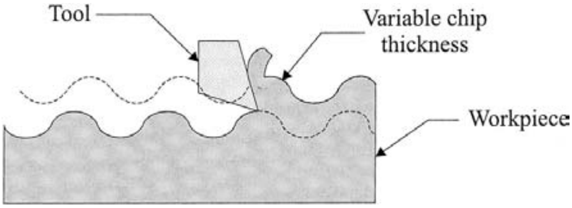


FIGURE 13 Regenerative chatter.

Also, honed or chamfered tools are less likely to cause chatter than those with sharp cutting edges.

8.2.4 Cutting Temperature and Fluids

Energy expended during the plastic deformation of the chip and overcoming frictional forces is (almost all) converted into thermal energy (i.e., heat). Significant research in this area has shown that the hottest zone in machining is where the chip goes through its stick-and-slip motion over the rake face of the tool (especially along the ‘‘stick’’ length of contact). It is thus no surprise that major tool wear occurs in this region of the rake face. Cutting temperatures can be over 1000°C in this region of the rake face and 600° to 700°C on the flank face near the cutting tool edge when cutting steel with carbide tools (Fig. 14).

Cutting temperatures increase with cutting velocity and feed rate. In intermittent cutting, as expected, the temperature profile is periodic as a function of time, thus subjecting the tool to thermal impact in addition to

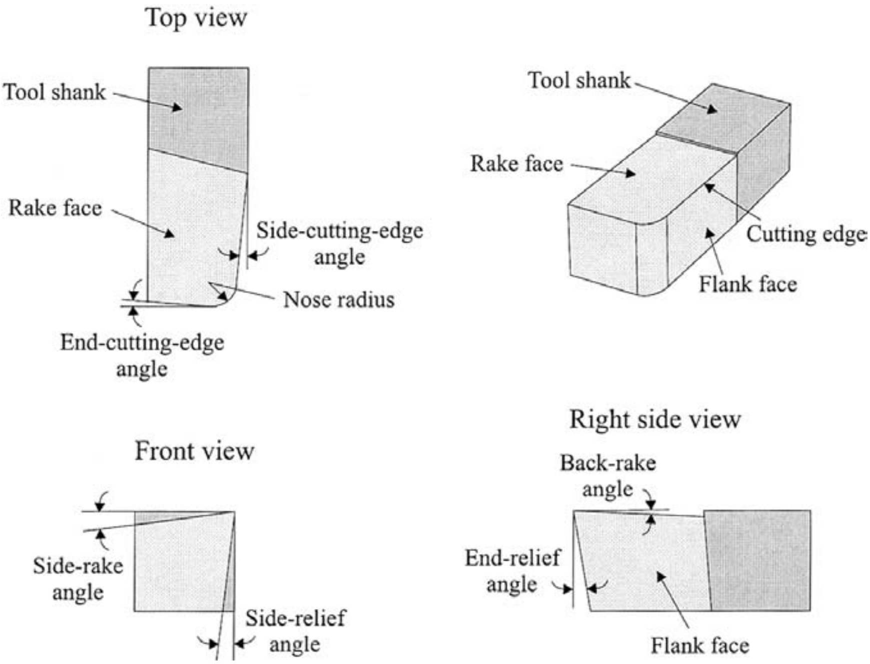


FIGURE 14 Single-point tool geometry; orthographic views.

mechanical impact. Thermal fatigue failure is a common problem, for example in tungsten carbide tools (especially at high cutting velocities and when coolants are utilized).

Cutting fluids can be used as effective coolants to reduce the temperature of the tool at the interface with the chip. Such fluids also provide a cooling effect to the workpiece to prevent thermal distortions, and, very importantly, they act as lubricators for friction reduction on the rake face. Cutting fluids can be water-based or oil-based. Water-based fluids may contain fatty soaps, sulphur, organic salt, and sulphides to provide better cooling action. Oil-based fluids may contain mineral oils, chloroform, phosphates, and polymeric ethers to provide better lubrication at the tool–chip interface. The application method of cutting fluids (flood versus mist) and the rate of application depend on cutting conditions (cutting velocity and feed rate).

8.3 TOOL WEAR AND SURFACE FINISH

The life of a cutting tool directly impacts machining costs. The longer the tool life is, the less the tooling cost, and furthermore the fewer the tool changes (i.e., lower setup and preparation costs). Despite a century of research in this area, most wear mechanisms reported in the literature should be treated as well-investigated conjectures, and not as proven theorems. Today, research in this area has shifted toward monitoring and predicting tool wear in real time, in order to prolong tool usage and also to prevent catastrophic failure of the tool. In many instances, breaking the tool's cutting edge (tip) can cause irreparable damage to the workpiece's surface. Thus it would be preferable to stop using the cutting tool well ahead of this point.

Although cutting tools have been classified as single-point and multipoint tools, many of the wear mechanisms for the former apply to the latter as well. This commonality is further strengthened by the widespread use of generic inserts (held in single- and multipoint tool holders) for turning, milling, and even for large-diameter drilling.

The tool regions of particular interest, from the wear point of view, are shown in Fig. 14. The rake face is the primary surface of contact between the chip and the cutting tool, and the flank of the tool is a region (especially at the cutting edge) where the tool comes into contact with the workpiece. The geometries of both rake and flank surfaces significantly affect cutting forces and surface quality. For example, cutting-edge strength would significantly diminish for back rake angles above 5°. In contrast, the cutting-edge strength would increase as the back-rake angle becomes negative and approaches an optimal value around -5°. The end-relief angle prevents contact between the end flank and the workpiece, though angles above 5° will start weakening the cutting edge.

8.3.1 Cutting-Tool Materials

The interface between a cutting tool and the workpiece can be characterized by high forces, severe friction, high temperature, and, in the case of intermittent cutting operations, high-frequency impact. Thus the ideal cutting tool should have both high hardness and high toughness—a rarity in the field. Ceramic tools, for example, have excellent hardness properties (even at temperatures of 500°C and above), but low toughness. High-speed steel (HSS) tools, on the other hand, have excellent toughness, but their hardness rapidly diminishes at high cutting temperatures (above 500°C).

HSS tools were developed at the turn of the 20th century for higher speed machining. They can have about 10% molybdenum or up to 18% tungsten as the alloying element. The former is tougher and thus widely used in drilling and end milling. HSS tools normally cut at velocities lower than 50 m/min. Carbide tools (also known as cemented or sintered carbides) were developed in the 1930s for hardness and cutting velocity characteristics that are better than those of HSS tools. Primary carbide inserts today are of tungsten or titanium type. They can cut steel at velocities of up to 200 m/min.

Carbide tools can be also coated for improved mechanical and thermal properties, as well as for lower friction and increased resistance to chemical reactions between tool and workpiece materials. They can cut steel at velocities of up to 400 m/min. Typical coating materials are titanium carbide on tungsten carbide, aluminum oxide (Al_20_3)—ceramic, and even synthetic diamonds. Coating is achieved through either chemical or physical vapor deposition.

Ceramic tools (introduced in 1950s) and cubic boron nitride (cBN) tools (introduced in the 1960s) are typically used for machining conditions that require high hardness at elevated temperatures. (cBN is almost the hardest material in existence, being second only to diamond). These tools can cut steel at velocities of up to 700 to 800 m/min.

The cutting edges of most carbide inserts are either chamfered or honed for strengthening purposes. It has been conjectured that such an edge preparation could prevent premature chipping (microfracture) of the cutting edge in the first (accelerated-wear) period of tool wear and thus prolong tool life (especially in high-impact, intermittent machining operations). Typical chamfers would be 20° to 45° inclined and up to 0.2 mm wide, while the radius of curvature of a honed edge would be 0.025 to 0.180 mm (Fig. 15).

8.3.2 Tool Wear Mechanisms

Tool wear has probably been the one machining issue most researched since the beginnings of machine tool history. The objective of toolmakers has always been to develop harder and tougher cutting tools in order to machine engineering materials that have been continuously evolving. Although significant progress has been made in the development of wear resistant tools, these still rapidly wear out under severe machining conditions present at the tool–chip interface. After a century of research, we still do not have an accurate wear prediction model and frequently use the tool life formula developed by Taylor almost a century ago (Sec. 8.3.3). However, with increasing achievements in the area of "intelligent machining," it is anticipated that tool wear will be able to be monitored in real time, where (software-based) digital filters will be utilized for predictions into the near-future behavior of the tool.

Cutting temperature is accepted as one of the most important process parameters that affect tool wear: cutting tools have much lower mechanical hardness and toughness at elevated temperatures. As one would expect, the other factor is the thermal and mechanical periodic impact that a tool gets subjected to in intermittent cutting, such as milling.

The exact mechanisms of wear in machining is still an open topic for research. However, the following list contains some mechanisms of wear that have been accepted by many researchers:

Adhesion: This wear mechanism is based on the formation of welded junctions and their subsequent breakage, i.e., tool particles on the rake face being removed by the chips. built-up edge (BUE) has also been noted as an adhesive wear mechanism, potentially causing chipping of the tool edge.

Abrasion: Hard particles in the workpiece material (e.g., carbides) abrade and dislodge (micro)particles from the surface of the cutting tool. This wear mechanism (as is adhesion) is more prominent at higher

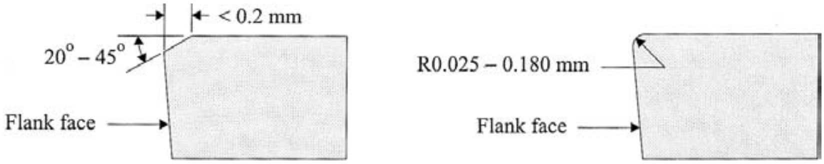


FIGURE 15 (a) Chamfered; (b) honed edge.

cutting velocities that yield increased cutting temperatures and weaken the tool's hardness.

Diffusion: This wear mechanism is present because of potential chemical affinity between the tool material and the workpiece material (e.g., cobalt, in tungsten carbide tools, diffusing into the steel workpiece chips).

Fatigue: Thermal and mechanical loading of the cutting tool results in microcracks that lead to chipping and, at worst, to catastrophic failure of the cutting edge (i.e., significant tool-edge breakage).

The progressive wear of cutting tools can be quantified by the following two metrics:

Crater wear: Also known as rake-face wear, crater wear corresponds to a formation of crater like shallow cavity on the rake face of the tool very near to the tool edge (Fig. 16a). All wear mechanisms discussed above contribute (at different degrees) to crater wear, typically measured by the depth of the crater. Although potentially advantageous at the beginning, lowering cutting forces owing to increased rake angles, this wear weaken the cutting edge and causes its failure through fracture.

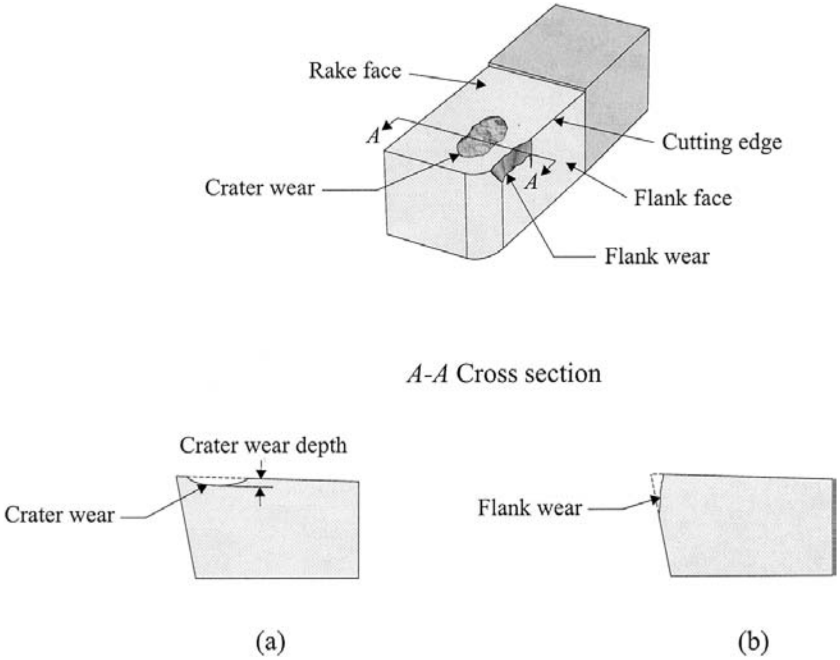


FIGURE 16 (a) Crater wear; and (b) flank wear.

Flank wear: In contrast to crater wear, which is most prominent in the machining of ductile materials, flank wear can be present under almost all cutting conditions. It refers to the wearing of the flank face, starting at the cutting edge and progressively developing downward and sideways (Fig. 16b). Flank wear results in the reduction of the cutting edge's sharpness, leading to higher cutting forces, eventually leading to tool fracture. It is primarily caused by abrasion.

8.3.3 Tool Life Equation

Over the past several decades, it has been established that tool flank wear (its width) can be expressed as a function of time utilizing a three-region (period) tool life curve (Fig. 17a). The first region refers to the exponen-

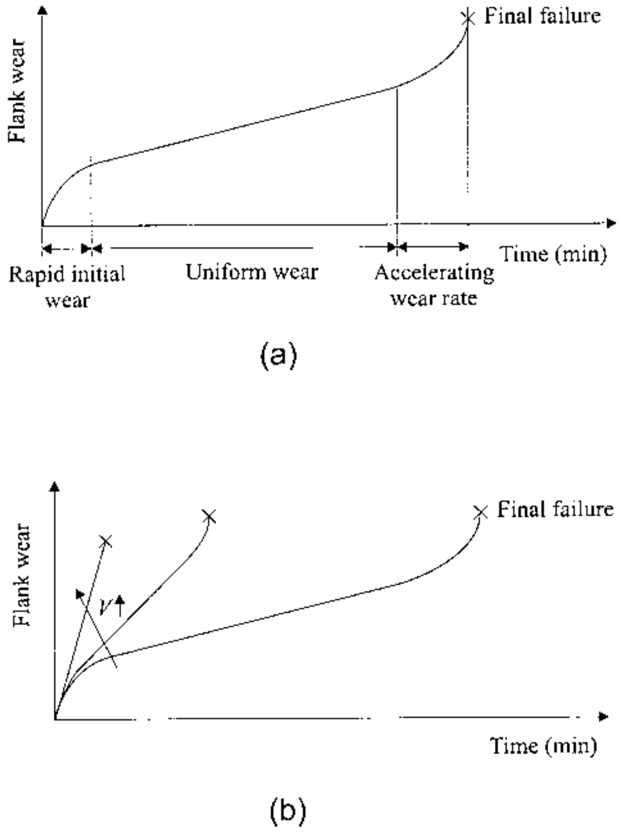


FIGURE 17 Flank-wear curve.

tial degradation of the tool edge area and could last up to 2 to 5 sec for carbide tools cutting steel. The second region can be approximated by a linear (uniform rate) relationship. This period can be assumed to represent the useful life of the tool. The third and last region corresponds to the final exponential degradation of the tool prior to its total failure. It is strongly advised to halt machining once the tool enters this period of its life.

As also shown in Fig. 17b, flank wear is a strong function of cutting velocity, V: the flank wear rate increases as the cutting velocity is increased. Based on much empirical data, Taylor proposed that the relationship between tool life and velocity can be expressed as a logarithmic function. In the logarithmic domain, tool life, T, is approximately a linear function of cutting velocity:

$$VT^n = C \tag{8.6}$$

where C is the cutting velocity (m/min) achievable for the tool–workpiece combination at hand that would correspond to one minute of tool life, n is the slope of the relationship in the logarithmic domain and primarily depends on the tool material (0.1 to 0.17 for HSS tools, 0.3 for titanium coated tungsten carbide tools, and up to 0.6 to 1.0 for ceramic tools).

Taylor's tool life formula has been modified over the years to include feed rate, f, and depth of cut, a:

$$VT^n f^{n_1} a^{n_2} = K \tag{8.7}$$

where K is a proportionality constant, and n, n_1, n_2 are tool material dependent (constant) exponents (typically, 0.5 to 0.8 for n_1 and 0.2 to 0.4 for n_2).

8.3.4 Workpiece Surface Finish

Surface finish (i.e., roughness) is an important dimensional requirement in machining and typically acts as a constraint on feed rates—the higher the feed rates, the worse the surface finish. The literature on machining categorizes factors that affect surface finish into two: those that affect the ideal finish of the workpiece surface and those that affect the natural finish. The former can be formulated (and accurately estimated) as a function of feed rate and tool geometry. Figure 18a shows the surface finish model for a (single-point) turning tool, while Fig. 18b shows the model for a face-milling tool. Although the topographic traces left on the workpiece are different for turning and milling (rotational versus planar motion), the profiles of finish are very similar.

The primary factors that contribute to natural surface finish are: the occurrence of BUE, chatter or other vibration mechanisms, inaccuracies in

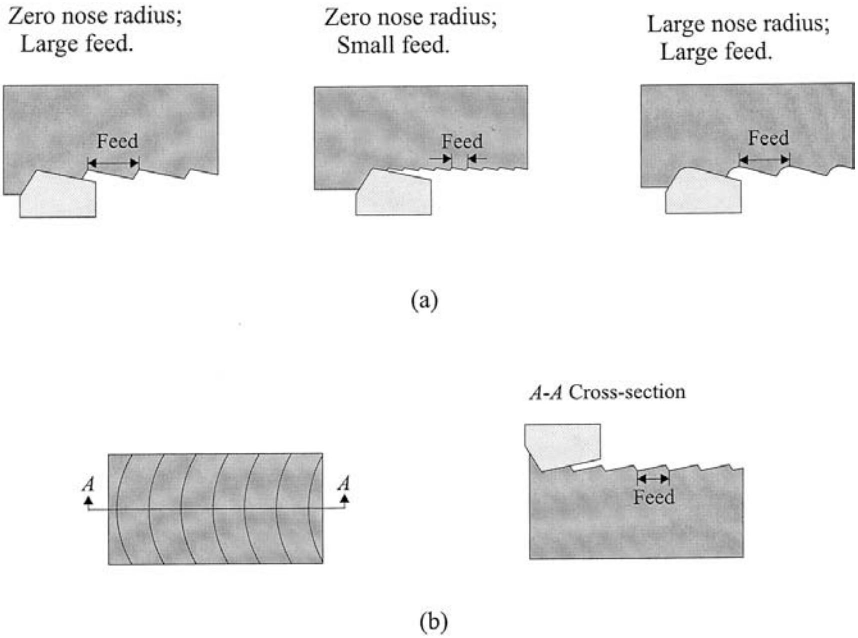


FIGURE 18 Ideal surface finish model for (a) turning and (b) face milling.

tool/workpiece motions, workpiece material inhomogeneuity, and tool wear. Surface roughness is almost impossible to model analytically because of these factors. Engineers would have to rely on past empirical data and additional run-time measurements to adjust the process parameters to reduce surface roughness to an acceptable level. The following guidelines can be used in this endeavor: increasing cutting velocity (to reduce BUE) and reducing feed rate—note that the former may cause chatter and the latter reduce productivity; increasing the tool nose radius and decreasing the cutting edge angle, as much as chatter would allow; and, in milling, tilting the spindle slightly in order to prevent contact between the tool and the already machined part of the workpiece behind the cut.

Surface integrity must also be considered as a measure of surface finish in machining. Residual tensile stresses are very common in machined surfaces due to severe temperature gradients that develop during metal cutting. Such stresses lead to microstructure damage (microcracks) and reduce the fatigue strength of the workpiece. Residual stresses can be reduced by utilizing a variety of surface treatment methods that yield high compressive residual stresses and a smooth surface and thus increased fatigue life. Shot peening, where the workpiece surface is bombarded with cast steel, glass, or ceramic balls of diameter up to 5 mm, is such a technique. Other similar techniques include laser peening and water jet peening.

8.4 ABRASIVE CUTTING

Abrasive cutting processes are primarily utilized as postmachining operations for improving surface quality in terms of reducing roughness. They may, however, add on further residual stresses and occasionally lead to surface burning at high cutting rates, especially in grinding. Thus care has to be exercised in the use of abrasive cutting tools even though they have been around for several millennia (dating back to the use of abrasive stones for the sharpening of hunting tools).

The most common abrasive cutting processes are grinding, honing, lapping, superfinishing, and polishing. All these processes use bonded hard, sharp, and friable abrasive grains for the removal of very thin layers of metals. Although grinding is the most versatile technique, it also yields the worst surface finish amongst the abrasive processes:

Grinding: This process utilizes an abrasive wheel for the internal and external machining of cylindrical as well as prismatic workpieces (Fig. 19a).

Honing: This process utilizes a set of abrasive "sticks" (stones) bonded on a mandrel for the (internal) machining of holes (bores) through a rotational motion that is in sync with a vertical reciprocating motion of the mandrel (Fig. 19b). Honing can yield a surface finish that is as twice as good (half the roughness) as one produced by grinding.

Lapping: This process utilizes a loosely bonded abrasive material (abrasive particles suspended in a viscous fluid) placed between the workpiece and a rotating lap tool (following an 8-shaped trajectory in three-dimensional space) (Fig. 19c). Lapping yields a surface finish of excellent quality—commonly utilized for optical lens, bearing surface, and gage surface machining (finishing).

Superfinishing: This process is similar to honing but differs in the high frequency of reciprocation of the tool (up to 1500 strokes per minute) and the shorter strokes (Fig. 19d). The result is a best achievable (mirrorlike) surface finish. Superfinishing can follow other abrasive processes for further refinement of the surface finish.

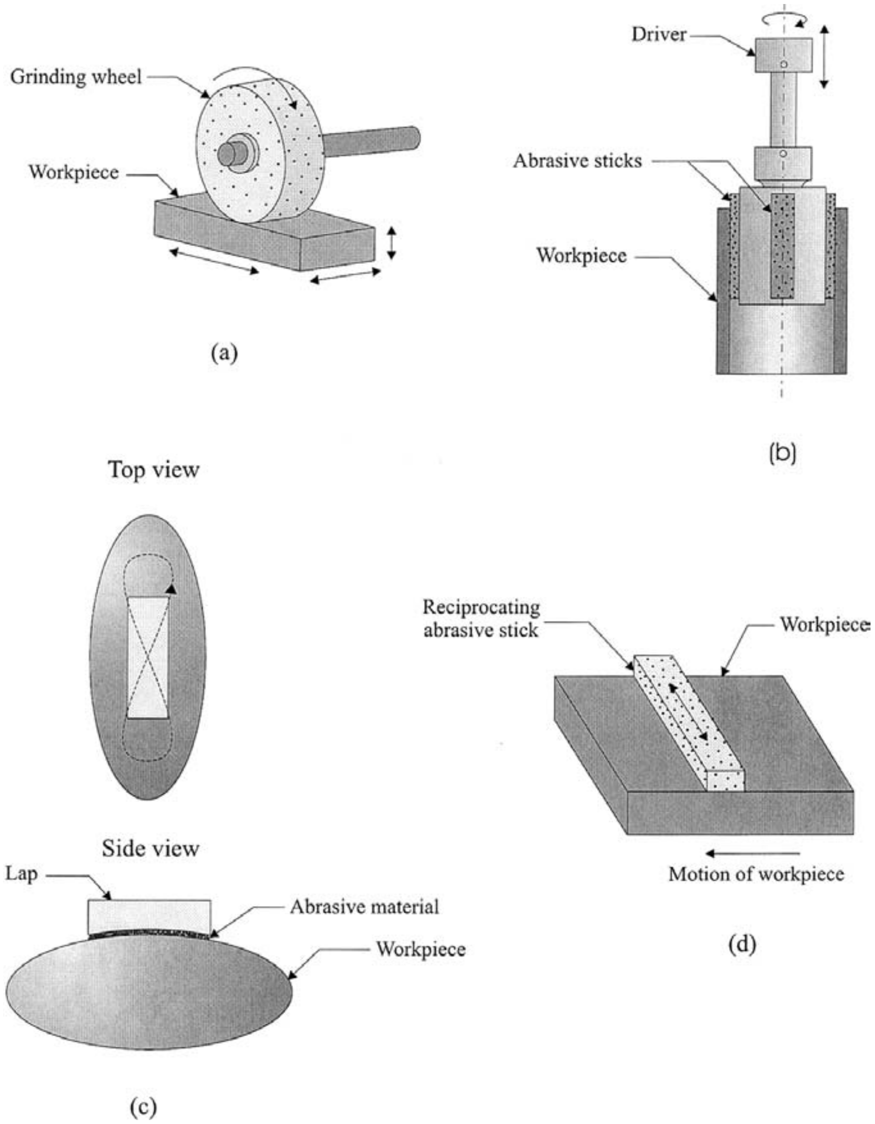


FIGURE 19 (a) Grinding; (b) honing; (c) lapping; (d) superfinishing.

Polishing: This process utilizes a high-speed polishing wheel/disc (made of leather, felt, or even paper): the abrasive grains are glued to the periphery of the wheel, for the removal of fine scratches or burrs.

In this section, only the grinding process will be detailed.

8.4.1 Grinding Operations

The grinding wheel has abrasive grains enveloped in a matrix of bonding material (Fig. 20a). These grains are of irregular shape and randomly dispersed within the matrix. Owing to this random dispersion, three mechanisms of interactions exist between the grains and the workpiece: cutting, plowing, and rubbing. Only cutting causes material removal, while plowing only causes deformation of the surface (Fig. 20b).

The three main types of grinding are

Surface grinding: This process is used for machining flat surfaces. The cutting process parameters, feed rate, cutting velocity, and depth of cut are defined as those for peripheral and face milling (Fig. 21). The table on which the workpiece is placed can translate or rotate in a planar motion with respect to a fixed-axis rotating grinding wheel. The table (i.e., the workpiece) is brought up by an increment equal to the depth of cut once the current pass has been completed (typically achieved by lowering the grinding wheel, as opposed to raising the table).

Cylindrical grinding: This process is used for the internal or external machining of rotational workpieces (Fig. 22). Normally, as in turning and boring, the grinding wheel (i.e., the cutting tool) translates with respect to a fixed-axis rotating workpiece in the feed direction, at a constant depth of cut for the pass at hand.

Centerless grinding: This process is also used for the internal or external machining of rotational workpieces (Fig. 23). In contrast to cylindrical grinding, the workpiece is not held by a chuck, but rotates freely between support rolls and a control wheel for internal grinding, or between a grinding wheel and a control wheel for external grinding. In the former configuration, the control wheel pushes the workpiece toward the internally placed grinding wheel.

The control wheel is tilted at an angle in order to feed the object forward (in the feed direction) (Fig. 23b). A continuous line of parts can be fed into the external grinding system, whereas parts are machined one at a time in internal grinding.

The primary advantage of this process over cylindrical grinding is reduction in setup time.

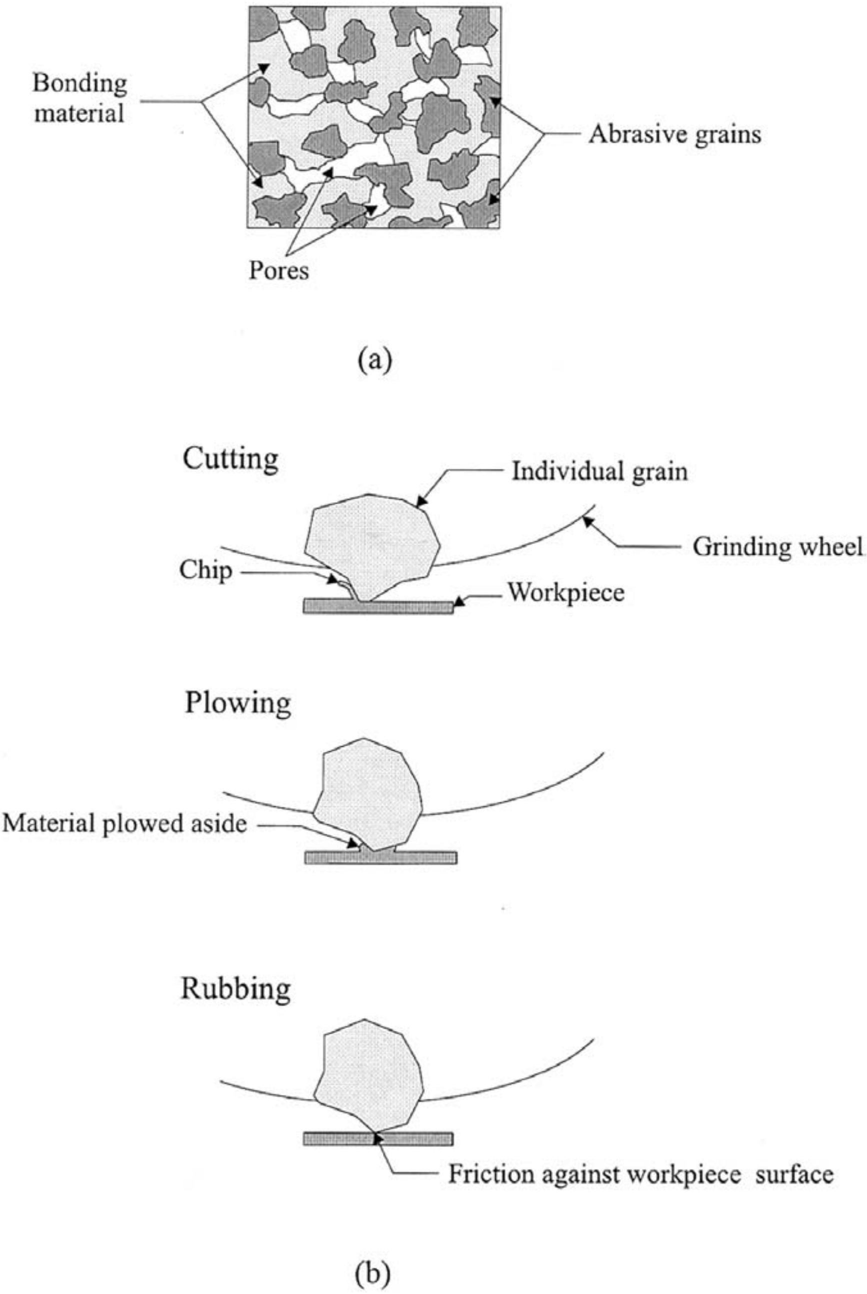


FIGURE 20 (a) Grinding wheel structure; (b) material removal.

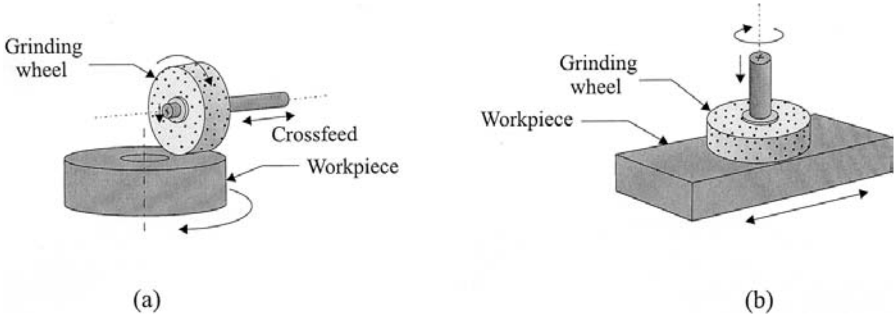


FIGURE 21 Surface grinding with (a) a horizontal spindle; (b) a vertical spindle.

8.4.2 Tool Materials and Tool Wear for Grinding

The grinding wheel has abrasive particles bonded together and formed into a desired shape for the specific grinding application. The abrasive particles are hard, brittle refractory materials that are classified according to their hardness, toughness, and friability (capacity to fracture and yield another cutting edge, in contrast to gradual wear into a dull shape). The hardest of abrasive materials, such as diamond and cBN, are often referred to as superabrasives.

Common abrasives used in grinding wheels include aluminium oxide (Al_20_3) and silicon carbide (SiC). The latter is harder and has much better friability, but it is not as tough as the former. Superabrasives include natural diamond (or graphite-based synthetic) and cBN. Superabrasives are two to four times harder than common abrasives. Synthetic diamonds are more friable than natural diamonds. cBN crystals need to be etched or coated for ease of bonding into a grinding wheel.

Common bonding materials (used as the matrix) in grinding wheel production include vitrified (a mixture of feldspar mineral and clay), silicate

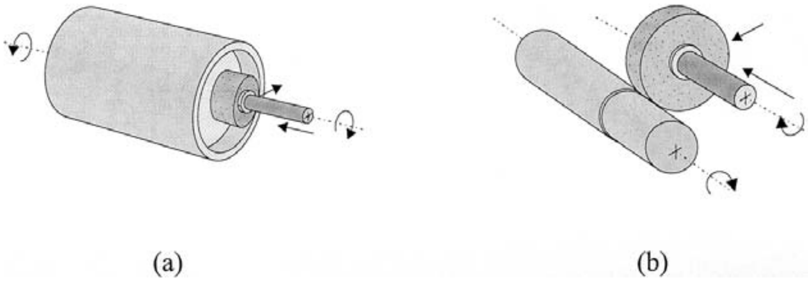


FIGURE 22 Cylindrical (a) internal and (b) external grinding.

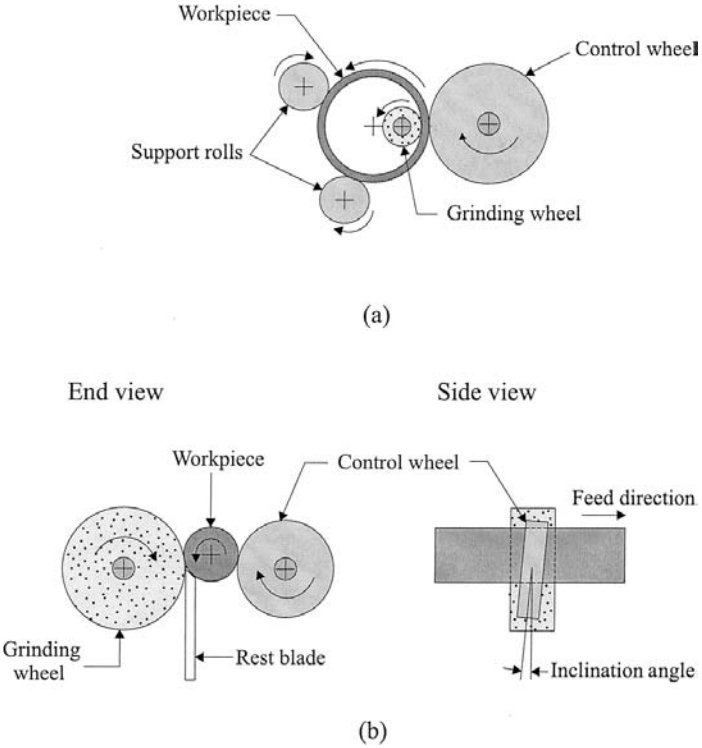


FIGURE 23 Centerless (a) internal and (b) external grinding.

(sodium silicate), shellac, resinoid (thermoset resin), rubber, and metallic (bronze, aluminum, etc.).

Grinding Tool Wear

Grinding occurs at elevated cutting temperatures (up to 1700°C), owing to the high negative rake angles of the particles when forming the chips, and high friction. Besides leading to rapid tool wear, high temperatures can also severely affect the dimensional and surface integrity (i.e., high residual tensile stresses) of the workpiece. As in other machining operations mentioned in this chapter, a variety of cutting fluids can be used in grinding for cooling and lubrication purposes.

The wear of the grinding wheel can be attributed to three common wear mechanisms: attrition wear (dulling of the individual grains), grain fracture wear (the breaking away of parts of the grain, yielding new sharp edges), and bond fracture wear (the dislodging of the grains from the wheel through the fracture of their bonds). The combination of these wear mechanisms yields a wear curve very similar to the three-region wear curve depicted in Fig. 17 for single-point cutting tools: For grinding tools, the *Y*-axis of the tool wear curve represents the volume of wheel wear, and the *X*-axis represents the volume of workpiece material removed.

REVIEW QUESTIONS

1. Machining is considered to be one of the most versatile fabrication processes for parts with complex geometries. What constraints (geometrical, material, batch size, etc.) would make such a manufacturing choice impractical?
2. List four primary issues researched in the past century for the innovation of machining processes.
3. Define continuous versus intermittent machining. Give examples of each.
4. Define depth of cut, feed rate, and cutting velocity in turning.
5. Since boring can be carried out on lathes, why would one use dedicated boring machines?
6. If holes fabricated via drilling were considered unacceptable due to poor dimensional or surface quality reasons, what would you recommend as a remedy? Explain.
7. Define depth of cut, feed rate, and cutting velocity in milling.
8. Define 2.5-, 3-, and 5-axis milling, respectively. Give some part geometry examples.
9. Would you recommend to fabricate (i.e., preshape) the blank to be machined to be as near as possible to the final desired geometry? Explain.
10. Why are through holes preferable to blind holes?
11. Why are holes easier to machine on flat surfaces perpendicular to the tool's motion axis?
12. Define the cutting and thrust forces in turning and milling. How would one measure forces in machining? What is the primary objective of monitoring machining forces?
13. How does chip formation affect surface quality? How can one control the chip formation process?
14. Define the need for cutting fluid use in machining.
15. Define chatter in machining. Explain the two mechanisms that cause chatter.
16. Define crater wear and flank wear. Explain the mechanisms that cause tool wear in machining.

17. Describe the primary machining (i.e., tool–workpiece interaction) mechanisms in grinding.
18. Why would one choose centerless grinding over cylindrical grinding?
19. Describe tool wear in grinding.

DISCUSSION QUESTIONS

1. Material removal techniques, as the name implies, are based on removing material from a given blank for the fabrication of the final geometry of a part. Compare material removal techniques to near–net shape production techniques, such as casting, powder processing, and forming, in the context of product geometry, material properties, and economics in mass-production versus small-batch production environments.
2. The mechanics of material removal operations (single-point and multipoint cutting) has been modeled extensively. Such models, when combined with heat transfer models, can help engineers predict chip formation, surface finish, tool wear, etc. Discuss the utilization of analytical (or heuristics-based) models in off-line process planning as well as in on-line adaptive control that would be based on the utilization of a variety of sensors for force, vibration, and temperature measurements.
3. Woodworking is a topic rarely addressed in manufacturing books since wood is not considered an engineering material. However, even when excluding the pulp-and-paper and construction industries, the large furniture industry is a testimony to the importance of woodworking. Discuss the issues of fabrication and assembly for wood-based products in comparison to metal-based products. Include in your discussion the problem of irregularities, defects, and other features of natural materials that the production engineer has to cope with.
4. When presented with a process planning problem for the machining of a nontrivial part, different (expert) machinists would formulate different process plans. Naturally, only one of these plans is (time or cost) optimal. Considering this and other issues, compare manual (operator-based) machining versus NC-based machining, as enterprises are moving toward integrated and computerized manufacturing. Formulate at least one scenario where manual machining would be favorable.
5. Process planning in machining (in its limited definition) refers to the optimal selection of cutting parameters: number of passes and tool paths for each pass, depths of cut, feed rates, cutting velocities, etc. It has been

often said that computer algorithms should be utilized in the search for the optimal parameter values. Although financially affordable for mass production environments, such (generative) programs may not be feasible for utilization in one-of-a-kind or small-production environments, where manufacturing times may be comparatively very short. Discuss the utilization of group technology (GT)–based process planners in such computation-time-limited production environments.

6. Several fabrication/assembly machines can be physically or virtually brought together to yield a manufacturing workcell for the production of a family of parts. Discuss the advantages of adopting a cellular manufacturing strategy in contrast to having a departmentalized strategy, i.e, having a turning department, a milling department, a grinding department, etc. Among others, an important issue to consider the transportation of parts (individually or in batches).
7. Machining centers increase the automation/flexibility levels of machine tools by allowing the automatic change of cutting tools via turrets or tool magazines and carry out a variety of material removal operations. Some machining centers also allow the off-line fixturing of workpieces onto standard pallets, which would minimize the on-line setup time (i.e., reduce the downtime of the machine). That is, while the machine is working on one part fixtured on Pallet 1, the next part can be fixtured on Pallet 2 and loaded onto the machine when it is has finished operating on the first part. Discuss the use of such universal machining centers versus the use of single-tool, single-pallet, unipurpose machine tools.

BIBLIOGRAPHY

Armarego, E. J. A., Brown, R. H. (1969). *The Machining of Metals*. Englewood Cliffs, NJ: Prentice-Hall.

Benhabib, B. (1982). Flank Wear of Carbide Tools in the First Period. M.Sc. thesis, Faculty of Mechanical Engineering, Technion, Haifa, Israel.

Ber, A., Friedman, M. Y. (1967). On the mechanism of flank wear in carbide tools. *CIRP Annals* 15:211–216.

Boothroyd, Geoffrey G., Knight, Winston A. (1989). *Fundamentals of Machining and Machine Tools*. New York: Marcel Dekker.

Childs, Thomas, et al (2000). *Metal Machining: Theory and Applications*. London: Arnold.

Cocquilhat, M. (1851). Expérience sur la résistance utile produites dans le forage. *Annales des Travaux Publics en Belgique* 10:199.

DeGarmo, E. Paul, Black, J. T., & Kohser, Ronald A. (1997). *Materials and Processes in Manufacturing*. Upper Saddle River, NJ: Prentice Hall.

DeVries, Warren R. (1992). *Analysis of Material Removal Processes*. New York: Springer-Verlag.

Doyle, Lawrence E., et al (1985). *Manufacturing Processes and Materials for Engineers*. Englewood Cliffs, NJ: Prentice-Hall.

Drozda, Thomas J., Charles, Wick (eds.) (1998). *Tool and Manufacturing Engineers Handbook*. Dearborn, MI: Society of Manufacturing Engineers.

Ernst, Hans, et al (1938). *Machining of Metals*. Cleveland, OH: American Society of Metals.

Ernst, H. (1938). Physics of metal cutting. *Machining of Metals*. Cleveland, OH: American Society of Metals.

Fenton, R. G., Oxley, P. L. B. (1969). Mechanics of orthogonal machining: allowing for the effects of strain rate and temperature on tool-chip friction. *Proceedings of the Institute of Mechanical Engineering* 178:417–438.

Fermer, Hugh (1995). *Machine Tools: A History 1540–1986*. Amberley, England: Amberley Museum.

Groover, Mikell P. (1996). *Fundamentals of Modern Manufacturing: Materials, Processes, and Systems*. Upper Saddle River, NJ: Prentice Hall.

Hine, Charles R. (1970). *Machine Tools and Processes for Engineers*. New York: McGraw-Hill.

Jahanmir, Said, Ramulu, M., & Koshy, Philip (1999). *Machining of Ceramics and Composites*. New York: Marcel Dekker.

Joessel, Philip (1864). Experiments on the most favorable form of tool in workshops from the point of view of economy of power. *Annuaire de la Société des Anciens Élèves des Écoles Impériales d'Arts et Métiers* 16.

Kalpakjian, Serope, Schmid, Steven R. (2000). *Manufacturing Engineering and Technology*. Upper Saddle River, NJ: Prentice Hall.

Kronenberg, M. (1943). Cutting angle relationship on metal cutting tools. *Mechanical Engineering* 65:901.

Kronenberg, M. (1966). *Machining Science and Applications*. Oxford: Pergamon Press.

Malkin, Stephen (1989). *Grinding Technology: Theory and Applications of Machining with Abrasives*. New York: John Wiley.

Merchant, M. E. (1944). Basic mechanics of the metal cutting process. *Journal of Applied Mechanics* 15:A-168.

Nee, John G. Ed. (1998). *Fundamentals of Tool Design*. Dearborn, MI: Society of Manufacturing Engineers.

Reuleaux, F. (1900). Über den Taylor Whiteschen Werkzeugstahl. *Verein zur Beförderung des Gewerbefleisses in Preussen, Sitzungsberichte* 79:179.

Schey, John A. (1987). *Introduction to Manufacturing Processes*. New York: McGraw-Hill.

Shaw, M. C. (1984). *Metal Cutting Principles*. Oxford: Oxford University Press.

Shaw, Milton Clayton (1996). *Principles of Abrasive Processing*. Oxford: Oxford University Press.

Stephenson, David A., Agapiou, John S. (1997). *Metal Cutting Theory and Practice*. New York: Marcel Dekker.

Taylor, F. W. (1907). On the art of cutting tools. *Transactions of the American Society of Mechanical Engineers* 28:31–350.

Tlusty, J. (2000). *Manufacturing Processes and Equipment*. Upper Saddle River, NJ: Prentice Hall.

Walsh, Ronald A. (1994). *Machining and Metalworking Handbook*. New York: McGraw-Hill.