# 15

# *Machinability*

## 15.1 Introduction

The term machinability refers to the ease with which a metal can be machined to an acceptable surface finish. Materials with good machinability require little power to remove material, achieve cutting at high speed, easily obtain a good finish, and do not cause tool wear. The factors that typically improve a material's performance often degrade its machinability. Therefore, to machine parts economically, engineers are challenged to find ways to improve machinability without harming performance. Machinability can be difficult to predict because machining has so many variables.

## 15.2 Conventional Machining

It is a term that has been suggested for the first time in the 1920s to describe the machining properties of workpiece materials. Since that time, it is frequently used but seldom fully explained, as it has a variety of interpretations depending upon the viewpoint of the person using it. In its broadest interpretation, a material of good machinability requires lower power consumption, with high tool life and achieving a good surface finish without damage. Accordingly, the machinability is not a material characteristic. It is also more or less related to the selected machining process. A material that is machinable by a certain process may not be machinable by another process. Moreover, a particular machining process found suitable under given conditions may not be equally efficient for machining the same material under other conditions.

### 15.2.1 Judging Machinability

The methods used to judge machinability of a material (Figure 15.1) are as follows:

1. *Tool life:* Metals that can be cut without rapid tool wear are generally thought to be machinable, and vice versa. A workpiece material having small hard inclusions may appear to have the same mechanical properties of a less abrasive metal. It requires the same power consumption during cutting. The machinability of this material would be lower because of its abrasive properties that are responsible for rapid tool wear. One problem arising from the use of tool life as a machinability index is its sensitivity to tool material.
2. *Surface finish:* The quality of the surface left on the workpiece during a machining operation is sometimes useful in determining the machinability rating of a material. The fundamental reason for surface roughness generation is the formation of the built-up edge (BUE) on the tool. In this regard, soft, ductile materials tend to form a BUE rather easily. Stainless steels, gas turbine alloy, and other metals with high strain-hardening ability also tend to machine with BUEs indicating poor machinability. Materials, which machine with high shear angles, tend to minimize BUE effects. These include the aluminum alloys, cold-worked steels, free-machining steels, and brass and titanium alloys of high machinability. In many cases, surface finish is a meaningless criterion of judging workpiece machinability. In roughing cuts, for example, no attention to surface finish is required. In many finishing cuts, the conditions producing the desired dimension on the part will inherently provide a good finish. Machinability ratings based on surface finish measurements do not always agree with those obtained by cutting force, cutting power, and tool life

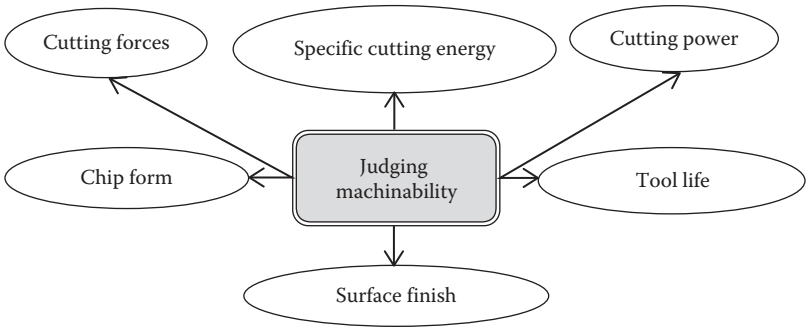


**FIGURE 15.1**
Judging machinability.

method. In this respect, stainless steels have a low rating by any of these standards, while aluminum alloys would be rated high. Titanium alloys would have a high rating by finish measurements, low by tool life tests, and intermediate by cutting force and power measurements.

3. *Cutting forces and power consumption:* The use of cutting forces or power consumption as a criterion of machinability of the workpiece material implies that a metal through which the cutting forces are low has a good machinability rating. The use of net power consumption during machining as an index of the machinability is similar to the use of cutting force. Machinability ratings could be presented in terms of specific energy that describes the power consumed to cut a certain volume in a unit time. Workpiece materials having a high specific energy of metal removal are said to be less machinable than those with a lower specific energy. One advantage of using specific energy of metal removal as an indication of machinability is that it is mainly a property of the workpiece material itself and is quite insensitive to tool material. By contrast, tool life is strongly dependent on tool material.

   The metal removal factor is the reciprocal of the specific energy and can be used directly as a machinability rating if forces or power consumption are used to define machinability. That is, metals with a high metal removal factor could be said to have high machinability.

   The relative importance of these three factors depends mainly on whether the machining is roughing or finishing. In actual production, tool life for rough cuts and surface finish for finish cuts are generally considered to be the most important criteria of machinability (Table 15.1).

4. *Chip form:* An additional machinability criterion sometimes to be highly considered is the chip disposal criterion. Long thin curled ribbon chips, unless being broken up with chip breakers, can interfere with the operation leading to hazardous cutting area. This criterion is of vital importance in automatic machine tool operation. Chip formation, friction at the tool/chip interface, and BUE phenomenon

**TABLE 15.1**

Relative Importance of Machinability Criterion in Roughing and Finishing

| Order of Machinability Criterion | Rough Cut | Finish Cut |
|---|---|---|
| 1 | Tool life | Surface finish |
| 2 | Power consumption | Tool life |
| 3 | Surface finish | Power consumption |

are determinant to machinability. A ductile material that has a tendency to adhere to the tool face or to form BUE is likely to produce a poor finish. This has been observed to be true with such materials as low-carbon steel, pure aluminum, Cu, and stainless steel. However, chip formation is a function of the machine variables as well as the workpiece material, and the ratings obtained by this method could be changed by provision of a suitable chip breaker.

### 15.2.2 Relative Machinability

When machining of a new material, it is essential to use the right cutting parameters like tool material, cutting speed, and feed rate and the right machine tool. Knowing how difficult or easy it is to machine when compared to a familiar material like free-cutting steel provides the machinability rating of the material. Since there is no unit of machinability, it is usually assessed by comparing one material against another, one of which is taken as a reference. Free-cutting steel (AISI B1112) is a steel with a chemical composition having carbon 0.08%–0.13%, manganese 0.60%–0.90%, phosphorous 0.09%–0.13%, and sulfur 0.16%–0.23% and having a hardness of 160 BHN as a reference material of a machinability rating/index of 1.0. Accordingly, a material having an index less than 1 is more difficult to machine in comparison with B1112 material. If the index is more than 1, it is comparatively easier to machine that material.

For roughing operations, the tool life is taken as a yardstick for ranking materials machinability. In this case, the machinability of the reference material can be expressed in terms of cutting speed $V_{60}$ for a tool life $T$ = 60 min for a given tool material. The machinability of any other material is determined in the same way. The relative machinability $R_m$ of a material (Figure 15.2) is therefore

$$R_m = \frac{V_{60} \text{ of the material}}{V_{60} \text{ of reference material}}$$

Table 15.2 lists the relative machinability of some common ferrous and nonferrous alloys in a descending order. The problem associated here is that if different tool materials are used to assess relative machinability, different ratings may occur. Thus, tables and data supplied should be used as guidelines.

### 15.2.3 Factors Affecting Machinability

Mechanical and physical properties play a role in the magnitude of energy consumption and temperatures generated during cutting. These include the following:

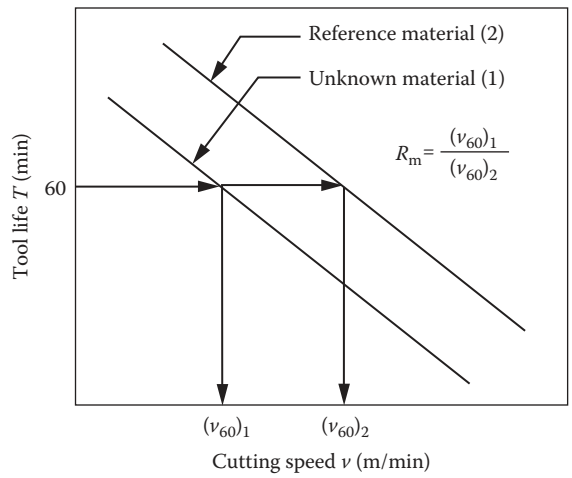


**FIGURE 15.2**
Relative machinability $R_m$ as determined by cutting speed for a tool life $T$ = 60 min.

**TABLE 15.2**
Relative Machinability Rating for Different Materials

| Machinability Rating | Materials |
|---|---|
| Excellent rating | Mg alloys, Al alloys, duralumin |
| Good rating | Zn alloys, gunmetal, gray CI, brass, free-cutting steel |
| Fair rating | Low-carbon steel, cast Cu, annealed Ni, low-alloy steel |
| Poor rating | Ingot iron, free-cutting 18-8 stainless steel |
| Very poor rating | HSS, 18-8 stainless steel, Monel metal |
| Not machinable | White CI, Stellite, carbides, ceramics |

#### *15.2.3.1 Condition of Work Material*

The following factors describe the condition of the work material that affects machinability (Figure 15.3):

1. *Microstructure:* The microstructure refers to material crystal or grain structure. Metals of similar microstructures have like machining properties. Variations in the microstructure of the same workpiece material will affect its machinability.
2. *Grain size:* Grain size serves as a general indicator of its machinability. A metal with small undistorted grains tends to cut and finish easily. Metals of an intermediate grain size represent a compromise that permits both cutting and good surface finish.
3. *Heat treatment:* A material may be heat-treated to reduce brittleness, remove stress, obtain ductility or toughness, increase strength, and

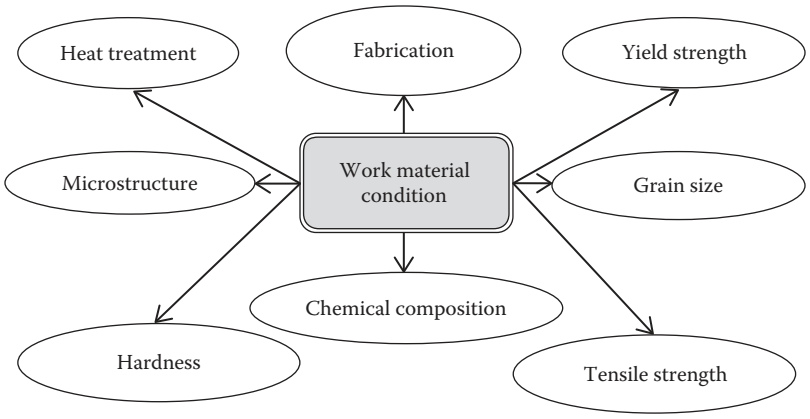


**FIGURE 15.3**
Various conditions of work material that affect machinability.

obtain a definite microstructure; to change hardness; or to make other changes that directly affect machinability.

4. *Chemical composition:* Chemical composition is a major factor in determining material machinability. The effect of composition depends on how the elements make up an alloy. Certain generalizations about chemical composition of steels in relation to machinability can be made, but nonferrous alloys are too numerous so that such generalizations are not valid.
5. *Fabrication:* Whether a metal has been hot rolled, cold rolled, cold drawn, cast, or forged, it will affect its grain size, ductility, strength, hardness, structure— and therefore—its machinability.
6. *Hardness:* The hardness of a metal is correlated to its grain size and it is generally used as an indicator of a material machinability. A harder material is thought to be less machinable.
7. *Yield strength:* The high yield strength of the material gives an indication to poor machinability due to the rise of the specific cutting energy and, hence, cutting forces and power consumption.
8. *Tensile strength:* Higher tensile strength gives a sign to the difficulty of machining and, hence, a poor machinability.

#### *15.2.3.2 Physical Properties of Work Materials*

Physical properties include the modulus of elasticity, thermal conductivity, thermal expansion, and work hardening (Figure 15.4):

1. *Modulus of elasticity:* The modulus of elasticity is a fixed material property that is used as an indicator of the rate at which a material

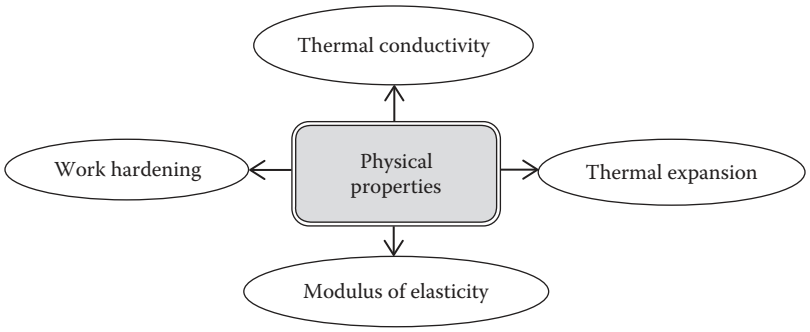


**FIGURE 15.4**
Physical properties of work material that affect machinability.

deflects when subjected to an external force. The higher the value, the lower the machinability of the material will be.

2. *Thermal conductivity:* Conductors tend to transfer heat from a hot/cold object at a high rate. Thermal conductivity is a measure of how efficiently a material transfers heat. In this respect, Ti is not machinable, partly because of the high temperature generated due to its poor thermal conductivity and partly because of its tendency to adhere to the cutting tool forming a BUE.
3. *Thermal expansion:* The rate at which metal expands is determined using the expansion coefficient. The greater the coefficient, the more a material will expand when subjected to a temperature rise. Materials having larger coefficient have poor machinability caused by the difficulty of controlling part dimensions during machining.
4. *Work hardening:* Many metals exhibit a physical characteristic that produces dramatic increases in hardness due to cold work. As the metal is cut, internal stresses develop that act to harden the part. The rate and magnitude of this internal hardening varies widely from one material to another. Heat generated during machining also plays an important role in the work hardening of a material. The higher the rate of work hardening during machining, the lower the machinability index will be.

#### *15.2.3.3 Machining Parameters*

Depending on the machinability of a material, one has to choose other cutting parameters to get the best results in machining a component to the required finish, production rate, and cost of machining (Figure 15.5):

1. *Tool material:* The lower the machinability rating of a material, the harder and tougher the tool material must be. The choice of

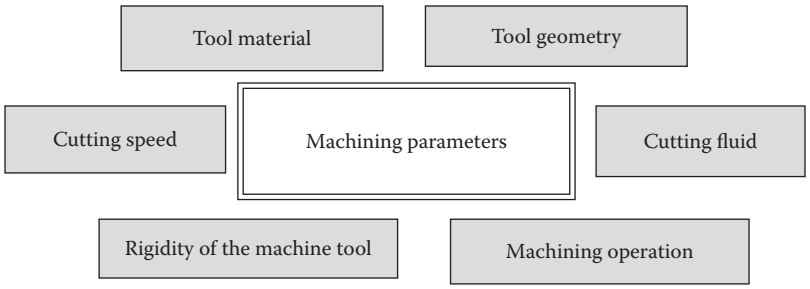


**FIGURE 15.5**
Cutting parameters affecting machinability.

appropriate cemented carbide grade and/or the type of coated carbide tools, CBN, and ceramic is recommended as the material to be cut is tougher.

2. *Tool geometry:* The choice of the cutting tool rake angle and the proper design of chip breaker are also to be considered, based on the machinability of the material.
3. *Cutting speed:* The cutting speed must be properly balanced with the tool material and the work material's machinability rating, in order to achieve the best possible tool life. High cutting speeds produce a poor surface finish, a rapid tool wear, and a loss of control and maintaining dimensions.
4. *Rigidity of machine tool:* The use of old machine tools with limited power may act as a hindrance in machining materials leading to a low machinability rating. The need for switching over to computer numerical control (CNC)-machine tools equipped with linear motion guides and ball screw drives with large spindle power may be warranted in case of machining very tough materials to very close tolerances and surface finish requirements.
5. *Cutting fluids:* The application of cutting fluids cools the tool and workpiece. It provides lubrication between the tool and workpiece and the chip and tool, which in turn reduces the frictional forces and consumed power. It avoids the formation of the BUE. Under these conditions, the material machinability in terms of surface roughness, cutting power, and tool life is enhanced.

### 15.2.4 Machinability of Engineering Materials

Due to the aforementioned described complex aspects of machinability, it is really difficult to establish quantitative relationship to evaluate the machinability of a material. For this reason, it is advisable to refer to machining recommendations that are based on extensive testing, practical experience,

data collected in manufacturing manuals, and specialized handbooks. In this section, brief guidelines concerning the machinability of various metals and nonmetallic materials are presented.

#### *15.2.4.1 Machinability of Steels and Alloy Steels*

In iron and steel, the presence of sulfur (up to 0.35%) helps in the breaking of chips and helps in improving machinability. Lead acts as a lubricant at the tool tip and facilitates ease of machining. The presence of nitrogen is also desirable. Phosphorus is yet another element whose presence improves machinability. Steels are the most important engineering material. Their machinability is affected considerably by the addition of alloying elements. The presence of Al and Si in steels is always harmful, because these elements react with $O_2$ and form aluminum oxide and silicates. These compounds are hard and abrasive, thus increasing tool wear and reducing machinability.

Carbon and manganese have various effects on the machinability of steels, depending on their composition. As the carbon content increases, machinability decreases; however, plain low-carbon steels (less than 0.15% C) can produce poor surface finish by forming a BUE. Tool and die steels are difficult to machine and usually require annealing prior to machining. Machinability of most steels is generally improved by cold working and has reduced the tendency for BUE formation. Other alloying elements such as Ni, Cr, Mo, and V improve the properties of steels and reduce their machinability. The role of gaseous element such as $O_2$, $H_2$, and $N_2$ has not been clearly established; however, any effect that they may have would depend on the presence and amount of other alloying elements. The machinability of two types of steels of special interest will be treated. These are free-machining steels and stainless steels:

1. *Free-machining steels:* Vast quantities of steels are machined and efforts are directed at improving their machinability mainly by adding lead (leaded steels), sulfur (sulfurized steels), and phosphorus (phosphorized steels) to obtain the so-called free-machining steels. These additions produce films of low shear strength and thus reduce the friction in the secondary shear zone at the tool–chip interface.
   a. *Leaded steels:* Lead is added to molten steels and takes the form of dispersed fine lead particles. Lead is insoluble in iron, copper, aluminum, and their alloys. Thus, during cutting, lead particles are sheared and smeared over the tool–chip interface, acting as a solid lubricant. It is also believed that lead probably lowers the shear stress in the primary shear zone, thus reducing the cutting forces and power consumption. Because of environmental concerns, the trend now is toward eliminating the use of leaded

steels in favor of bismuth and tin (lead-free steels). Leaded steels are identified by the letter L between the second and third numerals of AISI identification system, e.g., 10L45.

b. *Resulfurized and rephosphorized steels:* Increased sulfur content (resulfurized steels) forms MnS inclusions of controlled, globular shape, which act as stress raisers in the primary shear zone. As a result, the chips produced are small and break up easily, thus improving machinability. An undesirable consequence is reduced ductility and fatigue strength and slightly reduced tensile strength. Sulfur can severely reduce the machinability of steels because of the presence of iron sulfide, unless sufficient Mn is present to prevent the formation of iron sulfide. Phosphorus in steels also improves machinability by increasing their hardness. Rephosphorized steels are significantly less ductile than rephosphorized steels.

c. *Calcium-deoxidized steels:* In these steels, flakes of calcium aluminosilicate (CaO, $SiO_2$, and $Al_2O_3$) are formed; thereby, the crater wear of cutting tools, especially at high cutting speeds, can be reduced without impairing the mechanical properties of such steels.

2. *Stainless steels:* The higher strength and lower thermal conductivity of stainless steel result in higher cutting temperatures. The high strain-hardening rate of austenitic stainless steels (AISI 300 series) makes them more difficult to machine. Chatter could be a problem, which necessitates the use of rigid machine tools with high stiffness and damping capacity; however, ferritic stainless steels (also AISI 300 series) have good machinability. Martensitic steels (AISI 400 series) are abrasive, tend to form BUE, and require tool material with high hot hardness and resistant to crater wear. Precipitation hardening stainless steels are strong and abrasive and thus require hard, abrasion-resistant tool materials. When machining stainless steels, cutting fluids containing EP compounds must be used. If necessary, free-machining properties can be imparted using alloying elements such as sulfur, phosphorus, selenium, tellurium, lead, and bismuth. These grades have significantly lower corrosion resistance and they are particularly prone to pitting corrosion attack.

Some general rules for machining stainless steels are

- The machine tools must be sturdy, of sufficient power, and free from vibration.
- The cutting edge must be kept sharp all the time. Dull tools cause glazing and work hardening of the machined surface.

- Sharpening should be performed using suitable fixtures, and free-hand sharpening should be avoided.
- Depth of cuts should be substantial enough to prevent the tool from riding the work surface—a condition that promotes work hardening.
- Tools should be as large as possible to enhance heat dissipation.
- Tools of sufficient clearance angle and having chip breakers should be used.
- Proper coolants and lubricant are essential. They must be used in sufficient quantities and directed so as to flood the tool and workpiece.

#### *15.2.4.2 Machinability of Cast Irons*

The presence of primary cementite makes white cast irons very difficult to machine. Chill zones in castings reduce machinability and cause tool chipping or fracture, thus requiring tools with high toughness. Gray cast irons are basically free machining because the graphite lamella breaks up the chips. However, the machined surface is rough because graphite particles break out. Refining graphite particles improves the finish without impairing the free-machining properties. Gray cast irons are often cut dry, because fine chips clog filters. Nodular and malleable cast irons are ductile and stronger; however, they are machinable and can give surprisingly a longer tool life.

#### *15.2.4.3 Machinability of Nonferrous Metals and Alloys*

The machinability of some important nonferrous metals and alloys is briefly presented:

1. *Mg and Mg alloys:* The low ductility of Mg imparts free-machining properties, making Mg a highly machinable material and providing good surface finish and prolonged tool life. Very thin chips ignite spontaneously (pyrophoric) and, therefore, with chip thicknesses below 25 μm, are always done with oil-based cutting fluids. Mg–Al alloys form a BUE.
2. *Zn alloys:* Because of their low strength and low ductility, they are highly machinable.
3. Beryllium (Be) is highly machinable; machining is performed dry. Fine particles are toxic; hence, it requires machining in a controlled environment.
4. *Al and Al alloys:* Al is generally easy to machine; however, the softer grades tend to form BUE. High cutting speeds, high rake, and clearance angles are highly recommended. Wrought alloys with high Si

content and cast Al alloys may be abrasive, and hence they must be cut by harder tool materials such as PCBN or PCD tools. Dimensional control may be a problem in machining Al, because of its low elastic modulus and relatively high thermal expansion. High-speed steel (HSS) tools can be used provided that a cutting fluid is applied in a flood. Very high cutting speed (up to 4200 m/min) is possible with carbides and PCD. SiC cannot be used because of the solubility of Si in Al. Free-machining properties may be imparted by the addition of lead, bismuth, or tin.

5. *Co-base alloys:* They are abrasive and highly work hardening; they require sharp and abrasion-resistant tool materials and low feeds and speeds.
6. *Cu and Cu-base alloys:* Pure Cu is difficult to machine because of BUE formation, although cast Cu alloys are easy to machine. Like pure Al, pure Cu is best machined in the cold-worked condition.

Brasses (Cu–Zn alloys) are easy to machine, especially those to which lead has been added (free-machining brasses). Lead is being replaced in applications where contact with food is possible. Bronzes (Cu–Sb alloys) are more difficult to machine than brasses.

7. *Ni-base alloys:* They are abrasive, work hardening, and strong at high temperatures. Their machinability is similar to that of stainless steels. Their machining should be performed in the annealed or overaged condition. Sulfur must be avoided in cutting fluids because it forms a low melting eutectic with Ni.
8. *Molybdenum:* It is ductile and work hardening; hence, it can produce poor surface finish; thereby, sharp tools must be used.
9. *Tantalum:* It is very work hardening, ductile, and soft; hence, it produces poor surface finish, and tool wear is high.
10. *Ti and Ti alloys:* They have poor thermal conductivity (the lowest of metals), thus causing significant temperature rise and BUE; hence, it is difficult to machine. At low speeds, HSS tools are used with a heavily compounded oil or emulsion. At higher speeds (30–60 m/min), cemented carbides or cermets are preferred. Heavier feeds are preferred because frictional heat is reduced and more heat is taken away in the chip.
11. *Tungsten:* It is brittle, strong, and very abrasive; hence, it has low machinability. Its machinability improves continuously if machining is performed at elevated temperatures.
12. *Zirconium:* It is machinable; however, a coolant-type cutting fluid is a must to avoid the danger of explosion and fire.

#### *15.2.4.4 Machinability of Nonmetallic Materials*

The machinability of some selected nonmetallic materials using traditional machining processes is outlined as follows:

1. *Graphite:* It is abrasive, so it requires hard, abrasion-resistant sharp tools.
2. *Polymers:* They may be thermoplastics or thermosets.
   - Thermoplastics have generally low thermal conductivity, low modulus of elasticity, and low softening temperature. Their machining requires tools of positive rake and large relief angles to reduce the cutting forces. They also require small depth of cut and feed, relatively high speed, and proper support of the workpieces, because of the lack of stiffness. Tools should be sharp. External cooling of the cutting zone is necessary to keep the chips from becoming gummy and sticking to the tool. Cooling can usually be done with an air jet, vapor mist, or emulsion. To relieve developed residual stresses, machined parts should be annealed at temperature ranging from 80°C to 160°C.
   - Thermosets are brittle and sensitive to thermal gradients during cutting; however, their machinability is similar to that of thermoplastics.
   - Reinforced plastics are very abrasive and difficult to machine. Fiber tearing and pulling is a problem. Machining of these materials requires careful removal of debris to avoid human contact with, and inhalation of, fibers.
3. *Fiber-reinforced composites:* They are difficult to machine due to diverse fiber and matrix properties, fiber orientation, inhomogeneity, and nature of material. Glass-, graphite-, and boron-reinforced composites are difficult to machine because of rapid tool wear. Since cemented carbide tools wear rapidly, diamond-impregnated tools may have to be used; however, HSS tools are used in some cases but at the expense of tool durability. A variety of machining operations are performed on this material including drilling, reaming, countersinking, milling, and sawing using diamond-impregnated or diamond-plated tools. Recommended drilling speeds are between 60 and 200 m/min and a feed rate between 0.01 and 0.12 mm/rev. The use of cutting fluids and protecting the machine from the abrasive dust are recommended. To overcome rapid tool wear experienced in traditional machining of composites containing hard abrasive, nontraditional machining operations of noncontact nature such as laser machining, electrodischarge machining (EDM), water jet machining (WJM), and ultrasonic machining (USM) may be used.

4. *Ceramics:* Ceramics are most notable for their high temperature capability, hardness, corrosion resistance, and electrical properties. Machining of ceramics requires the right combination of machine tool, cutting tool, heat management, experience, and design for manufacturability. All abrasive processes such as grinding, honing, lapping, polishing, USM, and abrasive water jet machining (AWJM) are used for finishing and localized shaping of ceramic (including glass) parts. Ceramics that are susceptible to chemical attack can be etched. Creep-feed grinding can be economical for developing shapes from simple preform. Cutting speeds of 45 m/s, depth of cut 3–6 mm, and creep feed 0.25–0.60 can be used.

## 15.3 Nonconventional Machining

In conventional machining, tool life, surface finish, and power consumption determine the machinability of a material. A material may have a good machinability index with one criterion but poor machinability by another or when a different operation is carried out or when the condition of cutting or tool materials is changed. Conditions of such a material that determine machinability are composition, heat treatment, and microstructure. Hardness, tensile strength, and ductility give some indications to the machining properties to be expected, but cannot distinguish between free-cutting steel and austenitic stainless steel having similar mechanical properties. Nonconventional machining processes are established to cut more difficult-to-machine materials such as high-strength thermal-resistant alloys, carbides, fiber-reinforced composite materials, Stellites, and ceramic materials. The machinability of materials by conventional methods depends on the material removal mechanism, material properties, and machining conditions. The machinability indices in nonconventional machining processes are based on the following criteria:

- The material removal rate in $mm^3/min$
- Surface roughness produced by the machining process
- The depth of damaged layer occurring in thermal machining processes
- The specific power consumption $kW/mm^3\ min^{-1}$
- The maximum cutting speed in $mm^2/min$
- The tool electrode wear ratio (volume removal rate from the tool/volume removal rate from the workpiece)
- The material removal rate per unit ampere ($mm^3$/min Amp) in case of electrochemical machining (ECM)
- The number of pulses required to remove a certain volume of material in a unit time

1. *USM:* The material removal rate and hence the machinability depend on the brittleness criterion, which is the ratio of shearing to breaking strength of a material. Table 15.3 shows that glass has a higher machinability than that of a metal of similar hardness. Soft materials have lower machinability ratings than the hard and brittle ones.
2. *Electron beam machining (EBM):* In EBM, the number of pulses required in evaporating a particular volume or a mass of a material is taken as a measure of machining rate. Table 15.4 shows the relative machinability index based on cadmium as the best machinable material. The material that requires larger units of pulses is less machinable. A further index utilizes the power required divided by the material removal rate that shows the effectiveness with which the electrical energy is used in the machining process. The relative power consumption required to remove a certain volume per unit time is shown in Table 15.5. An index of one corresponds to the machinability rating of aluminum. Materials having higher index have low machinability rating. As a thermal machining process, material properties such as

**TABLE 15.3**

Relative Machinability Ratings for Some Materials by USM

| Work Material | Relative Removal Rate (%) |
|---|---|
| Glass | 100 |
| Brass | 66 |
| Tungsten | 4.8 |
| Titanium | 4 |
| Steel | 3.9 |
| Chrome steel | 1.4 |

**TABLE 15.4**

Relative Machinability Index and Number of Pulses Required to Erode a Certain Volume for Some Material by EBM

| Work Material | Relative Index | Relative Pulses |
|---|---|---|
| Cd | 100 | 1 |
| Zn | 62 | 1.6 |
| Fe | 39 | 2.36 |
| Ti | 34 | 2.9 |
| Ta | 33 | 3 |
| Ni | 32 | 3.12 |
| Cu | 27 | 3.75 |
| W | 33 | 4.5 |

**TABLE 15.5**

Relative Power Consumption for Different Materials Machined by EBM

| Work Material | Relative Index |
|---|---|
| Aluminum | 1 |
| Titanium | 1.5 |
| Iron | 1.8 |
| Molybdenum | 2.3 |
| Tungsten | 2.8 |

boiling point, melting point, thermal conductivity, and specific heat play a decisive role on the machinability of materials by EBM.

3. *Laser Beam Machining (LBM):* In LBM, the workpiece material is removed through several effects including reflection, absorption, and conduction of light that is followed by melting and evaporation. The behavior of the work material with respect to these effects determines the material machinability. Reflectivity depends on the wavelength, the properties of materials, surface finish, the amount to which it is oxidized, and its temperature. At a given wavelength, the higher the reflectivity of a material, the lower is the machinability. In this respect, metals have a lower machinability compared to nonmetallic materials. Materials of low thermal conductivity, diffusivity, and melting point have higher machinability rating. Figure 15.6 shows the relative machinability index for a wide range of materials. An index of 100 is taken for Ti.6Al.6V.2Sn that cuts at

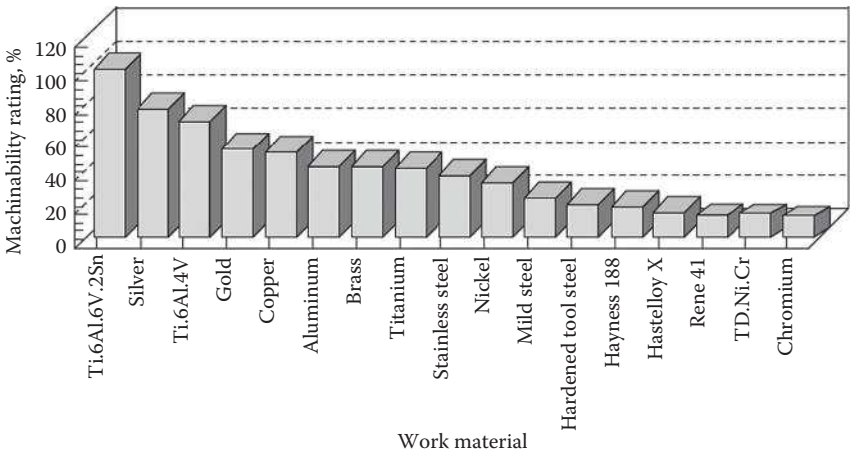


**FIGURE 15.6**
Machinability of some materials in LBM.

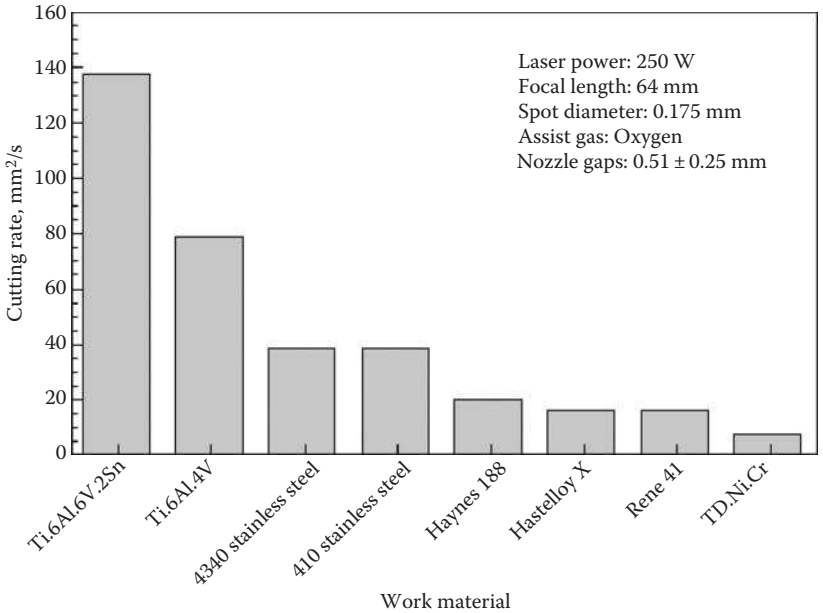


**FIGURE 15.7**
Machining speeds of aerospace alloys in gas-assisted LBM.

the highest speed of 1138 $mm^2/s$. Figure 15.7 shows the machining speeds of some aerospace alloys in gas assisted LBM.

4. *Plasma Beam Machining (PBM):* The cutting rate and, hence, the material machinability depend on the workpiece being machined as well as the type of the cutting and shielding gases. The maximum cutting speed as an index of machining by plasma beam is shown in Table 15.6 for dual gas plasma of different materials. Aluminum has the highest machinability index based on the maximum machining

**TABLE 15.6**

Machinability Ratings of Different Materials by Gas-Shielded Plasma

| | Thickness (mm) | | |
|---|---|---|---|
| | **8** | **19** | **38** |
| **Work Material** | **Maximum Speed, m/min** | | |
| Aluminum | 3.65 | 2.0 | 0.62 |
| Stainless steel | 3.25 | 1.4 | 0.42 |
| Carbon steel | 2.8 | 1.0 | 0.40 |

*Other conditions:* $N_2$ gas at 70 cfh, 30 psi.
*Second gas $CO_2$, 210 cfh, 430 psi.*

**TABLE 15.7**

EDM Removal Rate, Machinability Index, and Surface Roughness for Some Materials

| Work Material | Removal Rate $mm^3/min$ | Relative Removal Rate Index% | Surface Roughness Rz, μm |
|---|---|---|---|
| Aluminum | 600 | 100 | 0.75 |
| St. C-Cr | 240 | 40 | 0.65 |
| Copper | 180 | 30 | 0.65 |
| Carbide, 15% Co | 100 | 16.7 | 0.5 |
| Graphite | 90 | 15 | 0.45 |

speed in m/min. The maximum speed and, hence, the machinability index decrease with increasing workpiece thickness.

5. *EDM:* In EDM, the material is removed through successive sparks that caused melting and evaporation of the workpiece and the tool electrode materials. The machinability depends on the workpiece and tool electrode materials, the machining variables including pulse conditions and electrode polarity, and the machining medium. The amount of tool wear, material removal rate, and surface roughness must be considered when assessing the machinability of a material by EDM. Table 15.7 shows the material removal rates and the machinability indices taking aluminum as a reference material. The same table shows that the higher the removal rate, the rougher the machined surface would be. Materials that cause high electrode wear ratio have a low machinability. This ratio is expressed as the ratio of eroded volume from the tool to the workpiece. The low wear ratio indicates a small amount of tool wear accompanied by higher removal rates that reflects the high machinability of a material. Electrode wear ratio is considered whenever machining for high productivity is essential irrespective of the surface roughness and heat-affected depth. A material of low melting point has a high material removal rate and hence a rougher surface with a deeper heat-affected layer. A material is machinable when both surface roughness and damaged layer are kept as small as possible despite machining at low rate of material removal. The use of surface roughness index is recommended during machining of highly finished components with minimum damaged layer.
6. *ECM:* In ECM, the machinability is expressed in terms of the specific removal rates and surface finish. As shown in Table 15.8, the specific removal rate ($mm^3$/min A) describes how effectively the machining current is utilized for material removal from the workpiece. The higher the value, the better is the machinability of a material. Table 15.9 shows the machinability index for some alloys in terms of the linear

**TABLE 15.8**

Machinability Ratings for Some Alloys by ECM

| Work Material | Specific Removal Rate $10^{-3}$ mm$^3$/min A | Relative Index |
|---|---|---|
| 4340 st | 2.18 | 100 |
| 17-4 PH | 2.02 | 92.7 |
| A-286 | 1.92 | 88 |
| M 252 | 1.8 | 82.6 |
| UDIMET 500 | 1.8 | 82.6 |
| RENE 41 | 1.77 | 81.2 |
| UDIMET 700 | 1.77 | 81.2 |
| L 605 | 1.75 | 80.2 |

**TABLE 15.9**

Relative Machinability Index for Different Materials at Constant Current Density

| Work Material | Relative Index |
|---|---|
| Zirconium | 100 |
| Titanium | 92.4 |
| Nickel | 84.7 |
| Aluminum | 84.7 |
| Low-carbon steel | 77 |
| Steel | 69 |
| Stainless steel | 63 |
| Tungsten | 43 |
| Molybdenum | 36.5 |

cutting speed in mm/min at constant current density. It should be mentioned here that a material that is highly machinable in ECM has a good machinability index with respect to surface quality. The exact determination of the machinability indices by ECM becomes difficult since most metals may dissolve at different valences.

7. *Chemical machining (CHM):* In CHM, the machinability of materials is expressed in terms of removal/etch rate; it depends on the solution type, concentration, and temperature. The etch rate and surface quality depend on the chemical and metallurgical uniformity of the workpiece and the uniformity of the solution temperature. Table 15.10 shows the etch rate; the machinability index, based on Ta as the reference material; and the surface roughness for different materials. It is accordingly clear that etching rates are higher for hard materials and are low for softer ones. Generally, the high etch rate is accompanied by a low surface roughness and narrow machining tolerances.

**TABLE 15.10**

Machinability Ratings by CHM

| Material | Etch Rate (μm/min) | Relative Machinability Index | Surface Roughness Ra (μ) |
|---|---|---|---|
| Ta | 39 | 100 | 0.4 |
| Ti | 36 | 92 | 0.5 |
| Ni alloy | 32 | 82 | 0.8 |
| Steels | 28 | 71.7 | 1.0 |
| Columbium | 26 | 66.6 | 1.2 |
| Mo | 10 | 25.6 | 2.4 |
| Aluminum alloy | 6 | 15 | 2.7 |

**TABLE 15.11**

Machinability Measures of Some Nonconventional Methods

| Index | USM | EBM | LBM | PBM | EDM | ECM | CHM |
|---|---|---|---|---|---|---|---|
| Removal rate, $mm^3$/min. | X | | | | | | X |
| Surface roughness, μ | X | | | | X | X | X |
| Damaged layer, μ | | X | X | X | X | | |
| Power consumption, kW/$mm^3$ $min^{-1}$ | X | X | | | X | | |
| Cutting speed, mm/min or $mm^2$/min | | | X | X | | | |
| Electrode wear ratio | | | X | X | X | X | |
| Specific removal rate, $mm^3$/min Amp | | | | | | | |
| Number of pulses | | X | | | | | |

Table 15.11 summarizes the machinability indices for some nonconventional machining processes.

## Review Questions

**15.1** What is meant by machinability?
**15.2** What indices are used for machinability measurement?
**15.3** State the main measures of material machinability.
**15.4** Explain what is meant by the relative machinability.
**15.5** What are the main factors that affect materials machinability?
**15.6** What are the physical properties of work materials that are related to machinability?