7
Design for Machining

7.1 INTRODUCTION
In machining, material is removed from the workpiece until the desired shape is achieved. Clearly, this a wasteful process, and many engineers feel that a main objective should be to design components that do not require machining. Since most manufacturing machines are designed to remove metal by machining, the view that machining should be avoided must be considered impracticable for the immediate future. However, the trend toward the use of “near net shape” processes that conserve material is clearly increasing, and when large-volume production is involved, this approach should be foremost in the designer’s mind.

In this chapter we first introduce the common machining processes. Then we consider the ways in which the work material can be readily changed to the desired form by machining, and the ways in which the surfaces of the component are finished. Finally, an introduction to early cost estimating for designers is presented.

All machine tools provide a means of (i) holding a cutting tool or abrasive wheel, (ii) holding a workpiece, and (iii) providing relative motion between them in order to generate the required surfaces.

7.2 MACHINING USING SINGLE-POINT CUTTING TOOLS
Lathes are designed to rotate the workpiece and feed the cutting tool in the direction necessary to generate the required machined surface.
The workpiece is gripped in a chuck or collet or is mounted on a faceplate mounted on the end of the main spindle of the machine. The rotation of the workpiece is provided by an electric motor driving the main spindle through a series of gears. Cutting tools can be driven or fed parallel to or normal to the axis of rotation of the workpiece.

Modern lathes are provided with computer control of all workpiece and tool motions. These are known as computer numerical control (CNC) lathes, and the tools can be fed in any direction in the horizontal plane to generate a required contour on the workpiece. Figure 7.1 shows a cylindrical surface being generated in cylindrical turning.

The feed motion setting on the lathe is the distance moved by the tool during each revolution of the workpiece. The feed \( f \) is defined as the displacement of the tool relative to the workpiece, in the direction of feed motion, per stroke or per revolution of the workpiece or tool. Thus, to turn a cylindrical surface of length \( l_w \), the number of revolutions of the workpiece is \( l_w/f \), and the machining time \( t_m \) is given by

\[
t_m = l_w/(fn_w)
\]  
(7.1)

where \( n_w \) is the rotational speed of the workpiece.

It should be emphasized that \( t_m \) is the time for one pass of the tool (one cut) along the workpiece. This single pass does not necessarily mean, however, that the machining operation is completed. If the first cut is designed to remove a large amount of material at high feed (roughing cut), the forces generated during the operation will probably have caused significant deflections in the machine structure. The resulting loss of accuracy may necessitate a further machining operation at low feed (finish cut) to bring the workpiece diameter within the limits specified and to provide a smooth machined surface. For these reasons, the
workpiece is often machined oversize during the roughing cut, leaving a small amount of material that will subsequently be removed during the finishing cut. For very large depths it may be necessary to provide several rough cuts or passes. Figure 7.2 illustrates five typical lathe operations: cylindrical turning, facing, boring, external threading, and cut-off. In each case, the primary motion and the feed motion, together with certain other terms and dimensions, are indicated. In any machining operation the workpiece has three important surfaces:

1. The work surface, the surface on the workpiece to be removed by machining
2. The machined surface, the desired surface produced by the action of the cutting tool
3. The transient surface, the part of the surface formed on the workpiece by the cutting edge and removed during the following cutting stroke, during the following revolution of the tool or workpiece, or, in other cases (e.g., a thread-turning operation), (Fig. 7.2d) during the following pass of the tool.

In Fig. 7.2a, which shows the geometry of a cylindrical-turning operation, the cutting speed at the tool corner is given by \( \pi d_m n_w \), where \( n_w \) is the rotational speed of the workpiece, and \( d_m \) is the diameter of the machined surface. The maximum value of the cutting speed is given by \( \pi d_w n_w \), where \( d_w \) is the diameter of the work surface. Thus, the average, or mean, cutting speed \( v_{av} \) is given by

\[
v_{av} = \frac{\pi d_w (d_w + d_m)}{2}
\]  

(7.2)

FIG. 7.2 Lathe operations: (a) Cylindrical turning, (b) facing, (c) boring, (d) external threading, (e) parting or cut-off. (From Ref. 7.)
FIG. 7.2 Continued
The metal removal rate $Z_w$ is the product of the mean cutting speed and the cross-sectional area of the material being removed $A_c$. Thus

$$Z_w = A_c v_w$$

$$= \pi d_p n_w (d_w + d_m)/2$$

$$= \pi d_p n_w (d_m + a_p)$$

(7.3)

This same result could have been obtained by dividing the total volume of metal removed by the machining time $t_m$.

For a given work material machined under given conditions, the unit power or the energy required to remove a unit volume of material, $p_s$, can be measured. This factor is mainly dependent on the work material, and if its value is known, the power $P_m$ required to perform any machining operation can be obtained from

$$P_m = p_s Z_w$$

(7.4)

Finally, if the overall efficiency of the machine tool motor and drive systems is denoted by $E_m$, the electrical power $P_e$ consumed by the machine tool is given by

$$P_e = P_m / E_m$$

(7.5)

Approximate values of the unit power $p_s$ for various work materials are presented at the end of this chapter.

An operation in which a flat surface is generated by a lathe is shown in Fig. 7.2b and can be performed by feeding the tool in a direction at right angles to the axis of workpiece rotation. This operation is known as facing, and when the rotational speed of the workpiece is constant, the cutting speed at the tool corner varies from a maximum at the beginning of the cut to zero when the tool reaches the center of the workpiece.

The machining time $t_m$ is given by

$$t_m = d_m/(2 fn_w)$$

(7.6)

The maximum cutting speed $v_{\text{max}}$ and the maximum metal removal rate $Z_{w,\text{max}}$ are given by

$$v_{\text{max}} = \pi n_w d_m$$

$$Z_{w,\text{max}} = \pi d_p n_w d_m$$

(7.7)

(7.8)

With modern CNC lathes, the rotational speed of the workpiece can be gradually increased during a facing operation as the tool moves toward the center of the workpiece. In this case the machining time is reduced. However, as the tool approaches the center of the workpiece, the maximum rotational speed of the spindle will be encountered, and machining will then proceed at this maximum speed and, consequently, with diminishing cutting speed.
Figure 7.2c shows an internal cylindrical surface being generated. This operation is termed boring and can only be used to enlarge an existing hole in the workpiece. If the diameter of the work surface is $d_w$ and the diameter of the machined surface is $d_m$, the mean cutting speed is given by Eq. (7.2) and the metal removal rate by

$$Z_w = \pi \alpha_f \mu_w (d_m - a_p) \quad (7.9)$$

Finally, the machining time $t_m$ is given by Eq. (7.1) if $l_w$ is taken as the length of the hole to be bored.

The lathe operation illustrated in Fig. 7.2d is known as external threading, or single-point screw cutting. The combined motions of the tool and workpiece generate a helix on the workpiece and are obtained by setting the relationship between rotational speed and tool feed to give the required pitch of the machined threads. The machining of a thread necessitates several passes of the tool along the workpiece, each pass removing a thin layer of metal from one side of the thread. The feed is applied in increments, after each pass of the tool, in a direction parallel to the machined surface. In calculating the production time, allowance must be included for the time taken to return the tool to the beginning of the cut, to increment the feed, and to engage the feed drive.

The last lathe operation to be illustrated (Fig. 7.2e) is used when the finished workpiece is to be separated from the bar of material. It is known as a cut-off operation and produces two machined surfaces simultaneously. As with a facing operation at constant rotational speed, the cutting speed and hence the metal removal rate varies from a maximum at the beginning of the cut to zero at the center of the workpiece. The machining time is given by Eq. (7.6) and the maximum metal removal rate by Eq. (7.8). Again, with modern CNC lathes, the rotational speed of the workpiece can be controlled to give constant cutting speed until the limiting rotational speed is reached.

Multispindle automatic lathes are used for high volume or mass production of small components machined from work material in bar form. The various motions of these lathes are controlled by specially machined cams, and the operations are completely automatic, including the feeding of the workpiece through the hollow spindles.

The vertical-boring machine operates on the same principle as a lathe, but it has a vertical axis and is used for large components. Like the lathe, this machine rotates the workpiece and applies continuous, linear feed motion to the tool.

Another machine that uses single-point tools and has a rotary primary motion is a horizontal-boring machine. This machine is needed mostly for heavy, noncylindrical workpieces in which an internal cylindrical surface is to be machined. In general, the words “horizontal” or “vertical” used when describing a machine tool refer to the orientation of the machine spindle that provides
primary motion (main spindle). Thus, in the horizontal borer, the main spindle is horizontal.

The principal feature of the horizontal-boring machine is that the workpiece remains stationary during machining, and all the generating motions are applied to the tool. The most common machining process is boring and is shown in Fig. 7.3. Boring is achieved by rotating the tool, which is mounted on a boring bar connected to the spindle, and then feeding the spindle, boring bar, and tool along the axis of rotation. A facing operation can be carried out by using a special toolholder (Fig. 7.4) that feeds the tool radially as it rotates. The equations developed earlier for the machining time, and the metal removal rate in boring and facing also apply to this machine.

The planer is suitable for generating flat surfaces on very large parts. With this machine a linear primary motion is applied to the workpiece and the tool is fed at right angles to this motion (Fig. 7.5). The primary motion is normally accomplished by a rack-and-pinion drive using a variable-speed motor, and the feed motion is intermittent. The machining time \( t_m \) and metal removal rate \( Z_w \) can be estimated as follows:

\[
t_m = \frac{b_w}{(f n_t)}
\]

(7.10)

where \( b_w \) is the width of the surface to be machined, \( n_t \) is the frequency of cutting strokes, and \( f \) is the feed. The metal removal rate \( Z_w \) during cutting is given by

\[
Z_w = f a_p v
\]

(7.11)

where \( v \) is the cutting speed and \( a_p \) is the depth of cut (the depth of the layer of material to be removed).
FIG. 7.4 Facing on a horizontal-boring machine. (From Ref. 7.)

FIG. 7.5 Production of a flat surface on a planer. (From Ref. 7.)
7.3 MACHINING USING MULTIPOINT TOOLS

A drilling machine (or drill press) can perform only those operations in which the tool is rotated and fed along its axis of rotation (Fig. 7.6). The workpiece always remains stationary during the machining process. On small drill presses, the tool is fed by the manual operation of a lever (known as sensitive drilling). The most common operation performed on this machine is drilling with a twist drill to generate an internal cylindrical surface. A twist drill has two cutting edges, each of which removes its share of the work material.

The machining time $t_m$ is given by

$$t_m = l_w/(f n_i)$$  \hspace{1cm} (7.12)

where $l_w$ is the length of the hole produced, $f$ is the feed (per revolution), and $n_i$ is the rotational speed of the tool.

The metal removal rate $Z_w$ may be obtained by dividing the volume of material removed during one revolution of the drill by the time for one revolution. Thus

$$Z_w = (\pi/4)f d_i^2 n_i$$  \hspace{1cm} (7.13)

**FIG. 7.6** Drilling on a drill press. (From Ref. 7.)
where \( d_m \) is the diameter of the machined hole. If an existing hole of diameter \( d_w \) is being enlarged, then

\[
Z_w = \frac{\pi}{4} f (d_m^2 - d_w^2) n_i
\] (7.14)

Twist drills are usually considered suitable for machining holes having a length of no more than five times their diameter. Special drills requiring special drilling machines are available for drilling deeper holes.

The workpiece is often held in a vise bolted to the machine worktable. The drilling of a concentric hole in a cylindrical workpiece, however, is often carried out on a lathe.

Several other machining operations can be performed on a drill press, and some of the more common ones are illustrated in Fig. 7.7. The center-drilling operation produces a shallow, conical hole with clearance at the bottom. This center hole can provide a guide for a subsequent drilling operation to prevent the drill point from “wandering” as the hole is started. The reaming operation is intended for finishing a previously drilled hole. The reamer is similar to a drill but has several cutting edges and straight flutes. It is intended to remove a small amount of work material only, but it considerably improves the accuracy and surface finish of a hole. The spot-facing (or counterboring) operation is designed to provide a flat surface around the entrance to a hole; this flat surface can provide a suitable seating for a washer and nut, for example.

**FIG. 7.7** Some drill-press operations. (a) Center drilling, (b) reaming, (c) spot-facing. (From Ref. 7.)
There are two main types of milling machines: horizontal and vertical. In the horizontal-milling machine the milling cutter is mounted on a horizontal arbor (or shaft) driven by the main spindle.

The simplest operation, slab milling, is used to generate a horizontal surface on the workpiece, as shown in Fig. 7.8.

When estimating the machine time $t_m$ in a milling operation, it should be remembered that the distance traveled by the cutter will be larger than the length of the workpiece. This extended distance is illustrated in Fig. 7.9 in which it can be seen that the cutter travel distance is given by $l_w + \sqrt{a_e(d_t - a_e)}$, where $l_w$ is the length of the workpiece, $a_e$ the depth of cut, and $d_t$ the diameter of the cutter. Thus the machining time is given by

$$t_m = \frac{l_w + \sqrt{a_e(d_t - a_e)}}{v_f} \quad (7.15)$$

where $v_f$ is the feed speed of the workpiece.

The metal removal rate $Z_w$ will be equal to the product of the feed speed and the cross-sectional area of the metal removed, measured in the direction of feed motion. Thus, if $a_p$ is equal to the workpiece width,

$$Z_w = a_e a_p v_f \quad (7.16)$$

Figure 7.10 shows some further horizontal-milling operations. In form cutting, the special cutter has cutting edges shaped to form the cross section required on the workpiece. These cutters are generally expensive to manufacture, and form milling is used only when the quantity to be produced is sufficiently large. In slitting, a standard cutter is used to produce a rectangular slot in a workpiece. Similarly in angular milling, a standard cutter machines a triangular slot. The straddle-milling operation shown in the figure is only one of an infinite variety of operations.
operations that can be carried out by mounting more than one cutter on the machine arbor. In this way, combinations of cutters can machine a wide variety of cross-sectional shapes. When cutters are used in combination, the operation is often called gang milling.

A wide variety of operations involving the machining of horizontal, vertical, and inclined surfaces can be performed on a vertical-milling machine. As the name of the machine implies, the spindle is vertical.

A typical face-milling operation, where a horizontal flat surface is being machined, is shown in Fig. 7.11. The cutter employed is known as a face-milling cutter.

In estimating the machine time, allowance should again be made for the additional relative motion between the cutting tool and workpiece. As can be seen in Fig. 7.12, the total motion when the path of the tool axis passes over the workpiece is given by \((l_w + d_t)\), and, therefore, the machining time is given by

\[
t_m = \frac{(l_w + d_t)}{v_f}
\]  

(7.17)

where \(l_w\) is the length of the workpiece, \(d_t\) is the diameter of the cutter, and \(v_f\) is the feed speed of the workpiece.

When the path of the tool axis does not pass over the workpiece,

\[
t_m = \frac{[l_w + 2\sqrt{a_c(d_t - a_c)}]}{v_f}
\]  

(7.18)

where \(a_c\) is the width of the cut in vertical milling.

The metal removal rate \(Z_m\) in both cases is given by Eq. (7.16).

Various vertical-milling machine operations are illustrated in Fig. 7.13.
Another machine using multipoint tools is the broaching machine. In broaching, the machine provides the primary motion (usually hydraulically powered) between the tool and workpiece, and the feed is provided by the staggering of the teeth on the broach, each tooth removing a thin layer of material (Fig. 7.14). Since the machined surface is usually produced during one pass of the tool, the machining time $t_m$ is given by

$$t_m = l/v \tag{7.19}$$
FIG. 7.11  Face milling on a vertical-milling machine. (From Ref. 7.)

FIG. 7.12  Relative motion between the face-milling cutter and the workpiece during machining time. (From Ref. 7.)
where \( l_1 \) is the length of the broach and \( v \) is the cutting speed. The average metal removal rate \( Z_w \) can be estimated by dividing the total volume of metal removed by the machining time.

Broaching is widely used to produce noncircular holes. In these cases the broach can be either pulled or pushed through a circular hole to enlarge the hole to the shape required or to machine a keyway, for example (Fig. 7.15). Broaches must be designed individually for the particular job and are expensive to manufacture. This high cost must be taken into account when comparing broaching to slower, alternative machining methods.
FIG. 7.14  Broaching on a vertical-broaching machine. (From Ref. 7.)

FIG. 7.15  Methods of broaching a hole. (a) Pull broach; (b) Push broach. (From Ref. 7.)
The production of internal and external screw threads can be accomplished by the use of taps and dies. These multipoint tools can be thought of as helical broaches.

In Fig. 7.16, a tap is fed into a prepared hole and rotated at low speed. The relative motion between a selected point on a cutting edge and the workpiece is, therefore, helical; this motion is the primary motion. All the machining is done by the lower end of the tap, where each cutting edge removes a small layer of metal (Fig. 7.16) to form the thread shape; the fully shaped thread on the tap serves to clear away fragments of chips that may collect. A die has the same cutting action as a tap, but is designed to produce an external thread.

Internal threading using taps can be carried out on turret lathes and drill presses. External threading using dies can be carried out on turret lathes and special screw-cutting machines.
Chapter 7

7.4 MACHINING USING ABRASIVE WHEELS

Abrasive wheels (or grinding wheels) are generally cylindrical, disc-shaped, or cup-shaped (Fig. 7.17). The machines on which they are used are called grinding machines, or grinders; they all have a spindle that can be rotated at high speed and on which the grinding wheel is mounted. The spindle is supported by bearings and mounted in a housing; this assembly is called the wheel head. A belt drive from an electric motor provides power for the spindle. The abrasive wheel consists of individual grains of very hard material (usually silicon carbide or aluminum oxide) bonded in the form required.

Abrasive wheels are sometimes used in rough grinding, where material removal is the important factor; more commonly abrasive wheels are used in finishing operations, where the resulting smooth surface finish is the objective.

In the metal-cutting machine tools described earlier, generation of a surface is usually obtained by applying a primary motion to either the tool or workpiece and a feed motion to either the tool or the workpiece. In grinding machines, however, the primary motion is always the rotation of the abrasive wheels, but often two or more generating (feed) motions are applied to the workpiece to produce the desired surface shape.

In horizontal-spindle surface grinding (Fig. 7.18) the principal feed motion is the reciprocation of the worktable on which the work is mounted; this motion is known as the traverse. Further feed motions may be applied either to the wheel head, by moving it down (known as infeed), or to the table, by moving it parallel to the machine spindle (known as cross-feed). In Fig. 7.18 a horizontal surface is being generated on a workpiece by a cross-feed motion. This feed motion, which is intermittent, is usually applied after each stroke or pass of the table. The amount of cross-feed \( f \) may, therefore, be defined as the distance the tool advances across the workpiece between each cutting stroke. The operation is known as traverse grinding.

![Common shapes of abrasive wheels. (a) Cylindrical, (b) disc, (c) cup. (From Ref. 7.)](image)

FIG. 7.17
Figure 7.19 shows the geometries of both traverse grinding and plunge grinding on a horizontal-surface grinder. From Fig. 7.19a, the metal removal rate in traverse grinding is given by

\[ Z_w = f a_p v_{trav} \]  

(7.20)

where \( f \) is the cross-feed per cutting stroke, \( a_p \) is the depth of cut, and \( v_{trav} \) is the traverse speed.

The machining time \( t_m \) is given by

\[ t_m = b_w / (2 f n_t) \]  

(7.21)

where \( n_t \) is the frequency of reciprocation and \( b_w \) is the width of the workpiece.

In a similar way, for the plunge-grinding operation (Fig. 7.19b), the metal removal rate is given by Eq. (7.20).

Before estimating the machining time in the plunge-grinding operation, it is necessary to describe a phenomenon known as “sparking-out.” In any grinding operation where the wheel is fed in a direction normal to the work surface (infeed), the feed \( f' \), which is the depth of the layer of material removed during one cutting stroke, will initially be less than the nominal feed setting on the machine. This feed differential results from the deflection of the machine tool elements and workpiece under the forces generated during the operation. Thus, on completion of the theoretical number of cutting strokes required, some work material will still have to be removed. The operation of removing this material, called sparking-out, is achieved by continuing the cutting strokes with no further application of feed until metal removal becomes insignificant (no further sparks.
FIG. 7.19 Horizontal-spindle surface-grinding operations. (a) Traverse grinding; (b) plunge grinding. (From Ref. 7.)

appear). If the time for sparking-out is denoted by $t_s$, the machining time in plunge grinding is given by

$$t_m = \frac{a_t}{2/n_t} + t_s \quad (7.22)$$

where $a_t$ is the total depth of work material to be removed.

In vertical-spindle surface grinding (Fig. 7.20) a cup-shaped abrasive wheel performs an operation similar to face milling. The worktable is reciprocated and the tool fed intermittently downward; these motions are known as traverse and infeed, respectively. A horizontal surface is generated on the workpiece, and because of the deflection of the machine structure, the feed $f$ will initially be less
than the feed setting on the machine tool. This means that sparking-out is necessary, as in plunge grinding on a horizontal-spindle machine.

The metal removal rate is given by

\[ Z_w = f a_p v_{trav} \]  (7.23)

where \( a_p \) is equal to the width of the workpiece and \( v_{trav} \) is the traverse speed.

The machining time is given, as in plunge grinding on a horizontal-spindle machine, by Eq. (7.22).

Larger vertical-spindle surface grinders are available with rotary worktables on which several workpieces can be mounted. The machining time per part for this type of grinder is given by

\[ t_m = \left( \frac{n_w}{f n_w} + t_6 \right) / n \]  (7.24)

where \( n_w \) is the rotational speed of the worktable and \( n \) is the number of workpieces mounted on the machine.

In cylindrical grinding (Fig. 7.21) the workpiece is supported and rotated between centers. The headstock provides the low-speed rotational drive to the workpiece and is mounted, together with the tailstock, on a worktable that is reciprocated horizontally using a hydraulic drive. The grinding-wheel spindle is horizontal and parallel to the axis of workpiece rotation, and horizontal, hydraulic feed can be applied to the wheel head in a direction normal to the axis of workpiece rotation; this motion is known as infeed.

Figure 7.21 shows a cylindrical surface being generated using the traverse motion—an operation that can be likened to cylindrical turning, where the single-
point cutting tool is replaced by a grinding wheel. In fact, grinding attachments are available that allow this operation to be performed on a lathe.

The geometries of traverse and plunge grinding on a cylindrical grinder are shown in Fig. 7.22. In traverse grinding, the maximum metal removal rate is closely given by:

$$Z_{w_{\text{max}}} = \pi f d w v_{\text{trav}}$$

(7.25)

where $d_w$ is the diameter of work surface, $v_{\text{trav}}$ is the traverse speed, and $f$ is the feed per stroke of the machine table (usually extremely small compared to $d_w$). The machining time will be given by Eq. (7.22).
In the plunge-grinding operation shown in Fig. 7.22b, the wheel is fed into the workpiece, without traverse motion applied, to form a groove. If \( t_f \) is the feed speed of the grinding wheel, \( d_w \) the diameter of the work surface, and \( a_t \) the width of the grinding wheel, the maximum metal removal rate is given by

\[
Z_{w,\text{max}} = \pi a_t d_w v_f
\]  

(7.26)

and the machining time is

\[
t_m = (a_t/v_f) + t_s
\]  

(7.27)

where \( a_t \) is the total depth of material to be removed and \( t_s \) is the sparking-out time.

In internal grinding (Fig. 7.23), the wheel head supports a horizontal spindle and can be reciprocated (traversed) in a direction parallel to the spindle axis. A small cylindrical grinding wheel is used and is rotated at very high speed. The workpiece is mounted in a chuck or a magnetic faceplate and rotated. Horizontal feed is applied to the wheel head in a direction normal to the wheel spindle; this motion is known as infeed. Again, traverse and plunge grinding can be performed, the geometries of which are shown in Fig. 7.24.

Traverse grinding is shown in Fig. 7.24a, and the maximum removal rate, which occurs at the end of the operation, is given by

\[
Z_{w,\text{max}} = \pi f d_m v_{trav}
\]  

(7.28)
where \( f \) is the feed, \( v_{\text{trav}} \) is the traverse speed, and \( d_m \) is the diameter of the machined surface. The machining time is again given by Eq. (7.22).

Finally, in plunge grinding (Fig. 7.24b) the maximum removal rate is given by

\[
Z_{w,\text{max}} = \pi d_p d_m v_f
\]

and the machining time by Eq. (7.27).

Now that the various machine tools, machining operations, and basic equations for metal removal rate and machining time have been introduced, we can turn our attention to those design factors that affect the cost of machining and to cost estimating for designers.

### 7.5 STANDARDIZATION

Perhaps the first rule in designing for machining is to design using standard components as much as possible. Many small components, such as nuts, washers, bolts, screws, seals, bearings, gears, and sprockets, are manufactured in large quantities and should be employed wherever possible. The cost of these components will be much less than the cost of similar, nonstandard components.

Clearly, the designer will need catalogues of the standard items available; these can be obtained from suppliers. Supplier information is provided in standard trade indexes, where companies are listed under products. However, there is a danger in overemphasizing standardization. Many of the impressive successes brought about by the application of DFMA procedures were only made possible by breaking away from standardization. For example, the IBM “proprinter” was successful mainly because the designers departed from the customary approach to the design of dot-matrix printers. They included a novel new mechanism for
driving the print head; they also introduced new plastic materials for the base and 
departed from the use of standard components for securing important items such 
as the power transformer and drive motors. Taken to extremes, a slavish 
 adherence to company “standards” will prevent innovation in design.

A second rule is, if possible, minimize the amount of machining by preshaping 
the workpiece. Workpieces can sometimes be preshaped by using castings or 
welded assemblies or by metal deformation processes, such as extrusion, deep 
drawing, blanking, or forging. Obviously, the justification for preforming of 
workpieces will depend on the required production quantity. Again standardiza-
tion can play an important part when workpieces are to be preformed. The 
designer may be able to use preformed workpieces designed for a previous 
similar job; because the necessary patterns for castings or the tools and dies for 
metal-forming processes are already available.

Finally, even if standard components or standard preformed workpieces are not 
available, the designer should attempt to standardize on the machined features to 
be incorporated in the design. Standardizing on machined features means that the 
appropriate tools, jigs, and fixtures will be available, which can reduce manu-
facturing costs considerably. Examples of standardized machined features might 
include drilled holes, screw threads, keyways, seatings for bearings, splines, etc. 
Information on standard features can be found in various reference books.

7.6 CHOICE OF WORK MATERIAL

When choosing the material for a component, the designer must consider 
applicability, cost, availability, machinability, and the amount of machining 
required. Each of these factors influences the others, and the final optimum 
choice will generally be a compromise between conflicting requirements. The 
applicability of various materials depends on the component’s eventual function 
and is decided by such factors as strength, resistance to wear, appearance, 
corrosion resistance, etc. These features of the design process are outside the 
scope of this chapter, but once the choice of material for a component has been 
narrowed, the designer must then consider factors that help to minimize the final 
cost of the component. It should not be assumed, for example, that the least 
expensive work material will automatically result in minimum cost for the 
component. For example, it might be more economical to choose a material 
that is less expensive to machine (more machinable) but has a higher purchase 
cost. In a constant cutting-speed, rough-machining operation, the production cost 
$C_{pr}$ per component is given by

$$C_{pr} = M_{t1} + M_{tm} + (M_{ct} + C_t)\frac{h_m}{t}$$

(7.30)
where $M$ is the total machine and operator rate, $t_i$ is the nonproductive time, $t_m$ is the machining time (time the machine tool is operating), $t$ is the tool life (machining time between tool changes), $t_c$ is the tool changing time, $C_i$ is the cost of providing a sharp tool, including the cost of regrinding and/or the depreciation of the insert holder and insert where applicable.

The machining time is given by

$$t_m = \frac{K}{v} \quad (7.31)$$

where $K$ is a constant for the particular operation and $v$ is the cutting speed.

Also, the tool life $t$ is given by Taylor’s tool life equation:

$$vt^n = v_t t_r^n \quad (7.32)$$

where $v_t$ and $t_r$ are the reference cutting speed and tool life, respectively, and $n$ is the Taylor tool life index, which is mainly dependent on the tool material. Usually, for high-speed steel tools $n$ is assumed to be 0.125 and for carbide tools it is assumed to be 0.25.

If Eqs. (7.31) and (7.32) are substituted into Eq. (7.30), and the resulting expression differentiated, it can be shown that the cutting speed $v_c$ for minimum cost is given by

$$v_c = v_t \left(\frac{t_c}{t_r}\right)^n \quad (7.33)$$

where $t_c$ is the tool life for minimum cost and is given by

$$t_c = \left[\frac{(1/n) - 1}{t_m + C_i/M}\right] \quad (7.34)$$

Thus, if Eqs. (7.30) through (7.34) are combined, the minimum cost of production $C_{min}$ is given by

$$C_{min} = M t_i + \frac{MK}{(1-n) v_t} \left(\frac{t_c}{t_r}\right)^n \quad (7.35)$$

The first term in this expression is the cost of the nonproductive time on the machine tool and will not be affected by the work material chosen or by the amount of machining carried out on the workpiece. The second term is the cost of the actual machining operation, and for a given machine and tool design it depends on the values of $n$, $v_t$, $t_r$, and $K$. The factor $n$ depends mainly on the tool material; $v_t t_r^n$ is a measure of the machinability of the material; $K$ is proportional to the amount of machining to be carried out on the workpiece and can be regarded as the distance traveled by the tool cutting edge corner relative to the workpiece during the machining operation. For a given operation on a given machine tool and with a given tool material it is shown in Eq. (7.34) that the tool life for minimum cost would be constant and hence [from Eq. (7.35)] that the machining costs would be inversely proportional to the value of $v_t t_r^n$. Since $v_t$ is
the cutting speed giving a tool life of $t_t$, more readily machined materials have a higher value of $v_t' t_t'$ and hence give a lower machining cost.

Taking, for example, a machining operation using high-speed steel tools ($n = 0.125$) and a low carbon steel workpiece and typical figures of $M = 50.0.00833/s$, $t_l = 300 s$, $t_c = 3000 s$, $K = 183 m$ (600 ft), and $v_t = 0.76 m/s$ (150 ft/min) when $t_t = 60 s$, then from Eq. (7.35) the minimum production cost per component $C_{min}$ is $6.22. If, however, an aluminum workpiece for which a typical value of $v_t$ is 3.05 m/s (600 ft/mm) when $t_t$ is 60 s could be used, the use of aluminum would reduce the production cost to $3.43. In other words, an additional amount equal to the difference between these two costs could be spent for each workpiece in order to employ the more machinable material, i.e., as much as $2.79 additional per workpiece.

Clearly, the designer should try to select work materials that will result in minimum total component cost.

7.7 SHAPE OF WORK MATERIAL

With the exception of workpieces that are to be partially formed before machining, such as forgings, castings, and welded structures, the choice of the shape of the work material depends mainly on availability. Metals are generally sold in plate, sheet, bar, or tube form (Table 7.1) in a wide range of standard sizes.

**TABLE 7.1** Standard Material Shapes and Ranges of Sizes

<table>
<thead>
<tr>
<th>Name</th>
<th>Size</th>
<th>Shape</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plate</td>
<td>6–75 mm</td>
<td>(0.25–3 in.)</td>
</tr>
<tr>
<td></td>
<td>0.1–5 mm</td>
<td>(0.004–0.2 in.)</td>
</tr>
<tr>
<td>Round bar</td>
<td>3–200 mm dia.</td>
<td></td>
</tr>
<tr>
<td>or rod</td>
<td>(0.125–8 in. dia.)</td>
<td></td>
</tr>
<tr>
<td>Hexagonal bar</td>
<td>6–75 mm</td>
<td>(0.25–3 in.)</td>
</tr>
<tr>
<td>Square bar</td>
<td>9–100 mm</td>
<td>(0.375–4 in.)</td>
</tr>
<tr>
<td>Rectangular bar</td>
<td>3 x 12–100 x 150 mm</td>
<td>(0.125 x 0.5–4 x 6 in.)</td>
</tr>
<tr>
<td>Tubing</td>
<td>5 mm dia., 1 mm wall–100 mm dia., 3 mm wall</td>
<td>(0.1875 in. dia., 0.035 in. wall–4 in. dia., 0.125 in. wall)</td>
</tr>
</tbody>
</table>
The designer should check on the standard shapes and sizes from the supplier of raw material and then design components that require minimal machining.

Components manufactured from a circular or hexagonal bar or tube are generally machined on those machine tools that apply a rotary primary motion to the workpiece; these types of components are called rotational components (Fig. 7.25a). The remaining components are manufactured from square or rectangular bar, plate, or sheet and are called nonrotational components (Fig. 7.25b). Components partially formed before machining can also be classified as either rotational or non-rotational components.

Some of the machining techniques used to alter the initial workpiece shape will now be described and will help to illustrate some further design rules for machined components.

7.8 MACHINING BASIC COMPONENT SHAPES

7.8.1 Disc-Shaped Rotational Components ($L/D \leq 0.5$)

Rotational components where the length-to-diameter ratio is less than or equal to 0.5 may be classified as discs. For diameters to approximately 300 mm (12 in.) the workpiece would generally be gripped in a lathe chuck; for larger diameters it would be necessary to clamp the workpiece on the table of a vertical borer. The simplest operations that could be performed would be machining of the exposed face and drilling, boring, and threading a concentric hole. All these operations could be performed on one machine without regripping the workpiece (Fig. 7.26).

The realization that neither the unexposed face nor a portion of the outer cylindrical surface can be machined leads to some general guidelines for design: if possible, design the component so that machining is not necessary on the unexposed surfaces of the workpiece when it is gripped in the work-
holding device. Also, the diameters of the external features should gradually increase, and the diameters of the internal features should gradually decrease from the exposed face.

Of course, with the examples shown in Fig. 7.26 it would probably be necessary to reverse the workpiece in the chuck to machine the opposite face. However, if its diameter were less than about 50 mm (2 in.), the desired surfaces could probably be machined on the end of a piece of bar stock and the component then separated from the bar by a parting or cut-off operation (Fig. 7.27). It should be remembered that when a workpiece must be reversed in the chuck, the concentricity of features will be difficult to maintain (Fig. 7.28).

When machined surfaces intersect to form an edge, the edge is square; when surfaces intersect to form an internal corner, however, the edge is rounded to the
Difficult to maintain concentricity of these surfaces

FIG. 7.28  Machining of components stepped to both ends. (From Ref. 7.)

shape of the tool corner. Thus the designer should always specify radii for internal corners. When the two intersecting faces are to form seatings for another component in the final assembly, the matching corner on the second component should be chamfered to provide clearance (Fig. 7.29). Chamfering ensures proper seating of the two parts and presents little difficulty in the machining operations.

On rotational components some features may be necessary that can only be produced by machine tools other than those that rotate the workpiece. Consequently, the batch of workpieces requiring these features will have to be stacked temporarily and then transferred to another machine tool that may be in another part of the factory. This storage and transfer of workpieces around a factory presents a major organizational problem and adds considerably to the manufacturing costs. Thus, if possible, the components should be designed to be machined on one machine tool only.

FIG. 7.29  Rounded corners and chamfers. (From Ref. 7.)
Plane-machining operations may also be required on a rotational component. Such operations might be carried out on a milling machine. Finally, auxiliary holes (those not concentric with the component axis) and gear teeth may be required. Auxiliary holes would be machined on a drill press and would generally form a pattern as shown in Fig. 7.30. Axial auxiliary holes are usually the easiest to machine, because one of the flat surfaces on the workpiece can be used to orient it on the work-holding surface. Thus, the designer should avoid auxiliary holes inclined to the workpiece axis. Gear teeth would be generated on a special gear-cutting machine, and this process is generally slow and expensive.

7.8.2 Short, Cylindrical Components ($0.5 < L/D < 3$)

The workpieces from which short, cylindrical components are produced would often be in the form of bar stock, and the machined component would be separated from the workpiece by parting or cut-off as was shown in Fig. 7.27. The whole of the outer surface of this type of component can be machined without interference from the jaws of the chuck. However, it is important for the designer to ensure (if possible) that the diameters of a stepped internal bore are gradually decreasing from the exposed end of the workpiece and that no recesses or grooves are required on the surface produced in the parting or cut-off operation (Fig. 7.31).

7.8.3 Long, Cylindrical Rotational Components ($L/D \geq 3$)

Long, cylindrical rotational components would often be supported between centers or gripped at the headstock end by a chuck and supported by a center at the other end. If the $L/D$ ratio is too large, the flexibility of the workpiece creates a problem because of the forces generated during machining. Thus, the
designer should ensure that the workpiece, when supported by the work-holding devices, is sufficiently rigid to withstand the machining forces.

When a rotational component must be supported at both ends for machining of the external surfaces, internal surfaces of any kind cannot be machined at the same time. In any case, with slender components, concentric bores would necessarily have large length-to-diameter ratios and would be difficult to produce. Thus, the designer should try to avoid specifying internal surfaces for rotational components having large $L/D$ ratios.

A common requirement on a long, cylindrical component is a keyway, or slot. A keyway is usually milled on a vertical-milling machine using an end-milling cutter (Fig. 7.32a) or on a horizontal-milling machine using a side- and face-milling cutter (Fig. 7.32b). The shape of the end of the keyway is determined by the shape of the milling cutter used, and the designer, in specifying this shape, is specifying the machining process.

Before the ways of changing basic nonrotational shapes by machining operations are discussed, some general points should be noted regarding undesirable features on rotational components. These undesirable design features can be categorized as follows:

1. Features impossible to machine.
2. Features extremely difficult to machine that require the use of special tools or fixtures.
3. Features expensive to machine even though standard tools can be used.

FIG. 7.31  Machining components from bar stock. (a) Components that can be parted off complete; (b) components that cannot be parted off complete. (From Ref. 7.)
In considering the features of a particular design it should be realized that
1. Surfaces to be machined must be accessible when the workpiece is gripped in the work-holding device.
2. When the surface of workpiece is being machined, the tool and tool-holding device must not interfere with the remaining surfaces on the workpiece.

Figure 7.33a shows an example of a component with external surfaces impossible to machine. This is because during the machining of one of the cylindrical surfaces, the tool would interfere with the other cylindrical surface.

Figure 7.33b shows a component that would be extremely difficult to machine on a lathe because when the hole is drilled, the workpiece would have to be supported in a special holding device. Even if the workpiece were transferred to a drill press for the purpose of drilling the hole (in itself an added expense), a milled preparation would be required (Fig. 7.33c) to prevent the drill from deflecting sideways at the beginning of the drilling operation.

Figure 7.34 shows two examples where the tool or toolholder would interfere with other surfaces on the workpiece. The small radial hole shown in Fig. 7.34a would be difficult to machine because a special long drill would be required. The internal recess shown in the component in Fig. 7.34b could not be machined because it would be impossible to design a cutting tool that would reach through the opening of the bore.

Figure 7.35a shows a screw thread extending to a shoulder. Extending a screw thread to a shoulder would be impossible because when the lathe carriage is
FIG. 7.33 Difficulties arising when nonconcentric cylindrical surfaces are specified. (a) Impossible to machine, (b) difficult to machine, (c) can be machined on a drill press. (From Ref. 7.)

FIG. 7.34 Design features to avoid in rotational parts. (a) Special drill required to machine radial hole, (b) impossible to machine internal recess. (From Ref. 7.)
FIG. 7.35 Machined screw threads on stepped components. (a) Impossible to machine, (b) good design with run-out groove. (From Ref. 7.)

disengaged from the lead screw at the end of each pass, the threading tool generates a circular groove in the workpiece. Thus it is necessary to provide a run-out groove (Fig. 7.35b) so that the threading tool will have clearance and not interfere with the remaining machined surfaces.

7.8.4 Nonrotational Components ($A/B \leq 3, A/C \geq 4$)

Extremely thin, flat components should be avoided because of the difficulty of work holding while machining external surfaces. Many flat components would be machined from plate or sheet stock and would initially require machining of the outer edges. Outer edges would generally be machined on either a vertical- or horizontal-milling machine. Figure 7.36 shows the simplest shapes that can be

FIG. 7.36 Milling external shape of flat components. (a) Vertical milling (plan view), (b) horizontal milling (front view). (From Ref. 7.)
generated on the edge of a flat component. It can be seen that internal corners must have radii no smaller than the radius of the milling cutter used.

In general, the minimum diameter of cutters for horizontal milling (about 50 mm [2 in.] for an average machine) is much larger than the diameter of a cutter for vertical milling (about 12 mm [0.5 in.]). Thus, small internal radii would necessitate vertical milling. However, as can be seen from Fig. 7.36, a flat workpiece that must be machined around the whole periphery is generally clamped to the machine worktable with a spacer beneath the workpiece smaller than the finished component. This means of work holding requires at least two bolt holes to be provided in the workpiece. In horizontal milling the workpiece can be gripped in a vise.

With flat components required in reasonably large batch sizes, manufacturing costs can often be considerably reduced by simultaneous machining of a stack of workpieces.

Sometimes large holes (principal bores) are required in nonrotational components. These principal bores are generally normal to the two large surfaces on the component and require machining by boring. This operation could be performed on a lathe (Fig. 7.37a), where the workpiece would be bolted to a faceplate, or on a vertical borer (Fig. 7.37b), where the workpiece would be bolted to the rotary worktable. For small parts, however, where high accuracy is required, the bores would be machined on a jig borer. A jig borer is similar to a vertical-milling machine, but the spindle is fed vertically and can hold a boring tool (Fig. 7.37c). From these examples it can be seen that where possible, principal bores should be cylindrical and normal to the base of the component. It can also be seen that a spacer is required between the workpiece and the work-holding surface.

The next type of secondary machining operation to be considered is the provision of a series of plane surfaces such as the machining of steps, slots, etc., in one of the large surfaces on the workpiece. If possible, plane-surface machining should be restricted to one surface of the component only, thus avoiding the need for reclamping the workpiece. Plane surfaces might be machined on milling machines, or, in very large workpieces (such as machine beds), on planing machines. Figure 7.38 shows a variety of plane-surface machining operations, and it can be seen that plane-machined surfaces should, if possible, be either parallel or normal to the base of the component. Also, internal radii need not be specified for the milling operations, because the corners of the teeth on milling cutters are usually sharp.

Finally, auxiliary holes might be required in flat components; these would generally be machined on a drill press. Similar requirements to those discussed for the machining of auxiliary holes in disc-shaped rotational components apply. Thus, auxiliary holes should, if possible, be cylindrical and normal to the base of the component and preferably related by a pattern to simplify positioning of the workpiece for drilling.
7.8.5 Long, Nonrotational Components \((A/B > 3)\)

Long, nonrotational components would often be machined from rectangular- or square-section bar stock. Extremely long components should be avoided because of work-holding difficulties. The most common machining operations would be drilling and milling. Machined surfaces parallel to the principal axis of the component should be avoided because of the difficulties of holding down the entire length of the workpiece. Instead, the designer should, if possible, utilize work material preformed to the cross section required.

7.8.6 Cubic, Nonrotational Components \((A/B < 3, A/C < 4)\)

Cubic components should be provided with at least one plane surface that can initially be surface-ground or milled to provide a base for work-holding purposes and a datum for further machining operations.
If possible, the outer machined surfaces of the component should consist of a series of mutually perpendicular plane surfaces parallel to and normal to its base. In this way, after the base has been machined, further machining operations can be carried out on external surfaces with minimal reclamping of the workpiece. Figure 7.39, for example, shows a cubic workpiece where the external exposed surfaces can all be machined on a vertical-milling machine without reclamping. From this figure it can be seen that sharp internal corners parallel to the base can be machined readily but that sharp internal corners normal to the base should be avoided.

The workpiece shown in Fig. 7.39 is blocklike, but others may be hollow or boxlike. Main bores in cubic components will often be machined on a horizontal-boring machine. For ease of machining, internal cylindrical surfaces should be concentric and decrease in diameter from the exposed surface of the workpiece. Also, where possible, blind bores should be avoided because in horizontal boring the boring bar must usually be passed through the workpiece. Internal machined surfaces in a boxlike cubic component should be avoided unless the designer is certain that they will be accessible.

With small cubic components it is possible to machine pockets or internal surfaces using an end-milling cutter as shown in Fig. 7.40. Again it can be seen that internal corners normal to the workpiece base must have a radius no smaller than that of the cutter. Usually, the same cutter will be used to clear out the pocket after machining the outer shape, and the smaller the cutter diameter the longer it...
will take to perform this operation. Consequently, the cost of the operation will be related to the radii of the vertical internal corners. Thus, internal corners normal to the workpiece base should have as large a radius as possible.

Finally, cubic components will often have a series of auxiliary holes. Auxiliary holes should be cylindrical and either normal to or parallel to the base of the

FIG. 7.39 Milling outer surface of a cubic workpiece. (From Ref. 7.)

FIG. 7.40 Milling a pocket in a blocklike cubic workpiece. (From Ref. 7.)
component; they should also be in accessible positions and have $L/D$ ratios that make it possible to machine them with standard drills. In general, standard drills can produce holes having $L/D$ ratios as large as 5.

Figure 7.41a shows examples of features that would be difficult and expensive to produce in nonrotational components. In the first case the internal vertical corners are shown sharp; these features cannot be produced with standard tools. In the second case the through hole has an extremely large $L/D$ ratio and would be difficult to produce even with special deep-hole drilling techniques. Figure 7.41b shows examples of machined features virtually impossible to produce because a suitable tool cannot be designed that would reach all the internal surfaces. Figure 7.42 shows the design of some blind holes. A standard drill produces a hole with a conical blind end, and therefore the machining of a hole with a square blind end requires a special tool. Thus, the end of a blind hole should be conical. If the blind hole is to be provided with a screw thread, the screw thread will be tapped, and the designer should not specify a fully formed thread to the bottom of the blind hole since this type of screw thread is impossible to produce.

Holes that have a dogleg, or bend, should be avoided if possible. A curved hole (Fig. 7.42) is clearly impossible to machine; however, drilling a series of through holes and plugging unwanted outlets can often achieve the desired effect although this operation is expensive.

**FIG. 7.41** Design features to avoid in nonrotational components. (From Ref. 7.)
7.9 ASSEMBLY OF COMPONENTS

Most machined components must eventually be assembled, and the designer should give consideration to the assembly process. Design for ease of assembly is treated in Chapter 3; however, one or two aspects of this subject that affect machining are mentioned here. The first requirement is, of course, that it should be physically possible to assemble the components. Obviously, the screw thread on a bolt or screw should be the same as the mating thread on the screwed hole into which the bolt or screw is to be inserted. Some assembly problems, however, are not quite so obvious. Figure 7.43 shows some impossible assembly situations, and it is left to the reader to decide why the components cannot be assembled properly.

A further requirement is that each operating machined surface on a component should have a corresponding machined surface on the mating component. For example, where flanges on castings are to be bolted together, the area around the bolt holes should be machined perpendicular to the hole (spot-faced, for example) to provide a proper seating for the bolt heads, nuts, or washers. Also, internal corners should not interfere with the external corner on the mating component. Figures 7.29 and 7.35 give examples of how this interference can be avoided. Finally, incorrect specification of tolerances can make assembly difficult or even impossible.

FIG. 7.42 Design of blind holes. (From Ref. 7.)
7.10 ACCURACY AND SURFACE FINISH

A designer will not generally want to specify an accurate surface with a rough finish or an inaccurate surface with a smooth finish. When determining the accuracy and finish of machined surfaces, it is necessary to take into account the function intended for the machined surface. The specification of too-close tolerances or too-smooth surfaces is one of the major ways a designer can add unnecessarily to manufacturing costs. Such specifications could, for example, necessitate a finishing process, such as cylindrical grinding after rough turning, where an adequate accuracy and finish might have been possible using the lathe that performed the rough-turning operation. Thus, the designer should specify the widest tolerances and roughest surface that will give acceptable performance for operating surfaces.

As a guide to the difficulty of machining to within required tolerances it can be stated that

1. Tolerances from 0.127 to 0.25 mm (0.005 to 0.01 in.) are readily obtained.
2. Tolerances from 0.025 to 0.05 mm (0.001 to 0.002 in.) are slightly more difficult to obtain and will increase production costs.
3. Tolerances 0.0127 mm (0.0005 in.) or smaller require good equipment and skilled operators and add significantly to production costs.
Figure 7.44 illustrates the general range of surface finish that can be obtained in different operations. It can be seen that any surface with a specified surface finish of 1 μm (40 μin.) arithmetical mean or better will generally require separate finishing operations, which substantially increases costs. Even when the surface can be finished on the one machine, a smoother surface requirement will mean increased costs.

To illustrate the cost increase as the surface finish is improved, a simple turning operation can be considered. If a tool having a rounded corner is used under ideal cutting conditions, the arithmetical mean surface roughness $R_a$ is related to the feed by

$$R_a = 0.0321 f^2/r_c$$

(7.36)

where $f$ is the feed and $r_c$ is the tool corner radius.

The machining time $t_m$ is inversely proportional to the feed $f$ and related by the equation

$$t_m = L_w/n_w$$

(7.37)

where $L_w$ is the length of the workpiece and $n_w$ is the rotational speed of the workpiece.

**FIG. 7.44** General range of surface roughness obtainable by various machining operations. (From Ref. 7.)
Substitution of $f$ from Eq. (7.36) in (7.37) gives the machining time in terms of the specified surface finish:

$$t_m = \frac{0.18\mu_w}{[n_u(R_0r_e)^{0.5}]}$$

(7.38)

Thus, the machining time (and hence the machining cost) is inversely proportional to the square root of the surface finish. Figure 7.45 shows the relationship between production cost and surface finish for a typical turning operation. It can be seen that the costs rise rapidly when low values of surface finish are specified.

For many applications, a smooth, accurate surface is essential. This smooth, accurate surface can most frequently be provided by finish grinding. When specifying finish grinding, the designer should take into account the accessibility of the surfaces to be ground. In general, surfaces to be finish-ground should be

![Ideal surface roughness, µm](image)

**FIG. 7.45** Effect of specified surface roughness on production costs in a turning operation, where the corner radius $r_e = 0.03$ in. (0.762 mm), the rotational frequency of the workpiece $n_w = 200$ rpm (3.33 s$^{-1}$), and the length of the workpiece $l_w = 34$ in. (864 mm). (From Ref. 7.)
FIG. 7.46 Surfaces that can readily be finish-ground. (a) Surface grinding, (b) cylindrical grinding, (c) internal grinding. (From Ref. 7.)

raised and should never intersect to form internal corners. Figure 7.46 shows the types of surfaces that are most readily finish-ground using standard-shaped abrasive wheels.

7.11 SUMMARY OF DESIGN GUIDELINES

This section lists the various design guidelines that have been introduced, providing a summary of the main points a designer should keep in mind when considering the design of machined components.

*Standardization*

1. Utilize standard components as much as possible.
2. Preshape the workpiece, if appropriate, by casting, forging, welding, etc.
3. Utilize standard pre-shaped workpieces, if possible.
4. Employ standard machined features wherever possible.

Raw Materials
5. Choose raw materials that will result in minimum component cost (including cost of production and cost of raw material).

Component Design
a. General
7. Try to design the component so that it can be machined on one machine tool only.
8. Try to design the component so that machining is not needed on the unexposed surfaces of the workpiece when the component is gripped in the work-holding device.
9. Avoid machined features the company is not equipped to handle.
10. Design the component so that the workpiece, when gripped in the work-holding device, is sufficiently rigid to withstand the machining forces.
11. Verify that when features are to be machined, the tool, toolholder, work, and work-holding device will not interfere with one another.
12. Ensure that auxiliary holes or main bores are cylindrical and have $L/D$ ratios that make it possible to machine them with standard drills or boring tools.
13. Ensure that auxiliary holes are parallel or normal to the workpiece axis or reference surface and related by a drilling pattern.
14. Ensure that the ends of blind holes are conical and that in a tapped blind hole the thread does not continue to the bottom of the hole.
15. Avoid bent holes or dogleg holes.

b. Rotational Components
16. Try to ensure that cylindrical surfaces are concentric, and plane surfaces are normal to the component axis.
17. Try to ensure that the diameters of external features increase from the exposed face of the workpiece.
18. Try to ensure that the diameters of internal features decrease from the exposed face of the workpiece.
19. For internal corners on the component, specify radii equal to the radius of a standard rounded tool corner.
20. Avoid internal features for long components.
21. Avoid components with very large or very small $L/D$ ratios.
c. Nonrotational Components

22. Provide a base for work holding and reference.
23. If possible, ensure that the exposed surfaces of the component consist of a series of mutually perpendicular plane surfaces parallel to and normal to the base.
24. Ensure that internal corners normal to the base have a radius equal to a standard tool radius. Also ensure that for machined pockets, the internal corners normal to the base have as large a radius as possible.
25. If possible, restrict plane-surface machining (slots, grooves, etc.) to one surface of the component.
26. Avoid cylindrical bores in long components.
27. Avoid machined surfaces on long components by using work material preformed to the cross section required.
28. Avoid extremely long or extremely thin components.
29. Ensure that in flat or cubic components, main bores are normal to the base and consist of cylindrical surfaces decreasing in diameter from the exposed face of the workpiece.
30. Avoid blind bores in large cubic components.
31. Avoid internal machined features in cubic boxlike components.

Assembly

32. Ensure that assembly is possible.
33. Ensure that each operating machined surface on a component has a corresponding machined surface on the mating component.
34. Ensure that internal corners do not interfere with a corresponding external corner on the mating component.

Accuracy and Surface Finish

35. Specify the widest tolerances and roughest surface that will give the required performance for operating surfaces.
36. Ensure that surfaces to be finish-ground are raised and never intersect to form internal corners.

7.12 COST ESTIMATING FOR MACHINED COMPONENTS

Designers normally have a reasonable knowledge of the factors to bear in mind when attempting to minimize manufacturing costs for machined components and the previous section listed some design rules that might be followed. Ultimately, however, the designer will need to know the magnitude of the effects of design
decisions on manufacturing costs. The need for a method of estimating these costs is highlighted when considering the design of a product for ease of assembly. Techniques have been available for some time for analyzing an assembly for handling and insertion costs incurred as each part is added, and they are described in Chapter 3. As a result of such analyses, many suggestions for design simplifications arise—often involving the elimination of individual parts or components. However, it is also necessary to have methods for quickly estimating the cost of these parts and the cost of tooling so that the total savings in products costs can be quantified.

Before embarking on a discussion of how an estimating method for designers of machined components might be developed, we should consider how the requirements for such a method differ from conventional cost-estimating procedures. These conventional procedures are meant to be applied after the component has been designed and its production planned. Thus, every step in production is known and can be estimated with a high degree of accuracy. During the early stages of design, however, the designer will not wish to specify, for example, all the work-holding devices and tools that might be needed; most likely, detailed design will not yet have taken place. Indeed, a final decision on the specific work material might not have been made at this stage. Thus, what is wanted is an approximate method requiring the minimum of information from the designer and assuming that the ultimate design will avoid unnecessary manufacturing expense and the component will be manufactured under reasonably economic conditions.

Perhaps the simplest approach would be to have the designer specify the shape and size of the original workpiece and the quantity of material to be removed by machining. Then, with data on typical material costs per unit weight, an estimate can be made of the cost of the material needed to manufacture the component. If an approximate figure is available for the average cost of removal of each cubic inch of the material by machining, an estimate can also be made of the machining cost.

Unfortunately, this very simple approach will not take adequate account of the nonproductive costs involved in a series of machining operations. For example, if 1 in$^3$ of material were to be removed in one pass by a simple turning operation, the nonproductive costs would be quite small—the component would only need to be loaded into the lathe and unloaded once and the cutting tool would only be set and the feed engaged once. Compare this with 1 in$^3$ of the same material removed by a combination of turning, screw cutting, milling, and drilling. In this case the nonproductive costs accumulate and become a highly significant factor in the ultimate cost of the machined component; especially when the machined component is relatively small.

What is needed is a method that forms a compromise between this oversimplified approach and the traditional detailed cost-estimating methods used by manufacturing and industrial engineers.
TABLE 7.2  Approximate Costs in Dollars per Pound for Various Metals (to convert to dollars per kilogram multiply by 2.2)

<table>
<thead>
<tr>
<th>Density</th>
<th>lb/in³</th>
<th>Mg/m³</th>
<th>Bar</th>
<th>Rod</th>
<th>Sheet &lt; 0.5 in.</th>
<th>Plate &gt; 0.5 in.</th>
<th>Tube</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ferrous</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbon steel</td>
<td>0.283</td>
<td>7.83</td>
<td>0.51</td>
<td>0.51</td>
<td>0.36</td>
<td>0.42</td>
<td>0.92</td>
</tr>
<tr>
<td>Alloy steel</td>
<td>0.31</td>
<td>8.58</td>
<td>0.75</td>
<td>0.75</td>
<td>1.20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stainless steel</td>
<td>0.283</td>
<td>7.83</td>
<td>1.50</td>
<td>1.50</td>
<td>2.50</td>
<td>2.50</td>
<td></td>
</tr>
<tr>
<td>Tool steel</td>
<td>0.283</td>
<td>7.83</td>
<td>6.44</td>
<td>6.44</td>
<td>—</td>
<td>6.44</td>
<td></td>
</tr>
<tr>
<td>Nonferrous</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aluminum alloys</td>
<td>0.10</td>
<td>2.77</td>
<td>1.93</td>
<td>1.93</td>
<td>1.95</td>
<td>2.50</td>
<td>4.60</td>
</tr>
<tr>
<td>Brass</td>
<td>0.31</td>
<td>8.58</td>
<td>0.90</td>
<td>1.22</td>
<td>1.90</td>
<td>1.90</td>
<td>1.90</td>
</tr>
<tr>
<td>Nickel alloys</td>
<td>0.30</td>
<td>8.30</td>
<td>5.70</td>
<td>5.70</td>
<td>5.70</td>
<td>5.70</td>
<td></td>
</tr>
<tr>
<td>Magnesium alloys</td>
<td>0.066</td>
<td>1.83</td>
<td>3.35</td>
<td>3.35</td>
<td>6.06</td>
<td>6.06</td>
<td>3.35</td>
</tr>
<tr>
<td>Zinc alloys</td>
<td>0.23</td>
<td>6.37</td>
<td>1.50</td>
<td>1.50</td>
<td>1.50</td>
<td>1.50</td>
<td></td>
</tr>
<tr>
<td>Titanium alloys</td>
<td>0.163</td>
<td>4.51</td>
<td>15.40</td>
<td>15.40</td>
<td>25.00</td>
<td>25.00</td>
<td></td>
</tr>
</tbody>
</table>

7.12.1 Material Cost

Often, the most important factor in the total cost of a machined component is the cost of the original workpiece. This material cost will frequently form more than 50% of the total cost and, therefore, should be estimated with reasonable care. Table 7.2 gives densities and approximate costs in dollars per pound for a variety of materials in the basic shapes normally available. Provided the designer can specify the volume of material required for the original workpiece, the material cost can easily be estimated. Although the figures in Table 7.2 can be used as a rough guide, the designer would be able to obtain more accurate figures from material suppliers.

7.12.2 Machine Loading and Unloading

Nonproductive costs are incurred every time the workpiece is loaded into (and subsequently unloaded from) a machine tool. An exhaustive study of loading and unloading times has been made by Fridriksson [1]; he found that these times can be estimated quite accurately for a particular machine tool and work-holding device if the weight of the workpiece is known. Some of Fridriksson’s results are presented in Table 7.3, which can be used to estimate machine loading and unloading times. To these figures must be added the times for turning coolant on and off, cleaning the work-holding or clamping device, etc.
TABLE 7.3 Loading and Unloading Times (s) Versus Workpiece Weight

<table>
<thead>
<tr>
<th>Holding device</th>
<th>0-0.2</th>
<th>0.2-4.5</th>
<th>4.5-14</th>
<th>14-27 (kg)</th>
<th>30-60 (lb)</th>
<th>Crane</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angle plate (2 U-clamps)</td>
<td>27.6</td>
<td>34.9</td>
<td>43.5</td>
<td>71.2</td>
<td>276.5</td>
<td></td>
</tr>
<tr>
<td>Between centers, no dog</td>
<td>13.5</td>
<td>18.6</td>
<td>24.1</td>
<td>35.3</td>
<td>73.1</td>
<td></td>
</tr>
<tr>
<td>Between centers, with dog</td>
<td>25.6</td>
<td>40.2</td>
<td>57.4</td>
<td>97.8</td>
<td>247.8</td>
<td></td>
</tr>
<tr>
<td>Chuck, universal (4 jaws)</td>
<td>16.0</td>
<td>23.3</td>
<td>31.9</td>
<td>52.9</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>Chuck, independent (4 jaws)</td>
<td>34.0</td>
<td>41.3</td>
<td>49.9</td>
<td>70.9</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>Clamp on table (3 clamps)</td>
<td>28.8</td>
<td>33.9</td>
<td>39.4</td>
<td>58.7</td>
<td>264.6</td>
<td></td>
</tr>
<tr>
<td>Collet</td>
<td>10.3</td>
<td>15.4</td>
<td>20.9</td>
<td>—</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>Faceplate (3 clamps)</td>
<td>31.9</td>
<td>43.3</td>
<td>58.0</td>
<td>82.1</td>
<td>196.2</td>
<td></td>
</tr>
<tr>
<td>Fixture, horizontal (3 screws)</td>
<td>25.8</td>
<td>33.1</td>
<td>41.7</td>
<td>69.4</td>
<td>274.7</td>
<td></td>
</tr>
<tr>
<td>Fixture, vertical (3 screws)</td>
<td>27.2</td>
<td>38.6</td>
<td>53.3</td>
<td>—</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>Hand-held</td>
<td>1.4</td>
<td>6.5</td>
<td>12.0</td>
<td>—</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>Jig</td>
<td>25.8</td>
<td>33.1</td>
<td>41.7</td>
<td>—</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>Magnet table</td>
<td>2.6</td>
<td>5.2</td>
<td>8.4</td>
<td>—</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>Parallels</td>
<td>14.2</td>
<td>19.3</td>
<td>24.8</td>
<td>67.0</td>
<td>354.3</td>
<td></td>
</tr>
<tr>
<td>Rotary table or index plate (3 clamps)</td>
<td>28.8</td>
<td>36.1</td>
<td>44.7</td>
<td>72.4</td>
<td>277.7</td>
<td></td>
</tr>
<tr>
<td>&quot;V&quot; Blocks</td>
<td>25.0</td>
<td>30.1</td>
<td>35.6</td>
<td>77.8</td>
<td>365.1</td>
<td></td>
</tr>
<tr>
<td>Vise</td>
<td>13.5</td>
<td>18.6</td>
<td>24.1</td>
<td>39.6</td>
<td>174.2</td>
<td></td>
</tr>
</tbody>
</table>

Source: After Ref. 1.

7.12.3 Other Nonproductive Costs

For every pass, cut, or operation carried out on one machine tool, further nonproductive costs are incurred. In each case the tool must be positioned, perhaps the feed and speed settings changed, the feed engaged, and then, when the operation is completed, the tool must be withdrawn. If different tools are employed, then the times for tool engagement or indexing must also be taken into
TABLE 7.4  Some Nonproductive Times for Common Machine Tools

<table>
<thead>
<tr>
<th>Machine tool</th>
<th>Time to engage tool; etc.</th>
<th>Basic setup time (h)</th>
<th>Additional setup per tool (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal band saw</td>
<td>—</td>
<td>0.17</td>
<td>—</td>
</tr>
<tr>
<td>Manual turret lathe</td>
<td>9</td>
<td>1.2</td>
<td>0.2</td>
</tr>
<tr>
<td>CNC turret lathe</td>
<td>1.5</td>
<td>0.5</td>
<td>0.15</td>
</tr>
<tr>
<td>Milling machine</td>
<td>30</td>
<td>1.5</td>
<td>—</td>
</tr>
<tr>
<td>Drilling machine</td>
<td>9</td>
<td>1.0</td>
<td>—</td>
</tr>
<tr>
<td>Horizontal-boring machine</td>
<td>30</td>
<td>1.3</td>
<td>—</td>
</tr>
<tr>
<td>Broaching machine</td>
<td>13</td>
<td>0.6</td>
<td>—</td>
</tr>
<tr>
<td>Gear hobbing machine</td>
<td>39</td>
<td>0.9</td>
<td>—</td>
</tr>
<tr>
<td>Grinding machine</td>
<td>19</td>
<td>0.6</td>
<td>—</td>
</tr>
<tr>
<td>Internal grinding machine</td>
<td>24</td>
<td>0.6</td>
<td>—</td>
</tr>
<tr>
<td>Machining center</td>
<td>8</td>
<td>0.7</td>
<td>0.05</td>
</tr>
</tbody>
</table>

* Average times to engage tool, engage and disengage feed, change speed or feed. (Includes change tool for machining center.)

Also included in Table 7.4 are estimates of the basic setup time and additional setup time per cutting tool. The total set-up time must be divided by the size of the batch in order to obtain the setup time per component.

7.12.4 Handling Between Machines

One of the costs to be considered is that incurred in moving batches of partially machined workpieces between machines. Fridriksson [1] made a study of this by assuming that stacks of pallets of workpieces were moved around the factory using forklift trucks. He developed the following expression for $t_f$, the transportation time for a round trip by a forklift truck

$$t_f = 25.53 + 0.29(l_p + l_{rd}) \text{s}$$  \hspace{1cm} (7.39)

where $l_p$ is the length of the pathway between machines and $l_{rd}$ is the distance the truck must travel to respond to a request—both lengths are measured in feet.

Assuming that $(l_p + l_{rd})$ is 450 ft (137 m) on average and that for every trip with a load of full pallets, a trip must be made with empty pallets, the total time is

$$t_f = 315 \text{ s}$$  \hspace{1cm} (7.40)
If a full load of pallets and workpieces is 2000 lb, the number of workpieces of weight $W$ transported will be $2000/W$ and the time per workpiece $t_w$ will be given by

$$t_w = \frac{315}{(2000/W)} = 0.156W \text{ s} \quad (7.41)$$

Thus, for a workpiece weighing 10 lb, the effective transportation time is only 1.6 s, which is small compared with typical loading and unloading times for that size workpiece [Table 7.3]. However, allowances for transportation time can be added to the loading and unloading times, and these will become significant for large workpieces.

### 7.12.5 Material Type

The so-called machinability of a work material has been one of the most difficult factors to define and quantify. In fact, it is impossible to predict the difficulty of machining a material from a knowledge of its composition or its mechanical properties, without performing a machining test. Nevertheless, it is necessary for the purposes of cost estimating to employ published data on machinability. Perhaps the best source of such data, presented in the form of recommended cutting conditions, is the *Machining Data Handbook* [2].

### 7.12.6 Machining Costs

The machining cost for each cut, pass, or operation is incurred during the period between when the feed is engaged and, finally, disengaged. It should be noted that the tool would not be cutting for the whole of this time because allowances for tool engagement and disengagement must be made—particularly for milling operations. However, typical values for these allowances can be found and are presented for various operations in [Table 7.5] as correction factors to be applied to the actual machining time.

For an accurate estimation of actual machining time, it is necessary to know the cutting conditions, namely, cutting speed, feed, and depth of cut in single-point tool operations, and the feed speed, depth of cut, and width of cut in multipoint tool operations. Tables giving recommended values for these parameters for different work materials can fill large volumes, such as the Metcut *Machining Data Handbook* [2].

Analysis of the selection of optimum machining conditions shows that the optimum feed (or feed per tooth) is the largest that the machine tool and cutting tool can withstand. Then, selection of the optimum cutting speed can be made by minimizing machining costs [see Eq. (7.33)]. The product of cutting speed and feed in a single-point operation gives a rate for the generation of the machined surface that can be measured in in$^2$/min, for example. The inverse of such rates is presented by Ostwald [3] for a variety of workpiece and tool materials and for
TABLE 7.5 Allowances for Tool Approach

<table>
<thead>
<tr>
<th>Operations</th>
<th>Allowances</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turn, face, cut-off bore, groove, thread</td>
<td>( t_m = t_m + 5.4 \quad d_m &gt; 2 )</td>
</tr>
<tr>
<td>Drill (twist) (approach)</td>
<td>( t_m = t_m (1 + 0.5d_m/l_m) )</td>
</tr>
<tr>
<td>Drill (twist) (start)</td>
<td>( t_m = t_m + (88.5/y_f)d_m )</td>
</tr>
<tr>
<td>Helical, side, saw, and key slot milling</td>
<td>( t_m = t_m + 2(a_r(d_k - a_r)^{0.5} + 0.066 + 0.011d_l) )</td>
</tr>
<tr>
<td>Face and end milling</td>
<td>( t_m = t_m + d_i + 0.066 + 0.011d_l )</td>
</tr>
<tr>
<td>Surface grinding</td>
<td>( t_m = t_m + d_i/4 )</td>
</tr>
<tr>
<td>Cyl. and int grinding</td>
<td>( t_m = t_m + w_i )</td>
</tr>
<tr>
<td>All grinding operations</td>
<td>( t'_m = a_t + 0.004 )</td>
</tr>
<tr>
<td></td>
<td>( a_t \leq 0.01 )</td>
</tr>
<tr>
<td></td>
<td>( a_t &gt; 0.01 )</td>
</tr>
<tr>
<td></td>
<td>( a_t \leq 0.024 )</td>
</tr>
<tr>
<td></td>
<td>( a_t &gt; 0.024 )</td>
</tr>
<tr>
<td>Spline broaching</td>
<td>( t_m = t_m + 15d_m + 8l_m )</td>
</tr>
<tr>
<td>Internal keyway broaching</td>
<td>( t_m = 20 + 40w_k + 85d_k )</td>
</tr>
<tr>
<td>Hole broaching</td>
<td>( t_m = 6 + 6d_m + 6l_m )</td>
</tr>
</tbody>
</table>

\( t_m \) = machining time, s; \( d_m \) = diameter of machined surface, in.; \( l_m \) = length of machined surface in direction of cutting, in.; \( v_f \) = speed x feed, in\(^2\)/min (Table 7.6); \( a_r \) = depth of cut or depth of groove in milling, in.; \( d_i \) = diameter of cutting tool, in.; \( w_i \) = width of grinding wheel, in.; \( a_r \) = depth of material removed in rough grinding, in.; \( l_k \) = length of tool, in.; \( w_k \) = width of machined keyway, in.; \( d_k \) = depth of machine keyway, in.

Source: Adapted from Ref. 3.

Different roughing and finishing operations. A problem arises, however, when applying the figures for roughing operations. For example, Ostwald recommends a cutting speed of 500 ft/min (2.54 m/s) and a feed of 0.02 in. (0.51 mm) for the rough machining of low carbon steel (170 Bhn) with a carbide tool. For a depth of cut of 0.3 in. (7.6 mm) this would mean a metal removal rate of 36 in\(^3\)/min (9.82 cm\(^3\)/s). The Machining Data Handbook [2] quotes a figure of 1.35 hp min/in\(^3\) (3.69 GJ/m\(^3\)) (unit power) for this work material. Thus, the removal rate obtained in this example would require almost 50 hp (36 kW). Since a typical medium-sized machine tool would have a 5 to 10 hp motor (3.7 to 7.5 kW) and an efficiency of around 70%, it can be seen that the recommended conditions could not be achieved except for small depths of cut. Under normal rough-machining circumstances, therefore, a better estimate of machining time would be obtained from the unit horsepower (specific cutting energy) for the material, the volume of material to be removed, and the typical power available for machining, as described earlier in this chapter.
For multipoint tools such as milling cutters, the chip load (feed per tooth) and the cutting speed are usually recommended for given tool materials. However, in these cases the machining time is not directly affected by the cutting speed but by the feed speed, which is controlled independently of the cutter speed. Thus, assuming that the optimum cutting speed is being employed, the feed speed that will give the recommended feed per tooth can be used to estimate the machining time. Again, a check must be made that the power requirements for the machine tool are not excessive.

### 7.12.7 Tool Replacement Costs

Every time a tool needs replacement because of wear, two costs are incurred: (1) the cost of machine idle time while the operator replaces the worn tool, and (2) the cost of providing a new cutting edge or tool. The choice of the best cutting speed for particular conditions is usually made by minimizing the sum of the tool replacement costs and the machining costs, since both of these are affected by changes in the cutting speed.

The minimum cost of machining a feature in one component on one machine tool is given by Eq. (7.35). If the expressions for machining time $t_m$ [Eq. (7.31)] and cutting speed $v_c$ [Eq. (7.33)] are substituted, the minimum cost of production can be expressed by

$$C_{\text{min}} = M_{l1} + M_{t_m c}/(1 - n)$$

where $t_m$ is the machining time when the optimum cutting speed for minimum cost is used.

It can be seen that the factor $1/(1 - n)$ applied to the machining time will allow for tool replacement costs provided that the cutting speed for minimum cost is always employed. The factor would be 1.14 for high-speed steel tooling and 1.33 for carbides.

Under those circumstances where use of optimum cutting conditions would not be possible because of power limitations, it is usually recommended that the cutting speed be reduced. This is because greater savings in tool costs will result than if the feed were reduced. When the cutting speed has been reduced, with a corresponding increase in the machining time, the correction factor given by Eq. (7.42) will overestimate tool costs. If $t_{mp}$ is the machining time where the cutting speed $v_{po}$ giving maximum power is used, then the production cost $C_{po}$ for maximum power will be given by

$$C_{po} = M_{l1} + M_{t_{mp}} + (M_{t_{ct}} + C_{l})t_{mp}/v_{po}$$

(7.43)
where $t_{po}$ is the tool life obtained under maximum power conditions, which, from Taylor’s tool life equation, is

$$t_{po} = t_c (v_c/v_{po})^{1/n} \quad (7.44)$$

The tool life $t_c$ under minimum cost conditions is given by Eq. (7.34), and substituting Eqs. (7.44) and (7.34) in Eq. (7.43) and using the relation in Eq. (7.31) gives

$$C_{po} = M_{t_c} + M_{t_mp} (1 + [n/(1-n)](t_{mc}/t_{mp})^{1/n}) \quad (7.45)$$

Thus, Eq. (7.45) can be used instead of Eq. (7.42) when the cutting speed is limited by the power available on the machine tool and, therefore, when $t_{mp} > t_{mc}$.

### 7.12.8 Machining Data

In order to employ the approach described above, it is necessary to be able to estimate, for each operation, the machining time $t_{mc}$ for minimum cost conditions and the machining time $t_{mp}$ where the cutting speed is limited by power availability. It was shown earlier that machining data for minimum cost for single-point tools, presented in handbooks, can be expressed as speed $x$ feed ($vf$), or the rate at which the machined surface can be generated. Table 7.6 gives typical values of $vf$ for several material classifications selected and for lathe operations using high-speed tools or brazed carbide tools. These values were adapted from the data in the *Machining Data Handbook* [2]. Analysis of the handbook data shows that if disposable insert carbide tools are to be used, then the data for brazed carbide tools can be multiplied by an average factor of 1.17.

When turning a surface of diameter $d_m$ for a length $l_w$, the figures for $vf$ given in Table 7.6 would be divided into the surface area ($A_m = \pi l_w d_m$) to give the machining time $t_{mc}$.

Thus

$$t_{mc} = 60A_m/(vf) \quad s \quad (7.46)$$

For an estimate of the machining time $t_{mp}$ for maximum power it is necessary to know the power available for machining and the unit power $p_s$ (specific cutting energy) for the work material. Table 7.6 gives average values of $p_s$ for the selection of work materials employed here.

When estimating the power available for machining $P_m$, it should be realized that small components will generally be machined on small machines with lower power available, whereas larger components will be machined on large higher-powered machines. For example, a small lathe may have less than 2 hp available for machining, whereas an average-sized lathe may have 5 to 10 hp available. A larger vertical lathe will perhaps have 10 to 30 hp available. Typical power values for the selection of machines are presented in Fig. 7.47, where the horsepower
<table>
<thead>
<tr>
<th>Material</th>
<th>Hardness</th>
<th>Turning, facing and boring</th>
<th>Drilling and reaming (1 in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>( v_f ) (in(^2)/min)(^a)</td>
<td>( P_s ) (hp/in(^3)/min)(^b)</td>
</tr>
<tr>
<td>Low carbon steel (free machining)</td>
<td>150–200</td>
<td>25.6</td>
<td>100</td>
</tr>
<tr>
<td>Low carbon steel</td>
<td>200–250</td>
<td>18.2</td>
<td>78</td>
</tr>
<tr>
<td>Medium and high carbon steel</td>
<td>150–200</td>
<td>23.7</td>
<td>96</td>
</tr>
<tr>
<td>Alloy steel (free machining)</td>
<td>135–185</td>
<td>12.6</td>
<td>48</td>
</tr>
<tr>
<td>Stainless, ferritic (annealed)</td>
<td>200–250</td>
<td>12.8</td>
<td>54</td>
</tr>
<tr>
<td>Tool steels</td>
<td>80–360</td>
<td>9</td>
<td>42</td>
</tr>
<tr>
<td>Nickel alloys</td>
<td>200–275</td>
<td>12.6</td>
<td>24</td>
</tr>
<tr>
<td>Titanium alloys (free machining)</td>
<td>40–150</td>
<td>76.8</td>
<td>196</td>
</tr>
<tr>
<td>Copper alloys (soft)</td>
<td>80–100</td>
<td>58.5</td>
<td>113</td>
</tr>
<tr>
<td>Zinc alloys (die cast)</td>
<td>49–90</td>
<td>162</td>
<td>360</td>
</tr>
<tr>
<td>Magnesium and alloys</td>
<td>30–80</td>
<td>176</td>
<td>352</td>
</tr>
</tbody>
</table>
For Finishing Disposable insert
For Drilling and 1/16 1/8 1/4 reaming 1.59 3.18 6.35 12.7 19.7 25.4 38.1 50.8 mm
For <2 3 6 8 0.60 0.83 1.00 1.23 1.47
Turning, facing, boring
Milling

<table>
<thead>
<tr>
<th>Factor</th>
<th>For</th>
<th>Tool diameter (in.) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(k_f)</td>
<td>Finishing</td>
<td>0.60</td>
</tr>
<tr>
<td>(k_i)</td>
<td>Disposable insert</td>
<td>1.17</td>
</tr>
<tr>
<td>(k_h)</td>
<td>Drilling and reaming</td>
<td>0.08</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Factor</th>
<th>For</th>
<th>Length/diameter ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>(k_d)</td>
<td>Deep holes</td>
<td>&lt;2</td>
</tr>
</tbody>
</table>

\(a\) To convert \(\text{in}^2/\text{min}\) to \(\text{m}^2/\text{min}\), multiply by 6.45 \(\times 10^{-3}\).

\(b\) To convert \(\text{hp} \times \text{min}/\text{in}^3\) to \(\text{GJ}/\text{m}^3\), multiply by 2.73.

All data are for rough machining. For finish machining multiply by \(k\).

For cut-off or form tool operations, multiply by 0.2.

The term carbide refers to tools with brazed carbide inserts. For tools with disposable carbide inserts, multiply by \(k\).

Data for drilling are for 1.0 in. diameter tools with hole depth/diameter less than 2.

For sawing, multiply the data for turning with HSS tools by 0.33.

For tap or die threading, multiply data for turning with HSS tools by 10 and divide by TPI (threads per inch); for standard threads TPI = 2.66 + 4.28/\(d_p\).

For single-point threading, multiply result for die threading by number of passes, approximately 100/TPI, and add tool engagement time for each pass.

Source: Adapted from Ref. 2.
FIG. 7.47 Relation between horsepower and workpiece weight for some machine tools.

available for machining $P_m$ is plotted against the typical weight capacity of the machine.

The machining time for maximum power is given by

$$t_{mp} = \frac{60 V_m P_m}{P_m} \text{ s}$$

(7.47)

where $V_m$ is the volume of material to be removed in the machining operation. If $a_p$ is the depth of cut, then $V_m$ is given approximately by $\pi d_m l_w a_p$. However, for a facing or cut-off operation carried out at constant rotational speed, the power limitations apply only at the beginning of the cut and the machining time will be longer than that given by Eq. (7.47).

It was pointed out earlier that for milling operations, it is convenient to estimate machining time from a knowledge of the feed speed $v_t$ that will give the recommended feed per tooth. Data for milling selected materials are presented in Table 7.7.

The machining time $t_m$ for recommended conditions is thus given by

$$t_{mc} = \frac{60 l_w}{v_t} \text{ s}$$

(7.48)

where $l_w$ is the length of the feature to be milled. However, it is important to note that this result must be corrected for the approach and overtravel distances, which will often be as large as the cutter diameter.

The machining time for maximum power is given by Eq. (7.47), but, again, corrections must be made for cutter approach and overtravel.
TABLE 7.7    Machining Data for Milling Operations

<table>
<thead>
<tr>
<th>Material</th>
<th>Hardness (Bhn)</th>
<th>Side and face</th>
<th>End (1.5 in.)</th>
<th>( P_s ) (hp/in(^3)/min)(^b)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>HSS Brazed carb.</td>
<td>HSS Brazed carb.</td>
<td></td>
</tr>
<tr>
<td>Low carbon steel</td>
<td>150–200</td>
<td>19.2</td>
<td>52.9</td>
<td>4.5</td>
</tr>
<tr>
<td>(free machining)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low carbon steel</td>
<td>150–200</td>
<td>13.5</td>
<td>43.3</td>
<td>2.2</td>
</tr>
<tr>
<td>Medium and high</td>
<td>200–250</td>
<td>10.8</td>
<td>37.3</td>
<td>1.8</td>
</tr>
<tr>
<td>carbon steel</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alloy steel</td>
<td>150–200</td>
<td>13.7</td>
<td>40.2</td>
<td>2.7</td>
</tr>
<tr>
<td>(free machining)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stainless, ferretic</td>
<td>135–185</td>
<td>14.0</td>
<td>41.0</td>
<td>2.4</td>
</tr>
<tr>
<td>(annealed)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tool steels</td>
<td>200–250</td>
<td>6.7</td>
<td>23.7</td>
<td>0.9</td>
</tr>
<tr>
<td>Nickel alloys</td>
<td>80–360</td>
<td>4.1</td>
<td>7.7</td>
<td>1.0</td>
</tr>
<tr>
<td>Titanium alloys</td>
<td>200–275</td>
<td>3.9</td>
<td>13.2</td>
<td>1.5</td>
</tr>
<tr>
<td>Copper alloys (soft)</td>
<td>40–150</td>
<td>50.5</td>
<td>108.3</td>
<td>9.9</td>
</tr>
<tr>
<td>(free machining)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zinc alloys</td>
<td>80–100</td>
<td>28.0</td>
<td>60.1</td>
<td>9.8</td>
</tr>
<tr>
<td>(die cast)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Magnesium and alloys</td>
<td>40–90</td>
<td>77.0</td>
<td>240.6</td>
<td>27.5</td>
</tr>
<tr>
<td>Aluminum and alloys</td>
<td>30–80</td>
<td>96.2</td>
<td>216.5</td>
<td>20.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^a\)To convert \( \text{in/min} \) to \( \text{mm/s} \) multiple by 0.423.

\(^b\)To convert \( \text{hp/min} \) to \( \text{GJ/m}^3 \) multiply by 2.73.

Source: Adapted from Ref. 2.

7.12.9   Rough Grinding

Limitations on the rate at which grinding operations can be carried out depend on many interrelated factors, including the work material, the wheel grain type and size, the wheel bond and hardness, the wheel and work speeds, downfeed, infeed, the type of operation, the rigidity of the machine tool, and power available. It appears that, assuming adequate power, these limitations can be summarized in terms of the maximum metal removal rate per unit width of the grinding wheel \( Z_w/w \). For example, the Machining Data Handbook [2] gives the following recommendations for the rough grinding of annealed free-machining low carbon steel on a horizontal-spindle reciprocating surface grinder:
Wheel speed: 5500 to 6500 ft/min
Table speed: 50 to 150 ft/min
Downfeed: 0.003 in/pass
Crossfeed: 0.05–0.5 in/pass (1/4 wheel width maximum)
Wheel: A46JV (aluminum oxide grain, size 46, grade J, vitrified bond)

If the wheel width \( w_t \) were 1 in. and an average table speed (work speed) of 75 ft/min were employed, then a downfeed of 0.003 in. and a maximum crossfeed of 0.25 in. would give a metal removal rate \( Z_w \) of 0.68 in\(^3\)/min. In a plunge-grinding operation, the wheel width would be equal to the width of the groove to be machined and the rough grinding time \( t_{gc} \) for recommended conditions would be given by

\[
t_{gc} = 60V_m/Z_w
\]

where \( V_m \) is the volume of metal to be removed and \( Z_w \) is the metal removal rate (in\(^3\)/min). If the groove depth \( a_d \) were 0.25 in. and the groove length \( l_w \) were 4 in., the grinding time would be

\[
t_{gc} = 60a_d l_w/Z_w = 60(1)(0.25)(4)/0.68 = 88.2 \text{ s}
\]

The Machining Data Handbook [2] also gives values of the unit power (specific cutting energy) for the surface grinding of various materials. The unit power \( P_s \) depends to a large extent on the downfeed, and for a downfeed of 0.003 in., 13 hp min/in\(^3\) would be required for carbon steel. In our example, the removal rate for a 2 in. wide groove would be

\[
Z_w = 60(2)(0.25)/88.2 = 1.36 \text{ in}^3/\text{min}
\]

and the power required \( P_m \) would then be given by

\[
P_m = P_s Z_w = 13(1.36) = 17.7 \text{ hp}
\]

Clearly, for a particular rough-grinding operation, it will be necessary to check the grinding time \( t_{pp} \) when maximum power is used, and this will be given by

\[
t_{pp} = 60V_m p_s / P_m
\]

(7.50)

The estimated rough-grinding time \( t_{pp} \) would be given by the grinding time \( t_{gc} \) for recommended conditions or the grinding time \( t_{pp} \) for maximum power, whichever is the largest. Table 7.8 gives recommendations for typical conditions for the horizontal-spindle surface grinding of selected materials. These recommendations are expressed in terms of \( Z_w / w_t \), the metal removal rate per unit width of wheel in rough grinding, and the corresponding unit power \( P_s \).

If the operation is one of plunge grinding, the width of the grinding wheel will be known. In a traverse operation, the width of the wheel will depend mainly on the grinding machine.
### TABLE 7.8 Machining Data for Horizontal-Spindle Surface Grinding

<table>
<thead>
<tr>
<th>Material</th>
<th>Hardness (Bhn)</th>
<th>( Z_w/w_t ) (in³/min)</th>
<th>( P_s ) (hp/in³/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low carbon steel (free machining)</td>
<td>150–200</td>
<td>0.68</td>
<td>13</td>
</tr>
<tr>
<td>Low carbon steel</td>
<td>150–200</td>
<td>0.68</td>
<td>13</td>
</tr>
<tr>
<td>Medium and high carbon steel</td>
<td>200–250</td>
<td>0.68</td>
<td>13</td>
</tr>
<tr>
<td>Alloy steel (free machining)</td>
<td>150–200</td>
<td>0.68</td>
<td>14</td>
</tr>
<tr>
<td>Stainless, ferretic (annealed)</td>
<td>135–185</td>
<td>0.45</td>
<td>14</td>
</tr>
<tr>
<td>Tool steels</td>
<td>200–250</td>
<td>0.68</td>
<td>14</td>
</tr>
<tr>
<td>Nickel alloys</td>
<td>80–360</td>
<td>0.15</td>
<td>22</td>
</tr>
<tr>
<td>Titanium alloys</td>
<td>200–275</td>
<td>0.9</td>
<td>16</td>
</tr>
<tr>
<td>Copper alloys (soft) (free machining)</td>
<td>40–150</td>
<td>0.89</td>
<td>11</td>
</tr>
<tr>
<td>Zinc alloys (die cast)</td>
<td>80–100</td>
<td>0.89</td>
<td>6.5⁹</td>
</tr>
<tr>
<td>Magnesium and alloys</td>
<td>40–90</td>
<td>0.89</td>
<td>6.5</td>
</tr>
<tr>
<td>Aluminum and alloys</td>
<td>30–80</td>
<td>0.89</td>
<td>6.5</td>
</tr>
</tbody>
</table>

⁹ Estimated values.

For external cylindrical grinding, multiply \( Z_w/w_t \) by 1.24 and multiply \( P_s \) by 0.81.

For internal grinding, multiply \( Z_w/w_t \) by 1.15 and \( P_s \) by 0.87.

*Source: Adapted from Ref. 2.*

In a plunge-grinding operation, the depth of material to be removed will be specified by the geometry of the finished workpiece. In a traverse-grinding operation, it is necessary to remove the rough-grinding stock left by the previous machining operation.

### 7.12.10 Finish Grinding

The time for a finish-grinding operation is usually determined by the desired surface finish. This means that the metal removal rate must be slow enough to generate an acceptable surface finish, and it therefore becomes independent of the parameters affecting the removal rate in rough grinding. From the *Machining Data Handbook* [2], typical average values of the removal rate per inch of wheel width are 0.16 in³/min for horizontal-spindle surface grinding, 0.08 in³/min for cylindrical grinding, and 0.06 in³/min for internal grinding. Recommended stock allowances for finish grinding range from 0.002 to 0.003 in. for horizontal grinding and 0.005 to 0.01 in. for cylindrical grinding.
7.12.11 Allowance for Grinding Wheel Wear

In his analysis of the economics of internal grinding, Lindsay [4] shows that the costs per component associated with wheel wear and wheel changing are proportional to the metal removal rate during rough grinding and that the wheel costs due to dressing and finish grinding are negligible in comparison. Thus, the total cost $C_g$ of a grinding operation will be given by

$$C_g = Mf_c + Mf_{gr} + C_w$$  \hspace{1cm} (7.51)$$

where $M$ is the total rate for the machine (including direct labor, depreciation, and overhead), $t_c$ is a constant time that includes the wheel-dressing time (assumed to occur once per component), the loading and unloading time, the wheel advance and withdrawal time, and the finish-grinding time, $t_{gr}$ is the rough-grinding time, and $C_w$ represents the wheel wear and wheel-changing costs. If we substitute $C_w = k_1 Z_w$  \hspace{1cm} (7.52)$$

where $k_1$ is a constant and $Z_w$ is the metal removal rate during rough grinding, and

$$t_{gr} = k_2 / Z_w$$  \hspace{1cm} (7.53)$$

where $k_2$ is a constant, into Eq. (7.51) we get

$$C_g = Mf_c + Mk_2 / Z_w + k_1 Z_w$$  \hspace{1cm} (7.54)$$

Differentiating with respect to $Z_w$ and equating to zero for minimum cost, we find that the optimum condition arises when the wheel wear and wheel changing costs [represented by the third term on the right of Eq. (7.54)] are equal to the rough-grinding costs [represented by the second term]. This means that if optimum conditions are used in a grinding operation, wheel wear and wheel-changing costs can be allowed for by multiplying the rough-grinding time by a factor of 2.

However, it was pointed out earlier that the recommended conditions may exceed the power $P_m$ available for grinding. In this case, the metal removal rate must be reduced—resulting in a reduction in wheel wear and wheel-changing costs and an increase in rough-grinding costs with a consequent increase in the total operation costs.

If $Z_{wc}$ and $Z_{wp}$ are the metal removal rates for optimum (recommended) and maximum power conditions respectively, the corresponding costs $C_c$ and $C_p$ are given by

$$C_c = Mf_c + 2Mk_2 / Z_{wc}$$  \hspace{1cm} (7.55)$$

$$C_p = Mf_c + Mk_2 / Z_{wp} + k_1 Z_{wp}$$  \hspace{1cm} (7.56)$$
Also, since for optimum conditions

\[ k_i Z_{wc} = \frac{Mk_i}{Z_{wc}} \]

we can obtain, after substitution and rearrangement, the following expression for the cost \( C_p \), under maximum power conditions.

\[
C_p = M_{lc} + \frac{Mk_i}{Z_{wc}} \left( \frac{Z_{wc}}{Z_{wp}} + \frac{Z_{wp}}{Z_{wc}} \right) \\
= M_{lc} + M_{tp} \left[ 1 + \left( \frac{f_{gc}}{f_{gp}} \right)^2 \right]
\]

(7.58)

where \( f_{gc} \) and \( f_{gp} \) are the rough-grinding times for recommended and maximum power conditions given by Eqs. (7.49) and (7.50), respectively, and where \( f_{gp} > f_{gc} \).

This means that a multiplying factor equal to the term in square brackets in Eq. (7.58) can be used to adjust the rough grinding time and thereby allow for wheel wear and wheel-changing costs. Under circumstances where the recommended grinding conditions can be used (i.e., when \( f_{gp} < f_{gc} \)) the multiplying factor is equal to 2. If, for example, because of power limitations the metal removal rate were 0.5 of the recommended rate, then \( f_{gp} \) would be equal to \( 2f_{gc} \) and the correction factor would be 1.25. Under these circumstances, the rough-grinding costs would be double those for recommended conditions and the wheel costs would be one-half those for recommended conditions.

**Example**

Suppose the diameter \( d_w \) of a stainless steel bar is 1 in. and it is to be traverse ground for a length \( l_w \) of 12 in. If the wheel width \( w_i \) is 0.5 in., the power available \( P_m \) is 3 hp and the rough-grinding stock \( a_r \) left on the radius is 0.005 in., we get

Volume of metal to be removed

\[
V_m = \frac{\pi d_w a_r l_w}{2} = \frac{\pi(1)(0.005)(12)}{2} = 0.189 \text{ in}^3
\]

From Table 7.8 the recommended metal removal rate per unit width of wheel \( Z_{wc}/w_i \) is 0.45 in\(^3\)/min for horizontal-spindle surface grinding. Using a correction factor of 1.24 for cylindrical grinding, the rough-grinding time for recommended conditions is given by

\[
t_{gc} = 60 V_m / Z_{wc} \\
= 60(0.189)/(0.45)(0.5) = 40.65 \text{ s}
\]
However, Table 7.8 gives a unit power value of \( p_s = 14 \) hp in\(^3\) /min for stainless steels and, therefore, with a correction factor of 0.81, the rough-grinding time for maximum power would be

\[
t_{gp} = 60V_m p_{s}\, /\, P_m
\]

\[
= 60(0.189)(14)(0.81)/(3) = 42.9 \text{ s}
\]

Thus, insufficient power is available for optimum grinding conditions and the condition for maximum power must be used. Finally, using the multiplying factor to allow for wheel costs, we get a corrected value \( t'_{gp} \) for the rough-grinding time of

\[
t'_{gp} = t_{gp}[1 + (t_{gs}/t_{gp})^2]
\]

\[
= 42.9[1 + (40.6/42.9)^2]
\]

\[
= 42.9(1.9) = 81.3 \text{ s}
\]

As explained earlier, the metal removal rate for finish grinding is basically independent of the material and is approximately 0.08 in\(^3\) /min per inch of wheel width in cylindrical grinding. For the present example where the wheel width is 0.5 in., this would give a removal rate \( Z_w \) of 0.05 in\(^3\) /min with a correction factor of 1.24 applied. Assuming a finish-grinding radial stock allowance of 0.001 in., the volume to be removed is

\[
V_m = \pi(1)(0.001)(12) = 0.038 \text{ in}^3
\]

and the finish-grinding time is

\[
t_{gf} = 60(0.038)/(0.05) = 45.6 \text{ s}
\]

### 7.12.12 Allowance for Spark-Out

In spark-out, the feed is disengaged and several additional passes of the wheel or revolutions of the workpiece are made in order to remove the material remaining because of machine and workpiece deflections. Since the number of passes is usually given, this is equivalent to removing a certain finish stock. For estimating purposes, the finish grinding time can be multiplied by a constant factor of 2 to allow for spark-out.

### 7.12.13 Examples

We shall first estimate the machining cost for a facing operation on a free-machining steel bar 3 in. (76.2 mm) diameter and 10 in. (254 mm) long, where
0.2 in. (5.1 mm) is to be removed from the end of the bar using a brazed-type carbide tool. The surface area to be generated is

\[ A_m = \frac{\pi}{4}(3)^2 = 7.07 \text{ in}^2 \ (4.5 \text{ m}^2) \]

and the volume of metal to be removed is

\[ V_m = \frac{\pi}{4}(3)^3(0.2) = 1.41 \text{ in}^3 \ (23.1 \text{ m}^3) \]

For this work material–tool material combination, Table 7.6 gives a value of \( vf \) (speed \( \times \) feed) of 100 in\(^2\)/min. (0.065 m\(^2\)/min), and from Eq. (7.46) the machining time is

\[ t_{mc} = 60(2)(7.07/100) = 8.5 \text{ s} \]

where the factor of 2 allows for the gradually decreasing cutting speed when constant rotational speed is used in a facing operation.

The weight of the workpiece is estimated to be

\[ W = \frac{\pi}{4}(3)^3(10)(0.28) = 20 \text{ lb} \ (9.07 \text{ kg}) \]

From Fig. 7.47 the power available for machining on a CNC chucking lathe would be approximately given by

\[ P_m = 10 \text{ hp} \ (7.76 \text{ kW}) \]

Table 7.6 gives a value of specific cutting energy (unit power) of 1.1 hp min/in\(^3\) (3 GJ/m\(^3\)) and so, from Eq. (7.47), the machining time at maximum power is

\[ t_{mp} = 60(2)(1.1)(1.41/10) = 18.6 \text{ s} \]

Again, the factor of 2 has been applied for facing a solid bar.

It can be seen that, in this case, the conditions for minimum cost cannot be used because of power limitations and that a machining time of 18.6 s will be required. Now we can apply the factor given by Eq. (7.45) to allow for tool costs.

For carbide tools the Taylor tool life index is approximately 0.25, and since the ratio \( t_{mc}/t_{mp} \) is 8.5/18.6, or 0.46, the correction factor is

\[ \{1 + \left[0.25/(1 - 0.25)\right](0.46)^{1/(0.25)}\} = 1.01 \]

and the corrected machining time is 18.6 (1.01), or approximately 18.9 s.

In this example the correction factor for tool costs is quite small because cutting speeds below those giving minimum costs are being employed. If optimum speeds could be used, the correction factor would be 1.33 and the corrected machining time would be 11.2 s.

Finally, in Fig. 7.48, data are presented on the typical cost of various machine tools, where it can be seen that, for the present example of a CNC lathe, a cost of about $80,000 would be appropriate. Assuming that the total rate for the operator
and the machine would be $30 per hour, or $0.0083 per second, the machining cost for the facing operation would be $0.157.

Thus, using the approach described in this chapter, it is possible to estimate the cost of each machined feature on a component. For example, Fig. 7.49 shows a

FIG. 7.48 Relation between cost and workpiece weight for some machine tools.

FIG. 7.49 Turned component. Batch size, 1500; workpiece, 3.25 in. dia. x 10.25 in. long; material, low carbon free-machining steel.
Design for Machining

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turned component with the machining cost for each feature indicated. The small, nonconcentric hole and the keyway are relatively expensive features. This is because in order to machine them, the component had to be loaded on separate machine tools—significantly increasing the nonproductive costs. The designer who is able to make these estimates would clearly be encouraged to reconsider the securing operations that necessitated these features and thereby reduce the overall manufacturing costs of the product.

7.12.14 Approximate Cost Models for Machined Components

During the initial conceptual stages, the designer or design team will be considering a variety of solutions to the design problem. Selection of the most promising design may involve trade-offs between the cost of machined components and components manufactured by other methods. However, the designer or design team will not be in a position to specify all the details necessary to complete the type of analysis presented in the previous section. In fact, the information in the early stages of design may consist only of the approximate dimensions of the component, the material, and a knowledge of its main features. Surprisingly, it is possible to obtain fairly accurate estimates of the cost of a component based on a limited amount of information. These estimates depend on historical data regarding the types of features usually found in machined components and the amount of machining typically carried out.

As an example we can consider a rotational component machined on a CNC turret lathe. In a study of the turning requirements for British industry [5] it was found that the average ratio of the weight of metal removed to initial workpiece weight was 0.62 for light engineering. Also, in light engineering, only 2% of workpieces weighed over 60lb (27kg) and therefore required lifting facilities, and 75% of the workpieces were turned from bar. Usually, the proportion of initial volume of material removed by internal machining is relatively small for geometrical reasons.

The British survey [5] also showed a direct correlation between the length-to-diameter ratio and the diameter of turned components.

Using this type of data, Fig. 7.50 shows, for a low-carbon-steel turned component, the effect of the finished size of the component on the rough machining, finish machining, and nonproductive times per unit volume. It can be seen that, as the size of the component is reduced below about 5 in³ (82 μm³), the time per unit volume and hence the cost per unit volume increases dramatically—particularly for the nonproductive time. This increase is to be expected for the nonproductive time because it does not reduce in proportion to the weight of the component. For example, even if the component size were reduced to almost zero, it would still take a finite time to place it in the machine, to make speed and feed settings, and to start the cutting operations. For the rough-
machining time, the higher times per unit volume for small components are a result of the reduced power available with the smaller machines used. The finish-machining time is proportional to the area machined. It can be shown that the surface area per unit volume (or weight) is higher for smaller components—thus leading to higher finish-machining times per unit volume.

These results have not taken into account the cost of the work material, and Fig. 7.51 shows how the total cost of a finished steel component varies with component size. This total cost is broken down into material cost and machining cost, and it can be seen that material cost is the most important factor contributing to the total cost even though 62% of the original workpiece was removed by machining—a figure that results in relatively high rough-machining costs. In fact, for the larger parts, about 80% of the total cost is attributable to material costs.

From the results of applying the approximate cost models it is possible to make the following observations.

1. For medium-sized and large workpieces, the cost of the original workpiece mainly determines the total manufactured cost of the finished component.
2. The cost per unit volume or per unit weight of small components (less than about 5 in$^3$ or 82 $\mu$m$^3$) increases rapidly as size is reduced because:
   a. The nonproductive times do not reduce in proportion to the smaller component size.
b. The power available and hence the metal removal rate is lower for components.

c. The surface area per unit volume to be finish-machined is higher for smaller components.

This is illustrated in Fig. 7.52, where a series of turned components are shown, each being one-tenth the volume of the previous component. Although the cost per unit volume for the material is the same for all the components, the machining cost per unit volume increases rapidly as the components become smaller. For example, the total cost of the smallest component is $4.00 per in³ whereas for the largest it is $0.55 per in³. Stated another way, it would clearly be much less expensive to machine one of the largest components rather than 1000 of the smallest components when using the same types of machines.

3. The choice of tool materials and optimum machining conditions only affects the finish-machining time. Since finish machining represents only about 25% of the total manufacturing cost, which in turn represents only about 20% of the total component cost for larger components, the effects of changes in tool materials or recommended conditions can be quite small under many conditions.

4. The factors to be taken into account in making early estimates of machining costs are:
FIG. 7.52 Costs (dollars) for a series of turned components.

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume of finished part (in³)</td>
<td>40.0</td>
<td>4.0</td>
<td>0.4</td>
<td>0.04</td>
</tr>
<tr>
<td>Material cost/in³ of finished part</td>
<td>0.44</td>
<td>0.44</td>
<td>0.44</td>
<td>0.44</td>
</tr>
<tr>
<td>Manufacturing cost/in³ of finished part</td>
<td>0.11</td>
<td>0.35</td>
<td>1.32</td>
<td>3.56</td>
</tr>
<tr>
<td>Total cost/in³ of finished part</td>
<td>0.55</td>
<td>0.79</td>
<td>1.76</td>
<td>4.00</td>
</tr>
</tbody>
</table>

5. The factors that affect the nonproductive times are:

a. The number of times the component must be clamped in a machine tool—each clamping involves transportation, loading and unloading, and setup.
b. The number of separate tool operations required—each operation requires tool indexing, and other associated activities and increases setup costs.

It was found in previous studies [6] that common workpieces can be classified into seven basic categories. Knowledge of the workpiece classification and the production data not only allows the cost of the workpiece to be estimated, but also allows predictions to be made of the probable magnitudes of the remaining items necessary for estimates of nonproductive costs and machining costs.

For example, for the workpiece shown in Fig. 7.49, the total cost of the finished component was estimated to be $24.32, a figure obtained from knowledge of the work material, its general shape classification and size, and its cost per unit volume. A cost estimate for this component, based on its actual machined features and using approximate equations based on the type of data listed above gave a total cost of $22.83, which is within 6%. A more detailed estimate obtained using the traditional cost-estimating methods presented in this chapter gave a total cost of $22.95. Thus, approximate methods, using the minimum of information, can give estimates surprisingly close to the results of analysis carried out after detailed design has taken place.

REFERENCES