# Table 7.2

Approximate Costs in Dollars per Pound for Various Metals

**Density**

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
|  | **lb/in.3** | **mg/m3** | **Bar** | **Rod** | **Sheet** <**0.5 in.** | **Plate** >**0.5 in.** | **Tube** |
| Ferrous  Carbon steel | 0.283 | 7.83 | 0.51 | 0.51 | 0.36 | 0.42 | 0.92 |
| Alloy steel | 0.31 | 8.58 | 0.75 | 0.75 | 1.20 | — | — |
| Stainless steel | 0.283 | 7.83 | 1.50 | 1.50 | 2.50 | 2.50 | — |
| Tool steel | 0.283 | 7.83 | 6.44 | 6.44 | — | 6.44 | — |
| Nonferrous  Aluminum alloys | 0.10 | 2.77 | 1.93 | 1.93 | 1.95 | 2.50 | 4.60 |
| Brass | 0.31 | 8.58 | 0.90 | 1.22 | 1.90 | 1.90 | 1.90 |
| Nickel alloys | 0.30 | 8.30 | 5.70 | 5.70 | 5.70 | 5.70 | — |
| Magnesium alloys | 0.066 | 1.83 | 3.35 | 3.35 | 6.06 | 6.06 | 3.35 |
| Zinc alloys | 0.23 | 6.37 | 1.50 | 1.50 | 1.50 | 1.50 | — |
| Titanium alloys | 0.163 | 4.51 | 15.40 | 15.40 | 25.00 | 25.00 | — |

*Note:* To convert to dollars per kilogram multiply by 2.2.

conditions so the values given in Table 7.2 are included for the purposes of calculations in this Chapter.

# 7.12.2 Machine loading and unloading

Nonproductive costs are incurred everytime 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 fi gures must be added the times for turning coolant on and off, cleaning the work-holding or clamping device, and so on.

# 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the feed and speed settings changed, the feed engaged, and then, when the operation is completed, the tool must be withdrawn.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 account. Some time elements for these tasks for different types of machine tools are presented in Table 7.4.

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

## Table 7.3

Loading and Unloading Times (s) versus Workpiece Weight

**4.5–14**

**Holding Device**

**Workpiece Weight**

**Crane**

**0–0.2**

**0.2–4.5**

**14**

**–27 (kg**

**)**

**0–0.4**

**0.4–10**

**10**

**–**

**30**

**)**

**30**

**–60 (lb**

34.9

71.2

Between centers, no dog

13.5

18.6

24.1

35.3

73.1

Between centers, with dog

25.6

40.2

57.4

97.8

247.8

Chuck, universal

16.0

23.3

31.9

52.9

—

Angle plate (2 U-clamps) 27.6 43.5 276.5

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Chuck, independent (4 jaws) | 34.0 | 41.3 | 49.9 | 70.9 | — |
| Clamp on table (3 clamps) | 28.8 | 33.9 | 39.4 | 58.7 | 264.6 |
| Collet | 10.3 | 15.4 | 20.9 | — | — |
| Faceplate (3 clamps) | 31.9 | 43.3 | 58.0 | 82.1 | 196.2 |
| Fixture, horizontal (3 screws) | 25.8 | 33.1 | 41.7 | 69.4 | 274.7 |
| Fixture, vertical (3 screws) | 27.2 | 38.6 | 53.3 | — | — |
| Hand-held | 1.4 | 6.5 | 12.0 | — | — |
| Jig | 25.8 | 33.1 | 41.7 | — | — |
| Magnet table | 2.6 | 5.2 | 8.4 | — | — |
| Parallels | 14.2 | 19.3 | 24.8 | 67.0 | 354.3 |
| Rotary table or index plate (3 clamps) | 28.8 | 36.1 | 44.7 | 72.4 | 277.7 |
| “V” Blocks | 25.0 | 30.1 | 35.6 | 77.8 | 365.1 |
| Vise | 13.5 | 18.6 | 24.1 | 39.6 | 174.2 |

*Source*: Adapted from Fridriksson, L. Nonproductive Time in Conventional Metal Cutting. Report No. 3, *Design for Manufacturability Program*, University of Massachusetts, Amherst, February 1979.

## Table 7.4

Some Nonproductive Times for Common Machine Tools

|  |  |  |  |
| --- | --- | --- | --- |
| **Machine Tool** | **Time to Engage**  **Tool; etc.a (s)** | **Basic Setup Time (h)** | **Additional Setup per Tool (h)** |
| Horizontal band saw | — | 0.17 | — |
| Manual turret lathe | 9 | 1.2 | 0.2 |
| CNC turret lathe | 1.5 | 0.5 | 0.15 |
| Milling machine | 30 | 1.5 | — |
| Drilling machine | 9 | 1.0 | — |
| Horizontal-boring machine | 30 | 1.3 | — |
| Broaching machine | 13 | 0.6 | — |
| Gear hobbing machine | 39 | 0.9 | — |
| Grinding machine | 19 | 0.6 | — |
| Internal grinding machine | 24 | 0.6 | — |
| Machining center | 8 | 0.7 | 0.05 |

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

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

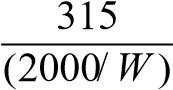
*t*f = 25.53 + 0 2. 9(*l*p + *l*rd ) *s* (7.39)

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 = 315s (7.40)

If a full load of pallets and workpieces is 2000 lb, the number of workpieces of weight *W* transported would be 2000/ *W* and the time per workpiece *t*tr is given by

 *t*tr == 0.156*W* s (7.41)

Thus, for a workpiece weighing 10 lb, the effective transportation time is only 1.6 s, which is small compared to 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 become significant for large workpieces.

# 7.12.5 Material Type

The so-called machinability of a work material has been one of the most diffi cult factors to define and quantify. In fact, it is impossible to predict the difficulty of machining a material from 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 fi ll 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.

## Table 7.5

Allowances for Tool Approach

|  |  |
| --- | --- |
| **Operations** | **Allowances** |
| Turn, face, cut-off bore, | *t*m′ = *t*m + 5 4. *d*m > 2 |
| groove, thread | *t*m′ = *t*m + (1 35. *d*m2 ) *d*m ≤ 2 |
| Drill (twist) (approach) | *t*m′ = *t*m (1 + 0.5*d*m/ *l*w ) |
| Drill (twist) (start) | *t*m′ = *t*m + (88. /5 υ*f* ))*d*m1 67. |
| Helical, side, saw, and key slot milling | *l*′w = *l*w + 2(*a*e (*d*t − *a*c )0.5 + 0 066. + 0 011. *d*t ) |
| Face and end milling | *l*′w = *l*w + *d*t + 0.066 + 0.011*d*t |
| Surface grinding | *l*w′ = *l*w + *d*t/ 4 |
| Cyl. and int. grinding | *l*′w = *l*w + *w*t |
| All grinding operations | *a*′r = *a*r + 0.004 *a*r ≤ 0 01.  *a*′r = *a*r + 0 29. (*a*r − 0 01. ) *aa*rr ≤>00 01.024.    *a*′r = *a*r + 0.008 *a*r > 0.024 |
| Spline broaching | *l*t = −5 + 15*d*m + 8*l*w |
| Internal keyway broaching | *l*t = 20 + 40*w*k + 85*d*k |
| Hole broaching | *l*t = 6 + 6*d*m + 6*l*w |

*Source*: Adapted from Ostwald, P.F. *AM Cost Estimator*, McGraw-Hill, New York, 1985/ 1986.

*Note:* *t*m = machining time, s; *d*m = diameter of the machined surface, in.; *l*w = length of the machined surface in the direction of cutting, in.; υf = speed × feed, in.2/ min (Table 7.6); *a*e = depth of cut or depth of the groove in milling, in.; *d*t = diameter of the cutting tool, in.; *w*t = width of the grinding wheel, in.; *a*r = depth of the material removed in rough grinding, in.; *l*t, = length of the tool, in.; *w*k = width of the machined keyway, in.; *d*k = depth of the machine keyway, in.

Then, selection of the optimum cutting speed can be made by minimizing machining costs (see Equation 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 different roughing and finishing operations. Problem arises, however, when applying the fi gures for roughing operations. For example, Ostwald recommends a cutting speed of 500 ft/ mm (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 μm3/ s). The *Machining Data Handbook* [2] quotes a figure of 1.35 hp min/ in.3 (3.69 GJ/ m3) (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 effi ciency of around 70%, it can be seen that the recommended conditions could not be achieved except for small depths of cut. Under normal roughmachining 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 independent of the cutter speed. Thus, assuming that the optimum cutting speed is employed, the feed speed that gives 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

Everytime 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 Equation 7.35. If the expressions for machining time *t*m (Equation 7.31) and cutting speed υc (Equation 7.33) are substituted, the minimum cost of production can be expressed by

*C*min = *Mt*l + (*Mt*1 −mc*n*) (7.42)

where *t*mc 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 allows 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 the 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 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 Equation 7.42 overestimates tool costs. If *t*mp is the machining time where the cutting speed υpo giving maximum power is used, then the production cost *C*po for maximum power is given by

(*Mt*ct + *C t*t ) mp

*C*po = *Mt*l + *Mt*mp + (7.43) *t*po

where *t*po is the tool life obtained under maximum power conditions, which, from Taylor’s tool life equation, is



= υ 1/ *n*

*t*po *t*c υpoc  (7.44)



The tool life *t*c under minimum cost conditions is given by Equation 7.34, and substituting Equations 7.44 and 7.34 into Equation 7.43 and using the relation in Equation 7.31 gives

#  

*C*po = *Mt*l + *Mt*mp 1 + ~~(~~1 −*n n*~~)~~ *tt*mpmc 1/ *n* (7.45)



Thus, Equation 7.45 can be used instead of Equation 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 D ata

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 × feed (υ*f* ), or the rate at which the machined surface can be generated. Table 7.6 gives typical values of υ*f* for several material classifi cations 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 fi gures for υ*f* given in Table 7.6 would be divided into the surface area (*A* m = π/ wd m) to give the machining time *t*mc. Thus

*t*mc = 60(υ*Af* )m s (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 are generally machined on small machines with lower power available, whereas larger components are machined on large higher-powered machines. For example, a small lathe may have less than 2 hp available for machining, whereas an averagesized lathe may have 5–10 hp available. A larger vertical lathe perhaps has 10–30 hp available. Typical power values for a selection of machines are presented in Figure 7.47, where the horsepower 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 = 60*V*m *p P*s/ m 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 π*d*m*l*w*a*p. However, for a facing or cut-off

### Table 7.6

Machining Data

**Turning, Facing and Boring**

**Drilling and Reaming**

**(1**

**in.**

**)**

***vf***

**(in**

**2**

**/min)**

**a**

**Brazed *p*s *vf*(in.2/min)a *p*s Material Hardness HSS Carbide (hp/in.3/min)b HSS (hp/in.3/min)b**

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Low carbon steel (free machining) | 150–200 | 25.6 | 100 | | 1.1 | 33.0 | | 0.95 |
| Low carbon steel | 150–200 | 22.4 | 92 | | 1.35 | 13.4 | | 1.2 |
| Medium and high carbon steel | 200–250 | 18.2 | 78 | | 1.45 | 15.1 | | 1.4 |
| Alloy steel (free machining) | 150–200 | 23.7 | 96 | | 1.3 | 16.4 | | 1.15 |
| Stainless, ferritic (annealed) | 135–185 | 12.6 | 48 | | 1.55 | 9.4 | | 1.35 |
| Tool steels | 200–250 | 12.8 | 54 | | 1.45 | 6.2 | | 1.4 |
| Nickel alloys | 80–360 | 9 | 42 | | 2.25 | 14.3 | | 2.0 |
| Titanium alloys | 200–275 | 12.6 | 24 | | 1.35 | 7.9 | | 1.25 |
| Copper alloys (soft) (free machining) | 40–150 | 76.8 | 196 | | 0.72 | 38.4 | | 0.54 |
| Zinc alloys (die cast) | 80–100 | 58.5 | 113 | | 0.3 | 51.1 | | 0.2 |
| Magnesium and alloys | 49–90 | 162 | 360 | | 0.18 | 75.2 | | 0.18 |
| Aluminum and alloys | 30–80 | 176 | 352 | | 0.28 | 79.8 | | 0.18 |
| **Factor** | **For** |  | **Turning, Facing Boring** | | | **Milling** | |  |
| *k* Finishing f | |  | 0.60 | | | | 0.89 |  |
| *k* Disposable Insert i | |  | 1.17 | | | | 1.13 |  |
| **Factor For** | |  |  | **Tool Diameter (in.) (mm)** | | | |  |
| 1/ 16 | | | 1/ 8 | 1/ 4 1/ 2 3/ 4 1 1.5 | | | | 2 in. |
| ***k*** 1.59 **h** | | | 3.18 | 6.35 12.7 19.7 25.4 38.1 | | | | 50.8 mm |
| Drilling and reaming 0.08 | | | 0.19 | 0.35 0.60 0.83 1.00 1.23 | | | | 1.47 |
| **Factor For** | | |  | **length/Diameter Ratio** | | | |  |
| < 2 | | | 3 | 4 5 6 | | | | 8 |
| *k* Deep holes 1.00 d | | | 0.81 0.72 0.56 0.52 | | | | | 0.48 |

*Source*: Adapted from *Machining Data Handbook*. Vols. 1 and 2, 3rd ed. Metcut Research Association Inc., 1980.

a To convert in.2/ min to m2/ min, multiply by 6.45 × 10−4. b To convert hp min/ in.3 to GJ/ m3 multiply by 2.73.

All data are for rough machining. For fi nish machining multiply by *k*f.

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, multiple by *k*i.

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 m.

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

1

1

10

Machining center

Surface grinder

Power drill

Manual

turret lathe

CNC lathe

Horsep

ower

av

ailable

100

10

100

1000

10,000

Average workpiece weight (lb)

**Figure 7.47**

Relation between horsepower and workpiece weight for some machine tools.

operation carried out at constant rotational speed, the power limitations apply only at the beginning of the cut and the machining time is longer than that given by Equation 7.47.

It was pointed out earlier that for milling operations, it is convenient to estimate machining time from knowledge of the feed speed υf that gives 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 = 60*l*w/ υf 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 are often as large as the cutter diameter.

The machining time for maximum power is given by Equation 7.47, but, again, corrections must be made for cutter approach and overtravel.

## 7.12.9 rough g rinding

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*t. 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: 5500–6500 ft/ min

Table speed: 50–150 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, vitrifi ed bond)

### Table 7.7

Machining Data for Milling Operations

**Material**

**Hardness**

**(**

**Bhn**

**)**

**Milling**

υ

**f**

**(in./min)**

**a**

**Side and Face HSS**

**Brazed Carb.**

**End (1.5 in.) HSS**

**Brazed Carb.**

***p***

**s**

**(hp/in.**

**3**

**/min)**

**b**

Low carbon

150–200

19.2

52.9

4.5

15.7

1.1

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| steel (free  machining) Low carbon steel  Medium and high carbon steel  Alloy steel (free machining)  Stainless, ferretic (annealed) Tool steels  Nickel alloys  Titanium alloys  Copper alloys  (soft) (free  machining)  Zinc alloys (die cast)  Magnesium and alloys  Aluminum and alloys | 150–200  200–250  150–200  135–185  200–250  80–360  200–275  40–150  80–100  40–90  30–80 | 13.5  10.8  13.7  14.0  6.7  4.1  3.9  50.5  28.0  77.0  96.2 | 43.3  37.3  40.2  41.0  23.7  7.7  13.2  108.3  60.1  240.6  216.5 | 2.2  1.8  2.7  2.4  0.9  1.0  1.5  9.9  9.8  27.5  20.4 | 9.9  8.9  10.5  6.0  4.5  —  7.1  20.7  16.0  55.0  36.7 | 1.4  1.6  1.3  1.7  1.5  2.15  1.25  0.72  0.4  0.18  0.36 |
|  | | | | | | |

*Source*: Adapted from *Machining Data Handbook*. Vols. 1 and 2, 3rd ed. Metcut Research Association Inc., 1980. a To convert in/ min to mm/ s multiple by 0.423. b To convert hp/ min/ in3 to GJ/ m3 multiply by 2.73.

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 = 60 *V*m/ *Z* w (7.49)

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 = 60*a*d *w l*t w/ *Z* w = 60(1 0)( .25)( )4 0/ .68 = 88.2 s