Engr. Dr. Chigbogu G. Ozoegwu (ME 212 Coordinator)
Mechanical Engineering, University of Nigeria, Nsukka

AN INTRODUCTION TO MACHINE SHOP THEORY, HEAT TREATMENTS AND APPLICATIONS

A LECTURE NOTE COVERING PART OF ME 212
Recommended Text[1]

1. Introduction

Machine tools are found in the machine shop section of a manufacturing workshop. Machining of metals is done using the *machine tools*. A widely accepted definition of machine tools, that has been adopted by the European Association of the Machine Tool Industries (CECIMO), (2011), is "A metal working machine tool is a power driven, not portable by hand, powered by an external source of energy, designed specifically for metal working either by cutting, forming, physico-chemical processing, or a combination of these techniques." The expression "physico-chemical processing" in the definition partly suggests the existence of non-traditional machining processes (chipless machining processes that were motivated by the need for economic and productive machining of hard metals and ceramics) which include: chemical machining, electrochemical machining, electro-discharge machining, electron beam machining, laser beam machining, plasma jet machining and jet machining. Some of the machine tools that can be found in the machine shop are lathe machine, milling machine, drilling machine, shaping machine (shaper), planning machine (planner), the abrasive machine tools, honing machine, broaching machine, power saw, slotting machine, etc.

From the early 21st century, the traditional classification of machine tools into lathe machine, milling machine, planer, shaper, slotting machine, broaching machine, drilling, power saw, grinding machine, etc is becoming obsolete because of the very recent development of machine tools with unusual combination of capabilities. It became awkward to classify machine tools but machining processes. Such multi-purpose manufacturing machines were developed to minimize downtime in a manufacturing line. In the adapted words of López de Lacalle and Lamikiz (2009), the multi-purpose machine tools include: (1) machining centre which is designed and constructed to use rotating tools, with capability of milling, drilling, boring and tapping, (2) turning centre which is derived from the lathe with capability of turning and milling, (3) multi-task machine is is designed and constructed to combine two machining processes like milling and turning, turning and grinding and milling and grinding, and (4) hybrid machine which is built to combine a machining process and other manufacturing processes like casting. In classifying machining processes, some of the operations include milling, turning, facing, drilling, boring, broaching, hobbing, shaping, planning, threading, gear cutting, grinding, super-finishing, honing, lapping, etc.

2. Machining process parameters and cutting action

These are the parameters that express the relative motion and relative positioning between the tool and the workpiece. They can be classified into speeds and depths. Speeds are usually of two types, the primary (cutting) and secondary (feed) speeds. The primary speeds derive directly from electric motors while the secondary speeds are tapped from the primary speeds using gear, belt or friction drive systems. Depth is the penetration of tool into the workpiece. Depths are also usually of two types, axial depth of cut and radial depth of cut. While the former implies a penetration parallel to the rotational axis, the latter means

[1] Black, J. T., and Kohser, R. A. (2008) Degarmo's Materials and Processes in Manufacturing, 10th Edition, John Wiley & Sons, United States of America.

a penetration normal to the rotational axis or parallel to a radial line of the spindle. Table 1.1 shows the types of depths and speeds prescribed on the tool and workpiece of various cutting operations.

The tabulated relative motions influence the force action in machining operations. During cutting processes, tools and workpieces are subjected to both active and reactive forces. When the tool is in motion, it acts against the workpiece and the workpiece reacts against it, and vice versa. For example, in lathe turning, the tool is in secondary motion thus exerts active secondary (feed or thrust) force on the workpiece which in turn reacts against the tool with equal and opposite force. At the same time the primary motion of the workpiece exerts an active primary (tangential) force on the tool which in turn reacts against the workpiece with equal and opposite force. Therefore, the resultant force on the tool has both active and reactive components. The same goes for facing and boring processes. The force components on drilling tool are entirely reactive. The forces on shaping and planning tools derive only from primary motions but the magnitudes are partly influenced by the size of intermittent feeds. The force is reactive in the former and active in the latter. A similar force action occurs in milling as in turning except that the causative motions are interchanged.

Table 1.1. The types of depths and speeds prescribed on the tool (T) and workpiece (WP) of various cutting operations.

Machining Process	Speed type and the moving body		Depth type
	Primary	Secondary	
Lathe turning	WP ↷	T →	Radial
Lathe facing	WP ↷	T →	Axial
Boring	WP ↷	T →	Radial
Drilling	T ↷	T →	Radial
Milling	T ↷	WP →	axial and radial
Planning	WP →	T ⇢	Radial
Shaping	T →	WP ⇢	Radial
Surface grinding	T ↷	WP →	Radial
Cylindrical grinding	T ↷	WP → ↷	Radial
Honing	T ↷	T →	Radial
Micro-honing	WP ↷	T →	Radial

Engr. Dr. Chigbogu G. Ozoegwu (ME 212 Coordinator)
Mechanical Engineering, University of Nigeria, Nsukka

3. Machining processes

3.1. Turning

3.1.1. Geometry and kinematics

In turning operation a primary rotary motion of the spindle Ω, in revolutions per minute (rpm), is imparted to the workpiece and a secondary speed v (also called feed speed), in meters per second, is imparted to a single–point tool parallel to the rotational axis. Therefore, a surface of revolution is generated in turning operation with the prescription of the machining process parameters; spindle speed Ω, depth of cut w and feed speed v. Turning is one of the several operations that can be carried out on a lathe machine, a turning centre or multi-task machine. When the feed motion is perpendicular to the rotational axis, flat surface perpendicular to the rotational axis is generated on a cylindrical component and the machining process is called facing. Some important machining process parameters associated with turning and facing are shown in Figure 1.1, and they together with their derived parameters are discussed as follows;

The primary or cutting speed V_t is the maximum relative tangential motion between the workpiece and the cutting edge due to the spindle rotation. It is given as

$$V_t = \frac{D}{2} \times \frac{2\pi\Omega}{60} = \frac{\pi D\Omega}{60} \tag{1.1}$$

where D is the diameter of the last generated cylindrical surface of the workpiece in meters. Actually, cutting speed varies along the edge of the tool in direct proportion with distance from rotational axis. The average cutting speed is

$$V_{ta} = \frac{\pi\,\Omega\,(D-w)}{60} \tag{1.2}$$

where w, the depth of cut, is the penetration of the cutting edge into the workpiece. Feed f is the distance advanced per spindle revolution by the cutting edge into the workpiece as a result of feed speed (feed rate) v of the carriage. In turning operation, the feed speed is the rate of displacement (as tapped from the feed screw) of the carriage which carries the tool post. The feed is then given as

$$f = v\tau \tag{1.3}$$

where τ is the period of revolution given as

$$\tau = \frac{2\pi}{\left(\frac{2\pi\Omega}{60}\right)} = \frac{60}{\Omega} \tag{1.4}$$

The distance *AB* as shown in Figure 1.1 covered by the turning tool while cutting the workpiece before idly going back to re-engage with the workpiece for another cutting action is called a cutting *pass*. If the cutting edge is inclined to the spindle axis at an angle i but still perpendicular to V_t (orthogonal cutting), then the depth of cut w of turning process, which is the amount of penetration of workpiece by the tool in a direction perpendicular to the spindle axis, becomes

$$w = b\sin(i) \tag{1.5}$$

where b is the contact length between the tool and workpiece.

In facing operation, the cutting speed varies continuously with time t and it is given as

$$V_t = \frac{\pi\,\Omega\,(D_1 - 2vt)}{60} \quad (1.6)$$

where D_1 is the initial diameter of the workpiece. The undeformed chip thickness h is the component of feed normal to the tool-workpiece contact length in a spindle revolution. It is the same as feed rate f when $i = 90^0$ but otherwise, it is given as

$$h = f\sin(i) \quad (1.7)$$

The undeformed chip cross-sectional area is given as

$$A_{uc} = hb = fw \quad (1.8)$$

The undeformed chip cross-sectional area is important in modelling of cutting forces as will be seen subsequently.

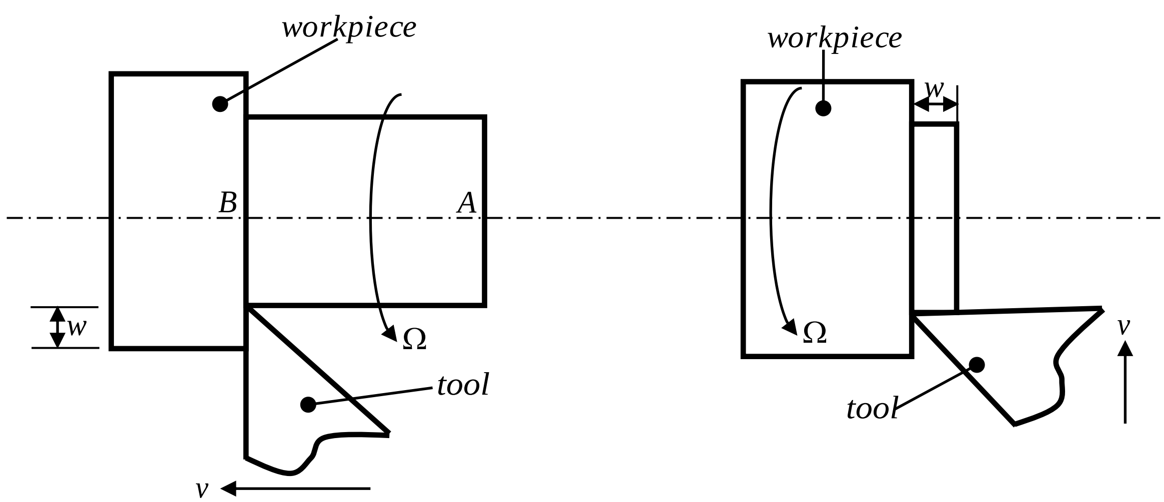


Figure 1.1. Important machining parameters associated with (a) turning operation (b) facing operation.

3.1.2. Cutting force and cutting power

As earlier discussed, the cutting force F_c has both feed component F_f and tangential component F_t which are both proportional to the undeformed chip cross-sectional A_{uc}. Therefore,

$$F_f = K_f A_{uc} = K_f f w \quad (1.9)$$

$$F_t = K_t A_{uc} = K_t f w \quad (1.10)$$

The cutting force, in magnitude and direction, becomes

$$F_c = \sqrt{F_t^2 + F_f^2} = fw\sqrt{K_t^2 + K_f^2} = K_t f w\sqrt{1+\chi^2} = K_t w v \frac{60}{\Omega}\sqrt{1+\chi^2} \quad (1.12)$$

$$\theta = \tan^{-1}\left(\frac{F_f}{F_t}\right) = \tan^{-1}\left(\frac{K_f}{K_t}\right) = \tan^{-1}(\chi) \quad (1.13)$$

where $\chi = F_f/F_t = K_f/K_t$. The cutting power is given as

$$P_t = F_t V_t \tag{1.14}$$

This power is consumed in the shearing of the workpiece material on the shear plane to generate chips, in overcoming the frictional rubbing between the tool rake face and the workpiece, in providing the surface energy needed for the formation of new surface areas (machined and chip surfaces), and in providing the impulsive force needed to change the direction of the motion of material from that on the workpiece to that on the chip (Shaw, 2005).

Example 1.1: The spindle speed, feed speed and depth of cut of orthogonal turning of a 10cm diameter workpiece are 4000rpm, 0.0025ms^{-1} and 2.5mm. Calculate the cutting speed during the first pass, the feed and the undeformed chip cross-sectional.

Solution:

Using the applicable equations, the needed quantities are respectively calculated as

$$V_t = \frac{\pi \times 0.1 \times 4000}{60} = 20.9440\text{ms}^{-1}$$

$$f = 3.7500 \times 10^{-5}\text{m} = 0.0375\text{mm}$$

$$A_{uc} = 9.3750 \times 10^{-8}\text{m}^2 = 9.3750 \times 10^{-2}\text{mm}^2$$

Example 1.2: In orthogonal cutting, the spindle speed, feed speed and depth of cut are respectively 350.14rpm, 1.2mm/sec and 6.35mm. (a) calculate the cutting force F_c (in magnitude and direction) if experimental measurements gave $K_t = 2.44 \times 10^9\text{Nm}^{-2}$, $\chi = K_f/K_t$=0.676. (b) calculate the cutting power P_t during the first pass of the tool if the workpiece diameter is 5cm.

Solution:

(a)

$$F_c = K_t w v \frac{60}{\Omega}\sqrt{1+\chi^2}$$

$$= 2.44 \times 10^9 \times 6.35 \times 10^{-3} \times 1.2 \times 10^{-3} \times \frac{60}{350.14} \times \sqrt{1+0.676^2}$$

$$F_c = 3845.7\text{N}$$

$$\theta = \tan^{-1}\left(\frac{F_f}{F_t}\right) = \tan^{-1}\left(\frac{K_f}{K_t}\right) = \tan^{-1}(\chi) = \tan^{-1}(0.676) = 34.1^o = 0.594 \text{ rad}$$

(b) The cutting speed is given as

$$V_t = \frac{\pi \times 0.05 \times 350.14}{60} = 0.9167\text{ms}^{-1}$$

and the tangential cutting force is given as

$$F_t = K_t f w = 2.44 \times 10^9 \times \frac{1.2}{1000} \times \frac{60}{350.14} \times \frac{6.35}{1000} = 3186.1\text{W}$$

Therefore, cutting power becomes

Engr. Dr. Chigbogu G. Ozoegwu (ME 212 Coordinator)
Mechanical Engineering, University of Nigeria, Nsukka

$$P_t = F_t V_t = 0.9167 \times 3186.1 = 2920.7\text{W}$$

Example 1.3: If Ω is spindle speed in revolutions per hour (rph), D is diameter in millimeters and f is feed in millimeters. (a) Derive the expression for the cutting speed in meters per minute. (b) Derive the expression for the feed speed in meters per minute.

(a) The cutting speed is given as

$$V_t = \omega \frac{D}{2\times1000}$$

where angular velocity ω in rad/min is given as

$$\omega = \frac{2\pi\Omega}{60}$$

Therefore,

$$V_t = \frac{2\pi\Omega}{60}\frac{D}{2\times1000} = \frac{\pi D\Omega}{60000}$$

(b)The feed in meters is

$$\frac{f}{1000} = v\tau$$

giving

$$v = \frac{f}{1000\tau}$$

Since $\tau = 60/\Omega$ in seconds then $\tau = 1/\Omega$ in minutes. Therefore, feed speed in meters per minute becomes

$$v = \frac{f\Omega}{1000}$$

Other units for feed, feed rate and cutting speed can be found in literature. This example illustrates how this can be handled.

3.2. Milling

Milling is a material removal process during which the workpiece is fed past a rotating multi-toothed (multi-point) cutter. While the cutting force of a stable turning is fixed, that of milling varies periodically. Two types of milling process are distinguished, namely; peripheral milling and face (or end) milling as illustrated in Figure 1.2. In peripheral milling a surface parallel to the cutter axis is produced. Peripheral milling is sub-divided into up-milling or conventional milling where the workpiece is fed against the rotating cutter and down-milling or climb milling where the cutter is rotated in the feed direction of the workpiece. The two types of Peripheral milling are shown in Figure 1.3. Each method of peripheral milling has its peculiar advantages and disadvantages for example down-milling is less prone to chatter vibration in most cases thus results in improved surface finish than up-milling but suffers from shock loads. The shock loads are encountered in down-milling because teeth engagement with the workpiece occurs at large chip thicknesses but in up-milling there are no shock loads since chip thicknesses grow from very small values to larger values. Massive adoption of up-milling pre-dated massive adoption of down-milling because it was initially difficult to deal with the shock loads of engagement between the cutting edges and the workpiece until the machine tool structures developed to systems with adequate rigidity.

Face milling process generates a surface that is normal to the cutter axis. End-milling tool is used to carry out face milling. Figure 1.4 below depicts an end-milling operation. End-milling cutters which are equipped with shanks for mounting on the spindle are utilized for end milling. End-milling can be executed in both up and down-milling modes much like what obtains in peripheral milling.

Milling can also be broadly classified as horizontal and vertical milling. In horizontal milling the tool is mounted on a shaft, called arbor, which is supported at two ends that rotate in a parallel plane to the plane of the workpiece surface. The tool is held only at one end by a tool holder in a plane normal to the plane of workpiece surface in vertical milling. Peripheral milling is horizontal milling while end-milling is vertical milling. The equivalent machining parameters associated with milling are shown in Figure 1.5.

The cutting speed of milling process is also given by Equation (1.1) where D is the diameter of the tool. The feed per tooth is as given in Equation (1.3) where τ is the period or time interval between two cutting edges. This period of milling process (τ) is given as

$$\tau = \frac{60}{\mathrm{N}\Omega} \tag{1.15}$$

where N is the number of cutting edges or flutes. The cutting process indicated in Figure 1.5 shows the radial depth of cut B. Radial depth of cut is usually non-dimensionalized to become radial immersion $\rho = B/D$.

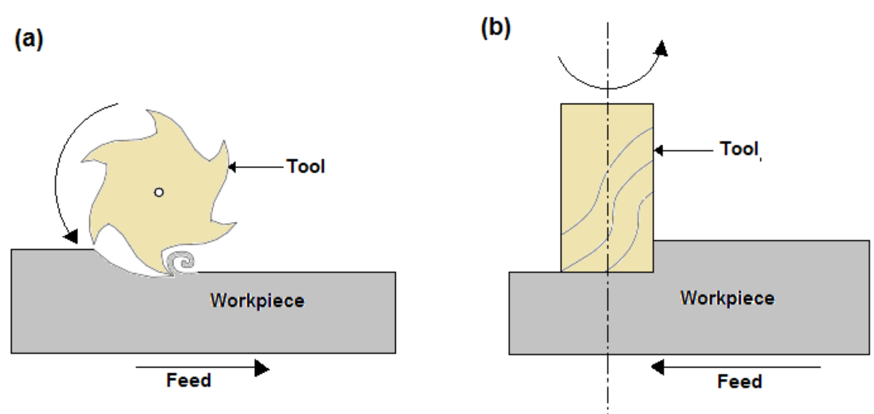


Figure 1.2. Milling classified into (a) peripheral (plain) milling and (b) face (end) milling. The arrows indicate spindle rotation and feed motion.

Engr. Dr. Chigbogu G. Ozoegwu (ME 212 Coordinator)
Mechanical Engineering, University of Nigeria, Nsukka

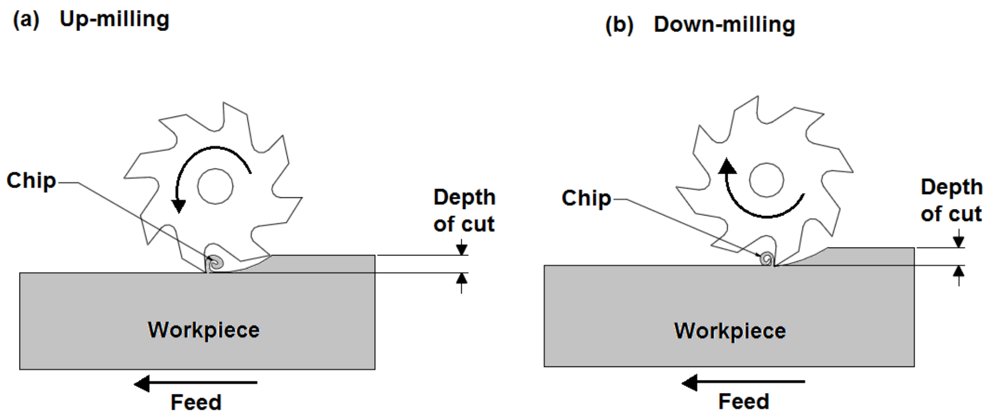


Figure 1.3. Two modes of peripheral milling are identified as (a) up-milling or conventional milling and (b) down-milling or climb milling

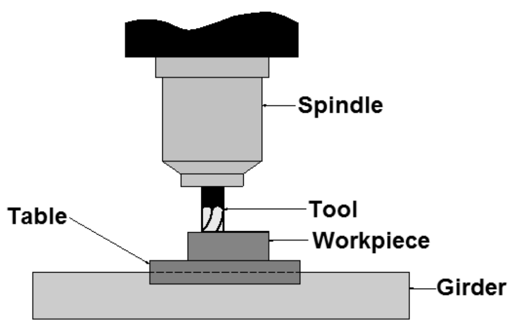
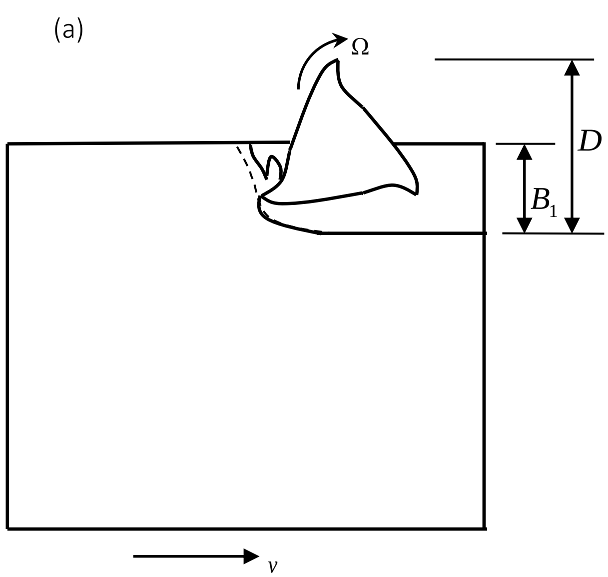


Figure 1.4. Depiction of end-milling operation.



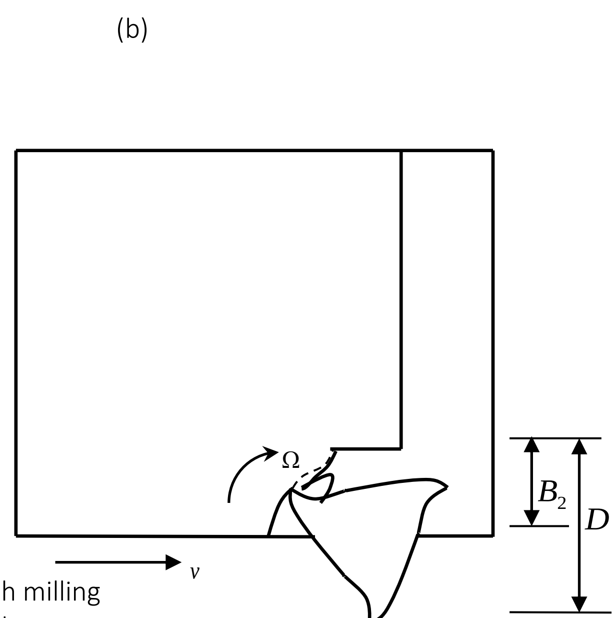


Figure 1.5. The machining parameters associated with milling
(a) The up end-milling and (d) down end-milling modes

Engr. Dr. Chigbogu G. Ozoegwu (ME 212 Coordinator)
Mechanical Engineering, University of Nigeria, Nsukka

3.3. Drilling

Drilling is a process for the production of cylindrical through or blind holes. The holes could either have been originated or enlarged by the drilling process. Drilling involves feeding a rotary cutting tool called drill along its axis of rotation into a stationary workpiece. Drilling is generally considered a roughing operation and, therefore, is usually followed by some finishing operations like reaming, boring, or grinding. Drills are available in mainly two types; the spade drill and the twist drill. Though the spade drill has been in used for thousands of years, the twist drill is mostly used today. The twist drill has two cutting edges at the end of two helical grooves. The inclination of the side edges of the grooves to the vertical is called helix angle. As indicated in Figure 1.6, the grooves provide ease of passage to cutting fluids and the chips. Twist drills are available in the diameter range 0.25 - 80 mm. The side edges of the grooves are usually inclined at standard helix angle of 30^o for drilling of steels. *Slow*-helix drills with helix angle less than 30^o are used for drilling such materials as brass, bronze and plastics. *Quick* helix drills with helix angle greater than 30^o are suitable for drilling softer materials such as aluminium alloys and copper.

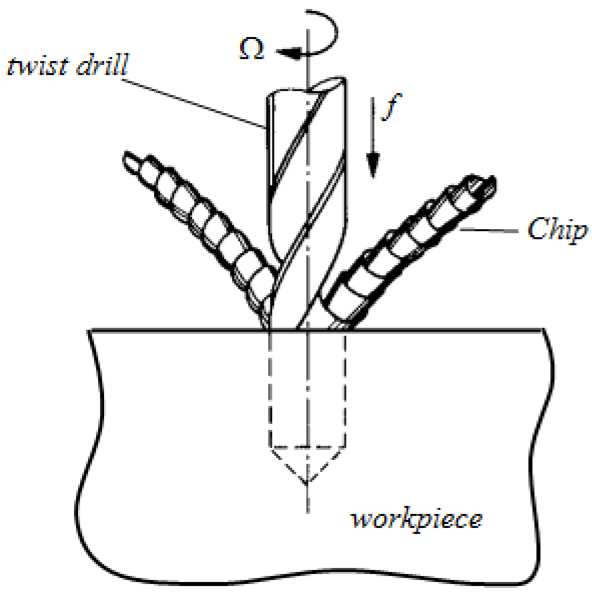


Figure 1.6. Drilling with a twist drill. Adapted from (Shaw, 2005)

3.4. Boring

Internal surface of a hollow cylindrical part is generated in boring process with single point tool. The feed is parallel to the axis of rotation of the spindle. Boring is frequently used for enlarging and finishing holes initiated with drilling process. Large holes in castings and forgings are also finished by boring operation. Note that the geometry and kinematics of turning process apply exactly to boring process. The only difference is that cutting speed and cutting power rises with more number of tool passes.

3.5. Shaping and Planning

Shaping and Planning are metal cutting processes for generating both planar surfaces (horizontal, vertical, and inclined) and contoured surfaces. Shaping and Planning differ only in the allocation of feed and cutting motions to the workpiece and the tool. While in the former a reciprocating cutting motion is imparted on the tool and intermittent feed motion is imparted on the workpiece, in the latter the vice versa is the case. The operations are illustrated in Figure 1.7. Shaping and Planning are intermittent. The intermittence stem from the fact that the *to* pass of the reciprocation cutting motion is the cutting pass while the *fro* (return) pass is an idle motion. And, the feed motion is intermittently executed after every idle pass followed by shock load of engagement for the next cutting pass. Thus shaping and planning require rigid machine tool structures and tools like climb milling. The machining parameters associated with shaping and planning are discussed as follows; the feed f is the intermittent movement of the tool or workpiece in length units per stroke in a direction perpendicular to the cutting motion. the Depth of cut w is the amount of penetration of tool in a direction perpendicular to the plane of machined surface.

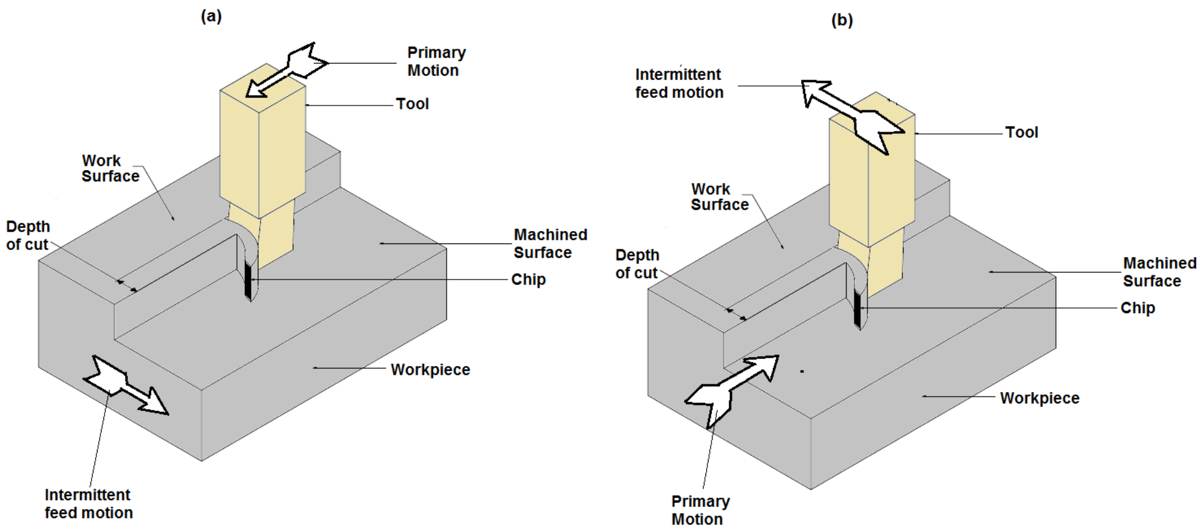


Figure 1.7. (a) Shaping and (b) Planning operations. Adapted from (Youssef and El-Hofy, 2008).

3.6. Grinding

Grinding is an abrasive machining process that utilizes grinding wheel or coated abrasives. The cutting edges on the grinding wheels or coated abrasives are grains of abrasive materials (grits) of high hardness and high refractoriness. The grits are irregular and non-definite in shape and randomly bonded along the periphery of grinding wheel and coated abrasive belts. As a result, the grits protrude to different extents thus producing chips of different volumes. The grits are single point tools of usually high negative rake angle in the range of -40 to -80 making the chip thickness to be relatively much larger than the uncut chip thickness (the shear angle is very low and the shear plane has larger area), see Figure 1.8. Grinding gives high accuracy and good surface finish because of small size of the grits and very low feed to cutting speed ratios typical of grinding process. As a result, it is usually employed for finishing operation on an unfinished work generated from annealed workpiece and then hardened. Since grits are both on the periphery and within the bonding material the Grinding wheel has a self-sharpening characteristic as wear, fracture or tearing off of abrasives expose new sharp grains to the work.

In the use of grinding wheels, the wheels are rotated at speed Ω_{gw} rpm, the longitudinal feed v_{lf} is imparted on the workpiece and the depth of cut w (feed/stroke) is imparted on the wheel normal to the machined surface. The peripheral speed of the grinding wheel is given by

$$V_{gw} = \frac{\pi \Omega_{gw} D_{gw}}{60} \tag{1.16}$$

The ratio of feed to the peripheral speed of the grinding wheel reads

$$r_{v_{lf}} = \frac{v_{lf}}{V_{gw}} = \frac{60\, v_{lf}}{\pi \Omega_{gw} D_{gw}} \tag{1.17}$$

According to Youssef and El-Hofy, (2008) the ratio $r_{v_{lf}}$ typically ranges from 1/20 (for rough grinding) to 1/120 (for finishing). The depth of cut w (feed/stroke) ranges from 10 µm (for finish cuts) to 100 µm (for roughing). The grinding process that leads to generation or finishing of a flat surface is called surface grinding. A grinding wheel or grinding belt of coated abrasive can be used in surface grinding. The grinding process that leads to generation or finishing a cylindrical surface is called cylindrical grinding. In cylindrical grinding, the workpiece is either rotated between centres or rotated centreless between two wheels (centreless grinding). The work is not supported between centres in centreless grinding but is held against two wheels and a supporting rest (see Figure 1.9). The small wheel in Figure 1.9 is the control or regulating wheel that is lined with fine abrasives bonded with rubber. This measure guarantees better friction between the workpiece and the regulating wheel such that the regulating wheel holds and rotates the workpiece at its peripheral speed which is normally in the range 20–30 m/min. By being slightly inclined to the grinding wheel, the control wheel imparts the necessary longitudinal feeds of the workpiece. An alternative arrangement for longitudinal feeding of the workpiece is giving the workpiece rest an inclination while making both wheels to align in same plane. If the plane of the regulating wheel is inclined at an angle α to that of the cutting wheel, then the longitudinal feed v_{lf} and the peripheral velocity of the workpiece (and also the regulating wheel) respectively becomes

$$v_{lf} = \frac{\pi}{60} \Omega_{rw} D_{rw} \sin(\alpha) \tag{1.18}$$

$$V_w = \frac{\pi}{60} \Omega_{rw} D_{rw} \cos(\alpha) = \frac{\pi}{60} \Omega_w D_w \tag{1.19}$$

where Ω_{rw} and D_{rw} are the rotational speed and diameter of the regulating wheel while Ω_w and D_w are the rotational speed and diameter of the work. The larger grinding wheel runs at a much more higher speeds to implement the material removal. The work is set above the centres of the wheels by amount e;

$$0.15 \le \frac{e}{D_w} \le 0.25 \text{ and } e \le 10\text{mm} \tag{1.20}$$

to ensure that a true cylindrical surface is ground on the work. When $e > 10$mm the system will be prone to chattering (a kind of vibration). Cylindrical grinding between centres requires centre holes, a drive system, and other fixtures for holding the workpiece. Though grinding is now mainly used for finishing process, it was traditionally used for machining hard material like hardened steel.

Example 1.4: How will you vary the inclination of a regulating wheel in order to vary cylindrical grinding operation between roughening and finishing operations

Solution:

The ratio of feed to the peripheral speed of the grinding wheel reads

$$r_{v_{lf}} = \frac{v_{lf}}{V_{gw}} = \frac{60\, v_{lf}}{\pi \Omega_{gw} D_{gw}}$$

where

$$v_{lf} = \frac{\pi}{60} \Omega_{rw} D_{rw} \sin(\alpha)$$

.

Therefore,

$$r_{v_{lf}} = \frac{\Omega_{rw} D_{rw}}{\Omega_{gw} D_{gw}} \sin(\alpha)$$

meaning that rougher grinding requires higher $r_{v_{lf}}$ while finishing grinding requires lower $r_{v_{lf}}$. **Therefore, the inclination of a regulating wheel ($\boldsymbol{\alpha}$) should be lowered for finishing and increased for roughening.**

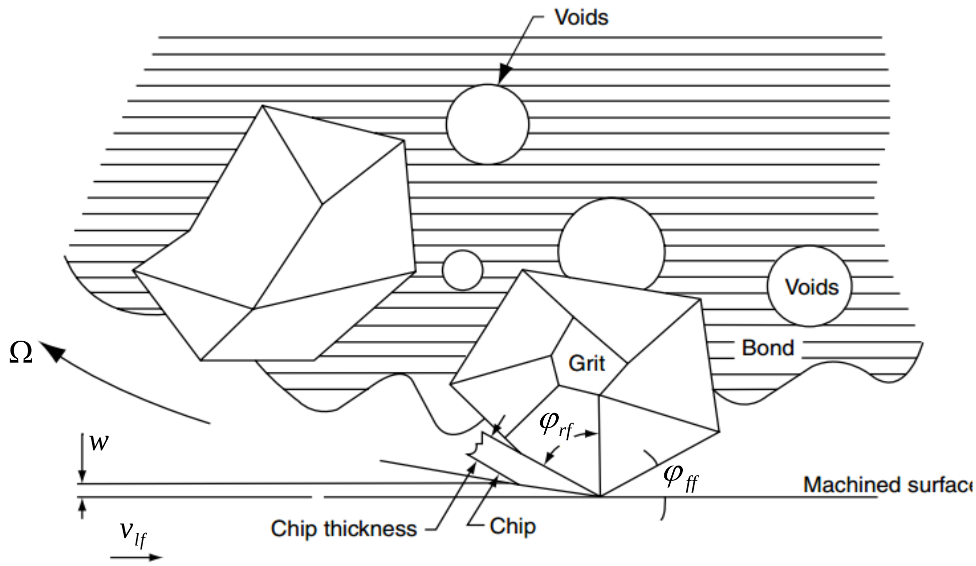


Figure 1.8. Basic parameters of grinding. Sourced from (Youssef and El-Hofy, 2008).

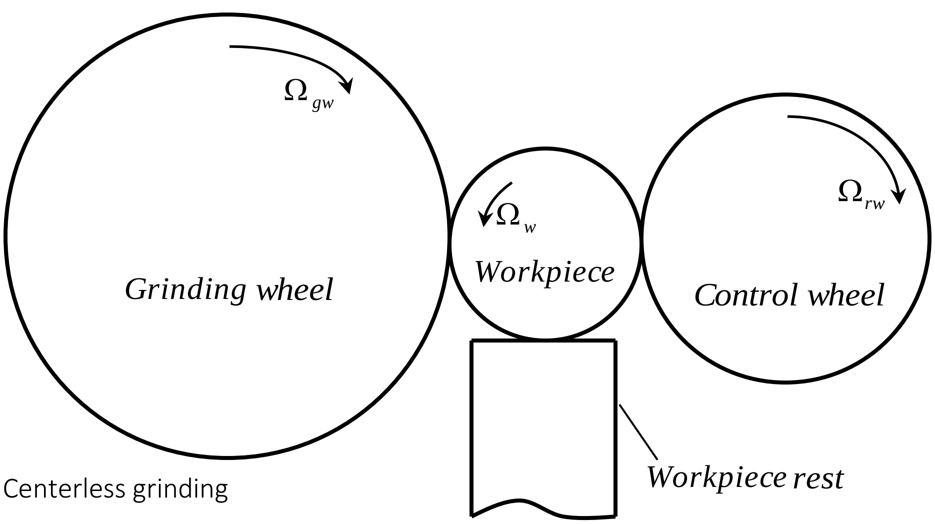


Figure 1.9. Centerless grinding

Engr. Dr. Chigbogu G. Ozoegwu (ME 212 Coordinator)
Mechanical Engineering, University of Nigeria, Nsukka

3.7. Broaching

Broaching is a multi-toothed metal cutting process which is executed by push (push broaches) or pull (pull broaches) action on a broach against a workpiece or vice versa. Any of the two types is called linear broaching. Pull broaches are subjected to tensile stress, thus are made longer (as long as 2m) since there are no possibilities of buckling. The length of the push broaches is usually limited below 15 times its diameter to avoid buckling under compressive stresses. In the much less common rotary broaching (used in generating spiral grooves and gun-barrel rifling etc) the tool is rotated by a lathe or screw machine to cut an axis-symmetric shape into a workpiece. Broaching was originally developed around the early 1850s for cutting keyways in pulleys and gears but now it is suitable for odd shapes like non-circular holes (circular holes are also broached), splines and keyways. Both internal and external surfaces are broached. The side view of a broach is similar to a saw (teeth projected from a bar) but differs in that successive teeth are made to have a progressive variation of height. The broach is made to have regions for roughening, semi-finishing and finishing processes, thus it is a highly productive cutting process in which roughing and finishing operations are completed in one pass. Figure 1.10 describes the basic features of a broach. The sizes of the chips are determined by the rise per tooth (RPT). The RPT, also called superelevation, is different for the different regions of the broach. The RPT of the finishing region is normally zero. It is obvious that RPT is also feed per tooth. The total depth of the material removed in one broaching stroke is the sum of RPT of all the active teeth in the length of cut l. The other geometric parameters of a broach are indicated in Figure 1.11. The pitch p is empirically correlated with RPT, l and chip space number χ as follows (Youssef and El-Hofy, 2008);

$$p = 3\sqrt{RPT.l.\chi} < l/2 \tag{1.21}$$

The condition $p < l/2$ in Equation (1.21) ensures better guidance of the tool and prevents the broach from drifting by simultaneous engagement of at least two teeth. Non-uniformity of the broaching pitch is sometime utilized in avoiding chatter. It can be understood that the feed of broaching is built into the broach rather than prescribed as in most other metal cutting operations.

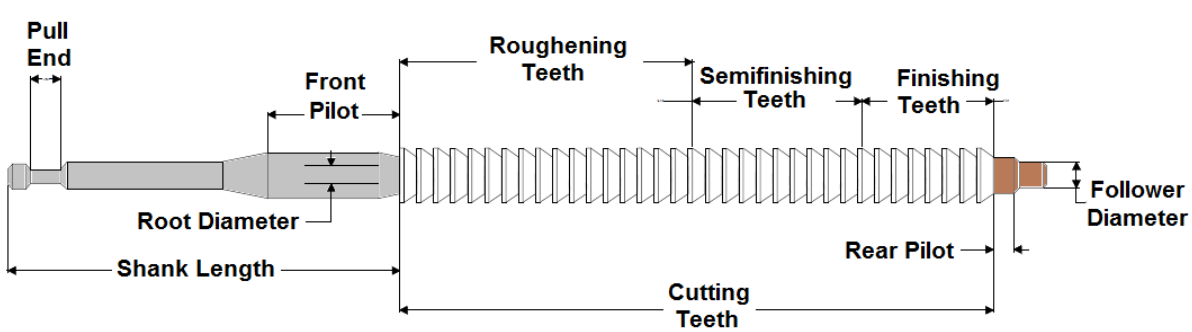


Figure 1.10. The basic features of a broach.

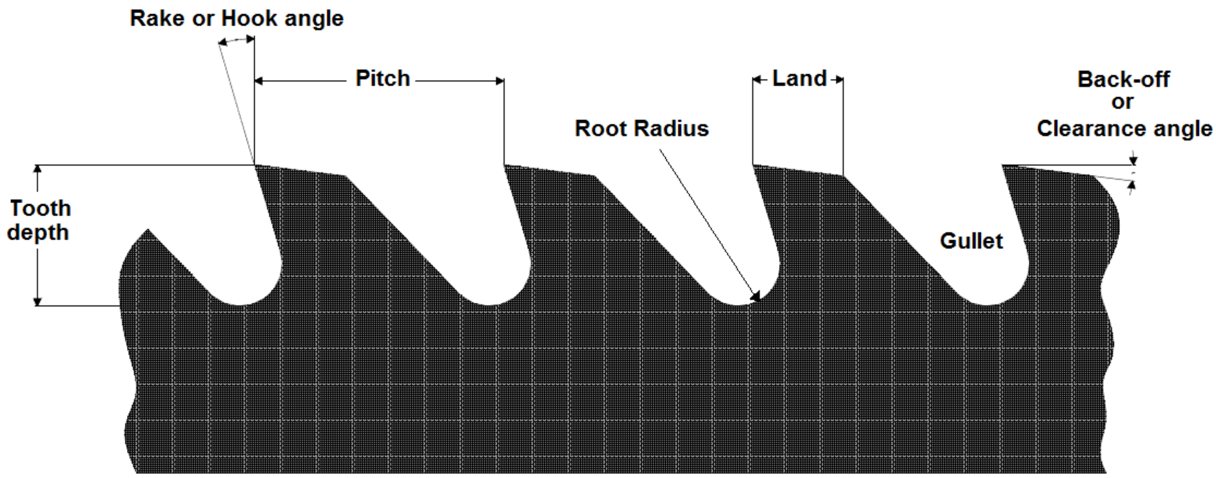


Figure 1.11. The geometric parameters of a broach.

3.8. Honing

Honing is one of the several micro-finishing operations. In honing a rotating and reciprocating honing head carrying abrasive stones touch lightly and slowly on the surface being finished. The vector sum of the rotating and reciprocating motions lead to inclined scratch lines. In a cycle of reciprocation, the scratching of the succeeding honing head on that of the preceding honing head leads to a hatched pattern. A honing head with honing sticks and hatched pattern are indicated in Figure 1.12. The cross-hatch angle is easily seen to be given by

$$\vartheta = 2\tan^{-1}\left(\frac{V_{rcp}}{V_{rt}}\right) \tag{1.22}$$

where V_{rcp} is the reciprocating velocity of the hone while V_{rt} is the surface rotational speed of the hone. The cross-hatch angle ϑ is normally specified in the range 20-45°. This range is realized within the usual ranges of 1.5-30 m/min and 15-90 m/min for V_{rcp} and V_{rt} respectively. The specified range of ϑ helps to retain lubricating fluids and thus reduce unneeded wear. Heat generated in machining basically rises with rise in cutting speed, so much heat is not generated in honing operation as the process is carried out at low speed. Thus, honed surfaces do not undergo thermally activated changes. Honing is most frequently applied in the finishing of bored holes and much less frequently employed in the finishing of external surfaces like gear teeth, valve components and races for antifriction bearings. Honing and micro-honing (super-finishing) can attain fine surface roughness in the range 0.1-0.8 µm and 0.025-0.2 µm. Micro-honing is about the best micro-finishing operation as suggested in Figure 1.13. Workpiece rotates in micro-honing (see Figure 1.14) as against honing in which the tool rotates. Micro-honing finishes surfaces to superfine quality without changing the dimensions of the workpiece.

Example 1.5: In honing process, suppose you maintain the ranges $V_{rcp,1} \le V_{rcp} \le V_{rcp,2}$ and $V_{rt,1} \le V_{rt} \le V_{rt,2}$, what will be the range for ϑ.

Solution:

If $V_{rcp,1} \le V_{rcp} \le V_{rcp,2}$ then $V_{rcp} \ge V_{rcp,1}$ and $V_{rcp} \le V_{rcp,2}$. These, also mean $V_{rt}\tan(\vartheta/2) \ge V_{rcp,1}$ and $V_{rt}\tan(\vartheta/2) \le V_{rcp,2}$. If $V_{rt,1} \le V_{rt} \le V_{rt,2}$ then $V_{rt} \ge V_{rt,1}$ and $V_{rt} \le V_{rt,2}$. Since $V_{rt} \ge V_{rt,1} \equiv V_{rt}\tan(\vartheta/2) \ge V_{rcp,1}$ then $\frac{V_{rcp,1}}{\tan(\vartheta/2)} = V_{rt,1}$ giving $\vartheta = 2\tan^{-1}(V_{rcp,1}/V_{rt,1})$. Also, since $V_{rt} \le V_{rt,2} \equiv V_{rt}\tan(\vartheta/2) \le V_{rcp,2}$ then $\frac{V_{rcp,2}}{\tan(\vartheta/2)} = V_{rt,2}$ giving $\vartheta = 2\tan^{-1}(V_{rcp,2}/V_{rt,2})$. The range for ϑ becomes $2\tan^{-1}(V_{rcp,1}/V_{rt,1}) \le \vartheta \le 2\tan^{-1}(V_{rcp,2}/V_{rt,2})$.

A numerical case where $5 \le V_{rcp} \le 25$ and $30 \le V_{rt} \le 60$ gives $18.92^o \le \vartheta \le 45.24^o$.

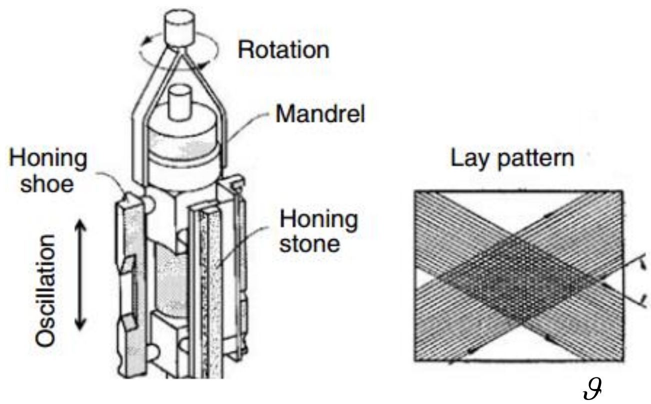


Figure 1.12. (a) A honing head with honing sticks and (b) hatched pattern. Sourced from (Youssef and El-Hofy, 2008).

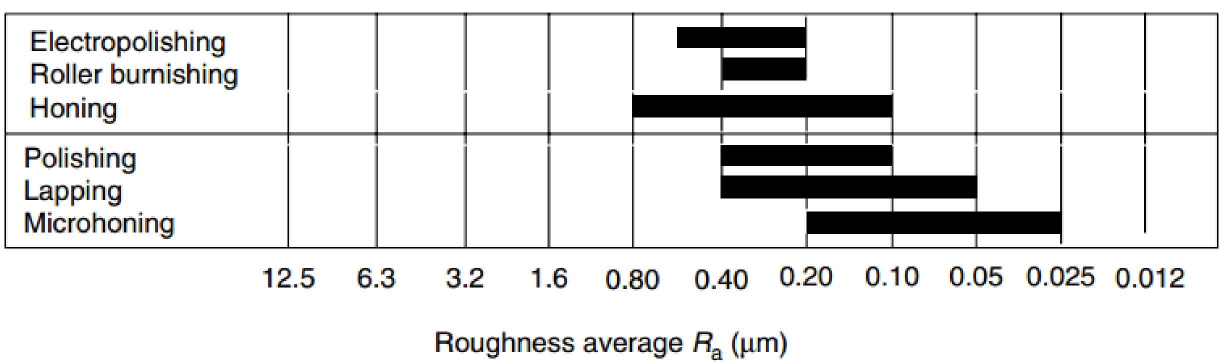


Figure 1.13. Average surface roughness of common microfinishing operations. Sourced from (Youssef and El-Hofy, 2008)

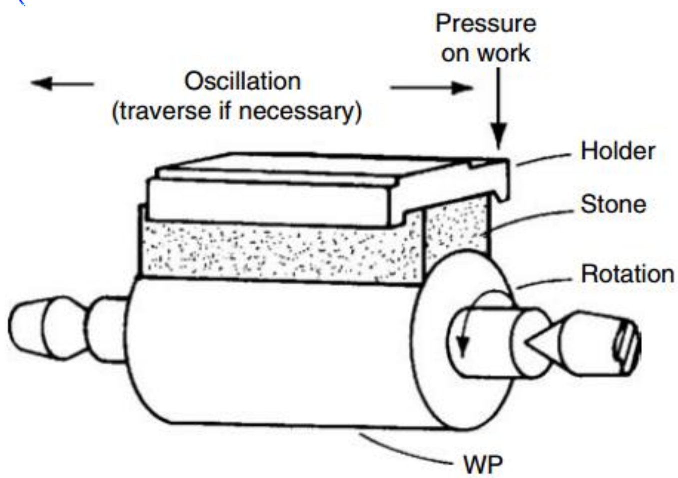


Figure 1.14. Micro-honing process. Sourced from (Youssef and El-Hofy, 2008)

3.9. Lapping

Lapping is a finishing process effected by rubbing two surfaces against each other with a powdery or pasty abrasive placed between them. It is a low-speed and low-pressure abrading process in which thermal metallurgical changes do not occur, like in honing. Normally the lower placed surface is a cast iron lap while the top placed surface is the one being finished.

4. Machine Tool Testing and Maintenance

4.1. Testing of Machine tools

Machine tool acceptance test or simply Machine tool test is usually required after manufacture or repair of any machine tool. It is necessary to guarantee accuracy and the surface quality of machined parts, to determine the level of precision and accuracy of the machine tool, to prepare plans for preventive maintenance and to determine the state hence the expected life of the machine tool. To ensure fidelity of result, test should be performed according to the approved general specification/standard. The usual procedure for acceptance tests is (Youssef and El-Hofy, 2008):

1. Checking the principal horizontal and vertical planes and axes using a spirit level
2. Checking the guiding and bearing surfaces for parallelism, flatness, and straightness, using dial gauge, test mandrel, straight edge, and squares
3. Checking the various movements in different directions using dial gauges, mandrels, straight edges, and squares
4. Testing the spindle concentricity, axial slip, and accuracy of axis
5. Conducting working tests to check whether the accuracy of machined parts are within the specified limits
6. Preparing acceptance charts for the machine tool that specify the type of test and the range of allowable limits of deformation, deflection, error in squareness, flatness eccentricity, parallelism, and amplitude of vibrations

Engr. Dr. Chigbogu G. Ozoegwu (ME 212 Coordinator)
Mechanical Engineering, University of Nigeria, Nsukka

Geometrical alignment tests and *Performance tests* are the two major categories of machine tool tests. The *Geometrical alignment tests* ascertain the manufacture accuracy of machine tools; that is, determine if the intended geometrical (under static conditions) relationships between the various machine tool elements are achieved. The tests include examining the parallelism of the spindle and a lathe bed, parallelism of the spindle and the carriage feed, squareness of the cross slide movement to the lathe spindle, squareness of the table movement to the milling machine spindle, straightness of guideways etc. The static tests are used in conjunction with the dynamic tests to fully judge the machine tool performance. *Performance tests* are carried out under dynamic conditions to check the working accuracy of machine tools through the following steps (Youssef and El-Hofy, 2008):

1. Performing an idle run test and operation check mechanisms
2. Checking for geometrical accuracy and surface roughness of the machined parts
3. Performing rigidity and vibration tests

4.2. Maintenance of machine tools

Since machine tools have moving parts in rubbing contact it must be routinely monitored to avoid excessive wear in their moving parts. Simple preventive measures improve possibility for machine tools to produce accurate parts throughout their working and delays fast deterioration and lowered productivity/higher production cost due to machine stoppage at failure. Maintenance of machine tools can be *preventive*, *corrective* or *reconditioning*. Preventative maintenance centres on reducing wear by routine lubrication of all the moving parts that are subjected to sliding or rolling friction. Preventive maintenance also includes minor and medium repairs. The benefits of preventive maintenance of machine tools are reliability, safety, and prompt functionality. A preventive maintenance scheme is summarized in Figure 1.15. A well-planned scheme of preventive maintenance includes (Youssef and El-Hofy, 2008):

1. adequate records covering the volume of work,
2. inspection frequency schedule,
3. identification of all items to be included in the maintenance program, and
4. well-qualified personnel.

A preventive maintenance scheme is presented in Figure 1.15. *Corrective maintenance* is carried out to avoid machine tool failure when wear in a machine tool in use wear has reached unacceptable level. The elements of the machine tool that according to records needed frequent preventive repairs can be subjected to corrective maintenance. The need for machine tool reconditioning is determined by the frequency of the corrective maintenance just as the frequency of the preventive maintenance determines the need for corrective maintenance. The need for machine tool reconditioning eventually arises as each machine tool component has its life span beyond which it cannot be remedied by preventive maintenance. Machine tool reconditioning is a major overhaul involving massive replacement of machine elements. Exceeding 50% of cost buying new equipment is usually not recommended. The cost of reconditioning depends on the collection of bad elements and labour time.

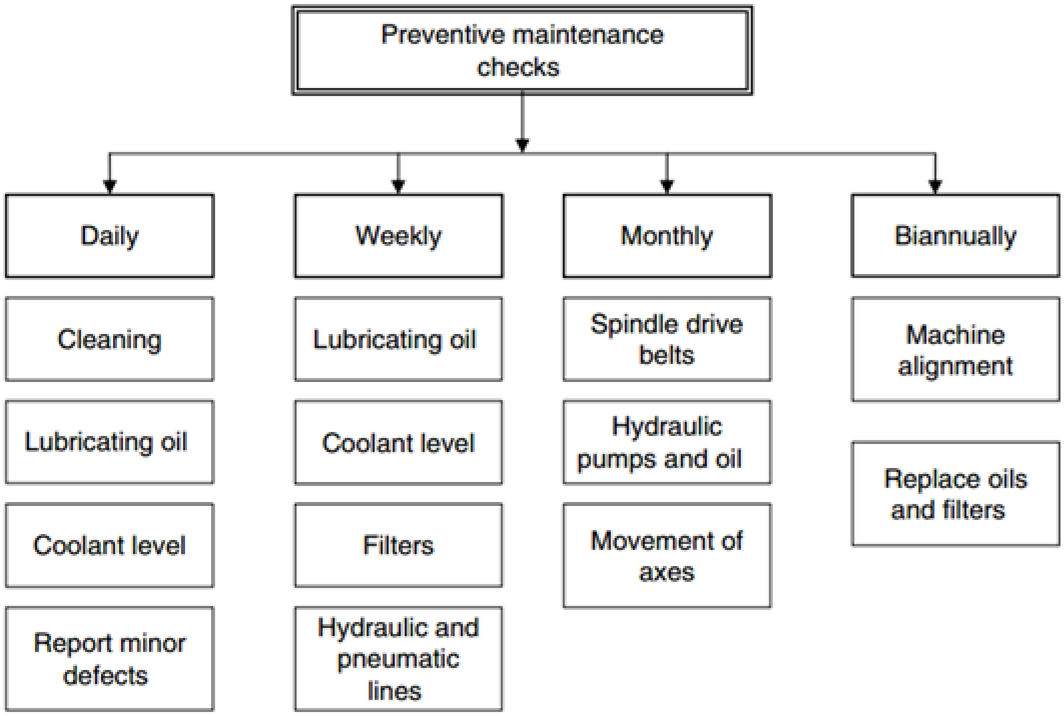


Figure 1.15. A preventive maintenance scheme. Sourced from (Youssef and El-Hofy, 2008).

5. Heat treatment

Heat treatment is the controlled heating and cooling of metallic solid solution for micro-structural modification in favour of desired service functions. A material for engineering application can appear with different microstructures and properties (strength, toughness, wear resistance, machinability, formability, corrosion resistance) depending on the requirements of its application. Heat treatment is a notable processing method to alter the microstructure and properties metallic materials. For better formability, a material can be heat-treated to be soft and ductile and later hardened for structural strength in service. Also, for ease of machining, a very hard/soft material can be heat-treated to improve machinability. These types of thermal processing for preparing materials for major manufacturing processes are called *processing heat treatments*.

Since heat treatment implies a controlled heating or cooling targeting the needed properties, heat-induced (thermo-metallurgical) changes, whether desirable or undesirable, that occur during welding, hot forming, casting and machining cannot be classified as heat treatment. The undesirable thermo-metallurgical changes are removed by remedial heat treatments.

Most structural applications of metals involve iron/steel, and 90% of all heat treatments is done on steel and ferrous metals (DeGarmo et al., 1997). Therefore, the discussion of heat treatment here is limited to plain carbon steel which is an interstitial solid solution of carbon in iron. The knowledge of iron allotropy is important to the understanding of heat treatment of plain carbon steel. The allotropy of iron is illustrated in Figure 1.16 (a). Ferrite is the body-centred cubic allotrope of iron found below 908°C - the alpha-iron (α-Fe) - and between 1388°C and 1535°C - the delta-iron (δ-Fe). The solid solutions of the body-centred cubic allotrope are also called ferrites. It is soft and ductile. It tolerates only a slight amount of dissolved carbon.

The maximum carbon content of ferrite is 0.04% occurring at 723°C (Vernon, 1992) and 0.006% at 200°C. The limiting carbon content is lower at lower temperatures: the maximum carbon content is 0.008% at room temperature[2]. Below this carbon content, heat treatment has negligible practical benefit. Austenite is the face-centred cubic allotrope of iron found between 908°C and 1388°C - the gamma-iron (γ-Fe). The solid solutions of the face-centred cubic allotrope are also called austenite. It is hard and brittle. It tolerates relatively large amount of dissolved carbon. The limits of carbon content in austenite are 0.87% at 723°C and 1.7% at 1130°C (Vernon, 1992). The curie temperature of 768°C is the temperature of transformation from ferromagnetic to non-ferromagnetic or vice versa.

The range of temperature in heat treatment of plain carbon steel does not penetrate the δ-Fe range and plain carbon steel has carbon content up to 1.5%; therefore, the applicable phase diagram lies in the range T<1388°C and % carbon $\leq$ 1.5. Such a phase diagram is as sketched in Figure 1.16 (b). At 723°C, a plain carbon steel of 0.87% carbon (said to be of eutectoid composition) transforms to pearlite which is a mixture of alternate layers of ferrite and cementite $\mathrm{Fe_3C}$. Therefore, 0.87% carbon content and temperature of 723°C jointly define the eutectoid point (point $\mathrm{P_3}$ on Figure 1.16 (b)) for plain carbon steels. Compositions are described as hypoeutectoid and hypereutectoid below and above the eutectoid composition. The temperature of 908°C at which α-Fe transforms to γ-Fe is called the upper critical temperature, see Figure 1.16 (a) or point $\mathrm{P_1}$ on Figure 1.16 (b). Carbon content depresses the upper critical temperature: the higher the carbon content the lower the upper critical temperature. Therefore, when a hypoeutectoid plain carbon steel is cooled at equilibrium rate from the austenitic range, ferrite begins to form at the depressed upper critical temperature causing the remaining austenite to be enriched in carbon and further depressing of the upper critical temperature. Continued cooling will eventually lead to a polycrystalline structure composed of ferrites and eutectoid austenite at the lower critical temperature. At this temperature, the eutectoid austenite transforms to pearlite to create the polycrystalline microstructure of hypoeutectoid steel which has ferritic crystals and eutectoid portions as illustrated in Figure 1.16 (b). Line $\mathrm{P_1P_3}$ in Figure 1.16 (b) represents the transformation along the upper critical temperature. The presence of layers of cementite in the pearlite makes pearlitic portions to have higher mechanical properties than the ferritic portions causing the transformed hypoeutectoid plain carbon steel to have higher mechanical properties when the carbon content is higher.

In the hypereutectoid range, carbon solubility limit in austinite is higher than the eutectoid composition and the solubility limit increases with increase in carbon content. When a superheated hypereutectoid austenite is cooled at equilibrium rate to the solubility limit, cementite begins to form as a network around the austenite crystals and as *Widman-Statten* needles in some of the austenite crystals causing the remaining austenite to deplete in carbon and further depressing the solubility limit. Continued cooling will eventually lead to a microstructure composed of cementite and eutectoid austenite crystals at the lower critical temperature. At the lower critical temperature, the eutectoid austenite transforms to pearlite creating a microstructure of hypereutectoid steel which has cementite network around pearlitic grains as illustrated in Figure 1.16 (b). Line $\mathrm{P_3P_4}$ in Figure 1.16 (b) represents the transformation along the carbon solubility limit (the *solvus line*). Hardness and strength increase while ductility (measured as elongation) decreases with increase in carbon content of slowly cooled plain carbon steels. The rate of increase of tensile strength with carbon content in normalized plain carbon steels is higher in the hypoeutectoid composition range than in the hypereutectoid composition range (Vernon, 1992).

[2] https://www.asminternational.org/documents/10192/1849770/ACF180B.pdf

Engr. Dr. Chigbogu G. Ozoegwu (ME 212 Coordinator)
Mechanical Engineering, University of Nigeria, Nsukka

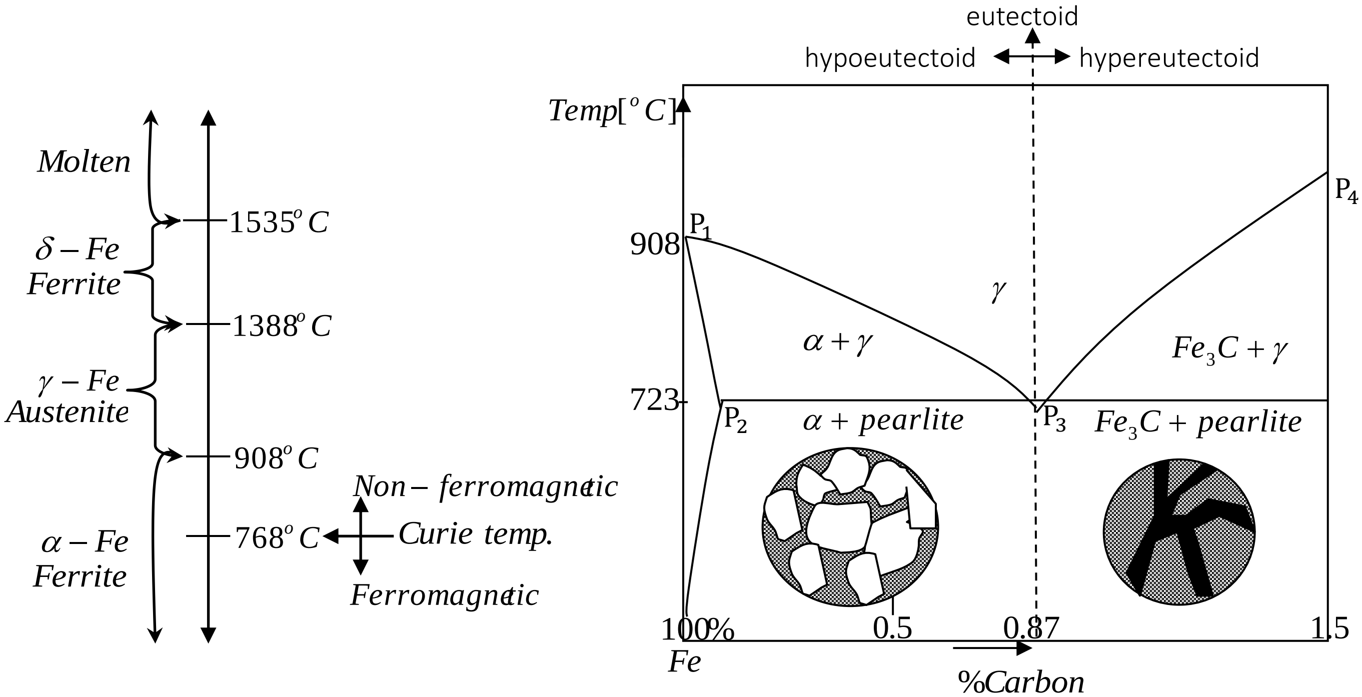


Figure 1.16. (a) allotropy of pure iron (b) the steel portion of iron-carbon phase diagram

When cooling rate is increased, the austenite of plain carbon steels gets undercooled (cooled below the lower critical temperature without passing through the decomposition into ferrite/cementite and carbon-enriched/depleted austenite) and gets transformed spontaneously to a pearlitic microstructure marked by lamella of ferrite and cementite, see Figure 1.17. This structure, which excludes coarse ferritic grains, increases the hardness and strength of plain carbon steel. The higher the cooling rate, the more the uncooling leading to finer pearlitic structure. The meaning is that pearlitic microstructure will not occur beyond a threshold cooling rate called the critical cooling velocity, instead non-equilibrium phases like bainite and martensite form. If the austenite is cooled extremely rapidly (quenched in water or oil for example), it will transform to ferrite with dissolved carbon in the lattice. Because of high carbon content, the ferrite is highly strained and the strain causes a deformation of the ferritic body-centred cubic lattice to body-centred tetragonal lattice. A plain carbon steel with this microstructure is called martensite. Martensites are extremely hard and brittle. Under a microscope they have acicular microstructure (series of fine needle-like structures), see Figure 1.17. The hardness and brittleness of martensites increase with increase in carbon content. The extreme results of undercooling are pearlitic (alternate layers of ferrite and cementite) and martensitic (dissolved carbon) microstructures. In between the extremes is the bainitic microstructure which has dispersed carbide particles or discontinuous carbide layers (rather than carbide layers) in ferrites, see Figure 1.17. Bainite, which is harder and stronger than pearlite but softer and not as strong as martensite, is produced by quenching austenite at a cooling rate higher than the critical cooling velocity to an undercooled temperature in the intermediate range, and sustaining a complete isothermal transformation. With higher carbon or alloying content, transformations become slower requiring slower cooling rates. Therefore, the critical cooling velocity reduces with higher carbon or alloying content in steel. Therefore, if the technically possible cooling rate (for example, quenching in water or oil) is slower than the critical cooling velocity of a steel then hardening of the steel via bainite or martensite formation is not possible in a quenching process. For example, the cooling rate attainable when quenched in water approximates the critical cooling velocity of mild steel with 0.3% carbon, therefore, steels with not more than this carbon content cannot be hardened by quenching in water.

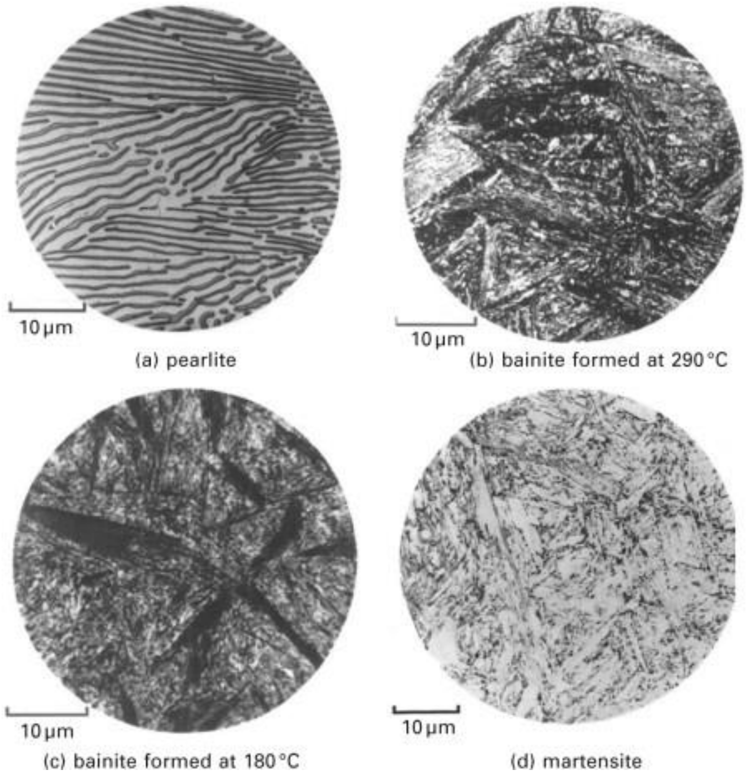


Figure 1.17. Possible microstructures carbon steel resulting from different cooling rates. Source[3]

When a thick plain carbon steel material is quenched, the rate of cooling will be highest at the surface and decrease deeper into the material. Therefore, beyond a critical depth below the surface, the critical cooling velocity will not be attained and hardening will not occur. This causes case hardening whereby the surface layer is transformed to martensite and the inner part is transformed to pearlite. The depth of hardening, called *hardenability*, increases with the increase of carbon content because of decrease of critical cooling velocity. Quenching of hypoeutectoid/hypereutectoid plain carbon steel from 30 to 50^oC above the upper/lower critical temperature to harden by martensite formation is called *hardening* heat treatment.

In terms of purpose, *tempering* is the opposite of hardening. Tempering relieves the extreme hardness and brittleness of martensites. It occurs at elevated temperatures beyond 200^oC during which carbon diffuses through the ferritic lattice and eventually precipitates as carbide particles thus relieving the carbon-induced straining of the lattice. The diffusion rate and the size of the carbide particles increase with increase of tempering temperature. At temperatures just below the lower critical temperatures, typically at 700^oC, the carbide particles coalesce into series of fairly large (visible under optical microscopes) spheroidal particles,

[3]https://www.google.com/url?sa=i&url=https%3A%2F%2Fwww.sciencedirect.com%2Ftopics%2Fengineering%2Fbainitic-microstructure&psig=AOvVaw3ipkKe4RT7Pv_tiErn-61R&ust=1617743660864000&source=images&cd=vfe&ved=0CAIQjRxqFwoTCNjwo_WC6O8CFQAAAAAdAAAAABAD

and the arising steel is soft and tough. Spheroidal annealing is used to describe this heat treatment when applied in softening hypereutectoid steels. *Full annealing* and *normalizing* are used to describe the heat treatments for softening mostly hypoeutectoid steels. Full annealing requires heating the steels to temperature above the upper critical temperature by about 30 to 50^{o}C, and allowing a slow cooling of the steel in the slowly cooling furnace. This gives the softest possible conditions with coarse ferrites and pearlites in the microstructure. Full annealing is time consuming thus costly, therefore, when admissible, the steels are allowed to cool in the air in the process called normalizing to give a reasonable soft and ductile material. Normalized steels are not as soft as the fully annealed ones because of undercooling effects which result in pearlitic microstructure.

6. Applications of Heat treatments in Manufacturing

Machinability of a workpiece refers to the relative ease of machining the workpiece to an acceptable level of surface finish without excessive tool wear, power consumption and chip evacuation problems. The indices of machinability are level of surface finish, extent of tool wear, power consumption and ease of chip evacuation. Machinability is a function of the chemical composition and microstructure of workpiece, and compatibility between workpiece and tool materials. Crystal structure can be altered by heat treatment with the aim of improving machinability. *Formability* (or malleability or workability) is the suitability of a material for processing through plastic deformation. Formability is affected by the material properties, processing method (such as rolling, drawing, etc) and processing conditions (such as cold-working, hot-working, straining rate, etc).

For good machinability, a workpiece material should neither be too soft and ductile nor too hard. When the material of a workpiece is too soft and ductile, the tool will plough rather than cut off chips giving a poor surface finish, and the chips will be gummy (causing built-up edge) and continuous (entangling the work zone thus creating a hazard situation for the machinist and the machine). When workpiece is too hard, there will be excessive tool wear (causing poor surface finish) and excessive power consumption (making the machining process costly). For best formability, a workpiece material should be as soft and ductile as possible (in the best annealed condition).

Mild steels ($\leq$0.3%C) are soft and cannot be hardened by water-quenching, but they harden over a duration of cold working because of distortion and fragmentation of crystal grains. The strain-hardened condition is usually favourable for machining processing because of higher tendencies for discontinuous chip and less built-up edges. On the other hand, the strain-hardened condition is not favourable for cold forming because of the danger of fracture and high energy/force needs, therefore, the steel is subjected to process annealing which is a type of *recrystallization heat treatment* that is aimed at grain re-growth and stress relief. Since there is no need for phase (crystal type) transformation, recrystallization heat treatments are carried out by soaking the heated steels at temperatures below the lower critical temperature. When the heat treatment is aimed at stress relief in large steel castings, welded assemblies and cold-formed parts, it is called *stress-relief annealing* which requires long period of soaking time in the furnace for a steel heated to between 550^{o}C to 650^oC before slow cooling (Black and Kohser, 2008).

High-carbon steels (steels for which there is $>$0.6%C. It is instructive to note that medium-carbon steels have carbon content in the range $0.3<\%C\leq0.6$) to be subjected to extensive machining processing and cold forming are first subjected to *spheroidization heat treatment* in order to reduce hardness. Figure 1.18 shows the soaking time ranges for the different heat treatments. In cases where high productivity in machining of low to medium carbon steels is paramount, sulphur and manganese are introduced leading to the formation of manganese sulphide inclusions in the steel microstructure. The inclusions in the so-called *free-machining steels* act as stress-raising voids which enhance chip breakage (formation of the preferred discontinuous chips). Moreover, sulphides form a lubricating layer on the rake face of the cutting tool, thereby reducing the frictional force between the chip and the tool. According to Luiz and Machado (2008), reduction of the frictional force will induce higher shear angle and, hence, more chip compression and breakage. Sometimes, lead (preferably, bismuth for environmental friendliness and better dispersion because of lower density) is introduced to improve the formation of inclusions by forming lead/bismuth inclusions and enveloping the manganese sulphide inclusions and improving the built-in lubrication properties of free-machining steels. Bismuth improves lubrication because the heat generated in the cutting process melts the bismuth, momentarily providing a lubrication film.

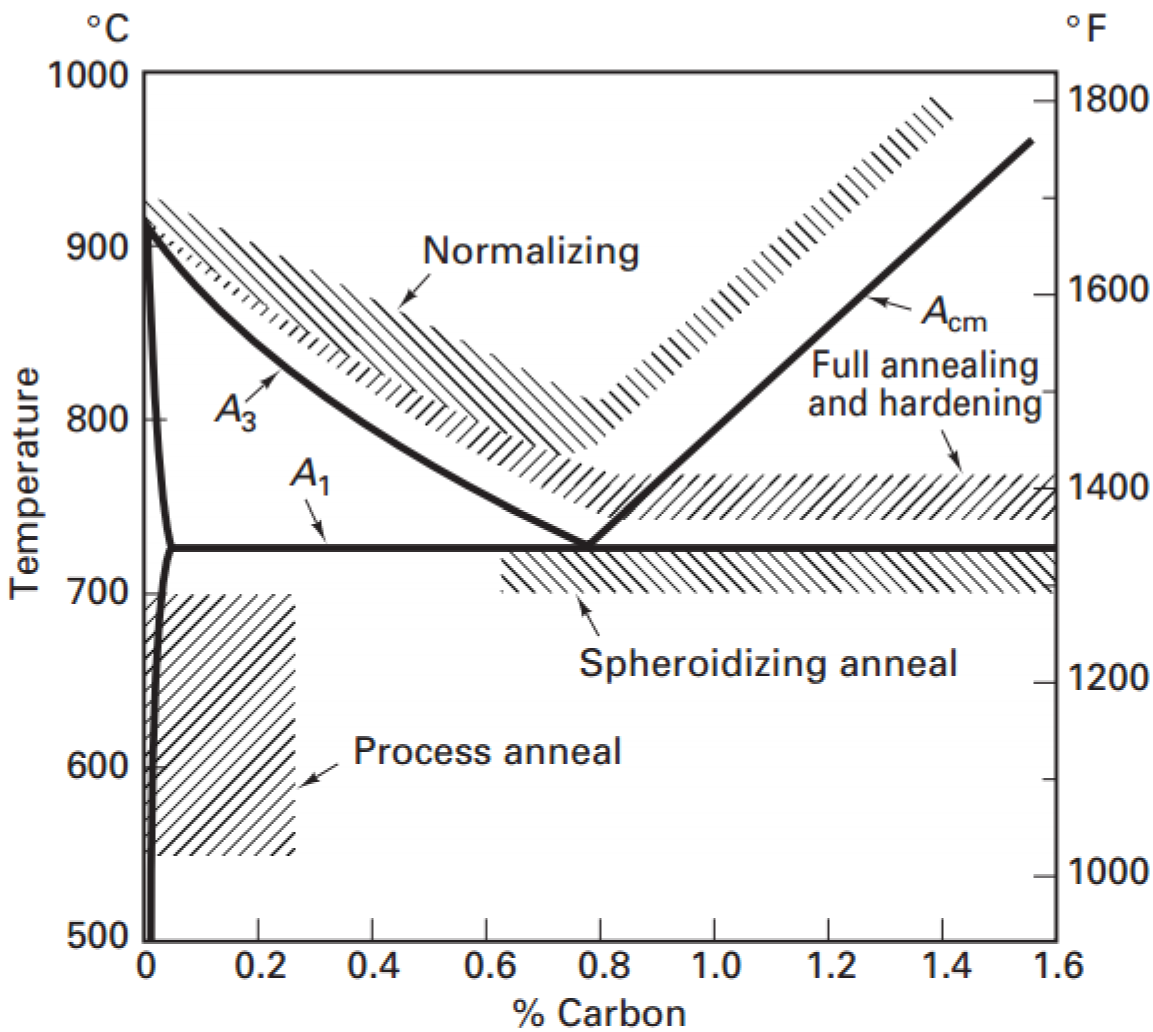


Figure 1.18. The soaking time ranges for the different heat treatments. Sourced from (Black and Kohser, 2008).

Many manufactured parts (products of cold/hot forming, machining, casting, etc), typically shafts and gears, are required to have soft and tough cores to avoid fracture but have hard surfaces to avoid plastic deformation and minimize wear. A heat treatment called *surface hardening* is carried out on such parts. When carbon content is in excess of 0.35%, *flame hardening* can be used in surface hardening by raising the temperature of the steel rapidly to the critical temperature range using a flame and quenching the heated steel to harden the surface by martensitic formation. *Induction hardening*, which is a substitute of *flame hardening*, achieves rapid heating of the steel by being enclosed within high-frequency induction coil. The martensitic surface layers are usually subsequently tempered by the outflow of heat from the inner layers. For low-carbon steels, *case carburization* which involves introduction of additional carbon in the surface layers is used. The two types of case carburization are *pack carburization* and *gas carburization*. The former requires bringing the steel in contact with wood or charcoal and barium carbonate in a cast iron container and heating the setup to temperatures above the upper critical temperature of the steel while in the later, the heating in done in a furnace filled with methane and/or other hydrocarbons. By heating steel in a bath of molten sodium cyanide and sodium carbonate at about 950^{o}C, hard iron nitrides are formed in the surface layers to harden the steel surface in the process called cyaniding. Diffusion of additional materials into the surface layers of steel during carburization and cyaniding increases the dimensions of the treated parts requiring grinding. Other surface hardening treatments are *nitriding, carbonitriding* and *siliconizing (ihrigising)*. The students are expected to read further on these treatments.

Exercises

1.1. Consider the turning process in Example 1.1, (a) calculate the cutting speed and cutting power during the tenth pass (b) assume that the inclination of cutting edge to the rotational axis is 60^o, what are the contact length and undeformed chip thickness. (c) if a facing operation is carried out instead, what is the cutting speed and cutting power after ten revolutions.

1.2. In orthogonal cutting of SAE 4130 workpiece using high-speed steel tool, width of cut was 12.1 mm, cutting speed in all tests was 27 m per min and the undeformed chip thickness was 0.089mm, calculate the undeformed chip cross-sectional area.

1.3. In orthogonal cutting (with sintered carbide tool) of 10cm diameter NE 9445 steel workpiece having a Brinell hardness of 187, the spindle speed, undeformed chip thickness and depth of cut are respectively 191rpm, 0.094mm and 6.35mm. Calculate the undeformed chip cross-sectional area.

1.4. Suppose in a rough centreless grinding, D_{rw} and D_w are respectively equal to 40 and 25cm and α= 4°, what Ω_{rw} will drive the workpiece at Ω_w=31.831rpm. Calculate the v_{lf}. Suppose $\Omega_{gw} = 50\Omega_w$, calculate the rotational speed of grinding wheel relative to the workpiece. Given that $r_{v_{lf}} =$ 0.0286 calculate the diameter and the cutting speed (the tangential speed of grinding wheel relative to the workpiece) of the grinding wheel.

1.5. (a) What is honing process pointing out when and why is it needed. (b) Suppose the rotational speed of a honing head of 20cm diameter is 39.8 rpm, what reciprocating velocity will give cross-hatch angle of 30^o.

1.6. Discuss the two types of machine tool acceptance tests

1.7 Differentiate the three aspects of machine tool maintenance

1.8. In a turning a 50mm diameter workpiece down to a 30mm diameter part, the feed and the spindle speed are 0.24mm and 5rph. Calculate (a) calculate the initial cutting speed in meters per second (b) calculate the ratio of the final cutting speed to the initial cutting speed (c) calculate the secondary speed in meters per second.

1.9. If the depth of cut, feed speed and spindle speed of turning and milling process are the same. Explain why it will be expected that the magnitude of cutting force will be lower in milling process.

References

Degarmo, E. P., Black, J. T., and Kohser, R. A. (1997) Materials and Processes in Manufacturing, 8th Edition, Prentice Hall, New York.

Black, J. T., and Kohser, R. A. (2008) Degarmo's Materials and Processes in Manufacturing, 10th Edition, John Wiley & Sons, United States of America.

European Association of the Machine Tool Industries. (2011, December). Study on the competitiveness of the European machine tool industry. CECIMO, Brussels.

López de Lacalle, L. N., Lamikiz A. (2009) Machine Tools for Removal Processes: A General View. In: Machine Tools for High Performance Machining, edited by L.N. López de Lacalle, A. Lamikiz.

Luiz, N. E. and Machado, A´.R. (2008), Development trends and review of free-machining steels. Proceedings of the Institution of Mechanical Engineers Part B: Journal of Engineering Manufacture, 222, 347-360.

Milton C. S., Metal Cutting Principles. Oxford, Oxford University Press 2005

Vernon, J. (1992), Introduction to Engineering Materials, 3rd Edition, Palgrave, New York.

Youssef, H. A. and El-Hofy, E. (2008). Machining Technology: Machine Tools and Operations. CRC Press Taylor &Francis Group; New York.