Module
3
Machinability

Lesson
13
Concept of Machinability and its Improvement

Instructional objectives

At the end of this lesson, the students would be able to

(i) Conceptualise machinability and state its
- Definition
- Criteria of judgement

(ii) Illustrate how machinability is governed or influenced by several factors,
- Chemical and physical properties of work material
- Processing parameters
- Cutting tool parameters
- Environmental factors

(iii) Suggest various methods of improvement of machinability

(i) Concept, Definition And Criteria Of Judgement Of Machinability

It is already known that preformed components are essentially machined to impart dimensional accuracy and surface finish for desired performance and longer service life of the product. It is obviously attempted to accomplish machining effectively, efficiently and economically as far as possible by removing the excess material smoothly and speedily with lower power consumption, tool wear and surface deterioration. But this may not be always and equally possible for all the work materials and under all the conditions. The machining characteristics of the work materials widely vary and also largely depend on the conditions of machining. A term; 'Machinability' has been introduced for gradation of work materials w.r.t. machining characteristics.

But truly speaking, there is no unique or clear meaning of the term machinability. People tried to describe "Machinability" in several ways such as:
- It is generally applied to the machining properties of work material
- It refers to material (work) response to machining
- It is the ability of the work material to be machined
- It indicates how easily and fast a material can be machined.

But it has been agreed, in general, that it is difficult to clearly define and quantify Machinability. For instance, saying 'material A is more machinable than material B' may mean that compared to 'B',
- 'A' causes lesser tool wear or longer tool life
- 'A' requires lesser cutting forces and power
- 'A' provides better surface finish

where, surface finish and tool life are generally considered more important in finish machining and cutting forces or power in bulk machining.
Machining is so complex and dependant on so many factors that the order of placing the work material in a group, w.r.t. favourable behaviour in machining, will change if the consideration is changed from tool life to cutting power or surface quality of the product and vice versa. For instance, the machining behaviour of work materials are so affected by the cutting tool; both material and geometry, that often machinability is expressed as "operational characteristics of the work-tool combination". Attempts were made to measure or quantify machinability and it was done mostly in terms of :

- tool life which substantially influences productivity and economy in machining
- magnitude of cutting forces which affects power consumption and dimensional accuracy
- surface finish which plays role on performance and service life of the product.

Often cutting temperature and chip form are also considered for assessing machinability.
But practically it is not possible to use all those criteria together for expressing machinability quantitatively. In a group of work materials a particular one may appear best in respect of, say, tool life but may be much poor in respect of cutting forces and surface finish and so on. Besides that, the machining responses of any work material in terms of tool life, cutting forces, surface finish etc. are more or less significantly affected by the variation; known or unknown, of almost all the parameters or factors associated with machining process. Machining response of a material may also change with the processes, i.e. turning, drilling, milling etc. therefore, there cannot be as such any unique value to express machinability of any material, and machinability, if to be used at all, has to be done for qualitative assessment.
However, earlier, the relative machining response of the work materials compared to that of a standard metal was tried to be evaluated quantitatively only based on tool life ($V_B^* = 0.33$ mm) by an index,
Machinability rating (MR)

$$= \frac{\text{speed (fpm) of machining the work giving 60 min tool life}}{\text{speed (fpm) of machining the standard metal giving 60 min tool life}} \text{x}100$$

Fig. 3.1.1 shows such scheme of evaluating Machinability rating (MR) of any work material.
The free cutting steel, AISI – 1112, when machined (turned) at 100 fpm, provided 60 min of tool life. If the work material to be tested provides 60 min of tool life at cutting velocity of 60 fpm (say), as indicated in Fig. 3.1.1, under the same set of machining condition, then machinability (rating) of that material would be,
$\text{MR} = \frac{60}{100}\text{x}100 = 60\%$ or simply 60 (based on 100% for the standard material)
or, simply the value of the cutting velocity expressed in fpm at which a work material provides 60 min tool life was directly considered as the MR of that

work material. In this way the MR of some materials, for instance, were evaluated as,

Metal	MR
Ni	200
Br	300
Al	200
CI	70
Inconel	30

But usefulness and reliability of such practice faced several genuine doubts and questions :

- tool life cannot or should not be considered as the only criteria for judging machinability
- under a given condition a material can yield different tool life even at a fixed speed (cutting velocity); exact composition, microstructure, treatments etc. of that material may cause significant difference in tool life
- the tool life - speed relationship of any material may substantially change with the variation in
    - o material and geometry of the cutting tool
    - o level of process parameters (V_c, s_o, t)
    - o machining environment (cutting fluid application)
    - o machine tool condition

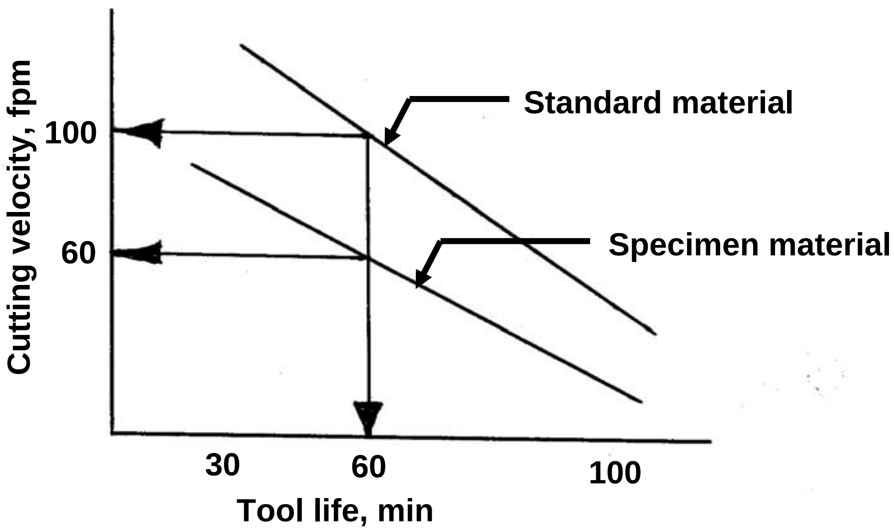

Fig. 3.1.1 *Machinability rating in terms of cutting velocity giving 60 min tool life.*

Keeping all such factors and limitations in view, Machinability can be tentatively defined as "ability of being machined" and more reasonably as " ease of machining".

Such ease of machining or machinability characteristics of any tool-work pair is to be judged by :

- magnitude of the cutting forces
- tool wear or tool life
- surface finish
- magnitude of cutting temperature
- chip forms

Machinability will be considered desirably high when cutting forces, temperature, surface roughness and tool wear are less, tool life is long and chips are ideally uniform and short enabling short chip-tool contact length and less friction.

(ii) Role Of Variation Of The Different Machining Parameters Or Factors On Machinability Of Work Materials.

The machinability characteristics and their criteria, i.e., the magnitude of cutting forces and temperature, tool life and surface finish are governed or influenced more or less by all the variables and factors involved in machining such as,

(a) properties of the work material
(b) cutting tool; material and geometry
(c) levels of the process parameters
(d) machining environments (cutting fluid application etc)

Machinability characteristics of any work – tool pair may also be further affected by,

- strength, rigidity and stability of the machine
- kind of machining operations done in a given machine tool
- functional aspects of the special techniques, if employed.

(a) Role of the properties of the work material on machinability.

The work material properties that generally govern machinability in varying extent are:

- the basic nature – brittleness or ductility etc.
- microstructure
- mechanical strength – fracture or yield
- hardness
- hot strength and hot hardness
- work hardenability
- thermal conductivity
- chemical reactivity
- stickiness / self lubricity.

- **Machining of brittle and ductile materials**

In general, brittle materials are relatively more easily machinable for :

- the chip separation is effected by brittle fracture requiring lesser energy of chip formation
- shorter chips causing lesser frictional force and heating at the rake surface

For instance, compared to even mild steel, grey cast iron jobs produce much lesser cutting forces and temperature. Smooth and continuous chip formation is likely to enable mild steel produce better surface finish but BUE, if formed, may worsen the surface finish.

For machining, like turning of ductile metals, the expression

$$P_Z = ts_o\tau_s f \qquad (3.1.1)$$

Indicates that cutting forces increase with the increase in yield shear strength, τ_s of the work material. The actual value of τ_s of any material, again, changes with the condition of machining and also on the ductility of the work material as,

$$\tau_s = 0.74\sigma_U\varepsilon^{0.6\Delta} \qquad (3.1.2)$$

where,

σ_u = ultimate tensile strength which is a classical property of the material

Δ = percentage elongation indicating ductility of the work material

ε = cutting strain

Role of microstructure

The value of τ_s of a given material depends sizeably on its microstructure. Coarse microstructure leads to lesser value of τ_s. Therefore, τ_s can be desirably reduced by

- proper heat treatment like annealing of steels
- controlled addition of materials like sulphur (S), lead (Pb), Tellerium etc leading to free cutting of soft ductile metals and alloys.

Free Cutting steels

Addition of lead in low carbon steels and also in aluminium, copper and their alloys help reduce their τ_s. The dispersed lead particles act as discontinuity and solid lubricants and thus improve machinability by reducing friction, cutting forces and temperature, tool wear and BUE formation. Addition of sulphur also enhances machinability of low carbon steels by enabling its free cutting. The added sulphur reacts with Mn present in the steels and forms MnS inclusions which being very soft act almost as voids and reduce friction at the tool – work interfaces resulting reduction of cutting forces and temperature and their consequences. The degree of ease of machining of such free cutting steels depend upon the morphology of the MnS inclusions which can be made more favourable by addition of trace of Tellurium.

Effects of hardness, hot strength and hot hardness and work hardening of work materials.

Harder materials are obviously more difficult to machine for increased cutting forces and tool damage.
Usually, with the increase in cutting velocity the cutting forces decrease to some extent making machining easier through reduction in τ_s and also chip thickness. τ_s decreases due to softening of the work material at the shear zone due to elevated temperature. Such benefits of increased temperature and cutting velocity are not attained when the work materials are hot strong and hard like Ti and Ni based superalloys and work hardenable like high manganese steel, Ni- hard, Hadfield steel etc.
Sticking of the materials (like pure copper, aluminium and their alloys) and formation of BUE at the tool rake surface also hamper machinability by increasing friction, cutting forces, temperature and surface roughness. Lower thermal conductivity of the work material affects their machinability by raising the cutting zone temperature and thus reducing tool life.
Sticking of the materials (like pure copper, aluminium and their alloys) and formation of BUE at the tool rake surface also hamper machinability by increasing friction, cutting forces, temperature and surface roughness.

(b) Role of cutting tool material and geometry on machinability of any work material.

- **Role of tool materials**

In machining a given material, the tool life is governed mainly by the tool material which also influences cutting forces and temperature as well as accuracy and finish of the machined surface. The composition, microstructure, strength, hardness, toughness, wear resistance, chemical stability and thermal conductivity of the tool material play significant roles on the machinability characteristics though in different degree depending upon the properties of the work material.
Fig. 3.1.2 schematically shows how in turning materials like steels, the tool materials affect tool life at varying cutting velocity.
High wear resistance and chemical stability of the cutting tools like coated carbides, ceramics, cubic Boron nitride (cBN) etc also help in providing better surface integrity of the product by reducing friction, cutting temperature and BUE formation in high speed machining of steels. Very soft, sticky and chemically reactive material like pure aluminium attains highest machinability when machined by diamond tools.

- **Role of the geometry of cutting tools on machinability.**

The geometrical parameters of cutting tools (say turning tool) that significantly affect the machinability of a given work material (say mild steel) under given machining conditions in terms of specific energy requirement, tool life, surface finish etc. are:

- tool rake angles (γ)
- clearance angle (α)
- cutting angles (ϕ and ϕ_1)

- nose radius (r)

The other geometrical (tool) parameters that also influence machinability to some extent directly and indirectly are:

— inclination angle (λ)
— edge bevelling or rounding (r')
— depth, width and form of integrated chip breaker

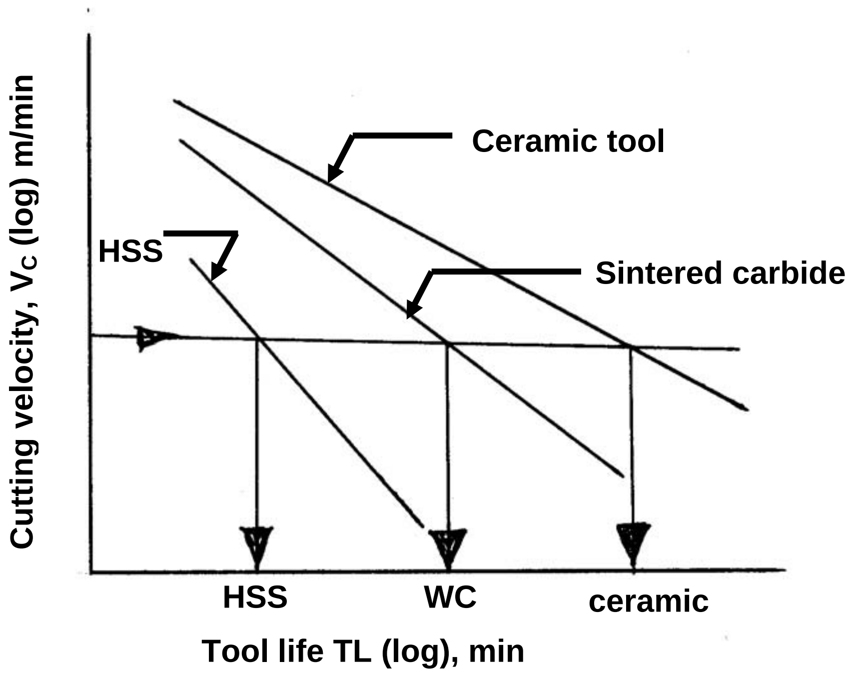

Fig. 3.1.2 *Role of cutting tool material on machinability (tool life)*

Effects of tool rake angle(s) on machinability

In machining like turning ductile material, the main cutting force, P_Z decreases as typically shown in Fig. 3.1.3 mainly due to,

$$P_Z = ts_o\tau_s f \tag{3.1.3}$$

where, $f = \zeta - \tan\gamma + 1$

$$\zeta = e^{\mu(\pi/2-\gamma)}$$

$$\tau_s = 0.74\sigma_U\varepsilon^{0.6\Delta}$$

$$\varepsilon \cong \zeta - \tan\gamma$$

The expressions clearly show that increase in γ reduces P_Z through reduction in cutting strain (ε), chip reduction coefficient (ζ) and hence τ_s and the form factor, f.

With P_Z, P_{XY} also decreases proportionally.

But too much increase in rake weakens the cutting edge both mechanically and thermally and may cause premature failure of the tool.

Presence of inclination angle, λ enhances effective rake angle and thus helps in further reduction of the cutting forces.

However, the tool rake angle does not affect surface finish that significantly.

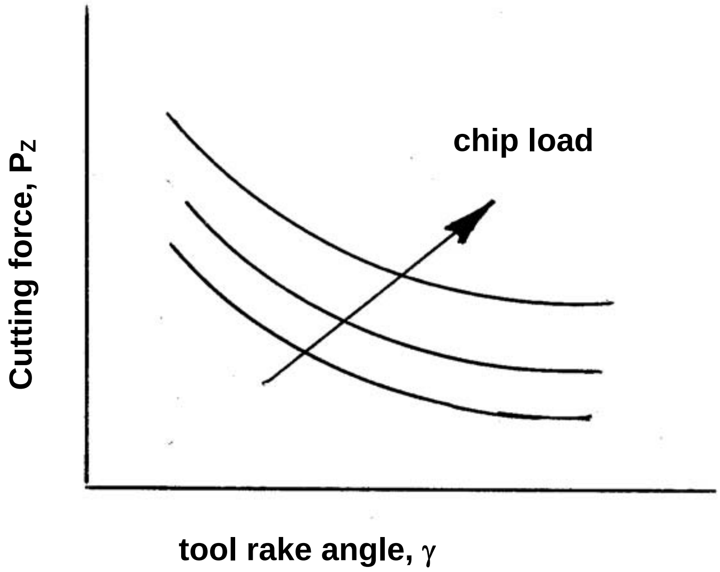

Fig. 3.1.3 *Effect of tool rake angle on machinability (cutting force, P_Z)*

Role of cutting angles (ϕ and ϕ_1) on machinability

The variation in the principal cutting edge angle, ϕ does not affect P_Z or specific energy requirement but influences P_Y and the cutting temperature (θ_C) quite significantly as indicated in Fig. 3.1.4 mainly for,

$$P_Y = P_{XY} \cos\phi \quad \text{i.e.,} \; \alpha \; P_Z \cos\phi \qquad (3.1.4)$$

$$\text{and} \quad \theta_C \;\; \alpha \;\; \sqrt{V_C s_o \sin\phi} \qquad (3.1.5)$$

The force, P_Y, if large, may impair the product quality by dimensional deviation and roughening the surface due to vibration.

Reduction in both ϕ and ϕ_1 improves surface finish sizeably in continuous chip formation, as

$$h_{max} = \frac{s_o}{\cot\phi + \cot\phi_1} \qquad (3.1.6)$$

where h_{max} (define h_{max} ?) is the maximum surface roughness due to feed marks alone.

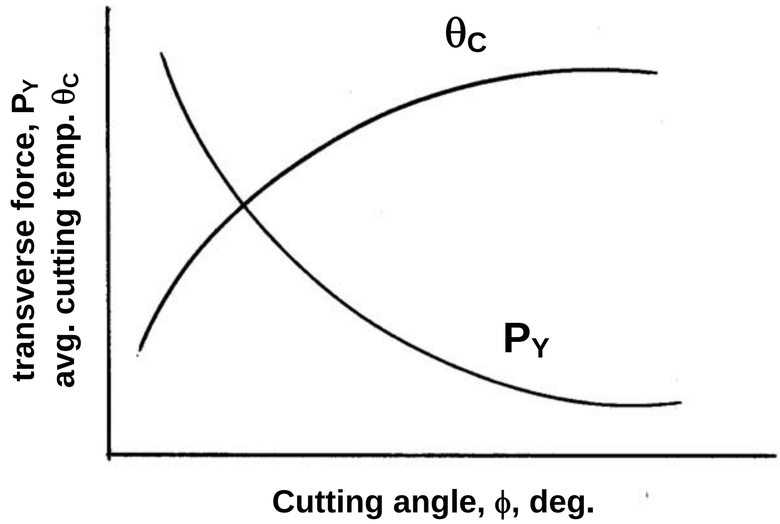

Fig. 3.1.4 *Effects of variation in cutting angle on machinability (θ_C and P_y)*

Effects of clearance angle (α)

Fig. 3.1.5 schematically shows how clearance angle, α affects tool life.

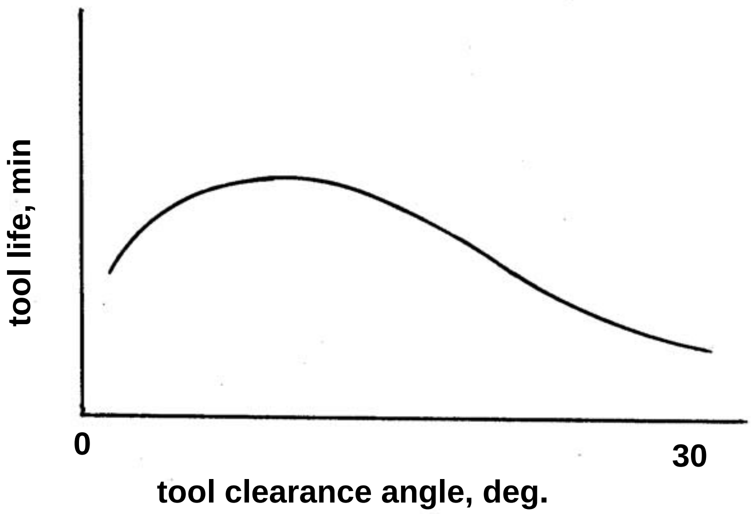

Fig. 3.1.5 *Influence of tool clearance angle on tool life.*

Inadequate clearance angle reduces tool life and surface finish by tool - work rubbing, and again too large clearance reduces the tool strength and hence tool life.

Role of tool nose radius (r) on machinability

Proper tool nose radiusing improves machinability to some extent through

- increase in tool life by increasing mechanical strength and reducing temperature at the tool tip
- reduction of surface roughness, h_{max}

  as $$h_{max} = \frac{(s_o)^2}{8r} \qquad (3.1.7)$$

Proper edge radiusing (r′) also often enhances strength and life of the cutting edge without much increase in cutting forces

(c) Role of the process parameters on machinability

Proper selection of the levels of the process parameters (V_C, s_o and t) can provide better machinability characteristics of a given work – tool pair even without sacrificing productivity or MRR.
Amongst the process parameters, depth of cut, t plays least significant role and is almost invariable. Compared to feed (s_o) variation of cutting velocity (V_C) governs machinability more predominantly. Increase in V_C, in general, reduces tool life but it also reduces cutting forces or specific energy requirement and improves surface finish through favourable chip-tool interaction. Some cutting tools, specially ceramic tools perform better and last

longer at higher V_C within limits. Increase in feed raises cutting forces proportionally but reduces specific energy requirement to some extent. Cutting temperature is also lesser susceptible to increase in s_o than V_C. But increase in s_o, unlike V_C raises surface roughness. Therefore, proper increase in V_C, even at the expense of s_o often can improve machinability quite significantly.

(d) Effects of machining environment (cutting fluids) on machinability

The basic purpose of employing cutting fluid is to improve machinability characteristics of any work – tool pair through :

- improving tool life by cooling and lubrication
- reducing cutting forces and specific energy consumption
- improving surface integrity by cooling, lubricating and cleaning at the cutting zone

The favourable roles of cutting fluid application depend not only on its proper selection based on the work and tool materials and the type of the machining process but also on its rate of flow, direction and location of application.

(iii) Possible Ways Of Improving Machinability Of Work Materials

The machinability of the work materials can be more or less improved, without sacrificing productivity, by the following ways :

- Favourable change in composition, microstructure and mechanical properties by mixing suitable type and amount of additive(s) in the work material and appropriate heat treatment
- Proper selection and use of cutting tool material and geometry depending upon the work material and the significant machinability criteria under consideration
- Optimum selection of V_C and s_o based on the tool – work materials and the primary objectives.
- Proper selection and appropriate method of application of cutting fluid depending upon the tool – work materials, desired levels of productivity i.e., V_C and s_o and also on the primary objectives of the machining work undertaken
- Proper selection and application of special techniques like dynamic machining, hot machining, cryogenic machining etc, if feasible, economically viable and eco-friendly.