CHAPTER III: TOOL WEAR, TOOL LIFE AND MACHINABILITY

1. Tool life

Definition: It may be defined as a period between two consecutive tool resharpenings or replacements. Usually, it is expressed in minutes. It is measured in terms of force, surface finish, tool wear, power consumption etc. Tool wear is the most popular and accepted method for determining tool life. However, tool life is said to be over when tool failure occurs. This is understood when,

a) Chatter or vibration shows up in the machining
b) Poor surface finish results in machining
c) Sudden increase in cutting force and power consumption occur,
d) Overheating and fuming take place due to heat of friction
e) Dimensional instability of the work pieces is observed.

1.1 Types of tool failure

Tool failure can be of three types:

a) Temperature failure: It occurs due to
   i) Plastic deformation of cutting edge due to high temperature and pressure. At high temperature, the strength (yield stress) and hardness of the tool material reduces to a considerable extent leading to plastic deformation of cutting edge.
   ii) Cracking of the cutting edge due to thermal stress
b) Mechanical failure: Chipping of the cutting edge or fracture occurs due to mechanical impact
c) Gradual microscopic wear, which is manifested as,
   i) Flank wear, and/or
   ii) Crater wear

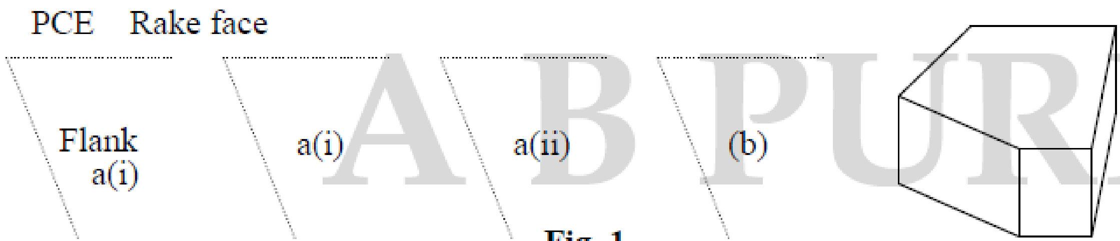

Fig. 1

All types of tool failures, except gradual wear, can be prevented by taking suitable precautions. They may or may not occur during machining. But gradual wear is inevitable and it occurs continuously from the commencement of machining. Hence, flank wear and crater wear or both are taken as the basis for practical evaluation of tool life. However, a quantitative term setting the limit of the permissible value of wear is known as 'criterion of wear' for tool failure or 'criterion of failure'.

1.2 Various mechanisms of wear

Abrasion wear: If one of the sliding surfaces contain very hard particles, then during the process of sliding, these particles may dislodge material from the other surface by the ploughing action. This is called abrasion wear.

Adhesion wear: It is also called attrition wear. When the bodies in contact are of a similar nature, the asperities on the contacting surfaces tend to get welded at high temperature and pressure. Sliding causes fracture of these welded joints (junctions) and material is lost from both the surfaces. The wear due to this mechanism is referred as adhesion wear.

Fig. 2:Adhesion wear

Diffusion wear: Atoms in a metallic crystal lattice move from a region of high concentration to that of low concentration. This process is known as diffusion. When two dissimilar bodies slide over each other at a very high temperature, the atoms of various constituent elements diffuse across the junction leading to wear on both bodies. This process is known as diffusion wear. Here metals do not reach their melting points, but they form an alloy layer, which is carried away with the chips due to high pressure at the rake face of the tool (or at flanks).

Oxidation wear: In some cases, oxidation of job-tool surfaces may also occur at a high temperature in the presence of atmospheric oxygen. Since oxides of elements, particularly that of iron are generally brittle, they are separated from the parent metal when rubbed by another surface. This also causes wear. The mechanism is known as oxidation wear.

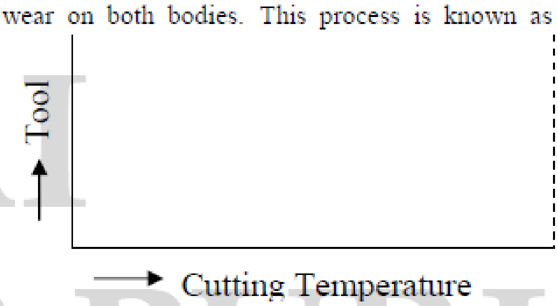

Fig. 3: Opitz Model

Electrochemical wear: Apart from the above, according to some researchers, the tool wear in general, may occur due to chemical action of electrolytic process. Ionic mass transfer takes place between job and tool due to electrolytic process under the presence of a self-generated emf between the pair. The cutting fluid acts as the electrolyte for the process. A thermoelectric emf is set up in the closed circuit due to formation of hot junction between the pair.

However, Opitz has concluded that a tool wears out due to diffusion, abrasion, oxidation and adhesion wear and the temperature plays an important role everywhere.

(a) Adhesive wear (pressure welding); (b) Abrasive wear (plastic deformation);
(c) Diffusion wear; (d) Oxidation wear

1.3 Flank wear and its criterion:

Flank wear occurs mainly on the nose part and on the flank surfaces. It is due to the abrasive action of hard micro-constituents including debris from BUE as the work material rubs the tool flanks and also due to the adhesion between job-tool surfaces. Flank wear primarily depends on the relative hardness of the work and tool materials at the operating temperature, the amount and distribution of hard constituents in the work materials and the degree of strain hardening in the chip. Flank wear is mainly due to abrasion and adhesion wear.

Flank wear is characterized by 'wear land' and is denoted as 'h_f'. As h_f increases, power consumption increases and surface finish worsens. Fig. 5 shows the plot of 'h_f' against time where a non-linear relation is formed in 3 zones.

Fig. 4: Types of flank wear

Zone I: It is called 'initial-break-in' where the sharp edge of the cutting tool rapidly breaks down and reaches a point 1 due to high contact stress.

Zone II: In this zone, the wear is gradual and uniform until point 2 is reached. This is uniform wear or 'mechanical wear' or 'temperature insensitive zone'.

Zone III: Beyond 2, rapid growth of wear starts and the wear process continues. The cutting tool fails very soon after reaching the point of inflexion (2). This point is often called critical point of flank wear or simply critical flank wear. The corresponding 'h_f'(flank wear) is called critical flank wear h_f^*.

Fig. 5

Zone I is unavoidable and wear in zone II is uniform and not so alarming. Therefore, h_f^* sets the limit to the tool life. The life corresponding to h_f^* can be called tool life. As the cutting speed is increased, it has been found that the time taken by the tool to reach h_f^* is decreased. Points A, B, C, D form a critical boundary of tool failure.

1.4 Crater wear and its criterion

Crater wear occurs on the face of the cutting tool at a short distance 'f' from the cutting edge. This is mainly due to diffusion wear. This kind of wear is encountered usually while machining ductile material like steel and its alloys. It leads to the weakening of the tool, increase in cutting temperature, friction and cutting force. It is characterized by width(l), depth(e) and depth of crater (e)

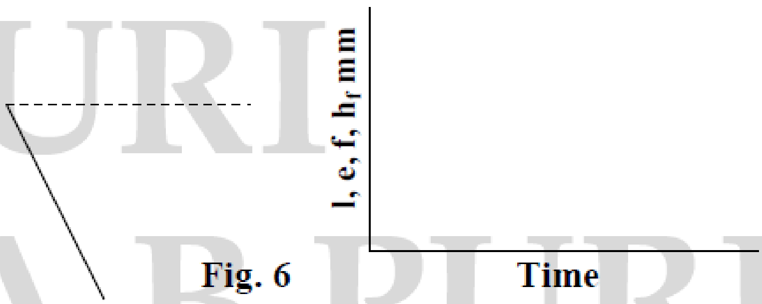

Fig. 6

as shown in the figure. The crater wear is expressed as an index h_k given by, $h_k = \dfrac{e}{\ell/2 + f}$. The criterion of crater wear h_k^* is set 0.4 for carbide tools and 0.6 for HSS tool.

2. Tool life and service life

Tool life data is of large importance in machining because of the following:
a) to arrive at an economical cutting condition,
b) to obtain the optimum tool geometry, and
c) to asses the performance of tool material, cutting fluid, work material and machine tool.

The classical equation for tool life given by Taylor is as follows:
VT^n = constant, V = cutting velocity, m/min; T = tool life, min; n = an index, depending on job-tool combination, tool geometry and cutting environment.
Hence, $\ln V + n \ln T = \ln C$; $\Rightarrow \ln V = -n.\ln T + \ln C$; $\Rightarrow Y = mX + C$

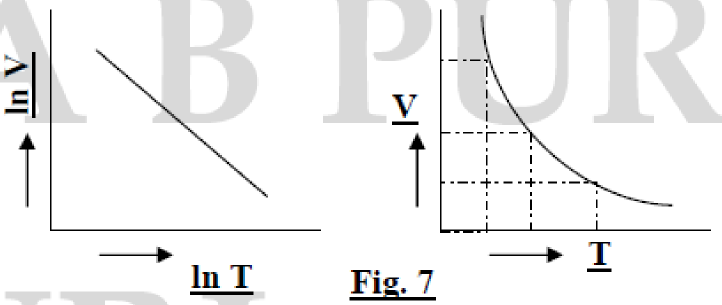

Fig. 7

In the above tool life equation, the effects of feed and depth of cut have not been taken into account, which is not correct. So, Taylor provided the modified tool life equation as: $VT^n f^{n1} d^{n2}$ = constant, f = feed, mm/rev, d = depth of cut, mm; n, n_1, n_2 = constants, depending on job-tool pair, tool geometry and cutting environment.

2.1 Service life of a tool:

Total useful life of a tool is called its service life. Say, m is the no. of regrindings out of a service life, then (m+1) . tool life = total service life = (m+1).T

3. Machinability

It is a property of work material. The most machinable material is one, which permits the fastest removal of the largest amount of material per grind of a tool with satisfactory surface finish. The most important factors, which are considered for evaluation of machinability, are:
a) Tool life, b) Chip removal rate, c) Cutting forces and power consumption, and
d) Surface finish

The term machinability is used to refer to the ease with which a given work material can be machined under a set of cutting conditions. It has considerable economic importance, since the knowledge of machinability prior to machining helps in planning the process.

3.1 Machinability criteria

Ease of machinability can be compared in terms of tool life, cutting forces, specific power consumption, surface finish under similar cutting condition and material removal rate (MRR). Other criteria may be chip disposal, cutting temperature and operator safety. Among all these, the most commonly used criterion are tool life and tool wear.

Machinability Index or Relative machinability = $M_R = \dfrac{[V_{60}]_{Test-material}}{[V_{60}]_{Standard-material}}$

V_{60} = cutting speed corresponding to 60 minute tool life
Standard material $\Rightarrow$ free cutting steel (by adding Pb and S) like, SAE 1212, etc.

$$M_R = \frac{\text{Sp. cutting energy for test material}}{\text{Sp. cutting energy for std. material}} \times 100\%$$

Other criteria:
a) Temperature developed at chip-tool interface
b) Depth of a hole cut in a given time by a standard drill bit rotating at standard speed

Different criteria give different results and there is no unique method. Still tool life criterion is commonly used.

****4. Surface Finish****

If the feed mechanism is perfect and there is no deflection in workpiece, i.e., workpiece is rigidly held – the generated surface will have

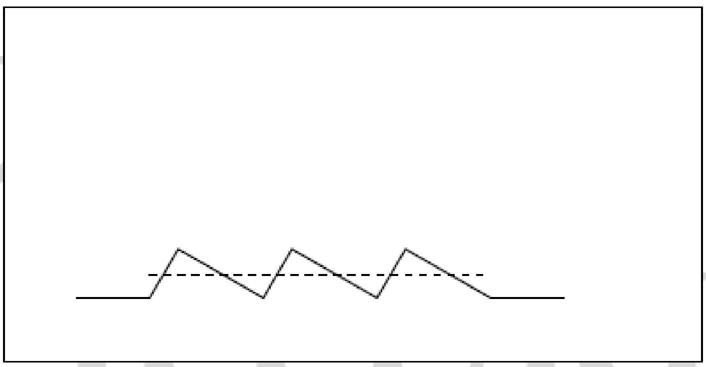
Fig. 8

only tool marks. Surface finish is a factor for rating machinability of metals. A poor surface finish speaks for poor machinability. In machining metals, there are two primary reasons for surface roughness; (a) the feed marks or ridges left by cutting tool and (b) fragments of BUE on the machined surface. The feed marks are due to tool shape, feed, chatter (machine vibration), inaccuracy in machine tool movement, work deflection, etc. Thus, an ideal surface roughness represents the best possible finish which may be obtained for a given tool shape and feed, and can only be obtained if BUE, chatter, inaccuracies in machine tool movement, workpiece deflection etc. are eliminated and a perfect feed mechanism is provided.

For the purpose of quantitative comparison and analysis, roughness of machined surface is expressed in terms of an index R_a. R_a is called 'arithmetic mean value of surface roughness'.

<u>Case I:</u> <u>For a sharp cornered single point tool</u>

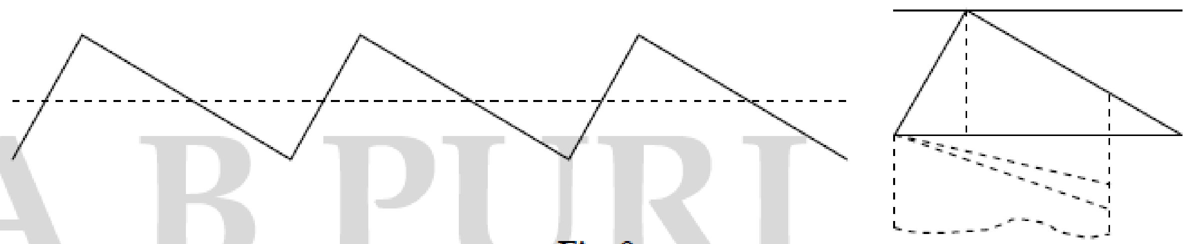

Fig. 9

R_a = (Sum of absolute values of all the areas above and below the mean line) / Sampling length = $\frac{1}{L}\int_0^l y\,dx$

$$\Rightarrow R_a = \frac{\Delta ABC + \Delta CDE}{AE} = \frac{2.\Delta ABC}{2.AC} = \frac{2.\frac{1}{2}.\frac{feed}{2}.\frac{h_{max}}{2}}{feed} = \frac{h_{max}}{4}. \qquad (i)$$

Now, AI/BI = $\cot\varphi$, and, CI = BI $\cot\varphi_a$

$$\Rightarrow AC = AI + CI = BI(\cot\varphi + \cot\varphi_a) = \frac{h_{max}}{2}.(\cot\phi + \cot\phi_a)$$

$\Rightarrow h_{max} = 2.\ AC/(\cot\varphi + \cot\varphi_a) = f/(\cot\varphi + \cot\varphi_a)$, putting this in (i)

$$R_a = \frac{feed}{4(\cot\varphi + \cot\varphi_a)}$$

<u>Case II:</u> <u>For a tool with a nose rounded off</u>

For a tool having nose radius, the CLA value of surface roughness may be expressed as:

$$h_{max} = r(1-\cos\phi_e) + f\sin\phi_e\cos\phi_e - \sqrt{(2f.r\sin^3\phi_e - f^2\sin_4\phi_e)} \text{ and, } R_a \approx \frac{h_{max}}{4} \text{ [Fig.(a)]}$$

If the feed rate is very small, as normally happen in finish turning, the surface is produced purely by the nose radius alone as shown in Fig. (b). the peak-to-valley measures of surface roughness in this case may be expressed as:

$$h_{max} = r - r\cos\theta = r(1-\cos\theta) = r\left\{1-(1-\sin^2\theta)^{1/2}\right\} = r\left[1-\left\{1-\frac{1}{2}\sin^2\theta\right\}\right] = r\frac{\sin^2\theta}{2}.$$

But, $\sin\theta = \frac{f}{2r}$. Hence, $h_{max} = \frac{f^2}{8r}$.

Also the CLA value in this case may be expressed as:

$$R_a = \frac{f^2}{18\sqrt{3}.r} = \frac{0.0321 \times f^2}{r}$$ [Sharma, Ghosh & Mallik, Kuppuswami]

Prob.1 What should be the corner radius of a tool to give a surface roughness value R_a= 10 μm while **finish** turning under ideal conditions with a feed of 0.25 mm/rev? What should be the expected value of peak-to-valley measures?

Prob.2 While finish turning a cylindrical workpiece, two different tools are used. One tool is sharp cornered and having φ and φ_a values 60° and 7° respectively. In the other tool the nose radius is 0.7 mm. If the feed is 0.125 mm/rev, then find the R_a and h_{max} for both the cases.

4.1 Natural surface roughness

In practice it is not possible to achieve the ideal surface roughness condition. The natural surface roughness forms a large proportion of actual roughness. One of the main factors contributing to natural surface roughness is BUE, which may form continuously, and break down intermittently – the fractured particles may be carried by the chips and work. So, larger the BUE, rougher the natural surface roughness. Factors which reduce chip tool friction and BUE formation, will improve surface roughness.

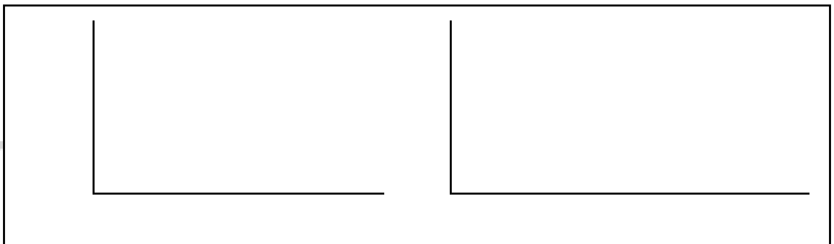

Fig. 11

Introduction of free machining steel (adding Sn, Pb, etc.), application of correct lubricating fluid at low cutting speed improves surface finish. Other factors, which commonly contribute to natural surface roughness in practice, are:

a) Occurrence of chatter or vibration of machine tool
b) Inaccuracy in machine tool movement (saddle)
c) Irregularity in feed mechanism
d) Defect in the structure of work material
e) Discontinuous chip formation
f) Tearing of ductile work material at low V_c
g) Surface damage caused by chip flow

4.2 Factors affecting surface finish

a) Cutting tool geometry and material: large rake, optimum clearance, optimum nose radius, and φ, φ_a, low co-efficient of friction at tool-chip interface.
b) Work geometry and material: short cylindrical work, work rigidity, chemical composition, hardness, microstructure, grain size, inclusions etc.
c) Machine tool rigidity and unworn guides: free from vibration, good alignment, accuracy of motions, uniform feed etc.
d) Cutting parameters and conditions: high cutting speed, low feed, low depth of cut, use of proper cutting fluid etc.,
In addition to the above, chip may sometime affect surface finish. So, chip breakers are used on the tool face to improve surface finish.

5. Effects of various factors on tool life

The various factors effecting tool life are: i) tool material, ii) work material, iii) cutting parameters, iv) tool geometry, v) cutting fluid, vi) machine tool – work system rigidity, vii) interrupted cutting and viii) formation of BUE.

i) Tool material
The properties, which improve tool life by reducing rate of wear, are:
a) (High) Hot hardness: It resists deformation in abrasion and adhesion mechanism. This is known as form stability.
b) (Greater) Toughness: It resists tool failure under impact load.
c) (Greater) Wear resistance: It reduces gradual wear of tool
d) Lack of chemical affinity with workpiece
e) High thermal diffusivity ($\kappa = k/\rho C$), high thermal conductivity (k) and low coefficient of expansion.
f) Lower coefficient of friction (μ). Powder metallurgy products have less μ than HSS; cutting fluid has less influence on powder metallurgy products.

$$1.50 > \left[\frac{H_{tool}}{H_{work}}\right]_{modified} > 1.35$$

If the strain rate deformation of work is very high, the strength of the work material becomes very high and the cutting forces increases. This leads to increase in temperature. Thus, hardness of tool decreases causing plastic deformation of PCE.

Fig. 12

ii) Tool geometry

Orthogonal Rake Angle(γ):
Increase in rake angle helps in larger heat dissipation to atmosphere causing larger metal removal and lesser cutting force and temperature. So tool wear decreases. After a limit, the tool looses mechanical strength and chipping of tool occurs.

Plan Approach Angle (φ): Decrease in φ, increases contact length of PCE without affecting the cross sectional area of uncut chip. Thus, P_z is distributed over a greater length of PCE and cutting stress on PCE is decreased. This reduces the chance of plastic deformation of PCE and a better tool life is expected. Also, when φ reduces, a_1 (= f sinφ) reduces and the chip-tool interface temperature ($\theta_i \propto \sqrt{a_i}$) reduces. This reduces the crater wear and tool life is improved. Also, as 'a_1' is reduced, a higher cutting speed may be used enhancing in MRR.
On the other hand, a lesser φ increases P_y. When workpiece is not rigid enough, it bends and results in chatter and vibration. This causes dimensional inaccuracy in workpiece. Altogether, a lesser φ is always desirable.(φ=60°-70°).

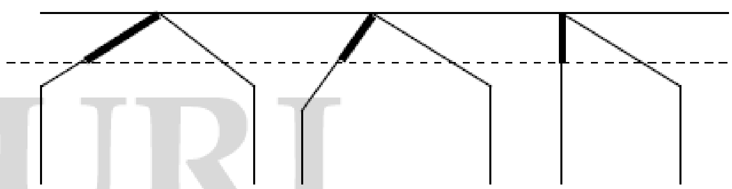

Fig. 13

Principal Clearance Angle(α): Increase in clearance angle avoids rubbing of flank against work piece. Thus, flank wear reduces and tool life is improved. But after a limit, tool strength is reduced and there is a chance of chipping of the tool.

Nose Radius (r): Increase in nose radius initially increases contact length, resulting more heat dissipation and rise in tool life. But, gradually the good effect is counterbalanced by the tendency to chatter and impact (the thrust or radial force increases) load and the tool life reduces.

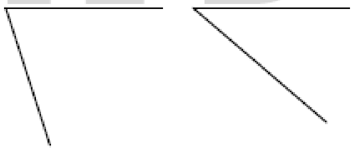

Fig. 14

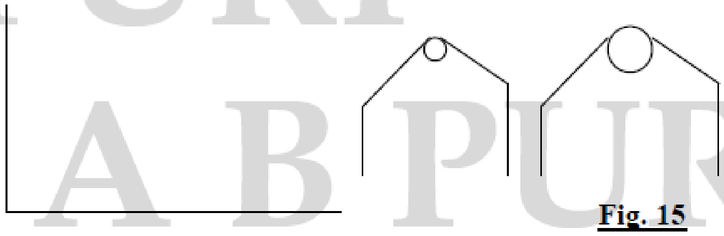

Fig. 15

iii) Cutting parameters

Increase in cutting velocity causes rise in tool temperature leading to softening of tool and higher wear (almost exponentially). Increase in feed means large area of uncut chip cross section, more cutting force and higher temperature which lead to gradual wear and chipping of cutting edge reducing tool life. Increase in depth of cut causes rise in cutting force, temperature, wear, and tendency of chipping of tool and ultimately tool life reduces. Mathematically,

$$VT^n f^{n1} d^{n2} = k; \quad \Rightarrow T^n = \frac{k}{Vf^{n1}d^{n2}}; \quad \Rightarrow T = \frac{k^{\frac{1}{n}}}{V^{\frac{1}{n}} f^{\frac{n1}{n}} d^{\frac{n2}{n}}}; \quad \Rightarrow T = \frac{k_1}{V^x f^y d^z};$$

But, it has been found experimentally that, $x > y > z$

Thus, out of these three, cutting velocity has the highest effect on tool life followed by feed and depth of cut respectively.

iv) Interrupted cutting and intermittent cutting

Variation in depth of cut causes vibration and impact loading, which reduces tool life. For interrupted cutting the tool should have negative rake angle when the high impact loads are transferred to tool shank.

v) Formation of built-up-edge

The overall effect of BUE is to increase flank wear and to reduce crater wear. Thus it affects tool life in two different ways. BUE covers the face adjacent to tool edge and protects it from crater wear. However, the tool sharpness is totally lost due to BUE and surface finish is worsened.

Fig. 16

vi) Cutting fluid

It serves in two ways: as a coolant and as a lubricant. Since the heat is carried away from the tool point, the 'form stability' of the tool improves. Again, with decrease in frictional resistance, temperature rise is lowered down. This beneficial effect is more prominent particularly on plain carbon and HSS tools.

vii) Work material

a) Softness of the work helps in maintaining the tool life for a longer time by reducing cutting temperature and wear.
b) Absence of hard constituents and inclusions like slag, scale, sand etc.
c) Presence of the free cutting additives – Pb, S and graphite which work as a boundary lubricant (have low shear stress and forms a thin layer between tool and chip).
d) Lack of work hardening tendency which limit cutting force, temperature rise and abrasion (if the hardness does not rise due to strain then cutting force decreases).
e) Presence of favourable microstructure: Spheroidal pearlite reduce wear, lamellar pearlite has harmful effect, graphite and ferrite in C.I reduce wear whereas Fe_3C (cementite) has armful effect. Also, increases in grain size reduce wear, smaller grain size increases hardness.

viii) Machine tool work system rigidity

The more the rigidity of the structure, the less is the vibration, more is damping. This reduces chances of tool failure by impact and fatigue load.