MANUFACTURING TECHNOLOGY – II

Theory of metal cutting

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Machining

Machining is a semi-finishing or finishing process essentially done to impart required or stipulated dimensional and form accuracy and surface finish to enable the product to

- fulfill its basic functional requirements
- provide better or improved performance
- render long service life

The form of the chips is an important index of machining because it directly or indirectly indicates :

- Nature and behaviour of the work material under machining condition
- Specific energy requirement (amount of energy required to remove unit volume of work material) in machining work
- Nature and degree of interaction at the chip-tool interfaces.

The form of machined chips depend mainly upon :

- Work material
- Material and geometry of the cutting tool
- Levels of cutting velocity and feed and also to some extent on depth of cut
- Machining environment or cutting fluid that affects temperature and friction at the chip-tool and work-tool interfaces.

Types of cutting tool

- ## Single point cutting tool

The cutting tool, which has only one cutting edge, is termed as single point cutting tool. Single point cutting tools are generally used while performing turning, boring, shaping and planing operation. The important elements in single point cutting tools are rake angle, principle cutting edge, nose etc.

Types of single point tools are as follows :

(a) Solid type tool bit

(b) Brazed tip tool

(c) Long indexable insert tool

(d) Throwaway indexable insert tool

- ## Multi point cutting tool

A cutting tool which has more than one cutting edge is multi point cutting tool. Multi point cutting tools are generally used while performing drilling, milling, broaching, grinding etc. Important elements are cutting edge, helix angle, the number of teeth.

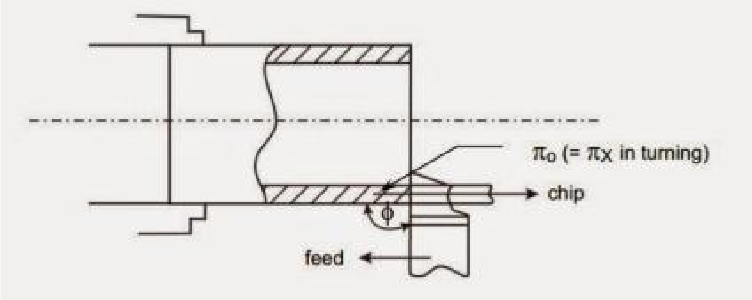
Types of cutting process

- Orthogonal Cutting

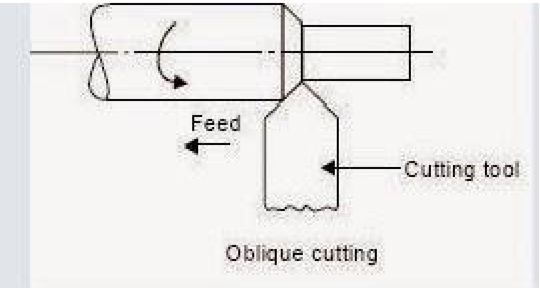
In orthogonal cutting, the tool approaches the work piece with its cutting edge parallel to the uncut surface and at right angles to the direction of cutting (90 degree).

- Oblique Cutting

In oblique cutting , the cutting edge of the tool is inclined at an acute angle with the direction of tool feed or work feed, the chip begin disposed of at a certain angle (less than 90 degree).

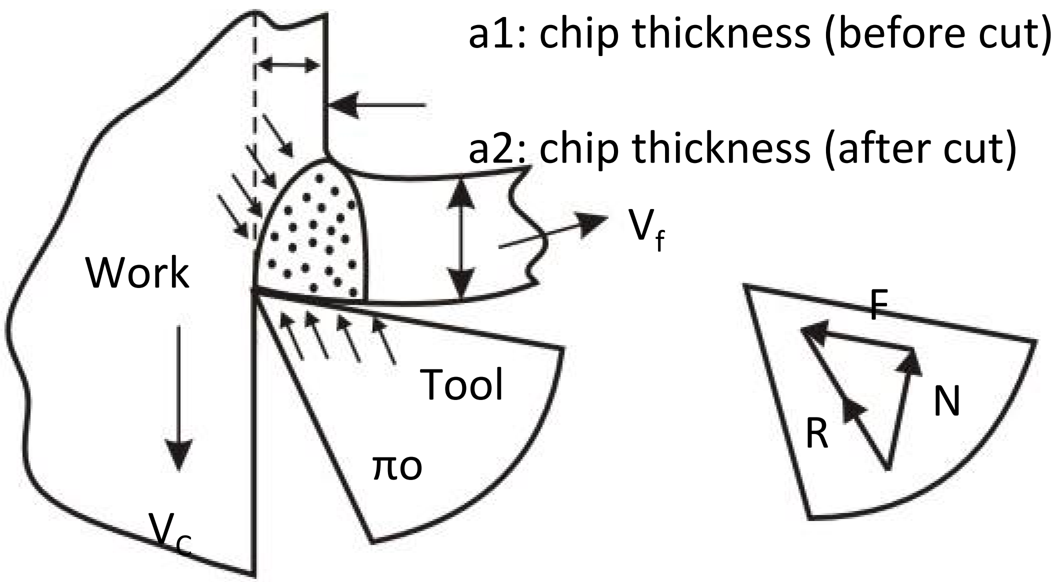


Orthogonal Cutting



Oblique Cutting

Mechanism of chip formation in machining ductile materials



Compression of work material ahead of the tool tip

Knowledge of basic mechanism(s) of chip formation helps to understand the characteristics of chips and to attain favorable chip forms.

During continuous machining the uncut layer of the work material just ahead of the cutting tool (edge) is subjected to almost **all sided compression**, hence **shear stress develops.**

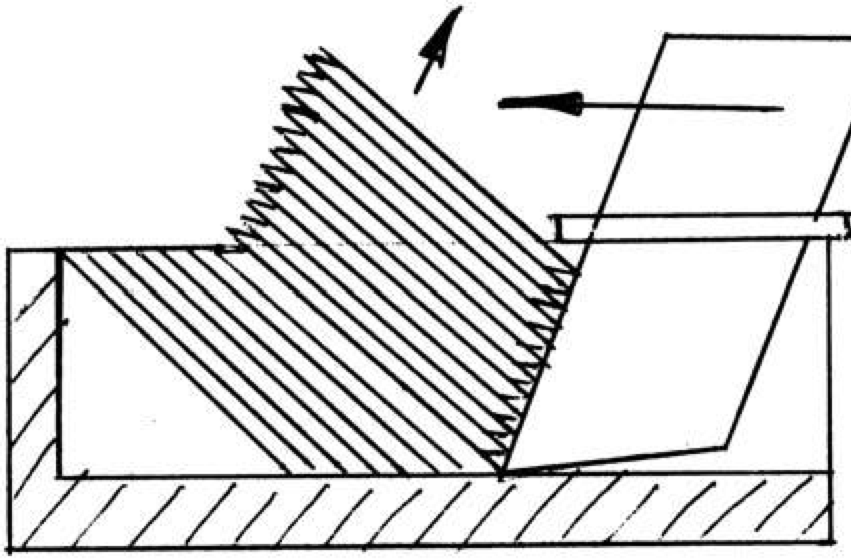
When the **shear stress reaches or exceeds the shear strength** of that work material in the deformation region, yielding or slip takes place resulting in shear deformation in that region and the plane of maximum shear stress.

The forces causing the shear stresses in the region of the chip quickly diminishes and finally disappears while that region **moves along the tool rake surface** towards and then goes beyond the point of chip-tool engagement. As a result the slip or shear stops propagating before total separation takes place.

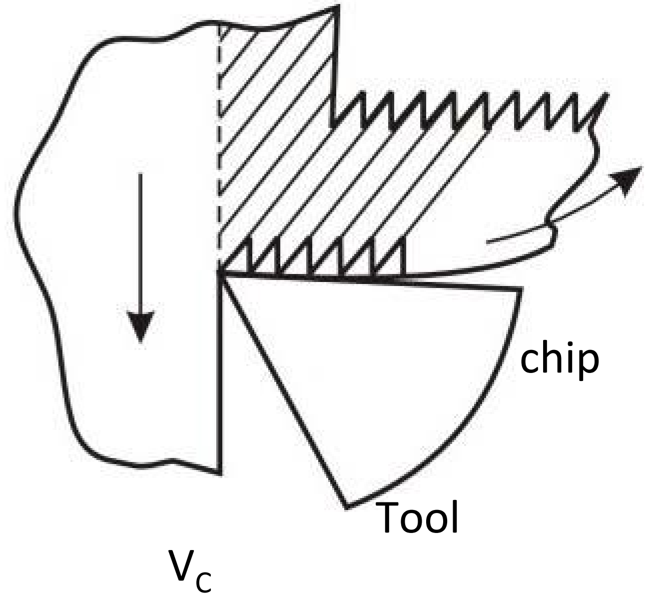
This phenomenon repeats rapidly resulting in formation and removal of chips in thin layer by layer. This phenomenon has been explained in a simple way by **Piispannen[1] using a card analogy**

[1] Piispannen V., "Theory of formation of metal chips", J. Applied Physics, Vol. 19, No. 10, 1948, pp. 876.

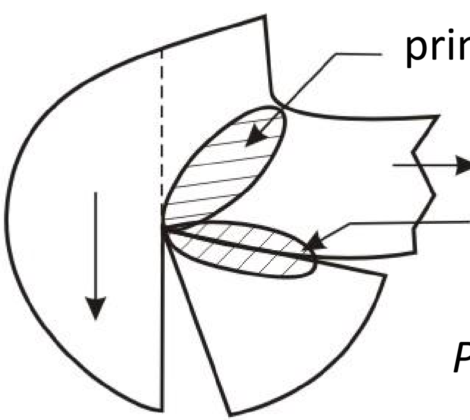
Piispannen model of card analogy to explain chip formation in machining ductile materials



(a) Shifting of the postcards by partial



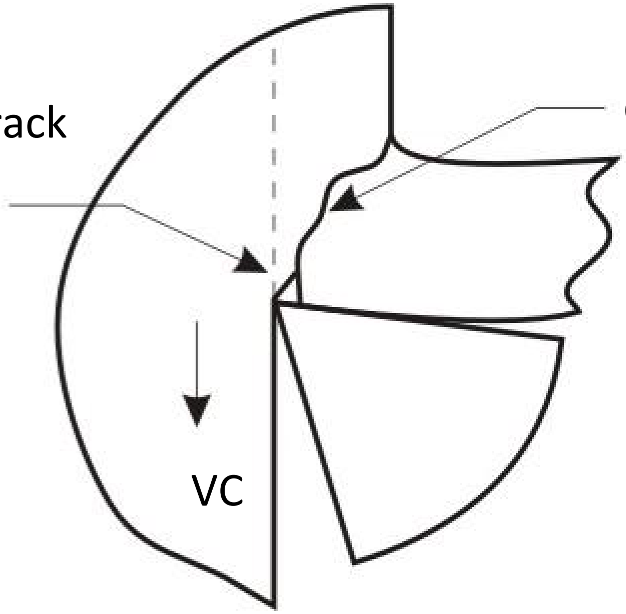
(b) Chip formation by shear in sliding against each other lamella.



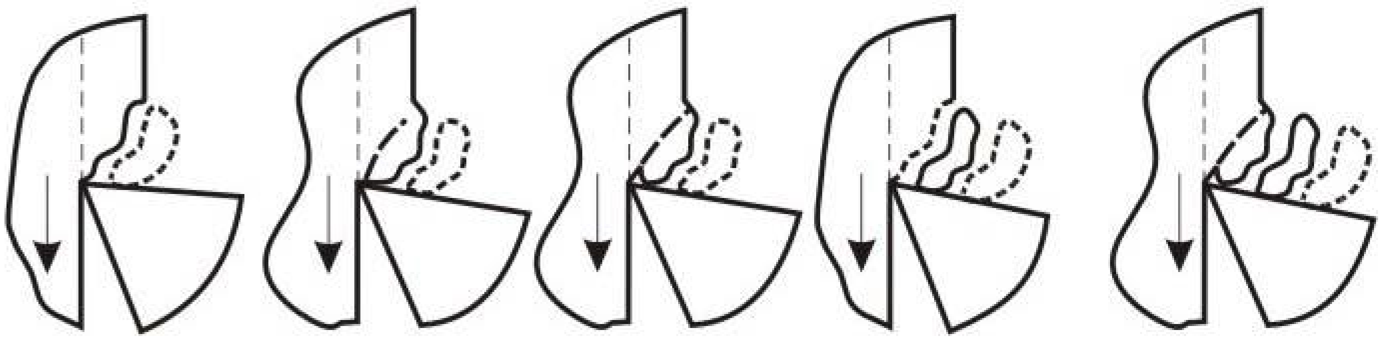
Primary and secondary deformation zones in the chip

Mechanism of chip formation in machining brittle materials

- During machining, first a small crack develops at the tool tip due to wedging action of the cutting edge. At the sharp crack-tip stress concentration takes place.
- In case of ductile materials immediately yielding takes place at the crack-tip and reduces the effect of stress concentration and prevents its propagation as crack.
- In case of brittle materials the initiated crack quickly propagates, under stressing action, and total separation takes place from the parent work piece through the minimum resistance path
- Machining of brittle material produces discontinuous chips and mostly of irregular size and shape. The process of forming such chips is schematically shown in figure.



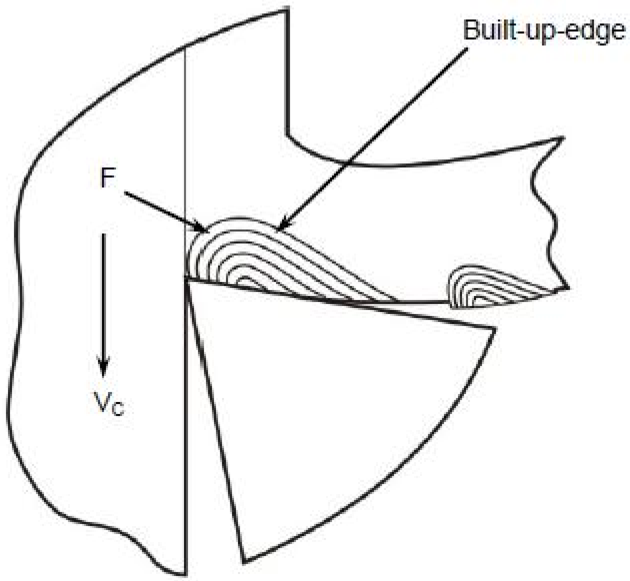
Development and propagation of crack causing chip separation



(a) separation (b) swelling (c) further swelling (d) separation (e) swelling again

Schematic view of chip formation in machining brittle materials

BUE – Built Up Edge



Scheme of built-up-edge formation

In machining ductile metals like steels with long chip-tool contact length, lot of stress and temperature develops in the secondary deformation zone at the chip-tool interface. Under such high stress and temperature in between two clean surfaces of metals, strong bonding may locally take place due to adhesion similar to welding. Such bonding will be encouraged and accelerated if the chip tool materials have mutual affinity or solubility. The weldment starts forming as an embryo at the most favorable location and thus gradually grows .

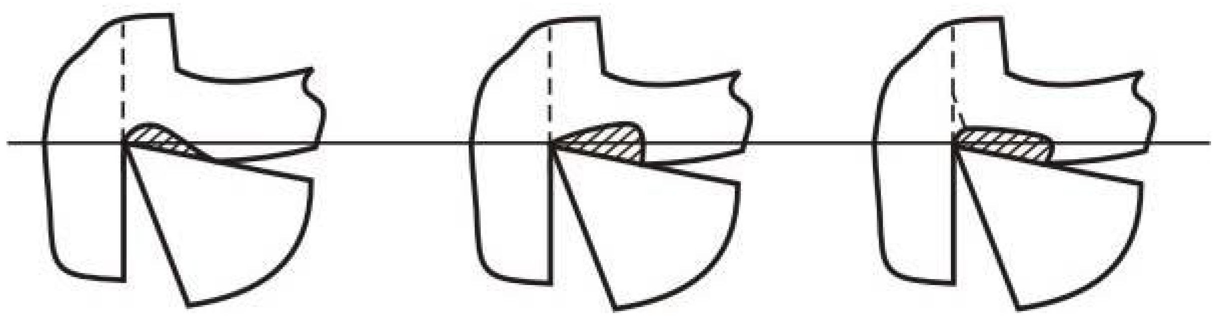
With the growth of the BUE, the force, F also gradually increases due to wedging action of the tool tip along with the BUE formed on it. Whenever the force, F exceeds the bonding force of the BUE, the BUE is broken or sheared off and taken away by the flowing chip. Then again BUE starts forming and growing. This goes on repeatedly.

Characteristics of BUE

Built-up-edges are characterized by its shape, size and bond strength, which depend upon:

- work tool materials
- stress and temperature, i.e., cutting velocity and feed
- cutting fluid application governing cooling and lubrication.

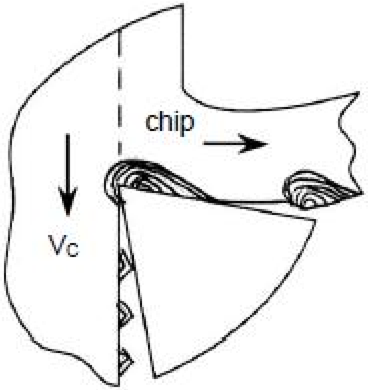
BUE may develop basically in three different shapes as schematically shown



(a) positive wedge (b) negative wedge (c) flat type

Different forms of built-up-edge.

In machining too soft and ductile metals by tools like high speed steel or uncoated carbide the BUE may grow larger and overflow towards the finished surface through the flank

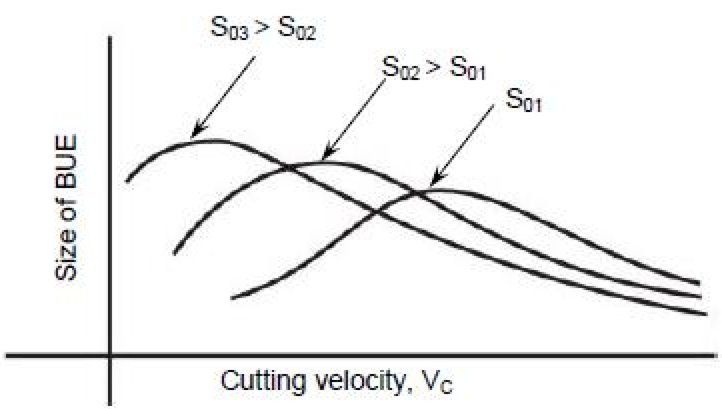


Overgrowing and overflowing of BUE causing surface roughness

Formation of BUE causes several harmful effects, such as:

- It un-favourably changes the rake angle at the tool tip causing increase in cutting forces and power consumption
- Repeated formation and dislodgement of the BUE causes fluctuation in cutting forces and thus induces vibration which is harmful for the tool, job and the machine tool.
- Surface finish gets deteriorated
- May reduce tool life by accelerating tool-wear at its rake surface by adhesion and flaking

Occasionally, formation of thin flat type stable BUE may reduce tool wear at the rake face.



Role of cutting velocity and feed on BUE formation.

Types of chips and conditions for formation of those chips

Discontinuous type

irregular size and shape : - work material – brittle like grey cast iron
regular size and shape : - work material ductile but hard and work hardenable
feed – large, tool rake – negative , cutting fluid – absent or inadequate

Continuous type

Without BUE : work material – ductile
Cutting velocity – high , Feed – low , Rake angle – positive and large
Cutting fluid – both cooling and lubricating

With BUE : work material – ductile
cutting velocity – medium , feed – medium or large
cutting fluid – inadequate or absent.

Jointed or segmented type
work material – semi-ductile
cutting velocity – low to medium , feed – medium to large
tool rake – negative , cutting fluid – absent

Need and purpose of chip-breaking

- Continuous machining like turning of ductile metals, unlike brittle metals like grey cast iron, produce continuous chips, which leads to their handling and disposal problems. The problems become acute when ductile but strong metals like steels are machined at high cutting velocity for high MRR by flat rake face type carbide or ceramic inserts. The sharp edged hot continuous chip that comes out at very high speed
- • becomes dangerous to the operator and the other people working in the vicinity
- • may impair the finished surface by entangling with the rotating job
- • creates difficulties in chip disposal.

- Therefore it is essentially needed to break such continuous chips into small regular pieces for

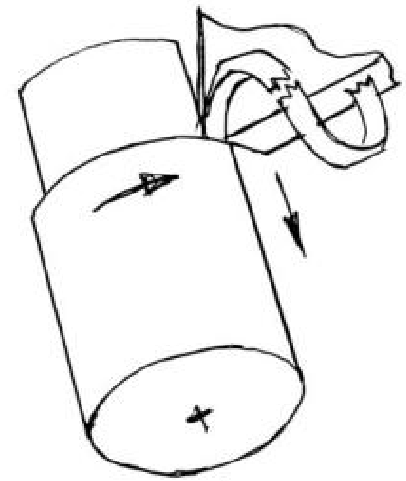
- • safety of the working people
- • prevention of damage of the product
- • easy collection and disposal of chips.

- Chip breaking is done in proper way also for the additional purpose of improving machinability by reducing the chip-tool contact area, cutting forces and crater wear of the cutting tool..

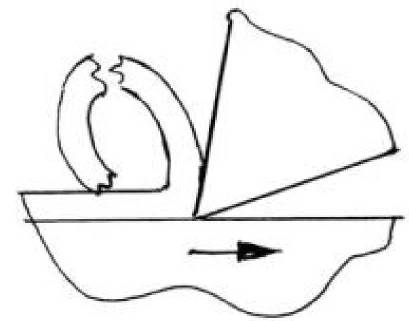
Principles of chip-breaking

Self breaking of chips

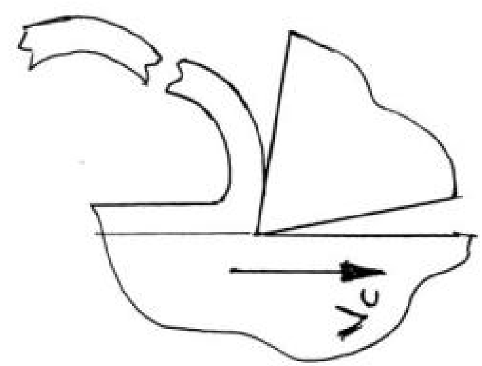
By striking against the tool flank after each half to full turn as indicated



By striking against the cutting surface of the job, as shown mostly under pure orthogonal cutting



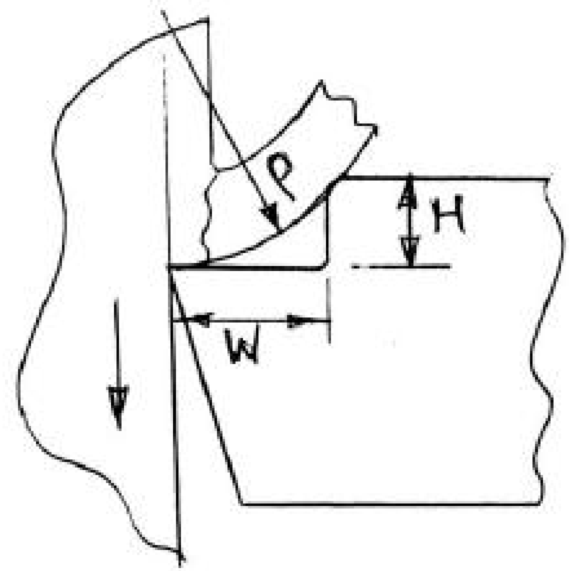
By natural fracturing of the strain hardened outgoing chip after sufficient cooling and spring back. This kind of chip breaking is generally observed under the condition close to that which favors formation of jointed or segmented chips



The possibility and pattern of self chip-breaking depend upon the work material, tool material and tool geometry (γ, λ, ϕ and r), levels of the process parameters (V_C and s_o) and the machining environment (cutting fluid application) which are generally selected keeping in view the overall machinability

Forced chip-breaking

The hot continuous chip becomes hard and brittle at a distance from its origin due to work hardening and cooling. If the running chip does not become enough curled and work hardened, it may not break. In that case the running chip is forced to bend or closely curl so that it breaks into pieces at regular intervals. Such broken chips are of regular size and shape depending upon the configuration of the chip breaker.



W = width, H = height, β = shear angle

Principle of forced chip breaking.

Chip breakers are basically of two types :

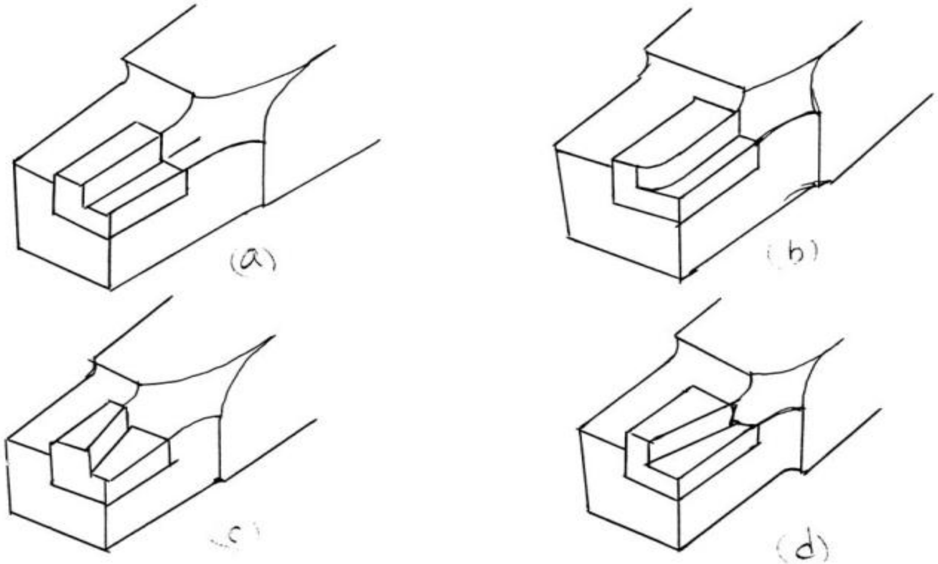
- In-built type
- Clamped or attachment type

In-built breakers are in the form of step or groove at the rake surface near the cutting edges of the tools. Such chip breakers are provided either

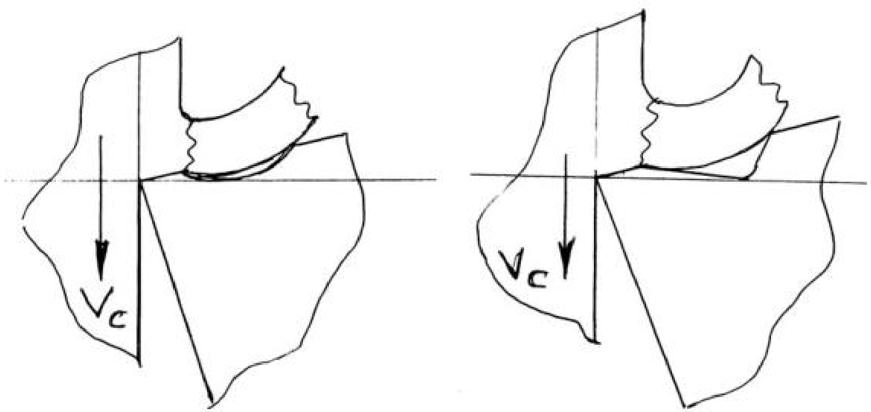
Δ after their manufacture – in case of HSS tools like drills, milling cutters, broaches etc and brazed type carbide inserts

Δ during their manufacture by powder metallurgical proc

In built chip breakers



Step type in-built chip breaker (a) parallel step
(b) parallel and radiused
(c) positive angular (d) negative angular



Groove type in-built chip breaker

(a) circular groove (b) tilted Vee-

The unique characteristics of **in-built chip** breakers are :

• The outer end of the step or groove acts as the heel that forcibly bend and fracture the running chip

• Simple in configuration, easy manufacture and inexpensive

• The geometry of the chip-breaking features are fixed once made (i.e., cannot be controlled)

• Effective only for fixed range of speed and feed for any given tool-work combination.

Clamped chip breakers

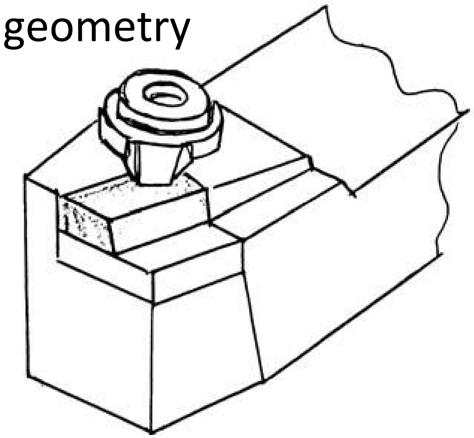
Clamped type chip breakers work basically in the principle of stepped type chip-breaker but have the provision of varying the width of the step and / or the angle of the heel.

- With fixed distance and angle of the additional strip – effective only for a limited domain of parametric combination

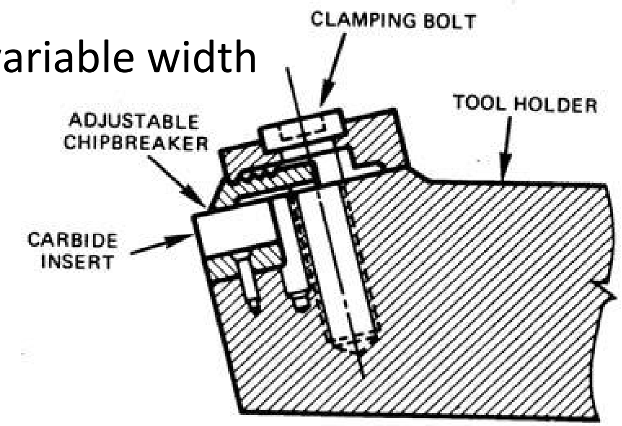
- With variable width (W) only – little versatile

- With variable width (W), height (H) and angle (β) – quite versatile but less rugged and more expensive.

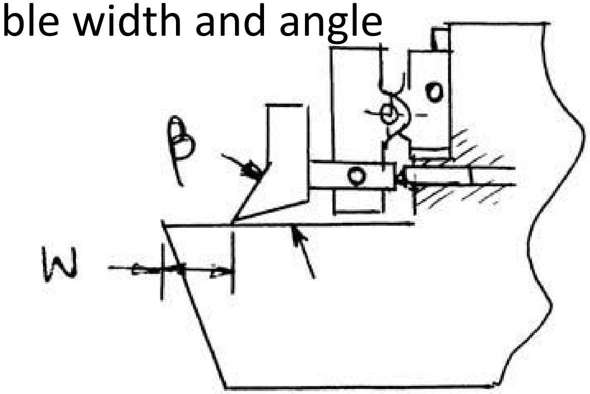
(a) fixed geometry



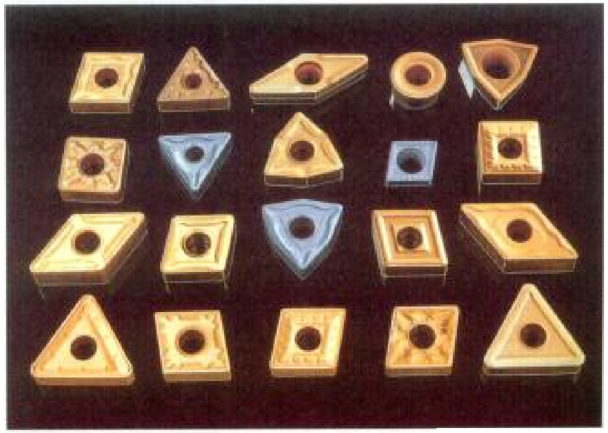
(b) variable width

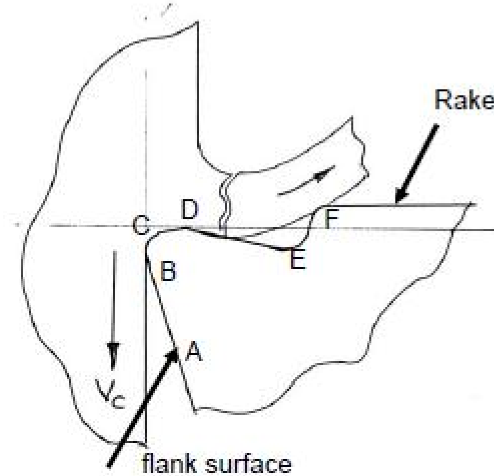


(c) variable width and angle

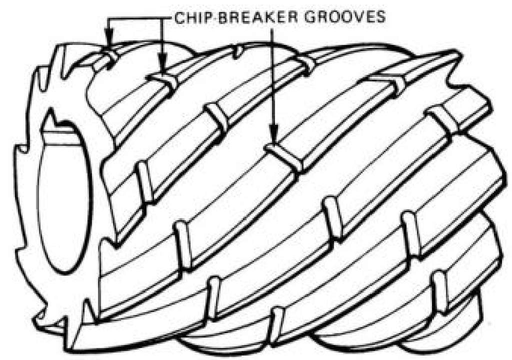


Various groove type inserts

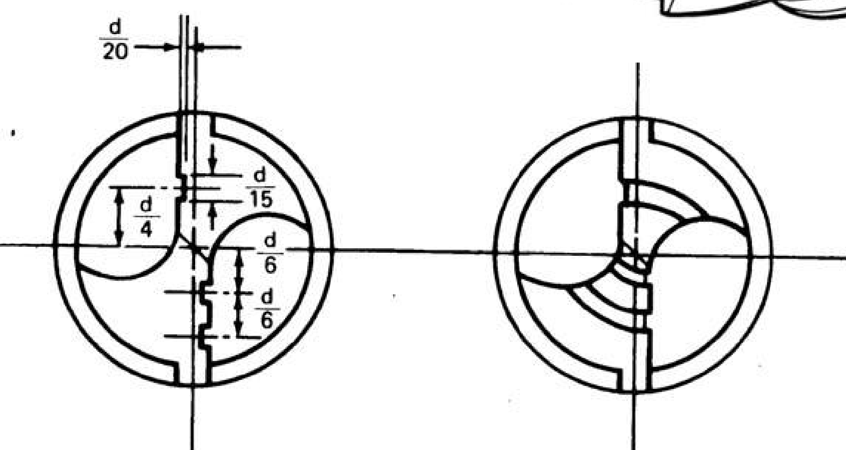




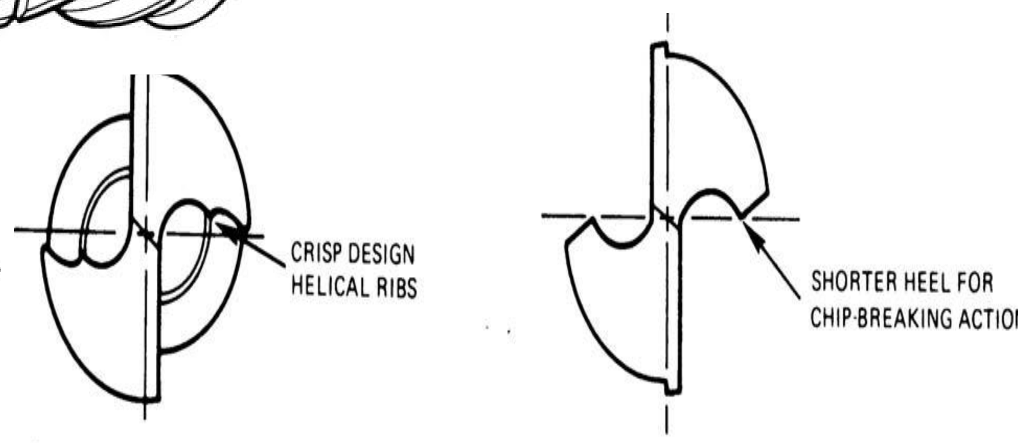
Schematic view of the typical form of inserts (cutting edge) with integrated chip-breaker.



Chip breaking grooves on a plain helical milling cutter



Chip breaking grooves in HSS

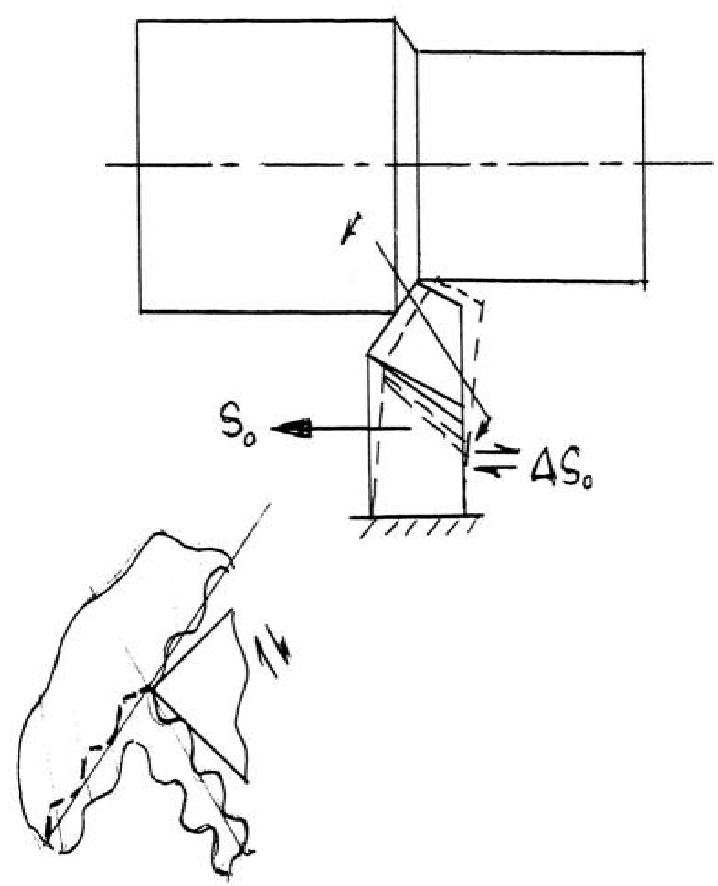


(a) Crisp design of chip-breaking drill (b) US industrial design of chip- breaking drill

Dynamic chip breaker

Dynamic turning is a special technique, where the cutting tool is deliberately vibrated along the direction of feed at suitable frequency and amplitude.

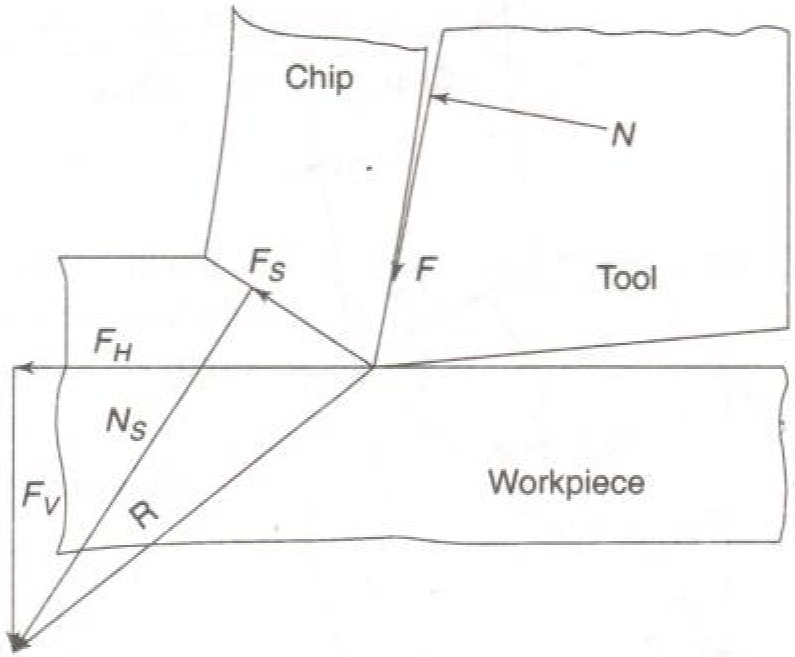
Such additional controlled tool oscillation caused by mechanical, hydraulic or electro-magnetic (solenoid) shaker improves surface finish. This also reduces the cutting forces and enhances the tool life due to more effective cooling and lubrication at the chip tool and work tool interfaces for intermittent break of the tool-work contact.

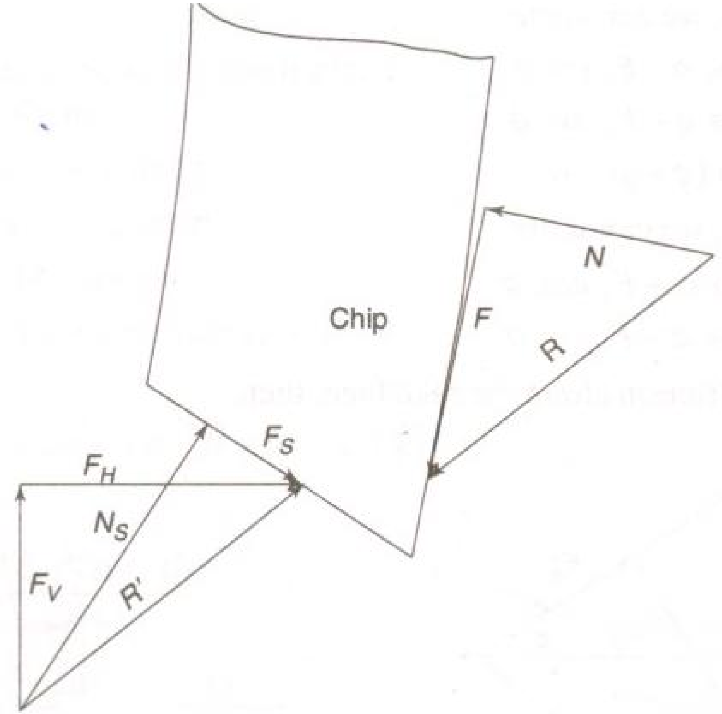


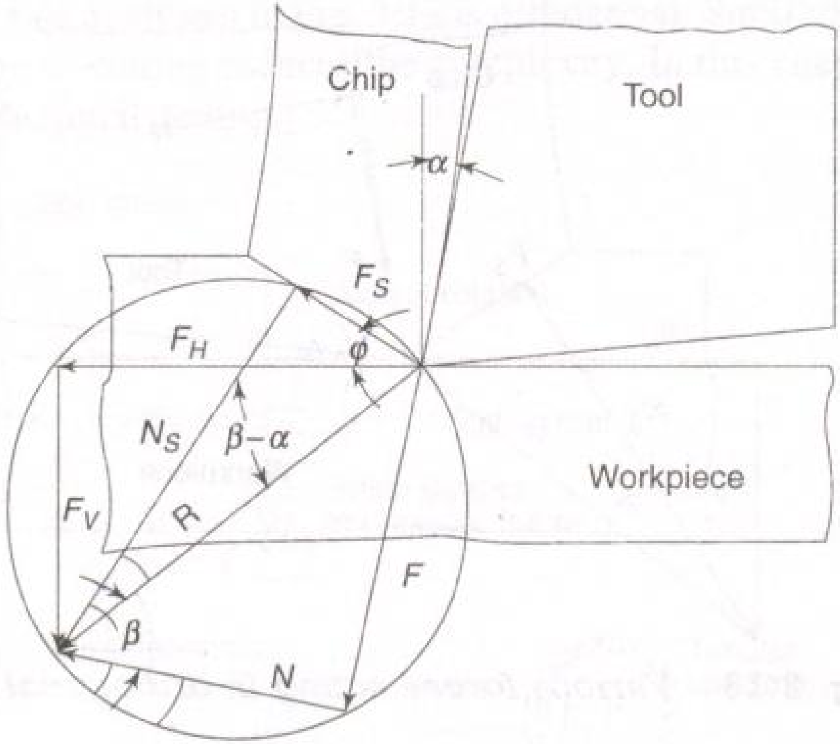
Such technique, if further slightly adjusted, can also help breaking the chips. When the two surfaces of the chip will be waved by phase difference of about 90°, the chip will either break immediately or will come out in the form of bids, which will also break with slight bending or pressure .

MECHANICS OF METAL CUTTING

Merchant’ s Circle Theory







$$F_s = F_H \cos\phi - F_V \sin\phi$$

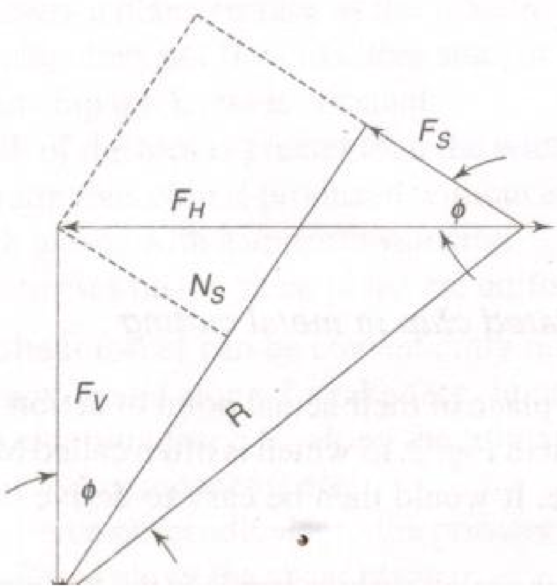
$$N_s = F_V \cos\phi + F_H \sin\phi$$

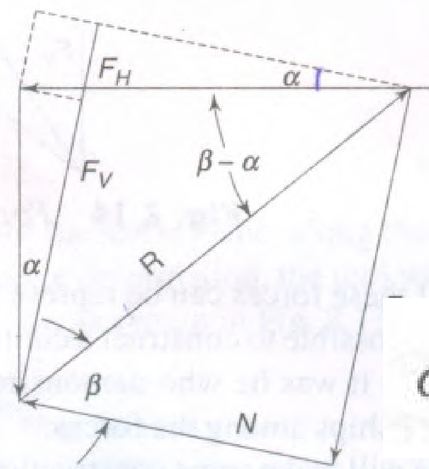
$$= F_s \tan(\phi + \beta - \alpha)$$

$$F = F_H \sin\alpha + F_V \cos\alpha$$

$$N = F_H \cos\alpha - F_V \sin\alpha$$

$$\mu = \tan\beta = \frac{F}{N} = \frac{F_V + F_H \tan\alpha}{F_H - F_V \tan\alpha}$$





$$A_s = \frac{bt}{\sin\phi}$$

$$F_s = \tau A_s = \frac{\tau bt}{\sin\phi}$$

$$\sigma = \frac{N_s}{A_s} \quad \text{or} \quad N_s = \frac{\sigma bt}{\sin\phi}$$

We can show that by resolving

$$F_H = F_s \cos\phi + N_s \sin\phi$$
$$F_V = N_s \cos\phi - F_s \sin\phi$$

$$F_H = F_s\,[\cos\phi + \sin\phi \tan(\phi + \beta - \alpha)]$$

$$F_V = F_s\,[\cos\phi \tan(\phi + \beta - \alpha) - \sin\phi]$$

$$F_H = F_s\left[\frac{\cos(\alpha - \beta)}{\cos(\phi + \beta - \alpha)}\right]$$

$$F_H = \frac{\tau b t \cos(\beta - \alpha)}{\sin(\phi)\cos(\phi + \beta - \alpha)}$$

$$F_V = \frac{\tau b t \sin(\beta - \alpha)}{\sin(\phi)\cos(\phi + \beta - \alpha)}$$

Merchant considered that τ would have the value of the yield shear stress for the work material and that μ would have the usual value for any dry sliding friction. To determine ϕ he assumed the minimum energy principle applied in metal cutting so that the deformation process adjusted itself to a minimum energy condition, or

$$\frac{dF_H}{d\phi} = \frac{\tau b t \cos(\beta - \alpha) \cos(2\phi + \beta - \alpha)}{\sin^2 \phi \cos^2 (\phi + \beta - \alpha)} = 0$$

or $\quad \cos(2\phi + \beta - \alpha) = 0$

or $$2\phi + \beta - \alpha = \frac{\pi}{2}$$

$$\phi = \frac{\pi}{4} - \frac{1}{2}(\beta - \alpha)$$

Substituting back, we can show that

$$F_H = 2\tau bt \cot \phi$$

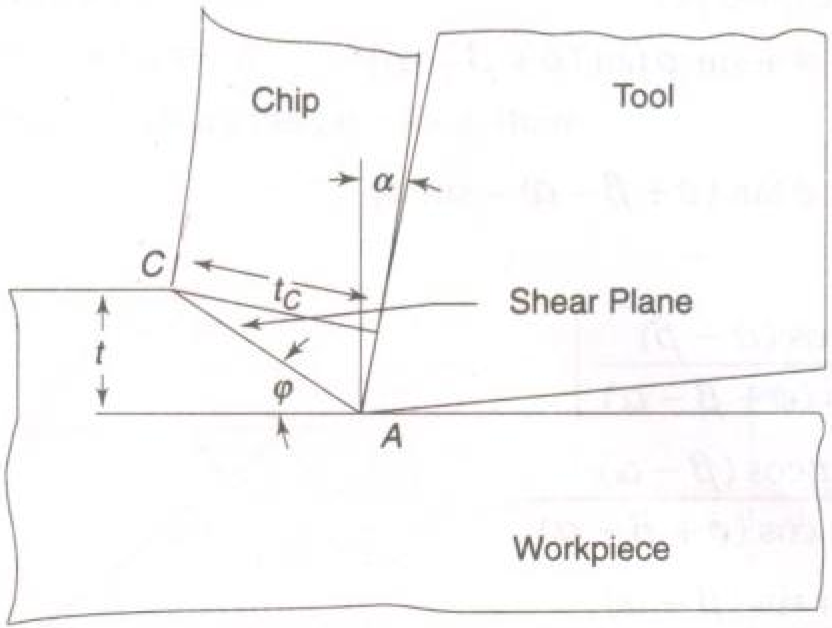
$$F_V = \tau bt (\cot^2 \phi - 1)$$

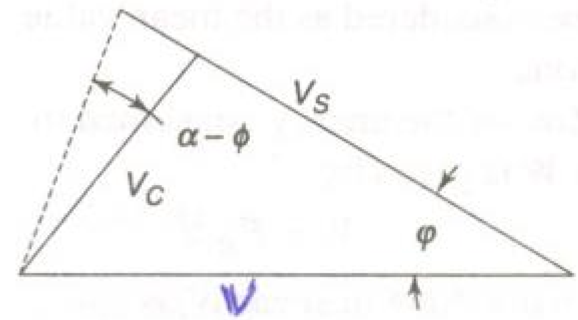
$$t = AB \sin \phi$$

$$t_c = AB \cos(\phi - \alpha)$$

$$t_c = \frac{t\,l}{l_c}$$

(2.2





$$r = \frac{t}{t_c} = \frac{\sin \phi}{\cos(\phi - \alpha)} = \frac{1}{\cot \phi \cos \alpha + \sin \alpha}$$

$$\frac{V}{\sin\{90 - (\phi - \alpha)\}} = \frac{V_s}{\sin(90 - \alpha)} = \frac{V_c}{\sin \phi}$$

$$\cot \phi \cos \alpha = \frac{1 - r \sin \alpha}{r}$$

$$V_c = \frac{V \sin \phi}{\cos(\phi - \alpha)}$$

$$\tan \phi = \frac{r \cos \alpha}{1 - r \sin \alpha}$$

$$V_s = \frac{V \cos \alpha}{\cos(\phi - \alpha)}$$

Shear strain γ is given by

$$\gamma = \frac{\Delta S}{\Delta Y} = \frac{AB}{CD} = \frac{AD}{CD} = \frac{DB}{CD} = \tan\phi + \cot(\phi - \alpha)$$

or
$$\gamma = \frac{\cos\alpha}{\sin\phi\cos(\phi-\alpha)} = \frac{V_s}{V\sin\phi}$$

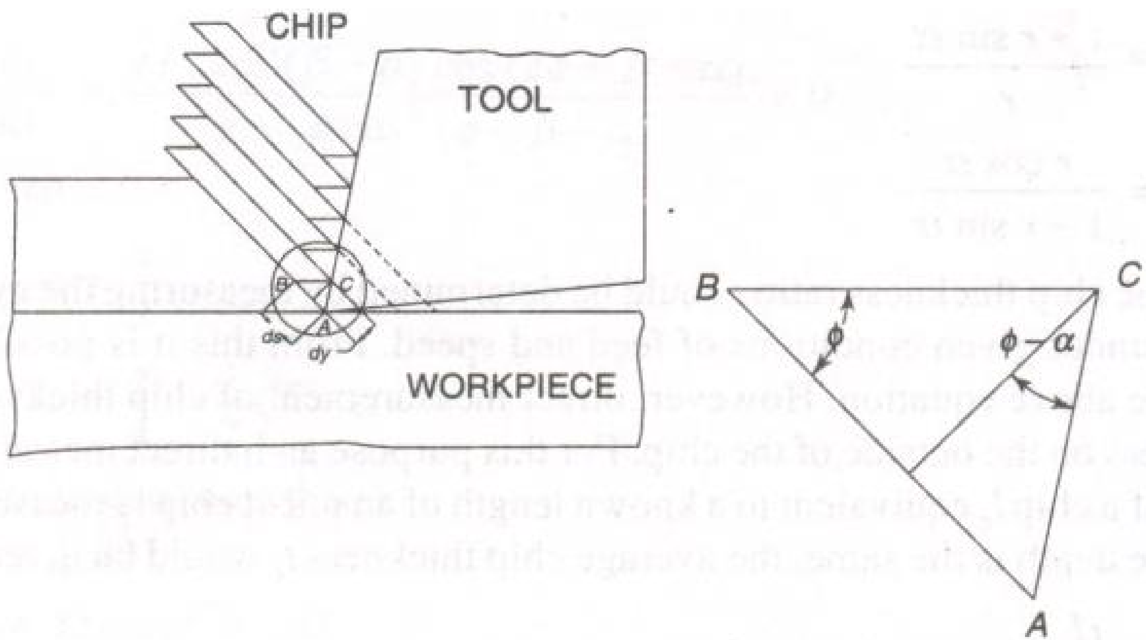


Fig. 2.20 *Strain and strain rate in orthogonal cutting*

$$\dot{\gamma} = \frac{\Delta S}{\Delta Y\,\Delta t} = \frac{V_s}{\Delta Y} = \frac{\cos\alpha}{\cos(\phi-\alpha)}\frac{V}{\Delta Y}$$

$$W = F_H V$$

The work done in shear W_s is

$$W_s = F_s V_s$$

Similarly the work done in friction W_f is

$$W_f = FV_c$$

Thus,

$$W = F_H V = F_s V_s + FV_c$$

The material removal rate is

$$MRR = Vbt$$

$$u_s = \frac{F_H V}{MRR} = \frac{\tau \sin(\beta - \alpha)}{\sin(\phi)\cos(\phi + \beta - \alpha)}$$

EXAMPLE 2.1 *A bar of 75 mm diameter is reduced to 73 mm by a cutting tool while cutting orthogonally. If the mean length of the cut chip is 73.5 mm, find the cutting ratio. If the rake angle is 15°, what is the shear angle?*

Length of uncut chip $l = \dfrac{\pi(75 + 73)}{2} = 232.4779$ mm

Cutting ratio $r = \dfrac{t_c}{t} = \dfrac{73.9}{232.4779}. = 0.3179$

Shear angle $\phi = \tan^{-1}\left[\dfrac{r \cos \alpha}{1 - r \sin \alpha}\right] = \tan^{-1}\left[\dfrac{0.3179 \cos 15}{1 - 0.3179 \sin 15}\right]$

Shear angle $\phi = \tan^{-1}(0.3346) = 19°.$

EXAMPLE 2.2 *In an orthogonal cutting test with a tool of rake angle 10°, the following observations were made:*

Chip thickness ratio = 0.3

Horizontal component of the cutting force = 1290 N

Vertical component of the cutting force = 1650 N

From Merchant's theory, calculate the various components of the cutting forces and the coefficient of friction at the chip tool interface, The shear plane angle ϕ is

$$\tan \phi = \frac{r \cos \alpha}{1 - r \sin \alpha} = \frac{0.3 \cos 10}{1 - 0.3 \sin 10} = 0.311679$$

shear angle, $\phi = \tan^{-1} (0.311679) = 17.31°$

Given $F_V = 1650$ and $F_H = 1290$,

The friction force along rake face is

$$F = F_H \sin \alpha + F_V \cos \alpha = 1290 \sin 10 + 1650 \cos 10 = 1848.94 \text{ N}$$

and the normal force on the rake face is

$$N = F_H \cos \alpha - F_V \sin \alpha = 1290 \cos 10 - 1650 \sin 10 = 983.88 \text{ N}$$

The coefficient of friction μ at the chip tool interface is given by

$$\mu = \frac{F}{N} = \frac{1848.94}{983.88} = 1.8792$$

The friction angle β is given by

$$\beta = \tan^{-1} \mu = \tan^{-1} (1.8792) = 62°$$

The resultant cutting force R is given by

$$R = \sqrt{1650^2 + 1290^2} = 2094.42 \text{ N}$$

The shear force along the shear plane is

$$F_s = F_H \cos \phi - F_V \sin \phi = 1290 \cos 17.31 - 1650 \sin 17.31 = 740.63 \text{ N}$$

The normal force on the shear plane is

$$N_s = F_V \cos \phi + F_H \sin \phi = 1650 \cos 17.31 + 1290 \sin 17.31 = 1959.10 \text{ N}$$

The area of the shear plane is given by

$$A_s = \frac{bt}{\sin \phi} = \frac{6 \times 0.10}{\sin 17.31} = 2.0165 \text{ mm}^2$$

To verify the shear angle from the relation suggested by Merchant,

$$\phi = \frac{\pi}{4} - \frac{1}{2}(\beta - \alpha) = \frac{\pi}{4} - \frac{(62 - 10)}{2} = 19°$$

EXAMPLE 2. 3 *An orthogonal cutting of steel is done with 10° rake tool, with a depth of cut 2 mm and feed rate of 0.20 mm / rev. The cutting speed is 200 m / min. The chip thickness ratio is 0.31. The vertical cutting force is 1200 N and the horizontal cutting force is 650 N. Calculate from the Merchant's theory, the various work done in metal cutting and shear stress.*

Given $r = 0.31$ and $\alpha = 10°$
shear plane angle ϕ is

$$\tan \phi = \frac{0.31 \cos 10}{1 - 0.31 \sin 10} = 0.32266$$

shear angle, $\phi = \tan^{-1} (0.32266) = 17.88°$
Given $F_V = 1200$ and $F_H = 650$, the shear force along the shear plane is

$$F_s = 650 \cos 17.88 - 1200 \sin 17.88 = 250.18 \text{ N}$$

The normal force on the shear plane is

$$N_s = 1200 \cos 17.88 + 650 \sin 17.88 = 1341.61 \text{ N}$$

The area of the shear plane is given by

$$A_s = \frac{bt}{\sin \phi} = \frac{2 \times 0.20}{\sin 17.88} = 1.3028 \text{ mm}^2$$

Friction force along rake face is

$$F = 650 \sin 10 + 1200 \cos 10 = 1294.64 \text{ N}$$

Normal force on the rake face is

$$N = 650 \cos 10 - 1200 \sin 10 = 431.75 \text{ N}$$

The coefficient of friction μ at the chip tool interface is given by

$$\mu = \frac{F}{N} = \frac{1294.64}{431.75} = 2.9986$$

The friction angle β is given by

$$\beta = \tan^{-1} \mu = \tan^{-1} (2.9986) = 71.56°$$

To verify the validity of the shear angle relationship suggested by Merchant,

$$\phi = \frac{\pi}{4} - \frac{1}{2}(\beta - \alpha) = \frac{\pi}{4} - \frac{(71.56 - 10)}{2} = 14.22°$$

It can be seen that the actual value of the shear angle obtained from measured values is 17.88, whereas the value calculated from the shear angle relation of Merchant's is 14.22, the resulting error being 20.5%.

The shear velocity V_s is given by

$$V_s = \frac{V \cos \alpha}{\cos (\phi - \alpha)} = \frac{200 \cos 10}{\cos (17.88 - 10)} = 198.84 \text{ m/min}$$

The chip velocity V_c is given by

$$V_c = \frac{V \sin \phi}{\cos (\phi - \alpha)} = \frac{200 \sin 17.88}{\cos (17.88 - 10)} = 61.99 \text{ m/min}$$

Shear strain γ is given by

$$\gamma = \frac{V_s}{V \sin \phi} = \frac{198.84}{200 \sin 17.88} = 3.2382$$

The strain rate is given by

$$\dot{\gamma} = \frac{V_s}{\Delta Y} = \frac{\cos \alpha}{\cos (\phi - \alpha)} \frac{V}{\Delta Y} = \frac{\cos 10 \times 200000}{\cos (17.88 - 10)\, 0.0025} = 79.5357$$

taking $\Delta Y = 2.5$ microns.

The shear work done W_s is

$$W_s = F_s \times V_c = 250.1767 \times 198.84 = 49745{\cdot}14 \text{ N m/min}$$

The work done in friction W_f is

$$W_f = F \times V_c = 1294{\cdot}64 \times 61.99 = 80254{\cdot}77 \text{ N m/min}$$

The total work done is

$$W = F_H \times V = 200 \times 650 = 130000 \text{ N m/min}$$

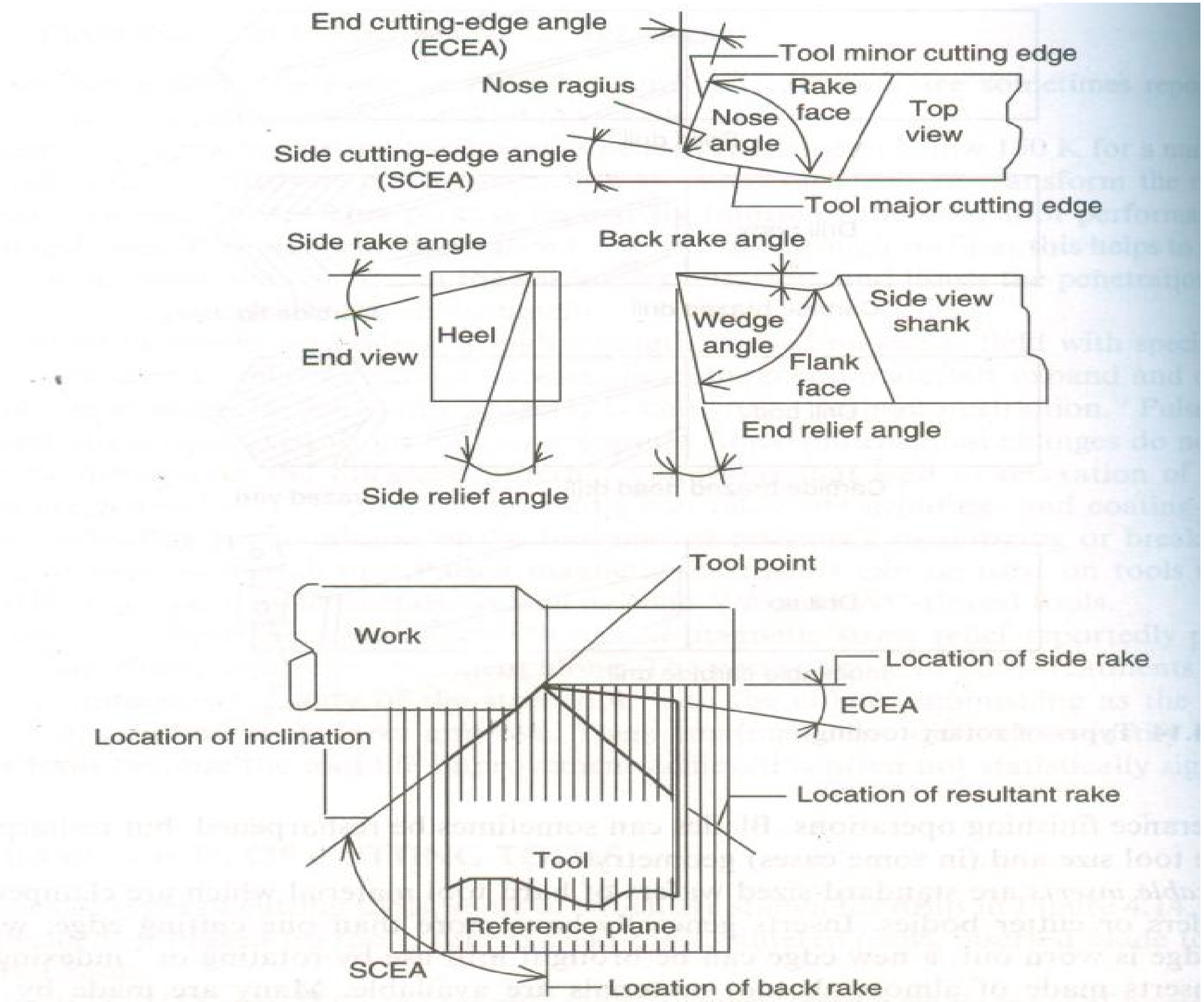
The shear work proportion out of the total work done is

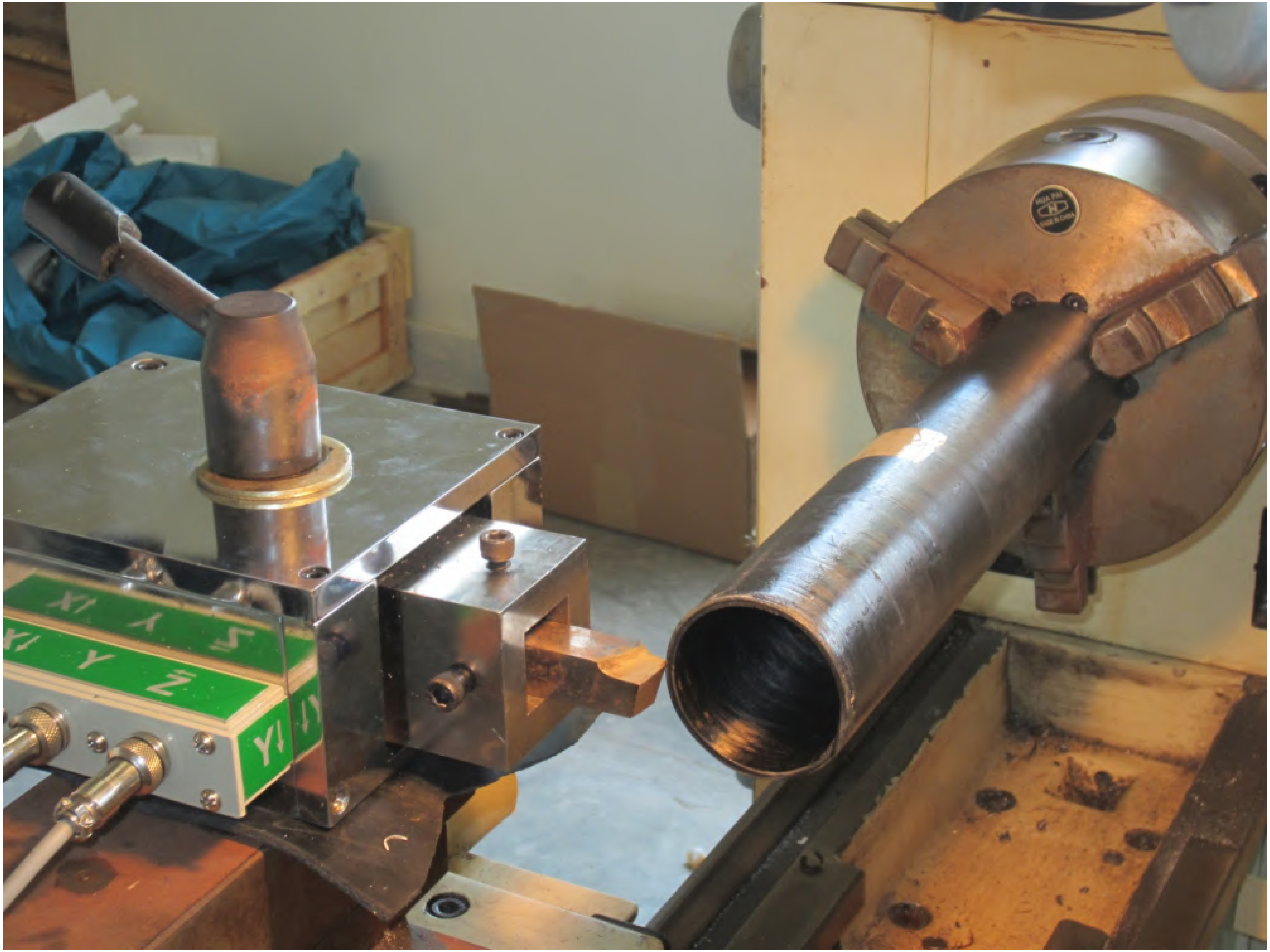
$$\frac{49745.14}{130000} = 38.27\%$$

Friction work proportion in total work done is

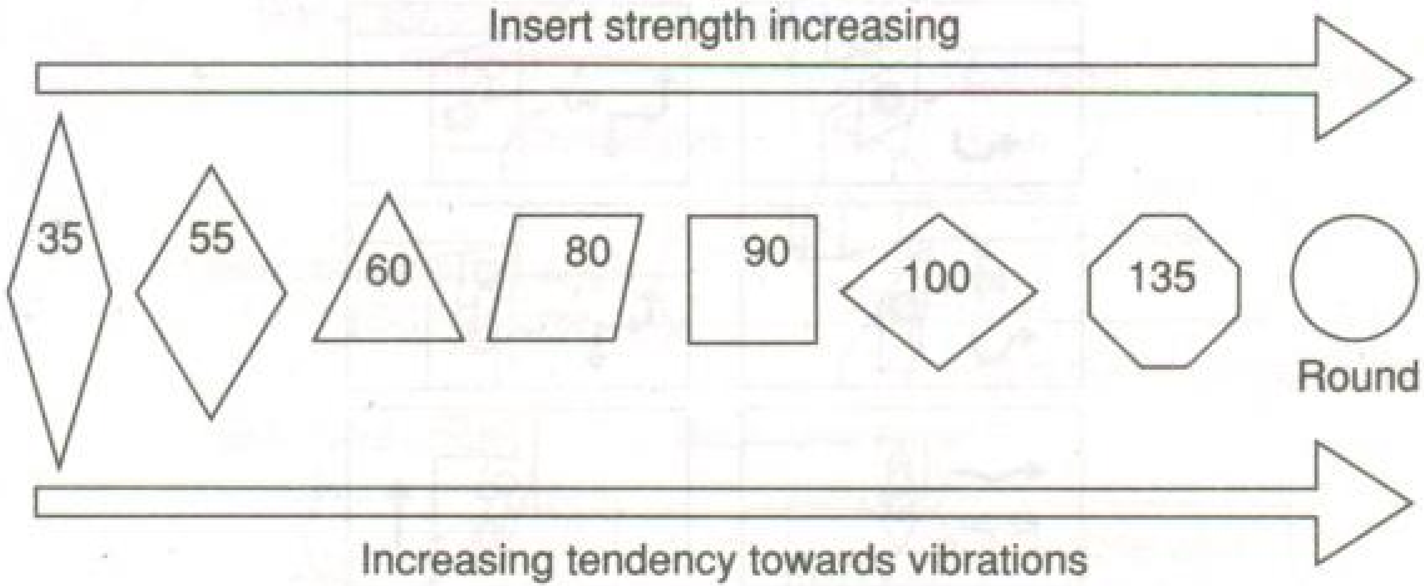
$$\frac{80254.77}{130000} = 61.73\%$$

Single point tool nomenclature



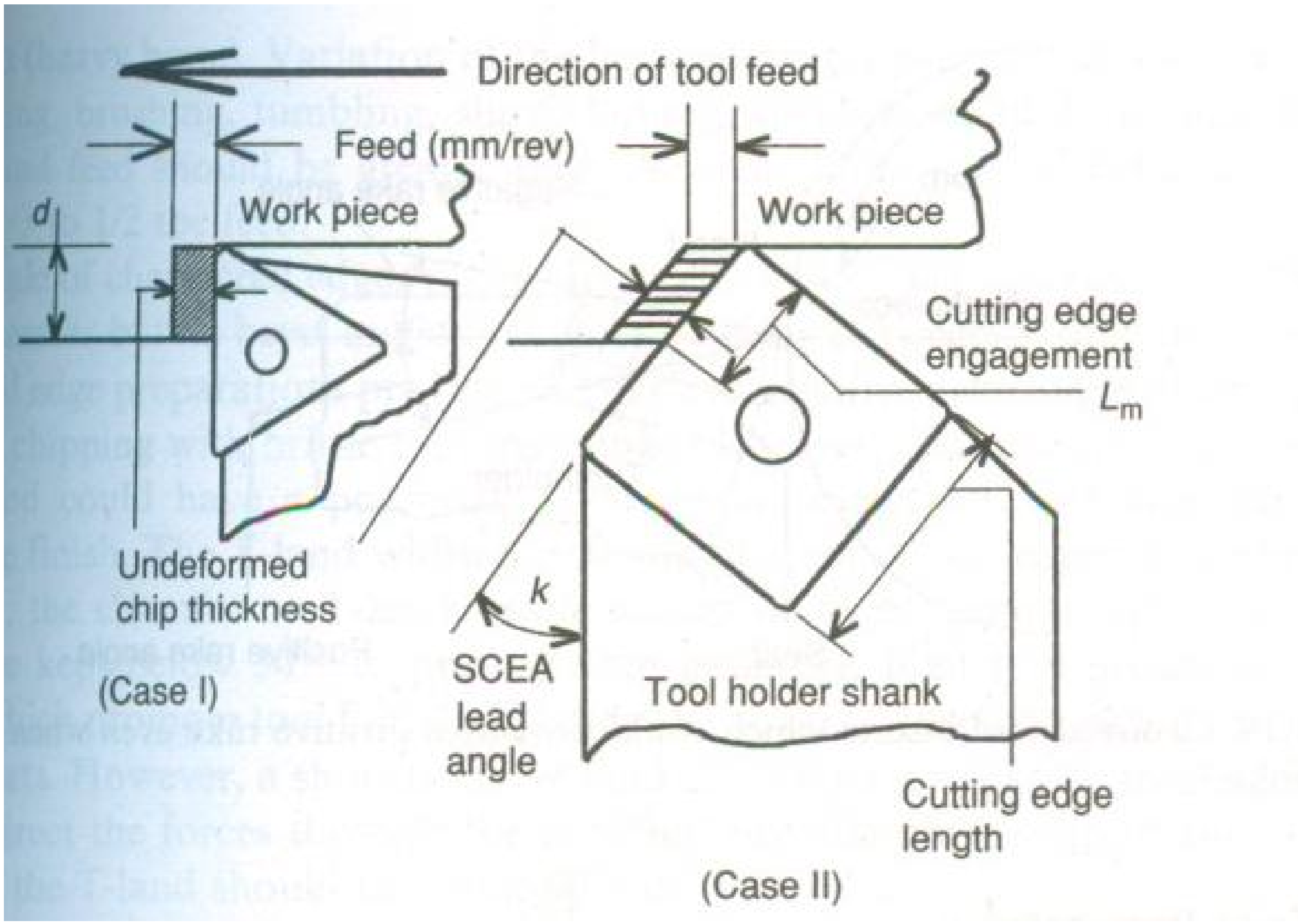


Insert relative strength

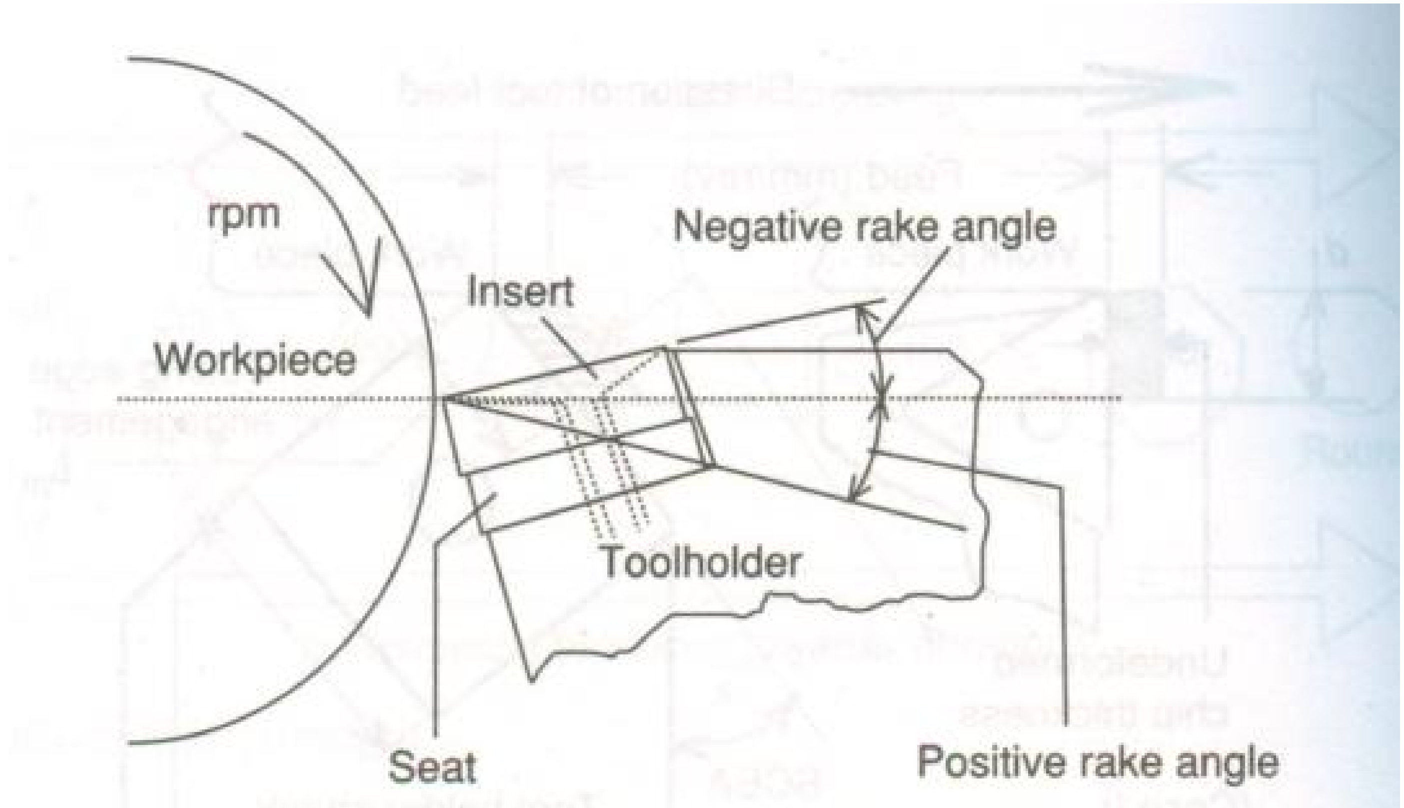


Relative insert strength.

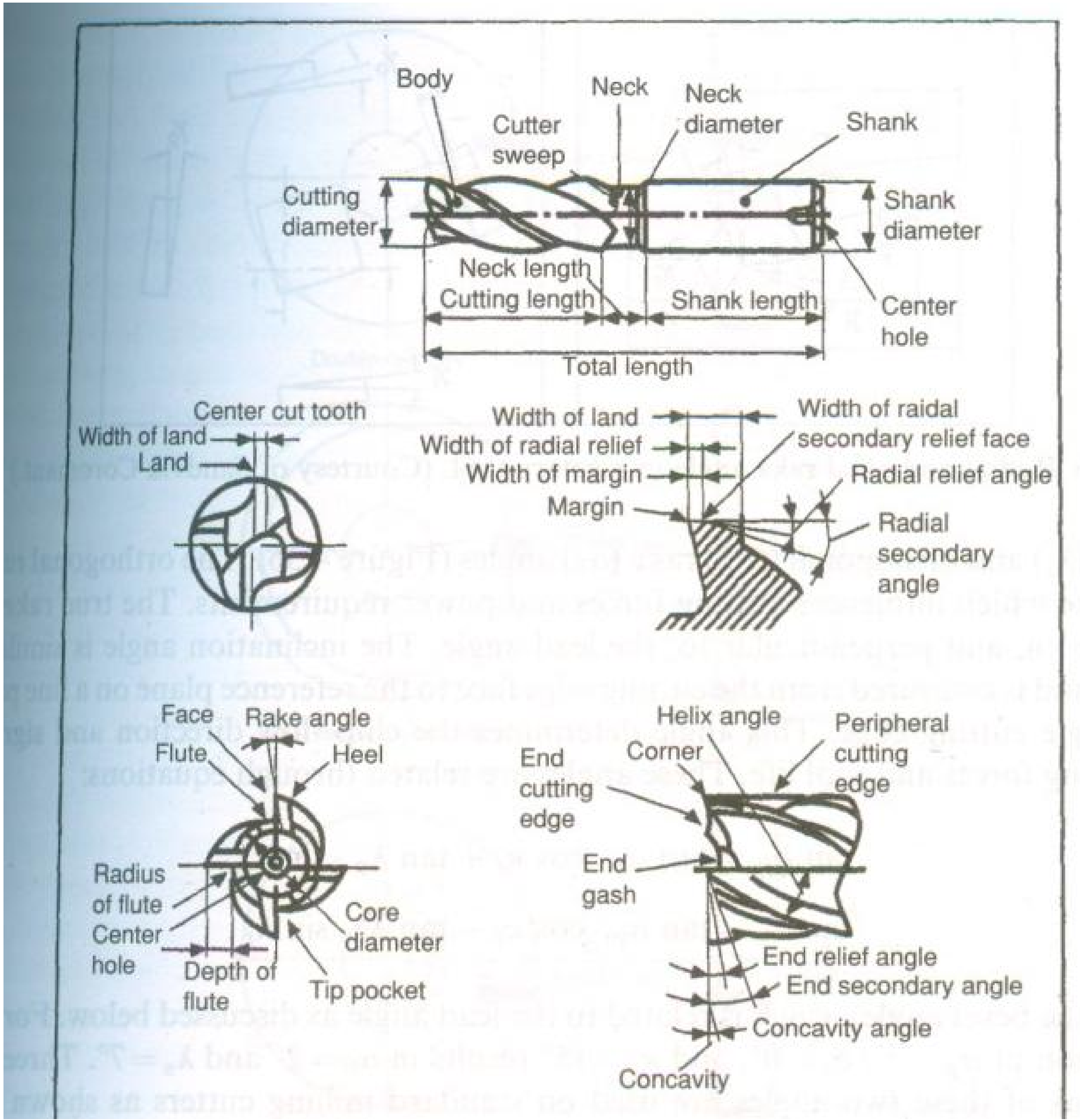
Effect of lead angle



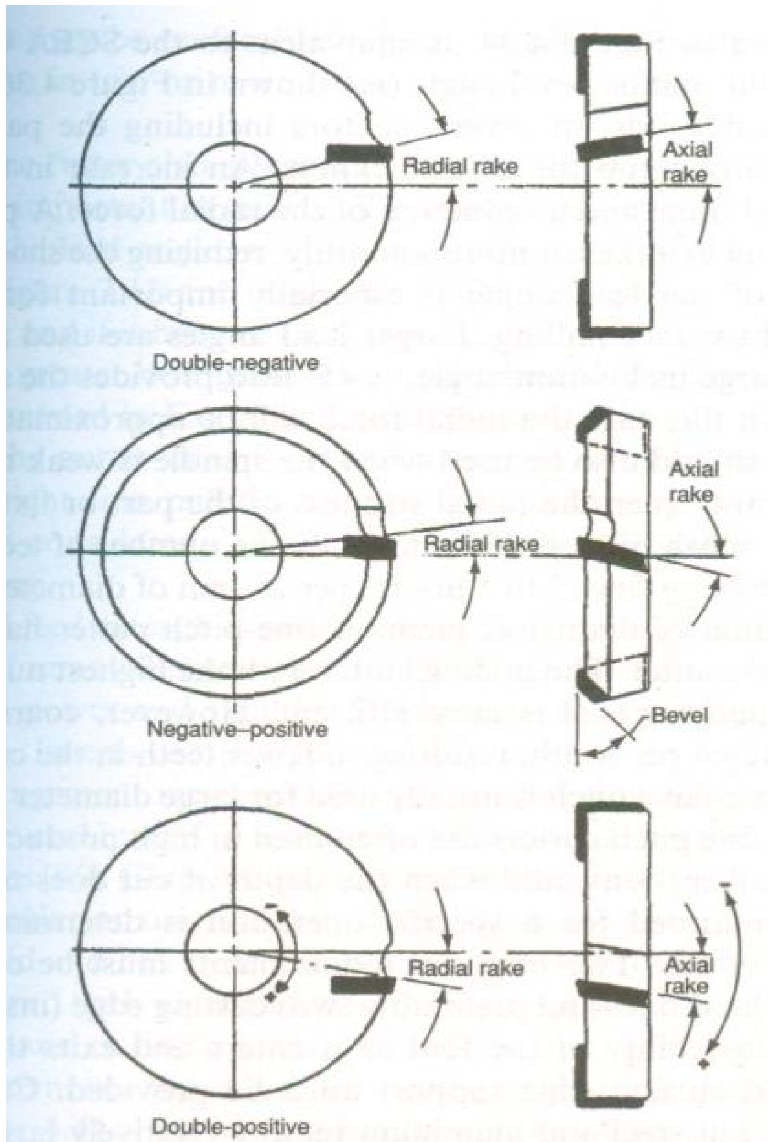
Effect of rake angle



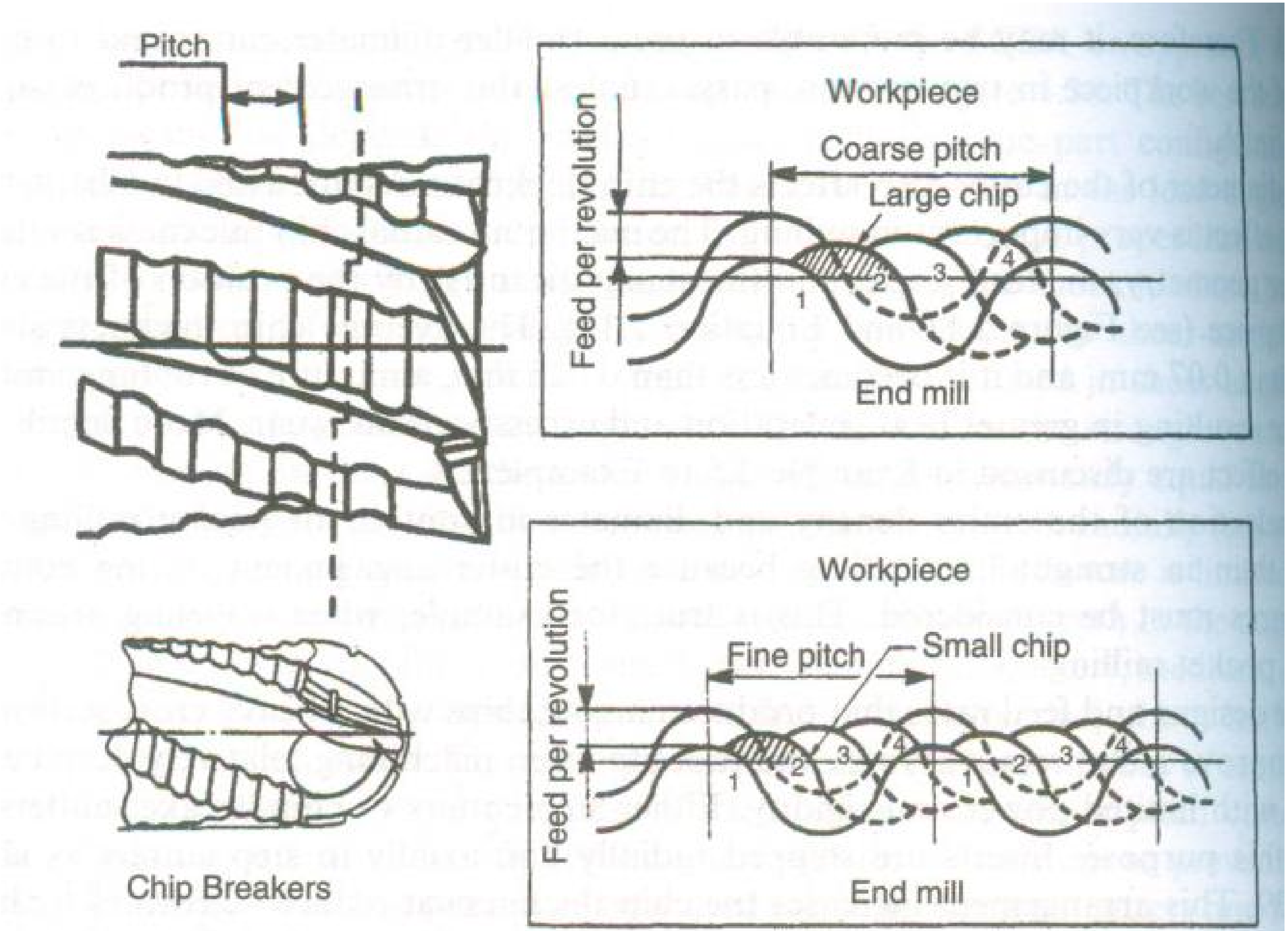
End mill nomenclature



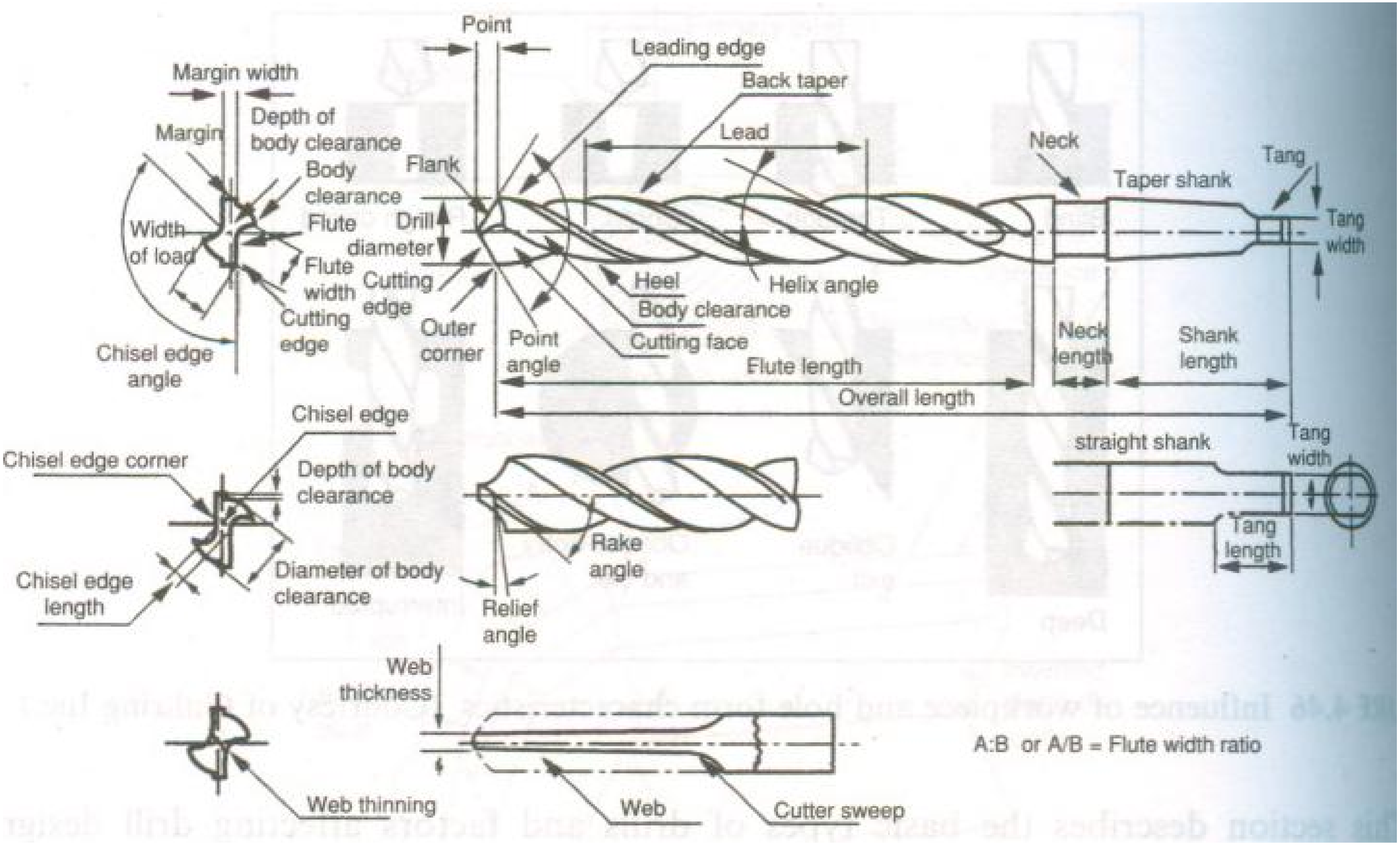
Effect of radial and axial rake angles



Chip breakers in Mills



Twist drill nomenclature



Needs Of Cutting Tool Materials

- to meet the growing demands for high productivity, quality and economy of machining
- to enable effective and efficient machining of the exotic materials that are coming up with the rapid and vast progress of science and technology
- for precision and ultra-precision machining
- for micro and even Nano machining demanded by the day and future.

The capability and overall performance of the cutting tools depend upon,

- the cutting tool materials
- the cutting tool geometry
- proper selection and use of those tools
- the machining conditions and the environments

Out of which the tool material plays the most vital role.

Essential requirements of tool materials

The cutting tools need to be capable to meet the growing demands for higher productivity and economy as well as to machine the exotic materials which are coming up with the rapid progress in science and technology.

The cutting tool material of the day and future essentially require the following properties to resist or retard the phenomena leading to random or early tool failure :

i) high mechanical strength; compressive, tensile, and TRA

ii) fracture toughness – high or at least adequate

iii) high hardness for abrasion resistance

iv) high hot hardness to resist plastic deformation and reduce wear rate at elevated temperature

v) chemical stability or inertness against work material, atmospheric gases and cutting fluids

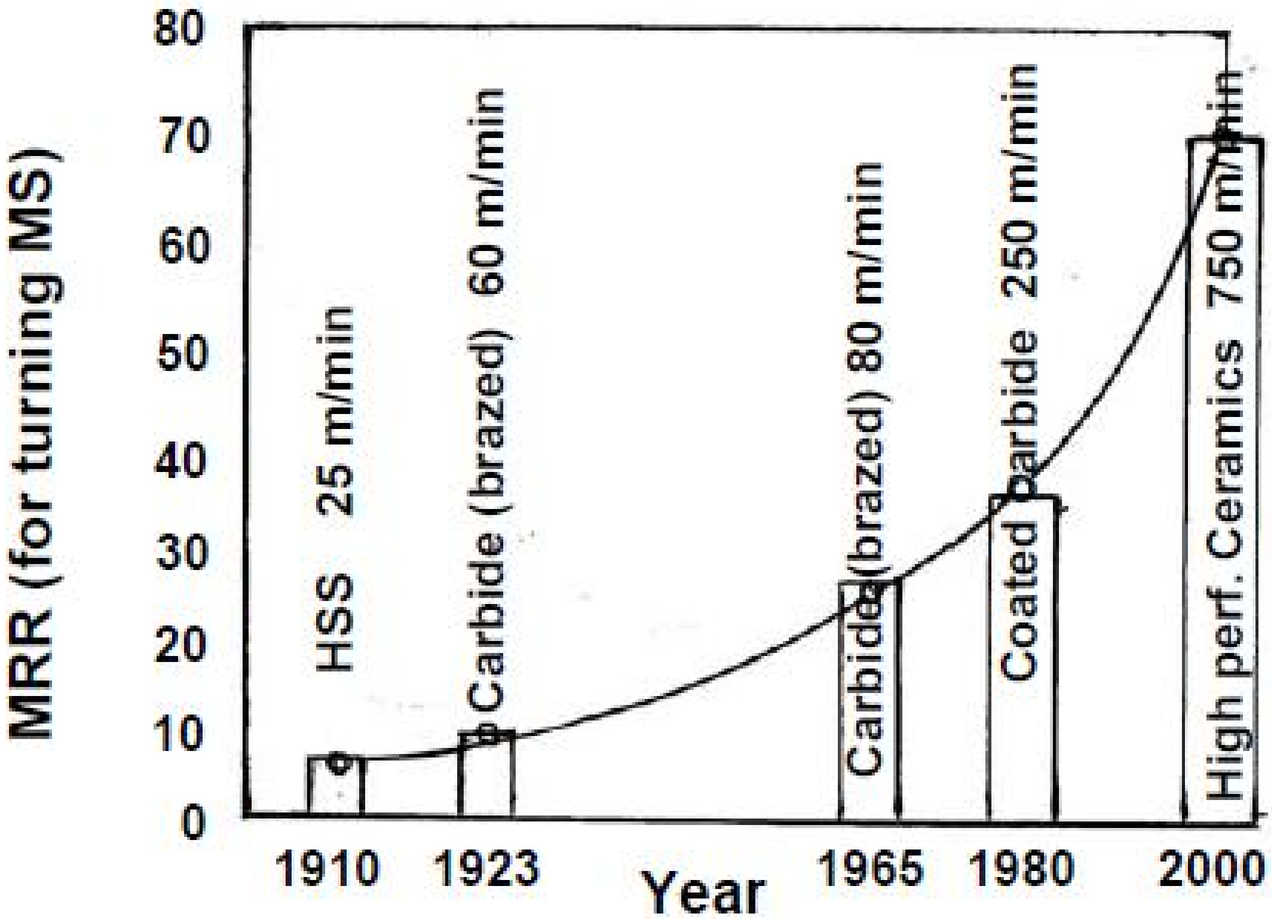
vi) resistance to adhesion and diffusion

vii) thermal conductivity – low at the surface to resist incoming of heat and high at the core to quickly dissipate the heat entered

viii) high heat resistance and stiffness

ix) manufacturability, availability and low cost.

Chronological Development Of Tool Materials
Vs
Productivity improvement



Need	Year	Development
	1900	
		HSS(W: 18%; Cr: 4%; V: 1%; C: 0.7
Automobile	1910	
		Stellite
WW - I	1920	HSS(V: 2~4%, Co: 5 – 12% in W &
Aircraft	1930	Sintered Carbide for C.I
WW - II	1940	Carbide for steels
Chem. Petro-chem., NU & polymer industries	1950	HSS with high V, Mo, Co & C Plain ceramics, Syn. Diamond
Jet engines Space programmes	1960	Ceramics and Cermets
Reduction of cost of manufacturing	1970	Coated carbides, PM – HSS, PCD
Defence Superalloys	1980	CBN, coated HSS, SIALON
	1986	High performance ceramics
Just-in-time	1990	Diamond coated carbides

Development Of Cutting Tool Materials

Characteristics And Applications Of Cutting Tool Materials

High Speed Steel (HSS)

The basic composition of HSS is 18% W, 4% Cr, 1% V, 0.7% C and rest Fe. Such HSS tool could machine (turn) mild steel jobs at speed only up to 20 ~ 30 m/min.

However, HSS is still used as cutting tool material where;

- the tool geometry and mechanics of chip formation are complex, such as helical twist drills, reamers, gear shaping cutters, hobs, form tools, broaches etc.
- brittle tools like carbides, ceramics etc. are not suitable under shock loading
- the small scale industries cannot afford costlier tools
- the old or low powered small machine tools cannot accept high speed and feed.
- The tool is to be used number of times by re-sharpening.

With time the effectiveness and efficiency of HSS and their application range were gradually enhanced by improving its properties and surface condition through – • Refinement of microstructure

• Addition of large amount of cobalt and Vanadium to increase hot hardness and wear resistance respectively

• Manufacture by powder metallurgical process

• Surface coating with heat and wear resistive materials like TiC, TiN, etc by Chemical Vapour Deposition (CVD) or Physical Vapour Deposition (PVD).

Addition of large amount of Co and V, refinement of microstructure and coating increased strength and wear resistance and thus enhanced productivity and life of the HSS tools remarkably.

Type	C	W	Mo	Cr	V	Co	R_C
T – 1	0.70	18		4	1		
T – 4	0.75	18		4	1	5	
T – 6	0.80	20		4	2	12	
M – 2	0.80	6	5	4	2		64.7
M – 4	1.30	6	5	4	4		
M – 15	1.55	6	3	5	5	5	
M – 42	1.08	1.5	9.5	4	1.1	8	62.4

Stellite

- This is a cast alloy of Co (40 to 50%), Cr (27 to 32%), W (14 to 19%) and C (2%).
- Stellite is quite tough and more heat and wear resistive than the basic HSS (18 – 4 – 1), But such stellite as cutting tool material became obsolete for its poor grindability and specially after the arrival of cemented carbides.

Sintered Tungsten carbides

- First the straight or single carbide tools or inserts were powder metallurgically produced by mixing, compacting and sintering 90 to 95% WC powder with cobalt.
- The hot, hard and wear resistant WC grains are held by the binder Co which provides the necessary strength and toughness. Such tools are suitable for machining grey cast iron, brass, bronze etc. which produce short discontinuous chips and at cutting velocities two to three times of that possible for HSS tools.

Composite carbides

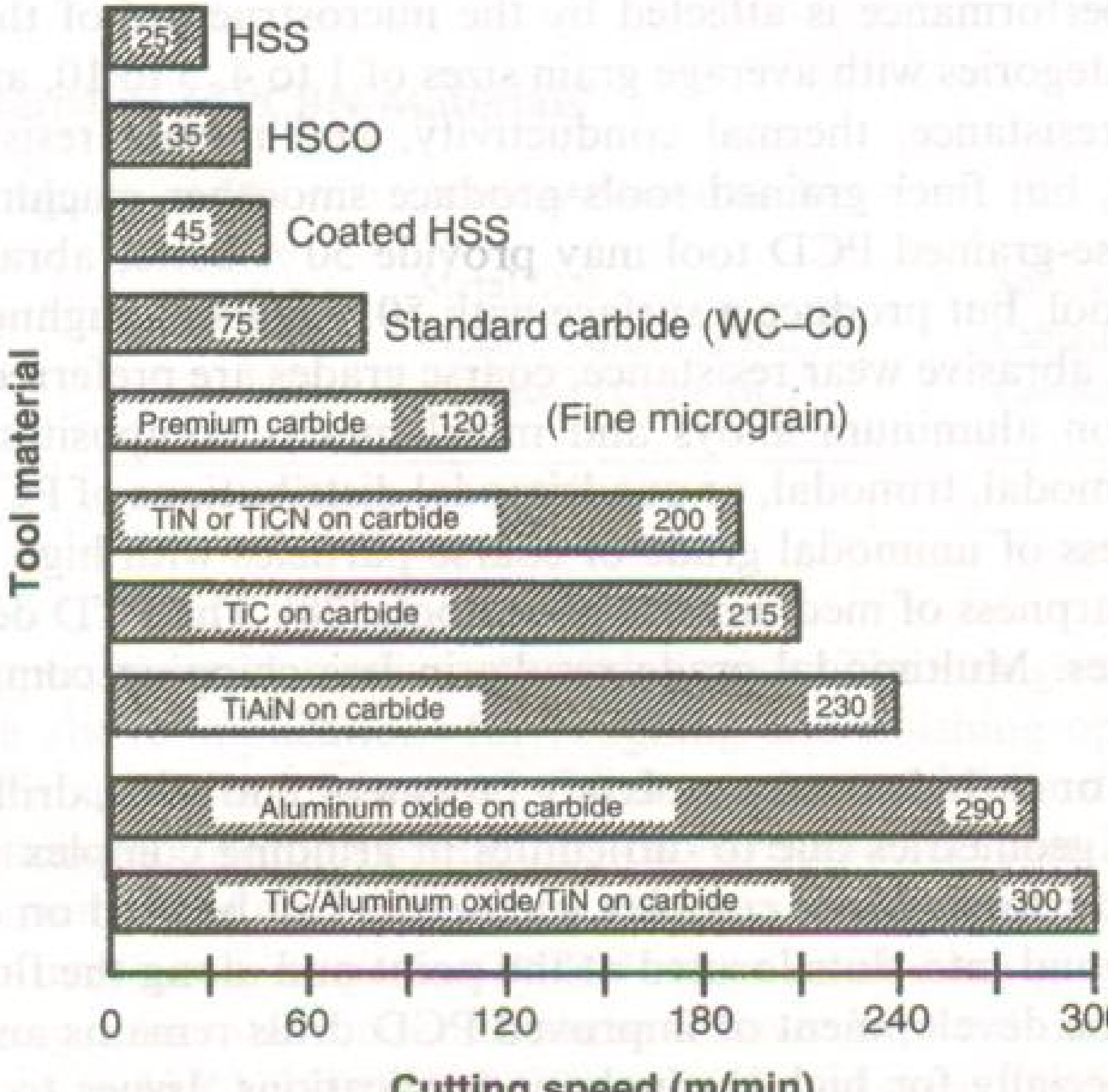
The single carbide is not suitable for machining steels because of rapid growth of wear, particularly crater wear, by diffusion of Co and carbon from the tool to the chip under the high stress and temperature bulk (plastic) contact between the continuous chip and the tool surfaces.

For machining steels successfully, another type called composite carbide have been developed by adding (8 to 20%) a gamma phase to WC and Co mix. The gamma phase is a mix of TiC, TiN, TaC, NiC etc. which are more diffusion resistant than WC due to their more stability and less wettability by steel.

- **Mixed carbides**

Titanium carbide (TiC) is not only more stable but also much harder than WC. So for machining ferritic steels causing intensive diffusion and adhesion wear a large quantity (5 to 25%) of TiC is added with WC and Co to produce another grade called Mixed carbide. But increase in TiC content reduces the toughness of the tools.

Therefore, for finishing with light cut but high speed, the harder grades containing upto 25% TiC are used and for heavy roughing work at lower speeds lesser amount (5 to 10%) of TiC is suitable.



Comparison of cutting speeds of coated and uncoated tools.

Gradation of cemented carbides and their applications

ISO Code	Colour Code	Application
P		For machining long chip forming common materials like plain carbon and low alloy steels
M		For machining long or short chip forming ferrous materials like Stainless steel
K		For machining short chipping, ferrous and non-ferrous material and non-metals like Cast Iron, Brass etc.

Detail grouping of cemented carbide tools

ISO Application group	Material	Process
P01	Steel, Steel castings	Precision and finish machining, high speed
P10	Steel, steel castings	Turning, threading and milling high speed, small chips
P20	Steel, steel castings, malleable cast iron	Turning, milling, medium speed with small chip section
P30	Steel, steel castings, malleable cast iron forming long chips	Turning, milling, low cutting speed, large chip section
P40	Steel and steel casting with sand inclusions	Turning, planning, low cutting speed, large chip section
P50	Steel and steel castings of medium or low tensile strength	Operations requiring high toughness turning, planning, shaping at low cutting speeds
K01	Hard grey C.I., chilled casting, Al. alloys with high silicon	Turning, precision turning and boring, milling, scraping
K10	Grey C.I. hardness > 220 HB. Malleable C.I., Al. alloys containing Si	Turning, milling, boring, reaming, broaching, scraping
K20	Grey C.I. hardness up to 220 HB	Turning, milling, broaching, requiring high toughness
K30	Soft grey C.I. Low tensile strength steel	Turning, reaming under favourable conditions
K40	Soft non-ferrous metals	Turning milling etc.
M10	Steel, steel castings, manganese steel, grey C.I.	Turning at medium or high cutting speed, medium chip section
M20	Steel casting, austentic steel, manganese steel, spherodized C.I., Malleable C.I.	Turning, milling, medium cutting speed and medium chip section
M30	Steel, austenitic steel, spherodized C.I. heat resisting alloys	Turning, milling, planning, medium cutting speed, medium or large chip section
M40	Free cutting steel, low tensile strength steel, brass and light alloy	Turning, profile turning, specially in automatic machines.

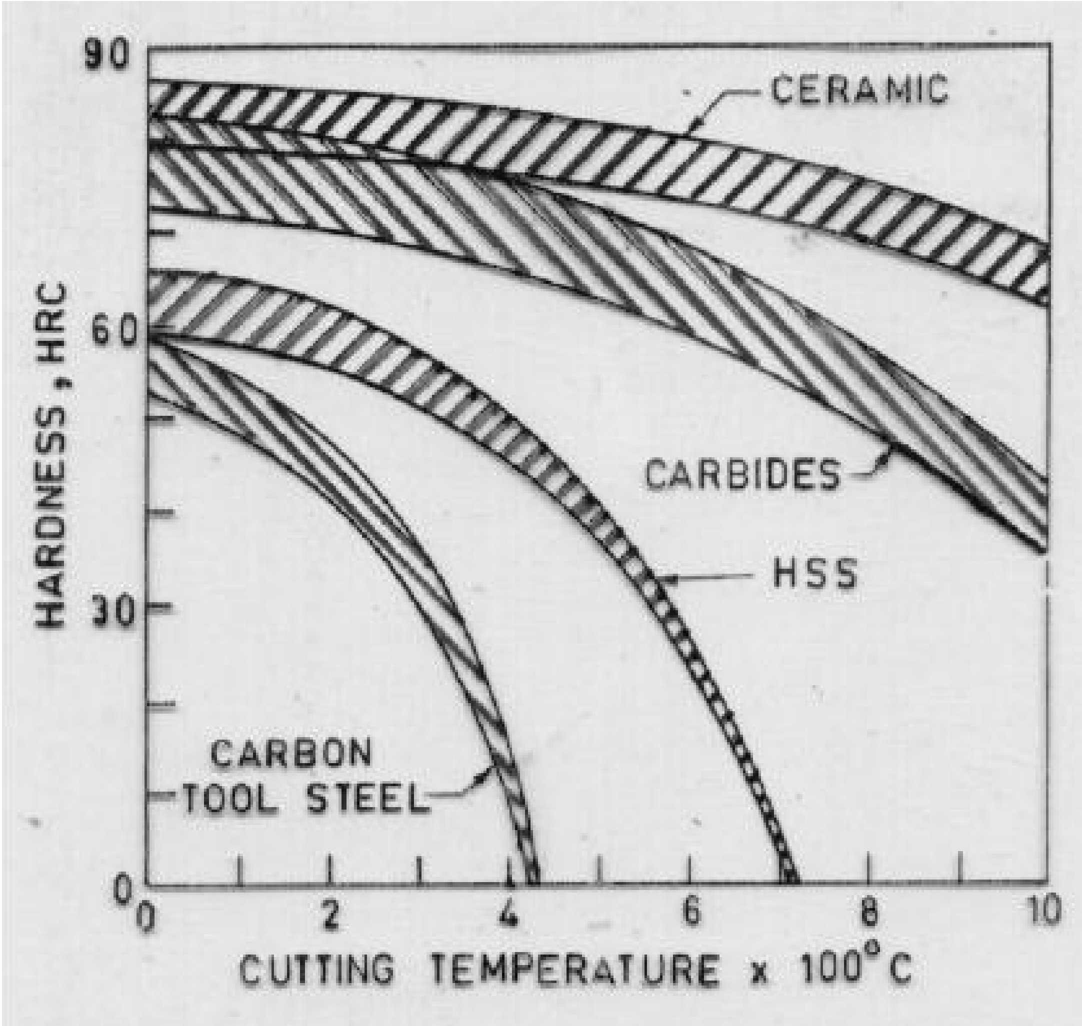
Plain ceramics

Inherently high compressive strength, chemical stability and hot hardness of the ceramics led to powder metallurgical production of indexable ceramic tool inserts since 1950.

Alumina (Al^2O^3) is preferred to silicon nitride (Si^3N^4) for higher hardness and chemical stability. Si^3N^4 is tougher but again more difficult to process. The plain ceramic tools are brittle in nature and hence had limited applications.

Advantages	Shortcoming
very high hardness	poor toughness
very high hot hardness	poor tensile strength
chemical stability	poor TRS
antiwelding	low thermal conductivity
less diffusivity	less density
high abrasion resistance	
high melting point	
very low thermal conductivity*	
very low thermal expansion coefficient	

Cutting tool properties of alumina ceramics



Hot hardness of the different commonly used tool materials.

ISO specification for Inserts

Turning

C	N	M	G	4	3	2
Shape	Clearance Angle	Tolerance	Groove / Hole	Size (IC)	Thickness	Radius

Milling

S	E	K	N	4	2		A	F	T	N
Shape	Clearance Angle	Tolerance	Groove / Hole	Size (IC)	Thickness	Radius	Wiper Lead Angle	Wiper Clearance Angle	Cutting Edge Preparation	Cutting Direction

Shape (e.g. "**C**NMG432" / "**C**CMT32.51")

Code Letter	Description	Diagram	Nose Angle
A	85° parallelogram		85°
B	82° parallelogram		82°
C	80° diamond		80°
D	55° diamond		55°
E	75° diamond		75°
H	hexagon		120°
K	55° parallelogram		55°
L	rectangle		90°
M	86° diamond		86°
N	55° parallelogram		55°
O	octagon		135°
P	pentagon		108°
R	round		full radius
S	square		90°
T	triangle		60°
V	35° diamond		35°
W	trigon		80°
X	sp. parallelogram		85°

Clearance or Relief Angle

C**N**MG432" / "C**C**MT32.51"

Code Letter	Angle	Diagram
N	0°	
A	3°	
B	5°	
C	7°	
P	11°	
D	15°	
E	20°	
F	25°	
G	30°	

Tolerance (e.g. "CN**M**G432" / "CC**M**T32.51")

Code Letter	Corner point (inches)	Thickness (inches)	Inscribed Circle (in)	Corner point (mm)	Thickness (mm)	Inscribed Circle (mm)
A	.0002"	.001"	.001"	.005mm	.025mm	.025mm
C	.0005"	.001"	.001"	.013mm	.025mm	.025mm
E	.001"	.001"	.001"	.025mm	.025mm	.025mm
F	.0002"	.001"	.0005"	.005mm	.025mm	.013mm
G	.001"	.005"	.001"	.025mm	.13mm	.025mm
H	.0005"	.001"	.0005"	.013mm	.025mm	.013mm
J	.002"	.001"	.002-.005"	.005mm	.025mm	.05-.13mm
K	.0005"	.001"	.002-.005"	.013mm	.025mm	.05-.13mm
L	.001"	.001"	.002-.005"	.025mm	.025mm	.05-.13mm
M	.002-.005"	.005"	.002-.005"	.05-.13mm	.13mm	.05-.15mm
U	.005-.012"	.005"	.005-.010"	.06-.25mm	.13mm	.08-.25mm

Hole / Chip breaker (e.g. "CNM**G**432" / "CCM**T**32.51")

Code Letter	Diagram	Hole	Hole Shape	Chip breaker Type
Null		No		None
A		Yes	Cylindrical	None
B		Yes	70-90° double countersink	None
D		Yes	Cylindrical	None
E		No		None
F		No		Double-sided
G		Yes	Cylindrical	Double-sided
H		Yes	70-90° single countersink	Single-sided
M		Yes	Cylindrical, or dbl countersink	Single-sided
N		No		None
P		Yes	Cylindrical	Hi-double positive
Q		Yes	40-60° double countersink	None
R		No		Single-sided
S		Yes	Cylindrical	Hi-double positive
T		Yes	40-60° double countersink	Single-sided
U		Yes	40-60° double countersink	Double-sided
W		Yes	40-60° double countersink	None
Z		Yes	Cylindrical	Double-sided hi-double positive

Size (e.g. "CNMG**4**32" / "CCMT**3**2.51")

ANSI Code No.	Inscribed Circle Size		ISO Code No. (metric cutting edge length) by shape code letter of insert						
	decimal in.	fractional in.	C	D	R	S	T	V	W
0.5	.0625"	1/16							
1.2 (5)	.15625"	5/32	S4	04 (4mm)	03 (3mm)	03 (3mm)	06 (6mm)		
1.5 (6)	.1875"	3/16	04 (4mm)	05 (5mm)	04 (4mm)	04 (4mm)	08 (8mm)	08 (8mm)	S3
1.8 (7)	.21875"	7/32	05 (5mm)	06 (6mm)	05 (5mm)	05 (5mm)	09 (9mm)	09 (9mm)	03 (3mm)
2	.25"	1/4	06 (6mm)	07 (7mm)	06 (6mm)	06 (6mm)	11 (11mm)	11 (11mm)	04 (4mm)
2.5	.3125"	5/16	08 (8mm)	9mm	07 (7mm)	07 (7mm)	13 (13mm)	13 (13mm)	05 (5mm)
3	.375"	3/8	09 (9mm)	11 (11mm)	09 (9mm)	09 (9mm)	16 (16mm)	16 (16mm)	06 (6mm)
3.5	.4375"	7/16	11mm	13mm	11 (11mm)	11 (11mm)	19 (19mm)	19mm	7mm
4	.5"	1/2	12 (12mm)	15 (15mm)	12 (12mm)	12 (12mm)	22 (22mm)	22 (22mm)	08 (8mm)
4.5	.5625"	9/16	14mm	17mm	14 (14mm)	14 (14mm)	24mm	24mm	9mm
5	.625"	5/8	16 (16mm)	19 (9mm)	15 (15mm)	15 (15mm)	27 (27mm)	27 (27mm)	10 (10mm)
5.5	.6875"	11/16	17mm	21mm	17 (17mm)	17 (17mm)	30mm	30mm	11mm
6	.75"	3/4	19 (19mm)	23 (23mm)	19 (19mm)	19 (19mm)	33 (33mm)	33 (33mm)	13 (13mm)
6.5	.8125"	13/16							
7	.875"	7/8	22 (22mm)	27 (27mm)	22 (22mm)	22 (22mm)	38 (38mm)	38 (38mm)	15 (15mm)
8	1"	1	25 (25mm)	31 (31mm)	25 (25mm)	25 (25mm)	44 (44mm)	44 (44mm)	17 (17mm)
10	1.25"	1-1/4	32 (32mm)	38mm	31 (31mm)	31 (31mm)	54 (54mm)	54 (54mm)	21 (21mm)
	1.26"				32 (32mm)				

Thickness (e.g. "CNMG4**3**2" / "CCMT3**2.5**1")

ANSI Code No.	ISO Code No.	Decimal Value	Fractional Value	Millimeter Value
.5 (1)	-	0.03125"	1/32	0.79mm
.6	T0	0.040"		1.00mm
1 (2)	01	0.0625"	1/16	1.59mm
1.2	T1	0.078"	5/64	1.98mm
1.5 (3)	02	0.094"	3/32	2.38mm
	T2	0.109"	7/64	2.78mm
2	03	0.125"	1/8	3.18mm
2.5	T3	0.156"	5/32	3.97mm
3	04	0.187"	3/16	4.76mm
	05	0.219"	7/32	5.56mm
4	06	0.25"	1/4	6.35mm
5	07	0.313"	5/16	7.9mm
6	09	0.375"	3/8	9.53mm
8		0.5"	1/2	12.7mm

Radius (e.g. "CNMG43**2**" / "CCMT32.5**1**")

ANSI Code No.	ISO Code No.	Decimal Value	Fractional Value	Millimeter Value
Null	Null	Wiper flat	Wiper flat	Wiper flat
V	M0	0	0	0
0.2	00	0.004"		0.1mm
X		0.004"		0.1mm
0.5		0.008"		0.2mm
0	00	0.008"		0.2mm
Y		0.008"		0.2mm
1	04	0.016"	1/64	0.4mm
	05	0.020"		0.5mm
2	08	0.031"	1/32	0.8mm
	10	0.040"		1.02mm
3	12	0.047"	3/64	1.2mm
4	16	0.062"	1/16	1.6mm
5	20	0.078"	5/64	2mm
6	24	0.094"	3/32	2.4mm
7	29	0.109"	7/64	2.9mm
8	32	0.125"	1/8	3.2mm

Wiper Lead Angle
(e.g. "SEKN42**A**FTN")

Code Letter	Angle
A	45°
D	60°
K	60°
E	75°
L	75°
P	0°
S	75°

Wiper Clearance Angle
(e.g. "SEKN42A**F**TN")

Code Letter	Angle
C	7°
D	15°
E	20°
F	25-26°
G	30°
N	0°
P	11°

Cutting Edge Preparation
(e.g. "SEKN42AF**T**N")

Code Letter	Edge Preparation
F	sharp
E	honed
T	T-land
S	honed T-land
X	special chamfer

Cutting Direction (e.g. "SEKN42AFT**N**")

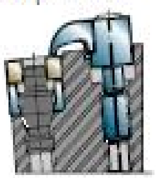
Code Letter	Direction
R	right-hand cutting only
L	left-hand cutting only
N	both right-hand and left-hand cutting

Toolholder Nomenclature

M W L N R 16 4 D

M — Insert Holding

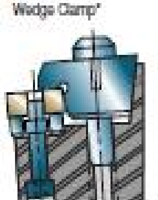
M
Clamp and Lock Pin



P
Pin Lock Only

S
Screw Only

W
Wedge Clamp*

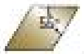


*Sumitomo Standard Only

W — Insert Shape

C Diamond

D Diamond



R Round

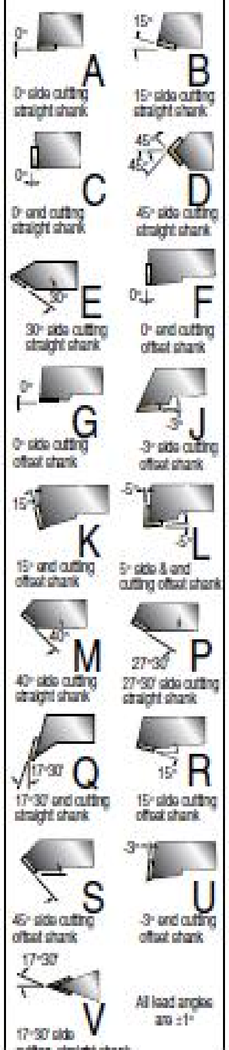
S Square

T Triangle

V Diamond

W Trigon

L — Toolholder Style

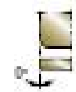


N — Insert Relief Angle

B

C

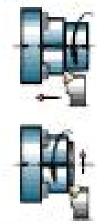
N



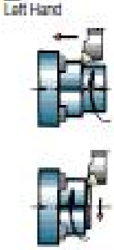
P

R — Hand

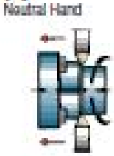
R
Right Hand



L
Left Hand



N
Neutral Hand



16 — Shank Size

Square Shanks

This indicates the A & B dimensions in sixteenths (1/16").

examples:
12 = 12/16"=3/4" sq.
16 = 16/16"=1.0" sq.
20 = 20/16"=1-1/4" sq.

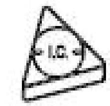
Rectangle Shanks

The first digit indicates the "A" dimension in eighths (1/8").

The second digit indicates the "B" dimension in quarters (1/4").

examples:
86 = A x B
1.0" x 1-1/2"
85 = A x B
1.0" x 1-1/4"

4 — Insert Size



For equal sided inserts this indicates the inscribed circle (I.C.) in eighths (1/8")

examples,

6 = 6/8 =
3/4" I.C.

4 = 4/8 =
1/2" I.C.

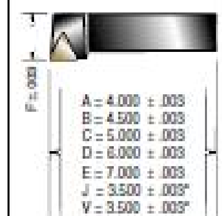
2.5 = 2.5/8 =
5/16" I.C.

For rectangles and parallelograms two digits are necessary.

1st digit =
number of eighths (1/8") in width.

2nd digit =
number of quarters (1/4") in length.

D — Qualifications



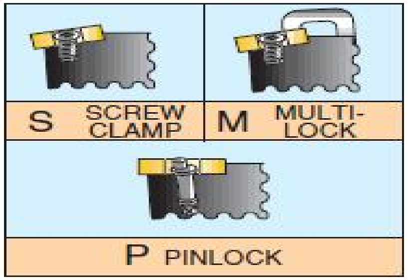
*Sumitomo standard only

Master Cage Insert Nose Radius Chart for Qualified Holders

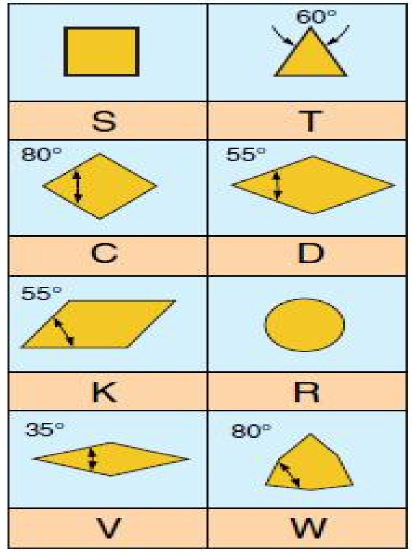
Insert I.C.	Nose Radius
1/4, 5/16	.015"
3/8, 1/2	.031"
5/8, 3/4	.047"
1.0	.062"

TOOLHOLDER IDENTIFICATION SYSTEM

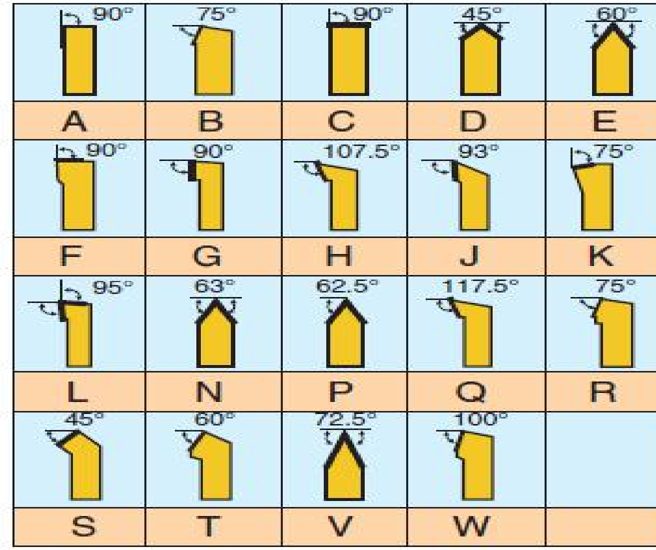
1 Clamping System



2 Insert Shape

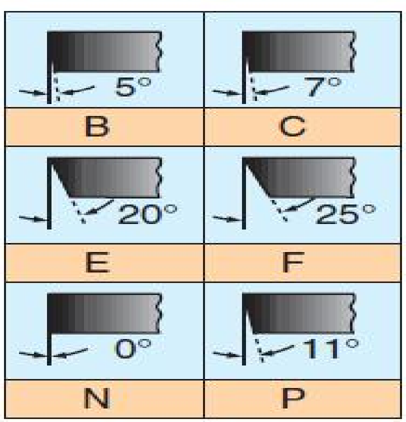


3 Holder Style



C	S	K	P	R	-	16	4	C
1	2	3	4	5		6 7	8	9

4 Rake Angle



6 7 Shank Size

06 = 3/8 square
08 = 1/2 square
10 = 5/8 square
12 = 3/4 square
16 = 1 square
20 = 1 1/4 square
24 = 1 1/2 square
32 = 2 square
44 = 1/2 x 1
55 = 5/8 x 1 1/4
64 = 3/4 x 1
66 = 3/4 x 1 1/2
85 = 1 x 1 1/4
86 = 1 x 1 1/2
88 = 1 x 2

Square Shanks
6th & 7th Positions
Width & Height in
1/16" increments

Rectangular Shanks
6th Position—Width
in 1/8" increments
7th Position—Height
in 1/4" increments

8 Insert I.C.

2 = 1/4
3 = 3/8
4 = 1/2
5 = 5/8
6 = 3/4
7 = 7/8
8 = 1
10 = 1 1/4

Inscribed Circle
in 1/8" increments

9 Qualified Surface & Length

Back & End
A = 4.000" long
B = 4.500" long
C = 5.000" long
D = 6.000" long
E = 7.000" long
F = 8.000" long
G = 5.500" long
H = 9.000" long
K = 12.000" long
L = 14.000" long

Front & End
M = 4.000" long
N = 4.500" long
P = 5.000" long
R = 6.000" long
S = 7.000" long
T = 8.000" long
U = 5.500" long
V = 9.000" long
X = 12.000" long
Y = 14.000" long

End Only
Z = Length must be specified

5 Hand of Tool

Tool Life

- Tool life generally indicates, the amount of satisfactory performance or service rendered by a fresh tool or a cutting point till it is declared failed.

- Tool life is defined in two ways :

- (a) In R & D : Actual machining time (period) by which a fresh cutting tool (or point) satisfactorily works after which it needs replacement or reconditioning. The modern tools hardly fail prematurely or abruptly by mechanical breakage or rapid plastic deformation. Those fail mostly by wearing process which systematically grows slowly with machining time. In that case, tool life means the span of actual machining time by which a fresh tool can work before attaining the specified limit of tool wear. Mostly tool life is decided by the machining time till flank wear, V^B reaches 0.3 mm or crater wear, K^T reaches 0.15 mm.
- (b) In industries or shop floor : The length of time of satisfactory service or amount of acceptable output provided by a fresh tool prior to it is required to replace or recondition.

Assessment of tool life

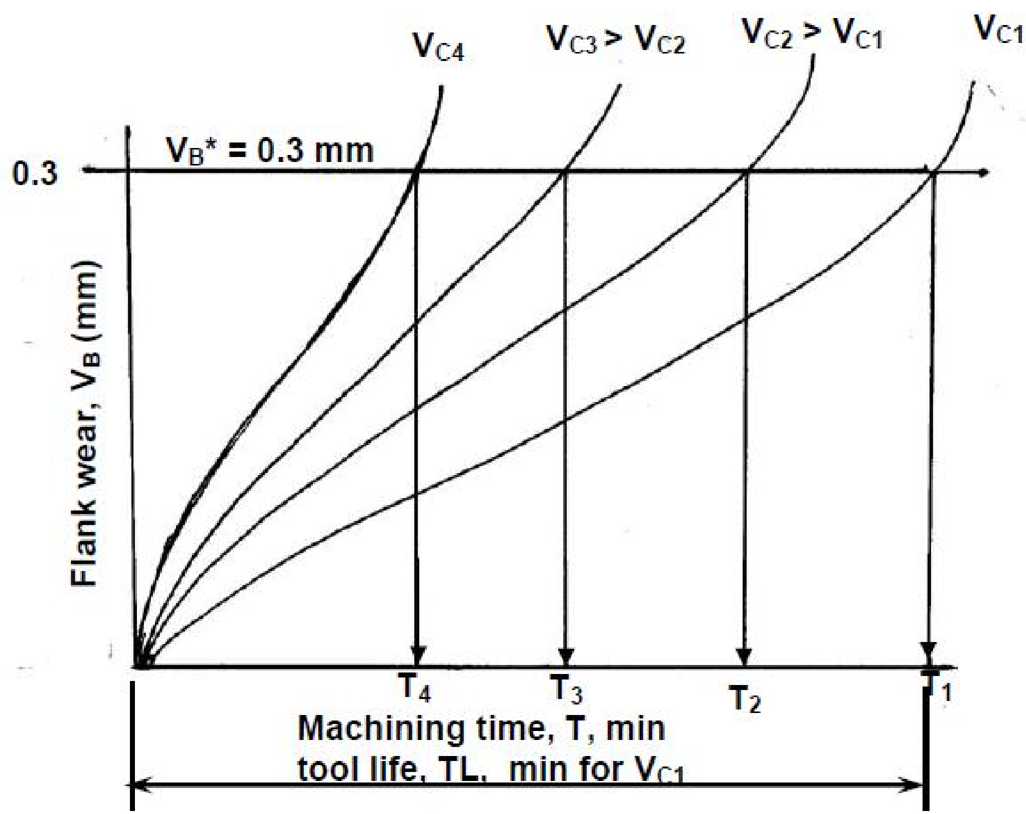
- For R & D purposes, tool life is always assessed or expressed by span of machining time in minutes, whereas, in industries besides machining time in minutes some other means are also used to assess tool life, depending upon the situation, such as
- no. of pieces of work machined
- total volume of material removed
- total length of cut.

Measurement of tool wear

- The various methods are :
- i) by loss of tool material in volume or weight, in one life time – this method is crude and is generally applicable for critical tools like grinding wheels.
- ii) by grooving and indentation method – in this approximate method wear depth is measured indirectly by the difference in length of the groove or the indentation outside and inside the worn area
- iii) using optical microscope fitted with micrometer – very common and effective method
- iv) using scanning electron microscope (SEM) – used generally, for detailed study; both qualitative and quantitative
- v) Talysurf, specially for shallow crater wear.

Taylor's tool life equation

Wear and hence tool life of any tool for any work material is governed mainly by the level of the machining parameters i.e., cutting velocity, (V^C), feed, (s^o) and depth of cut (t). Cutting velocity affects maximum and depth of cut minimum.



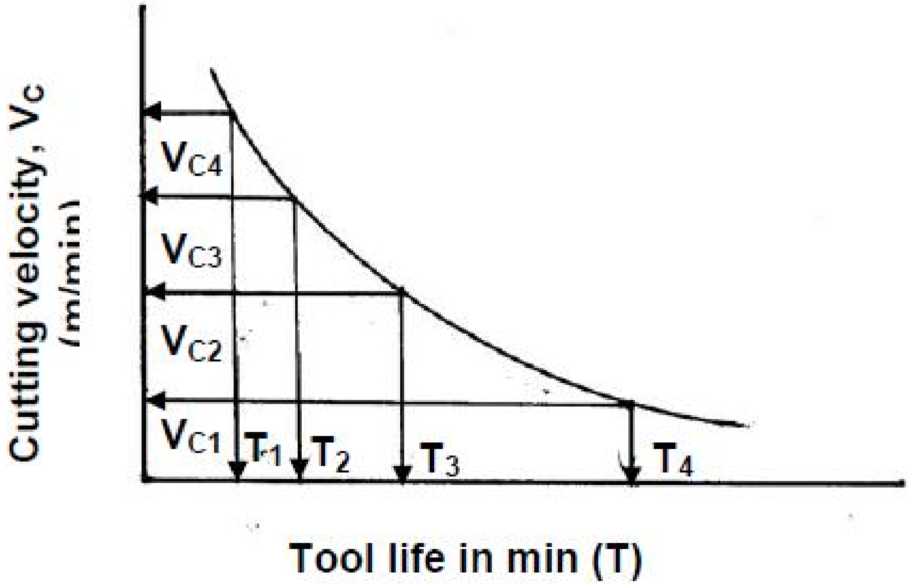
Growth of flank wear and assessment of tool life

- The tool life obviously decreases with the increase in cutting velocity keeping other conditions unaltered as indicated.

- If the tool lives, T^1, T^2, T^3, T^4 etc are plotted against the corresponding cutting velocities, V^1, V^2, V^3, V^4 etc, a smooth curve like a rectangular hyperbola is found to appear. When F. W. Taylor plotted the same figure taking both V and T in log-scale, a more distinct linear relationship appeared as schematically.
- With the slope, n and intercept, c, Taylor derived the simple equation as

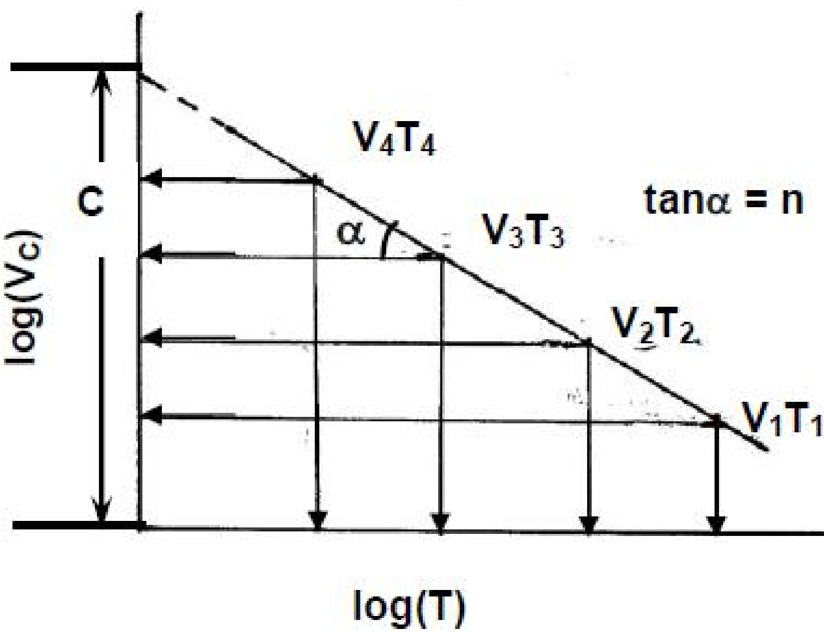
$$VT^n = C$$

- where, n is called, Taylor's tool life exponent. The values of both 'n' and 'c' depend mainly upon the tool-work materials and the cutting environment (cutting fluid application). The value of C depends also on the limiting value of V^B undertaken (i.e., 0.3 mm, 0.4 mm, 0.6 mm etc.)



Cutting velocity – tool life relationship

n=0.2 to 0.25 for HSS
n=0.25to 0.45 for carbide tools
n=0.4 to 0.55 for ceramic tools



Cutting velocity vs tool life on a log-log scale

Example of use of Taylor's tool life equation

- **Problem :**
- If in turning of a steel rod by a given cutting tool (material and geometry) at a given machining condition (s^o and t) under a given environment (cutting fluid application), the tool life decreases from 80 min to 20 min. due to increase in cutting velocity, V^C from 60 m/min to 120 m/min., then at what cutting velocity the life of that tool under the same condition and environment will be 40 min.?

Solution :

Assuming Taylor's tool life equation, $VT^n = C$

$V_1T_1 = V_2T_2 = V_3T_3 = \ldots\ldots\ldots\ldots\ldots = C$

Here, V_1 = 60 m/min; T_1 = 80 min.

V_2 = 120 m/min; T_2 = 20 min.

V_3 = ? (to be determined); T_3 = 40 min.

Taking,

$$V_1T_1^n = V_2T_2^n$$

i.e,

$$\left(\frac{T_1}{T_2}\right)^n = \left(\frac{V_2}{V_1}\right)$$

or

$$\left(\frac{80\,\text{min}}{20\,\text{min}}\right)^n = \left(\frac{120\,m/\text{min}}{60\,m/\text{min}}\right)$$

from which, n = 0.5

Again

$$V_3T_3^n = V_1T_1^n$$

i.e,

$$\left(\frac{V_3}{V_1}\right) = \left(\frac{T_1}{T_3}\right)^n$$

or

$$V_3 = \left(\frac{80}{40}\right)^{0.5} x60 = 84.84\,m/\text{min}$$ ***Ans***

Modified Taylor's Tool Life equation

In Taylor's tool life equation, only the effect of variation of cutting velocity, V_C on tool life has been considered. But practically, the variation in feed (s_o) and depth of cut (t) also play role on tool life to some extent.

Taking into account the effects of all those parameters, the Taylor's tool life equation has been modified as,

$$TL = \frac{C_T}{V_c^x s_o^y t^z}$$

where, TL = tool life in min

C_T — a constant depending mainly upon the tool – work materials and the limiting value of V_B undertaken.

x, y and **z** — exponents so called tool life exponents depending upon the tool – work materials and the machining environment.

Generally, x > y > **z** as V_C affects tool life maximum and t minimum.

The values of the constants, C_T, x, y and **z** are available in Machining Data Handbooks or can be evaluated by machining tests.

Problems

Problem – 1

During turning a metallic rod at a given condition, the tool life was found to increase from 25 min to 50 min. when V_C was reduced from 100 m/min to 80 m/min. How much will be the life of that tool if machined at 90 m/min ?

Problem – 2

While drilling holes in steel plate by a 20 mm diameter HSS drill at a given feed, the tool life decreased from 40 min. to 24 min. when speed was raised from 250 rpm to 320 rpm. At what speed (rpm) the life of that drill under the same condition would be 30 min.?

Solution to Problem 1.

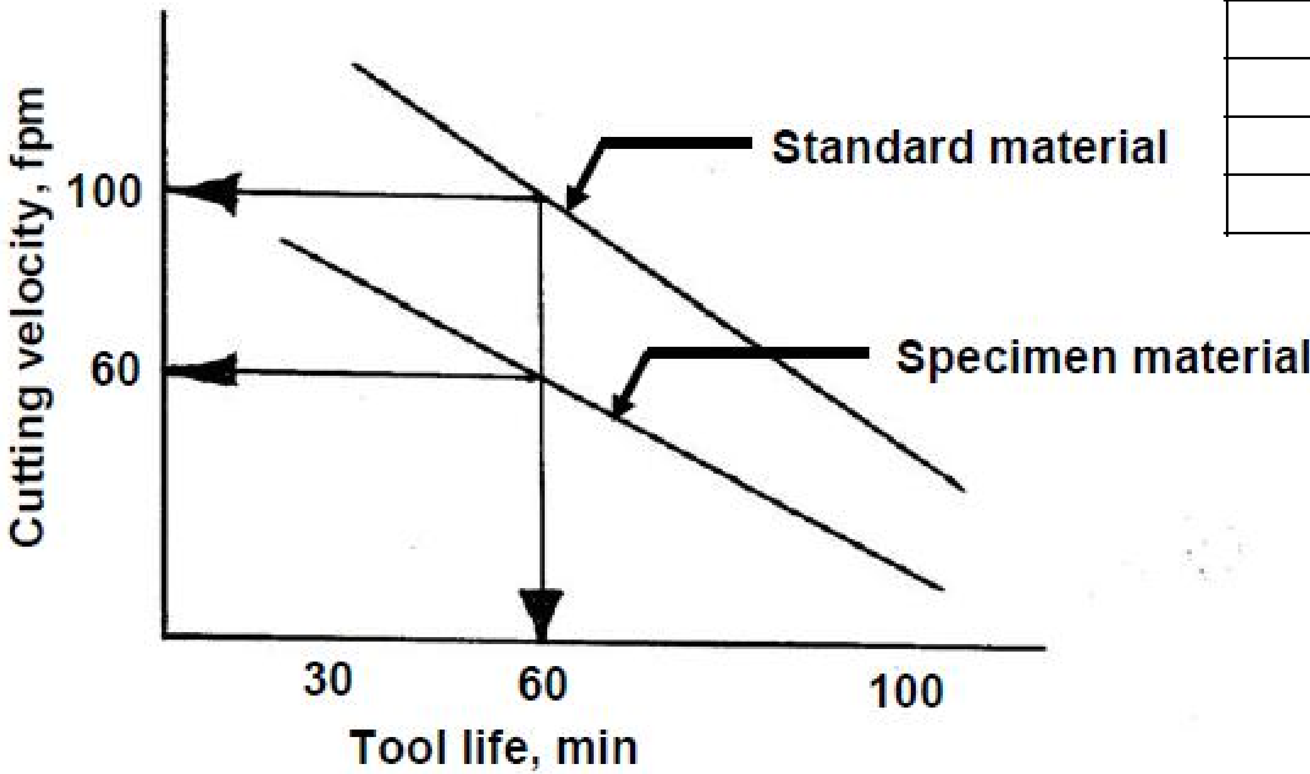
Ans. 34.6 min

Solution to Problem 2

Ans. 287 rpm.

Machinability rating (MR)

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



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

Tool Wear

Tool wear is a gradual process ,much like the wear of the tip of a pencil.

The *rate of tool wear (i.e., volume worn per unit time) depends on*
work piece material,
tool material and its coatings,
tool geometry,
process parameters,
cutting fluids, and
the characteristics of the machine tool.

Tool wear and the resulting changes in tool geometry are generally classified as
flank wear,
crater wear,
nose wear,
notching,
plastic deformation,
chipping, and
gross fracture.

(a) Features of tool wear in a turning operation; the VB indicates average flank wear. (b) through (e) Examples of wear in cutting tools: (b) flank wear, (c) crater wear, (d) thermal cracking, and (e) flank wear and built-up edge.

Flank Wear

Flank wear occurs on the relief (flank) face of the tool. It generally is attributed to

(a) rubbing of the tool along the machined
surface, thereby causing adhesive or abrasive wear and

(b) high temperatures, which adversely affect tool-material properties.

In a classic study by F.W. Taylor (1856–1915) on the machining of steels conducted in the early 1890s, the following approximate relationship for tool life, known as the *Taylor tool-life equation, was established:*

$VT^n = C$, where *V is the cutting speed, T is the time (in minutes) that it takes to develop* a certain flank **wear land,** *n is an exponent that* depends on tool and work piece materials and cutting conditions, and *C is a* constant. Each combination of work piece and tool materials and each cutting condition have their own *n and C values, both of which are determined experimentally* and often are based on surface finish requirements.

Also, the Taylor equation is often applied even when flank wear is not the dominant wear mode or if a different criterion (such as required machining power) is used to define *C and n. Generally, n depends on the tool material* and *C on the work piece material. Note that the magnitude of C* is the cutting speed at $T = 1$ *min.*

Crater Wear

Crater wear occurs on the rake face of the tool. It readily can be seen that crater wear changes the tool–chip interface contact geometry.

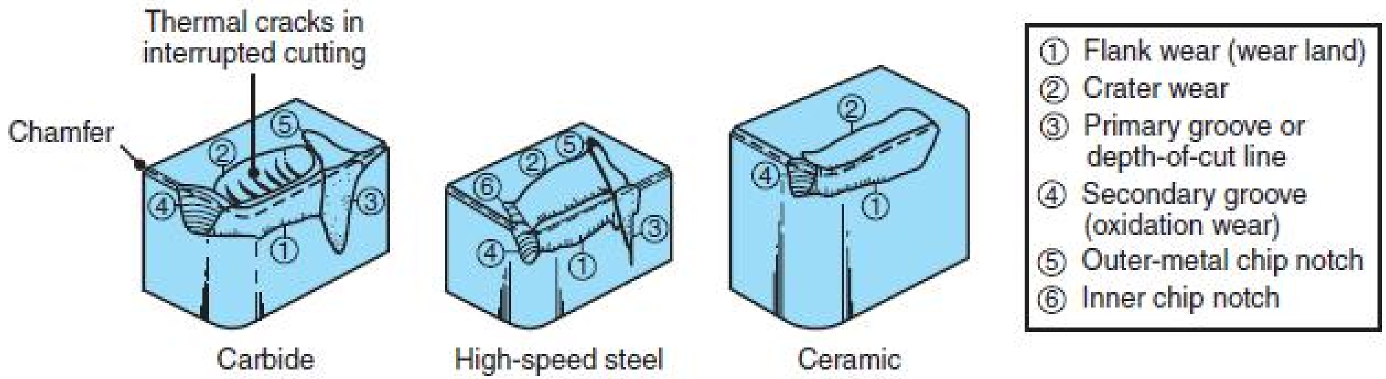
The most significant factors that influence crater wear are

(a) the temperature at the tool–chip interface and
(b) the chemical affinity of the tool and work piece materials.
(c) Additionally, the factors influencing flank wear may affect crater wear.

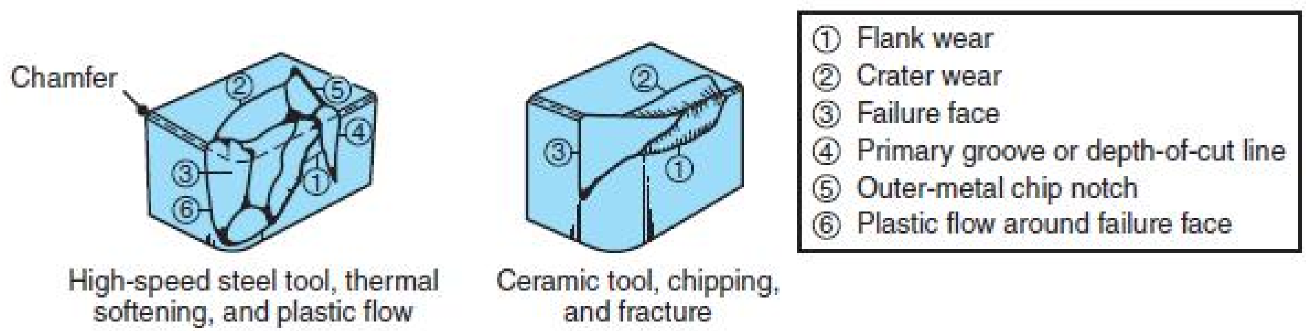
Crater wear generally is attributed to a **diffusion mechanism,** that is, the movement of atoms across the tool–chip interface. Since diffusion rate increases with increasing temperature, crater wear increases as temperature increases.

Applying protective *coatings to tools is an effective means of slowing the diffusion process,* and thus reducing crater wear.

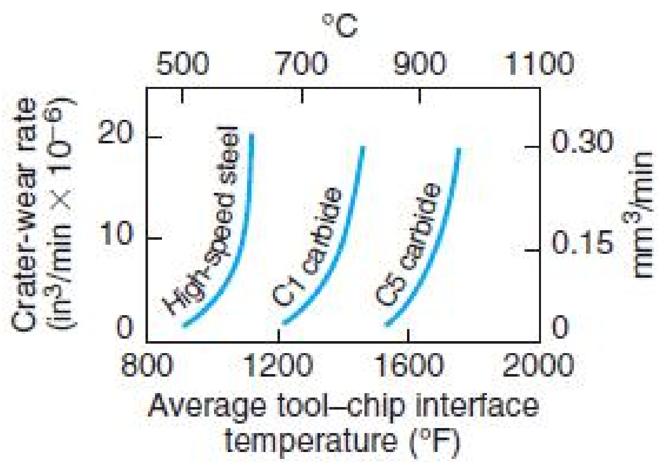
Typical tool coatings are titanium nitride, titanium carbide, titanium carbo nitride, and aluminum oxide. It can be seen that the location of the *maximum depth of crater wear, KT, coincides with* the location of the *maximum temperature at the tool–chip interface.* An actual cross section of this interface, for steel machined at high speeds, is shown . The crater-wear pattern on the tool coincides with its discoloration pattern, an indication of the presence of high temperatures.



(a)



(b)



Allowable Average Wear Land (See *VB* in Fig. 21.15a) for Cutting Tools in Various Machining Operations

	Allowable wear land (mm)	
Operation	High-speed steel tools	Carbide tools
Turning	1.5	0.4
Face milling	1.5	0.4
End milling	0.3	0.3
Drilling	0.4	0.4
Reaming	0.15	0.15

Note: Allowable wear for ceramic tools is about 50% higher.

Nose wear is the rounding of a sharp tool due to mechanical and thermal effects. It dulls the tool, affects chip formation, and causes rubbing of the tool over the work piece, raising its temperature and inducing residual stresses on the machined surface.

A related phenomenon is **edge rounding,** An increase in temperature is particularly important for high speed steel tools.

Tools also may undergo **plastic deformation because of temperature rises in** the cutting zone, where temperatures can easily reach 1000◦C in machining steels, and can be higher depending on the strength of the material machined.

Notches or grooves observed on cutting tools, have been attributed to the fact that the region where they occur is the boundary where the chip is no longer in contact with the tool. Known as the **depth-of-cut line**(DOC) , this boundary oscillates, because of inherent variations in the cutting operation.

In orthogonal cutting or with low feed rates, the region is at least partially in contact with the newly generated machined surface; the thin work-hardened layer that can develop in the work piece will contribute to the formation of the wear groove. If sufficiently deep, the groove can lead to gross chipping of the tool tip because of (a) its now reduced cross section and (b) the notch sensitivity of the tool material.

Scale and oxide layers on a work piece surface also contribute to notch wear, because these layers are hard and abrasive. Thus, light cuts should not be taken on such work pieces.

Tool materials undergo **chipping,** in which a small fragment from the cutting edge of the tool breaks away. This phenomenon, which typically occurs in brittle tool materials such as ceramics, is similar to chipping the tip of a pencil if it is too sharp.

The chipped fragments from the cutting tool may be very small (called **micro chipping** or **macro chipping,** depending on its size**),** or they may be relatively large, in which case they are variously called **gross chipping, gross fracture,** and **catastrophic failure.**

Chipping also may occur in a region of the tool where a small crack or defect already exists during its production. Unlike wear, which is a gradual process, chipping is a sudden loss of tool material, thus changing the tool’s shape.

As can be expected, chipping has a major detrimental effect on surface finish, surface integrity, and the dimensional accuracy of the work piece.

Two main causes of chipping are:

- **Mechanical shock,** such as impact due to interrupted cutting, as in turning a splined shaft on a lathe

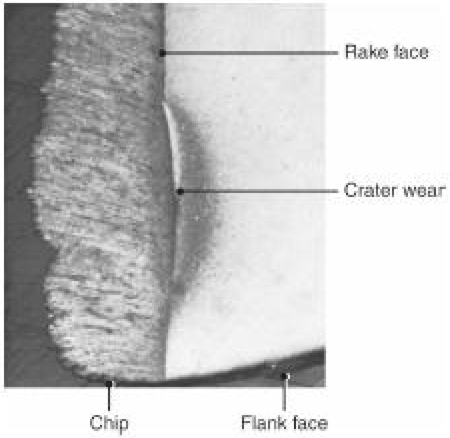
- **Thermal fatigue,** due to cyclic variations in the temperature of the tool in interrupted cutting.

Thermal cracks usually are perpendicular to the cutting edge of the tool. Major variations in the composition or structure of the work piece material also may cause chipping, due to differences in their thermal properties.

Chipping can be reduced by selecting tool materials with high impact and thermal shock resistance.

High positive rake angles can contribute to chipping because of the small included angle of the tool tip.

Also, it is possible for the crater-wear region to progress toward the tool tip, thus weakening the tip because of reduced volume of material.



Metal cutting processes can entail three different types of mechanical vibrations that arise due to the lack of dynamic stiffness of one or several elements of the system composed by the machine tool, the tool holder, the cutting tool and the work piece material.

These three types of vibrations are known as free vibrations, forced vibrations and self-excited vibrations.

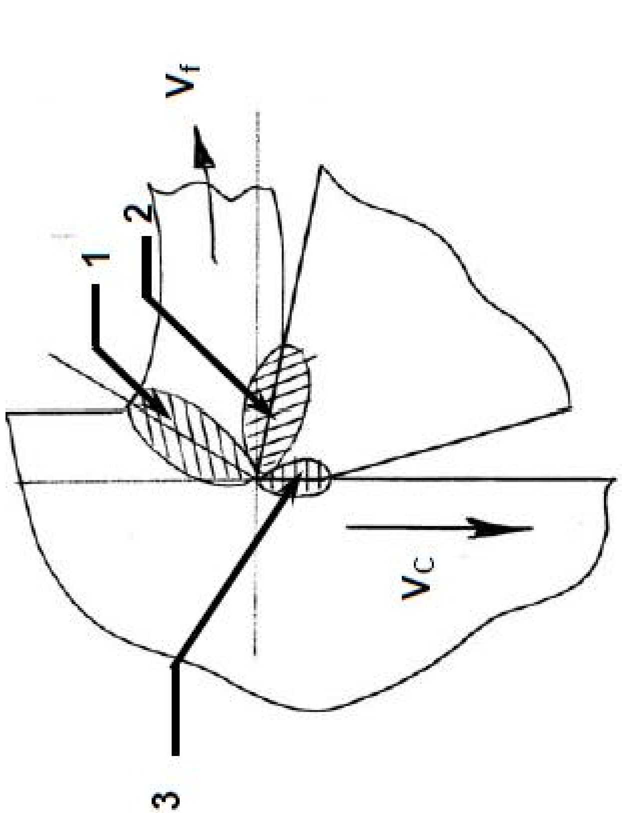
Free vibrations occur when the mechanical system is displaced from its equilibrium and is allowed to vibrate freely. In a metal removal operation, free vibrations appear, for example, as a result of an incorrect tool path definition that leads to a collision between the cutting tool and the work piece.

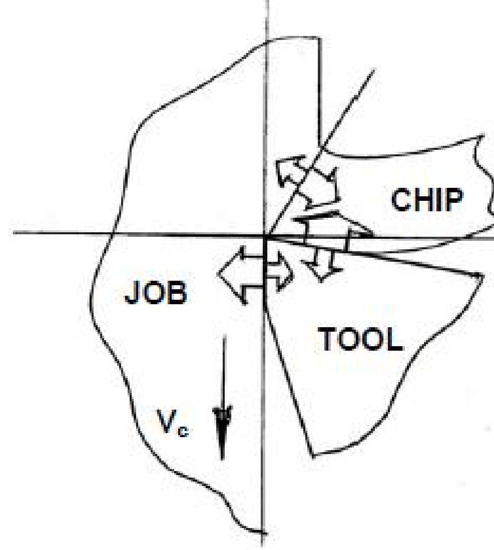
Forced vibrations appear due to external harmonic excitations. The principal source of forced vibrations in milling processes is when the cutting edge enters and exits the work piece. However, forced vibrations are also associated, for example, with unbalanced bearings or cutting tools, or it can be transmitted by other machine tools through the workshop floor. Free and forced vibrations can be avoided, reduced or eliminated when the cause of the vibration is identified. Engineers have developed several widely known methods to mitigate and reduce their occurrence.

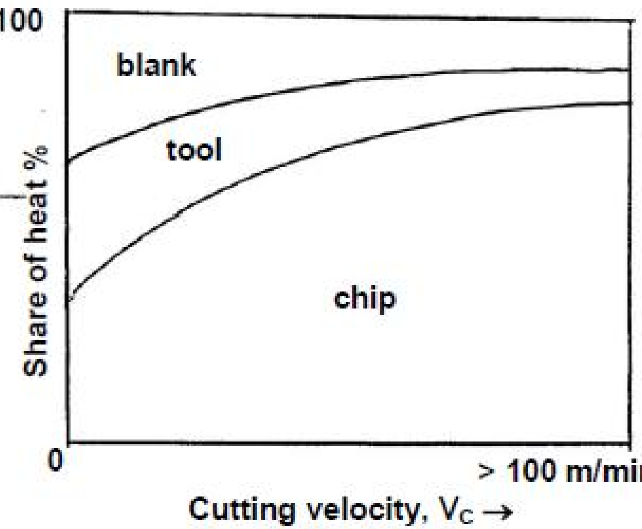
Self-excited vibrations extract energy to start and grow from the interaction between the cutting tool and the work piece during the machining process. This type of vibration brings the system to instability and is the most undesirable and the least controllable. For this reason, **chatter** has been a popular topic for academic and industrial research.

THERMAL ASPECTS
Heat distribution in machining

- Primary shear zone (1) where the major part of the energy is converted into heat
- Secondary deformation zone (2) at the chip – tool interface where further heat is generated due to rubbing and / or shear
- At the worn out flanks (3) due to rubbing between the tool and the finished surfaces.







The heat generated is shared by the chip, cutting tool and the blank. The apportionment of sharing that heat depends upon the configuration, size and thermal conductivity of the tool – work material and the cutting condition.

The Figure visualizes that maximum amount of heat is carried away by the flowing chip. From 10 to 20% of the total heat goes into the tool and some heat is absorbed in the blank. With the increase in cutting velocity, the chip shares heat increasingly.

Effects of the high cutting temperature

- rapid tool wear, which reduces tool life
- plastic deformation of the cutting edges if the tool material is not hot-hard and hot-strong
- thermal flaking and fracturing of the cutting edges due to thermal shocks
- built-up-edge formation
- dimensional inaccuracy of the job due to thermal distortion and expansion-contraction during and after machining
- surface damage by oxidation, rapid corrosion, burning.
- induction of tensile residual stresses and micro cracks at the surface / subsurface

Effect of various parameters on temperature

- Work material : specific energy requirement ductility, thermal properties
- process parameters : cutting velocity, feed, depth of cut
- cutting tool material : thermal properties, wear resistance, chemical stability
- tool geometry : rake angle , cutting edge angle, clearance angle, nose radius
- cutting fluid : thermal and lubricating properties, method of application

Methods of Temperature measurement in machining

- <u>The magnitude of the cutting temperature need to be known or evaluated to facilitate </u>• assessment of machinability which is judged mainly by cutting forces and temperature and tool life • design and selection of cutting tools
- • evaluate the role of variation of the different machining parameters on cutting temperature • proper selection and application of cutting fluid
- • analysis of temperature distribution in the chip, tool and job.

- <u>The temperatures which are of major interests are:</u>
- θ^s : average shear zone temperature
- θ^i : average (and maximum) temperature at the chip-tool interface
- θ^f : temperature at the work-tool interface (tool flanks)
- θ^{avg} : average cutting temperature

- <u>Cutting temperature can be determined by two ways :</u>
- • analytically – using mathematical models (equations) if available or can be developed. This method is simple, quick and inexpensive but less accurate and precise.
- • Experimentally – this method is more accurate, precise and reliable.

Cutting fluids

- *Cutting fluids* is used to:

1. Reduce friction and wear
2. Cool the cutting zone
3. Reduce forces and energy consumption
4. Flush away the chips from the cutting zone
5. Protect the machined surface from environmental corrosion

- Depending on the type of machining operation, a **coolant**, a **lubricant**, **or** both are used
- Effectiveness of cutting fluids depends on type of machining operation, tool and workpiece materials and cutting speed

Cutting-fluid Action

- Cutting fluid seep from the sides of the chip through the *capillary action* of the interlocking network of surface asperities in the interface
- Discontinuous cutting operations have more straightforward mechanisms for lubricant application, but the tools are more susceptible to thermal shock

EXAMPLE

Effects of Cutting Fluids on Machining

A machining operation is being carried out with a cutting fluid that is an effective lubricant. What will be the changes in the mechanics of the cutting operation if the fluid is shut off?

Solution

Effects of Cutting Fluids on Machining

Chain of events taking place after the fluid is shut off:

1. Friction at the tool–chip interface will increase
2. The shear angle will decrease in accordance
3. The shear strain will increase
4. The chip will become thicker
5. A built-up edge is likely to form

Solution

Effects of Cutting Fluids on Machining

As a result:

1. The shear energy in the primary zone will increase
2. The frictional energy in the secondary zone will increase
3. The total energy will increase
4. The temperature in the cutting zone will rise
5. Surface finish will to deteriorate and dimensional tolerances may be difficult to maintain

Types of Cutting Fluids

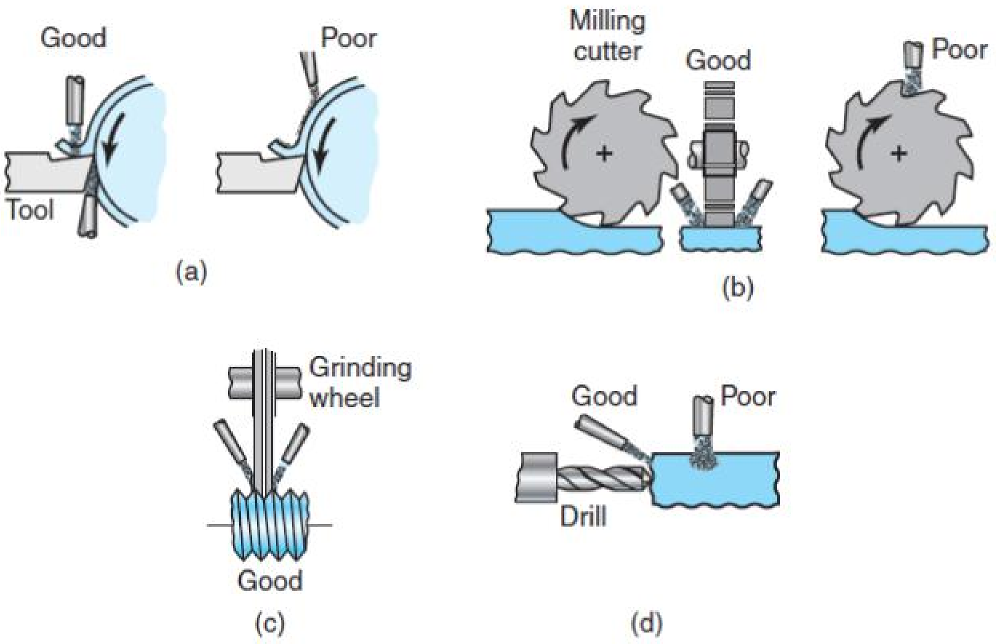
- 4 general types:

1. **Oils -** mineral, animal, vegetable, compounded, and synthetic oils,
2. **Emulsions -** a mixture of oil and water and additives
3. **Semisynthetics -** chemical emulsions containing little mineral oil
4. **Synthetics -** chemicals with additives

Methods of Cutting-fluid Application

4 basic methods

1. Flooding
2. Mist
3. High-pressure systems
4. Through the cutting tool system



Surface finish

Machining operation are utilized in view of the better surface finish that could be achieved by it compared to other manufacturing operations. Thus it is important to know what would be effective surface finish that can be achieved in machining operation.

Consideration into two factors:

1. The ideal surface finish, which is a result of the geometry of the manufacturing process, which can be determined by considering the geometry of the machining operation, and
2. The natural component, which is a result of a number of uncontrollable factors in machining which is difficult to predict

$$R_{cla} = 8f^2 / 18\sqrt{3}R$$

R_{cla} – centre line average surface index, f – feed rate, R – nose Radius

The above are essential geometric factors and the values represent an ideal situation. The actual surface finish obtained depends to a great extent upon a number of factors such as:

1. The cutting process parameters, speed, feed and depth of cut
2. The geometry of the cutting tool
3. Application of cutting fluid
4. Work and tool material characteristics
5. Rigidity of the machine tool and the consequent vibrations

The major influence on surface finish is exerted by the feed rate and cutting speed. As the feed decreases, from the above equation, we can see that the roughness index decreases. Similarly as the cutting speed increases, we have better surface finish. Thus while making a choice of **cutting process parameters for finish, it is desirable to have high cutting speed and small feed rates**.

Machinability

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”.

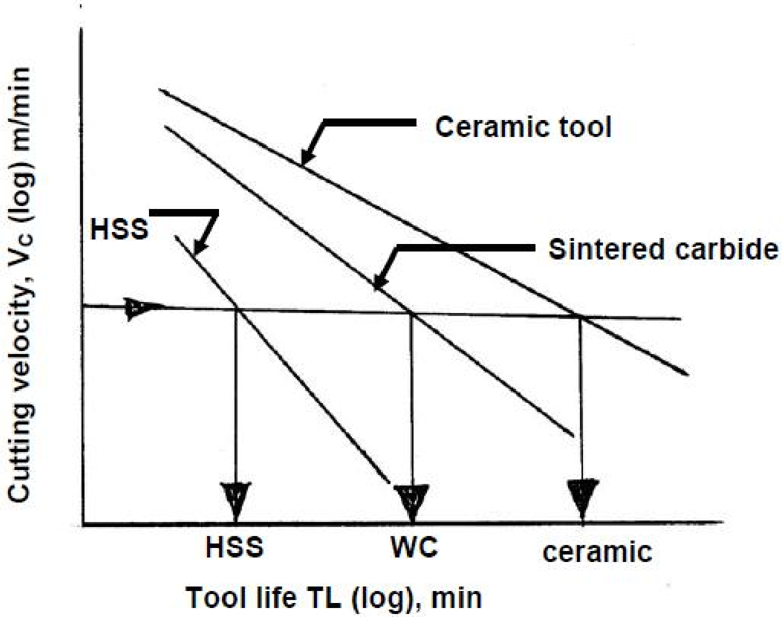
Such ease of machining or machinability characteristics of any tool-work pair is to be judged by :

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

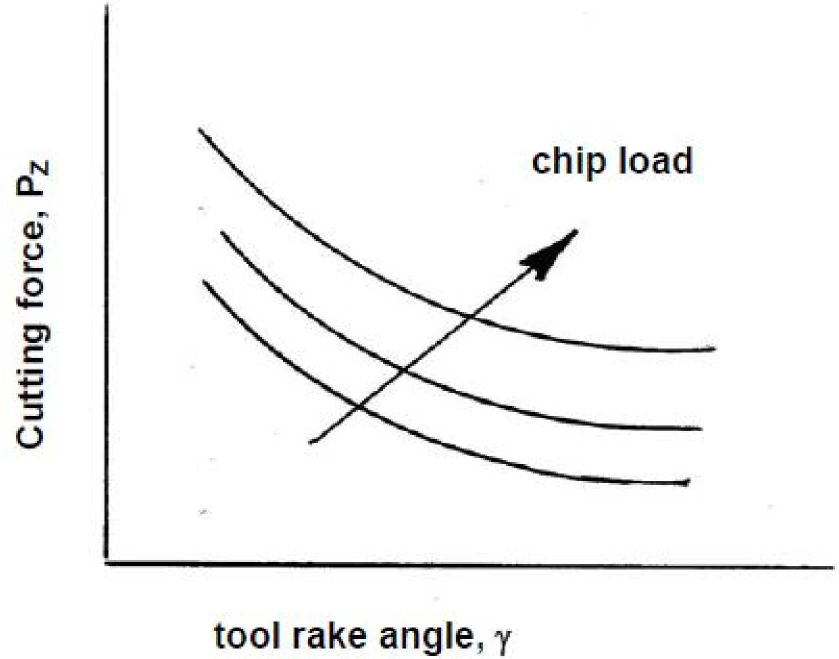
- Machinability will be considered desirably high when cutting forces, temperature, surface roughness and tool wear are less, tool life is long and chips are ideally uniform and short enabling short chip-tool contact length and less friction.

Role of the properties of the work material on machinability

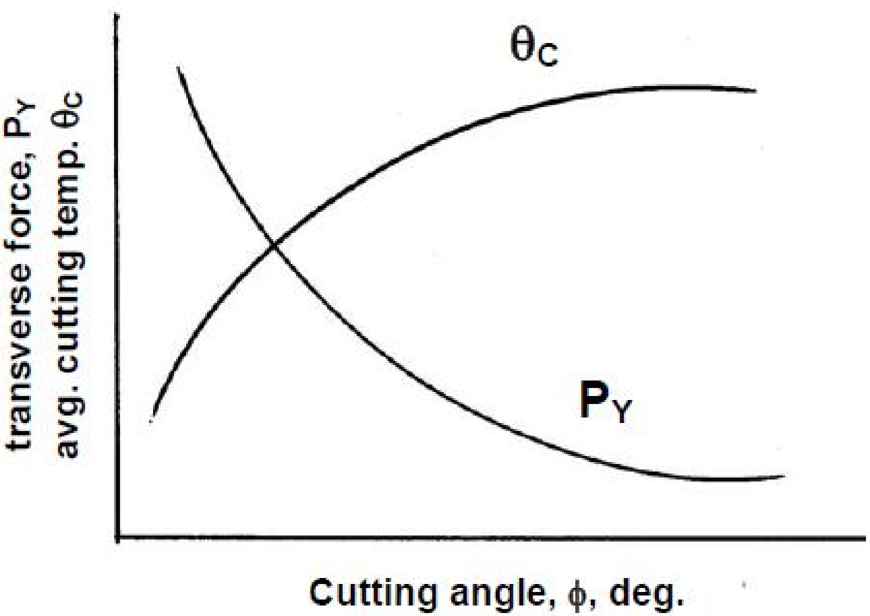
- The work material properties that generally govern machinability in varying extent are:
- the basic nature – brittleness or ductility etc.
- microstructure
- mechanical strength – fracture or yield
- hardness
- hot strength and hot hardness
- work hardenability
- thermal conductivity
- chemical reactivity
- stickiness / self lubricity



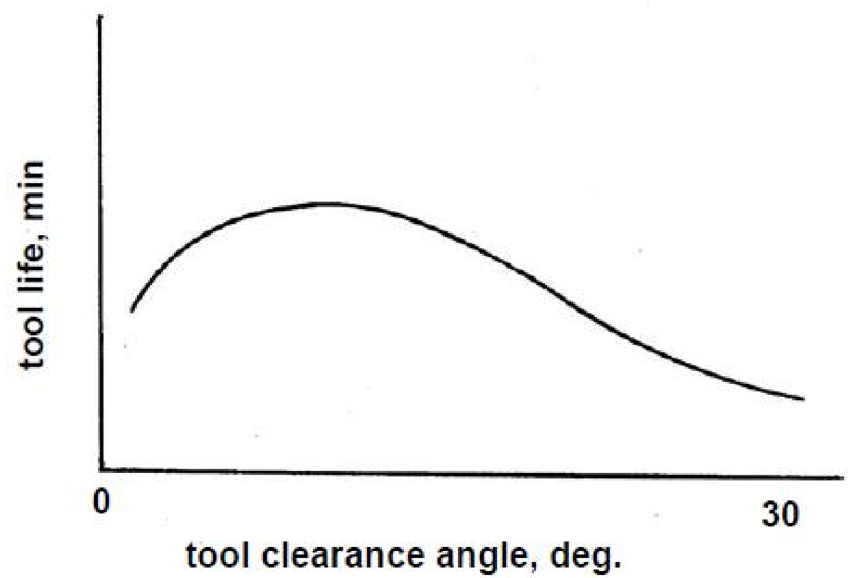
Ceramic tool
HSS
Sintered carbide
Cutting velocity, V_C (log) m/min
HSS
WC
ceramic
Tool life TL (log), min



chip load
Cutting force, P_Z
tool rake angle, γ



θ_C
P_Y
transverse force, P_Y
avg. cutting temp. θ_C
Cutting angle, ϕ, deg.



tool life, min
0
30
tool clearance angle, deg.

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.