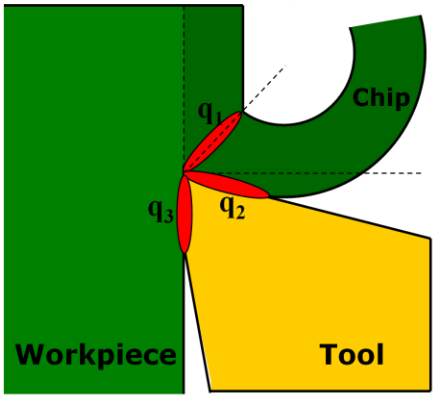
Thermal Aspect of Chip Formation

Machining is inherently characterized by generation of heat and high cutting temperature. At such elevated temperature the cutting tool if not enough hot hard may lose their form stability quickly or wear out rapidly resulting in increased cutting forces, dimensional inaccuracy of the product and shorter tool life. The magnitude of this cutting temperature increases, though in different degree, with the increase of cutting velocity, feed and depth of cut, as a result, high production machining is constrained by rise in temperature. This problem increases further with the increase in strength and hardness of the work material. Knowledge of the cutting temperature rise in cutting is important, because increases in temperature:

- adversely affect the strength, hardness and wear resistance of the cutting tool
- cause dimensional changes in the part being machined, making control of dimensional accuracy difficult and
- can induce thermal damage to the machined surface, adversely affecting its properties and service life.

In addition, the machine tool itself may be subjected to temperature gradients, causing distortion of the machine. The main sources of heat in metal cutting are shown in the following Figure. These three distinct heat sources are:



- the shear zone (q_1), where the main plastic deformation takes place
- the chip-tool interface zone (q_2), where secondary plastic deformation due to friction between the heated chip and the tool takes place
- the work tool interface (q_3), at flanks where frictional rubbing occurs.

The heat balance in chip formation can be written as :

$$\begin{bmatrix} \text{Total amount} \\ \text{of heat generated} \end{bmatrix} = \begin{bmatrix} \text{Amount of heat away in chips} + \text{Amount of heat remaining in the} \\ \text{cutting tool} + \text{Amount of heat passing into the workpiece} + \text{Amount} \\ \text{of heat radiated into the surroundin g air} \end{bmatrix}$$

Various studies have been made of temperatures in cutting, based on heat transfer and dimensional analysis, using experimental data. A simple and approximate expression for the mean temperature for orthogonal cutting is

$$T = \frac{0.4\,U}{\rho\,C}\left(\frac{V_c\,t}{K}\right)^{0..333}$$

where,

T = mean temperature rise at the tool-chip interface (°C)
U = specific energy in the operation (N-m/mm^3)
V_c = cutting velocity (m/sec)
t = depth of cut (mm)
pC = volumetric specific heat of the workpiece (J/mm^2-C)
K = thermal diffusivity (ratio of thermal conductivity to volumetric specific heat) of the workpiece material (m^2/sec).

Cutting Fluid

Machining is inherently characterized by generation of heat and high cutting temperature. At such elevated temperature the cutting tool if not enough hot hard may lose their form stability quickly or wear out rapidly resulting in increased cutting forces, dimensional inaccuracy of the product and shorter tool life. The magnitude of this cutting temperature increases, though in different degree, with the increase of cutting velocity, feed and depth of cut, as a result, high production machining is constrained by rise in temperature. This problem increases further with the increase in strength and hardness of the work material. So, the use of a cutting fluid during a machining operation is very essential. Its application at the workpiece-tool interface produces the following effects:

i. Reduce friction and wear
ii. Improve tool life, surface finish
iii. Cool cutting zone-reduce temperature and distortion
iv. Wash chips away
v. Prevent corrosion
vi. Reduces forces and energy consumption

Properties of Good Cutting Fluid

- Good cooling capacity and lubricating qualities
- Rust resistance and stability- for long life
- Resistance to rancidity and foaming
- Non-toxic
- Transparent-to allow the operator to see the work clearly during machining
- Relatively low viscosity-to permit the chips and dirt to settle quickly
- Nonflammable-to avoid burning easily and should be non-combustible
- Ability to dispose of in an environmentally responsible way.
- In addition, it should not smoke excessively, form gummy deposit which may cause machine slide to become sticky, or clog the circulating system.

Types of Cutting Fluids

Cutting fluids are used in metal machining for a variety of reasons such as improving tool life, reducing work piece thermal deformation, improving surface finish and flushing away chips from the cutting zone. Practically all cutting fluids presently in use fall into one of four categories:

- Straight oils
- Soluble oils
- Semi-synthetic fluids
- Synthetic fluids

Straight oils are non-emulsifiable and are used in machining operations in an undiluted form. They are composed of a base mineral or petroleum oil and often contain polar lubricants such as fats, vegetable oils and esters as well as extreme pressure additives such as Chlorine, Sulphur and Phosphorus. Straight oils provide the best lubrication and the poorest cooling characteristics among cutting fluids.

Soluble oil fluids form an emulsion when mixed with water. The concentrate consists of a base mineral oil and emulsifiers to help produce a stable emulsion. They are used in a diluted form (usual concentration = 3 to 10%) and provide good lubrication and heat transfer performance. They are widely used in industry and are the least expensive among all cutting fluids.

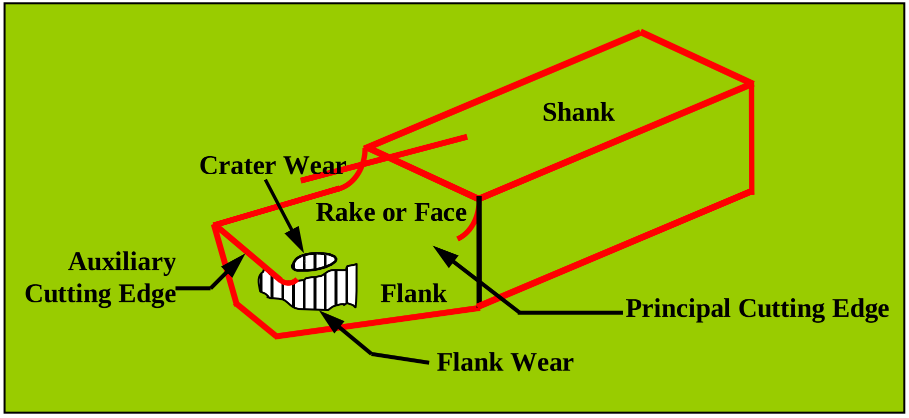
Semi-synthetic fluids are essentially combination of synthetic and soluble oil fluids and have characteristics common to both types. The cost and heat transfer performance of semi-synthetic fluids lie between those of soluble oil fluids and synthetic fluid.

Synthetic fluids contain no petroleum or mineral oil base and instead are formulated from alkaline inorganic and organic compounds along with additives for corrosion inhibition. They are generally used in a diluted form (usual concentration = 3 to 10%). Synthetic fluids often provide the best cooling performance among all cutting fluids.

Tool Wear and Tool Life

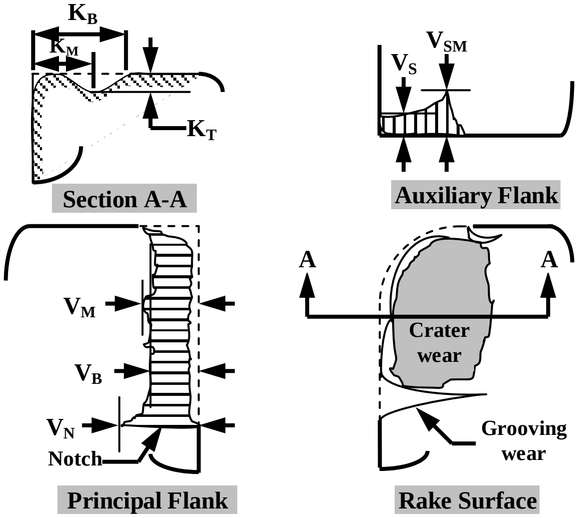
Tool Wear

Productivity and economy of manufacturing by machining are significantly affected by life of the cutting tools. Cutting tools may fail by brittle fracture, plastic deformation or gradual wear. Turning carbide inserts having enough strength, toughness and hot hardness generally fail by gradual wears. With the progress of machining the tools attain crater wear at the rake surface and flank wear at the clearance surfaces, as schematically shown in following Figure (next slide) due to continuous interaction and rubbing with the chips and the work surfaces respectively. Among the aforesaid wears, the principal flank wear is the most important because it raises the cutting forces and the related problems.



Major Features of Wear of Turning Tool

VB = Average flank wear
VN = Flank notch wear
VM = Maximum flank wear
VS = Average auxiliary flank wear
VSM= Maximum auxiliary flank wear
KT = Crater depth
KM = Distance from center of crater
KB = Crater width



The life of the tools, which ultimately fail by systematic gradual wear, is generally assessed at least for R&D work, by the average value of the **principal flank wear (VB)**, which aggravates cutting forces and temperature and may induce vibration with progress of machining. The pattern and extent of **wear of the auxiliary flank (VS)** affects surface finish and dimensional accuracy of the machined parts.

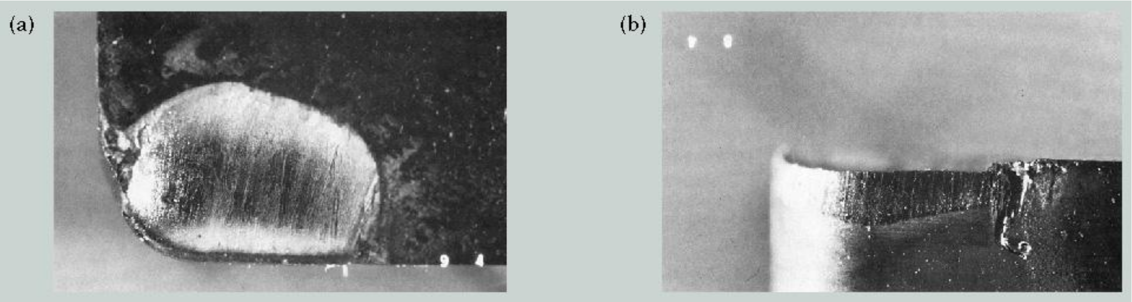


Fig.(a) Crater wear and (b) flank wear on a carbide tool.

However, tool rejection criteria for finishing operation were employed in this investigation. The values established in accordance with **ISO Standard 3685** for tool life testing. A cutting tool was rejected and further machining stopped based on one or a combination of rejection criteria:

i.	Average Flank Wear	≥	0.3 mm
ii.	Maximum Flank Wear	≥	0.4 mm
iii.	Nose Wear	≥	0.3 mm
iv.	Notching at the depth of cut line	≥	0.6 mm
v.	Average surface roughness value	≥	1.6 µm
vi.	Excessive chipping (flanking) or catastrophic fracture of cutting edge.		

Effects of Tool Wear

The wear on a tool causes the following effects.

- The cutting force increases
- The dimensional accuracy of the work decreases
- The surface roughness of the work increases
- The tool-work system may start vibrating
- The workpiece may get damaged or tool may break ultimately.

Mechanism of Tool Wear

To know the right mechanism of tool wear and its reasons, the researchers all over the world conducted lots of experiments. Due to the inabilities of the researchers to observe the wear actually taking place on different places of a tool, the bulk of the knowledge is based primarily on theory supported by limited investigations. In general there are seven basic types of wear that affect a cutting tool:

Abrasion: Mechanical wearing, hard particles in workpiece removes small portions of the tool, that cause flank and crater wear. This is the dominant cause of flank wear.

Adhesion: Two metals contact under high pressure and temperature that cause welding between the materials.

Diffusion: Atoms on the boundry of workpiece and tool changes place. This is the principle cause for crater wear.

Chemical Reactions: The high temperatures and clean surfaces at the chip-tool interface in machining at high speeds can result in chemical reactions, in particular, oxidation, on the rake surface of the tool. The oxidized layer, being softer than the parent tool material, is sheared away, exposing new material to sustain the reaction process.

Plastic Deformation: Cutting forces acting on the cutting edge at high temperature cause the edge to deform plastically. This cause flank wear.

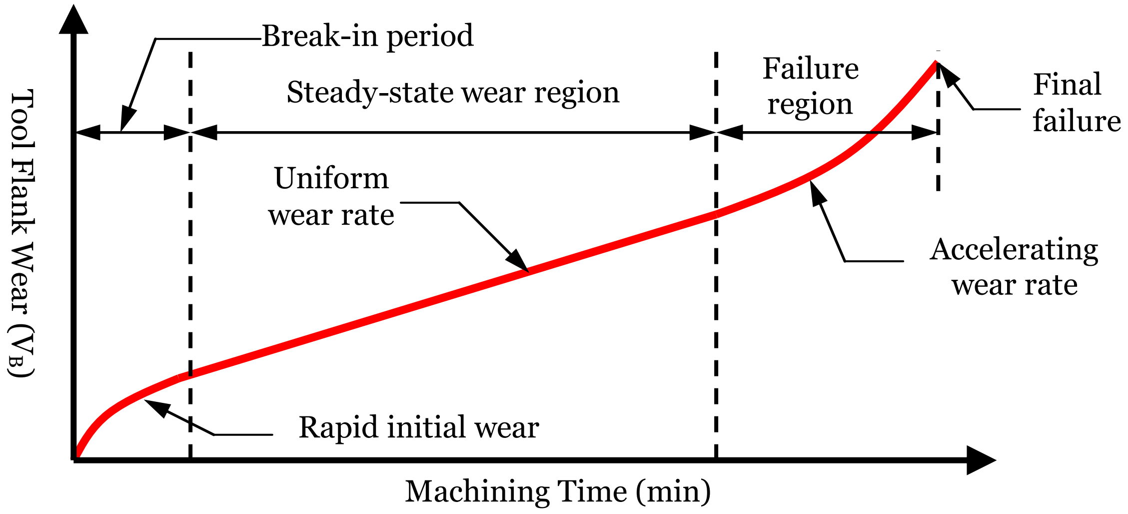
Tool Life

It is difficult to define adequately the tool life. In a general way, it has been defined as the cutting time required for complete failure of the tool, or as the time necessary to produce a given amount of flank wear on the tool. Tool life is a measure of the length of time a tool will cut satisfactorily and, like machinability, way be measured in a number of ways. Tool life is an important factor in production work since considerable time is lost wherever a tool is ground and reset. The tool life is affected by several variables, the important ones being:

- Cutting speed (Vc)
- Feed rate (So)
- Depth of cut (t)
- Work material hardness
- Tool material
- Shape and angles of cutting tool
- Types of cutting fluid and its method of application

Tailor Tool Life Equation

As cutting proceeds, various wear mechanisms result in increasing levels of wear on the cutting tool. The general relationship of tool wear versus cutting time is shown in following Figure. Although the relationship shown is for flank wear, a similar relationship occurs for crater wear. Three regions can usually be identified in the typical wear growth curve.



The first is the **break-in Period**, in which the sharp cutting edge wears rapidly at the beginning of its use. This first region occurs within the first few minutes of cutting. The break-in period is followed by wear that occurs at a fairly uniform rate. This is called the **steady state wear** region. In this figure, this region is pictured as a linear function of time, although there are deviations from the straight line in actual machining. Finally, wear reaches a level at which the wear rate begins to accelerate. This marks the beginning of the **failure region**, in which cutting temperatures are higher and the general efficiency of the machining process is reduced. If allowed to continue, the tool finally fails by temperature failure.

Frederick W. Taylor did pioneering work in the field of metal cutting. He conducted numerous experiments and in 1907 gave the following relationship between tool life and cutting speed.

$$V_c T^n = C$$

Where,

V_c = Cutting velocity

T = Tool life

n = Tool life index. It depends on tool and work combination and environment.

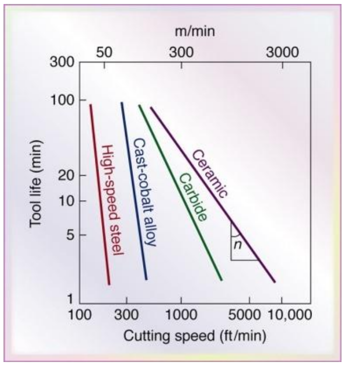
C = Constant

Tool-life curves for a variety of cutting-tool materials as shown in the following **Figure**. The negative inverse of the slope of these curves is the exponent *n* in the Taylor tool-life equations and *C* is the cutting speed at *T* = 1 min.

$$V_c T^n = C$$

The following values may be taken for **n**

n = 0.10 to 0.15 for HSS tools
n = 0.20 to 0.40 for carbide tools
n = 0.40 to 0.60 for ceramic tools



Cutting Tool Materials for Machining

A wide variety of tool materials have been developed to fulfill the severe demand of present-day production. No one of' these materials is superior in all respects, but rather each has certain characteristics which limits its field of application. Depending upon the type of service, the proper tool material should, therefore, be selected. The best material to use for a certain job is the one that will produce the machined part at the lowest cost. A good type of tool material should possess certain desired properties such as

- The material must remain harder than the work material at elevated operating temperature.
- The material must withstand excessive wear even though the relative hardness of the tool-work materials changes.
- The frictional coefficient at the chip-tool interface must remain low for minimum wear and reasonable surface finish.
- The material must be sufficiently tough to withstand the shocks of intermittent cutting; if not reinforcement must be provided.

- The tool material should also possess high thermal conductivity for quickly removing heat from the chip-tool interface, have a low coefficient of thermal expansion, not be distorted after heat treatment, be easy to regrind and also easy to weld to the tool holder

Types of Cutting Tool Materials

Carbon Tool Steels

- medium alloy steels
- poor properties above 200°C
- Inexpensive
- Uses: Taps and core drills for machining soft materials and wood working tools

High Speed Steels (HSS)

- Hot hardness is quite high, so the HSS cutting tools retain the cutting ability upto 600°C
- Wear resistance is high
- The hardenability is good
- Uses: Drills, reamers, broaches, milling cutters, taps, lathe cutting tool, gear hobs etc. are made of HSS.

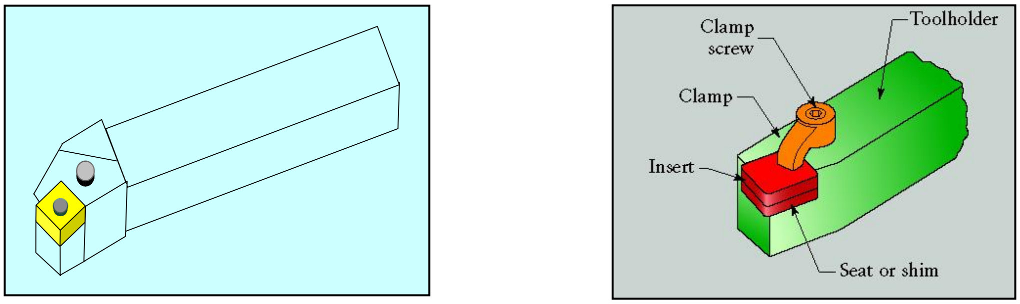
Carbides

- "A hard material made of compacted binary compounds of carbon and heavy metals, used to make tools that cut metal."
- made using powder metallurgy
- usually as an insert

Ceramics

- high abrasion and high hot hardness
- not good for interrupted cutting
- requires dry, or constant profuse cutting fluids

All carbides, when finished, are extremely brittle and weak in their resistance to it impact and shock loading. Due to this, vibrations are very harmful for carbide tools. The machine tools should be rigid, faster and more powerful. Light feeds, low speeds and chatter are harmful. Due to the high cost of carbide tool materials and other factors, cemented carbides are used in the form of inserts or tips which are brazed or clamped to a steel shank as shown in the following Figure.



Methods of attaching inserts to tool shanks

Machining Economics

Optimizing cutting speed is formulated by W. Gilbert with respect to Taylor's tool life formula. There are two objectives in this optimization

- Maximizing production rate
- Minimizing unit cost

Both objectives seek a balanced MRR and tool life.

Maximizing Production Rate

- Choose cutting speed to minimize machining time per production unit.
- In turning 3 elements contribute to the total production cycle time for one part, such as:

    - Part handling time (loading+ unloading+ starting the machining)=T_h
    - Machining time (actual machining)=T_m
    - Tool change time (at the end of tool life, the tool must be changed)=T_t .

Therefore total time per unit product for the operation cycle
$T_c = T_h + T_m + T_t / n_p$
Where n_p =integer number of parts we can produce within the tool life.

Our objective is to minimize T_c, which is the function of the cutting speed.

Remember in Turning operation, $T_m = \pi .D. L/ V .S_o$
Taylor's tool life formula, $V.T^n = C \Rightarrow T=(C/ V)^{1/n}$
$n_p = T/ T_m \Rightarrow n_p = (C/ V)^{1/n} . V .S_o / \pi .D. L = C^{1/n}. S_o / \pi .D. L. V^{(1/n) -1}$

So, Tc becomes, $T_c = T_h + \pi .D. L/ V .S_o + (T_t. \pi .D. L. V^{(1/n) -1})/ C^{1/n}. S_o$
To minimize we need to take derivative of T_c w.r.t V, and equate it to 0 (zero).
Therefore the maximum V= $\mathbf{V_{max} = C/[\{(1/n)-1\}T_t]^{n}}$

We have maximum production for this value of V. The corresponding tool life is
$\mathbf{T_{max} = [(1/n) - 1]. T_t}$

Minimizing Cost per Unit

- Choose cutting speed to minimize production cost per unit product.
- In turning 4 elements contribute to the total production cost for one part (cost rate is $/min)
    - Cost of part handling time(cost of the time that operator spends loading and unloading the part)=$C_o .T_h$
    - Cost of machining time= $C_o . T_m$
    - Cost of tool change time= $C_o . T_t / n_p$
    - Tooling cost= C_t / n_p,

Where, C_t =Cost for cutting edge=P_t/n_e
P_t =Price of the tool
n_e =Number of cutting edges
C_o=Cost rate ($/min) for the operator and machine

If the tool is regrindable, $C_t = P_t/n_g + T_g \, . \, C_g$
Where,
n_g =number of tool lifes
T_g =time to grind
C_g =grinding labor cost

Therefore total cost per unit product for the operation cycle,

$$C_c = C_o T_h + C_o T_m + \frac{C_o T_t}{n_p} + \frac{C_t}{n_p} = C_c = C_o T_h + \frac{C_o \pi DL}{V S_o} + \frac{\left(C_o T_t + C_t\right)\left(\pi DLV^{\frac{1}{n}-1}\right)}{S_o C^{\frac{1}{n}}}$$

To minimize the cost we need to take derivative of C_c w.r.t V, and equate it to 0.
Therefore the minimum V,
$V_{min} = C. \, [\{n/(1-n)\}. \, (C_o / (C_o. \, T_t + C_t)]^n$

Means that it is the cost minimizing speed, and the corresponding tool life is
$T_{min} = [(1/n)-1].(C_o. \, T_t + C_t)/ C_o$