Meaning of Tool Wear:

Cutting tools are subjected to an extremely severe rubbing process. They are in metal-to-metal contact between the chip and work piece, under high stress and temperature. The situation becomes severe due to the existence of extreme stress and temperature gradients near the surface of the tool.

Tool wear is generally a gradual process due to regular operation. Tool wear can be compare with the wear of the tip of an ordinary pencil. According to Australian standard, the tool wear can be defined as “The change of shape of the tool from its original shape, during cutting, resulting from the gradual loss of tool material”.

Tool wear depends upon following parameters:

i. Tool and work piece material.

ii. Tool shape.

iii. Cutting Speed.

iv. Feed.

v. Depth of cut.

vi. Cutting fluid used.

vii. Machine Tool characteristics etc.

Tool wear affects following items:

i. Increased cutting forces.

ii. Increased cutting temperature.

iii. Decreased accuracy of produced parts.

iv. Decreased tool life.

v. Poor surface finish.

vi. Economics of cutting operations.

Types of Tool Wear:

The high contact stresses are developed in machining process due to rubbing action of:

(i) Tool rake face and chips.

(ii) Tool flank face and machined surface.

These results in a variety of wear patterns observed at the rake face and the flank face. We call this gradual wear of the tool.

The gradual wear is unavoidable but controllable. It is the wear which cannot be prevented. It has to occur after certain machining time.

The gradual wear can be controlled by remedial action. The gradual wear can be divided into two basic types of wear, corresponding to two regions in the cutting tool as shown in Fig. 9.16.

These are following:

(i) Flank wear.

(ii) Crater wear.

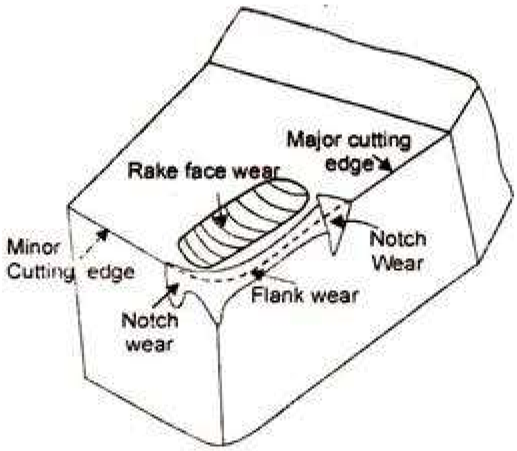


Fig. 9.16. (a) Tool Wear Phenomena.

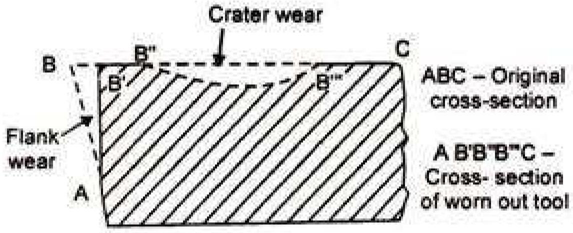
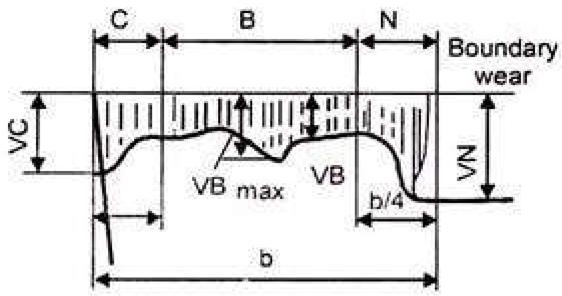


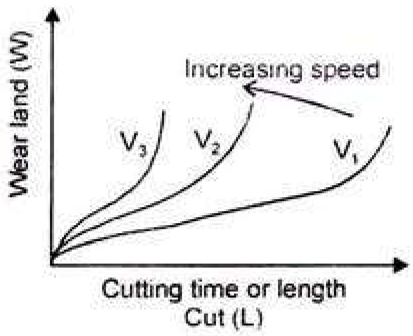
Fig. 9.16. (b) Flank and Crater wear.

(i) Flank Wear:

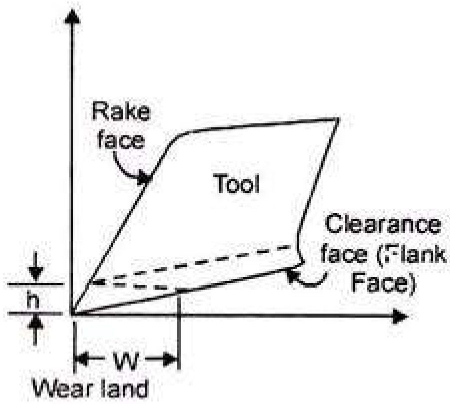
Wear on the flank face (relief or clearance face) of the tool is called flank wear. The flank wear is shown in Fig. 9.17 (a, b, c).



(a)



(b)



(c)

Fig. 9.17. The Flank Wear.

The characteristics of flank wear are following:

i. It is the most important wear that appears on the flank surface parallel to the cutting edge. It is most commonly results from abrasive/adhesive wear of the cutting edge against the machined surface.

ii. It is generally results from high temperatures, which affect tool and work material properties.

iii. It results in the formation of wear land. Wear land formation is not always uniform along the major and minor cutting edge of the tool.

iv. It can be measured by using the average wear land size (V_3) and maximum wear land size (VB_{max}).

v. It can be described using the Tool Life Expectancy Equation.

$$V_C T^n = C$$

A more general form of the equation (considering depth of cut and feed rate) is

$$V_c T^n D^x F^y = C$$

where,

V_c = Cutting Speed

T = Tool life

D = Depth of cut (mm)

F = Feed rate (mm/rev. or inch/rev.)

x and y = Exponents that are determined experimentally for each cutting condition.

C = Machining constant, found by experimentation or published data book. Depends on properties of tool materials, work piece and feed rate.

n = exponential

Values of n = 0.1 to 0.15 (For HSS tools)

= 0.2 to 0.4 (For carbide tools)

= 0.4 to 0.6 (For ceramic tools)

Reasons of Flank Wear:

i. Increased cutting speed causes flank to wear grow rapidly.

ii. Increase in feed and depth of cut can also result in larger flank wear.

iii. Abrasion by hard panicles in the work piece.

iv. Shearing of micro welds between tool and work-material.

v. Abrasion by fragments of built-up edge, which strike against the clearance face (Flank face) of the tool.

Remedies for Flank Wear:

i. Reduce cutting speed.

ii. Reduce feed and depth of cut.

iii. Use hard grade of carbide if possible.

iv. Prevent formation of built-up edge, using chip breakers.

Effects of Flank Wear:

i. Increase in the total cutting force.

ii. Increase in component surface roughness.

iii. Also affect the component dimensional accuracy.

iv. When form tools are used, flank wear will also change the shape of the components produced,

(ii) Crater Wear:

Wear on the rake face of the tool is called crater wear. As the name suggests, the shape of wear is that of a crater or a bowl. The crater wear is shown in Fig.9.18 (a, b, c).

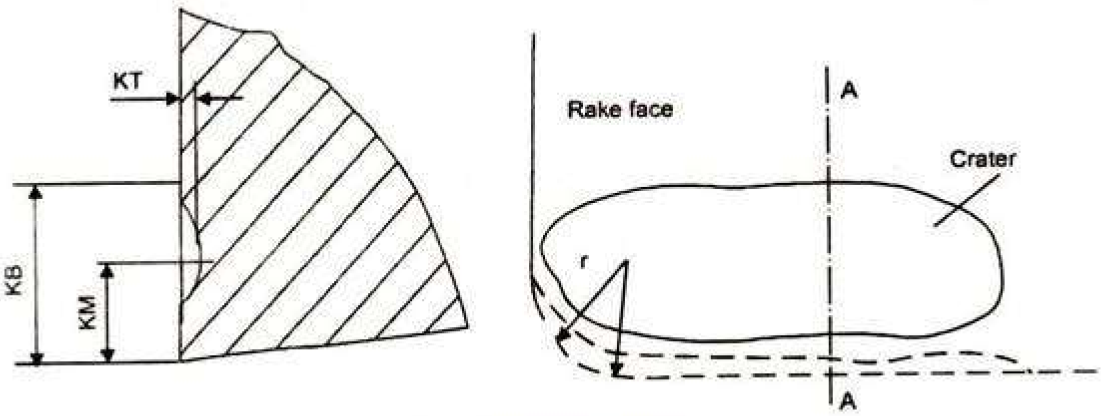


Fig. 9.18.(*a*) Crater Wear.

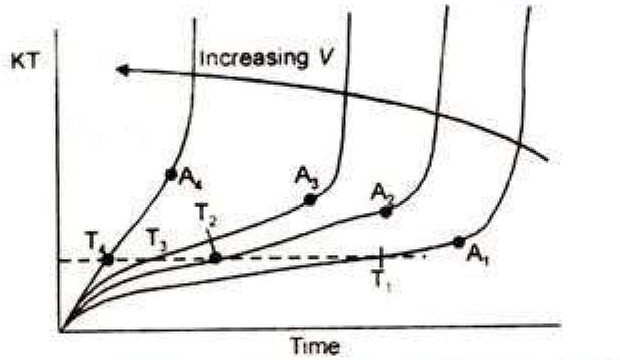


Fig. 9.18. (*b*) Effects of Cutting Speed V and Cutting Time T on Crater Wear Depth KT.

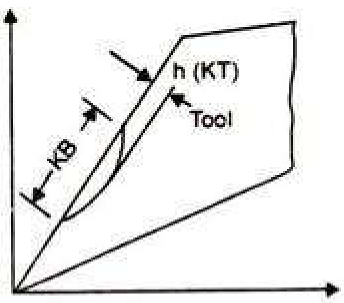


Fig. 9.18. (*c*) Crater Wear.

The characteristics of crater wear are following:

i. In crater wear chips erodes the rake face of tool.

ii. The chips flows across the rake face develop severe friction between the chip and rake face. This produces a scar on the rake face which is usually parallel to the major cutting edge.

iii. It is somewhat normal for tool wear and does not seriously degrade the use of a tool until it becomes serious enough to cause a cutting edge failure.

iv. The crater wear can increase the working rake angle and reduce the cutting force, but it will also weaken the strength of the cutting edge.

v. It is more common in ductile materials like steel which produce long continuous chips. It is also more common in H.S.S. (High Speed Steel) tools than the ceramic or carbide tools which have much higher hot hardness.

vi. The parameters used to measure the crater wear can be seen in the Fig. 9.18. The crater depth KT is the most commonly used parameter in evaluating the rake face wear.

vii. It occurs approximately at a height equal to the cutting depth of the material, i.e., Crater wear depth ≃ cutting depth.

viii. At high temperature zones (nearly 700°C) create wear occurs.

Reasons of Crater Wear:

i. Severe abrasion between the chip-tool interfaces, specially on rake face.

ii. High temperature in the tool-chip interface.

iii. Increase in feed results in increased force acting on tool interface, this leads to rise in temperature of tool-chip interface.

iv. Increase in cutting speed results in increased chip velocity at rake face, this leads to rise in temperature at chip-tool interface and so increase in crater wear.

Remedies for Crater Wear:

i. Use of proper lubricants, can decrease the abrasion process, and so decrease in crater wear.

ii. Proper coolant for rapid heat dissipation from tool-chip interface.

iii. Reduced cutting speeds and feed rates.

iv. Use tougher and hot hardness materials for tools.

v. Use positive rake tool.

Causes of Tool Wear:

There are large numbers of causes for tool wear.

Some of them are important to discuss here from the subject point of view:

(i) Abrasive wear (Hard particle wear).

(ii) Adhesive wear.

(iii) Diffusion wear.

(iv) Chemical wear.

(v) Fracture wear.

(i) Abrasive Wear (Hard Particle Wear):

Abrasive wear is basically caused by the impurities within the work piece material, such as carbon nitride and oxide compounds, as well as the built-up edge fragments. It is a mechanical type of wear. It is the main cause of the tool wear at low cutting speeds.

(ii) Adhesive Wear:

Due to high pressure and temperature at tool-chip interface, there is a tendency of hot chips to weld on to the tool rake face. This concept leads to subsequently formation and destruction of welded junctions. When the weld intermittently breaks away picking particles of cutting tool. This leads to a crater wear. Fig. 9.19 shows adhesive wear.

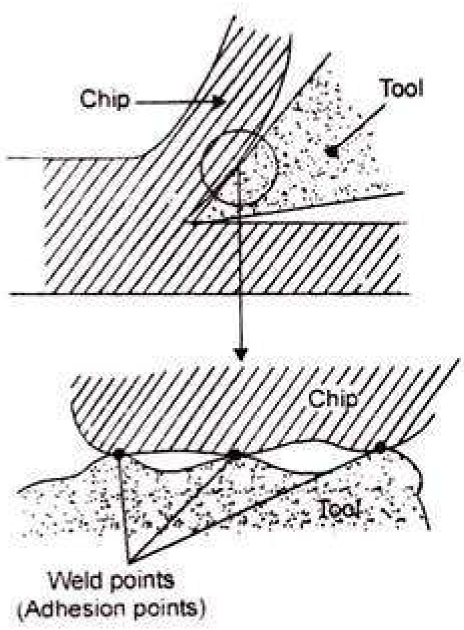


Fig. 9.19. Adhesion Wear.

(iii) Diffusion Wear:

Diffusion wear is usually caused by atomic transfer between contacting materials under high pressure and temperature conditions. This phenomena starts at chip-tool interface. At such elevated temperatures, some particles of tool materials diffuse into the chip material. It can also happen that some particles of work material also diffuse into the tool materials.

This exchange of particles changes the properties of tool material and causes wear, as shown in Fig. 9.20:

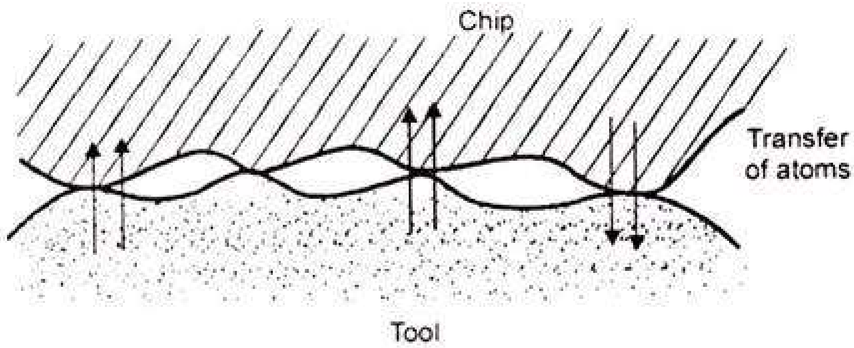


Fig. 9.20. Diffusion Wear.

This diffusion results in changes of the tool and work piece composition.

There are several ways of diffusions like:

(a) Gross Softening of the Tool:

Diffusion of carbon in a relatively deep surface layer of the tool may cause softening and subsequent plastic flow of the tool. It may produce major changes in the tool geometry.

(b) Diffusion of Major Tool Constituents into the Work:

The tool matrix or a major strengthening constituent may be dissolved into the work and chip surfaces as they pass the tool. For example: Demand tool, cutting iron and steel is the typical examples of carbon diffusion.

(c) Diffusion of a Work Material Component into the Tool:

A constituent of the work material diffusing into the tool may alter the physical properties of a surface layer of the tool. For example: The diffusion of lead into the tool may produce a thin brittle surface layer, this thin layer can be removed by chipping.

(iv) Chemical Wear:

The chemical wear is caused due to chemical attack of a surface.

For example:

Corrosive wear.

(v) Facture Wear:

The facture wear usually caused by breaking of edge at end or length. The bulk breakage is the most harmful and undesirable type of wear, and it should be avoided as far as possible.

Growth of Tool Wear:

The growth pattern of tool wear is shown in Fig. 9.21:

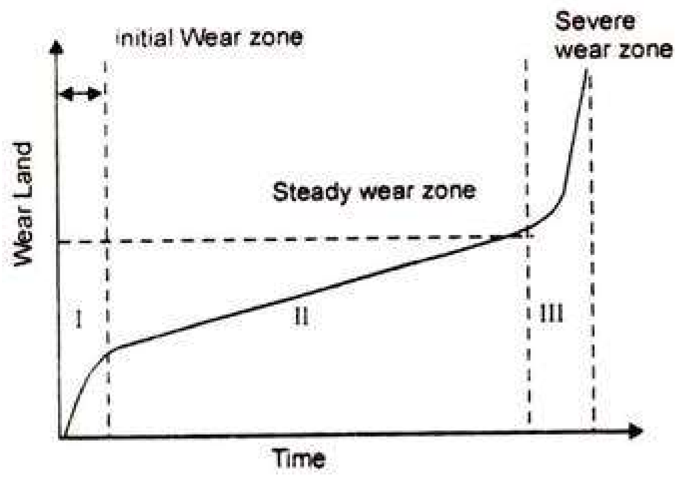


Fig. 9.21. The Growth of Tool Wear.

We can divide the growth into following three zones:

(i) Severe wear zone.

(ii) Initial Wear zone.

(iii) Severe or ultimate or catastrophic wear zone.

(i) Initial Preliminary or Rapid Wear Zone:

Initially, for the new cutting edge, the growth of wear is faster. The initial wear size is VB = 0.05 to 0.1 mm normally.

The causes of initial or rapid wear are:

i. Microcraking.

ii. Surface oxidation.

iii. Carbon loss layer.

iv. Micro-roughness of tool tip grinding.

(ii) Steady Wear Zone:

After the initial wear we found that the wear rate is relatively steady or constant. In this zone, the wear size is proportional to the cutting time.

(iii) Severe or Ultimate or Catastrophic Wear Zone:

In this zone, the rate of growth of wear is much faster and result in catastrophic failure of the cutting edge.

When the wear size increases to a critical value, the surface roughness of the machined surface decreases, cutting force and temperature increases rapidly, and the wear rate increases. Then the tool loses its cutting ability. In practice, this zone of wear should be avoided.

Allowable Wear Land:

As we decide to sharpen a knife edge when the quality of the cut begins to deteriorate and the cutting forces required increase too much, similarly re-sharpen or replace cutting tools when.

(a) The quality of machined surface begins to deteriorate.

(b) The cutting forces increases significantly.

(c) Pre-temperature rise significantly.

The average width of allowable flank wear varies from 0.2 mm (for a precision turning operation) to 1 mm (for a rough turning operation).

The following Table gives some recommended values of allowable average wear land (VB) for various operations and cutting tools:

Table 9.11. Allowable Wear Land.

Table (*a*) : Allowable width of wear land (VB) for various operations.

Operations	Allowable Width of Wear Land (VB)
Precision Turning	Below 0.2 mm
Finish Turning	0.3 to 0.4 mm
Rough Turning	0.6 to 1.2 mm
Wheel Set Turning	1.2 to 1.5 mm
Roll Turning	1.0 to 1.5 mm
Precision Milling	Below 0.2 mm
Finish Milling	0.3 to 0.4 mm
Rough Milling	0.5 to 0.8 mm

Table (*b*) : Allowable average wear land (VB) for various cutting tools and operations.

Operations	Allowable Average (VB)	
	H.S.S.	Carbides
Turning	1.5 mm	0.4 mm
Face milling	1.5 mm	0.4 mm
End milling	0.3 mm	0.3 mm
Drilling	0.4 mm	0.4 mm
Reaming	0.15 mm	0.15 mm

Forms of Tool Wear:

Flank and crater wear are very common type of wears already discussed.

Some other forms of tool wear are:

(i) Thermo-Electric Wear.

(ii) Thermal Cracking and Tool Fracture.

(iii) Cyclic Thermal and Mechanical Load Wear.

(iv) Edge Chipping.

(v) Entry or Exit Failures.

(i) Thermo-Electric Wear:

It can be observed in high temperature region. The high temperature results in the formation of thermal-couple between the work piece and the tool.

Due to this effect voltage established between the work piece and tool. It may cause an electric current flow between the two. However, this type of wear has not been clearly developed.

(ii) Thermal Cracking and Tool Fracture:

It is common in case of milling operation. In milling, tools are subjected to cyclic thermal and mechanical loads. Teeth may fail by a mechanism not observed in continuous cutting. Thermal cracking can be reduced by reducing the cutting speed or by using a tool material grade with a higher thermal shock resistance.

(iii) Cyclic Thermal and Mechanical Load Wear:

The cyclic variation in temperature in milling process induce cyclic thermal stress at the surface layer of the tool expands and contracts. It may leads to the formation of thermal fatigue cracks near the cutting edge.

Mostly, such cracks are perpendicular to the cutting edge and begin formation at the outer corner of the tool, spreading inward as cutting progresses. The growth of these cracks eventually leads to edge chipping or tool breakage. An insufficient coolant can promote crack formation.

(iv) Edge Chipping:

Edge chipping is commonly observed in milling operation. It may occur when the tool first contacts the part (Entry Failure) or, more commonly, when it exits the part (Exit Failure).

(v) Entry or Exit Failures:

Entry failure most commonly occurs when the outer corner of the insert strikes the part first. This is more likely to occur when the cutter rake angles are positive. Entry failure is therefore most easily prevented by switching from positive to negative rake angle cutters.

Consequences (Effects) of Tool Wear:

The effects of the tool wear on technological performance are following:

(i) Increase in Cutting Forces:

The cutting forces are normally increased by wear of the tool. Crater wear, flank wear (or wear land formation) and chipping of cutting edge affect performance of the cutting tool in various ways. Crater wear may, however under certain circumstances, reduce forces by effectively increasing the rake angle of the tool. Clearance face (Flank or wear-land) wear and chipping almost invariably increase the cutting forces due to increased rubbing forces.

(ii) Increase in Surface Roughness:

As the tool wear increases, the surface roughness of machined component also increases. This is particularly true for a tool worn by chipping .Although, there are circumstances, in which a wear land may burnish (polish) the work piece and produce a good finish.

(iii) Increase in Vibration or Chatter:

Vibration or chatter is an another important aspect of the cutting process which may be influenced by tool wear.

A wear land increases the tendency of a tool to dynamic instability or vibrations. When the tool is sharp, the cutting operation is quite free of vibrations. On the other hand, when the tool wears, the cutting operation is subjected to an unacceptable vibration and chatter mode.

(iv) Decreases in Dimensional Accuracy:

Due to flank wear, the plan geometry of a tool may disturb. This may affect the dimensions of the component produced. It may influence the shape of the component.

For example:

If tool wear is rapid, cylindrical turning could result in a tapered work piece.

(i) Failure of cutting tools

Smooth, safe and economic machining necessitate

• prevention of premature and catastrophic failure of the cutting tools

• reduction of rate of wear of tool to prolong its life

To accomplish the aforesaid objectives one should first know why and how the cutting tools fail.

Cutting tools generally fail by:

i) Mechanical breakage due to excessive forces and shocks. Such kind of tool failure is random and catastrophic in nature and hence are extremely detrimental.

ii) Quick dulling by plastic deformation due to intensive stresses and temperature. This type of failure also occurs rapidly and are quite detrimental and unwanted.

iii) Gradual wear of the cutting tool at its flanks and rake surface.

The first two modes of tool failure are very harmful not only for the tool but also for the job and the machine tool. Hence these kinds of tool failure need to be prevented by using suitable tool materials and geometry depending upon the work material and cutting condition.

But failure by gradual wear, which is inevitable, cannot be prevented but can be slowed down only to enhance the service life of the tool.

The usual pattern or geometry of wear of turning and face milling inserts are typically shown in Figures respectively.

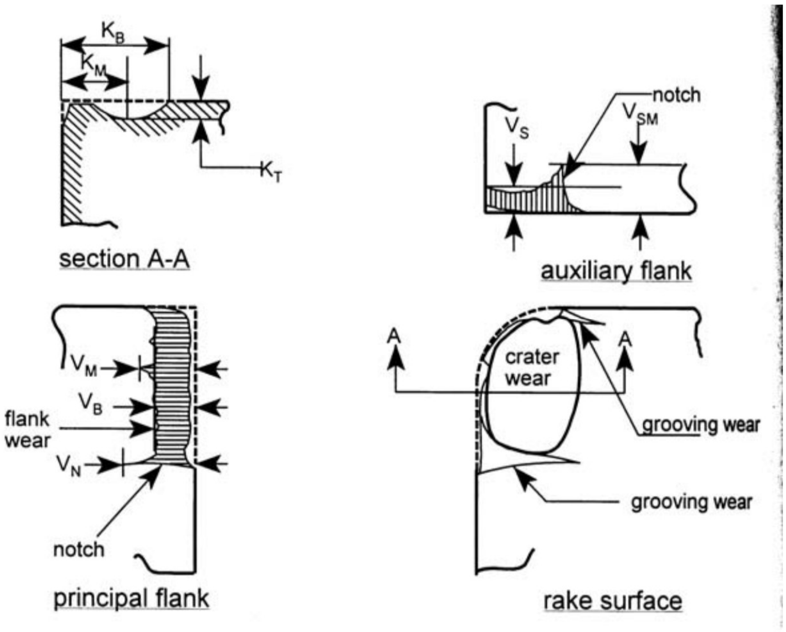


Fig.- *Geometry and major features of wear of turning tools* **KT**

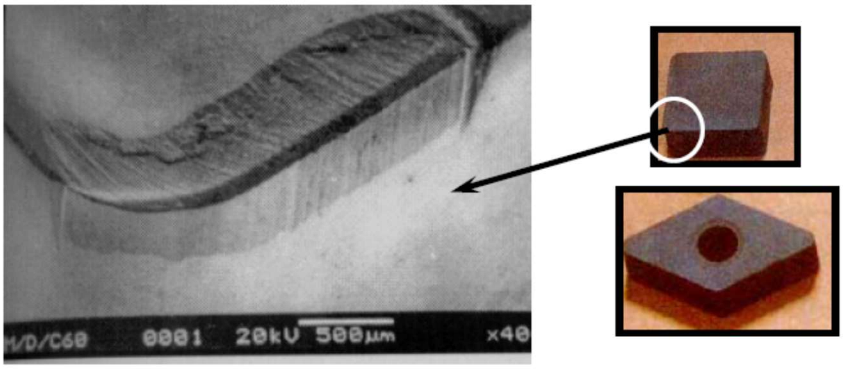


Fig.- *Photographic view of the wear pattern of a turning tool insert*

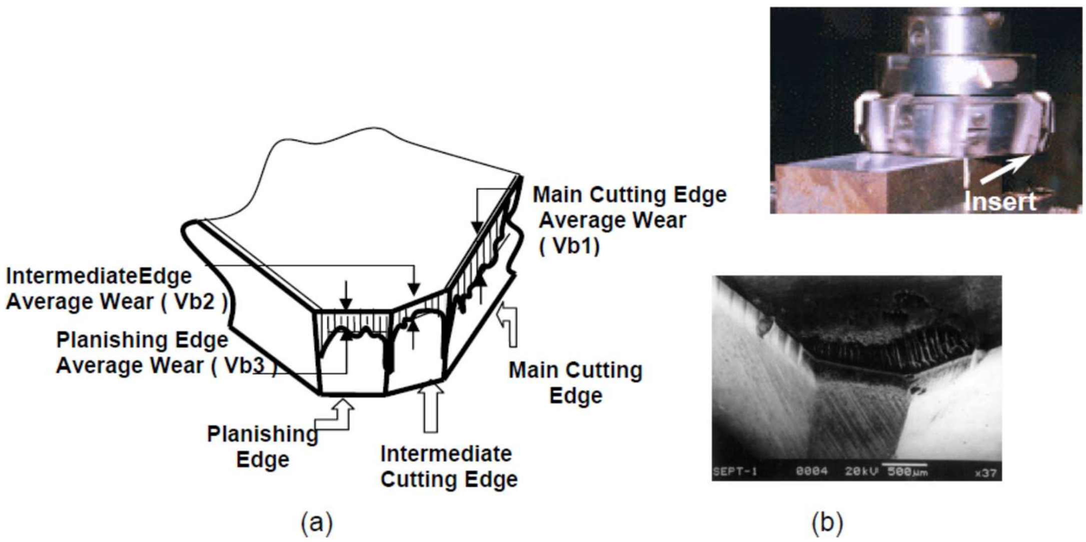


Fig. - *Schematic (a) and actual view (b) of wear pattern of face milling insert*

In addition to ultimate failure of the tool, the following effects are also caused by the growing tool-wear :

• increase in cutting forces and power consumption mainly due to the principal flank wear

• increase in dimensional deviation and surface roughness mainly due to wear of the tool-tips and auxiliary flank wear (V_s)

• odd sound and vibration

• worsening surface integrity

• mechanically weakening of the tool tip.

(iii) Essential properties for cutting 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.

Tool Life

Definition – 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.

(vi) 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.

The usual pattern of growth of cutting tool wear (mainly V_B), principle of assessing tool life and its dependence on cutting velocity are schematically shown in Fig.3.2.3.

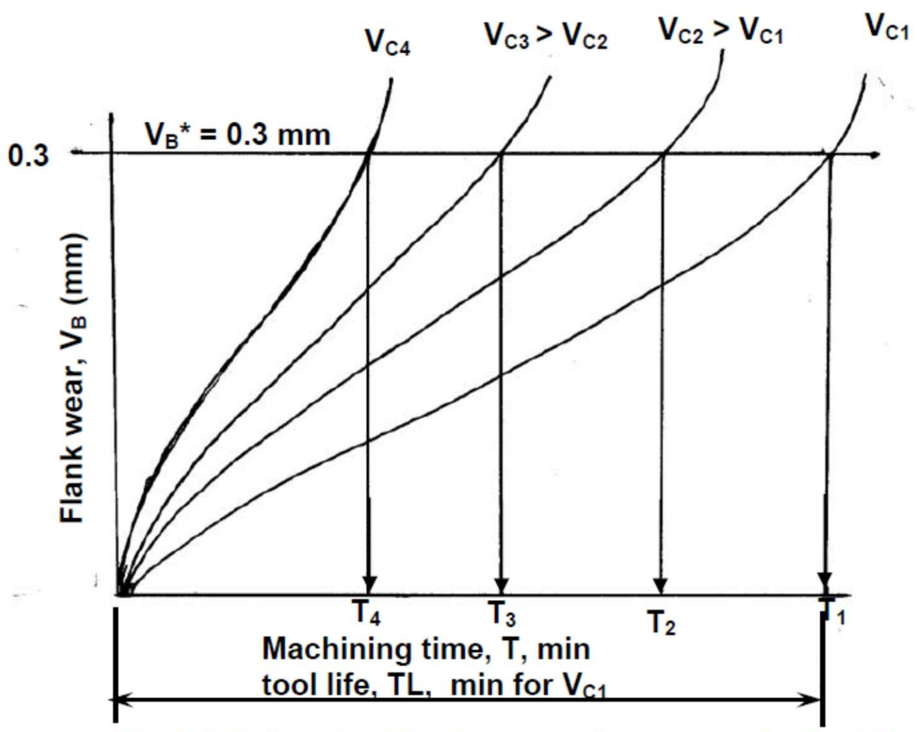


Fig. 3.2.3 *Growth of flank wear and assessment of tool life*

The tool life obviously decreases with the increase in cutting velocity keeping other conditions unaltered as indicated in Fig. 3.2.3.

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 as shown in Fig. 3.2.4, 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 shown in Fig. 3.2.5.

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.)

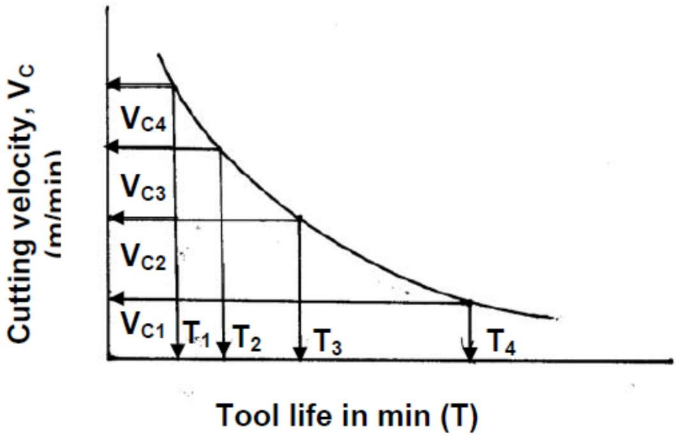


Fig. 3.2.4 *Cutting velocity – tool life relationship*

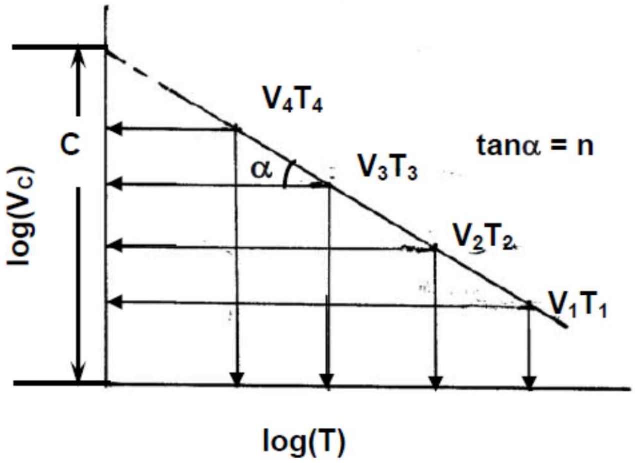


Fig. 3.2.5 *Cutting velocity vs tool life on a log-log scale*

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, $VT^n = C$

$V_1T_1=V_2T_2=V_3T_3=V_4T_4=$................$=C$

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

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 $V_{B\ \text{undertaken.}}$

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.

Exercise

Quiz Test

Identify the correct answer from the given four options.

1. In high speed machining of steels the teeth of milling cutters may fail by

(a) mechanical breakage

(b) plastic deformation

(c) wear

(d) all of the above

2. Tool life in turning will decrease by maximum extent if we double the

(a) depth of cut

(b) feed

(c) cutting velocity

(d) tool rake angle

3. In cutting tools, crater wear develops at

(a) the rake surface

(b) the principal flank

(c) the auxiliary flank

(d) the tool nose

4. To prevent plastic deformation at the cutting edge, the tool material should possess

(a) high fracture toughness

(b) high hot hardness

(c) chemical stability

(d) adhesion resistance

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.?

Answers of the questions of Exercise – 3.2

Quiz Test

Q. 1 : (d)

Q. 2 : (c)

Q. 3 : (a)

Q. 4 : (b)

Solution to Problem 1.

Ans. 34.6 min

Solution to Problem 2

Ans. 287 rpm.

Cutting Tool Materials

Training Objectives

After watching the program and reviewing this printed material, the viewer will gain knowledge and understanding of cutting tool metallurgy and specific tool applications for various types of metalcutting.

- High-speed steels, the forms of carbides, ceramics, cermets, and the superhard cutting tool materials are discussed
- tool selection for various applications are outlined
- types of tool failure modes are detailed

Cutting Tool Materials

Principal categories of cutting tools include single point lathe tools, multi-point milling tools, drills, reamers, and taps. All of these tools may be standard catalog items or tooling designed and custom-built for a specific manufacturing need.

The number one error when selecting tooling is calculating monetary savings based on lowest cost per tool, rather than on maximized productivity and extended tool life. To effectively select tools for machining, a machinist or engineer must have specific information about:

- the starting and finished part shape
- the workpiece hardness
- the material's tensile strength
- the material's abrasiveness
- the type of chip generated
- the workholding setup
- the power and speed capacity of the machine tool

Changes in any of these conditions may require a thorough review of any cutting tool selection. Different machining applications require different cutting tool materials. The ideal cutting tool material should
have all of the following characteristics:

- harder than the work it is cutting
- high temperature stability
- resists wear and thermal shock
- impact resistant
- chemically inert to the work material and cutting fluid

No single cutting tool material incorporates all these qualities. Instead, trade-offs occur among the various tool materials. For example, ceramic cutting tool material has high heat resistance, but has a low resistance to shock and impact. Every new and evolving tool development has an application where it will provide superior performance over others. Many newer cutting tool materials tend to reduce, but not eliminate the applications of older cutting tool materials.

As rates of metal removal have increased, so has the need for heat resistant cutting tools. The result has been a progression from high-speed steels to carbide, and on to ceramics and other superhard materials.

Developed around 1900, high-speed steels cut four times faster than the carbon steels they replaced. There are over 30 grades of high-speed steel, in three main categories: tungsten, molybdenum, and molybdenum-cobalt based grades. Since the 1960s the development of powdered metal high-speed steel has allowed the production of near-net shaped cutting tools, such as drills, milling cutters and form tools. The use of coatings, particularly titanium nitride, allows high-speed steel tools to cut faster and last longer. titanium nitride provides a high surface hardness, resists corrosion, and it minimizes friction.

In industry today, carbide tools have replaced high-speed steels in most applications. These carbide and coated carbide tools cut about 3 to 5 times faster than high-speed steels. Cemented carbide is a powder metal product consisting of fine carbide particles cemented together with a binder of cobalt. The major categories of hard carbide include tungsten carbide, titanium carbide, tantalum carbide, and niobium carbide.

Each type of carbide affects the cutting tool’s characteristics differently. For example, a higher tungsten content increases wear resistance, but reduces tool strength. A higher percentage of cobalt binder increases strength, but lowers the wear resistance.

Carbide is used in solid round tools or in the form of replaceable inserts. Every manufacturer of carbide tools offers a variety for specific applications. The proper choice can double tool life or double the cutting speed of the same tool. Shock-resistant types are used for interrupted cutting. Harder, chemically-stable types are required for high speed finishing of steel. More heat-resistant tools are needed for machining the super-alloys, like Inconel and Hastelloy.

There are no effective standards for choosing carbide grade specifications so it is necessary to rely on the carbide suppliers to recommend grades for given applications. Manufacturers do use an ANSI code to identify their proprietary carbide product line.

Two-thirds of all carbide tools are coated. Coated tools should be considered for most applications because of their longer life and faster machining. Coating broadens the applications of a specific carbide tool. These coatings are applied in multiple layers of under .001 of an inch thickness. The main carbide insert and cutting tool coating materials are titanium carbide, titanium nitride, aluminum oxide, and titanium carbonitride.

Ceramic cutting tools are harder and more heat-resistant than carbides, but more brittle. They are well suited for machining cast iron, hard steels, and the superalloys. Two types of ceramic cutting tools are available: the alumina-based and the silicon nitride-based ceramics.

The alumina-based ceramics are used for high speed semi- and final-finishing of ferrous and some non-ferrous materials. The silicon nitride-based ceramics are generally used for rougher and heavier machining of cast iron and the superalloys.
Cermet tools are produced from the materials used to coat the carbide varieties: titanium carbides and nitrides. They are especially useful in chemically reactive machining environments, for final finishing and some turning and milling operations.

Superhard tool materials are divided into two categories: cubic boron nitride, or "CBN", and polycrystalline diamond, or "PCD". Their cost can be 30 times that of a carbide insert, so their use is limited to well-chosen, cost effective applications. Cubic boron nitride is used for machining very hard ferrous materials such as steel dies, alloy steels and hard-facing materials. Polycrystalline diamond is used for non-ferrous machining and for machining abrasive materials such as glass and some plastics. In some high volume applications, polycrystalline diamond inserts have outlasted carbide inserts by up to 100 times. All cutting tools are “perishable,” meaning they have a finite working life. It is not a good practice to use worn, dull tools until they break. This is a safety hazard which creates scrap, impacts tool and part costs, and reduces productivity.

Review Questions

1. High-speed steel cuts faster than carbon steel by a factor of:
a. 2
b. 4
c. 8
d. 10

2. High tungsten content in a carbide tool will:
a. increase strength, but decrease wear-resistance
b. increase wear-resistance, but decrease tool strength
c. allow increased feed speeds while improving heat-resistance
d. improve the chemical-resistance of the tool

3. Inconel and Hastelloy require cutting tools that are:
a. tough
b. wear-resistant
c. heat-resistant
d. shock-resistant

4. Compared to carbide tools, ceramic cutting tools are very:
a. porous for cutting fluid retention
b. shock-resistant
c. resistant to wear
d. brittle

5. Polycrystalline diamond cutting tools can outlast regular carbide by a factor of:
a. 10
b. 20
c. 50
d. 100

6. For machining purposes, cast iron is considered:
a. abrasive
b. hard

c. brittle
d. soft

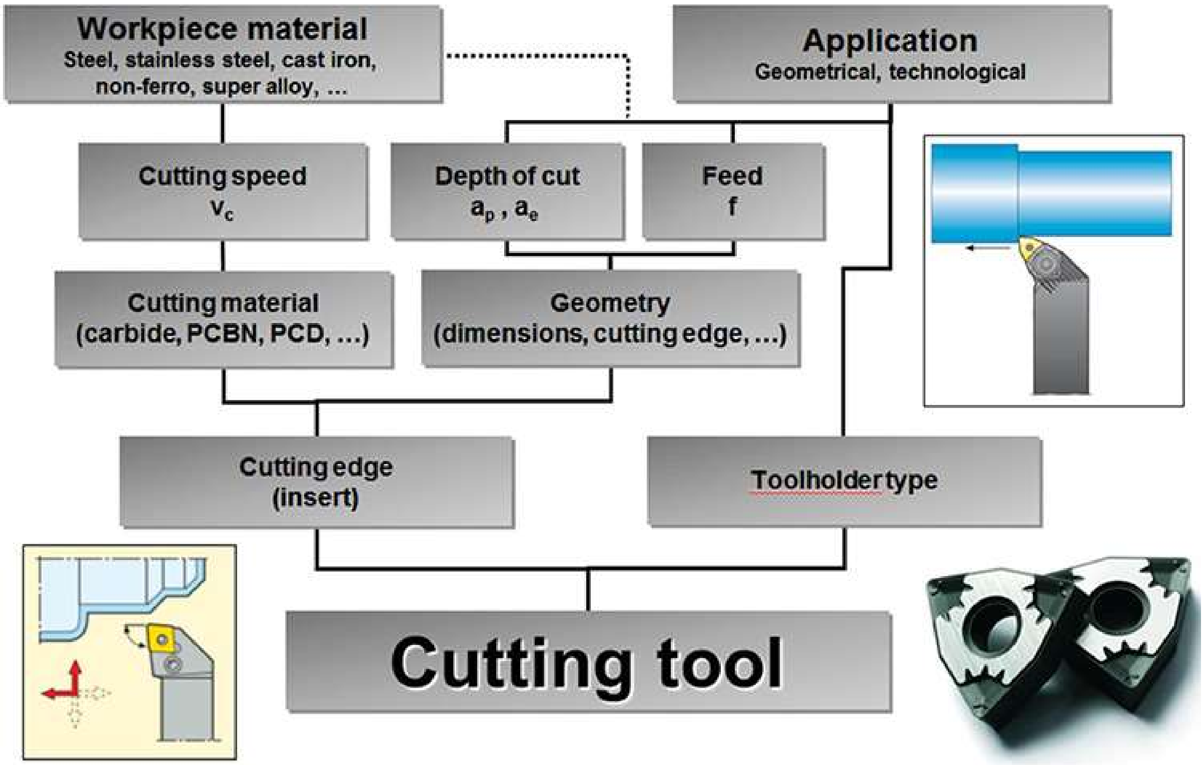
Answer Key-
1. b
2. b
3. c
4. d
5. d
6. a

Factor to choose before selecting cutting tool material

Cutting tools may not demand high investment in overall production process but it plays a vital role in productivity of the end product. Many people do not pay much attention in choosing right cutting tool and incur loss.

Things to consider before choosing the cutting tools

Cutting tools play an important role while defining a strategy for machining process. It becomes more important when all the new materials like Ni and Ti based alloys, composites and other difficult to cut materials are coming in. The right selection of cutting parameters, grades and geometries not only do the efficient machining, but also helps to maintain the geometrical tolerances of workpiece, improves productivity and maintains the cost per component ratio (*See picture below)*. The selection of right cutting tools is based on the material to machine, power available on machine, fixture stability, machine dynamics which leads to the right selection of cutting tool material, grades, geometries, depth of cuts and the feeds.



<u>Factors impact the productivity of the end product</u>

The selection of right strategy to machine the component/operation is the key to success. Rather than going for the conventional way of machining, adopting the right strategies that suits the application can improves the material removal rates. The other important factor is to maintain the average chip thickness ratio which improves the productivity in multiples. This can be done by selecting the right cutting speeds and feeds depending on radial engagement of the tool. One more important aspect is the know-how training for the effective utilization of the cutting tools and machining process.

What is cutting fluid?

For some machining operations including sawing, turning, processing, drilling and grinding, cutting fluids can be utilized to enable higher cutting speed to be utilized, to increase the cutting tool life, and, to some degree lessen the tool-work surface grating amid machining. The fluid is utilized as a coolant and furthermore greases up the cutting surfaces.

Most of the cutting fluids utilized are fluids as extended mineral oils or potentially manufactured fluids, which emulsify in water. These fluids can be connected as a pumped stream or through an oil mist with the help of compressed air. Various specific machining operations utilize infused gasses (compacted air or latent gasses). Strong or paste cutting substances are additionally utilized which incorporate greases, pastes, waxes, soaps, graphite based substances etc e.g tallow for tapping

What are the different types of cutting fluid?

Straight Cutting Oils

Straight Cutting Oils or Neat Oils are petroleum-based mineral oils augmented with “Extreme pressure” additives (EP additives). For purposes where the velocity of the tool is extremely low, depth of cut needed is high, cutting pressures are high; the primary role of coolant is to offer:

- Lubricity is provided by the mineral oil.
- Stop chip welding of the tool of edge build up.
- Sufficient lubricity so that resistance is reduced.
- Wash away the chips from the cutting zone.

Generally, EP used additives are sulfur and chlorine. These additives create a low shear force chloride or sulfide coating covering the tool rake preventing chip welding. Selection of one or both of these additives is dictated by the nature of the purpose and the material that is being manufactured.

- **Emulsifiable cutting oil**

Emulsifiable cutting fluids are likewise known as water-soluble oils, which isn’t right since oils don’t form genuine water solutions.

Emulsifiable cutting oils are mineral oil based and contain emulsifiers, EP, and different added substances. Emulsifiers diminish interfacial strain between oil droplets and water, giving stable finely scattered oil emulsion in water. Emulsifiable oils are blended with water in a concentration 2-10%.

Advantage	**Disadvantages**
Good lubrication, good cooling capability, some corrosion protection, low cost, non-flammable	Anti-bacteria additives, and maintenance are needed, toxic mist, susceptible to hard water (may form insoluble precipitates).

- **Synthetic cutting fluids**

Synthetic cutting oils are water-based solutions (or emulsions) of synthetic lubricants (soaps and other wetting agents), corrosion inhibitors, water softeners, EP, anti-bacteria additives (biocides), glycols and other additives.

Synthetic fluids are delivered in form of concentrates, which are mixed with water before use.

Advantages	**Disadvantages**
Very good cooling capability, good lubrication properties, good stability in hard water, good corrosion protection, low mist, easy handling, cleaning, and maintenance.	Toxicity, easily contaminated by foreign oils, relatively high cost.

Synthetic oils are used in an extensive range of cutting operations including poorly machinable heavy duty grinding, alloys and high-speed cutting.

- **Semi-synthetic metalworking fluids.**

Semi-synthetic fluids are a water-based mixture (solution and emulsion) of synthetic lubricants, additives, emulsifiers and some amount (2%-30%) of mineral oil.

Semi-synthetic fluids combine **advantages** (and **disadvantages** to some extent) of mineral emulsions and synthetic fluids.

They have enhanced corrosion protection that synthetic fluids and better cooling and wetting abilities, simpler handling and support than mineral emulsions.

Cutting Oil Applications

Cutting (metalworking) fluids are used in following metalworking operations:

Cutting (separation of metal from a workpiece in the form of chips)	Milling	Turning	Boring	Drilling

Broaching	Threading	Sawing	Abrading (rubbing away the surface by friction)	Grinding
Polishing	Lapping	Metal forming (changing the shape of a workpiece by a pressure)	Rolling	Forging
Extrusion	Deep drawing	Drawing	Stamping	

Various functions of cutting fluids are

1. Cutting fluid cools the work piece and tool by carrying away the heat generated during machining.
2. It acts as lubricant at the friction zones, hence tool life increases.
3. As friction get reduced, the forces and electricity power consumption decreases.
4. Using cutting fluids produces better surface finish to the work piece.
5. It causes to break the chips into small pieces.
6. It washes away the chips from the tool.
7. It prevents the corrosion of chips and machine.
8. Improves dimensional accuracy and control on the work piece.
9. It permits maximum cutting speed hence the time for machining reduce and cost of manufacturing increases.

Properties to be possessed by the cutting fluids are

1. Cutting fluids should have low viscosity to permit free flow of the liquid.
2. It should posses good lubricating properties.
3. It should have high specific heat, high heat conductivity and high heat transfer coefficient.
4. It should be non-corrosive to work and machine.
5. It should be non-toxic to operating person.
6. It should be odourless.
7. It should stable in use and storage.
8. It should be safe.
9. It should permit clear view of the work operation.

Most commonly used cutting fluids are

1. *Cast Iron:* No cutting fluids are used.
2. *Steels:* Lord oil with mineral oil is used.
3. *Alloy steel:* Sulphur brass oil with mineral oil is used.
4. *Copper:* Soluble oil with 90 to 95% of water is used.
5. *Aluminium:* Mineral oil with soluble oil cutting fluids are used as cutting fluids.

Cutting Fluid Functions

The main functions of cutting fluids are:

· **Lubrication** at low cutting speeds;

· **Cooling at high cutting speeds;**

And less important:

· **To help the chip removal of the cutting zone;**

· **To protect the machine tool and workpiece against corrosion.**

At low cutting speeds, cooling is not very important, while lubrication is important to reduce friction and avoid the formation of built-up-edge. In this case, an oil based fluid must be used. At high cutting speeds, the conditions are not favorable to fluid penetration, to reach the interface and work as a lubricant. In these conditions cooling becomes more important and a water based fluid must be used. As lubricant, the cutting fluid works to reduce the contact area between chip and tool and its efficiency depends on the ability of penetrating in the chip-tool interface and to create a thin layer in the short available time. This layer is created by either chemical reaction or physical adsorption and must have a shearing resistance lower than the resistance of the material in the interface. In this way it will also act indirectly as a coolant because it reduces heat generation and therefore cutting temperature.

As coolers, cutting fluids decrease cutting temperature through the heat dissipation (cooling) When water based fluids are used cooling is more important than lubrication. It was experimentally proved (Shaw, et al., 1951) that the cutting fluid efficiency in reducing temperature decreases with the increase of cutting speed and depth of cut.
The cutting fluid ability of sweeping the chips away from the cutting zone depends on its viscosity and its volume flow, besides, of course, the kind of machining operation and chip type formed. In some machining operations such as drilling and sawing, this function is very important, because it may avoid chip obstruction and, consequently, tool breakage.

Applications {Detailed Discription]
When a cutting fluid is applied, it may cause benefits, do not interfere or even be negative to harm the processes, depending on the cutting conditions, workpiece and tool material.

Applications Where Cutting Fluid Offers Benefits
Cutting with low strength tools, like high speed steels, demands the use of cutting fluid. This is due to the fact that the heat generated during cutting increases a lot the tool temperature, reducing its mechanical strength and, thus, making easier the occurrence of plastic deformation and complete failure. In this case, cutting fluids reduce the temperature, not allowing the tool to loose its strength and making possible the use of relatively high cutting speeds. Drilling, broaching, milling, threading with high speed steel tools are typical examples of these operations where the use of cutting fluids is essential.
Another important application of cutting fluid is in operations where low surface roughness and/or tight dimensional tolerances are required. In these cases, the lubricant guarantees a good surface finish and the cooling fluid guarantees the tight tolerances, because it avoid thermal expansion of the workpiece.
When drilling materials that generate discontinuous chips, like grey cast iron, cutting fluid application becomes fundamental, mainly in deep drilling. In this case, the main cutting fluid function is to carry the chips away from the cutting zone, what other wise could cause chip jamming and, consequently, a possible tool breakage.
It can be seen in below figure that when dry cutting is used tool life is much shorter than when any kind of cutting fluid is used.

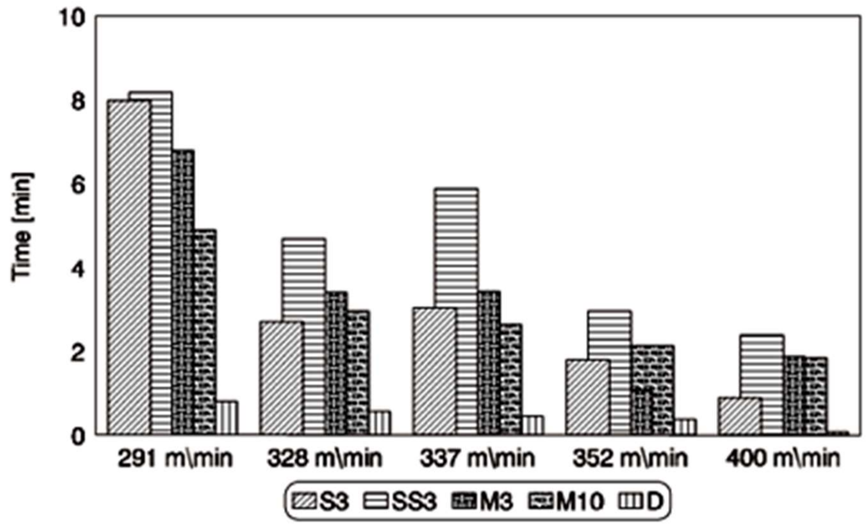


Figure 7. Tool Life Against Cutting Speed for several kinds of Cutting Fluids – Turning of AISI 8640 Steel with P35 Coated Carbide. S3 = Synthetic Fluid - 3%; SS3 = Semi-Synthetic 3%; M3 = Emulsion 3%; M10 = Emulsion 10%; D = Dry Cutting (Machado et al. 1997).

Applications Where Cutting Fluid Does Not Interfere in the Process

Actually cutting fluids always, in some way, interfere in the process. They may either pollute the work environment or impregnate workpiece and machine components, what may cause the washing of the machined parts necessary. However, in terms of tool life, there are some applications where cutting fluid either do not contribute or contribute just marginally for the efficiency of the process. Typical examples are the machining of grey cast iron (exception is deep drilling), magnesium and aluminum alloys. Other examples are the machining of plastic materials or resins. The machining of these kinds of materials depends strongly on how abrasive the material is, and therefore, it is impossible to affirm whether cutting fluids interfere or not in the process.

In machining of grey cast iron, cutting fluid may increase tool life, mainly in the cases where diffusion

When machining magnesium and aluminum alloys, dry cutting is also very common. These materials have high machinability, because they have low melting point (650°C and 659°C, respectively). The exceptions are some aluminum-silicon alloys. In the hypereutetics alloys (Si above 11%) Si is in the form of hard particles (> 400 HV), abrasive and with high melting point (~1420°C) in the aluminum matrix. These large particles of Si (average diameter up to 70 mm) generate high tension and temperature on the tool faces causing rapid tool wear. In such cases, the flood application of an emulsion or synthetic fluid is fundamental to reduce the wear. Another alternative that will be treated in detail later is the application of minimum quantity of fluid (MQF). This may be sufficient to prevent accelerated tool wear.

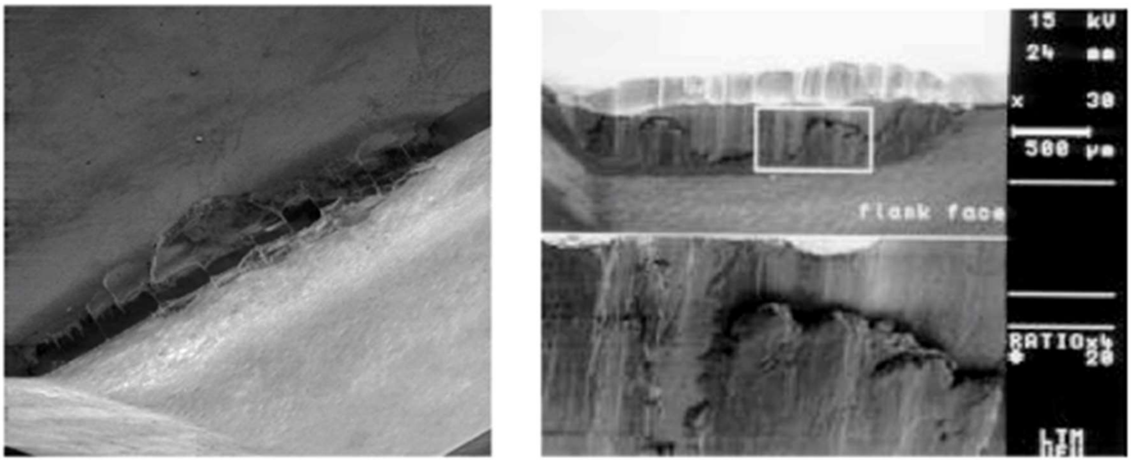
Another exception to the use of dry cutting when machining aluminum alloy is in drilling operations. In this case, the chips tend to stick on the tool and make difficult the evacuation of them, what can cause drill breakage. Therefore, in this case an abundant volume of cutting fluid or even MQF must be used. In other operations, in general, dry cutting is recommended, unless tight dimensional tolerances and low surface roughness are required. Due to the high ductility of the material, it tends to stick on the tool, producing poor surface roughness. They also have high thermal expansion coefficient, causing the obtaintion of high tolerances difficult. In these cases application of cutting fluids acting both as a lubricant and as a coolant will contribute to reduce the inherent problems.

When machining magnesium, more serious problems may occur when water based fluids are applied, because water reacts with the chips, releasing hydrogen, which may cause ignition and fire hazards.

Applications Where Cutting Fluid Is Negative to the Process

There are typical examples where cutting fluid application harm the harms process and, therefore, it must not be used.

Generally, machining with ceramic tools must be performed without fluid, because it may promote thermal shocks and, eventually, cause tool breakage. Some ceramic tools, mainly those based on Si_3N_4 and the *"whiskers"*, because they have higher toughness and thermal shock resistance, can avoid this kind of failure and, so, allow some advantages when cutting fluid is applied.
Other examples of dry machining are interrupted cuttings (like milling) with carbide tools, where the main kind of wear are cracks of thermal origin that leads to the formation comb of cracks. In such cases, cracks of thermal origin, transversal to the tool cutting edge appear just after a few minutes of cut. They look like those seen in Figure. They are originated by the cyclic variation of the temperature, due to the interrupted nature of cutting. The cutting edge is heated during the cutting period and cooled during the idle period. These cracks, as cutting goes on, will increase and propagate, leading to the formation of comb cracking type of wear. Figure illustrates the comb cracks in a worn tool at the end of its tool life.



a) b)

Figure 8. a) Thermal cracks; b) Comb cracks in carbide tools used in milling (De Melo et al., 2000 and Vieira et al., 1997).

When this kind of wear is dominant, cutting fluid application will increase even more the temperature variation and accelerate the process of crack generation, decreasing tool lives.

Machining of hardened materials is another typical example where cutting fluid can be detrimental to the process. Cutting fluid should work just as a coolant for the tool, but the regular process of application makes the fluid to reach all chip formation zones, cooling also the workpiece. Therefore, the softening effect caused by the large amount of heat generated is not substantial, requiring higher amount of energy to shear the material and to form the chip, demanding high cutting forces and generating high temperatures in the chip-tool interface. Due to the high hardness of this kind of materials (usually higher than 30 HRc), softening caused by the process of heat generation is fundamental to increase the performance of the process. Cutting fluid hinders this and will be negative to the process. Teixeira et al. (2000) turned 52100 steel with 60 HRc of hardness using PCBN tools under several cutting speeds and using three types of cooling system: dry cut, minimum quantity of fluid (10 ml/h) and flood application of a soluble oil. The main conclusions of their work are: a) dry cutting presented the best performance related too tool life; b) flood application, besides presenting a shorter tool life, caused a poorer workpiece surface roughness; c) MQF condition presented an intermediary performance between dry cutting and cutting with emulsion.

Application of Minimun Quantity of Fluid (MQF)
The choice of a cutting fluid and its method of application depend on important points such as cost (not just costs of acquisition, but also costs of recycling and maintenance), environmental effects and influence on human health. These points are becoming more and more important as the law restrictions on environmental issues become more strong. An alternative for the use of flood of cutting

fluid is the application of a mist of oil or minimum quantity of fluid (MQF), as is being coined among the scientists. Actually this technique consists of a mixture of drops of cutting fluids (neat oils or emulsions) in a flow of compressed air, generating an *"spray"* which is directed to the cutting region to work as lubricant and coolant.

The MQF technique decreases feed and cutting forces when machining medium carbon steel with low cutting speeds, mainly for feeds higher than 0,25 mm/rev, as can be seen in Figure (Machado and Wallbank, 1997). In these conditions the values of forces obtained with the mist system were even lower than those obtained with the application of an emulsion using conventional method (overhead flood). For these experiments, a venturi was designed and both water and soluble oil was mixed with air at flows of 294 ml/h and 196 ml/h respectively.

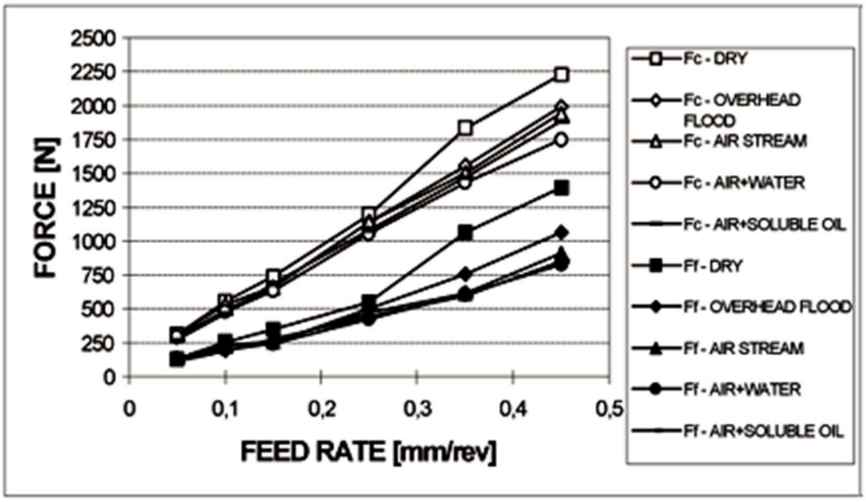


Figure 10. Feed and cutting forces against feed for several kinds of cooling/lubrication systems - vc = 30 m/min (Machado and Wallbank, 1997).

In these experiments the authors also found little reduction on surface roughness parameter (R_a) and on chip thickness when MQF was used, compared with dry cutting and flood of cutting fluid. **See Figure-**

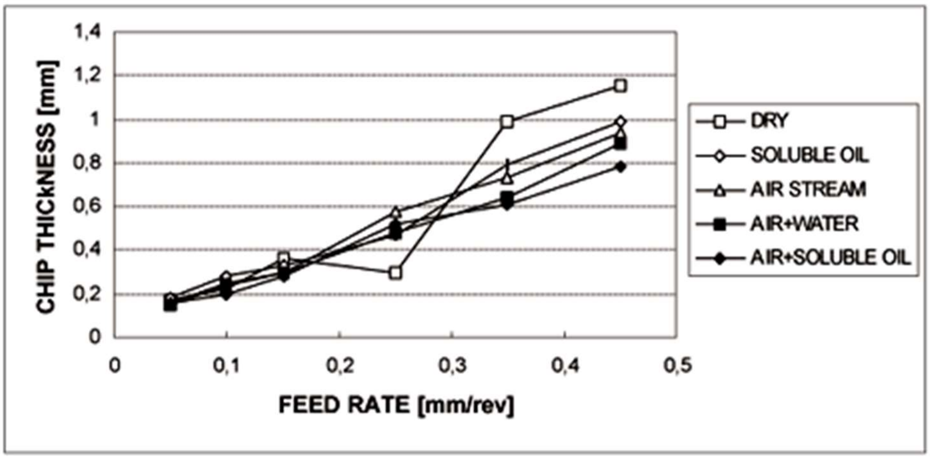


Figure 11. Chip thickness against feed rate when machining AISI 1045 steel; vc = 30 m/min (Machado e Wallbank, 1997).

Braga et al. (1999a and b) tested the use of several cooling/lubrication systems in drilling of an aluminum-silicon alloy (7.5% of silicon), using solid carbide drills with and without PCD coating.

These systems were: dry cutting, cooling just with dry compressed air, MQF with oil flow of 10, 30 e 60 ml/h and overhead flood of soluble oil.

The main conclusions of the work were:
a) it is impossible to carry out the operation with either dry cutting or pure dry compressed air, because the chip sticks to the spiral channels of the drill, causing its breakage after few holes. The use of MQF makes the operation feasible, and the increase of oil flow in the mixture (from 10 to 60 ml/h) does not make the process performance better;
b) comparing MQF with 10 ml/h and flood of soluble oil, it can be verified that both cooling systems generate holes with similar qualities (roughness, roundness, diameter accuracy and cylindricity). Drilling with both systems also presented, in the majority of the experiments, similar values of tool life and cutting forces;
c) based on these results, the authors concluded that it is not necessary too much cooling (which can be achieved when high amount of cutting fluid is used) for drilling this alloy and to efficiently lubricate the process it is not necessary a large volume of oil.

To contribute further with the discussion of using or not MQF, some points must be raised.
They are:
Environmental Pollution – The substitution of abundant oil by MQF is based, among other factors, on environmental issues. But it must be remembered that even MQF causes pollution, because the pulverization of oil in the air flow causes the suspension of a lot of oil particles on the air, which also demands some requirements of the system, like a machine completely encapsulated with protection guards and a good exhaustion system with particle control. According to Heisel et al., (1998) the size and kind of particles (steam, mist or oil smoke) are important information for this particle control.
Consumption – The application of mist frequently is made with total loss of the cutting fluid used. Even with low oil flow (< 50 ml/h) the fluid consumption must be calculated and considered. Just as an example, if we had a flow of neat oil of about 10 ml/h, with a continuous use of 8 h/day (considering just one work shift per day), we would have, at the end of the day, 80 ml of consume. At the end of the month (with 22 days of work) 1760 ml of fluid would be consumed. In three months more than 5 liters of fluid would be pulverized. Some synthetic fluids at a concentration of 5% may have lower consumption than that. Considering a machine tank of 60 liters it would demand 3,15 liters of fluid to have this concentration. These products may have a continuous use with a life longer than six months. Even considering possible losses, the consumption of this product in this period could be lower than when pulverization is used.
Noise – A line of compressed air must be used for MQF, which works intermittently during the whole process. These air lines make a lot of noise, usually higher than what human ear can support (< 80 dB). Besides this damage to human health it makes the communication more difficult, what is also bad for the environment.
Actually, the attempt of using MQF for machining may be considered an intermediary situation between the conventional use of fluid and the dry cutting. But the results published up to now does not allow to conclude that this procedure can be widely used in the industry.
To avoid all this problems, the ideal situation is the dry cut, called by some researchers ecological machining. A lot have been done lately on this subject. Some experts (Batzer e Sutherland, 1998 e Graham, 2000) states that either when cutting fluid application is not clearly cheaper or when technical reasons demands its application, the ecological issues should be priority. Moreover, as already stated, there are some cases where dry cutting is economically advantageous.