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TOOL WEAR MECHANISMS IN METAL CUTTING - A REVIEW

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Abstract: Functional requirements of a product driven by customer leads to the introduction of new materials and manufacturing processes. Development of machining processes i.e. macro and micro are progressing effectively. In order to achieve successive products by conventional machining the consideration of machine tools should be focused. In this paper an overview of tool wear mechanisms, effects of wear on machinability criteria, measurement of tool wear, selection of the tool material & tool geometry is discussed. It can be concluded that combination of tool and workpiece materials, machining parameters such as spindle speed, feed and depth of cut, tool geometry, tool coatings and coolants selection plays major role in conventional machining.

***Index Terms* - Component, formatting, style, styling, insert.**

I. INTRODUCTION

A machine tool is a power-driven device in which energy is utilized in deformation of material for shipping, sizing or processing a product to a desired accuracy by removing the excess material in the form of chips as well as wearing its own material in the cutting process. Wear is defined as a process where interaction between surfaces or bounding faces of solids within the working environment results in dimensional loss of one solid, with or without any actual decoupling and loss of material or more specifically the removal and deformation of material on a surface as a result of mechanical action of the opposite surface. In materials science, wear is erosion or sideways displacement of material from its derivative and original position on a solid surface performed by the action of another surface.

Wear is a very complex phenomenon and is influenced by many factors. The causes of wear do not always behave in the same manner nor do they always effect wear to the same degree in similar cutting conditions. In recent year's great strides have been made by various researchers. For the purpose of controlling tool wear one must understand the various mechanisms of wear that the cutting tool undergoes under different conditions. Even though there is some disagreement regarding the true mechanism by which wear actually takes place, most investigators feel that common mechanisms of cutting tool wear are: [1-10]

i) Mechanical wear.
- Thermally insensitive type; like abrasion (abrasive action of hard particles contained in the work material), chipping and delamination.
- Thermally sensitive type; like adhesion, fracturing, flaking etc.

ii) Thermochemical wear.
  - Macro-diffusion by mass dissolution.
  - Micro-diffusion by atomic migration.

iii) Chemical wear.

iv) Galvanic wear.

Chemical Wear: Chemical wear, leading to damages like grooving wear may occur if the tool material is not enough chemically stable against the work material and/or the atmospheric gases.

Galvanic wear: Galvanic wear is based on electrochemical dissolution, seldom occurs when the work tool materials are electrically conductive, cutting zone temperature is high and the cutting fluid acts as an electrolyte.

Mechanical and thermochemical wear has been explained below in detail.

The fundamental nature of the mechanism of wear can be very different under different conditions. In metal cutting, three main forms of wear are known to occur: adhesion, abrasion and diffusion wear.

• ***Adhesion Wear:*** The wear is caused by the fracture of welded asperity junctions between the two metals. In metal cutting, junctions between the chip and tool materials are formed as part of the friction mechanism; when these junctions are fractured, small fragments of tool material can be torn out and carried away on the underside of the chip or on the new workpiece surface. The conditions that exist in metal cutting are well suited to adhesive wear as new material surfaces uncontaminated with oxide films are continually produced, and this facilitates the formation of welded asperity junctions.

• ***Abrasion Wear:*** The Wear is caused when hard particles on the underside of the chip pass over the tool face and remove tool material by mechanical action due to the high localized contact stresses. These hard particles may be highly strain-hardened fragments of an unstable built-up edge, fragments of the hard tool material removed by adhesion wear, or hard constituents in the work material, including oxide scales on the work surface.

• ***Diffusion Wear:*** Solid–state diffusion occurs when atoms in a metallic crystal lattice move from a region of high atomic concentration to one of low concentration. This process is dependent on the existing temperature, and the rate of diffusion increases exponentially with increases in temperature. In metal cutting, where intimate contact between the tool and work materials ensues then high temperatures and contact pressures exists, diffusion can occur where atoms move from the tool material to the work material, typically at an area on the tool tip that corresponds to the location of maximum temperature e.g., cemented carbide tools used to machine steel. This process, which takes place within a very narrow reaction zone at the interface between the two materials and causes a weakening of the surface structure of the tool, is known as diffusion wear. High–speed machining results in higher chip temperatures, making this an increasingly important wear mode.

From the above three main forms of wear it has been classified into following wear mechanisms as described and shown in figure 1 [1-10].

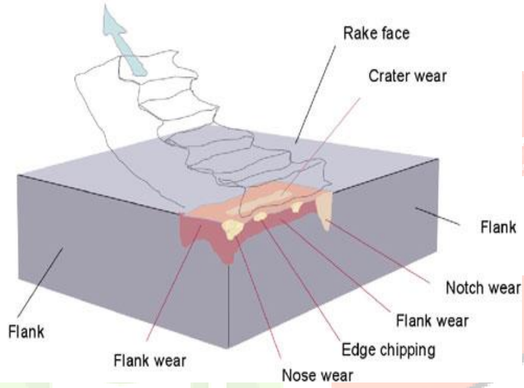


Figure 1. Different Wear Mechanisms on Tool Insert [10].

• ***Crater Wear:*** As shown in figure 2, wear on the tool face is characterized by the formation of a crater and resulting from the action of the chip flowing along the face. The crater formed on the tool face conforms to the shape of the chip underside and is restricted to the chip-tool contact area. In additions, the region adjacent to the cutting edge where sticking friction or a built-up edge occurs is subjected to relatively slight wear. In metal cutting, highest temperatures occur some distance along the tool face, at high cutting speeds these temperatures can easily reach the order of 1000°C or more. Under these high-temperature conditions, tools wear very rapidly because of thermal softening of the tool material. Although the tool materials retain their hardness at these high temperatures, solid state diffusion can cause rapid wear. Under very high-speed cutting conditions, crater wear is often the factor that determines the life of the cutting tool. In high-speed cutting conditions cratering becomes so severe that the tool edge is weakened and eventually fractures. However, when tools are used under economic conditions, the wear of the tool on its flank, known as flank wear, is usually the controlling factor.

Figure 2. Crater Wear [10]

• ***Flank Wear***: Wear on the flank where a wear land is formed as shown in figure 3 from the rubbing action of the newly generated workpiece surface. Wear on the flank of a cutting tool is caused by friction between the newly machined workpiece surface and the contact area on the tool flank. Because of the rigidity of workpiece, the worn area, referred to as the flank wear land, must be parallel to the resultant cutting direction. The width of the wear land is usually taken as a measure of the amount of wear and can be readily determined by means of a toolmaker's microscope.

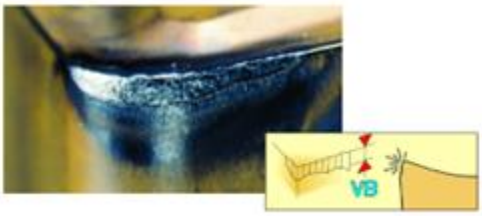


Figure 3: Flank Wear [10].

- ***Notch Wear:*** Insert wear characterized by excessive localized damage on both the rake face and flank of the insert at the depth of cut line, caused by adhesion (pressure welding of chips) and a deformation hardened surface as shown in figure 4.

Figure 4. Notch Wear [10].

- ***Built-Up Edge (BUE):*** Figure 5 shows the BUE which is caused by pressure welding of the chip to the insert. It is most common when machining sticky materials. Low cutting speed increases the formation of built-up edge.

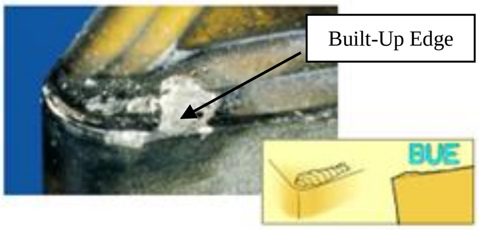


Figure 5. Built-Up Edge (BUE) [10].

- ***Edge chipping/breakage***: Chipping or breakage is the result of an overload of mechanical tensile stresses as shown in figure 6. These stresses can be due to a number of reasons, such as chip hammering, a depth of cut or feed that is too high, sand inclusions in the workpiece material, built-up edge, vibrations or excessive wear on the insert.

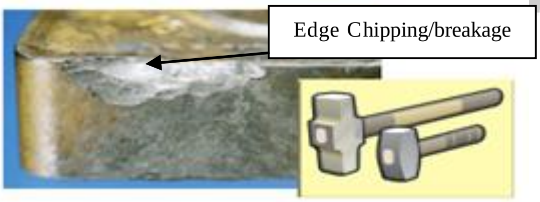


Figure 6: Edge chipping/breakage [10].

- ***Thermal Cracks:*** When the temperature at the cutting edge changes rapidly from hot to cold, multiple cracks may appear perpendicular to the cutting edge as shown in figure 7. Thermal cracks are related to interrupted cuts, common in milling operations, and are aggravated by the use of coolant.

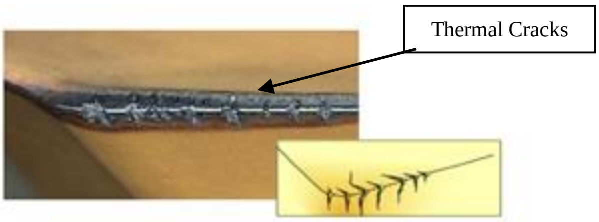


Figure 7: Thermal Cracks [10].

- ***Plastic deformation:*** Plastic deformation takes place when the tool material is softened. This occurs when the cutting temperature is too high for a certain grade as shown in figure 8. In general, harder grades and thicker coatings improve resistance to plastic deformation wear.

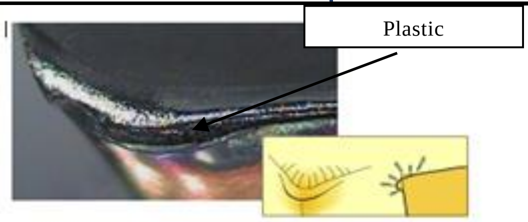


Figure 8. Plastic deformation [10].

- ***Brittle fracture:*** Catastrophic failure of the tool can occur if the tool is overloaded by an excessive depth of cut and/or feed rate as shown in figure 9.

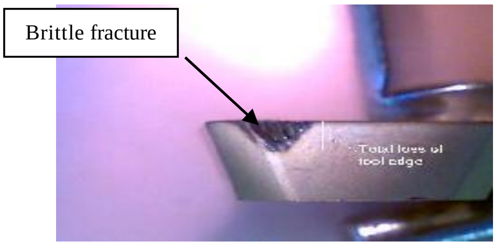


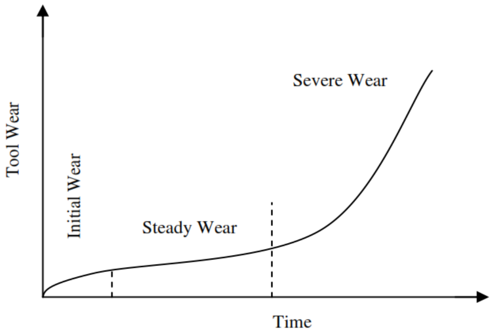
Figure 9. Brittle fracture [10].

- ***Electrochemical:*** In the presence of a cutting fluid, an electrochemical reaction can occur between the tool and the workpiece, resulting in the loss of a small amount of tool material in every chip [1-10].

II. EFFECTS OF WEAR ON MACHINABILITY CRITERIA

Machinability is defined in terms of total tool life, power requirements, and resultant workpiece surface finish. Machining is important in manufacturing because it is capable of creating geometric configurations, tolerances, and surface finishes that are often unobtainable by other methods. The shape of the final machined product is programmed and therefore many different parts can be made on the same machine tool and just about any arbitrary shape can be machined. In machining, the product contour is created by the path, rather than the shape, of the cutter.

The study of machinability involves certain criteria which play a prominent part in the valuation of the cutting process. Machinability ratings for a given material are entirely relative in that only one material is used as a base. The ratings can vary not only among the machining processes, but also with the criterion used in the evaluation for a given process. Many of the available data, particularly w.r.t cutting forces, specific power requirements and surface quality are based upon the results of sharp tool investigations. These investigations serve a valuable purpose in analysis of the cutting process and in determination of initial levels of performance, but they give no indication as to how long the initial level of performance will be maintained when tools begin to wear. From figure 10 which shows Tool Wear Vs. Time, it is clearly seen that as the cutting process starts the initial wear begins upto certain amount of period then gradually remains constant wear to certain amount of time after which severe wear forms leading to complete tool wear or end of tool life.



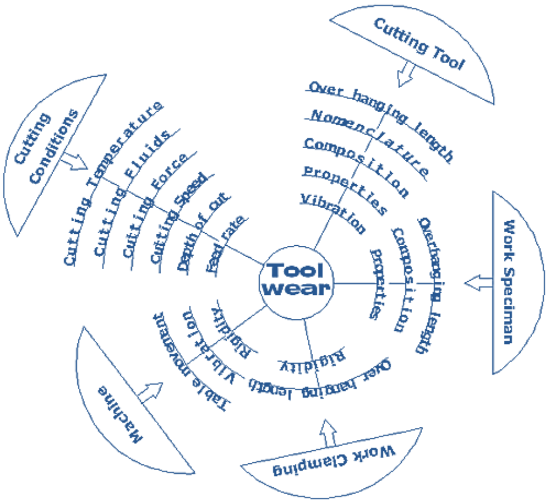


Figure 11. Causes of Tool Wear [1-8].

The figure 11 presents the causes of tool wear, if work specimen and work clamping are considered then the quality of a machined surface, over hanging length, composition, properties, and rigidity are used to denote tool wear or failure of any tool material. From the same figure 11, if cutting tool and cutting conditions are considered then cutting temperature, cutting fluids, cutting force, cutting speed, depth of cut, feed rate, over hanging length, composition, properties, nomenclature, vibration or deflection are used to denote tool wear or failure of any tool material. From the figure 11, machine vibration, rigidity and unwanted table movements are considered to denote tool wear or failure of any tool material.

The most important factor influencing tool wear is cutting temperature. Cutting temperatures are important for two basic reasons: (1) most tool materials show rapid loss of strength, hardness and resistance to abrasion above some critical temperature and (2) the rate of diffusion between work and tool material rises very rapidly as temperature increases past the critical.
Tool wear has a definite effect upon cutting forces; the ratio of increase can be beyond expectation. Cutting tools are subjected to large forces under conditions of high temperature and stresses. Mechanical forces are imposed on the workpiece by the application of a tool with sharp edges and higher hardness than the workpiece to avoid tool wear. However, many new materials are either harder than conventional cutting tools or cannot withstand the high cutting forces involved in traditional machining. The plastic deformation and friction inherent in machining generate considerable heat which raises the temperature of the tool and lowers wear resistance. The dominating physical mechanism at the tool/workpiece interface in conventional machining is either plastic deformation or controlled fracture of the workpiece. Because of clearances in machine tool assemblies, the typical force - deflection exists such as for small change in force can result in a rather large deflection. As the play between parts is taken up and elastic resistance increases, a comparable change in force results in a smaller deflection of the tool [1-10].

The effects of the manipulating factors upon tool wear are concerned either with modifications that influence the cutting process directly for a given tool and workpiece material or with inherent properties of materials that resist or promote wear. For a given tool and workpiece material combination, cutting temperatures are influenced most by cutting speed and feed. Adjustments in speed or feed, or both will effect tool wear, it may be possible to substitute another tool material that has inherently better temperature resistant properties to maintain original or even higher production rates with less sensitivity to temperature failure. The cost of the second material may be higher than that of the first, but it may be more than justified by higher production rates for optimum tool Life. Changes in tool geometry that result in higher shear angles, less chip distortion, lower frictional resistance and thinner chips will lower cutting forces and decrease cutting temperatures, and thus contribute to decrease the rate of tool wear for given cutting coniditions. Within practical and design limitations, rake, relief, and side cutting edge angles and nose radii, are their equivalence, should be as large as possible, yet small enough to prevent mechanical tool breakage and chatter. Heat transfer characteristcs may also be adversely effected if the point of the tool is too thin as a result of high relief and rake angles. The heat at the point does not dissipate as rapidly and higher temperatures prevail.

Workpiece materials that have relatively high hardness, high shear strength, high coefficient of friction and high work-hardening capacities and contain hard constituents promote more rapid wear for given cutting conditions. Materials such as Titanium or Stainless steels, which have poor thermal conductivity, do not dissipate heat from the cutting zone as rapidly as others, and tempeature failures are more pronounced [11-20].

III. SELECTION OF THE TOOL MATERIAL & TOOL GEOMETRY:

Machine tools can be grouped into two broad categories:
- Those that generate surfaces of rotation
- Those that generate flat or contoured surfaces by linear motion.

Selection of equipment and machining procedures depends largely on these considerations:
Size of workpiece, configuration of workpiece, equipment capacity (speed, feed, horsepower range), dimensional accuracy, number of operations, required surface condition and product quality.

Process Kinematics in Traditional Machining: In all traditional machining processes, the surface is created by providing suitable relative motion between the cutting tool and the workpiece. There are two basic components of relative motion: primary motion and feed motion. Primary motion is the main motion provided by a machine tool to cause relative motion between the tool and workpiece. The feed motion, or the secondary motion, is a motion that, when added to the primary motion, leads to a repeated or continuous chip removal. The two motion components often take place simultaneously in orthogonal directions. The functional definitions of turning, milling, drilling, and grinding are not distinctively different, but machining process specialists have developed terminology peculiar to a given combination of functions or machine configurations. Commonly used metal–cutting machine tools, however, can be divided into three groups depending upon the basic type of cutter used: single–point tools, multipoint tools, or abrasive grits.

Dynamic Stability and Chatter: One of the important considerations in selecting a machine tool is its vibrational stability. In metal cutting, there is a possibility for the cutter to move in and out of the workpiece at frequency and amplitude that cause excessive variations of the cutting force, resulting in poor surface quality and reduced life of the cutting tool.

***Forced vibrations*:** During cutting these are associated with periodic forces resulting from the unbalance of rotating parts, from errors of accuracy in some driving components, or simply from the intermittent engagement of workpiece with multipoint cutters. Self–excited vibrations occur under conditions generally associated with an increase in machining rate. These vibrations are often referred to as chatter.

Basic Machine Tool Components: Advances in machine–tool design and fabrication philosophy are quickly eliminating the differences between machine types. The addition of automatic turrets, tool–changers, and computerized numerical control (CNC) systems allowed lathes to become turning centers and milling machines to become machining centers.

Machine tool frame: This supports all the active and passive components of the tool — spindles, table, and controls. Factors governing the choice of frame materials are: resistance to deformation (hardness), resistance to impact and fracture (toughness), limited expansion under heat (coefficient of thermal expansion), high absorption of vibrations (damping), resistance to shop–floor environment (corrosion resistance), and low cost.

Guide ways: They carry the workpiece table or spindles. Each type of way consists of a slide moving along a track in the frame. The slide carries the workpiece table or a spindle. The oldest and simplest way is the box way. As a result of its large contact area, it has high stiffness, good damping characteristics, and high resistance to cutting forces and shock loads. Box slides can experience stick–slip motion as a result of the difference between dynamic and static friction coefficients in the ways. This condition introduces positioning and feed motion errors. A linear way also consists of a rail and a slide, but it uses a rolling– element bearing, eliminating stick–slip. Linear ways are lighter in weight and operate with less friction, so they can be positioned faster with less energy. However, they are less robust because of the limited surface contact area

Slides: These are moved by hydraulics, rack–and–pinion systems, or screws. Hydraulic pistons are the least costly, most powerful, most difficult to maintain, and the least accurate option. Heat buildup often significantly reduces accuracy in these systems

***Electric motors*:** These are the prime movers for most machine tool functions. They are made in a variety of types to serve three general machine tool needs: spindle power, slide drives, and auxiliary power. Most of them use three–phase AC power supplied at 220 or 440 V. The spindle delivers torque to the cutting tool, so its precision is essential to machine tool operation. The key factors influencing precision are bearing type and placement, lubrication, and cooling.
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. Cutting tool materials are continuously being improved either by conventional way or powder metallurgy based. 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.

The different available cutting tool materials are as follows:Cast cobalt alloys: Cast Cobalt alloys popularly known as Stellite tools, were introduced in 1915. These alloys have 38 to 53% cobalt, 30 to 33% chromium, and 10 to 20% tungsten. Though comparable in room temperature hardness to HSS tools, cast cobalt alloy tools retain their hardness to a much higher temperature, and they can be used at 25% higher cutting speeds than HSS tools.

Cemented carbides: They are much harder, but more brittle and less tough. The first widely used cemented carbide was tungsten carbide (WC) cemented in a ductile cobalt binder. Most carbide tools in use now are a variation of the basic WC–Co material. For instance, WC may be present as single crystals or a solid solution mixture of WC–TiC or WC–TiC–TaC. These solid solution mixtures have a greater chemical stability in the cutting of steel. In general, cemented carbides are good for continuous roughing on rigid machines, but should avoid shallow cuts, interrupted cuts, and less rigid machines because of likely chipping.

Ceramic tools: These tools used for machining are based on alumina (Al_2O_3) or silicon nitride (Si_3N_4). They can be used for high–speed finishing operations and for machining of difficult–to–machine advanced materials, such as super alloys. The alumina–based materials contain particles of titanium carbide, zirconia, or silicon carbide whiskers to improve hardness and/or toughness. Silicon nitride–based materials have excellent high–temperature mechanical properties and resistance to oxidation. These materials also have high thermal shock resistance, and thus can be used with cutting fluids to produce better surface finishes than the alumina tools. These tools can be operated at two to three times the cutting speeds of tungsten carbide, usually require no coolant, and have about the same tool life at higher speeds as tungsten carbide does at lower speeds. However, ceramics lack toughness; therefore, interrupted cuts and intermittent application of coolants can lead to premature tool failure due to poor mechanical and thermal shock resistance.

Cermets: These are titanium carbide (TiC) or titanium carbo-nitride particles embedded in a nickel or nickel/molybdenum binder. These materials, produced by the powder metallurgy process, can be considered as a type of cemented carbide. They are somewhat more wear resistant, and thus can be used for higher cutting speeds. They also can be used for machining of ferrous materials without requiring a protective coating.

Cubic boron nitride (CBN): It is the hardest material at present available except for diamond. Its cost is somewhat higher than either carbide or ceramic tools but it can cut about five times as fast as carbide and can hold hardness up to 200°C. It is chemically very stable and can be used to machine ferrous materials.

Diamonds: Industrial Diamonds are now available in the form of polycrystalline compacts for the machining of metals and plastics with greatly reduced cutting force, high hardness, good thermal conductivity, small cutting edge radius, and low friction. Recently, diamond–coated tools are becoming available that promise longer life cutting edges. Shortcomings with diamond tools are brittleness, cost, and the tendency to interact chemically with workpiece materials that form carbides, such as carbon steel, titanium, and nickel.

IV. Effect of Tool Geometry & Machining Parameters:

The size and shape of a tool used for material removal on workpiece in order to have required size and shape is known as tool geometry. Chip formation takes place in metal cutting which is purely dependent on tool geometry. Tool geometry is essential in order to cut the different work materials according to the required shapes giving higher productivity within a less time. In attaining these requirements tool geometry plays the key role for having a better tool life, as the cutting forces, tool defection and vibrations comes into play at tool-workpiece location. According to the specific machining operation such as face milling in which tool geometry differs for contouring, roughing, finishing and semi-finishing having the round, square, rhombus, triangular, pentagonal, hexagonal, heptagonal and octagonal. High spindle speed with low depth of cut and low feed rate gives good surface finish. High feed rate and depth of cut leads to tool fracture and high surface roughness formation. Based on the product delivery time and product application, the machining parameters, coolant selection, type of tools to be used has to be judged by firm's capabilities. In bio medical and aerospace application parts, dry machining is preferred by researchers and as well as if environmental pollution control is considered then coolants usage is reduced or replaced with advanced coolants like nano particles introduced in the coolant [1-20].

V. Measurement of Tool Wear:

Tool wear measurement is essential in metal cutting process to decide whether surface finish produced on work material is of standard or not. In macro machining, tool edge reaching 0.3 mm is considered as the standard in rejecting the tool for further machining. In micro machining, the macro machining approach does not work out as the tool and work material parts size limitation.

The various methods of measurement 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. When flank wear reaches 0.3 microns on the tool insert then it is said to be worn out.
iv) Using scanning electron microscope (SEM) – used generally, for detailed study; both qualitative and quantitative.
v) Talysurf method, especially for shallow crater wear [1-20].

VI. CONCLUSIONS:

The selection of cutting tool materials is one of the key factors in determining the effectiveness of the machining process. During metal cutting, the tool usually experiences high temperatures, high stresses, rubbing friction, sudden impact, and vibrations. Therefore, the two important issues in the selection of cutting tool materials are hardness and toughness. Hardness and toughness do not generally increase together, and thus the selection of cutting tool often involves a trade–off between these two characteristics. For highest efficiency in removing metal considering surface finish while minimizing chatter conditions, the optimum feed per tooth should be considered. The optimum feed rate is influenced by a number of factors: type of cutter, number of teeth on the cutter, cutter material, workpiece machinability, depth of cut, width of cut, speed, rigidity of the setup, and machine power. It can be concluded that combination of tool and workpiece materials, machining parameters such as spindle speed, feed and depth of cut, tool geometry, tool coatings and coolants selection plays major role in conventional machining.

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