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Introduction

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Diamond is a transparent solid made mostly of one kind of atom, carbon. It serves mankind in two very different ways - as a gem stone and as an industrial tool. Diamond is often regarded as the most beautiful of all gems and it is the hardest of all materials.

One of the basic factors which lifts diamond, both as a gem and as a cutting tool , far above all other crystalline materials is its extreme hardness. This is obviously the primary reason why diamond is so valuable as an industrial tool. The same property of hardness, combined of course with its optical properties which produce luster, makes it supreme as a gem stone. Other minerals such as zircon and topaz also show a very high brilliance, but the lack of hardness makes them inferior as gem stones.

Diamonds, once regarded as rare and extraordinary-are now of everyday use in many parts of the world. They are used in grinding wheels to sharpen tools or to precisely machine materials. Diamond tools are found to be very efficient for grinding and shaping hard metal carbides, ceramics, plastics, crystals and other hard and abrasive materials. Diamonds are also used in drill crowns for the production of long holes, for sampling and prospecting purposes. Of late, diamond tools have been used in the manufacture of micron-sized features in applications such as - micro heat exchangers, microshafts, micromirrors, microreactors and others.

A Brief History of Diamond Machining [38]

Diamond has been valued as a gem for many years. As a cutting tool it was apparently first used in 1779 for cutting hardened steel threads. The significance of diamond tools in precision machining was realized in the 1850's . A diamond pointed pantograph made in the 1850's was reported to be able to engrave legible characters 2.5 :m high. The Lord=s prayer was reportedly engraved into an area 100 x 40 :m by 1920. By 1926, it was claimed that 80 Abibles per square inch@ could be engraved (3,556,480 letters/bible). These are dimensions requiring a scanning electron microscope, which was not developed until decades later. The outstanding importance of diamond as a tool capable of cutting the hardest metal alloys and the most abrasive materials was first appreciated in the period between the world wars. The full importance of this technical advance was realized during the second world war. By the 1960's diamond machining was pervasive at government research labs and was moving into the optics industries.

From the mid-thirties onwards, the demand for industrial diamond has increased steadily so that the consumption has risen to the very high figure of about 20 million carats per year. Man was forced to study the possibility of making diamonds with fewer impurities. Recent developments in this field has resulted in the synthesis of diamonds suitable for use as abrasive on an industrial scale.

Cutting with very small(tens of microns) tools was further developed by the Japanese in the 1980's . Diamond tools have found application in this burgeoning field as well. They have been employed, highly successfully, in making micron-sized features.

Features of Diamond Machining

High quality tools can be made of single crystal natural diamond. They are used to make high precision parts in metals, plastics, ceramics and a host of other materials.

The advantages of using diamond cutting tools often include improved workpiece quality, increased productivity, and reduced costs. High hardness and wear resistance result in good surface finishes over long production runs, consistent control of dimensions for extended periods, and long tool life.

Diamonds have a much higher thermal conductivity at room temperature than other materials, and this plays an important part in the industrial use of the stones. When a tool is cutting at high speed, the removal rate of heat from the cutting point is very important in preventing loss by burning or thermal fracture of the work piece. Hence it is the combination of extreme hardness and high thermal conductivity that makes diamond so important as an industrial tool. It is not sufficient to have either of these properties alone. This consideration suggests that development of any equivalent industrial material will be extremely difficult if not impossible.

Diamond has maximum hardness among natural materials. The hardness of a diamond varies greatly with the cleavage direction. Best results are obtained from a diamond mounted as a cutting tool when it is correctly oriented to within one degree. The stone must be mounted so that the tool approaches the work piece along one of its hard planes, rather than parallel to its cleavage planes, to prevent premature wear and possible flaking or chipping.

Structure and Properties of Diamond

Diamond is a crystalline form of carbon and has the crystal structure shown in fig 1. Diamond crystallizes most commonly in octahedra whose faces are {111} planes or in dodecahedra whose faces are {110} planes. The simple cube (with {100} faces) is found but is less common. Very often the crystal shape is not perfect, for example the dodecahedra have round surfaces and the octahedra may develop as thin plates.

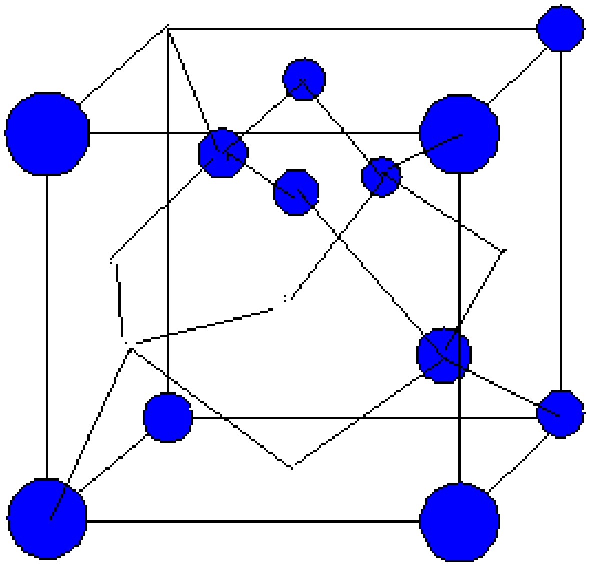

Fig 1. Crystal structure of diamond[1]

Table 1. Diamond structure characteristics[1].

Unit Cell	Cubic, a = 3.567 Angstroms
Space group	O^7_h

Location of Atoms	(000), (2 2 0), (0 2 2), (2 0 2), (1/4 1/4 1/4), (3/4 3/4 1/4), (1/4 3/4 3/4),(3/4 1/4 3/4)
Distance between nearest neighbors	1.544 Angstroms
Density	3.52 g/cm^3

Although diamond has been made synthetically it does not appear to have been sintered or bonded in any way that remotely resembles these natural products. On theoretical grounds sintering of diamonds should not be easy, yet it is difficult to suggest any other method of bonding these strongly[1]. Twins occur in natural diamonds and are a source of difficulty in shaping gem stones. Diamond has a cleavage direction along the {111} planes and this is used in dividing large stones and in shaping processes.

Optical Properties

Diamond has a high refractive index of 2.417 at 5890 Angstroms. When it is free from strain it is isotropic, being a cubic crystal, but many natural diamonds show strain bands when examined between a polarizer and analyzer. The >fire= of a gem stone depends first on its high refractive index, which implies a low angle of total reflection, and secondly on its high dispersion, which makes the light refracted in a given direction change in color as the stone is moved slightly. The absence of small inclusions is also very important, since such inclusions, even if too small to be seen by the naked eye, would act as >sinks= for the light within the crystal.

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Thermal Properties of Diamond

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Diamond has a much higher thermal conductivity at room temperature than other hard materials and this plays an important part in the industrial use of the stone. When a tool is attacking a material moving at high speed, the removal of heat from the cutting point is moving at high speed, the removal of heat from the cutting point is very important in preventing loss by burning or thermal fracture.

It is the combination of extreme hardness and high thermal conductivity that makes diamond so important as an industrial tool. It is not sufficient to have either of these properties alone. This consideration suggests that development of any equivalent industrial material will be extremely difficult if not impossible.

Diamonds of gem quality have thermal conductivities at room temperature greater than that of any other substance. A type IIa diamond conducts heat five times better than copper, and this difference is accentuated at lower temperature, the ratio being twenty-five at liquid air temperature[1]. Also, thermal conductivity is sensitive to structural imperfections and could reflect the differences between the various types of diamond.

Types of Diamond

Diamonds have been classified as type I and type II in relation to their absorption in the infrared, visible and ultraviolet regions[36]. Type II diamonds transmit well in the ultraviolet down to the absorption edge at 2200 ^{0}A but type I diamonds show absorption starting at 3300 ^{0}A and this increases fairly rapidly at shorter wavelengths. This difference forms the basis of a convenient method for discriminating between the two types.

The difference in the absorption spectra indicate that type II diamonds are more nearly perfect crystals than type I diamonds. For example type I diamonds show absorption in the region of 7 -8 :m and this absorption is not present in the type II diamonds. In most type II diamonds there is a weak continuous absorption which is probably due to the presence of a minute amount of graphite or amorphous carbon in the structure.

Most diamonds are extremely good insulators and this property is used in one method of separating them from associated minerals, but it has been shown that a small proportion of type II diamonds are semiconductors. Based on this property there is a further classification in diamonds . The non-conducting type II diamonds are classified as type IIa and the semi-conducting type II are classified as type IIb.

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Physical Properties of Diamond

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Table 2: Other Physical Properties of Diamond

Other Properties of Diamond	
Elastic Modulus	1000 GPa
Shear Modulus	300 GPa
Critical Tensile Cleavage Stress	4 GPa

There is no detectable plastic flow up to critical tensile cleavage stress and less than 1600 °C.

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Wear of Diamond

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Consequences of Microshaft Deflection

As a result of the deflection of the microshaft the tool no longer cuts with a zero rake angle. The effective rake angle is Sin^{-1}\{(y-dy)/r*\}, where r* is the instantaneous radius.

The actual depth of cut is lesser than the indicated depth of cut and is (R-r*). The change in rake angle causes a change in the depth of cut and is partially responsible for change in cutting forces. The depth of cut must be varied to maintain precision along the length of shaft because shaft deflection is less as the tool approaches the fixed end.

The tool does not cut on the center of rotation of part. The tool must be initially placed above the center of rotation so that the deflection results in tool centering.

Vertical deflection causes the microshaft to roll up onto the rake face thereby resulting in shaft breakage. Because of the deflection of the microshaft there is a change in the cutting forces.

L_c %W = constant

This relation is consistent with the view that flow occurs at a critical hot-spot temperature. If the area of contact is given by the ratio of the load W toyield pressure of the softer material, then the hot-spot temperature rise is given by

$2 = 0.47\!: L_c W^{1/2} p^{1/2} . (K_A+K_B)$

Where **:**= Coefficient of friction,

K_A & K_B are the thermal conductivities of the two sliding bodies.

Thus if **:** and p are constant, a given hot spot temperature is reached when $L_c\ W^{1/2}$ is a constant.

For **:**=0.2 and a yield pressure equal to the room-temperature hardness of glass, the calculated value of 2 at which flow just occurs is found to be 840EC for a glass known to have a softening temperature of 745EC.

There are two significant features of the wear process. First, the wear increases very rapidly with speed; secondly , the wear of diamond is accompanied by the production of a black powder which collects around the diamond slider and is also rubbed into the glass. From chemical tests this powder has been identified as carbon. The wear is due, atleast in part, to the degradation of diamond to amorphous carbon.

It has been found that thermal oxidation does not contribute to the wear of diamond. Wear rate of diamond is reduced rather than increased by the presence of oxygen.Therefore burning is not a major factor in the wear. The reduction of wear by the presence of oxygen is related to the influence of oxygen on the lubricating properties of graphite in dry conditions.

High Speed Sliding of Metals on Diamond

Studies on sliding of Chromium on diamond indicate that for speeds above about 250 m/sec the friction is high . At these speeds sliding on diamond resembles metal sliding on metal. At speeds below 200 m/sec the friction is of the order of **:**= 0.05[15]. Fig 2. shows the variation of coefficient of friction with respect to the sliding speed.

In the high friction range (>250 m/sec) diamond is found to be covered with a thin transferred film of chromium and there is no wear of the diamond surface. In the low friction range (<200 m/sec) diamond is readily abraded and a smooth spherical depression is rapidly produced. Also degradation of diamond to amorphous carbon occurs.

Sliding with steel surfaces also show similar behavior. However with copper surfaces sliding on diamond there is a very small change in friction at the translational speed as shown by Fig 3[15].

At sufficiently high sliding speeds a film of soft or molten metal is smeared over the surface of diamond. The friction is similar to that observed with metals sliding on metals and practically no wear of the diamond occurs. Below a critical speed, however, the frictional heating is insufficient to cause a large scale melting of the metal, which can cover the diamond and protect it. Instead hot spots are formed on the diamond surface, the hot-spot temperature being limited by the melting point of the sliding metal. At high temperatures diamond is transformed into amorphous carbon, the process being slow at 1000 EC but very rapid above 1600EC. In addition the high temperatures decrease the hardness and mechanical strength of the surface layers so that mechanical fracture can result[15].

Table 3 : Wear of Diamond by Sliding Metals

(Sliding speed 100-200 m/sec) (Sliding speed 100-200 m/sec)

Metal Surface	**Melting -Point (EC)**	**Diamond Wear (10^{-9} g/1000 m)**
Copper	1083	1-2
Ball-bearing steel	about 1500	30-60
Chromium	1615	200-500

It is seen from Table 3 that the effectiveness of the different metals in wearing diamond increases rapidly with their melting point. This is because at sufficiently high sliding speeds a film of soft or molten metal is smeared over the surface of diamond. Therefore metals with a higher melting point do not deposit on the diamond as much as those with a lower melting point.

The difference in behavior of copper compared with steel and chromium has not yet been explained. However, it has been suggested by Kenyon[37] that the frictional behavior of metals on graphite depends on their chemical nature. If the metal can react with the graphite to form a carbide, or can form solid solutions with carbon, the friction may rise to a much higher value. This suggests that the chemical nature of the metal, as well as its melting point, may be of importance in the friction and abrasion of diamond.

In addition, there is evidence that some of the wear is due to scratching and mechanical fracture of the surface layers. Abrasion of diamond is due in a large measure to a high temperature carbonization or graphitization of the surface.

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Concepts of Microshaft Machining

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Two basic methods of metal cutting using a single point diamond tool are orthogonal or two dimensional cutting and oblique or three dimensional cutting. Orthogonal cutting uses a single cutting edge. The most important characteristic of orthogonal cutting is that the velocity of the workpiece is orthogonal to this cutting edge. It is assumed that the chip flows up the surface of the wedge shaped edge with the chip velocity in the same plane as the in coming velocity. If the cutting edge is inclined at an angle less than 90 to the workpiece velocity, the cutting action is known as oblique. When orthogonal cutting and oblique cutting are compared, oblique cutting has more advantages than orthogonal cutting because for the same feed and depth of cut, the force which cuts or shears the metal acts on a larger area of the tool in the case of oblique cutting. The tool in oblique cutting will thus have a longer life as the heat developed per unit area due to friction along the tool-workpiece interface is less. Alternatively, a tool used in oblique machining will generally remove more metal in the same life as orthogonal cutting. True orthogonal cutting is confined mainly to such operations as broaching and slotting whereas other cutting processes are mainly oblique.

During the cutting process the metal is severely compressed in the area in front of the cutting tool. This causes high temperature shear, and plastic flow if the material is ductile. When the stress in the workpiece just ahead of the cutting tool reaches a value exceeding the ultimate strength of metal, particles will shear along a plane ("shear plane") to form a chip element which moves up along the rake face of the tool. The outward or the shearing movement of each successive element is arrested by work hardening and the movement is transferred to next element.

The process is repetitive and a continuous chip is formed having a highly compressed and burnished underside, and a minutely serrated top side caused by shearing action. The chip developed like this, will have rectangular cross-section, and the cutting does not take into account the effect of tool nose radius.

Mathematical Models

Theories of macromachining have been postulated by Merchant and others [32]. He analyzed the chip geometry and developed a force system for the case of orthogonal cutting. He assumed continuous chip formation with no built up edge on the tool . The effect of the nose radius on the cutting forces was neglected. The force relationships help in determining stresses, the coefficient of friction between chip and cutting tool, and work done in shearing the metal and in overcoming friction on the tool rake face, quite reasonably.

This theory agreed with the results in the case of synthetic plastics but not in case of metals. Due to this, Merchant modified his theory taking into consideration that the shear stress is not completely independent of the normal stress.

Burnham, M.W.[33] analyzed the machining theory in relevance to micromachining. He compared conventional machining and micromachining. The concepts that are important to optical surface finishes and surface characteristics are dealt with in his study. He considered the influence of nose radius and tool sharpness on the side flow produced by the flow of material out of contact zone under the tool edge. His study concludes that parameters such as rake angle, depth of cut, feed rate, tool nose radius and cutting speed are very important in controlling the cutting force and reducing figure error.

Nair, R et al. [34] presented a method which identified the wear-affected component in turning as well as some other machining parameters by measuring the forces during one transient. The sharp tool-chip formation component is proportional to the cross-sectional area of the cut normal to the main cutting velocity, which takes a wide range of values during each transient. The results showed a linear relationship between the cross-sectional area of the cut and the tangential force.

Mathematical Model for Chip Formation

The chip area may be defined as the product of the workpiece under cutting and the uncut thickness. In ideal cases these two parameters will equal the feed and depth of cut respectively. A tool with a negligible nose radius is the other assumption in the orthogonal conventional cutting process. Whereas in almost all practical cases, tools have a nose radius that affects the cutting forces and the chip formation and this is especially true in micromachining where all of the cutting takes place on the tool nose radius.

In the case of conventional machining, the chip area is considered as a rectangular cross-section where cutting takes place along a straight side cutting edge whereas when cutting takes place at the nose radius the chip geometry will be entirely different. The geometry of the theoretical cross-section of the chip formed by cutting at the nose radius of the tool is shown in Fig. 5. The chip thickness is not constant along the cutting edge. It takes a maximum value where the cutting edge and the uncut surface intersect and becomes gradually smaller along the cutting edge at the tangent point.

Therefore, the total uncut chip area A* is equal to the sum of area BED and area CED.

$A^* = AC + AC$

$DB = l = RZ$

$Z = \mathrm{Cos}^{-1}\,(1 - d^*/R)$

$ED = H = A\cos(90-Z)$

$AC_1 = \mathrm{AreaBED} = l_c h_{max}/2 = (aR/2)\,\mathrm{Cos}^{-1}(1-d^*/R)\{\mathrm{Sin}(\mathrm{Cos}^{-1}(1-d^*/R))\}$

$AC_2 = \mathrm{Area\ ECD} = a^2/2[\sin(\mathrm{Cos}^{-1}(1-d^*/R))]\,(1-d^*/R)$

$A^* = \mathrm{Sin}\,(\mathrm{Cos}^{-1}(1-d^*/R))\,[aR/2\ \mathrm{Cos}^{-1}(1-d^*/R) + a^2/2(1-d^*/R)]$

where R is the nose radius of the tool,

d^* is the actual depth of cut,

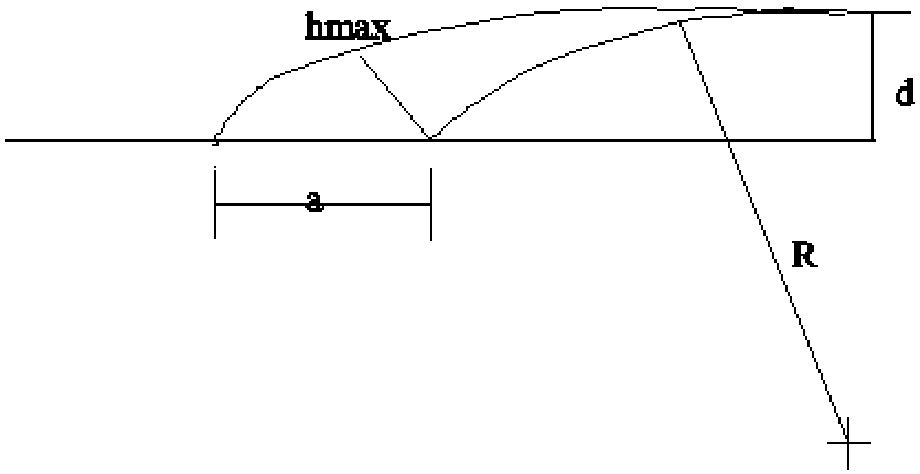
a is the feed rate,

l_c is the length of the arc,

h_{max} is maximum chip thickness and

Z is the included angle.

Fig 5. Geometry of the cross-section of the chip



Deflection of Microshafts

Under the action of applied forces, the axis of a cantilever beam deflects from its initial position. Accurate values for beam deflections are sought in many practical cases. Elements of machines must be sufficiently rigid to prevent misalignment and to maintain dimensional accuracy under load [4]. Similarly, information on deformation characteristics of members is essential in the study of the precision to which the tolerance can be met and for surface finish of a shaft. A model was developed to predict the deflections in the direction of radial feed and also in the direction perpendicular to the radial feed.

The standard cantilever beam deflection equation is the starting point for deriving the model.

$$y = \frac{F z^2 (3l - z)}{6 E I}$$

Where y is the deflection of the shaft in the direction of the force,

F is the vector force acting on the shaft,

L is the length of the shaft,

z is some distance on the shaft from the fixed end,

E is the Young's modulus and

I is the moment of inertia of the shaft.

The deflection in the X and Y directions are

$$y_x = \underline{F_x z^2 (3l - z)}$$

6 E I

$$y_y = \frac{F_y z^2 (3l - z)}{6 E I}$$

where Fx and Fy are forces acting along X and Y directions respectively. These forces can be computed by resolving the cutting and thrust forces. (Ref Fig. 6)

$F_x = F_q \text{ Cos } g^* + F_p \text{ Sin } g^*$

$F_y = -F_q \text{ Sin } g^* + F_p \text{ Cos } g^*$

Maximum Deflection Along X Direction

The maximum deflection that can occur along the X direction can be predicted depending upon the indicated depth of cut and the shaft diameter. The geometry based on which the maximum deflection along X direction is shown in Fig 6.

$AB = R_0W$

$W = \text{Sin}^{-1}(Y^*/R_0)$

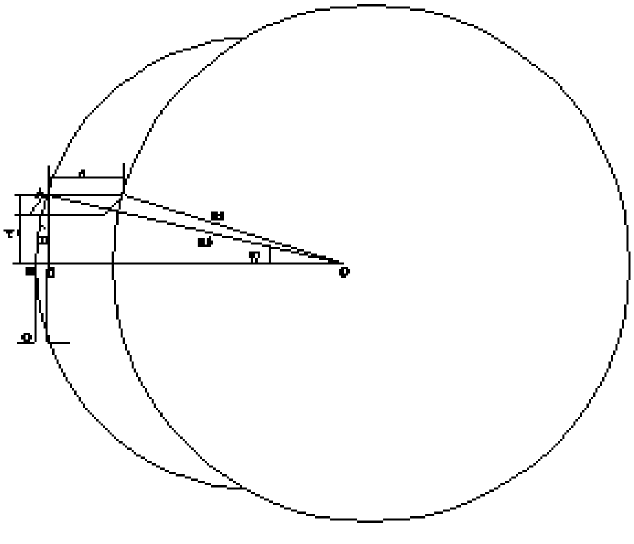
$D = \text{Cos}^{-1} (Y^*/R_0 W)$

$Q = R_0 \text{ W Sin D}$

$Max\_D_x = Q + d$

For any shaft diameter or indicated depth of cut, the maximum deflection in the X direction can be calculated by using this relation.

Fig 6. Maximum Deflection Along X Direction



Consequences of Microshaft Deflection

As a result of the deflection of the microshaft the tool no longer cuts with a zero rake angle. The effective rake angle is $\mathrm{Sin}^{-1}\{(y-dy)/r^*\}$,

where r^* is the instantaneous radius.

The actual depth of cut is lesser than the indicated depth of cut and is $(R-r^*)$. The change in rake angle causes a change in the depth of cut and is partially responsible for change in cutting forces. The depth of cut must be varied to maintain precision along the length of shaft because shaft deflection is less as the tool approaches the fixed end.

The tool does not cut on the center of rotation of part. The tool must be initially placed above the center of rotation so that the deflection results in tool centering.

Vertical deflection causes the microshaft to roll up onto the rake face thereby resulting in shaft breakage. Because of the deflection of the microshaft there is a change in the cutting forces.

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Chemical Aspects of Tool Wear

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The term **diamond turnable** practically means that the cost of tool wear is acceptable in terms of the value of the component. In other words, the area of useful optical surface generated is limited by tool wear[2]. Different mechanisms can contribute to diamond wear and multiple mechanisms may be at work under certain circumstances. The following mechanisms contribute to diamond tool wear in a large way[3]:

Adhesion and formation of built-up edge;

Abrasion, microchipping, fracture and fatigue;

Tribothermal wear;

Tribochemical wear.

In the case of commercial aluminum alloys, the dominant wear mechanism is likely to be abrasion and chipping caused by impurities on the grain boundaries. Adhesion between clean surfaces may also be a significant tool wear mechanism[6]. In steels, the chemical effects combined with the mechanical interactions between carbides and the tool edge contribute to the tool wear[3-5]. A complete understanding of diamond tool wear can only follow understanding of the individual mechanisms. To an extent, these mechanisms can be separated under carefully selected conditions.

Chemical wear may be distinguished experimentally by examining micrographs of the surface of the worn tool[7]. Processes that result in scratches or gouges are signs of nonchemical wear. A theory proposed by Paul et.al.[2] states that the unpaired d electrons in the workpiece allow carbon-carbon bond breaking in diamonds followed by metal-carbon complex formation, leading to chemical wear of diamond tools.

A number of listings of diamond turnable materials have been published. However such listings should be treated with caution because they are typically incomplete and do not necessarily provide sufficient information on the materials or on the machining conditions. For example, although aluminum alloys are generally diamond turnable, not all of them produce good optical surfaces. Conventional electroplated nickels give rapid tool wear, but Aelectroless nickel@ with phosphorous contents above about 10% and appropriate heat treatment can be machined effectively[8,9].

A number of researchers have demonstrated that chemical mechanisms are significant, however they are not well understood. There are empirical correlations that relate melting points and crystal structures to materials that excessively wear diamond tools. There is also some correlation with hardness, although care is needed in interpreting the data.

The chemically significant step in tool wear is when carbon atoms are pulled from tightly bonded diamond lattice. Once an atom leaves the diamond, it may diffuse(into the workpiece), graphitize(by combining with other carbon atoms in a loose graphite arrangement), or react(with oxygen to form CO or $C0_2$,or with the workpiece to form a carbide). Each of these processes is preceded by the carbon-carbon bond breaking step that is the chemical equivalent of tool wear[2].

Chemical reactions proceed from reactants to products through a metastable energy state, the activated or transition state intermediate complex. When the energy of the complex is not too high, the reaction proceeds quickly. For high-energy complexes, the overall reactions are slow. Several metals listed in the Table 6.2 have been found to be good catalysts for reactions involving carbon atoms. They cause the formation of lower-energy intermediate complexes that speed up the process of tool wear[2].

Table 4.2:Data for elements with known diamond turning properties[2].

Element	Melting Point(C)	Crystal Structure	Brinell Hardness (Kg/mm)	No. of unpaired d-shell electrons	Diamond Turnable (y/n)
Tin	232	fcc	9	0	y
Zinc	420	hcp	51	0	y
Aluminum	660	fcc	25	0	y
Silver	962	fcc	96	0	y
Gold	1064	fcc	96	0	y
Copper	1083	fcc	76	0	y
Beryllium	1277	hcp	60	0	y
Silicon	1410	diamond	1211	0	y*
Nickel	1453	fcc	189	2	n
Iron	1535	bcc	50	4	n
Chromium	1857	bcc	250	5	n

y*- Tool wear is substantial

Metal-carbon-oxygen complexes that are formed in the presence of oxygen are energetically more favorable than those formed in its absence. Thus reactions in air or oxygen are predicted to proceed faster and diamond tool wear to be higher than in oxygen free environments.

Metals with more unpaired d electrons are expected to form complexes with more than one carbon atom, leading to the expectation that the amount of wear should correlate with the number of unpaired d electrons in the metal atom[2].

To compare predictions of diamond tool wear Table 6.3 provides data on melting point, crystal structure, hardness and the number of unpaired d electrons.

Chemical wear of diamond tools has been observed experimentally for many alloys. The results[10,11] agree with the unpaired d electron theory. For most alloys, the behavior reflects the parent material. Thus, in terms of chemical wear, aluminum alloys are generally diamond turnable, as are copper-based alloys such as brass(copper-zinc) and beryllium copper. Ferrous steels with unpaired d electrons, are not generally diamond turnable. That steels show less tool wear than iron is attributable to the presence of carbon atoms in the alloy.

The theory seems to imply that the number of unpaired d electrons in materials being diamond turned is significant. Metals with more unpaired d electrons should wear diamond tools more than metals with fewer of them.

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Wear of Diamond Graphic

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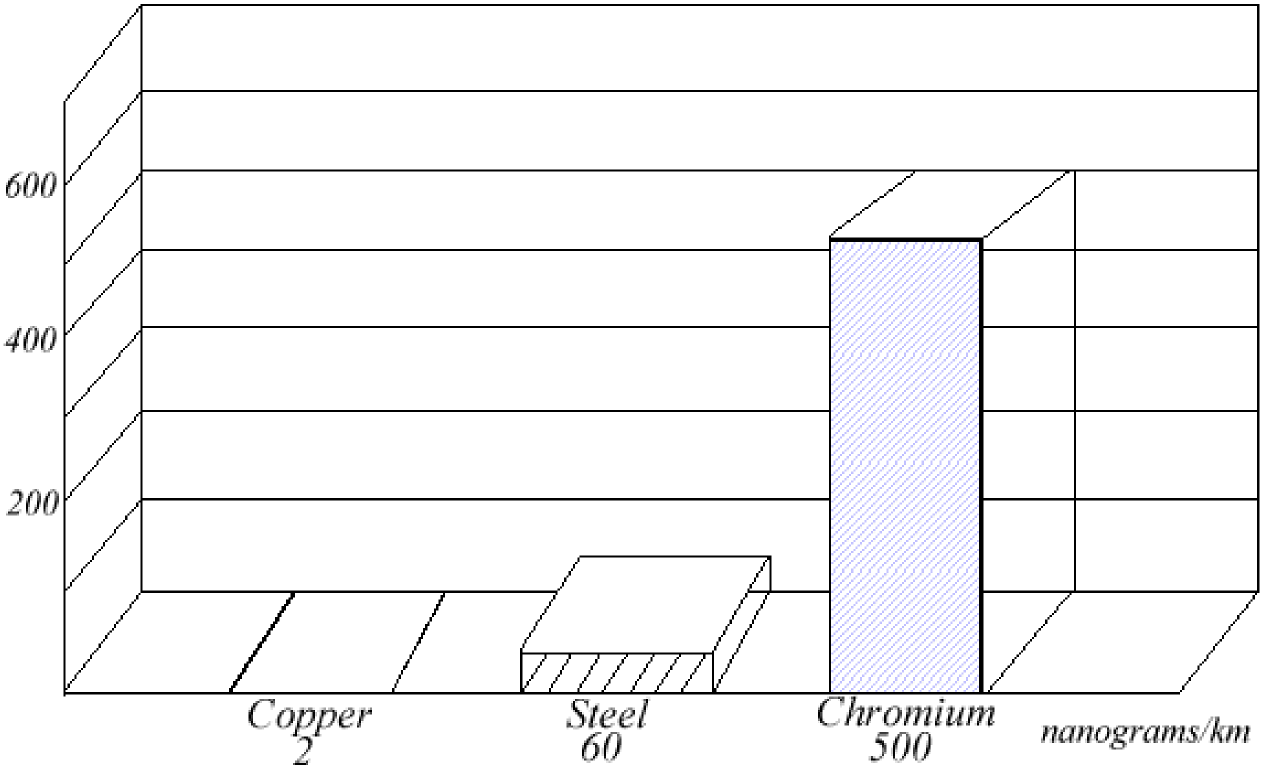
Fig 5. Wear of Diamond by Sliding Metals
Sliding Speed: 100-200 m/sec Load: 50g



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Diamond Machining of Polymers

Intro to Diamond Machining	Thermal Properties of Diamond	Physical Properties of Diamond	Wear of Diamond	Concepts of Microshaft Machining
Chemical Aspects of Tool Wear	Wear of Diamond Graphic	Diamond Machining of Polymers	Handling Diamond Turned Surfaces	References for Diamond Machining

Machining of polymeric materials has become increasingly important in the field of precision engineering. Often, injection, extrusion or compression molding of plastic components does not have the accuracy or precision required for applications in optics and electronics.

The three main factors that influence the roughness and product shape are[16]

1. Machine and Environmental factors such as slide straightness, temperature stability and vibration isolation [17-23]. These parameters, in addition to diamond quality, have the ultimate responsibility in determining the surface roughness and dimensional accuracy of materials such as copper.

2. The response of the machined material to tooling and process parameters such as cutting speed, depth of cut, infeed rate and geometry of the diamond.

3. The physical and chemical properties of the materials. Often, this factor is substantially less important than the other two. However an exception to rule is the behavior of a number of polymeric materials. The properties of these polymers are the limiting factors in determining product dimension and the quality of the surface finish, These properties include glass transition temperature (Tg), melt temperature(Tm), molecular weight (MW), viscosity and relaxation rate.

An earlier study on machining of polymers by Kobayashi 1962[24-28] considered cutting with standard machine tools other than diamond. In his approach, Kobayashi considered tool parameters to be most important with respect to surface quality, which is true for a certain class of brittle materials. Consequently the rake angle was identified as the most important parameter determining surface roughness in polymer machining. Kobayashi used viscoelastic models to explain the observed time dependencies (cutting speed). He argued that the obtained surface roughness of a polymer depends on the interplay between elastic and plastic deformation, which introduces time dependency. Plastic behavior is observed at low speeds.

In a more recent model by Smith and Scattergood[29], the glass transition temperature of polymers(Tg) was taken into account. This model suggests that the surface roughness depends mainly on the temperature of the cutting zone, i.e., whether the polymer is above or below its Tg. They concluded that a rough surface signified that the glass transition temperature was not reached under the cutting conditions and the material had experienced brittle fracture. When a smooth surface was produced, it was assumed that the glass transition temperature of the polymer had been exceeded and material was removed in a ductile manner. this model is in agreement with their experimental finding that brittle regions were encountered at low speeds, a region of little frictional heating. As the spindle speed was encrust, frictional heating eventually brought the polymer above its glass transition and into the ductile region where smooth surface finishes were obtained.

The Kobayashi model recognizes that changing the time frame of the experiment (tool speed) changes the viscoelastic response of the material. The Smith and Scattergood model [29] used temperature (which is related to the tool speed through the effects of frictional heating) as a reference point.

Polymer Viscoelasticity

The theory of polymer viscoelasticity attempts to describe how a polymer responds to a disturbance. the description can be given in the time or temperature frame. In the time frame the temperature frame. In the time frame the temperature is held constant. At a given temperature every polymer has a fixed response time that is related to the sum of its vibrational, rotational and translational movements. This characteristic time is defined as a relaxation time.

In the temperature frame, the time over which a disturbance is applied is kept constant. increasing the temperature will increase the vibrational, rotational and translational motions in a polymer, thus decreasing the time it takes to respond to a disturbance in a given manner. In other words the relaxation time decreases with increasing temperature. This can be interpreted as a change in hardness, with the polymer becoming softer and more ductile with increasing temperature.

Carr and Feger [16] combined time and temperature frames and suggested that a polymer will more completely respond to a disturbance if it is applied more slowly (at a given temperature) or if the temperature is increased (for a given time frame). The phenomenon where an identical effect (in this case a change in relaxation time of a polymer) can be obtained by two different means, specifically a change in time or temperature, is called the Time - Temperature Superposition Principle[30,31]. Carr and Feger have used this correspondence principle in describing the behavior of polymers.

Stress - strain relation for polymers

Linear, amorphous polymers exhibit three distinct behaviors. They can be in a glassy state, in the rubbery plateau, or in the flow regime as shown in Fig 7. The transition between the glassy and the other states is the glass transition. The behavior in the vicinity of the glass transition is also distinct. However, because the glass transition is often sharp, it is often difficult to keep a system within the narrow boundaries during an experiment.

Below the glass transition temperature, usually a region can be found in which glassy behavior is exhibited by all polymers whether they are cross-linked or linear, amorphous or semicrystalline. Glassy behavior is usually characterizing the mechanical properties of glassy polymers is by establishing stress-strain curves. The stress-strain curves show several types of behavior: brittle, ductile or tough, cold flow and rubbery. The brittle behavior is characterized by materials that support a high level of stress, but exhibit small elongation with no apparent yielding; the yield point is reached before occurs. Materials exhibiting cold flow show extensive deformation. High levels of stress and strain are supported.

Just above Tg, polymers enter the rubbery region. Rubbers like materials support only small stresses at small to intermediate strains. A high strains, the stress supported by a rubber can be substantial (strain hardening). This behavior is evident when trying to stretch a large rubber band. At first, the material can be elongated with very little effort. However, a point is reached where considerable effort is required for further extension.

The rubbery plateau behavior is characterized by rubber elastic behavior. In a rubber-like polymer above its glass transition temperature, the chains are hindered from moving past each other for long distances, but short-range motion is possible. It is essentially a cross-linked liquid. Rubber elastic behavior is characterized by high elongation at break and low moduli. Linear, amorphous polymers above the "critical molecular weight" Mc, also go through a rubbery plateau before they enter the flow region. In the rubbery region, directly above the glass transition, linear amorphous polymers with molecular weights above Mc do not flow because the chain motions that allow the polymer chains to slip past each other are still slow. This implies that a certain time is needed for the usually entangled chains to disentangle. Thus for a given strain rate, a temporary network, sometimes called the entanglement network, is formed. The extent of entanglement depends on molecular weight, stress rate, and temperature.

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Diamond turned surfaces are to be handled with extreme care and caution. Skin oil and even dry cotton may damage the surface. The marks left over by skin oil are difficult to be removed. Diamond turned surfaces should never be laid face down on anything. Saliva marks are difficult to remove. Hence conversations must be avoided over diamond turned surfaces. An established procedure should be adopted to clean these surfaces. Some of them are discussed below.

Cleaning Diamond Turned Surfaces

Pure liquid soap (sodium lauryl sulfate) has to be used to clear heavy contamination. A soaked cotton ball could be used with very light pressure to clean the surface. The surface is rinsed with distilled water. The water residue is removed with acetone. The meniscus is removed with edge of tissue.

Qualitative Testing Diamond Turned Surfaces

Reflected image of an overhead diffuse light is examined over the diamond turned surface. The surface is slowly tilted to move the light across. Waviness, diffraction patterns and sharp breaks in image are looked for. This technique of testing diamond turned surfaces is good down to the microinch region.

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1. Berman, R. Physical Properties of Diamond, Oxford university press, London, 1995.
2. Paul, E., Evans, C.J., Mangamelli, A. and McGlauflin, M.L. AChemical Aspects of Tool Wear in Single Point Diamond Turning, Precision Engineering, Vol.18, pp. 4-19, 1996.
3. Evans, C.J. Cryogenic Diamond Turning of Stainless steel, Ann CIRP, Vol.40, pp 571-75, 1991.
4. Casstevens, J. Diamond Turning of Steel in Carbon Saturated Environments, Precision Engineering, Vol.5, pp. 9-15, 1983.
5. Moriwaki, T. Ultrasonic Diamond Turning of Steel by Applying Ultrasonic Vibration, Ann CIRP, Vol.40, pp.559-62, 1991.
6. Kendall, K. Adhesion: Molecules and Mechanics, Science, Vol.263, pp 1720-25, 1994.
7. Thornton, A.G. and Wilks, J. Clean Surface Reactions Between Diamond and Steel, Nature, Vol.114, pp 327-38, 1978.
8. Taylor, J.S., Syn, C.K., Saito, T.T. and Donaldson, R.R. Surface Finish Measurements of Diamond Turned Electroless-Nickel Plated Mirrors, Opt Eng, Vol.25, pp.1013-20, 1986.
9. Syn, C.K., Taylor, J.S. and Donaldson, R.R Diamond Tool Wear VS Cutting Distance on Electroless Nickel Mirrors, Proc SPIE, Vol.676, pp.128-40, 1986.
10. Sanger, G.M. The Precision Machining of Optics, Appl Opt Eng, Vol.10, pp.251-390, 1987.
11. Fischer, R.E. Diamond Turning in Encyclopedia of Material Science and Engineering, M.B. Bevar, ed. Tarytown, NY: Pergamon, 1986.
12. Bowden, F.P. and Scott, H.G. Proc. Roy. Soc. A, 248,368, 1958.
13. Bowden, F.P. and Tabor, D. The Friction and Lubrication of Solids, Part I(Chap II). Oxford University Press, 1954.
14. Savage, R.H. Journal of Applied Physics, Vol.19, 1948.
15. Bowden, F.P. and Freitag, E.H. Proc. Roy. Soc. A,248, 1958.
16. Carr, J.W. and Feger, C. Ultra Precision Machining of Polymers Precision Engineering, Vol.15, pp.221-237, Oct 1993.

Donaldson, R.R. Large Optics Diamond Turning Machine Technical Report, Lawrence Livermore Laboratory, April 1981.

18. McKeown, P.A., Wills-Morren, W.J., Read, R.F.J. and Mdjarrad, H. The Design and Design and Development of a Large Ultra Precision CNC Diamond Turning Machining SME MR82-931, 1982.
19. Donaldson, R.R. and Patterson, S.R. Design and Construction of a Large Vertical Axis Diamond Turning Machining, Proc SPIE, 1983, 433, 62-67.
20. DeBra, D.B. Design of Laminar Flow Restrictors for Damping Pneumatic Vibration Isolators, CIRP Ann 33, 1984, 351-356.
21. Donaldson, R.R. and Maddux, A.S. Design of a High Performance Slide and Drive System for a Small Precision Machining Research Lathe, CIRP Ann, Vol.33, pp 234-248, 1984.
22. Falter, P.J. and Dow, T.A. Design and Performance of a Small Scale Diamond Turning Machine, Precision Engineering, Vol.9, pp.122-131, 1978.
23. Franse, J. Manufacturing Techniques for Complex Shapes With Submicron Accuracy, Rep Prog Phys, Vol.53, pp.1049-94, 1990.
24. Kobayashi, A.K. and Hirakawa, H. Ultraprecision Machining of Plastics. Part I. Polymethyl Methacrylate, Polym Plast Technol Eng, Vol.22, pp.15-25, 1984.
25. Kobayashi, A.K. Ultraprecision Machining of Plastics, SPIE Vol.508, pp.31-36, 1984.
26. Kobayashi, A.K. and Satio,K. On The Cutting Mechanism of High Polymers, J Polymer Sci, Vol.58, pp.1377-1395, 1962.
27. Kobayashi, A.K. Machining Plastic. Part I., Modern Plastics, Vol.110, July 1963.
28. Kobayashi, A.K. Machining of Plastics Huntington, NY:Robert E.Kreiger, 1981.
29. Smith, E.F. Single-Point Turning of Amorphous Thermoplastic Polymers, M.S. Thesis, North Carolina State University, Raleigh, NC, 1989.
30. Akloins, J.J. and MacKnight, W.J. Intro to Polym. Viscoelasticity New York: J.Wiley and Sons, 1983.
31. Plazek, D.J. J Phys Chem, Vol.69, 1964.
32. Merchant, M.E. Mechanics of Metal Cutting Process. Journal of Applied Physics, Vol.16, pp.267 and 318, 1945.
33. Burnham, M.W. The Mechanics of Micromachining. Proceedings SPIE-Advances in Precision Machining of Optics, Vol.93, pp.38-43, 1976.
34. Nair, R., Danai, K. and Malkin, S. An Improved Model for Force Transients in Turning, Journal of Engineering for Industry, Vol.114, pp.400-403, November 1992.
35. Ramamrutham, R. Strength of Materials, Dhanpatrai and Sons Pvt Ltd, New Delhi, 1991.
36. Robertson, R., Fox, J.J. and Martin, A.E. Phil. Trans. Roy. Soc. A., Vol. 232, 1934.
37. Keynon, D.M., Thesis, Cambridge University, 1956.

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