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Significance of Diamond as a Cutting Tool in Ultra-Precision Machining Process

P. Suya Prem Anand

Abstract

This chapter focuses on the purpose of using diamond as a cutting tool in various ultra-precision machining applications. The complicated structures such as resin and ceramic mold used for making optical lenses are machined by the diamond tool to improve the precision of the finished product. It is difficult to machine hard and brittle materials such as glasses, ceramics, and composites with the assistance of diamond tool due to the complexity in the aspheric surfaces. Moreover, the tool wear is a major problem in machining these hard materials to a fine dimensional accuracy and tolerances. The microscopic defect forms at the cutting edge lead to the damage of the surface finish of the workpiece material. Therefore, the discussions are associated with the achievement of machining hard materials using a diamond tool in ultra-precision applications.

Keywords: cutting tool, optical lenses, ceramics, glasses, diamond coating, tool wear, AE sensor

1. Introduction

The ultra-precision machining is the process of improving the dimensional accuracy and the surface quality of the product in the submicron level. Therefore, the magnitude of surface roughness must be less than 10 nm, and the machining accuracy will be in the range of 0.1–100 nm. The brittle materials such as glasses, silicon, and germanium are machined with high-speed ultra-precision lathe to understand the material removal mechanism in different modes. When the applied depth of cut is below the critical value, it is considered to be in the ductile mode, and it can be easily machined without crack formation. Therefore, there is a significance to identify the ductile to brittle transition for these materials where the magnitude of the critical depth of cut varies depending on the properties of the components. The experiments are conducted in different atmospheres such as dry, water, methanol, octane, ethanol, and propane to form a crack-free surface for the brittle materials. The machining performance of BK7 glass in the ductile mode under the methanol and ethanol conditions gives a smooth crack-free surface [1].

Generally, the single crystal silicon is frequently used in the microelectro-mechanical system (MEMS), where the material is finally machined to a quality product with the effect of ultra-precision grinding and polishing operation. Although the behavior of silicon material is brittle at room temperature, it is

advisable to machine the silicon in the ductile mode by using a diamond turning tool. This reduces the damage caused by the brittle fracture of the ceramic material and improves the productivity of the final part [2]. The high-speed machining of nonferrous materials such as copper, aluminum, and nickel with the diamond tool is performed to evaluate the tool wear, cutting force, and surface finish. The experiments are conducted for different cutting speed such as lower speed of 150 m/min and higher speed of 4500 m/min. The rate of tool wear observed in the lower cutting speed is more than the higher cutting speed. This may be due to the reduction in the time taken for the tool engagement with the workpiece per revolution at higher speed [3]. It also reduces the chemical affinity between the tool and the workpiece interface. The diamond tool with high negative rake angle is used to finish this material in the ultra-precision accuracy. However, it provides a good surface finish to the material, but the tool wear is a major problem in machining the hard brittle material. For example, the flank and crater wear occurs obviously in the turning operation, which results in increased production cost and deteriorates the product quality.

2. Significance of diamond as a cutting tool

There is an increase in demand for preparing the plastic molds that are required for making the aspheric lens of CD optical pickup and smart lenses of the camera. The cutting edge of the tool must be sharp and free from irregular shape to process high-precision aspheric surfaces. There exists a major difference between the single crystal diamond (SCD) and the polycrystalline diamond (PCD) based on the sharpness of the tool. The cutting edges of the SCD tool are homogeneous and free from irregularities, whereas the cutting edges of the PCD tool show microscopic irregularities which lead to the removal of diamond particles. The major drawback of the SCD tool is the shorter life period compared to the PCD tool due to the abrasion wear [4, 5]. It is also used to machine the aluminum substrates to a fine mirror finish, which is used in the hard disk drive of the computer storage system. The different types of diamond cutting tools used in the ultra-precision machining are depicted in **Figure 1**.

The aspheric lenses made of glasses are used in the optical sensor for the automobile industry, where the glass lenses are pressed at high temperature in a ceramic mold. The schematic diagram of glass lens formation is depicted in **Figure 2**. These molds are produced by the ultra-precision secondary machining processes like



Figure 1.
Ultra-precision diamond cutting tools [5].

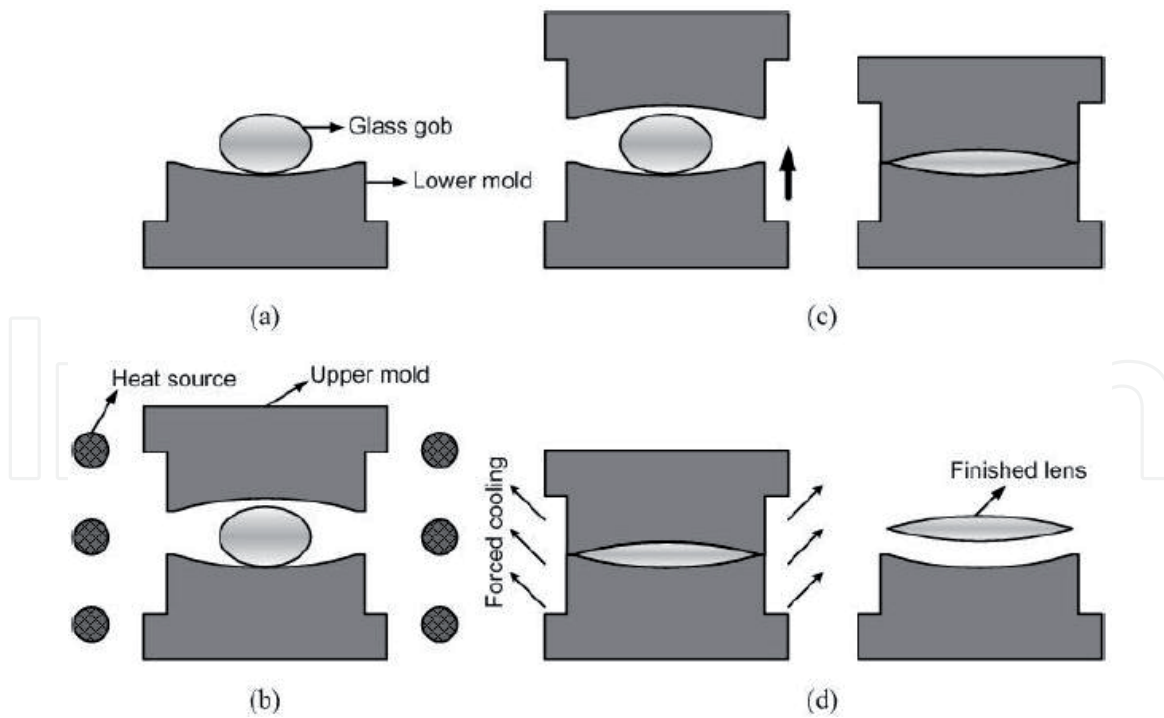


Figure 2. Schematic diagram of glass lens formation. (a) Molds and glass gob, (b) Heating, (c) Heating and pressing, (d) Cooling and release [7].

micro-turning and micro-milling processes. While the ceramic material like tungsten carbide is initially used for making these molds, harder tools like single crystal diamond are used to shape the ceramic materials. In recent times, silicon carbide ceramic is used for making the ceramic mold instead of tungsten carbide due to the high hardness [6]. The single crystal diamond tool is not suitable to machine this type of SiC ceramic mold because of the increase in the tool wear. The damages easily occur to the SCD tool during the machining of silicon carbide ceramics due to the cleavage and the anisotropic property of the diamond tool. This scenario can be overcome by using a nano-polycrystalline diamond (NPCD) tool as an alternative to the SCD tool. Since the NPCD tool consists of fine grains of nanometer size over the length with no additional binder materials, the properties of the NPCD tool are much better than that of the SCD. The performance of the NPCD tool is improved compared to the SCD, where the tool life is longer for the NPCD. This may be due to the hardness property and thermally stable characteristics of the NPCD tool [5, 7].

Recently, plastic lenses have been produced more instead of the optical glass lenses. This may be due to the increase in mass production and reduction in the cost of the product. The different types of lenses used in the microelectronic applications are shown in **Figure 3**. Generally, the aspheric lenses are produced by the injection molding process in mass production, where the ultra-precision lathe is used as a secondary machining process to finish these lenses. This machining has the capability to control the cutting edges of the tool to 1 nm accuracy. If the cutting edge circular arc of the tool is deformed in the grinding process, it will transfer the error to the aspheric lenses and deteriorate the accuracy of the finished product. It is hard to grind the single crystal diamond to a circular arc due to the anisotropic property of the material. Another form of the lens is the hologram which is used to focus the laser light to different points, where two portions of the lens are responsible for projecting the light to the target field. In addition, the aspheric surface is considered to be a portion, and the other portion is a diffraction grating inscribed in the lens. The sharp edges and the circular profile of the

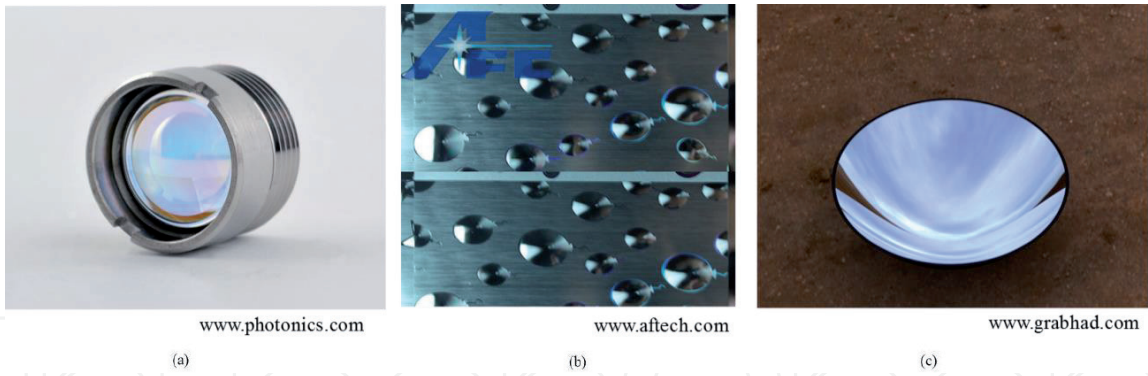


Figure 3. Different types of lenses (a) aspheric lens, (b) hologram lens, (c) parabolic mirror.

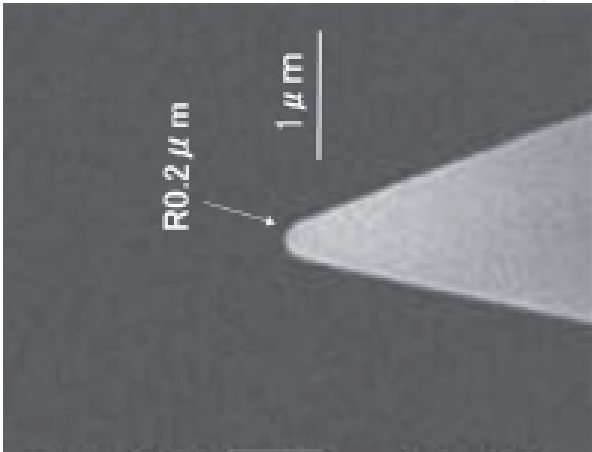


Figure 4. Circular cutting edge of diamond tool [5].

cutting edges are the essential characteristics used to machine the hologram lens mold. Moreover, the circular cutting edge has a smaller corner radius of $0.2 \mu m$ to machine the molds in high accuracy surface as shown in **Figure 4**. The ultra-precision diamond tool is also used to slice the parabolic mirror that is available in the solid CO_2 laser to condense the light at a focal point and reflect the laser light from the mirror finished surface. The parabolic mirror produced by the copper material consists of high thermal conductivity [5].

3. Diamond-coated tools

The diamond film is coated on different substrates to improve the hardness, corrosion resistance, and wear resistance of the tool. It also removes the heat generation from the cutting edge due to the high thermal conductivity of diamond. This leads to the increase in the durability of the coated tools in the machining process. The deposition of diamond films on the substrates such as metal alloys, cemented tungsten carbide, and stainless steel has not been consistent due to the adhesion difficulty at the interface. Additionally, a chemical affinity reaction takes place between the substrate and the diamond deposited films. This enhances the formation of carbide layer when the carbon from the diamond film interacts with air particles. However, when the coating is not regular on the substrate, the diamond film peels off from the surface and reduces the tool life.

The cemented tungsten carbide with the diamond coating is used in the recent periods to enhance the tool life and the cutting performance of the dental

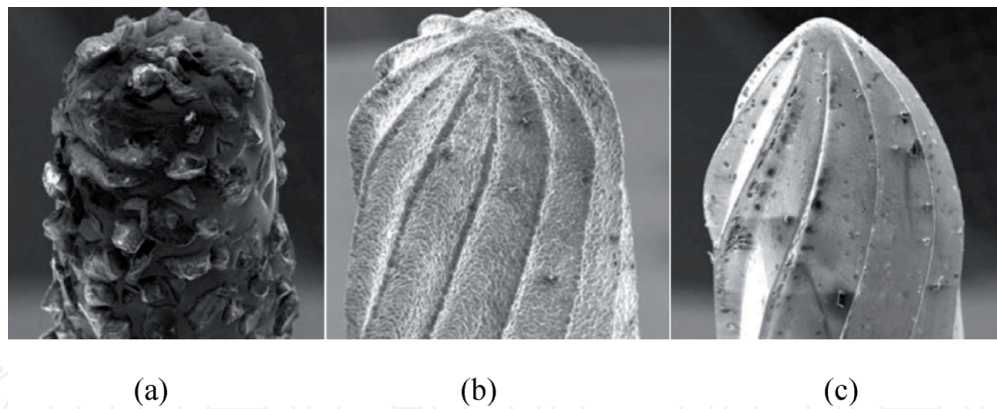


Figure 5. Diamond coated tools (a) sintered diamond tool, (b) diamond coated (WC) tool, (c) titanium nitride interlayer tool [8].

materials as shown in **Figure 5**. The tool contains 6% cobalt metal, which is removed from the surface of the substrate by the etching process to improve the adhesion of diamond film with the tungsten carbide substrate. The alternative method to increase the adhesion between both the surfaces is by introducing a new layer of titanium nitride, which provides better adhesion and improves the diamond growth of the tool. Therefore, different types of tools such as diamond-coated (WC), diamond-embedded (sintered), and titanium nitride interlayer tools are used to investigate the drilling performance of the human tooth, glasses, and artificial tooth materials. The deposition of titanium nitride between the diamond film and the substrate performs well compared to the other tools for the orthodontic application [8].

The diamond film deposits as different layers such as monolayer, bilayer, and multilayer on the surface of the cemented tungsten carbide milling tool by the chemical vapor deposition process. The cutting performance of the milling tool is determined on the sintered zirconia ceramic, where the tribological behavior of the tool is identified by using the reciprocal tribometer. The experiments are carried out in the CNC milling machine by comparing the microcrystalline and nanocrystalline layers of the diamond tool without considering the lubrication. The monolayer deposition with nanocrystalline diamond includes a lower coefficient of friction (0.126) due to its smooth surface, the monolayer deposition with microcrystalline diamond provides more coefficient of friction as 0.290. The monolayer diamond coated has a poor tool life due to the higher hardness of the workpiece material. The performance of the multilayer diamond-coated tool exceeds in terms of durability (3–7 times higher) compared to the monolayer and bilayer deposition [9, 10]. Hence, the small particles of diamond are embedded in the tool material for performing different micromachining operations such as turning, milling, drilling, and grinding. This enhances the tool life of the substrate by reducing the wear, built-up edges, and thermal damages to the tool surface.

4. Ductile regime machining of brittle materials

The ductile regime machining of brittle materials produces the material removal in the plastic deformation zone when the applied stress is below the critical stress of the material, which is insufficient to cause the macrocrack formation. The mechanism of material removal is identified by the occurrence of radial, lateral cracking, chipping, and pileup formation on the surface level. The morphology of machined surfaces provides the regular or irregular lay pattern, which confirmed the mode of

S. no	Materials	Fracture toughness, K_{IC} (MPa m ^{1/2})	Young's modulus, E (GPa)	Hardness HV (GPa)	Critical depth of cut (μm)
1	SiC	4	420	24	0.5
2	BK7 glass	0.2	81.5	5.1	0.2
3	Silica	0.75	70	6	0.1
4	Zirconia	8.05	210	13	0.97

Table 1.
Critical depth of cut of different materials [1].

deformation. The chances of both the ductile and brittle mode of deformation occur in the ceramic materials depending on the critical depth of cut. The critical depth of cut d_c (μm) is calculated by Eq. (1) given as.

$$d_c = 0.15 (E/H) (K_c/H)^2 \tag{1}$$

where E is the Young modulus (GPa), H is the Vickers hardness (GPa), and K_c is the fracture toughness (MPa m^{1/2}) of the material [11]. When the depth is below the critical depth of cut, it leads to a ductile regime of machining, where the material removal takes place by plastic deformation. On the other hand, when the depth of cut exceeds the critical depth, it removes the material by brittle fracture. The indentation and scratch tests are conducted on different materials using a diamond tool to understand the ductile-brittle transition as listed in **Table 1**. The tool consists of a different rake angle that is used to study the quality of the surface by varying the depth of cut [12].

4.1 Scratch test behavior of brittle materials

The scratch experiment indicates the scratching of the ceramic material with a diamond grit, which is used to simulate the ceramic machining process. The diamond grit with high negative rake angle is considered to investigate the mode of material removal of brittle components, where the microscopic interaction between the tool and the workpiece is studied in detail [13]. The examiners have identified the definite method of indentation fracture mechanics to estimate the material removal mechanism of different ceramic materials without performing the machining process [14]. The material removal mechanisms of the machining process depend on the nature of the interaction of individual diamond grain with the workpiece material.

Most of the researchers carried out a single grit scratch test to identify the mechanism of material removal. The elastoplastic deformation occurs as the material removal mechanism along with brittle fracture that takes place during the scratching of hard brittle materials as shown in **Figure 6**. The scratch test has been conducted on alumina ceramic by using a single diamond grit of conical shape. The formation of plastic deformation, scalelike cracking, and cracking occurs depending on the increase in grit penetration. The chipping and cracks are produced below a certain critical depth of cut of 3 μm. The pileup area forms on both sides of the scratches at a smaller scratch depth below 3.5 μm based on the processing of microcracks. However, if the depth of cut increases more than 5 μm, the macrocrack initiates and extends within the material [15]. Therefore, the generation of cracks and the material removal rate are more, when the scratch depth increases above 5 μm. The plastic deformation not only occurs based on the undeformed chip thickness but also depends on the hydrostatic stress below the contact area of the single grit.

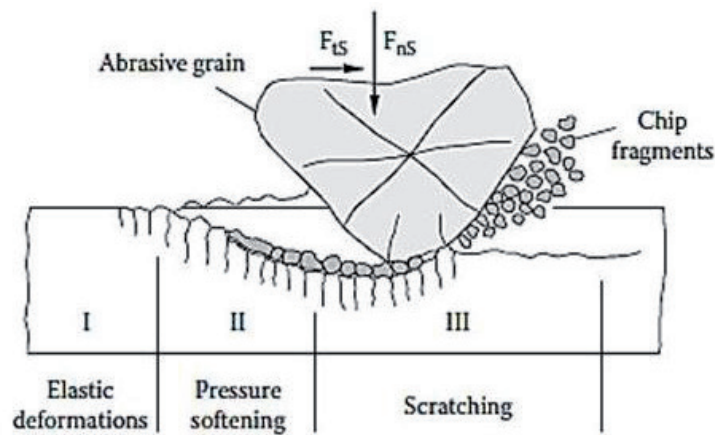


Figure 6.
Material removal process in machining of brittle materials [13].

The transition from ductile to brittle behavior is influenced by the grit shape and the material properties of the workpiece (hardness, fracture toughness, and modulus of elasticity). The mode of material removal also depends on the size of the grains which makes the structure of the material [16].

4.2 Materials having a fine grain structure

When the single grit comes in contact with the fine-grained material, it leads to the plastic deformation based on the shape of the diamond grit and the shear stress level of the material. The shear stress starts increasing depending on the penetration depth of the single grit. While the applied stress exceeds the critical stress of the material, the lateral cracks are formed parallel to the scratch direction along the sides as shown in **Figure 7**. This is associated with the easy material removal during the scratch test. The median cracks occur perpendicular to the cross section of the scratches, which extend toward the inside of the material. This causes the material strength of the workpiece to deteriorate.

4.3 Materials having a coarse grain structure

The material removal observed in the coarse structure takes place in a dissimilar way as shown in **Figure 8**, where the single grit with sharp edges plastically split the grains and the cracks are formed along the grain boundary. This leads to the break-off or chipping near the edges of the scratch. The grit with blunt edges forms a plastically deformed zone at a higher scratch depth

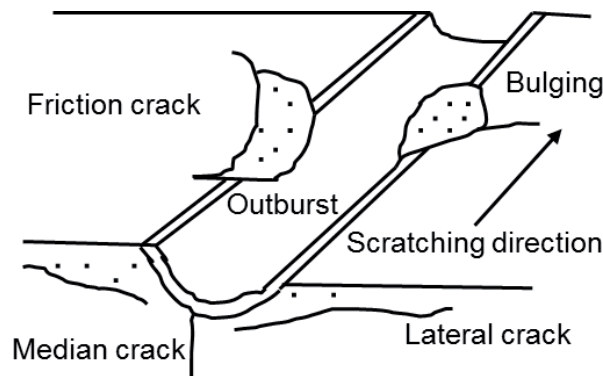


Figure 7.
Different crack system and plastic deformation in the fine-grained structure.

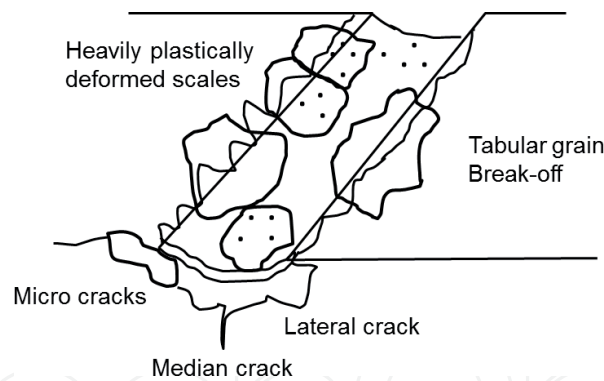


Figure 8.
Slight plastic deformation and break off in coarse grained structure.

due to the increase in shear stress. This enhances the formation of flakes around the scratch surfaces, where the material is pushed forward with more breaking chips at the edges. The single grit scratch test is usually performed to understand the interaction of a single abrasive grain with the work surface. This will enable us to understand the mode of material removal by choosing the parameters for efficient machining of the required material.

5. Tool wear of diamond in ultra-precision machining

The tool wear observed in the ultra-precision machining process is not well understood due to the incomplete studies in the past. The different types of wear mechanisms such as abrasion, adhesion, diffusion, and chemical reaction are formed on the tool surface during the machining process. The tool wear will vary depending on the machining condition and the lubrication used in the experiments. The tool wear is a significant parameter which affects the quality of the machined components and economics of the part produced. The tool wear rate is based on the properties of the work material such as strength, hardness, and fracture toughness. In order to quantify the tool wear in the turning operation, an experiment is carried out for machining the nonferrous and glass materials in the high-speed lathe. The tool wear is observed to be smooth and uniform for the nonferrous materials such as aluminum, copper, and nickel. However, the tool wear is observed to be rougher when machining the amorphous glass material. The abrasion wear occurs during the machining of glass material with the diamond tool, which is caused by the microcleavage that takes place along the crystallographic planes. The cutting edge of the diamond tool is subjected to large chipping. This is caused by the flaws and defect already present in the single crystal diamond. The increase in temperature between the tool and the workpiece interface causes thermal damage to the tool surface. The wear mechanism such as oxidation, graphitization, and diffusion occurs to the diamond tool due to the increase in the heat generation [17, 18]. The materials like glasses are difficult to machine using a sharp diamond tool due to the material property of workpiece such as low fracture toughness, amorphous structure, brittle, and fragmentation. It will also affect the material property of the diamond tool and leads to increase in the wear rapidly. A test is also carried out to evaluate the wear mechanism of the diamond tool during the machining of the glass products. The tool wear is investigated depending on the measurement of the temperature variation of the cutting tool, surface roughness of the material, and the wear zone [19]. The microchipping and cleavage are identified as the dominant wear mechanism during the machining of glass material using a diamond tool as

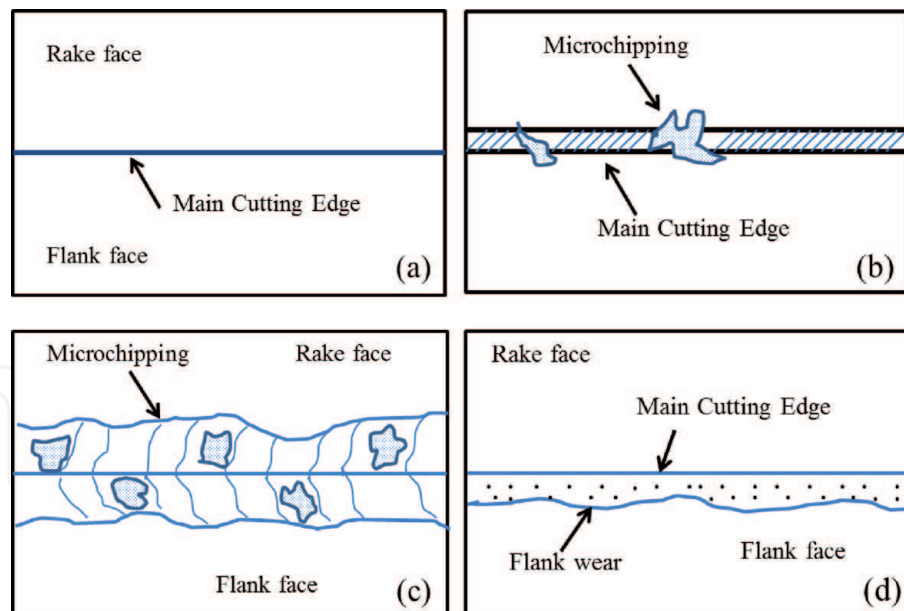


Figure 9. Formation of wear in single point diamond turning tool (a) sharp cutting edge, (b) formation of microchipping, (c) microchipping formed over the entire length, (d) flank wear.

shown in **Figure 9a–c**. The tool life of single crystal diamond is based on the defects like nitrogen impurities present in the chemical composition. The quantity and the types of defects present in the tool material are evaluated by the infrared absorption. The result indicates that the material containing a low amount of impurities will have larger wear resistance. In contrast, the material with high B₂ aggregates will provide resistance to chipping [20].

While machining the ferrous material with the diamond tool, there is more possibility of chemical affinity between the tool and the workpiece interface. This leads to the diffusion tool wear, where the quantities of carbon content from the tool diffuse into the workpiece material. A new method of supplying nitrogen cold plasma associated with ultrasonic vibration is used to reduce the chemical affinity between the interfaces. Moreover, it also reduces the tool wear in the machining of the ferrous materials. This also supports the machining process by reducing the temperature and the surface roughness of the component [21, 22]. In another experiment, the diamond-coated tool is used to turn the graphite bar in high-speed lathe machine under the influence of both the air and nitrogen atmosphere. In addition, the oxidation forms in the presence of air, which causes wear to the cutting tool and decreases the tool life, whereas the blowing of nitrogen in the turning operation reduces the wear of the cutting tool by weakening the oxidation process. The volume of wear of the cutting edge is estimated using a coherence scanning interferometer, where the depth of wear distribution on the cutting edge is measured as a significant parameter. This chemical wear leads to rust formation on the tool edges, which is caused by the heat generated during the experiments [23].

The tool wear is observed during the machining of curved surfaces of optical components under both the ductile mode and brittle mode. In the brittle mode, the undeformed chip thickness is maintained at a certain magnitude of 900 nm, where the material removal is higher before the secondary finishing process, whereas in the ductile mode, the machining is performed at a magnitude of 90 nm undeformed chip thickness. The formation of wear on the rake face of the tool is reduced in the brittle mode. This may be due to the brittle fracture and microchipping behavior of the workpiece, where the wear land is smaller at the cutting edge. However, different types of wear such as crater wear and flank wear occur in the ductile mode as

shown in **Figure 9d**, which looks smooth and uniform along the cutting edges. This shows the development of tool wear is gradual and stable throughout the machining process.

6. Monitoring of ultra-precision machining process

The online monitoring sensors are used to generate control signals during the machining process to improve the productivity of the ultra-precision manufacturing system. Some of the online monitoring sensors are given as temperature, force, power, vibration, and acoustic emission sensors, which are used to control the process effectively. The online monitoring system discusses the requirement of sensor technology in precision and ultra-precision machining process. Online sensors are used to improve the control and productivity of manufacturing systems. Therefore, the features of the sensors are correlated with the changes occurred in the output parameters of the machining conditions as shown in **Figure 10**. This involves the performance of both the tool and the workpiece material.

6.1 Machining forces

The force measurement gives detailed information about the tool wear and the surface integrity of the machined components with the help of tangential force. The power is indirectly calculated by multiplying the tangential force with the cutting velocity. The force sensor uses strain gauges in the earlier period (1950) to record the data during the machining process. Although it provides good substantial data on different operations, it is not frequently used due to the reduction in the stiffness. Recently piezoelectric quartz is used to measure the forces such as normal, tangential, and radial forces. The force sensor is placed on the machine table below the workpiece during the experiments.

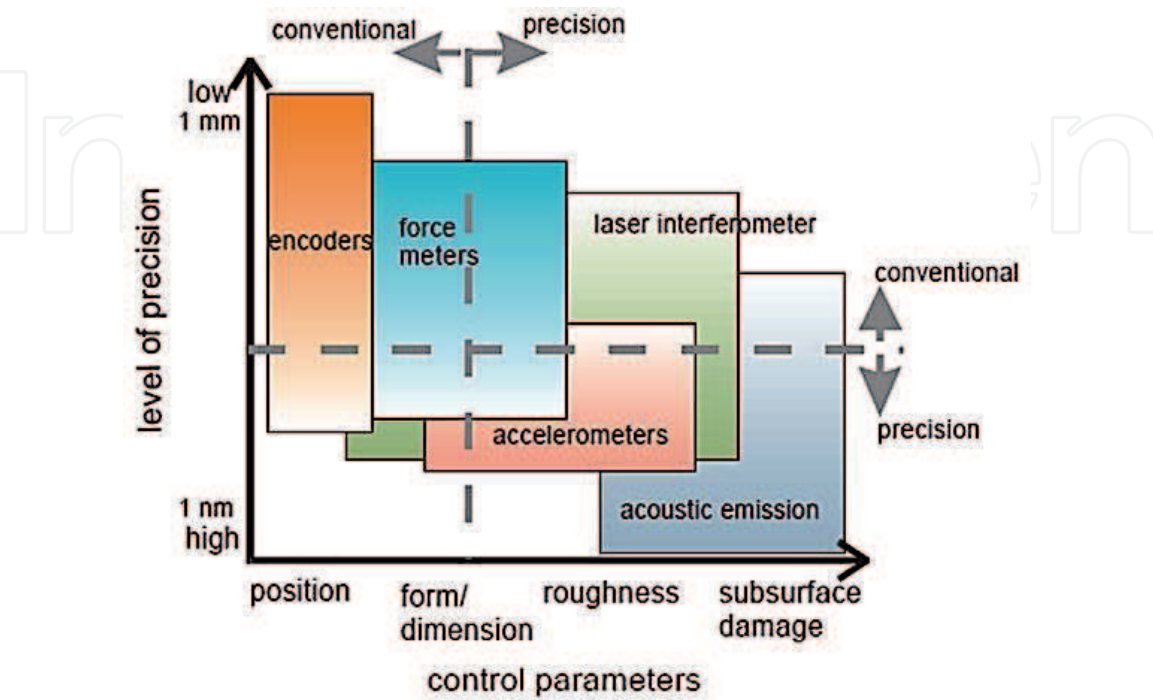


Figure 10.
Level of precision and error control parameters of sensors [19].

6.2 AE signal in ultra-precision machining

Acoustic emission (AE) is the sound waves produced when a material undergoes internal stresses as a result of mechanical loading. AE is commonly defined as the elastic waves in a material caused by the release of localized stress energy. The AE sensor is fixed to the tool or the workpiece to monitor the response of the material during the machining process. It is used to investigate the surface and subsurface damages induced by machining under different environments. The sources of the AE signals obtained from previous research works are listed as crack initiation, chipping, and material deformation. The acoustic emission signals can be generated due to the friction and wear mechanism of the scratch test, where these signals are correlated to the shape, size of abrasive grit, the coefficient of friction, and surface morphology of scratches produced. The requirements of AE sensor application in precision manufacturing and ultra-precision machining process are discussed. The online monitoring sensors are used to generate control signals to improve the control and productivity of the manufacturing systems. The sensitivity of the AE signals is related to the subsurface damages and the mode of deformation based on the type of brittle material used. The purpose of the AE sensor satisfies the corresponding requirement of machining processes such as finer finish and tighter tolerances of the workpiece material [24]. The characteristic of AE signals like root mean square (RMS) value is directly proportional to the uncut chip thickness in the diamond turning process. The sensitivity of the AE signal is related to the variation of uncut chip thickness for different diamond tools such as coated, sharp cutting edge, and worn surfaces. Therefore, an AE sensor is also used as an online monitoring system to identify the cracks of the tool in the machining process.

7. Ultra-precision grinding and polishing

The superabrasive wheels such as diamond and CBN wheels are used as ultra-precision tools to grind hard—brittle glass, ceramic, and composite materials. The problem encountered in the conventional wheel like alumina is wheel loading, which is overcome by the usage of superabrasive wheel. The diamond wheel is used to grind nonferrous material, hardened alloys, and optical glasses for the automotive application. However, the CBN wheel is used to grind hardened steels, heat-resistant alloys, and ductile metals. Although the diamond wheel is essential to grind the hardest, high-strengthened, and wear-resistant material, it resulted in self-sharpening difficulty compared to the conventional wheel. Recently diamond wheel is used to grind silicon wafer and sapphire substrate for the microelectronic application. Moreover, the conventional dressing methods like single point diamond dressing and roller dressing are supposed to remove the grain by shearing and cause damage to the grain structure of the grinding wheel. This will shorten the tool life of the grinding wheel. The dressing process of grinding operation is changed to new technologies such as electric in-process dressing (ELID), laser-assisted dressing, and water jet in-process dressing to improve the dressing efficiency of the ultra-precision grinding. Ultra-precision polishing is an extension of conventional machining method, where the small particles are used to remove the material in the micron size. The material is removed in the elastic plastic deformation in that the formation of brittle fracture is avoided [25]. Mostly it is used to polish the silicon wafer for the microelectromechanical system. Initially, the wafer is chemically etched to form a flat surface, and then the chemical mechanical polishing of silicon wafer is carried out in a single-sided polishing machine as shown

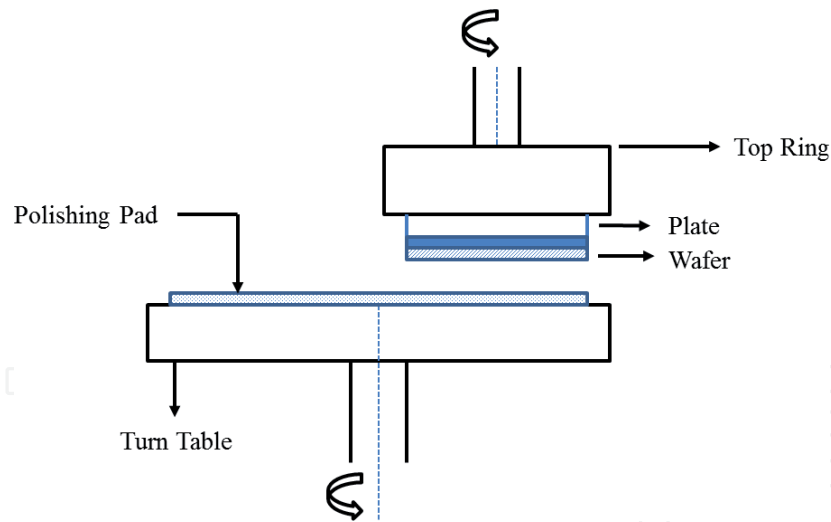


Figure 11.
Single sided ultraprecision polishing machine.

in **Figure 11**, where the wafer is fixed to a plate by the vacuum. The polishing is performed on a rotating table to which the polishing pad is attached and the load is applied to the plate through a top ring. The polishing pad is made up of synthetic leather, and the colloidal silica mixed with the alkaline solution is used as slurry to this process. This produces a mirror and smooth surface finish of the optical devices used in various applications.

8. Conclusion

There is an increase in demand for producing the high dimensional accuracy product in the optical device applications. The diamond tool is required to machine the hard and brittle materials to the specified tolerance limit. But, the occurrence of tool wear is more during the machining of molds of the optical devices, and it will deteriorate the surface finish of the part produced. This increases the cost of the production in the ultra-precision machining process. In order to overcome this scenario, the diamond film is coated to the substrate tungsten carbide to enhance the wear and corrosion resistance of the tool.

An alternative method is also used to machine this ceramic material in ductile regime, where the formation of brittle fracture is restricted. The different types of tool wear such as microchipping and crater and flank wears are observed during the machining process, and the causes responsible for these tool wears are also discussed in detail. Moreover, the monitoring of the ultra-precision machining using AE signals plays an important role in identifying the tool wear. Finally, this chapter gives an idea to understand the ductile-brittle transition of different materials and the efficient way of machining the ceramic molds using the diamond tool in ultra-precision process.

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