Chapter 2

Overview of Diamond Polishing

2.1 Introduction

Polishing is the process of macro-flattening and micro-smoothing of non-uniform surfaces using mechanical, chemical, electrolytic or thermal methods, or a synergistic combination of these. Diamond polishing seems to have been recognized since diamond were found and extracted from the ground as early as 16 A.D. Historically diamond polishing was related to jewellery needs, and remained a trade secret for centuries. The first record of diamond jewels that were polished dates back to 1352 in the French royal inventories [Sudarshan, 1995]. The fabrication of diamond is traditionally based on the use of the hardness of diamond powder or another diamond stone counterpart in accordance with the principle "diamond cuts diamond" [Ralchenko and Pimenov, 1998]. Its evolution as a technique has been based solely on empirical observation.

Since 1980s, the technology "chemical vaporized deposition (CVD)" has rapidly been developed to produce diamond film, which has fuelled hopes of high-tech devices manufactured from diamond, ranging from semiconductors to optical windows and heat spreaders along with diamond's more traditional industrial roles as an abrasive and as a

tool. However, these CVD diamond films are always very rough and usually cannot be directly used in most cases, therefore a polishing process is necessary and indispensable. Many of the techniques developed for gems were extended to polishing diamond films. But these techniques are inefficient, have extremely low polishing rates of the order of 10 nm/h [Bhushan *et al.*, 1994, Sudarshan, 1995], and the film is likely to be damaged and crushed because these CVD films are often very thin with high hardness and low body strength.

Since 1988, various physical and chemical means have been explored to polish diamond and diamond films [Bhushan *et al.*, 1994]. Reviews of these techniques of processing diamond, particularly CVD diamond, can be found in [Bhushan *et al.*, 1994, Malshe *et al.*, 1999, Ralchenko and Pimenov, 1998, Sudarshan, 1995]. With the advancement of the technology, some new methods are being developed to polish diamond and diamond film. The physical and chemical methods for polishing diamond can be broadly classified into contact and non-contact methods. The diamond polishing techniques using mechanical, chemical or thermal method, or a synergistic combination of these include: mechanical polishing, chemo-mechanical polishing, thermo-chemical polishing, dynamic friction polishing, high energy beam (laser/plasma/ion beam) polishing, and electrical discharge machining (EDM).

It is very important to select a proper polishing technique based on the application requirement, shape of workpiece, existing equipment, polishing efficiency and economic constraints. In this chapter, various polishing techniques are reviewed, current understanding of material removal mechanisms is examined with regard to each polishing technique, and features of polishing techniques with their mechanisms are compared.

By comparing these polishing techniques and based on the present application requirement, a polishing method for the present project is selected and developed. Finally, the aims of the present project are presented.

2. 2 Diamond and PCD Polishing Techniques

2.2.1 Mechanical polishing

Mechanical polishing of diamond has been used for a long time; detailed reviews on the mechanical polishing can be found in [Field, 2001, Hird, 2002, Wilks and Wilks, 1991]. The traditional method is usually carried out using a cast iron wheel (called a scaife) of carefully selected porosity, charged with diamond powder and rotating at high speed [Grillo and Field, 1997b, Malshe *et al.*, 1999, Wilks and Wilks, 1991]. The diamond powder is mixed with olive oil, or some other base, to form a paste or suspension which is rubbed over the metal scaife and then left for some time for the suspension to be absorbed by the pores. The surface to be polished is placed against the scaife typically about 300 mm diameter rotating at 2500 rpm under a load of the order of 1 kg. It is recommended to apply a contact pressure of 2.5-6.5 MPa for diamond grinding and 1-2.5 MPa for polishing [Ralchenko and Pimenov, 1998].The final surface finish is controlled by the size of the abrasive powder used. A coarse powder (up to 40 μm) is used in the initial stage of polishing, which allows for fast material removal. A sequence of polishing steps with smaller and smaller diamond particles (finally <1.0 μm) can be used to obtain the desired final surface finish. However, as the particle size decreases, the polishing time increases.

Mechanical polishing is commonly used for polishing single crystal diamond, which may be polished fairly readily by choosing a direction of easy abrasion and avoiding other directions. But the individual grains of diamond in PCD are randomly oriented, so there will always be many grains which present themselves in orientations which are difficult to polish.

In order to avoid having to recharge the wheels with diamond grit, diamond-bonded scaifes are used. These scaifes are more expensive than cast-iron scaifes. However, they avoid the interruptions and skilled labour required to keep cast-iron scaifes charged with abrasive powder.

The rate of material removal during diamond polishing increases with the speed of a scaife and with the load [Hird and Field, 2005, Ralchenko and Pimenov, 1998]. The rate of material removal during grinding and polishing of diamond crystals depends strongly on the crystal orientation and direction of abrasion [Ralcheko and Pimenov, 1998]. Maximum removal rates for the (110), (100) and (111) planes are in the ratio 1:0.6:0.1. Table 2.1 gives some typical values for the removal rate of PCD and single crystal diamond when polished on a cast iron scaife or on a bonded wheel [Wilks and Wilks, 1991]. The wheel speed is 2932 rpm and load is 2015g.

Table 2.1 Removal rates of diamond when polished on a cast-iron scaife / bonded wheel [Wilks and Wilks, 1991]

Material	Direction	Removal rates (10^{-4} mm^3/s)	
		Cast iron wheel	Bonded wheel
PCD, 75 µm grain size	-	-	0.04
PCD, 25 µm grain size	-	12.9	0.04
PCD, 75 µm grain size	-	19.7	–
Single crystal diamond	<100>	5.9	3.3
	<011>	0	0.14

The removal rates with the bonded wheel are much lower when polishing PCD, because diamond powder in the wheel is bonded in a matrix of cobalt which will tend to adhere to the binder in the PCD. Despite the lower removal rates, PCD is generally polished by bonded wheels to avoid the difficulties arising from the loss of powder from cast iron scaifes. Acceptable removal rates are generally obtained by using high speeds and applying large loads to the wheel. Figure 2.1 shows a schematic illustration of the mechanical polishing of PCD using a diamond bonded wheel used in industry, and an example of a polished PCD surface from that diamond-bonded polishing machine. The chemical quality of a PCD surface is not drastically changed by the polishing.

(a) Schematic diagram of apparatus   (b) Surface morphology
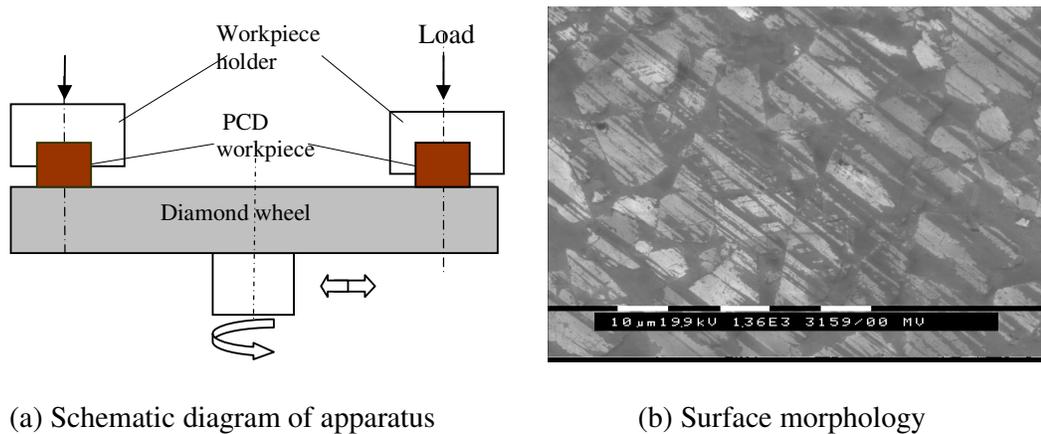
Fig.2.1 Mechanical polishing of PCD

The material removal mechanism during mechanical polishing of diamond is widely accepted as the mechanical process of micro-cleavage, as first postulated by Tolkowsky in 1920 [Tolkowsky, 1920] and further developed by Wilks and Wilks [Wilks and Wilks, 1991]. The abrasion resistance of the diamond is dependent on the position of the cleavage planes relative to the surface being polished.

Since 1981, a number of interesting researches have been conducted to investigate the material removal mechanism [Grillo and Field, 1997a, 1997b, Grillo *et al.*, 2000, Hird and Field, 2004, 2005, Hitchiner *et al.*, 1984, Jarvis *et al.*, 1998, Van Bouwelen, F. M., 2000, Van Bouwelen, F. M. *et al.*, 2003, Van Bouwelen, F. M. and Van Enckevort, 1999, Wilks and Wilks, 1991, Zong *et al.*, 2005]. Since high resolution microscopes have allowed detailed studies of polished diamond surfaces, it has been found that there are also some other wear mechanisms associated with diamond polishing at the sliding velocities and pressures normally used in industry. These mechanisms include:

1) **thermal wear** in which burning or carbonization take place because of the temperature rise at individual hot spots. The high temperature will modify the mechanical properties of the diamond enhancing the mechanical component of wear.

2) **chemical wear** process where irreversible phase transformation of the diamond to sp^2 bonded carbon takes place on the surface of the diamond whilst it is being polished, because the debris produced in polishing the soft direction consists of less dense forms of carbon. Diamond transforms during sliding, and material is then detached from the surface, as it is weakly bonded to it.

3) **electrical wear** in which an attractive force due to tribocharging has been observed for diamond sliding on a rotating surface of amorphous carbon. However, it has been

found that although sparking may occur during polishing, it does not cause material removal [Grillo and Field, 1997b].

Hird and Field proposed two main material removal mechanisms after investigating the topography of polished diamond surfaces that were produced under normal industry conditions [Hird and Field, 2004, 2005]. The first is a phase transformation of the diamond to sp^2 bonded carbon, and is the mechanism that is sought after to produce a good surface finish and acceptable wear rates (e.g. polishing in the 'soft' direction). The second wear mechanism is micro-fracture, but in this way the wear rate is very slow, tending to damage both the diamond and polishing wheel, thus this is usually avoided.

In order to increase the polishing rate, some techniques have been used to improve mechanical polishing. These are discussed below.

Tang *et al.* [Tang, 2003] propose a new elegant technique for polishing thick polycrystalline diamond films. The technique employs a thick polycrystalline CVD diamond film as the polishing abrasive to polish another thick CVD diamond film, and can achieve high polishing rates, up to 10 μm /h, and the mean surface roughness Ra of the films is reduced significantly, e.g. for one film Ra reduced from 5.2 to 1.35 μm, and the other from 3.2 to 0.55 μm. The principal advantages of this new polishing technique are simplicity, flexibility and time saving. This simple method can serve as "rough chipping" to quickly remove the rough top surface and then combine with conventional polishing methods for precision machining to further reduce the surface roughness to a specific desired degree.

In mechanical abrasive polishing, since force applied to the sample to effect polishing can cause subsurface micro-cracking, amorphous silicon oxide (SiO_x) is coated on a rotating scaife [Kim, 1987]. When the diamond layer being polished is rubbed on the scaife, the SiO_x (x=1.97) reacts with the diamond (and its carbon) to form CO and CO_2 thereby removing carbon from the surface chemically in addition to the carbon being removed mechanically. This technique produces precision ultra-smooth, sing-crystal cutting tools at a polishing rate of 20-40 μm/h. A surface roughness of 10 Å rms is achievable using this technique.

A patent application due to [Hall *et al.*, 1987] gives details that scratch-free polished diamond is obtained by rubbing a surface of the diamond to be polished against a smooth complementary diamond surface with sufficient pressure and velocity to heat the surface being polished above the spontaneous thermal degradation temperature of the diamond. Excessive thermal degradation of the diamond is avoided by cooling the surface being polished, preferably by cooling intermittently.

A catalytic grinding wheel was developed by Tsai *et al.* [2007] to shorten the polishing time and decrease surface roughness of a diamond film [Tsai *et al.*, 2007]. Cast iron was used as the binder in the primary diamond grinding wheel and acted as catalyst. Thus, a catalytic reaction occurred on the contact area between the grinding wheel and the diamond surface during polishing. The catalytic reaction and grinding combined to reduce the diamond surface roughness effectively. In this process, a heating apparatus was needed to heat the diamond film to increase reaction activity. After polishing, the surface roughness of diamond film was measured to be about 30 nm Ra.

2.2.2 Chemo-mechanical polishing

Chemo-mechanical (or thermal oxidation) polishing was first used on diamond film by Thornton and Wilks [Thornton and Wilks, 1974], and was further developed by Malshe *et al.* [Malshe *et al.*, 1995, Malshe *et al.*, 1998], and Kuhnle and Weis [Kuhnle and Weis, 1995] to obtain an extra-fine surface finish. This combination technique uses mechanical polishing in conjunction with chemicals to enhance the removal rate. This method exploits the high temperature oxidation property of diamond [Malshe *et al.*, 1999, Ollison *et al.*, 1999]. Figure 2.2 shows a schematic diagram of a chemical/mechanical polishing apparatus [Wang *et al.*, 2006]. In this technique, diamond, under load, comes in contact with a polishing plate in the presence of oxidizing chemicals at elevated temperatures (slightly above the melting point of the oxidizing agents). The polishing disks are commonly made of cast iron [Kuhnle and Weis, 1995, Wang *et al.*, 2006] or ceramic plate (e.g. polycrystalline alumina Al_2O_3) [Bhushan *et al.*, 1993, Graebner *et al.*, 1998, Hocheng and Chen, 2006, Malshe *et al.*, 1995, Ollison *et al.*, 1999] . Oxidizing agents, such as NaNO3, KNO_3 and KOH (the melting temperatures are 308, 324 and 360 °C, respectively) were commonly used for the chemo-mechanical polishing. Recently some mixtures of oxidizing agents have been used in the polishing process to decrease the operating temperature and increase the material removal rate, such as $KMnO_4 + H_2SO_4$ (polish at temperature 70 °C) [Cheng *et al.*, 2005], $LiNO_3 + KNO_3$ (melt point at 130 °C and polish at 350 °C) [Wang *et al.*, 2006]. In addition, diamond abrasive powder can be used to assist the polishing and increase the removal rate.
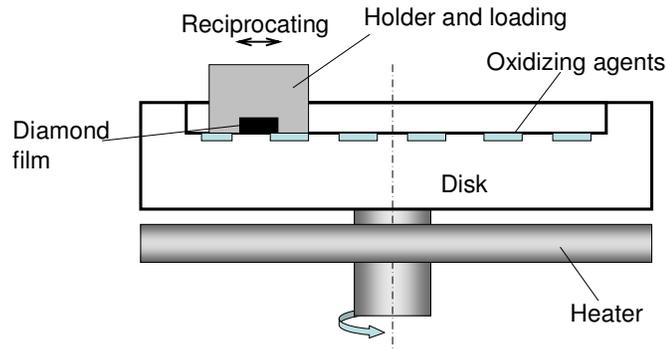
Fig.2.2 Schematic structure of chemo-mechanical polishing apparatus [Wang *et al.*, 2006].

With this polishing method, a typical speed is about 40 m/s, pressure 1.4 Mpa (load 13 N on 3×3 mm^2 specimen) and the polishing rate is in the order of 0.5 µm/h [Kuhnle and Weis, 1995]. Cheng *et al.* [Cheng *et al.*, 2005] reported that by using this method in the presence of potassium permanganate ($KMnO_4$) and diamond powders and polishing at 70 °C, the produced specimen will have an average surface roughness less than 20 nm. Moreover, it was found that damages after chemo-mechanical polishing were much less than those after mechanical polishing [Hsieh *et al.*, 2002], and it took a shorter process time than mechanical polishing. After five hours of polishing at rotating speed 82 rpm, pressure 12 g/cm^2, the surface roughness of the diamond specimen reduced from 1200 nm down to 600 nm with mechanical polishing. It reduced from 1200 nm down to 100 nm after chemical assisted polishing.

In chemo-mechanical polishing, the compound effect of mechanical abrading and oxidant etching plays the main role in the material removal process. The shearing action is a necessary part of this process. Both the oxidizing agents and the polishing plate are known to reduce the diamond surface's roughness. During polishing, the protruding

portions of the diamond specimen contact with diamond powder or the surface of the polishing plate and then micro-cracks are generated on the brittle diamond crystal surface due to the mechanical contact [Ollison *et al.*, 1999]. The oxidizing chemicals enter the micro-cracks and, under pressure and elevated temperatures, react with the fresh diamond material and form CO or CO_2. The reactions open the micro-cracks even further, a higher removal rate than conventional mechanical polishing is therefore obtained. The carbon from the diamond is transferred not only to the alumina (the polishing plate)   but also diffuses into the molten KNO_3 (oxidizing agents). The fresh surface in the cracks reacts with the chemicals resulting in polishing. Thus, the portions of the diamond surface in contact with the polishing plate are oxidized, whereas other areas are not, allowing for the creation of a smooth surface by the polishing. Wang *et al.* [Wang *et al.*, 2006] found that graphite and amorphous carbon could be detected on the surface of polished diamond films by Raman spectroscopy, and concluded that the oxidization and graphitisation combined with mechanical cracking account for the high material removal rate in chemo-mechanical polishing of diamond.

2.2.3 Thermo-chemical polishing

Thermochemical polishing (or hot-metal-plate polishing) which was proposed by Yoshikawa *et al.* [Tokura *et al.*, 1992, Yoshikawa, 1990, Yoshikawa and Okuzumi, 1996] is based on the thermo-chemical reaction between a diamond surface and a hot metal plate. Figure 2.3 shows a schematic diagram of a thermo-chemical polishing apparatus [Tokura *et al.*, 1992]. In this technique, the diamond surface is pressed against a rotating metal plate at elevated temperatures: a typical polishing velocity 2.8 mm/s and nominal pressure 15 kPa, which are much smaller than those for conventional mechanical polishing. The plate temperature during polishing is from 730 to 950 ℃. A

metal plate made of various materials such as iron, nickel, manganese and molybdenum has been used for polishing diamond experimentally [Choi *et al.*, 1996, Chou *et al.*, 2007, Lee, W.-S. *et al.*, 1995, Ramesham and Rose, 1998, Tokura *et al.*, 1992], and it has been found that iron yields the highest polishing rate.
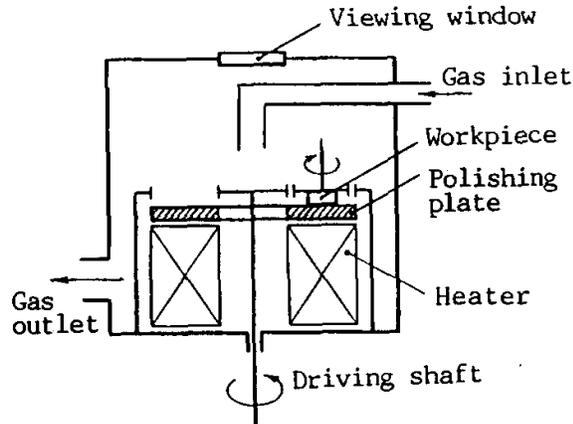

Fig.2.3 Schematic diagram of thermo-chemical polishing apparatus [Tokura *et al.*, 1992]

The polishing rate depends on the diffusion of carbon atoms from the diamond surface into the hot metal plate, with the polishing rate increasing with increasing temperature. If the temperature is too low, polishing is not very efficient because of insufficient chemical reactivity. At high temperatures, some voids, due to selective etching of diamond in the presence of oxygen, are observed and the numbers of voids increase with increasing temperature [Malshe *et al.*, 1999]. However, there is no apparent difference between the polishing rates of diamond as a function of orientations [Hickey *et al.*, 1991].

Hot-metal-plate polishing is affected by the surrounding atmosphere. Polishing has been performed in a vacuum, and in hydrogen, nitrogen, helium, and argon ambient, and the polishing rate is the highest at 950 °C in vacuum (7 µm/h), because carbon diffuses easily into the polishing plate under the close contact between a diamond film and a polishing plate. However, the finished surface is rougher than that obtained in a hydrogen atmosphere, even though the polishing rate of diamond in a 950 °C hydrogen atmosphere is low (about 0.5µm/h). Hence, it is recommended that thermo-chemical polishing is initially performed in a vacuum to take advantage of the high removal rate, then in hydrogen to obtain a smoother finish. The role of hydrogen is a decarburization of the iron disk via methane molecule formation, thus keeping the disk in active state, i.e., able to dissolve new portions of carbon from the diamond surface [Ralcheko and Pimenov, 1998]. A very fine surface could be obtained by this technique, the surface roughness of polished diamond using this method could be reduced to Ra 1.5 nm [Weima *et al.*, 2000a] and 2.2nm [Weima *et al.*, 2000c] as measured by atom force microscope.

The mechanisms of thermo-chemical polishing involve the interaction of diamond with transition metals at an elevated temperature and conversion of diamond into non-diamond carbon by the hot metal, followed by the diffusion of this carbon into the metal [Chou *et al.*, 2007, Jiang *et al.*, 2002, Weima *et al.*, 2001a, Weima *et al.*, 2000a, Weima *et al.*, 2000b, Weima *et al.*, 2001b, Weima *et al.*, 2000c, Weima *et al.*, 1999, Zaitsev, 1998]. Weima *et al.* [2001] found that both the conversion and diffusion rates are temperature dependent, thus the material removal rate increases exponentially with increasing temperature. Also, the increase in the removal rate with increasing pressure applied on the film is due to the pressure-enhanced surface contact between the

polishing plate and the film. Moreover, the removal rate is seen to drop exponentially with increasing speed of the polishing plate. This drop is attributed to the reduction in the surface contact between the diamond film and the polishing plate. However, a high removal rate does not imply good quality polishing. Final smooth polishing can be attained at a low temperature (750 °C) when there is good contact but no adhesive forces between the diamond film and the polishing plate.

The polishing rate depends on the diffusion of carbon atoms from the diamond surface into the hot metal plate [Zaitsev *et al.*, 1998]. This is because the diffusion is an atomic process and requires a good physical diamond-metal contact literally for every diffusing atom, while graphitization is a collective process and the graphitization of a relatively large amount of diamond can be triggered by a comparatively small number of carbon atoms directly contacting with the metal surface. The area of the graphitized surface is believed to be much larger than that involved in the diffusion until the physical diamond-interface is spread over most of the diamond surface.

Zaitsev *et al.* [1998] developed a diffusion model for thermo-chemical polishing. Assuming that the graphitization rate is much higher than the diffusion rate, the removal rate of diamond *R(T, t)* by thermo-chemical polishing can be calculated as:

$$R(T,t) = \frac{A_p}{A_s} \int_0^d C(x,T,t)dx - C_0 d \qquad (2.1)$$

where

$$C(x,T,t) = C_s(T) + [C_0 - C_s(T)erf[\frac{x}{2\sqrt{tD(T)}}] \qquad (2.2)$$

 is the concentration of the carbon at a depth *x* in the polishing plate,

$$D(T) \ [cm^2 \ s^{-1}] = D_0(T) \ exp \ [-\frac{Q(T)}{RT}] \qquad (2.3)$$

is the diffusion coefficient, $R=8.3145 \ J \ K^{-1} \ mol^{-1}$ is the gas constant, T is the temperature, t is the time, C_o is the initial (background) carbon concentration in the polishing plate, d is the polishing plate thickness, C_s is the carbon concentration at the surface of the polishing plate, A_p is the area of the polishing plate swept by the sample, and A_s is the area of the polished sample's surface.

The carbon concentration at the surface of the polishing plate can be written as

$$C_s=\alpha(P) \ C_l, \qquad (2.4)$$

where the coefficient $\alpha(P)$ shows the quality of the diamond–metal contact (the α value depends on the pressure of the sample against the polishing plate, $\alpha=1$ for the ideal contact). The change of the frequency factor $D_0(T)$ and the activation energy $Q(T)$ with temperature can be approximated by the expressions:

$$D_0(T) \ (cm^2 S^{-1}) = 7 \ x \ 10^{-8} \ exp(1.2 \ x \ 10^{-2}T) \qquad (2.5)$$

$$Q(T) \ (kJmol^{-1}) = 2.5 \ x \ 10^2 \ exp \ (1.5 \ x \ 10^{-3}T). \qquad (2.6)$$

The removal rate by thermo-chemical treatment has been quantitatively well described by the diffusion mechanism, provided that the carbon content on the surface of the metal attains its solubility limit. To provide this condition, the metal must decompose the diamond lattice into a non-diamond carbon rapidly enough and work as a good absorber of this carbon.

Thermo-etching

Another thermo-chemical method, diamond etching has been developed at AT & T Bell Laboratories by using the principle of diffusion reactions [Jin *et al.*, 1992a]. A

schematic illustration of the experimental diamond-etching assembly is shown in Fig.2.4 [Mccormack *et al.*, 1994]. Metal (iron, Ce-Ni alloy, etc) foils have been placed in contact with the diamond films under load at an elevated temperature (around 900 °C for iron) in an argon atmosphere. The diffusion of carbon into metal resulted in the formation of a carbide layer on the surface that could be easily removed by placing the films in a 50% HCl solution for 5 minutes. The thinning process also creates relatively smooth surfaces by eliminating much of the roughness from the top faceted surface of the film. A very sharp Raman peak at 1332 cm^{-1} indicates the high quality of the diamond produced by the thinning heat treatment [Jin *et al.*, 1992a].
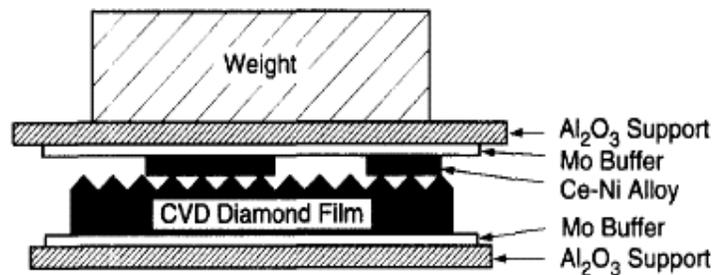

Fig. 2.4 Schematic illustration of the experimental diamond-etching assembly [Mccormack *et al.*, 1994]

This technique was extended further by replacing iron with manganese [Jin *et al.*, 1992b] or molten rare earth metals/alloy (such as Ce or La) where the same diffusion reaction principle has been used but at lower contact pressures [Jin *et al.*, 1993a, Jin *et al.*, 1993b, Jin *et al.*, 1993c, Jin *et al.*, 1992b, Jin *et al.*, 1995, Johnson, 1994, Mccormack *et al.*, 1994, Sun *et al.*, 2006, Wang, J. Y. *et al.*, 2002]. The manganese powder has been found to be much more efficient than iron powder in diamond polishing, since it offers faster reaction kinetics and creates smoother surfaces [Jin *et al.*, 1992b]. A significant

reduction in the process temperature from 900°C to 600°C has been achieved by using rare-earth/transition-metal alloys, such as 89% Ce 11% Ni (by weight) with a eutectic point of 477°C [Mccormack *et al.*, 1994].

The advantages of this smoothing technique are that it is applicable simultaneously to a large number of diamond films, avoiding the polishing of individual films, and it has good perspectives for the shaping of diamond into a non-flat geometry. However, the etching method does not provide a fine finish of the treated surface resulting in a roughness of the order of a few micrometers Ra. Some orientation-dependent anisotropy in etching rate is seen. Etching kinetics more than 60 μm/min have been observed [Sun *et al.*, 2006].

Another new patent for polishing diamond comprises placing the surface of the diamond against the surface of a metal plate and heating the diamond and the plate to a temperature greater than the melting point of metal carbide and less than the melting point of the metal itself [Tzeng, 2000]. The carbon atoms in the diamond diffuse or dissolve through solid state diffusion into the metal to form metal carbide. The metal carbide melts around the points of contact between the diamond and the metal surface, which accelerates the diffusion or dissolution of the diamond and thereby accelerates the smoothing of the diamond surface. When the surface of the diamond is smoothed it is cooled, removed from the plate, and cleaned of residual metal carbide. Moreover, the method could be used for polishing configured surfaces with three dimensional structures.

2.2.4 Dynamic friction polishing

The dynamic friction polishing (DFP) method was developed by Suzuki *et al.* [1996] from a thermo-chemical technique to polish single crystal and then applied to polycrystalline diamond [Iwai *et al.*, 2004, Iwai *et al.*, 2001, Suzuki *et al.*, 2003, Suzuki *et al.*, 1996]. In this method, as shown in Fig. 2.5, a diamond workpiece is polished without using abrasives but by pressing it at a predetermined pressure onto a metal disk rotating at a high speed in the atmosphere. This polishing method utilizes thermo-chemical reaction induced by dynamic friction between a diamond sample and a metal disk tool rotating at a high peripheral speed to generate dynamic friction, and enables highly efficient abrasive-free polishing.
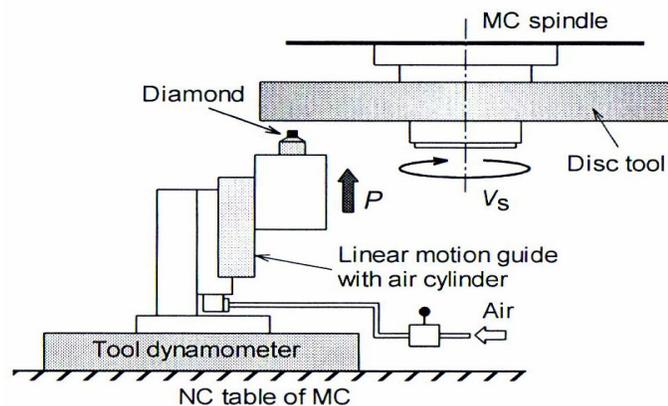

Fig. 2.5 Schematic illustration of the dynamic friction polishing [Iwai *et al.*, 2004]

DFP was first carried out on a single crystal diamond specimen [Suzuki *et al.*, 1996]. When the polishing was carried out at a high speed 66.7 m/s and pressure 114 MPa, a high polishing rate could be achieved leading to 2600 μm/min (0.94 mm^3/min) for a square pillar shaped single crystal diamond specimen (surface 0.6 mm× 0.6 mm). Diamond could not be polished at all when the speed was below 25 m/s under pressure

100 MPa. Also, efficient polishing was only performed when the pressure was greater than 75 MPa at speed 42 m/s. By increasing the speed, the polishing could be carried out at lower pressure [Iwai *et al.*, 2004]. The polishing parameters used are in the ranges of velocity from 42 to 167 m/s, and pressure from 25 to 114 MPa.

Later this method was applied to polishing PCD [Iwai *et al.*, 2001], and it was found that the PCD could not be polished at pressure 27 MPa and at speeds lower than 10.5 m/s; at higher speeds, polishing rate increased with the increase in sliding speed at this pressure. A rather high polishing rate of 1.12 mm^3/min was attained at speed 53.3 m/s and pressure 27 Mpa for a (3 mm × 1 mm) PCD surface. The polishing parameters used are in the following range: sliding speed from 10.5 to 53 m/s and pressure from 3 to 27 MPa.

The DFP experiments by [Iwai *et al.*, 2004, Iwai *et al.*, 2001, Suzuki *et al.*, 2003, Suzuki *et al.*, 1996] were performed on a machining centre, and the finial surface roughness achieved was Rmax 0.06 µm for single crystal diamond and 0.45 µm for PCD.

A metal disk made of nickel and stainless steel has been used for dynamic friction polishing, and stainless steel yielded a much higher polishing rate. Moreover, in a US patent [Abe *et al.*, 2003a, 2003b], a disk tool was made of an intermetallic compound consisting of one or more elements selected from the group of Al, Cr, Mn, Fe, Co, Ni, Cu, Ru, Rh, Pd, Os, Ir and Pt and one kind or more of elements selected from the group of Ti, V, Zr, Nb, Mo, Hf, Ta and W. The diamond polishing was performed by pushing the disk tool against the diamond specimen and rotating them. The polishing could be

conducted at room temperature (when the thickness of diamond was less than ten µm), or heating the diamond (thicker than tens µm) to a temperature within the range 100-800 °C. The polishing could be carried out on a normal grinding machine. The surface roughness of the sintered diamond compact after polishing on the grinder was 0.5 µm or less.

The material removal mechanism of dynamic friction polishing was interpreted by Iwai *et al.* [Iwai *et al.*, 2001] and Suzuki *et al.* [Suzuki *et al.*, 2003] as rapid diffusion of carbon from the diamond to the disk and then evaporation of carbon by oxidization based on the polishing efficiency in various atmospheres. They also carried out X-ray diffraction analyses of the polishing debris and the surface of the metal disk tool. They ruled out the possibility of carbonization of diamond because they did not find graphite in the polishing debris or on the metal disk surface after polishing.

2.2.5 High energy beam polishing

These high energy beam methods include Plasma/Ion beam and laser. Ion/plasma beam and laser polishing are non-contact polishing techniques, which generally do not require force applied to the sample or heating the bulk sample, so can allow polishing of non-planar surfaces and localized polishing of small areas. In plasma and ion-beam polishing techniques, the surface asperities are removed by sputtering and etching by the oxygen ions produced by plasma or by an ion beam. In laser polishing, asperities on the diamond surface are removed by localized heating resulting in high-temperature oxidation. But these techniques require a controlled environment, generally a vacuum, and expensive equipment.

Ion/plasma beam polishing uses the principle of bombardment of the diamond surface with reactive /non-reactive ion beams [Sudarshan, 1995, Zhao, 1990]. In the non-reactive ion irradiation process there is atomic removal of surface atoms as a result of momentum transfer between incident ionic species and the surface atoms [Hirata *et al.*, 1992, Ilias *et al.*, 1996, Koslowski *et al.*, 2000, Seki and Matsuo, 2004]. In reactive ion etching (RIE), interaction between incident ions and surface atoms results in the reactive atomic removal of the surface atoms for smooth surface generation [Buchkremer-Hermanns *et al.*, 1996, Silva *et al.*, 2003, Vivensang *et al.*, 1996]. Polishing can be achieved at incidence angles between 0 and 80° [Hirata *et al.*, 1992]. The polishing rates are dependent on the incidence angle of ion irradiation with respect to the diamond surface and the type and energy of irradiating ions. RIE is faster than non-reactive ion bean sputtering because oxygen oxidizes the carbon [Leech *et al.*, 2002, Malshe *et al.*, 1999], but may cause surface contamination due to plasma heating. The etching rate of diamond that could be obtained is about 9.5 μm/h with very smooth surface of Ra≤0.4 nm [Ando *et al.*, 2002].

In ion beam polishing, the material removal mechanism is that the diamond surface is bombarded with ions that strike the surface at an angle and physically remove carbon atoms [Malshe *et al.*, 1999]. The process of ion bombardment results in localized heating and sputtering. An incident ion with sufficient energy to overcome the surface gas potential barrier will penetrate several surface layers of the solid, and then become neutralized only after several collisions with the host (diamond) atoms [Bhushan *et al.*, 1994]. The ion's kinetic energy and ionization energy are then converted upon recombination into heating of the surrounding lattice so that one or more of the host lattice atoms are sublimated. Alternatively, the incident ion can simply knock off a host

atom by sputtering. In RIE polishing, local heating due to ion bombardment leading to oxidation, as well as sputtering in addition to the chemical pathway exist in this method. These are reactive channels wherein O, O_2, O_3, OH, H, etc. interact and remove carbon from the diamond surface via heterogeneous chemical reactions.

Laser polishing is based on the transient thermal oxidation and/or evaporative ablation of the rough diamond surface. Among a variety of lasers, two types of lasers –Nd-YAG Q-switched pulsed [Ascarelli *et al.*, 1998, Ozkan *et al.*, 1997, Tezuka and Yosikawa, 1990, Tokarev *et al.*, 1995] and excimer lasers [Bogli *et al.*, 1993, Chein *et al.*, 1995, Gloor *et al.*, 1999, Gloor *et al.*, 1998, Pimenov *et al.*, 1993] are widely used for diamond polishing. One of the main advantages of the excimer lasers is a high value of light absorption in diamond, whereas the pulse repetition rate is not very high (typically up to 200 pulses per second). This technique is well suited for coarse material removal from large areas. The polishing rate is limited by grain size, microstructure, laser spot size with respect to grain size, and laser power [Malshe *et al.*, 1999]. A polishing rate of about 100 nm/min could be obtained using a high peak power YAG laser in an oxygen ambient [Bhushan *et al.*, 1994, Malshe *et al.*, 1999]. Laser polishing also depends on the incidence angle of a laser beam, since the power density decreases as the beam incidence angle increases; lower etch rates were observed at large incidence angles. However, incidence angles of 30-60° produced smoother surfaces. Figure 2.6 shows a schematic diagram of a laser polishing apparatus used for polishing of diamond films in different atmospheres [Gloor *et al.*, 1998]. The laser beam is focused on to the diamond film, which is mounted on a programmable stage to produce the scanning patterns.
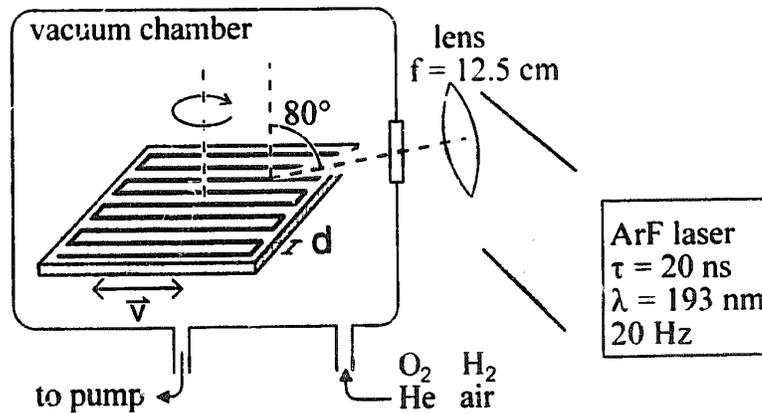
Fig. 2.6 Schematic diagram of laser polishing apparatus [Gloor *et al.*, 1998]

In laser polishing, the material removal mechanism is probably due to the thermal activation of the surface resulting in plasma and graphitization, followed by recombination and removal of the graphite in the presence of oxygen [Park *et al.*, 2000]. During the short laser pulse interaction with the diamond surface, atomic or molecular bonds of the material are disintegrated due to the transmission of high-energy from the laser pulse, and released from the surface, forming plasma due to their high-energy states. The surface of the irradiated spot is heated by the high-temperature plasma, which results in graphitization and possibly oxidation, and then the ejection of materials and deposition of debris around the irradiated spot.

2.2.6 Electrical discharge machining

Peters *et al.* [1947] first applied a high voltage to the pointed tip of a platinum/iridium electrode for the drilling of the initial hole in a wire drawing die [Peters *et al.*, 1947, Wilks and Wilks, 1991], and this electrical discharge machining (EDM) process has been used in cutting electrical conductive material and then PCD [Lee, J. and Schafrik,

1998, Olsen *et al.*, 2004, Spur and Appel, 1997]. EDM removes workpiece materials by harnessing thermal energy produced by pulsed spark discharges across a gap between tool and workpiece. A spark discharge generates a very small plasma channel having a high energy density and a very high temperature (up to 10,000 °C) that melts and evaporates a small amount of workpiece material.

Recently, Guo *et al.* introduced this process to undertake the task of polishing CVD diamond film [Guo *et al.*, 2004, Guo *et al.*, 2002, Guo *et al.*, 2001, Wang, C. Y. *et al.*, 2002]. In order to polish dielectrically conductive polycrystalline diamond, the film is coated with a thin layer of electrically conductive material before polishing, and then EDM is used to machine the coated surface. As a result, peaks on the surface of the diamond film are removed rapidly. During machining, graphitization of the diamond enables the EDM process to continue. Figure 2.7 shows a schematic diagram of wire EDM with high traveling speed. The diamond removal process is complex, it is accomplished possibly by four mechanisms: explosion caused by the spark, graphitization of diamond, evaporation and oxidation of carbon, and chemical reaction of interface to form carbides [Guo *et al.*, 2004, Guo *et al.*, 2002, Guo *et al.*, 2001, Wang, C. Y. *et al.*, 2002].

The polishing rate from a typical polishing experiment shows that it takes four minutes for the surface roughness of a 25 mm × 25 mm sample to be reduced from 13.3 to 1.5 µm Ra [Guo *et al.*, 2004]. It can be seen that the EDM process can reduce the surface roughness efficiently; however, the machined roughness could not meet many industry requirements. EDM is suitable for rough polishing, which should be combined with other polishing techniques to achieve a required surface roughness.
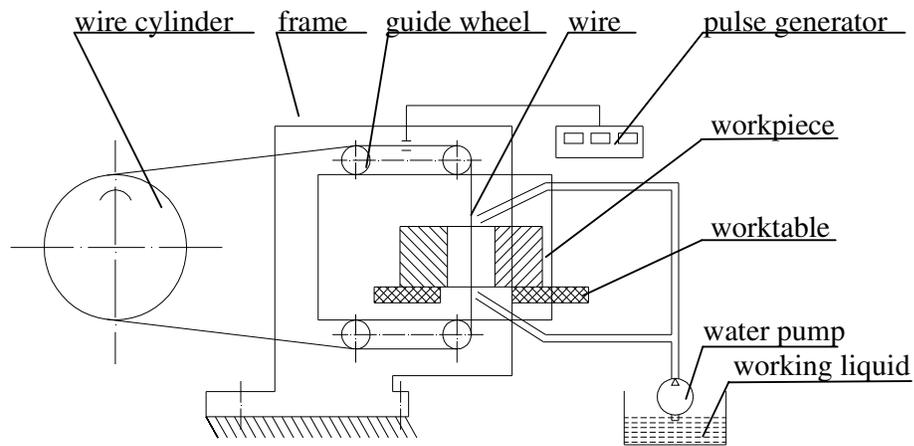
Fig. 2.7 Schematic diagram of wire EDM [Guo *et al.*, 2004]

The material removal mechanisms involved with the above-discussed polishing techniques are now discussed.

2.3 Material Removal Mechanisms

There are a number of different ways of reduction of surface roughness of polycrystalline diamond and they consist of removal of carbon atoms from the diamond substrate by the following processes [Malshe *et al.*, 1999]:

a) Micro chipping

b) Conversion of diamond to graphite, followed by removal of non-diamond forms by micro-chipping, atomic diffusion or chemical reaction

c) Diffusion of carbon into soluble metals

d) Chemical reaction

e) Evaporation/ablation and sputtering

In all the above polishing mechanisms except micro chipping, temperature plays an important role in that these chemical reactions occur only at high temperatures. The above processes are discussed in detail in the following sections.

2.3.1 Micro-chipping

If two moving surfaces come into contact with each other, friction arises between the two surfaces [Malshe *et al.*, 1999]. When the friction force is higher than the atomic binding energy of the material, atoms on the surface layer cannot resist the friction force and are deformed or chipped away from the surface, depending on the brittleness of the material [Bhushan and Gupta, 1991]. Protruding portions of a substrate experience higher friction forces, and are easily chipped away by a process called micro-cleavage, creating a smooth surface.

If an abrasive powder is used in the micro-chipping process, the polishing rate and the final roughness are related to the size of the powder used. Because diamond is the hardest known material, the use of diamond powder is the general way of polishing a diamond surface by the micro-chipping mechanism. This mechanism controls mechanical polishing and chemo-mechanical polishing.

2.3.2 Phase transformation of diamond to non-diamond carbon

There are several types of carbon lattice structures including graphite, amorphous carbon, diamond and fullerene [Pierson, 1993]. Thermodynamically, graphite has a stable structure under atmospheric conditions, while the other lattice structures are metastable. Hence, diamond can be easily transformed into graphite if any activation

energy for phase transformation is supplied [Malshe *et al.*, 1999]. Catalytic materials, such as iron, cobalt, and nickel, decrease the activation energy required to transform diamond into graphite. Thus, protruding crystals on the surface of a diamond that come into contact with a catalytic material at elevated temperature lose their lattice structure and are transformed into graphite or other non-diamond carbon. After the transformation, the graphite is easily removed mechanically/chemically due to the weaker type of binding forces. This mechanism plays a major role in thermo-chemical polishing, dynamical friction polishing, and is involved in more or less all the diamond polishing techniques, more detail will be discussed in Chapter 7.

2.3.3 Diffusion of carbon into soluble metals

Carbon atoms easily diffuse into carbon soluble metals such as Fe, Ni, Mo and rare earth alloys. These metals are ready to react with any source of free carbon and absorb this carbon into their surface. Such a reaction is easily triggered under the temperature and pressure conditions occurring in the diamond polishing process. When the diamond surface comes into contact with the metal disk at an elevated temperature, carbon atoms in the diamond diffuse into the metal disk until it is saturated. The diffusion path for atoms from protruding parts of the specimen is shorter and these areas are attacked at a greater rate. One of the main factors involved in diamond polishing is considered to be carbon diffusing into the metal disk and forming iron austenite. The carbon concentration depends on the distance from the interface, the diffusion coefficient, and time. As the carbon diffusion coefficient and the carbon solubility of the mating material increase, the polishing rate also increases. A thick piece of metal can accommodate more carbon atoms than a thin piece.

2.3.4 Chemical reaction

Chemical reaction may be accomplished with gas, liquid or solid metal/metal oxides and they are involved with different diamond polishing techniques.

There would be gas-surface reactions when diamond is exposed to a reactive atmosphere, such as oxygen or hydrogen at elevated temperatures. Carbon in diamond would convert into CO_x or CH_x gas and then evaporate. In addition, there are channels wherein O, O_2, O_3, OH, H etc. interact and remove carbon from the diamond surface via heterogeneous chemical reactions. These reactions mainly happen in laser and RIE polishing.

Diamond will also react with oxidizing reagents such as KOH or KNO_3 under pressure and at elevated temperatures. The temperatures should be slightly above the melting temperatures of KNO_3 and KOH which are 324 and 360 °C, respectively [Ollison *et al.*, 1999]. The supplied heat and pressure decompose the liquid into oxygen and other constituents near the sample surface. The oxygen generated reacts with the diamond and forms CO or CO_2. This reaction occurs in chemo-mechanical polishing. In oxygenic ambient or direct contact with oxyacid, e.g. H_3PO_4 or $NaNO_3$, diamond will be oxygenated before graphitized.

In addition, diamond reacts with some metals to form carbide such as Ti, Fe, V, Mn and Cr under pressure and elevated temperatures. Furthermore, during thermo-chemical or dynamic friction polishing, metals such as iron would be oxidized and then have a reductive reaction with carbon or hydrogen. In these reactions, metal oxides such as Fe_2O_3 will reduce the level of carbon in metal disk and convert it into free iron and form

CO or CO_2. It is thought that polishing takes place due to evaporation of converted carbon of the diamond into CO or CO_2 gas. Non-diamond carbon then diffuses into the free Fe formed from the above reactions along with the evaporation of carbon in the form of CO or CO_2. These chemical reactions are involved in most reactive contact polishing which includes thermo-chemical polishing, dynamic friction polishing and chemo-mechanical polishing.

2.3.5 Evaporation and sputtering

If sufficient heat is applied to a material surface, the surface will melt and/or evaporate thus the protruding crystals on the surface of a diamond can be evaporated to produce a smooth surface. Different heating sources, such as electric arcs and lasers can be used to heat a diamond surface. This mechanism is dominant in laser and EDM polishing techniques.

When high-energy ions or atoms collide with a diamond surface, the diamond structure is broken and carbon atoms are detached from the surface; this physical process is referred to as sputtering [Malshe *et al.*, 1999]. The ion source must be stable and have a uniform current density to produce a good finish. The sputtering rate can be controlled by changing the collision energy and the number of colliding ions. This rate depends on the material, mainly the relative amount of graphite contained. The more graphite that diamond contains, the higher the sputtering rate, since the sputtering rate of graphite is higher than that of diamond. This material removal mechanism takes place in ion beam polishing.

2.3.7 Summary of polishing pathways

The above material removal mechanisms involve different PCD polishing techniques. Each technique consists of one or more different mechanisms. Figure 2.8 shows a schematic of polishing pathways relevant for diamond polishing.
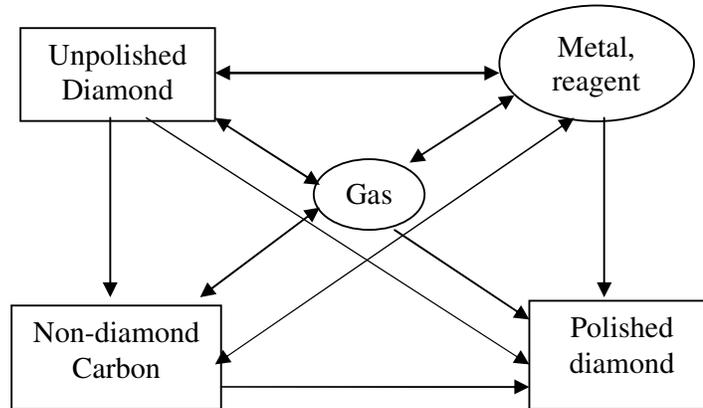

Fig.2.8 Schematic of polishing pathways relevant to diamond polishing

Diamond can be directly polished via micro chipping by mechanical polishing, via sputtering by ion bean, or via evaporation by EDM or laser polishing, respectively.

Carbon in a diamond surface may convert into non-diamond carbon under pressure and at elevated temperatures with or without contact with catalytic metals, and then the non-diamond carbon is detached from the surface by micro-chipping, atomic diffusion into metal or chemical reaction with gas and/or metal to form CO_x, CH_x or carbides.

Carbon atoms in protruding portions of the diamond surface may directly diffuse into molten earth metal or transition metal under pressure at elevated temperatures through the diamond etching method. Also, a diamond oxidation process can occur at lower

temperatures and atmospheric pressure in the presence of an oxidizing agent such as potassium nitrate (KNO_3) or potassium hydroxide (KOH). These processes happen in chemo-mechanical polishing.

Diamond might have a gas-surface reaction in different ambient atmospheres. A reactive gas such as oxygen and/or hydrogen might have a chemical reaction with carbon in the protruding diamond surface to form CO_x /CH_x and then evaporate in EIR or laser polishing. Also the ambient gas (such as hydrogen, oxygen and water vapour) used during the thermochemical or dynamic friction polishing acts as an agent influencing the diamond-metal contact conditions and removing the non-diamond carbon formed on the polished diamond surface. Moreover, these gases will inter-react with metals. A metal such as iron would be oxidized and then have a reductive reaction with carbon or hydrogen. The metal oxides such as Fe_2O_3 will reduce the level of carbon in a metal disk and convert it into free iron and form CO or CO_2.

2.4 Comparison of Various Polishing Techniques

A summary of the variety of polishing techniques is given in Table 2.2. Mechanical, chemo-mechanical, thermo-chemical and DFP techniques are contact techniques which are normally used for planar application. Plasma, ion beam, laser and EDM polishing are non-contact techniques and they can be readily used for non-planar surfaces.

Table 2.2 Summary of various polishing techniques

	Mechanical polishing	Thermo-chemical	Chemo-mechanical	Dynamic friction	Iron beam	Laser	EDM
Bulk processing temperature	Room		>350 °C	Room, Friction heat	Room or 700 °C for RIB	Room	Room
Nature of processing	Contact	Reactive contact	Reactive contact	Reactive contact	Non-contact	Non-contact	
Polishing mechanism	Abrasive wear	Graphitization, diffusion,	Abrasive wear, Oxidation	Diffusion, Chemical reaction	Sputtering	Evaporation	Evaporation
Main applications	Planar surfaces	Planar surfaces	Planar surfaces	Planar surfaces	Non-planar surfaces possible	Non-planar surfaces possible	Non-planar surfaces possible
Size limitations	No limit	Plate size	Plate size	Disk size	Beam size	No limit	No limit
Special requirements	None	Need environmental control	None	None	Need high vacuum	Need scanning of the sample	None
Set-up	Rigid and geometry sensitive	Rigid and geometry sensitive	Simple	Rigid and geometry sensitive	Complex	Simple	Geometry sensitive
Equipment cost	Low	Medium	Low	Low	High	High	Medium
Large area processing cost	Low	Low	Low	Low	High	Medium	Low
Reported roughness	20 nm Ra	5 nm Ra	20 nm Ra	450 nm Rmax	1-50 nm Ra	5-70 nm Ra	1330 nm Ra
Polishing rate	Tens of nm/hr	Few µm/hr	Few µm/hr	1000 µm/hr	Tens of µm/hr	Hundreds of µm/hr	Few µm/min
Surface contamination	Little	Yes	Yes	Yes	Yes	Yes	Yes
Potential for commercialization	High	Poor	Medium	High	Medium	High	High

From reviewing the various polishing techniques for smoothening of diamond and possible mechanisms of the polishing processes, it is found that each polishing technique has technological advantages and also suffers from one or more disadvantages. Polishing rates are highest for DFP, EDM and laser polishing, while thermo-mechanical and ion beam polishing can achieve final surface roughness of the order of a few nanometres. A polishing technique should be selected based on the shape of the diamond sample to be polished, the final surface finish required, the polishing process time and equipment cost. Also optimization of polishing parameters for the various methods used is essential to ensure the best possible polishing results.

Mechanical polishing is a relatively straightforward process and there is no requirement for substrate heating. It has been used for a long time and is widely used by industry. This method produces a polished surface with roughness of the order of 0.02 μm Ra, and the polishing does not drastically change the chemical quality of the diamond surface. But this polishing method has extremely low polishing rates that are of the order of a few tens nm/h and the consuming abrasive diamond or diamond wheel is expensive.

The chemo-mechanical method can provide a higher material removal rate, better surface roughness and less surface damage than mechanical polishing. However, the reaction products tend to accumulate on the polishing disk, so it needs to be removed in order to maintain a continuous polishing process. Also, heating the polishing disk and adding oxidizing agents make the polishing process more complicated.

The thermo-chemical technique offers a fine surface finish, and the polishing rate is much higher than mechanical polishing (in the order of a few μm/h). However, an efficient polishing can only be achieved by heating the polishing disk to temperatures over 750 °C and needs to be conducted in an evacuated atmosphere or in a reductive atmosphere so as to prevent the metal from being oxidized, especially when using iron at high temperatures. Thus, other problems relating to the facilities arise which complicate the polishing process. In addition, surface non-uniformities are introduced partially from the mating metal surface, and contamination occurs with the formation of a diamond-like carbon layer and metal residues in the grain boundaries [Shirk *et al.*, 1998].

The significant features of the laser-based polishing method and its potential superiority over the other existing methods include [Sudarshan, 1995]: polishing at room temperature and short polishing time (from a few seconds to a few minutes); it is a non-contact process and there is no restriction on the shape of the surface to be polished; surface roughness Ra values on the order of a few nm can be achieved. On the other hand, laser polishing has the following disadvantages: chemical non-uniformity of the surface limits the polishing process; polishing area is restricted to laser spot size and scanners are required for polishing large areas of contoured surfaces; graphitic layers could contaminate the surface after polishing of the diamond.

Ion beam polishing methods can achieve final surface roughness of the order of a few nanometres; they are very suitable for many electronic device applications requiring precision polishing in small areas. However, this technique suffers from a complicated experimental set up and large capital cost coupled with critical requirements for

orientation of the sample with respect to ion beam incidence. This restricts the area of polishing to the size of the ion beam [Sudarshan, 1995]. Also, these methods achieve highly non-uniform polishing and contamination in the form of residue formation on the surface between grain boundaries.

The EDM polishing method can provide a very high material removal rate, but the finial surface finish is only up to a few microns Ra. It needs to combine with other polishing techniques to obtain the surface finish requirements of different applications.

The significant features of the dynamic friction polishing (DFP) method and its potential superiority over the other existing methods include:

- Abrasive free polishing by pressing diamond to a metal disk rotating at a high speed to generate frictional heat.
- Short polishing time (in the order of a few tens of seconds to a few minutes), material removal rate up to 0.94 mm^3/min for single crystal diamond and 1.12 mm^3/min for PCD with cobalt binder.
- Polishing at room temperature and not requiring special equipment for heating the polishing disk and diamond specimen
- Polishing in dry atmospheric environment and not requiring a vacuum chamber.
- Surface roughness values of the order of 60 nm Rmax for single crystal diamond and 450 nm for PCD with cobalt binder can be achieved.

Compared to the existing methods utilizing thermo-chemical reaction, the DFP method has a bigger potential for practical applications, as it doesn't require a vacuum chamber and/or equipment to heat a disk.

However, Dynamic Friction Polishing is a relatively recent technique and there are only a few publications available in the literature. Additionally, only two Japanese groups are conducting research in this area. The control and optimization of the process have not been studied. In order to make the technique suitable for practical application, further investigations need to be carried out.

In addition, the reported polishing experiments have been conducted on a machining centre in the laboratory [Iwai *et al.*, 2004, Iwai *et al.*, 2001, Suzuki *et al.*, 2003]. There is no commercial machine available to carry out the polishing experiments, and the material removal mechanisms are far from being fully understood. Also the control and optimization of the process require further investigation.

2.5 Current Understanding and Existing Gaps

The PCD used in the present project is a thermally stable compact containing diamond, SiC and Si. This PCD material is electrically conductive and available in cylindrical blank form in size 32 mm diameter by 40 mm height. From a large blank, Electrical Discharge Machining (EDM) equipment is used to cut the PCD into the desired shape/size. The surface roughness can be reduced from the rough sintered surface down to 0.7-2 μm Ra. But this EDM process can not reduce the roughness further.

The shaped PCD composite surface must be polished to meet the required precision, for example, the surface roughness Ra values of commercial PCD cutting tools were found to be 0.06 μm. Thus a mechanical polishing technique with diamond bonded wheel is

used to polish the PCD surface down to 0.06 µm Ra. However, the polishing rate is so low that it takes about 3 hours to polish a single 12.7 mm diameter PCD surface. Also the diamond wheel is expensive making the process time consuming and costly. So the industry has sought other techniques to polish the PCD compacts effectively.

Because of the advantages of dynamic friction polishing (DFP) discussed earlier, and based on the present application, including the shape of the diamond compacts to be polished, the final surface finish requirements, polishing efficiency and economic constraints, the DFP method was selected to polish the diamond cutting tools.

As noted earlier, a number of studies have been reported in the literature on the DFP process [Iwai *et al.*, 2004, Iwai *et al.*, 2001, Suzuki *et al.*, 2003, Suzuki *et al.*, 1996]. These investigations were involved with polishing efficiency [Iwai *et al.*, 2004, Iwai *et al.*, 2001, Suzuki *et al.*, 1996], polishing mechanisms [Iwai *et al.*, 2001, Suzuki *et al.*, 2003] and final specimen surface finish [Iwai *et al.*, 2001, Suzuki *et al.*, 1996]. The required experimental works for these studies were carried out on a machining centre with the metal disk mounted on the machine spindle, as shown in Fig 2.5. With this type of set-up, it is impossible to carry out the polishing process efficiently and also difficult to control the process parameters such as applied pressure; it can only carry out polishing tests for a single crystalline surface dimension of 0.6 mm × 0.6 mm, PCD surface up to 3 mm × 5 mm (3×1, 3×2 and 3×3). Thus it can be seen that no suitable machine has so far been developed for carrying out the DFP process. A requirement of the present project is to design and manufacture a machine for carrying out the DFP process efficiently and in a controllable manner for a diamond compact of at least 12 mm diameter by 4 mm high.

However, the material removal mechanisms of DFP are far from being fully understood. Iwai *et al.* [Iwai *et al.*, 2001] and Suzuki *et al.* [Suzuki *et al.*, 2003] suggested that rapid diffusion of carbon from the diamond to the disk and then evaporation of carbon by oxidization were the mechanisms. They ruled out the possibility of carbonization of diamond because they did not find graphite in the polishing debris and on the metal disk surface after polishing. However, owing to high temperatures at the diamond–metal interface, the possibility of conversion of diamond to non-diamond carbon during DFP is very high. Furthermore, when grinding or machining ferrous metals with diamond tools, the dominating wear mechanism of diamond is due to its graphitization accelerated by the thermally activated catalytic reaction of iron and ambient oxygen [Ikawa, 1971, Shimada *et al.*, 2004, Wilks and Wilks, 1994]. Thus the present research needs to explore whether chemical/phase transformations occur during dynamic friction polishing and then needs to further investigate the precise material removal mechanisms.

Moreover, it is clear that the chemical reaction of carbon plays an important role in the material removal of polishing PCD, since carbon can react with metals or oxidate at an elevated temperature. It is necessary to estimate the temperature rise during the process, find out the most effective ranges of polishing speed and pressure, and then establish their relation to the material removal rate. Hence, the present research needs to develop a model to predict the temperature rise of the PCD surface during polishing. Such calculations would help determine whether the temperature rise is high enough to stimulate a chemical reaction.

Since the two major constituents, diamond and SiC, have very different properties, e.g., hardness, chemical reactivity, etc. The material removal rates for diamond and SiC would be different during DFP. In addition, a high polishing rate may not result in a good quality polished surface. Thus the polishing process needs to be controlled and optimized to obtain the required surface finish both efficiently and economically.

Aims of the present work:

1. Development of a special polishing machine to carry out dynamic friction polishing of diamond and diamond composites efficiently and in a controllable manner.

2. A comprehensive investigation of the material removal mechanism in dynamic friction polishing by using a variety of material characterization methods and theoretical analyses.

3. Estimation of the interface temperature rise for the polishing, and link the temperature to the chemical reactions.

4. Optimization and control of the polishing process.