Chapter 4

Design and Manufacture of a Polishing Machine

4.1 Introduction

As discussed in Chapter 2, the dynamic friction polishing (DFP) technique utilizes the thermo-chemical reaction between a diamond surface and a metal disk tool rotating at a high speed. In the reported research, the DFP process was carried out on a machining centre [Iwai *et al.*, 2004, Iwai *et al.*, 2001, Suzuki *et al.*, 2003]. With this type of set-up, as shown in Fig.2.5, the polishing load/pressure was only applied in a small area away from the centre of the polishing disk, which could cause disk deformation under the high polishing load/pressure. This can easily result in polishing of only part of the PCD specimen surface. In addition, it can be seen in the machining centre (Fig 2.5), the heavy polishing disk was held on the machine spindle while the PCD specimen and its holder, and the oscillation drive assembly was held on the machine table making the polishing assembly lack rigidity. This type of set up will limit the range of process parameters such as specimen surface area, applied pressure, etc, making comprehensive investigation of the polishing process and its optimization impossible tasks.

It is noted that there is no commercial machine available so far to directly perform the DFP process. Thus, the first task of the present research project is to develop a machine for carrying out the DFP process for PCD composites efficiently and in a controllable manner.

This chapter will discuss the design and manufacture of a special machine for polishing PCD composites. This will include the machine requirements, design considerations of the machine structure and some component assemblies, their manufacture and calibration.

4.2 Machine Requirement and Design Plan

In order to polish PCD composite by the dynamic friction method, the interface temperature needs to be high enough to stimulate a chemical reaction between PCD and a catalytic metal disk during polishing. This elevated temperature is due to the heat generated from the dynamic friction between PCD and the disk. Thus the disk material must be made of appropriate catalytic metals, and the polishing parameters need to be in a proper range to produce a suitable temperature range for effective polishing. According to the literature, the polishing parameters should be in the range of sliding speed from 10.5 to 53 m/s and pressure from 3 to 27 MP for polishing PCD with cobalt binder [Iwai *et al.*, 2001]. In the present project, a theoretical model has been developed to estimate the temperature rise at the interface during polishing at different speeds, pressures, etc (as detailed in Chapter 6). The polishing parameters, in the range of speed from 10 to 30 m/s and pressure from 1 to 8 MPa, could provide suitable temperatures for polishing the thermally stable PCD considered in the present work. In addition, sliding speed and pressure are the most important polishing parameters to control polishing quality and material removal rate. In order to control and optimize the polishing process, the sliding speed and pressure need to be easily controlled and adjustable.

In order to obtain a high speed in a limited size polishing disk, the specimens need to be polished near the edge of the disk. If the load through the specimen is exerted on one side of the disk, the resulting bending moment will deform the disk. To reduce this deformation, the load on the polishing disk needs to be symmetrical. Two specimen holders were designed to polish four PCD specimens simultaneously and the total load is shared equally by the four specimens.

In order to polish the PCD surface uniformly, the load/pressure, relative speed and contact between specimens and polishing disk need to be even over the entire polishing surface. In the present design, specimen holders are designed to rotate in order to ensure the even polishing of PCD specimens.

The polishing disk is driven by a main AC motor which is big and heavy. Thus they need to be placed on the bottom part of the machine to lower the machine centre of gravity and to ensure a stable operation. In addition, the machine is designed for polishing a typical size of PCD specimen of 12.7 mm diameter and 4 mm thick. To polish other sizes of PCD, the specimen holder needs to change dimensions.

The following requirements are also considered for achieving precise and efficient PCD polishing:

- Accurate motion of the polishing disk and specimens, low vibration and a high degree of stiffness of the polishing disk
- Rotational speeds of polishing disk and polishing loads exerted on disk must be continuously variable to enable control of the material removal rate and polishing quality, and consequently optimize the polishing process.
- Simultaneous production of four specimens, and high load/pressure and rotating speed must be achievable in order to polish efficiently.

4.3 Design of Polishing Machine

4.3.1 Structure

Figure 4.1 shows a schematic illustration of the polishing machine. The polishing of PCD specimens is achieved by pressing the specimens at predetermined pressure (1-8 MPa) onto a metal disk rotating at high speed (10-30 m/s). These specimens which slide on the metal disk are mounted on specimen holders which are rotated at low speed for uniform polishing of PCD. The material removal rate is controlled by varying the metal disk rotational speed and/or pressure applied on PCD specimens, which will be discussed in Chapter 8.

The machine consists of two main parts: the lower part covered by a metal housing, and the upper part including two specimen holders and their drive assemblies which are carried up/down by a sliding cross beam. The components of the polishing machine and/or their functions are described below.

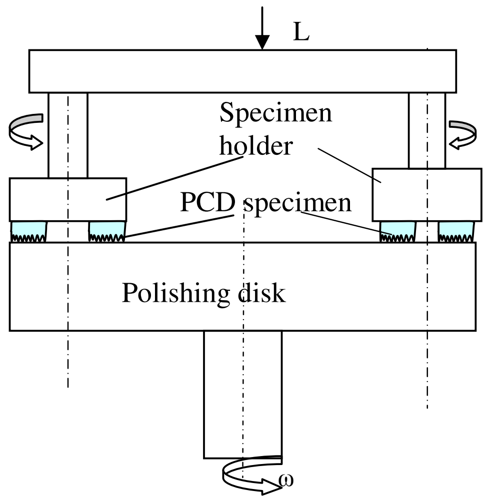

Fig. 4.1 Schematic illustration of the polishing machine

The lower part of the machine in a hosing includes the metal polishing disk and its drive assembly. The metal disk is 450 mm diameter and made of SUS304 stainless steel. The disk is bolted on to a 450 mm diameter mild steel backing disk so that a rigid disk tool for polishing of diamond is obtained. The disk drive assembly includes main AC motor, pulleys and toothed belt, transmission shaft, bearings and their housing, etc. The main AC motor power rating is 18.4 kW with speed continuously variable in the range 0-2800 rpm. The housing for the metal disk and its drive assembly is made of 12.5 mm thick steel plates for rigidity, stability and operator safety.

The upper part of the machine comprises two specimen holders and their drive assemblies, cross beam, etc. The specimen holders can hold up to four PCD specimens and the collets made of steel are used for this purpose. Specimen holder drive assemblies include two 370 W AC gear-motors, coupling, etc. The motors have reduction gear assemblies so that continuously variable speeds in the range 0-95 rpm can be achieved. The sliding cross beam which carries the two specimen holders and their drive assemblies slides up/down on linear bearings mounted on the two columns which are fixed on flat surfaces made on the housing. The upper cross beam could prevent any deflections of the columns under load. The pneumatic cylinder that is mounted on the cross beam controls the movements of the slicing cross beam and the load/pressure on specimens.

Under the present set up, the machine allows simultaneous polishing of four PCD specimens. During polishing, in order to control the speeds of the polishing disk driving the main motor and the two specimen holders driving the gear motors, separate digital control units are used. Based on a predetermined sliding speed for PCD specimens, the metal disk is rotated at the appropriate rotational speed (eg. 1300 rpm) using the digital controller of the main motor. Using the digital controllers of gear motors, the specimen holders are also rotated at predetermined speed (eg. 30 rpm) and the specimens are lowered gradually on to the disk. The specimens slide on the disk under full load within a second. The required load is achieved by regulating the air pressure to the pneumatic cylinder.

4.3.2 Polishing disk

As noted earlier, the polishing disk material is made of stainless steel SUS304. Table 4.1 shows the material components and their weight percentage.

Table 4.1 Components and their weight percentage of stainless steel SUS304

Component	Weight percentage
Fe*	65-74
Cr	18-20
Ni	8-12
Mn	Max 2
C	Max 0.08
Si	Max 0.75
N	Max 0.1
P	Max 0.045
S	Max 0.03

* Iron content calculated as remainder

The reasons for using stainless steel as the polishing disk material are: 1) the elements in stainless steel, in particular Fe, Cr, Ni and Mn which are major alloying components of catalysts used for the commercial production of synthetic diamond under high pressure, can also catalyse the conversion of diamond to graphite at low pressure and at temperatures above 700 °C; 2) the elements of Cr, Ni etc can also catalyse the oxidation of carbon; 3) low thermal conductivity which will help to maintain a high temperature of the diamond sample without releasing the heat generated by dynamic friction; 4) low carbon content (<0.08%) having advantages of carbon diffusion by thermochemical reaction; 5) austenitic structure of SUS304 steel that may also be advantageous to the diffusion of carbon. Chapter 7 will discuss the polishing mechanism in greater detail.

The diameter of the polishing disk is determined based on the requirement of the polishing speeds which are from 10 to 30 m/s, as discussed in section 4.2. The rotating metal disk has the highest linear velocity at its edge, and the lowest one at its centre. The disk diameter needs to be within a certain range to attain the required sliding speed corresponding to the motor rotational speed range. When the required sliding speeds are known, the mean sliding diameter of the polishing disk could be calculated from [Oberg *et al.*, 1978]:

$$V = \frac{\pi D_d n}{60}, \quad (4.1)$$

thus we can determine

$$D_d = \frac{60V}{\pi n}. \quad (4.2)$$

V is sliding speed at mean diameter of polishing disk, in m/s, the required maximum speed is 30 m/s in present work; D_d is the mean rotating diameter of polishing disk, in meter, we need to calculate; n is number of revolutions per minute (rpm), the maximum n of present selected motor is 2920 rpm.

Substitute the maximum V and n in the equation (4.2), D_d can be calculated as 0.2 m. Assuming a safety factor of 1.7 for safe operation, the mean rotating diameter is determined to be 350 mm. Since the specimens is proposed to rotate on the polishing disk within a ring area 100 mm from the edge, the disk outer diameter is designed to be 450 mm, and its inner polishing diameter 250 mm.

4.3.3 Motors and their controllers

The polishing disk and the two specimen holders are driven by a main AC induction motor and two AC gear motors, respectively. AC induction motors are the most common motors used in industrial motion control systems. The main advantages of AC induction motors are simple and rugged construction, low-cost, easy maintenance and an ability to directly connect to an AC power source.

The power requirement of the main motor is based on polishing speed and pressure/load. The polishing parameters are in the range of sliding speed 10 to 30 m/s and pressure 1 to 8 MPa. The size of the PCD specimen is assumed to be 12.7 mm diameter and 4 mm thick.

At maximum pressure P= 8 MPa, specimen diameter d=12.7 mm, the load L exerted on one specimen is:

$L=PS=\pi d^2P/4$ = 1013 N. (4.3)

The motor needs to provide the required energy to drive the polishing disk and overcome the frictional force. The coefficient of friction between the disk and PCD is taken to be 0.15 based on the measurement by Iwai *et al.* [Iwai *et al.*, 2001],[1] then the friction force can be calculated as:

$F= \mu L$=152 N. (4.4)

Under maximum required speed V=30 m/s, the motor power W required to drive the metal disk for polishing one specimen can be calculated as [Juvinall and Marshek, 2000]:

$W=FV$= 4560 w (4.3)

If four specimens need to be polished simultaneously, the power of the main motor should be four times, that is 18.2 kW. Thus the selected motor is an 18.5 kW AC motor EMM4107-58 with maximum rpm of 2920, three phrases 400V to drive the polishing

[1] The coefficient of dynamic friction was measured to be from 0.13 to 0.2 at pressures 17 and 27 MPa with a mean value of about 0.15.

disk. The dimensions of the motor are 597 mm length, 423 mm width and 397 height. The weight of the motor is 132 kg, so it is placed on the bottom part of the machine.

The selected motor can also be used to polish bigger PCD specimens, since its selection is based on maximum speed and pressure requirements. Generally, polishing PCD requires low pressure combined with high speed, and high pressure with low speed. The speed/pressure requirements will be discussed in greater detail in Chapter 8. If higher loads are needed to polish much bigger PCDs, it can be done by polishing less than four specimens (eg., two specimens, that is one in each holder) at one time.

To ensure uniform polishing of PCD surfaces, the specimens need to rotate onto the polishing disk by using specimen holder drive systems to control the rotation of PCD specimens. The motors also need to overcome the frictional force to drive the specimen holders. The rotating speed of the motors is considered to be less than 100 rpm. The specimens are proposed to rotate in a circle of 100 mm diameter onto the polishing disk. At these conditions (rotating diameter D_h= 0.1 m, and n=100 rpm, maximum pressure is 8 MPa and one motor drive two specimens), the motor power required to drive one specimen could be calculated as [Juvinall and Marshek, 2000]:

$$W=FV=F(\pi D_h n)/60= 80\text{W} \quad (4.6)$$

To drive two specimens simultaneously, the required power is 160W. Considering factors of safety and availability to polish larger specimens, two 0.37 kW AC gear motors GMP5346 – three phase- parallel shaft are selected to drive the specimen holders. This gear motor is attached with hardened and ground steel helical gears for quiet and reliable continuous duty. The gear box could reduce the rotating speed from

1430 rpm to 95.4 rpm with a gear ratio of 15:1. The maximum torque is 34 Nm and the full load output rotating speed is 95 rpm. It can provide continuous duty and also provide reversible rotation. The weight of the motor is 14 kg with dimensions of 384 mm length, 132 mm width and 194 height.

The rotating speeds of the motors are controlled by Variable Frequency Drive (VFD), which is a system made up of active/passive power electronics devices and a high speed central controlling unit (a microcontroller). The basic function of the VFD is to act as a variable frequency generator in order to vary the speed of the motor as required by the user. The rectifier and the filter convert the AC input to DC with negligible ripple. The inverter, under the control of the microcontroller, synthesizes the DC into three-phase variable voltage, variable frequency AC.

The base speed of the motor is proportional to supply frequency. By changing the supply frequency, the motor speed can be changed. The AC drives are based on pulse-width modulation (PWM). The constant AC line voltage with 60 or 50 cycles per second from the supply network is rectified, filtered, and then converted to a variable voltage and variable frequency. When this output from the frequency converter is connected to an AC motor, the motor speed could be adjusted.

The main 18.5 kW motor was controlled by a three phase inverter KBN2-4320-1, which can be used in variable torque applications. The input is three phase 380-460 VAC, 50/60 Hz. The output of the inverter was microprocessor controlled PWM. Its output frequency ranged from 0.1 to 400 Hz. Its resolution was 0.01 Hz (digital), also the frequency is displayed by light emitting diode (LED). It had easy start/stop control and digital speed control and programming.

The 370 W specimen motors were driven by a KBE2-2150 PF inverter, which used single phase input 200–240 VAC and 50/60 Hz voltage supply, and was attached with an Electro Magnetic Interference (EMI) filter. The inverter has a microprocessor controlled PWM output, with frequency range from 0.1 to 400 Hz, and 0.01 Hz frequency resolution.

4.4 Manufacture and Assembly of the Machine

Since a polishing machine needs to operate at high speed and pressure, vibration should avoided uniform polishing with very tight surface roughness, the parts need to be machined in tight tolerance and assembled with perfect fit. All parts were separately machined and heat treated as required.

The polishing disk driving assembly was first manufactured. The shaft was welded to the backing disk and then precisely machined together. Bearings and the main shaft were assembled and then installed in the bearing housing. After that the polishing disk was mounted to the backing disk, and the motor was connected to the shaft through pulleys, belt and coupling. This assembly was then tested to ensure smooth operation without vibrations. The whole assembly was mounted on the frame and covered by the housing for safe operation.

The specimen holders were made separately and connected to their driving gear motors by coupling, bearings and their housing. These two specimen holder assemblies were mounted to a sliding cross beam which was controlled by a pneumatic cylinder. Figure 4.2 depicts an image of the completed machine. The sliding cross beam was mounted through linear bearings on the two columns which were fixed on the housing.

Fig. 4.2 Image of the polishing machine

4.5 Machine calibration

4.5.1 Load

The load applied on the specimen was calibrated by a load cell, which was connected to a data taker DT800 and a computer. The load applied on the load cell could be read from the computer via time. The load cell was first calibrated using a standard load from INSTRON 4302 Universal Testing Machine.

A load cell is a force transducer, which converts force or weight into an electrical signal. Usually it includes two distinct parts: a spring element which deforms under the load, and a sensor element which measures the deformation. The strain gauge is the heart of a load cell, and it changes resistance when it is stressed. One or more strain gauges are used in making a load cell. Each gauge patch consists of one or more fine wires cemented to the surface of a load cell. As the surface to which the gauge is attached becomes strained, the wires stretch or compress changing their resistance proportional to the applied load. Multiple strain gauges are connected to create the four legs of a Wheatstone-bridge configuration. When an input voltage is applied to the bridge, the output becomes a voltage proportional to the force on the cell. This output can be amplified and processed by conventional electrical instrumentation, such as a data taker and computer.

Figure 4.3 shows the applied load on the specimen holder with the time. It can be seen that the load stayed nearly constant over one and a half hours at about 450 N. However when it was unloaded and reloaded again, the load was slightly smaller than when it was loaded before (in Fig. 4.3). But the difference was less than 1%, which is negligible.

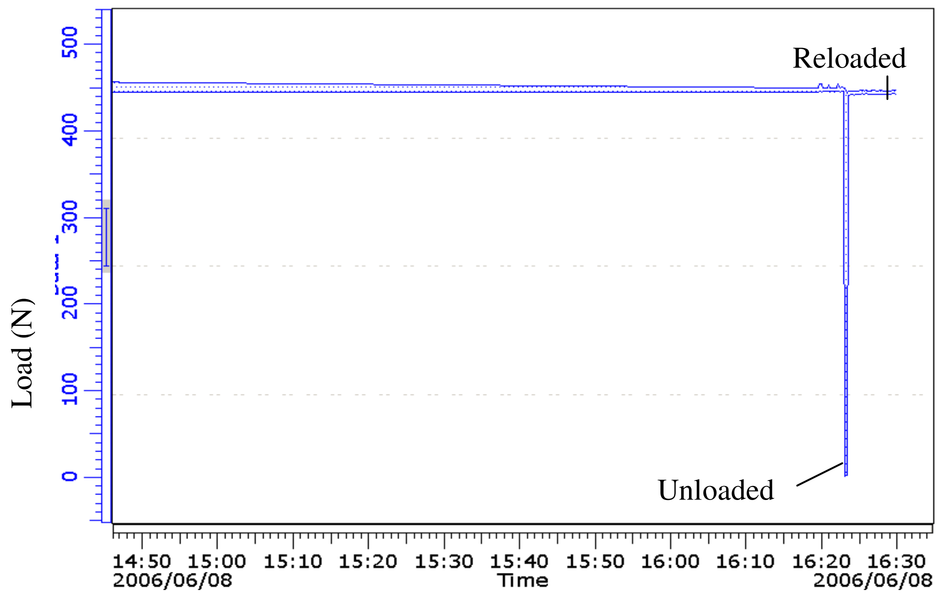

Fig.4.3 Load variation via time, unload and reload.

The loads used for the experiments were calibrated and are shown in Table 4.2. Before a polishing test, the load was checked by a weighing scale.

Table 4.2 Calibrated loads used for polishing experiments

Load		Pressure on 12.7 mm diameter specimen (MPa)
kg	N	
96	940	7.4
64.5	630	5.0
48.5	470	3.8
40	390	3.1
35	340	2.7

4.5.2 Speed

The actual speed of the polishing disk and specimen holder was measured by a hand-held tachometer. The tachometer measured the speed of the rotating metal disk or the specimen holders in rpm. It has three measurement ranges: 0-400 rpm, 0-2000 rpm and 0-10000 rpm. This traditional tachometer requires physical contact between the instrument and the rotating disk or the specimen holder.

Tachometers operate on the principle that the voltage produced by a rotor is directly proportional to the angular velocity of the rotor. The proportionality constant that is used to translate mechanical motion into voltage has typical values of 1 to 30 volts per 1000 rpm. Tachometers are used to measure speeds (of linear or rotary movement). Pulses are fed to the tachometer at the frequency to be measured. A scale factor is applied to produce readings of the desired type. The tachometer totals the number of pulses received during a fixed period of time known as the time base. At the end of this period, a value for the frequency measured is shown on the display.

Figure 4.4 shows the measuring results of variations of the metal disk's rpm via different output frequency of the motor control system. The output frequencies were displayed on the motor drive controller screen. According to Fig. 4.4, it can be seen that the frequency and the rpm of the disk follow a linear relation with a coefficient 52.3. Thus the rpm of the rotating disk can be calculated by multiplying the displayed frequency by the coefficient 52.3. The sliding speed can then be calculated by Equation (4.1).

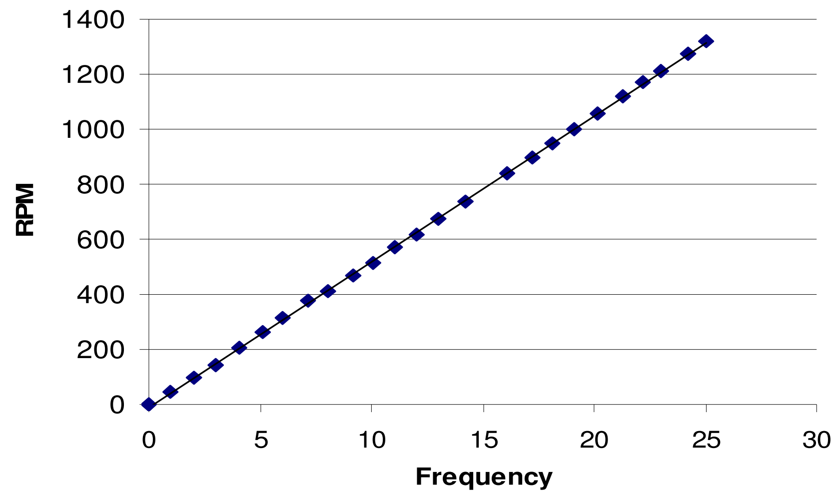

Fig. 4.4 RPM of disk rotating via frequency of the output control

By using the same method, it was found that the coefficients for the two gear-motors are 1.75, so that their speeds can be calculated by multiplying the displayed frequency of the specimen motor by the coefficient 1.75.

4.6 Summary

For polishing PCD using the dynamic friction method, the polishing machine is required to provide appropriate ranges of speed and pressure to generate high temperatures, and to facilitate the PCD surface contacting a suitable catalytic metal disk. The load/pressure and relative speed between specimen and polishing disk need to be distributed evenly over the whole polishing surface during polishing to obtain a uniform polishing surface. A special PCD polishing machine was designed according to these requirements. In addition, the machine was built in-house. The polishing speed and pressure have been calibrated and can be varied for different polishing conditions.