Chapter 1

General Introduction

1.1 Background of this Thesis

“A diamond is forever”. Diamond is known as the ultimate gemstone of perfect clarity, brilliance, hardness, and permanence. Diamond has long been the king of all jewels, and it is also a very attractive material for many industrial applications because of its unique combination of optical, thermal, mechanical, chemical and semiconductor properties. These include the highest hardness and the highest thermal conductivity of any known material, high electrical resistance, large optical band gap, high transmission from ultraviolet to infrared regions, chemical inertness to most corrosive environments, and low adhesion and friction, extremely low thermal expansion coefficient [Field, 1979, 1992, Nazaré and Neves, 2001, Pierson, 1993, Prelas *et al.*, 1998, Sung, 2003, Valentinas, 1997, Wilks, J. and Wilks, E., 1991]. For example, diamond is an ideal material for cutting tools and wear resistant components because of its extreme hardness and low coefficient of friction. Further, diamond is highly resistant towards chemicals, making it an ideal material for protection of components in harsh environments. Another important application is as substrate material for integrated circuits, non-memory semiconductors, and laser diodes due to its combination of high thermal conductivity, high electrical resistance, high mechanical strength, low dielectric constant, and low coefficient of thermal expansion.

However, the full industrial exploitation of this unique combination of properties has been limited by the scarcity and expense of natural diamond. In 1954, General Electric first synthesized diamond grits under high pressure and high temperature and then commercialized synthesized diamond [Bundy *et al.*, 1955, Hall, 1955, 1960, 1961]. But their small sizes had restricted applications, e.g., only for making grinding wheels. Many useful applications require a surface larger than a grit. In early 1960s both General Electric and Megadiamond began to develop polycrystalline diamond (PCD) by sintering diamond grits together [De Lai, 1964, Hall, 1970, Horton *et al.*, 1974, Pope *et al.*, 1974]. This is a short cut to get a larger diamond because the sintering process avoids the problem involved in growing large single crystals, and PCD is a much tougher material than diamond, because the crystallites of PCD are oriented in random directions so the passage of a crack tends to be held up when passing from one crystallite to another, and PCD will be worn uniformly in all direction [Sung, 2000, Wilks, E. and Wilks, J., 1991].

However, these PCD compacts which contain significant amounts of bonding metals (e.g cobalt, nickel) are thermally unstable. First they are made under very high pressures and temperatures and thus require highly specialised and expensive apparatus. Moreover, the sizes of PCD compacts are relatively small. If the compacts are subjected to high temperatures (e.g. >800 °C.) as can be produced during drilling of hard rocks or machining hard ceramics, the metallic inclusions can catalyze the retrogressive transformation of diamond to graphite, which results in a reduction in strength and/or complete degradation of the material. The solvent/catalyst is also responsible for a second undesirable effect: because diamond has a very low coefficient of thermal expansions, much lower than that of bonding metals, heating the PCD produces differential expansions and internal stresses, additional to those caused by the volume changes associated with any graphitization.

Therefore, a new class of thermally stable PCD composite systems has been developed by the industrial partner of this project, Ringwood Diamond Material Technologies (DMT) Pty. Ltd. These compacts use silicon carbide (SiC) and related materials to form strong inter-particle bonds among diamond grains at intermediate high pressures [Ringwood, 1986, 1991, 1992]. They are very attractive cutting tool materials because of their properties, such as ultra high hardness and thermal conductivity and strength, low coefficient of friction, excellent wear resistance, and chemical inertness to most corrosive environments. Moreover, since these PCD composites are made under intermediate high pressure, they can be made significantly thicker with lower cost equipment. The electrically conductive silicon carbide binder further stabilizes the diamond composites and allows them to be shaped into virtually required shapes by Electrical Discharge Machining (EDM).

To conduct quality precision machining, the cutting tool must have an excellent surface finish and cutting edge sharpness. 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. However, because of the ultra high hardness and chemical inertness of diamond and ceramic bond SiC, effective polishing of the cutting tools has been very difficult. In addition, the two phases in a compact (diamond and SiC) have very different properties, such as, hardness, chemical reactivity, etc., thus the material removal rates for diamond and SiC would be different during polishing.

The polishing technique employed at Ringwood DMT for PCD compacts is traditional mechanical abrasive polishing, which uses a diamond wheel to polish PCD compacts. The polishing rate is extremely low, it takes about 3 hours to polish a 12.7 mm diameter PCD surface, and therefore is time consuming and costly, and greatly contributes to the high cost of PCD tools. Moreover, if a high force is applied to the workpiece to effect polishing, it would cause subsurface micro-cracking. Thus an effective PCD polishing method needs to be developed.

1.2 Aim of this Thesis

This present work aims to develop an effective (efficient and economical) PCD polishing technique to improve the quality of PCD cutting tools, raise the surface integrity of a machined component to the highest possible level and reduce the tool production cost. There are five issues to be addressed:

- Development of an effective polishing technology for cutting tools made of sintered, thermally stable composites of diamond
- Design and manufacture of a new machine for polishing PCD composite
- Experimental and theoretical investigation of the material removal mechanisms in PCD polishing to gain a better understanding of the process
- Modelling of the polishing process

- Control and optimization of the polishing parameters and conditions by establishing relationships between surface integrity and processing parameters to find out the most suitable parameters to obtain the required surface finish efficiently.

1.3 Thesis Organization

This thesis consists of nine chapters. Following this introduction, Chapter 2 reviews the diamond polishing techniques and the material removal mechanisms involved. By comparison of the various polishing techniques and based on the project application, an effective PCD polishing technique is developed in the thesis work.

Chapter 3 describes the characterization methods used in our experiment for examination of the surface integrity, and investigation of the PCD polishing mechanisms by micro-structural and chemical structure analyses and temperature measurement.

The design of a new polishing machine for PCD and its manufacture, fabrication and calibration are presented in Chapter 4.

Chapter 5 presents the polishing experiments and experimental study of the material removal mechanisms by investigating the PCD specimen surface and polishing debris using microscopy, spectroscopy and diffraction analyses.

A theoretical model to predict temperature rise at the interface during polishing is presented in Chapter 6. Additionally the temperatures at subsurface are measured experimentally and compared with the theoretical predictions.

In Chapter 7, the material removal mechanisms of PCD are analysed based on the theoretical and experimental results, including reaction of carbon with metal, carbon phase transformation, diffusion and chemical reactions at elevated temperatures.

Chapter 8 presents the optimization process by investigating the effect of polishing parameters on material removal rate and surface characteristics of polished specimens to obtain the required good quality surface at a very high polishing rate.

In the last Chapter 9, conclusions drawn from the present work and suggestions for future work are given.

Overall, the work conducted in present project seeks to develop a sound scientific methodology for the effective and efficient polishing of thermally stable PCD composite, and to optimize the processing conditions to obtain the cutting tool application requirement with surface roughness less than 0.06 µm Ra. It includes development of a new polishing machine, extensive investigation of the material removal mechanism, presentation of a theoretical model and optimization of the polishing process.