STRUCTURE, MATERIAL PROPERTIES AND APPLICATIONS OF DIAMOND-LIKE MATERIALS

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ABSTRACT: In this paper are reviewed the fundamental properties of diamond and similar materials as suitable to the requests of the today manufacturing. A number of studies are given where these so-called 'superabrasive materials' are utilised in industry. Several types of new materials, used as cutting edges, are also discussed and their possible impacts on increasing even further the use of such kind of materials. In addition, this paper gives details about the role of polycrystalline diamond and cubic boron nitride tools in the area of machining of new materials with relevant contributions from scientific literature. In the end are presented the advantages and benefits in using electro discharge machining in shaping the form of the cutting edge of the cutting tool.

KEY WORDS: diamond, polycrystalline diamond, cubic boron nitride, electro discharge machining

1. INTRODUCTION

Nowadays requirements in machining industry are becoming higher and higher in terms of quality in order to reduce machining time. This is why the high speed machining is the answer to these demands. Developing a machine tool able to provide great performances is somehow an attainable goal but is only a part of equation. The tool represents the other part more precisely the cutting part of it. In order to maintain the tool life, during high speed machining, the cutting edge is made from materials with great mechanical characteristics. One of these materials is diamond, a well-known material from hardness point of view (1.0 x 104 kg/mm^2). Other favourable characteristic of diamond is the ability to conduct heat from cutting area (diamond has one of the greatest thermal conductivity - typical 1000 to 1200 W/m°K). Unfortunately, it has proved very difficult to exploit these properties, due to both the cost and lack of large natural diamonds, and the fact that diamond was only available in the form of stones or grit. Another restriction is given by the fact that diamond has a natural affinity to ferrous materials in the presence of heat (over 600 ^{0}C) [1]. Hence, diamond cannot be used for dry machining of ferrous materials; still, is a perfect solution for machining nonferrous ones and composites structures. For ferrous materials, the solution comes from cubic boron nitride materials.

It had been known for many years that diamond is composed solely of carbon and many attempts were made to artificially synthesise diamond using, as a starting material, another commonly occurring form of carbon, graphite. This proved extremely difficult, mainly because at room temperature and pressure, graphite is the thermodynamically stable form of carbon. The simple explanation resides in a large activation barrier that separates the two phases preventing inter-conversion between them at room temperature and pressure. This large energy barrier, which makes diamond so rare, is also responsible for its existence, since diamond, once formed, cannot spontaneously convert to the more stable graphite phase. Consequently, diamond is said to be meta-stable, that is, kinetically stable but not thermodynamically stable [2].

To overcome these problems, the knowledge of the conditions under which natural diamond is formed deep underground suggested that diamond could be formed by heating carbon under extreme pressure. This process forms the basis of the so-called high-pressure high-temperature (HPHT) growth technique. This method has been used to produce industrial diamond for several decades. In this process, graphite is compressed in a hydraulic press to tens of thousands of atmospheres (P ~ 50 - 100 kbar), heated to over 2000 K in the presence of a suitable metal catalyst, and left until diamond crystallises. The diamond crystals, this produced, are used for a wide range of industrial processes, which use the hardness and wear resistance properties of diamond, such as cutting and machining mechanical components, and for polishing and grinding of optics. However, the drawback of the HPHT method is that it still produces diamond in the form of single crystals ranging in size from nanometres to millimetres, and this limits the range of applications for which it can be used. What is required is a method to produce diamond in a form that can allow many more of its superlative properties to be exploited, in other words, as a diamond thin film.

2. METHODS FOR OBTAINING MATERIALS

Chemical vapour deposition (CVD), as its name explains, involves a gas-phase chemical reaction occurring above a solid surface, which causes deposition onto that surface. All CVD techniques for producing diamond films require a means of activating gas-phase carbon-containing precursor molecules. This generally involves thermal (e.g. hot filament) or plasma (D.C., R.F., or microwave) activation, or use of a combustion flame (oxyacetylene or plasma torches).

Figure 1 and 2 [2] illustrates two of the more popular experimental methods and gives some indication of typical operating conditions. Whereas each method differs in detail, they share some common features. For example, growth of diamond normally requires that the substrate to be maintained at a temperature in the range 720 - 1200 ^{o}C. Beside that, the precursor gas (typical CH_4) has to be diluted in an excess of hydrogen. Whatever the method is used in CVD, this involves much lower pressures than in high-pressure high-temperature (HPHT) process and there would be an obvious advantage in terms of equipment and energy costs.

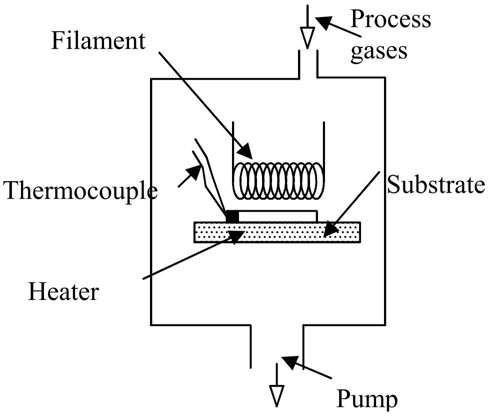


Figure 1. Hot filament reactor [2].

Hot filament CVD method (HFCVD) (figure 1) uses a vacuum chamber continually pumped using a pump, while process gases are metered in at warily controlled rates. Throttle valves maintain the pressure in the chamber at typically 0.2 - 0.3 bar, while a heater is used to bring the substrate up to a temperature of 700 - 900 °C. The substrate to be coated sits on the heater, a few millimetres beneath a filament, which is electrically heated to temperatures more than 2200 °C. The filament is made from a metal that will be able to survive these conditions and not react significantly with the process gas. Metals such as tungsten and tantalum are most often used, although they do eventually react with the carbon gases and carburise, to form the metal carbide. This changes their resistivity and makes them brittle, reducing their lifetime and hence the maximum deposition time that can be performed in one run. The HFCVD method is relatively cheap and easy to operate, producing reasonable polycrystalline diamond films, in quality terms, at a rate of approximately 1 - 10 μm/hour, depending upon exact deposition conditions. However, it also suffers from a number of major disadvantages. The hot filament is particularly sensitive to oxidising or corrosive gases, and this limits the variety of gas mixtures that can be used. It is also very difficult to avoid contamination of the diamond film with filament material. For diamond to be used in mechanical applications, metallic impurities are not an important problem, but it becomes unacceptable for electronic applications.

Microwave plasma CVD (MWCVD) reactors (figure 2) use very similar conditions to HF reactors and, despite being more expensive, are now among the most widely used techniques for diamond growth.

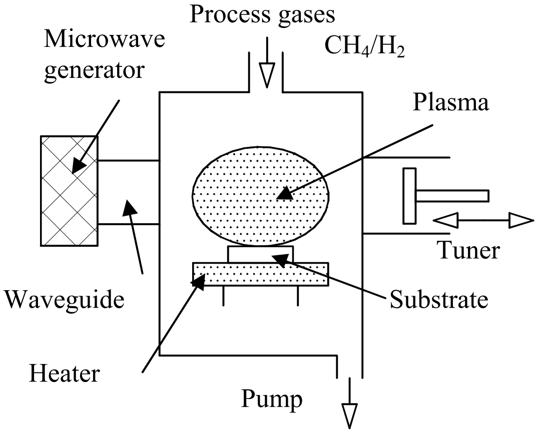


Figure 2. Microwave plasma enhanced reactor [2].

In short, in a microwave reactor, microwave power is coupled into the chamber via a dielectric window (usually quartz) in order to create a discharge. The microwaves couple energy into gas phase electrons, which in turn transfer their energy to the gas through collisions. This leads to heating and dissociation of the gas molecules. At the end, diamond is deposited onto a substrate, which is immersed in the plasma.

Thermodynamically, graphite, not diamond, is the stable form of solid carbon at ambient pressures and temperatures. The fact that diamond films can be formed by CVD techniques is linked to the presence of hydrogen atoms, which are generated because of the gas is activated either thermally or via electron bombardment. These hydrogen atoms are believed to play a number of crucial roles in the CVD process. Hydrogen atoms terminate the carbon bonds on the growing diamond surface and prevent them from cross-linking, thus reconstructing to a graphite-like surface.

The major problem that is in attention is the mechanism of growth, more exactly, the initial stages by which diamond nucleates upon a non-diamond substrate. Several studies have shown that pre-abrasion of non-diamond substrates reduce the induction time for nucleation and increase the density of nucleation sites. Enhanced growth rates inevitably follow since formation of a continuous diamond film is essentially a process of crystallisation, proceeding via nucleation, followed by three-dimensional growth of the various micro-crystallites to the point where they eventually come together.

Most of the CVD diamond films experiments been grown on single crystal silicon wafers, but this is by no means the only possible substrate material. The substrate must have a melting point (at the process pressure) higher than the process temperature implied for diamond growth. This excludes the use of existing CVD techniques to diamond-coat plastics or low melting metals like aluminium. Somewhat, it is difficult to grow on materials with which carbon is too reactive (i.e. many of the transition metals like iron, cobalt, etc.) with which carbon exhibits a high solubility. Hence, materials like Si, Mo and W, which form carbides, are more suitable as a substrate material. The carbide layer can be seen as well as glue and a promoter of CVD diamond growth.

These restrictions regarding materials have ensured the continuing popularity of silicon as a substrate material. Unfortunately, this is not a very adequate material to be used in cutting processes. Tungsten and molybdenum display similar qualities and are also widely used as substrate materials.

3. MATERIAL PROPERTIES

3.1. Synthetic and Natural Diamond

Edge sharpness and its retention are main advantages of diamond cutting tool products. Machining of fibrous (plastics, carbon fibre, acrylics) and composite materials requires a clean and accurate cutting to avoid removal of the fibres from adjacent areas. The availability of polycrystalline diamond (PCD) in a number of grades, Chemical Vapour Deposited (CVD) thick film and synthetic single crystal diamond enables a range of edge qualities to be obtained. Figure 3 gives an example of these edge qualities, although it should be noted that methods of edge shaping and the time devoted to edge preparation varies widely. From figure 3 it can be seen that CVD diamond materials can produce edge qualities better than fine grained PCD [3]. The single crystal synthetic diamond has an edge quality similar to CVD diamond. The data from figure 3 was generated on a tool and cutter-grinding machine. Traditionally the best edge quality has been achieved with ultra fine grain carbides or high-speed steel tools. The introduction of CVD and single crystal synthetic diamond has significantly improved edge quality capabilities with diamond based tool materials.

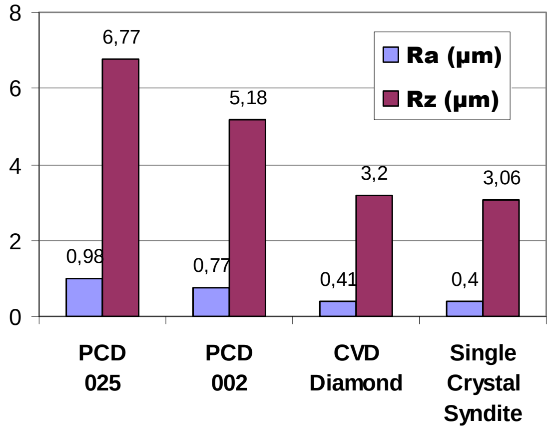


Figure 3. Edge quality comparisons of PCD, CVD and single crystal synthetic diamond tools.

3.2. Polycrystalline Cubic Boron Nitride (PCBN)

Structures of diamond and Cubic Boron Nitride - CBN are similar, as shown in figure 4. In both cases, each of the atoms in the structure is bonded to four others with perfectly tetrahedral arranged bonds (bond angle 109° 28').

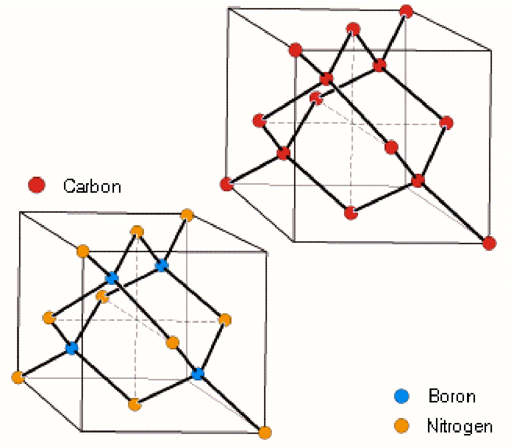


Figure 4. Atomic structure of CBN (left) and diamond (right).

For diamond, each carbon atom is bonded to four other carbon atoms with pure covalent bonding [4]. In the case of CBN, the bond is predominantly covalent, but because boron and nitrogen are dissimilar atoms, there is a small degree of ionic bonding. In CBN, each nitrogen atom is bonded to four boron atoms and, in turn, each boron atom to four nitrogen atoms, in a tetrahedral manner.

The crystal morphology of this synthetic diamond like material can range from a pure cube to a pure octahedron, depending on the relative rates of growth of the crystal faces along the main crystallographic directions. This, in turn, can be manipulated by the synthesis process conditions.

A range of crystal forms can, therefore, exists between the two extremes of the cube and the octahedron (figure 5). The morphology of cubic boron nitride is more complex than that of diamond. Both have the same atom-to-atom geometric structure (based on the diamond structure) but in the case of CBN there is a loss of symmetry because of the fact that the atoms alternate between boron and nitrogen.

In diamond, the octahedral crystal faces are chemically identical. In CBN, the eight octahedral crystal faces are of two different types, with four faces being terminated with boron and four faces terminated with nitrogen. If the growth rates of these two types of octahedral faces are equal, then an octahedron will result (figure 3, position 8). If one type grows to the exclusion of the other, then the result will be a tetrahedron. It has been an observation thus far that tetrahedra is most commonly of the type terminated with nitrogen atoms [5]. The morphology of a CBN particle can therefore vary between cubic and octahedral (similar to that of diamond), and also between octahedral and tetrahedral.

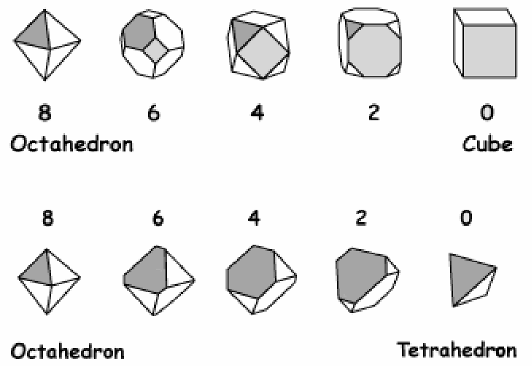


Figure 5. CBN Crystal Morphology.

The synthesis conditions to produce these products have been selected such that each falls into a different domain in the morphology chart. This chart shows part of the range of possible morphologies and the areas where these materials are positioned. This affects the way in which they fracture, which in turn affects their behaviour during use.

Resulted from physical characteristics, the thermal stability of CBN is an important attribute for the machining of high allied work pieces. As these materials have good high temperature strength, they do not soften during cutting in the same way as steels. Cutting interface temperatures remain high, and the same, workpiece hardness, thus hardness of CBN is crucial in obtaining improved performance.

The high compressive strength that CBN exhibits assists also in edge stability. Again, this is particularly important when machining high-allied materials that, in addition to their high temperature strength, have a predisposition to work harden during machining. This machining region imposes a high level of stress on the tool cutting edge, so good edge stability is important. Finally, chemical wear mechanisms, both diffusive and adhesive, are known to occur when machining high-allied materials. CBN products are generally chemically inert and exhibit good resistance to these types of wear.

3.3. Polycrystalline Diamond (PCD)

In order to benefit from the great hardness of diamond and have, as a cutting edge, a reasonable priced material more tools are tipped with materials made from polycrystalline diamond - PCD. As mentioned above, these materials are in fact synthetic diamonds, often grown by the high-pressure high-temperature technique (HPHT diamond) or obtained by Chemical Vapour Deposition technique (CVD Diamond). Polycrystalline diamond composite material is backed with cemented tungsten carbide substrate (figure 6). Manufactured by sintering together synthetic diamond particles at very high temperature and pressure in the presence of a solvent/catalyst metal, these PCD combines the hardness, abrasion resistance and thermal conductivity of diamond with the toughness of cemented tungsten carbide. The result is a composite material consisting of diamond crystals embedded in a matrix, which is usually metal (cobalt binder phase) on a carbide substrate.

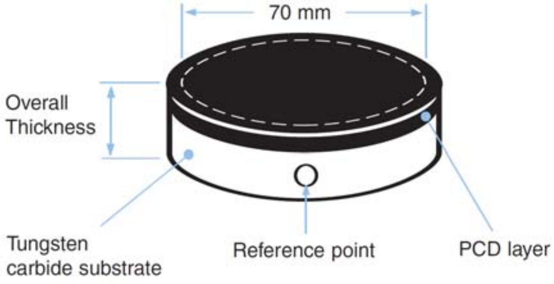


Figure 6. Polycrystalline diamond structure.

4. CUTTING TOOLS AND INDUSTRIAL APPLICATIONS

Given these many notable properties, it is understandable that diamond already finds use in many diverse applications: as a heat sink, as an abrasive, and as inserts and/or wear-resistant coatings for cutting tools. Obviously, given its many exceptional properties it is possible to foresee many other potential applications for this material, but progress in implementing many of such ideas has been disadvantaged by the scarcity of natural diamond. For this reason are presented, in the beginning of this article, the long running quest for routes to synthesise diamond in the laboratory. The interest in diamond has been further increased by the much more recent discovery that it is possible to produce polycrystalline diamond films, or coatings, by a wide variety of chemical vapour deposition techniques using, as process gases, nothing more exotic than a hydrocarbon gas (typically methane) in an excess of hydrogen. The result material can show mechanical, tribological, and even electronic properties comparable to those of natural diamond.

In the beginning, due to the fact that synthetic diamond and similar materials could only be produced in very small sizes, the first applications where to incorporate them in grinding wheels and grinder blades (figure 7). Another way of using these materials was in tipped tools that can be found in mining and cutting applications.

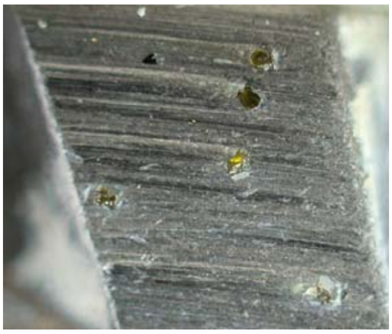


Figure 7. Synthetic diamonds incorporated in a grinder blade

During the grinding operation, material removal rate, surface finish, material integrity, wheel life and dimensional tolerances are some of the more important factors that are considered. In terms of the abrasive, these factors can be influenced by such characteristics as hardness and abrasion resistance, hot hardness, fracture mode, thermal conductivity and chemical reactivity. When it comes to grinding difficult to machine materials, particularly where the dimensional and material integrity considerations are of great importance, a high performance super abrasive such as CBN has the potential to be the ideal material. The hardness of CBN is second only to that of diamond and well above that of the conventional abrasives. This gives it superior resistance to abrasion. Its thermal conductivity at room temperature is also the highest known except for diamond which, in turn, means that heat generated in the grinding zone is conducted away by the CBN, resulting in lower grinding temperatures being produced. Finally, CBN is resistant to chemical attack. Hence, in demanding applications, these properties provide the potential solutions to many grinding problems.

In addition to these basic properties, because CBN is a manufactured material, other characteristics can be incorporated, in particular, particle impact strength and fracture properties. High strength mono-crystalline particles tended to be very blocky in shape and had a characteristic fracture pattern whereby small fragments tended to break away from around the periphery of the particle. CBN products have high strength and thermal stability together with a more angular characteristic particle shape, and fracture in a micro-cleaving mode to leave very sharp angular cutting points that are more efficient in the chip removal process. This, in turn, leads to lower grinding power being required and good free-cutting behaviour. In the past, to gain free-cutting characteristics, friable abrasive could be used which fractured at relatively low grinding loads and thus was able to maintain low grinding power. High strength CBN particles could wear to form wear flats which could give rise to higher power (and temperatures) being generated.

Figure 8 shows an example of a high strength, sharp, angular CBN material (ABN 600, De Beers Industrial Diamond Division) [6]. ABN600 present high-strength abrasive potential and is commonly used in conjunctions with metal bond.

The wear mechanisms associated with the CBN particles in this type of product ensure good grit protrusion from the wheel bond (due to the high impact strength), which is important for high stock removal rates and allows sufficient chip clearance between the wheel and the workpiece. In addition, these particles exhibit a sharp, angular chipping wear characteristic, which ensures that a free-cutting action of the wheel is maintained during operation

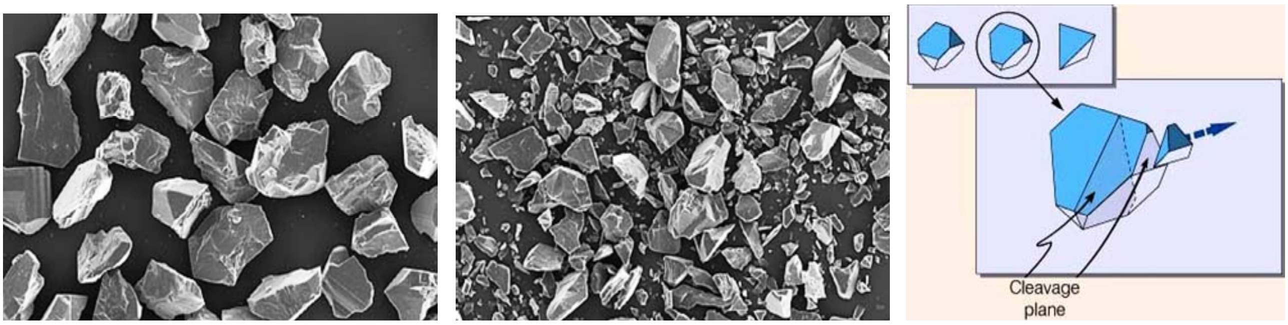


Figure 8. Particles and fractured particles of ABN600.

For the past years, work has been done to coat metallic tools with synthetic diamond, and though the work still shows promise it has not significantly replaced yet traditional PCD tools [7].

In order to obtain a significant size for a cutting edge to be brazed on cutting tools several machining techniques were used but that leads to another problems. In case of CVD the only solution is to coat the future tool with the hope that the result is the desired one. More results that are positive were obtained in case of PCD. Produced synthetically, polycrystalline diamond (PCD) was first used for turning and milling operations on abrasive non-ferrous metals. The new tool material was found to perform equally successfully on non-metallic materials such as glass fibre-reinforced plastics, wood particleboards, etc. The tool lives may be several hundred times longer than those of carbide (depending on the application).

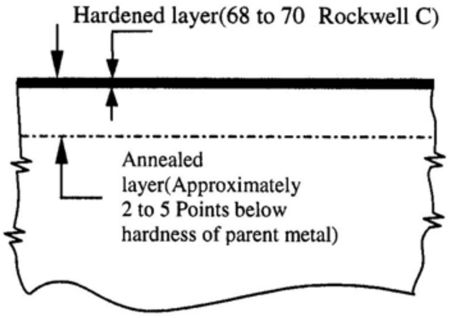
As presented in figure 6, most common form of PCD blanks are rounded disks. As an exception from all materials presented, PCD is the only material that present electrical conductivity. The presence of the metallic solvent/catalyst and the cemented tungsten carbide substrate make PCD suitable for processing by electro-discharge machining (EDM).

One of the principal advantages of the EDM process is that machinability is independent of material hardness. However, productivity is highly dependent on the level of workpiece electrical conductivity. The bulk electrical resistivity for PCD is up to 14,700 μΩcm [8]. This value remains fairly constant despite gross differences in product grain size which typically varies from ~2 to ~25 μm. Theoretically, the resistivity of PCD would be expected to be about ~600 μΩcm. The fact that experimental measurements show otherwise suggests that the diamond crystals in the PCD are not completely covered / surrounded by the cobalt, which is understandable in view of the diamond intergrowth evident with PCD products. It is estimated that a high proportion of the cobalt is localised and that what is available as a conductive network incorporates narrow channels, some of which are discontinuous [9].

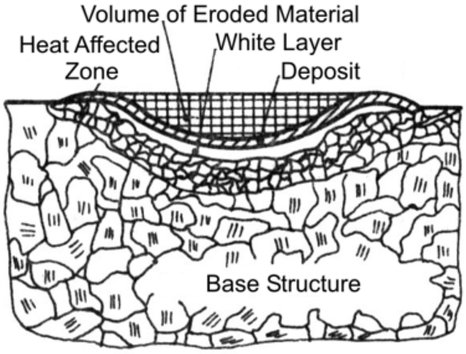
Several studies present the possibility to wire EDM this disk [9, 10, and 11]. This technological option is good in order to reduce the size of PCD bits but does not offer the possibility to profile the blanks in order to develop cutting edges.

An important parameter factor affecting the life of eroded tools is the damage in the surface zone. Wire Electrical discharge machined PCD tools exhibit cracks in the surface zone layer, regardless of the EDM parameters applied. According to several investigations, the damage layer is always less than 0.05 mm thick [9]. This layer can be removed by grinding. In addition, the sparks create a heat-affected zone that contains a thin layer of recast, also called "white layer". Being a thermal process, EDM lead to some annealing of the work piece can be expected in a zone just below the machined surface (figure 9.a). In addition, not all of the workpiece material melted by discharge is expelled into dielectric. The remaining material is quickly chilled, primary by heat condition into the bulk of workpiece, resulting in an exceedingly hard surface (figure 9.b).

The special features in the wire EDM cutting of PCD result from the structure and material properties of the PCD blanks, in particular its laminar structure as a composite material, the structure of the PCD layer itself and this layer's relatively low electrical conductivity. The latter reduces the productivity and stability of the process. This reduced productivity is due to energy losses arising from the relatively low conductivity of the material. The stability of the process is impaired by a reduction in voltage over the workpiece proportional to the discharge current. The voltage combines with the average working voltage, which serves as the standard variable of the federate control loop, and thus leads to an overvaluation of the spark gap. The in-feed motion that then follows can lead to process fluctuations [9]. The special characteristics of the shape and topography of the cutting surface are due to the laminar structure of the PCD blanks and the structure of the diamond matrix.



a. Diagram of affected zone



b. Schematic of material microstructure

Figure 9. EDM heat affected zone.

The most significant fact in wire cutting of PCD is the development of a notch between the carbide substrate and the PCD layer, which can be explained by the structure of the material [9]. Due to the manufacturing process, the cobalt concentration is higher in the transition zone between the carbide substrate and the diamond matrix. The low resistance of the cobalt to thermal erosion, compared with the other components, gives rise to increased material removal in this area.

Furthermore, with wire EDM in the water bath it must be assumed that electrochemical processes also lead to increased erosion in the cobalt region, because the cobalt has a much higher electrochemical equivalence than the other components in the material. A second characteristic of the cut surface is a clear offset, or dimensional difference, between the surface of the PCD layer and the carbide substrate. This is normal due to the difference in electrical conductivity between PCD and tungsten carbide.

The spark gap in the PCD is accordingly much smaller than in the area of the carbide, the reason being the PCD layer's greater resistance to thermal erosion. Apart from these two features, which can be observed particularly in EDM cutting at high power, the emergence of another notch, formed directly beneath the top edge of the PCD, becomes evident during cutting at lower power. The reasons for this subsurface undercut are yet unexplained.

The hardness of the surface layer is a good result for a cutting tools but is unfavourable when it comes to define (shaping) the angles for the future cutting tool. This and the fact that the PCD layer is somehow affected by wire EDM has lead to the necessity to find alternate machining solutions. Based on sufficient electrical conductivity of PCD die sink EDM experimental researches were performed. The very first attempts were based on the fact that the substrate (tungsten carbide) was successfully eroded in the past but the result, regarded edge quality, was inadequate. More successfully, results were conducted using die sinking EDM [12].

5. CONCLUDING REMARKS

This paper has illustrated the benefits of polycrystalline diamond and cubic boron nitride when grinding and machining high allied materials, including improved tool life, higher productivity, improved surface finish and lower machining forces. In addition, benefits can also increase by employing PCD in rotary tooling when machining speciality plastics and composites, where edge quality and abrasion resistance combine to give excellent performance. This is similarly the case in the machining of acrylic plastics, where PCD and single crystal synthetic diamond complement each other perfectly to produce benefits in precision, productivity and the service life of components.

However, superabrasive grinding and cutting tool materials have certainly not reached their full potential in their application and the challenge for the industry in the future is to find ways improve the capitalisation of this potential.

From a material point of view, diamond and CBN abrasive developments have been impulsion largely by the needs of the volume production industries, where manufacturing throughput and tool cost dominate. The key workpiece material types have included the hard ferrous materials, aluminium alloys and non-ferrous composites, and the machining operations that go with these have dominated development objectives.

In conclusion, PCD and CBN products have the capabilities to maintain high strength and to absorb loads generated in metal removal process, but the sharp, angular shape of the particles ensures that this is achieved with minimum grinding force.

As a final conclusion, the electrical discharge machining of PCD avoids the use of expensive diamond grinding wheels/low wheel life and the absence of significant cutting forces means that cutters, can be produced without distortion or the use of excessive fixturing. The viability of the process however, depends on the nature of the PCD blank and the integrity of the skeletal structure of solvent/catalyst metal between the diamond crystals, in order to provide an electrically conductive network.

Polycrystalline diamond can be machined reproducibility to a high surface quality using both the wire and die sinking EDM techniques. However, because it is less electrically conductive than homogeneous metallic materials, productivity is much lower. The benefit of die sinking of PCD relies in the fact that is the simplest way to shape the cutting tool.

The choice of using electro discharge in machining PCD, of course, belongs to technological engineers who have to balance the pro and cons, including here the economical aspect, energy consumptions etc.

Further researches will be conducted in order to apply the method for obtaining the PCD to other material categories such as doped diamond particles or to apply CVD method to other substrates. In order to obtain a high accuracy in EDM is important that tool electrode to maintain its original shape and this could be done only by minimize the wear of the electrode. Due to the fact that electrical conductive PCD and CVD are currently produced (to serve as cutting tools) is possible to use them also as electrodes in die sinking electro discharge machining, in order to benefit from very high thermal conductivity and extremely low wear.

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