PCD Tools in Milling Cutting Graphite Molds

William Wang
Simple Technology, Inc.
522 Dawn Cove Dr.
Henderson, NV 89052
diamondteam1@hotmail.com

Abstract: PCD insert failure in cutting graphite mold was mostly brittle fracture through its binding phase in our tests. It is caused by overheating diamond powders with cobalt and tungsten metals during PCD sintering process in HPHT press. Too much carbon diffused from diamond powders into metal phase forming carbides, such as WC, WC-Co, and Co_2C, which enbrittle the binding phase and lead to chipping fracture during PCD cutting process. Reducing sintering temperature and time could maintain good ductility of PCD binding phase and hence improve PCD insert cutting quality.

Key Words: PCD Insert, Brittle Fracture, Cutting Graphite Mold

Introduction

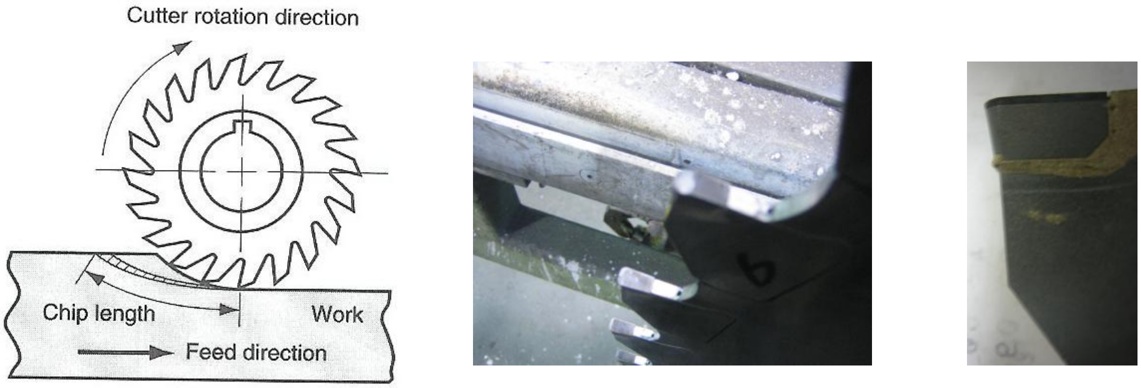
Polycrystalline diamonds (PCD) are fine diamond crystals bonded during sintering process under high temperature and pressure [1]. The crystals are randomly oriented to reduce crack propagation potential in certain directions, which also results in hardness and wear resistance uniformly high in all directions [2]. The small PCD cutting edges are brazened to cemented carbide inserts, which offers excellent strength and shock resistance to the tool.

PCDs are used in a wide variety of tools for cutting hard or abrasive materials such as rock, nonferrous metal, ceramics, composites and wood-containing materials [3-6]. Graphite molds are abrasive in nature and are traditionally cut by carbides and CBN tools in the past, where CBNs are about 10 times more outperforming carbide tools in machining. As PCDs are generally harder and more wear resistant than CBNs, it also offers lower coefficient of friction during cutting, these characteristics provide substantial benefit to the machining operation of graphite products, mold manufacturers are actively designing a variety of PCD tools for graphite cutting aiming at longer tool life, increased productivity, and better part dimensional accuracy and consistency [7-9].

The test results differ significantly. In some applications the PCD tools last 30,000 cycles of cut, which is 50 times more than carbide tools. However, in some other cases, it may cut only 30 cycles before PCD failure, which yield tool life worse than carbides. This paper is to study PCD failure mechanisms in cutting graphite mold for the objective of developing more wear resistant PCD tools with longer cutting life and better quality.

Experimental Set Up

The milling cutters are 1200 mm in diameter with 50 PCD teeth (fig 1). It cuts 80 mm wide grooves in graphite mold block 1200 mm in length and 350mm in depth. Cutting parameters are as following: tool rotation 60rpm, feed rate 1200mm per min, and the depth of cut 350mm. No coolant is used during cutting operation due to the graphite work-piece will be used as mold later on to contain molten metal.



(a) Schematic View (b) PCD Teeth and Graphite Block (c) PCD Tip

Figure 1: PCD Milling Cutter

In cutting tests only five PCD tips were brazed on to the milling cutter, the rest of the teeth were not used. Before cutting SEM pictures were taken on PCD surface profile at 500x and 2000x magnifications respectively. It shows that diamond powders in 10-30 microns are sintered together with cobalt. Along particle edges of diamond powders, zigzag lines are visible, indicating chemical reactions between cobalt and diamond at high temperature and high pressure during sintering process.

(a) 500X Magnification (b) PCD Tip (c) 2,000x Magnification

Figure 2: SEM Views of PCD Profile

X-ray diffraction (*XRD*) tests were performed to identify the chemical composition in PCD. It shows diamond structure in the particles, cobalt in between, and cobalt carbides are along the boundaries. More detailed data will be presented in the next session.

Experiment Results

The first round tests were conducted with 30 cycles of cut, fractures were immediately observed on PCD surfaces (fig. 3a). Thin layers of PCD peeled off from their base structure caused by abrasion of graphite mold material during milling process. Visible propagation wave lines can be seen on many fractured surfaces, where by tracing back along these propagation wave lines, a starting point of crack initiation could be identified, which are mostly located somewhere on the cutting edges.

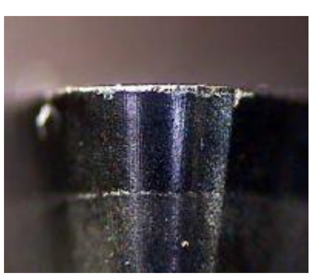
(a) Fracture of PCD Tool Tips in First Test

(b) Fracture of PCD Tool Tip in Second Test

Figure 3: Fracture of PCDs in Milling Graphite Mold

The second round tests were conducted under the same cutting condition and parameters as given in the experimental setup section. After 30 cuts, views of fractured PCD rake faces are given in figure 3b. It exhibits similar fracture patterns as seen in the first set of tests, thin layers of PCD peeled off from the tool, which all originated from some sort of cracks/voids on the cutting edges. It is interesting to see that some portions of the cutting edges on the 3rd and the 4th tools in fig 3b remain good integrity, a crack separates the damaged PCD surface and the undamaged surface.

A view of the flank faces of some of the PCD tips (fig. 4) reveals notch wear mark on the cutting edge (fig 4a), which could be caused by the abrasion of some hard particles in graphite mold material, or by a small void or crack on the cutting edge induced by wire EDM cutting and grinding operations during PCD tip preparation. Some levels of material peel off are visible in fig. 4b along the edge near the notch area. After losing it cutting edge integrity, more PCD thin shins peel off during milling process and quickly lead to large area fracture on PCD tools as seen in fig 3.



(a) Notch Wear and Flank Wear (b) Flank Wear

Figure 4: Frank View of PCD Tips

EDS Study of Fractured PCD Tools

Chemical composition of PCD tips were analyzed by EDS method at multiple locations on the PCD tips. Results for two of them are showing below, with figure 5a on the binding phase between diamond particles and figure 5b on one diamond particle.

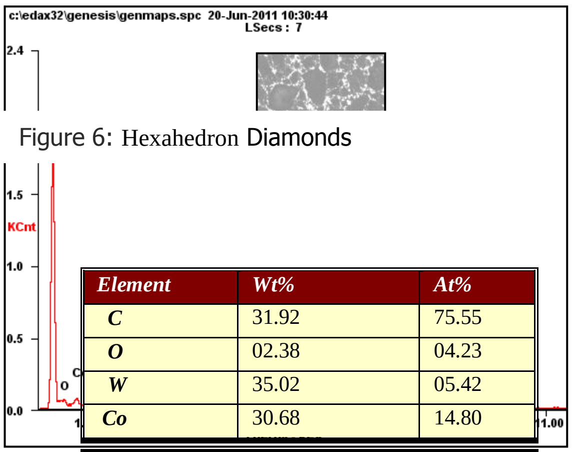
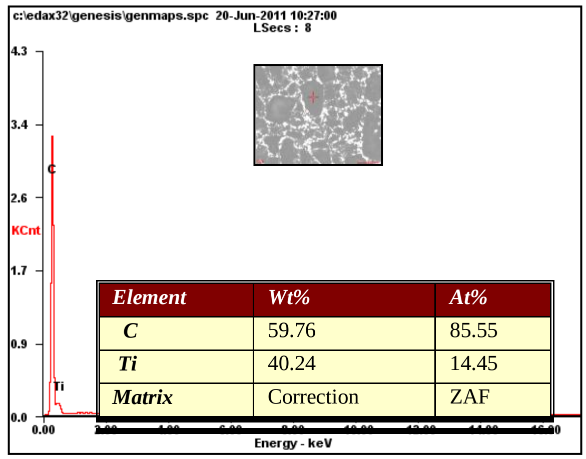


Figure 6: Hexahedron Diamonds

Element	Wt%	At%
C	31.92	75.55
O	02.38	04.23
W	35.02	05.42
Co	30.68	14.80



Element	Wt%	At%
C	59.76	85.55
Ti	40.24	14.45
Matrix	Correction	ZAF

(a) Binding Phase (b) Diamond Particle

Figure 5: EDS Study of PCD Tips

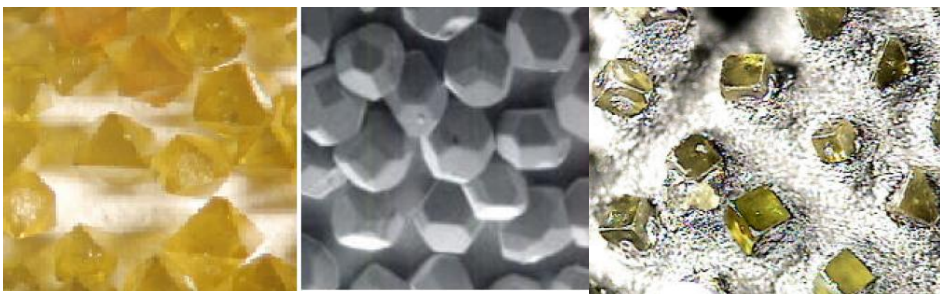
For the EDS check point between diamond particles, nearly 32% by weight is carbon (C) in fig 5a, which equals to 75.6% by atomic volume. Some other points checked between diamond powders show a variation from 5% to 70% by weight is carbon. Cobalt (Co) in the binding phase is found to be about 30.7% by weight, Tungsten (W) is found to be 35% by weight. A small trace of oxygen is also identified in the binding phase in weight amount about 2.4%.

C, Co, W and O co-exist in the binding phase between diamond powders as chemical compounds, such as WC, WO3, CoO, Co_2O_3, Co_3O_4, WC-Co, and Co_2C. Large variation of carbon amount in the binding phase also indicates that some portion of diamond on particle edges converted into graphite without chemically bonded with other elements and diffused into the binding phase, which significantly weakens the fracture strength of PCD.

To certain extent, the strength of PCD is primarily affected by the strength of the binding phase, WC, WO_3, CoO, Co_2O_3, Co_3O_4, WC-Co, Co_2C, and graphite. As they are washed away by work-piece material during cutting process, diamond particles will eventually be taken away from it PCD structure piece by piece.

In fig. 5b, diamond powders were checked, it is found about 60% of carbon by weight, or 85.6% by atomic volume. There are about 40.2% titanium by weight (14.5% by volume) were identified on the surface of diamond particle, which were pre-coated on diamond powders before sintering process for better binding strength. By checking different points on diamond particles the titanium amount varies from nearly 40% to 85% by weight, which is an indication of uneven titanium coating thickness on diamond powders. The variation also means many uncoated spots on diamond particles (fig. 6c).

There is no trace of titanium found in the binding phase between diamond powders, which indicating the sintering temperature was less than the melting point of titanium (1668 ℃) but higher than the melting point of cobalt (1495 ℃) which converts some diamond on skin layer of the powders into graphite. SEM picture in figure 2c illustrates that diamond particles lost their sharp hexahedron crystal edges due to high temperature sintering process. Fig 6 is a comparison of coated, uncoated, and partially coated diamond particles before sintering into PCDs, they all show straight edges.



(a) Uncoated (b) Coated (c) Partially Coated [10]

Figure 6: Diamond Sharp Edges (before sintering)

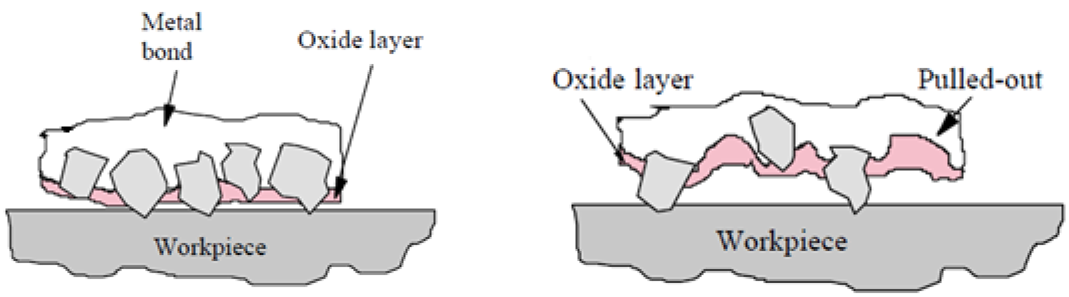
During PCD sintering process, carbon atoms diffuse through titanium coating layer from its diamond skins, the high sintering pressure (about 5.4 GPa) collapse titanium film and squeeze them onto the newly formed diamond surfaces without much chemical bounding between the diamond and titanium. As a result, when PCD is used in cutting work-piece, the fracture strength is largely affected by the strength of titanium coating layers. Once they are worn away by the work-piece, diamond particles may come loose and being washed away quickly.

PCD Failure Mechanism in Milling Cutting Process

EDS study revealed that the fracture strength of PCD in cutting graphite mold is less determined by the diamond fracture strength, but more by the strength of titanium films and their binding metals, such as cobalt and tungsten.

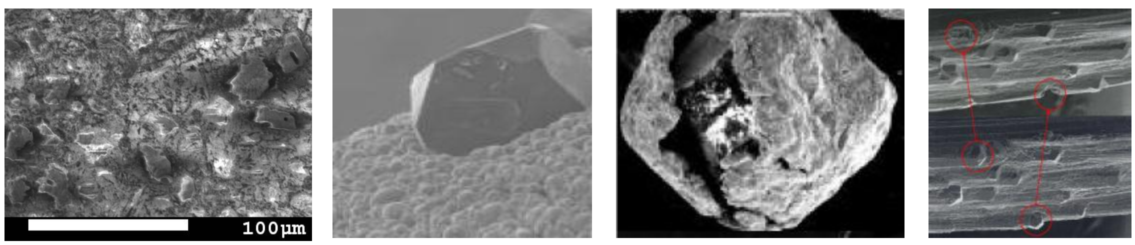
In a way PCD cutting tool could be viewed as a metal bonded grinding wheel (fig. 7a, 8a), where cobalt, tungsten, their carbides, and their oxides hold diamond particles together. In a cutting process, work-piece material gradually "washes away" binding metals around diamond (fig. 7b, 8b) and also cracks open the titanium coating layer on diamond particles (fig. 8c) in a PCD surface layer by abrasion wear, which exposes more diamond particles on its PCD surface.

As this "wash away" process continues during a cutting operation, less binding metals are available to hold diamond particles in place and these diamond particles are eventually pulled out from their original locations one after another by cutting force (fig. 7b, 8d). These dislocated diamond powders flow away along PCD rake face and mix up with cutting chips of the graphite work-piece during cutting operation.



(a)Metal bonded diamond particles (b) Exposed and pulled-out diamonds

Figure 7: Grinding Nature of PCD Milling Tool



(a)Before cutting (b) Exposed Diamond (c) Cracked Coating [10] (d) Wash Away [10]

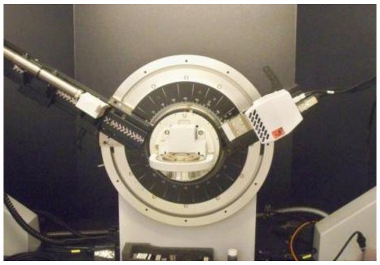
Figure 8: PCD Wear Process

As diamond particles are pulled out from its PCD surface, the metal binding phase is quickly "washed" away by the workpiece material by abrasion mechanism, exposing another layer of diamond particles which start to cut workpiece again.

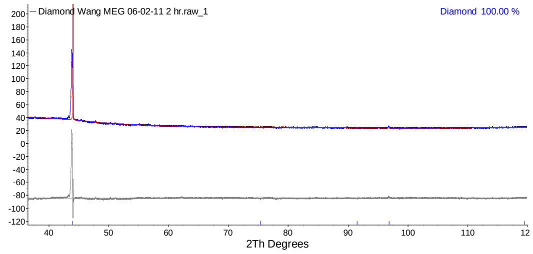
If the metal binding phase is not ductile due to over saturation of carbon during PCD sintering process, too much WC, WC-Co, Co_2C, and graphite may co-exist in the binding phase, causing brittleness of the binding phase, which is good for hardness and wear resistance improvement, however, its failure mechanism becomes brittle fracture. Large and/or small pieces of PCD aggregates chip away from its base due to crack development through binding phase (fig. 3). This type of PCD failure is not desirable for cutting tool. To avoid it from happening, PCD sintering process should be carried out at less temperature and less time duration.

XRD Stress Analysis

X-ray diffraction (*XRD*) is a powerful technique for identifying the presentence of crystal planes [11]. In addition to scanning electron microscopy and Raman spectroscopy, XRD is a common characterization tool used to confirm that diamond synthesis has indeed been achieved. The quantitative high accuracy measurements of inter-atomic spacing provided by XRD are also used in study of strain, grain size, preferential orientation and epitaxy [12].



(a) XRD Equipment



(b) Test Results

Figure 9: XRD Study of PCD Quality

In the previous sessions binding phase was the main focus of study, results show that PCD is more prone to failure in its binding phase. In this session, XRD is used to measure crystallographic planes inside PCD diamond crystals, and hence to calculate stresses inside the powders. Fig. 9a is a picture of the equipment in the test, test data are given in figure 9b. More detailed data are given in table 1 below.

Table 1

Phase name	Diamond
R-Bragg	0.834
Spacegroup	Fd-3mS
Scale	0.0063(36)
Cell Mass	96.088
Cell Volume (Å^3)	45.4291(18)
Strain L	**0(19)**
Strain G	**0.2(19)slight strain indication**
Crystal Density (g/cm^3)	3.51226(14)
Preferred Orientation (Dir 1 : 1 1 1)	0.195(37)
Lattice parameters	**3.568163 Å (46)**

XRD test data shows that diamond crystal lattice parameter is 3.568 Å and crystal density is 3.52 g/cm^3, which are all in line with book values [13]. There is little or near zero strain measured in the XRD test, indicating very small stresses inside diamond crystals.

Conclusions:

The failure mechanisms of PCD inserts in cutting graphite mold could be gradual wear or brittle failure. Its fracture strength is not determined by the strong phase, which is diamond particles, but by its binding phase, which is constituted of cobalt, tungsten, and their carbides.

When the binding phase is ductile, its binding metals are worn away gradually by workpiece during cutting operation, diamond particles are exposed and isolated as they lose support from surrounding binding materials, as this process continues, diamond particles are being washed away before fully used in cutting.

The lost of diamond particles may become initial voids on PCD surface, which cause crack propagation and fracture of PCD tool.

When the binding phase was over heated and the sintering process was too long, too much WC, WC-Co, Co_2C, and graphite may co-exist in the binding phase, causing brittleness of the binding phase, which changes the failure mechanism of PCD from gradual wear to brittle fracture. Large and/or small pieces of PCD aggregates chip away from its base due to crack development through binding phase.

XRD test data indicate little strains and stresses are found inside diamond particles.

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