CVD Diamond Coated Rotating Tools for Composite Machining

Niels Chris Engdahl
Crystallume

ABSTRACT

The technology for the Chemical Vapor Deposition (CVD) of pure diamond coatings on rotating cutting tools has developed rapidly during the past several years. Tungsten Carbide round tools are regularly being coated with continuous, well adherent, diamond films that improve machining performance and increase tool lifetimes in composite materials by 15 to 30 times over uncoated tools. This paper reveals the process methods involved in CVD diamond film growth on tungsten carbide tool surfaces and the unique properties of diamond thin films. The surface of the diamond films can be controlled to create a faceted cutting edge that is ideally suited to machining abrasive composite materials and produces superior surface finishes. Application materials for diamond coated tools include carbon fiber reinforced composites, fiber reinforced plastics, green ceramics, advanced fiberglass structures and aluminum metal matrix composites.

INTRODUCTION

After more than ten years of commercialization, CVD (Chemical vapor deposition) of diamond-coated tooling is still a novelty in some machining circles. Even some of the shops currently using more established diamond tooling (bonded grit, PCD) are not generally aware of CVD Diamond's capabilities. And some of the best applications for this new technology are not traditional diamond applications. Some of the problem can be confusion over just what CVD diamond is and how it is different from other diamond tooling. Some simple definitions will be useful to distinguish between the different types of diamond tooling before going into details of how the CVD diamond coating is applied to cutting tools and a discussion of a few primary applications.

BONDED DIAMOND GRIT TOOLS

Bonded diamond grit tools have probably been around since people first had diamond dust and glue. These are what most people think of when you say "diamond coated tools". Today's diamond grit tools use sophisticated methods to bond natural and synthetic diamond particles to a large variety of cutting, grinding and polishing tools. These tools are used primarily in the construction and mining trades, but they are also very popular for edge finishing of carbon fiber composite structures and grinding hard materials like ceramics and glasses.

PCD DIAMOND TOOLS

Most engineers and machinists also know about PCD (Poly-crystalline diamond) tooling. PCD also starts with fine diamond particles but they are then formed into a dense sintered material using cobalt as a binder. These cemented compacts of diamond and cobalt are cut into shape and brazed into solid carbide tool bodies. One popular manufacturer forms the sintered material directly into a slot in the tool body, allowing them to create a wide variety of helixed tools and longer lengths of cut. The PCD tool edge is then ground to a finished shape and can be reground for repeated use. PCD tools have been around for over 50 years and are widely used in the aerospace industry for hole drilling in carbon fiber composites. The automotive industry was the first to accept this technology and uses a large number of PCD tipped inserts for machining highly abrasive cast aluminum-silicone engine components. The tools produced today still have a limited variety of geometries available and a high initial cost but they can be the best option in applications demanding a very sharp edge or high impact resistance.

CVD DIAMOND TOOLS

CVD diamond is something completely different. Using this new technology, diamond coatings are actually grown atom by atom onto the surface of the tool. Several technologies are used to produce CVD diamond films commercially, but the primary method used for coating cutting tools is known as Hot Filament Deposition. Inside the typical coating system, an array of superheated tungsten wires are used to activate hydrogen and a carbon-containing gas (usually methane). This reactive vapor mixture will condense onto the part to be coated, producing the diamond film over the entire surface of the tool. The diamond crystal growth is carefully controlled to produce a high-purity diamond film with a microstructure suited to the machining application. The coatings are from 4 to 40 microns in thickness depending on tool diameter and application. These films are pure diamond with no binder; they are both mechanically and chemically bonded to the tool surface. The result is the ability to combine the latest in cutting tool geometry with the superior mechanical properties of diamond.

CVD COATED DIAMOND TOOLING

ADVANTAGES OF DIAMOND TOOLS

Diamond has many unique physical properties and some that make it an ideal material for cutting tool applications (Figure 1). Of course it is the hardest known material and so is extremely abrasion resistant. And the extremely high thermal conductivity of diamond removes damaging heat from the cutting edge. Diamond's low coefficient of friction (similar to Teflon) aids in chip formation and material flow up the flutes of the coated tools. These thermal and wear properties mean diamond tools can be run at speeds that would destroy all other coating materials. And when used at normal speeds diamond tools operate cooler than other tool materials, reducing damage to heat sensitive work-piece materials.

Property	**CVD Diamond**	**Comparison**
Microhardness (HV)	7000-9000	CBN 5000
Thermal Conductivity (w/cm-C)@25C	10-18	Copper 4.0
Coefficient of Friction	0.05- .07	Teflon 0.05
Density (x1000 Kg/m3)	3.52	PCD 4.12

Figure 1

So what does CVD diamond machine well? Many of the advanced composite materials that are gaining in popularity lately are perfectly suited to be machined with CVD diamond tooling. Carbon fiber composites, metal matrix materials, green ceramics, fiber reinforced plastic and graphite/graphite composites are all materials that rapidly wear out standard tooling, and they are also materials where CVD diamond has proven its performance. Other suitable materials are graphite, high silicone aluminum, and copper alloys.

Diamond is not for everything though; it will not machine any of the ferrous materials due to a chemical reaction between the iron in these metals and the carbon atoms making up the diamond film. And no, it is not the answer to all of your titanium problems, though it can machine it, but diamond films are a new solution to many other difficult to machine materials.

The ideal CVD Diamond tooling applications are those where machining the material forms powder or small grit. These are situations where the primary operation at the cutting edge is basically abrasive wear rather than chip formation. Materials like graphite or fiberglass are perfect examples. The best application is machining ceramics in the green state (unfired), when machining these waxy abrasive materials, the CVD diamond coating will last from 50 to 70 times longer than standard carbide.

CVD COATED DIAMOND TOOLING

TOOL MATERIAL

Selection of the proper tool material is crucial to the success of the diamond coating process. The prolonged high temperature necessary during the coating process will damage all but cemented tungsten-carbide and ceramic cutting tool materials. And for the optimum coating adhesion, a C-2 grade of tungsten-carbide must be used (6% cobalt binder, grain size above 1 micron).

Once you obtain the correct material, the tool grinding must be carefully performed. Any overheating of the tungsten-carbide during grinding operations (burning) will damage the carbide surface and cause the diamond film to flake off of the burned areas.

SURFACE PREPERATION

Careful preparation of the tungsten-carbide tools before diamond coating is another of the keys to consistent performance. The parts to be coated are carefully cleaned and then typically put through a two-step chemical preparation. The first step roughens the carbide surface for improved mechanical adhesion (Figure 2) and the second step removes cobalt from the surface to optimize chemical adhesion. Other methods involve micro-blasting processes to optimize the physical roughening, interlayer films and re-sintering steps designed to improve chemical adhesion.

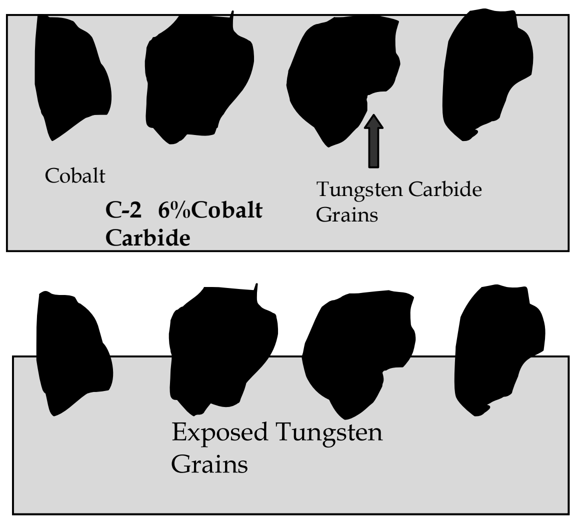


Figure 2

COATING PROCESS

Next the parts are loaded into vacuum chamber containing hydrogen and methane gasses at a pressure from 10 to 100 torr. A series of tungsten wires, heated to over 2300 degrees C, are used to provide the energy necessary to both break-up the gas molecules and heat the tools to over 750 degrees C (Figure 3). When the proper conditions are achieved, the activated carbon atoms can recombine into a pure diamond film over the entire tool surface.

CVD Diamond Coating Process

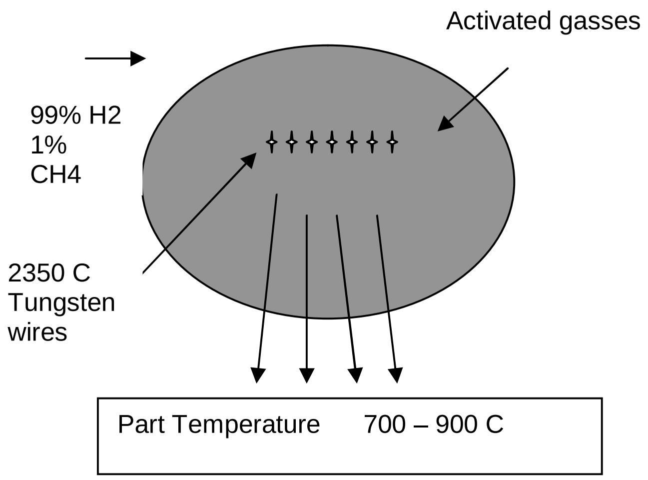


Figure 3

During the initial growth phase the carbon atoms will form diamond crystallites in the crevasses between the tungsten carbide grains. These crystallites will grow to form a continuous film that is both mechanically interlocked with the etched tungsten carbide structure and chemically bonded to the carbide grains. (Figure 4).

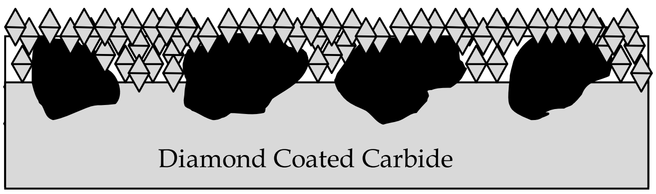


Figure 4

This coating process is very slow, with typical film growth rates of only .5 to 1.5 microns per hour. Since functional coating thicknesses range from 2 to 40 microns, this can mean very long growth cycles of 2 days or longer.

Another unique advantage of the CVD diamond coating process is the ability to grow a wide range of surface structures and optimize the film for a given application. (See Figures 5-8) When tool edge sharpness is a primary issue, the diamond film can be grown thin and very smooth. If abrasion is the main wear, mechanism and thicker films are needed, growing a faceted surface has been shown to reduce the cutting forces and increase lifetime.

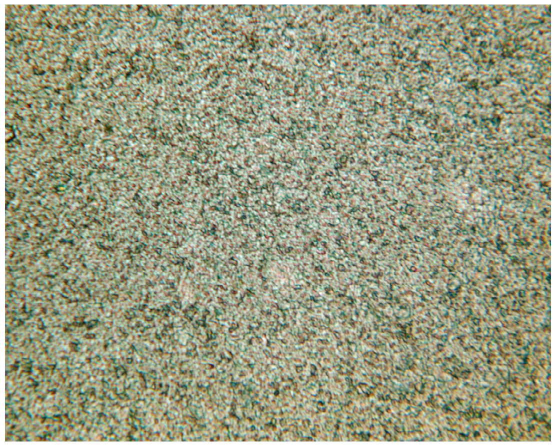


Figure 5 Ultra Fine film 1000x

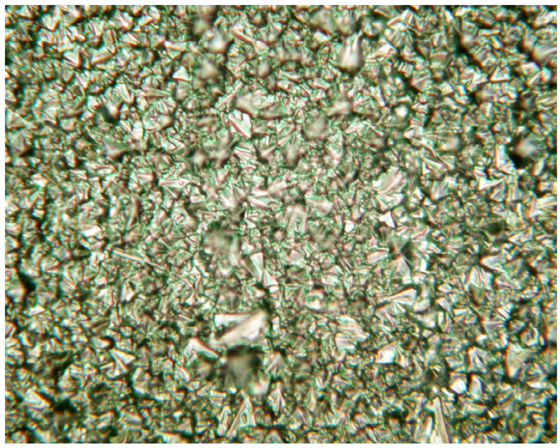


Figure 6 Smooth film 1000x

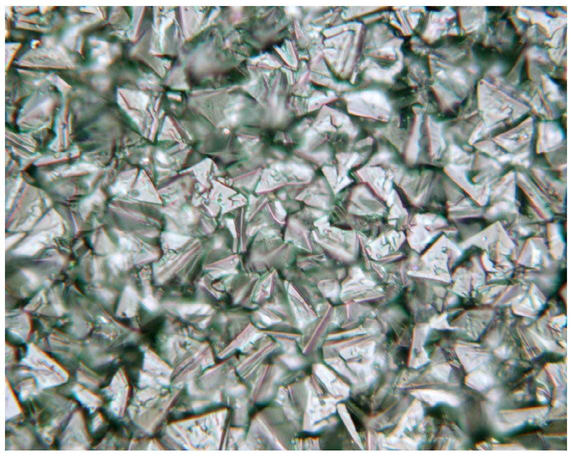


Figure 7 Standard film 1000x

Figure 8 Cubic film1000x

APLICATION EXAMPLES

CARBON FIBER COMPOSITES

Drilling and countersinking in carbon fiber composites are just the type of abrasive machining operations that are perfect for CVD diamond coatings. The first example is drilling and countersinking rivet holes in a 0.76cm thick carbon fiber laminate. The tool used was a combination 6.1mm diameter drill / 13mm diameter countersink running at 3000 rpm and a feed rate of 28 cm/min. Results of testing conducted at Boeing Aircraft in Seattle, WA are shown in the graph. (Figure 9)

The coating used here has a faceted surface and cutting edge (Figures 10 & 11) as compared to the ground edge of the carbide and PCD tools. This faceting is responsible for reducing the cutting forces that could normally be expected with such a thick coating (20 microns).

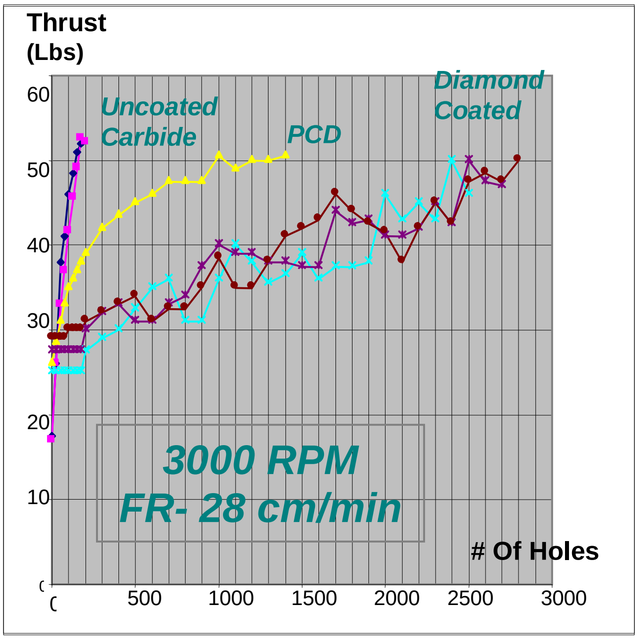


Figure 9

The data (Figure 9) show how abrasive this material is on standard carbide tooling, typically wearing out a tool in less than 200 holes. Due to the sharp grind on the uncoated tool, the initial thrust is low but rises quickly as the edge wears away. A PCD tool can do the job quite well, but still has a shorter life. The CVD coated tool has the best performance with low thrust, very nice quality holes and minimal backside delamination. Although end of life for this test was 50 lbs, the CVD tools were still producing high quality holes, with very graceful wear. The tools will last longer on the shop floor where end of life is closer to 60 lbs.

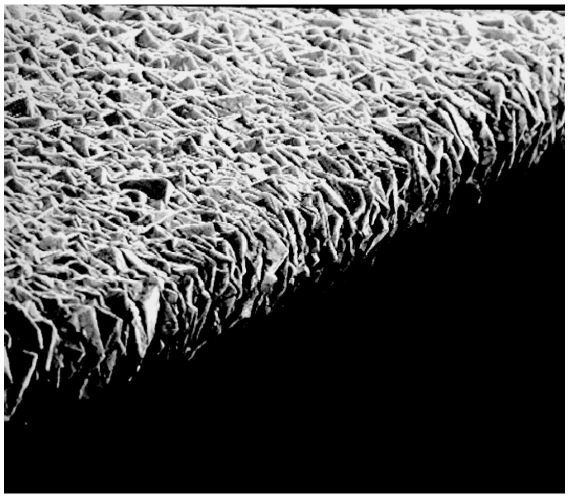


Figure 10 Faceted edge 1000x

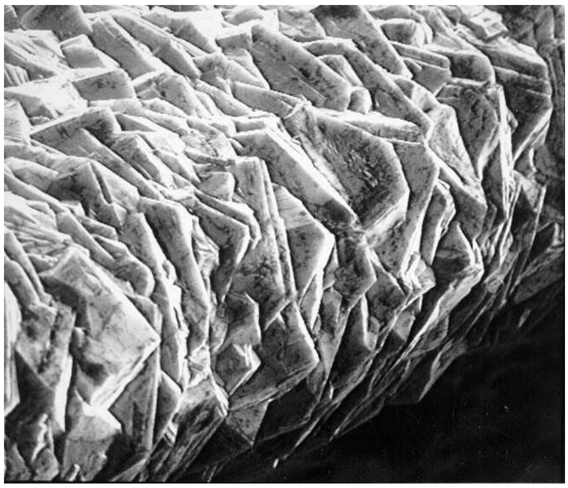


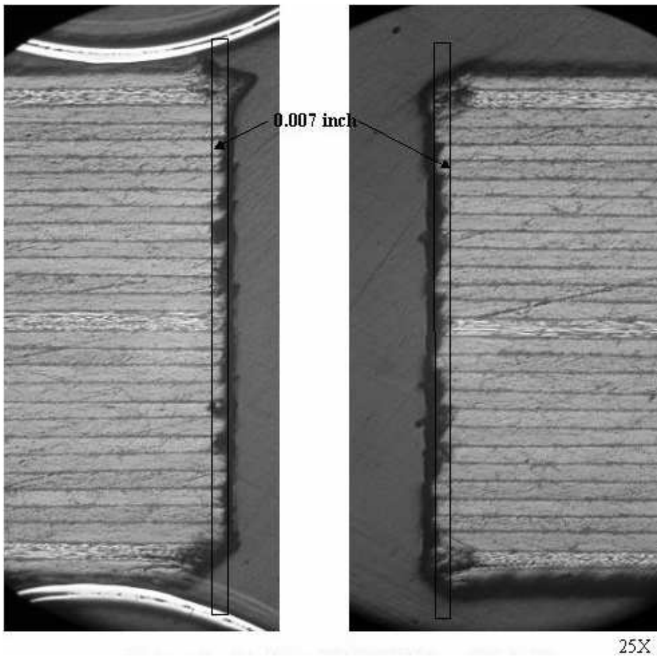
Figure 11 Faceted Edge 4000x

HOLE QUALITY ISSUES

Often the most important criteria used for tool performance in carbon fiber material will be the amount of fiber breakout created during the drilling operation. Drill lifetime is a key issue, but damage of the composite structure will always be a very costly mistake.

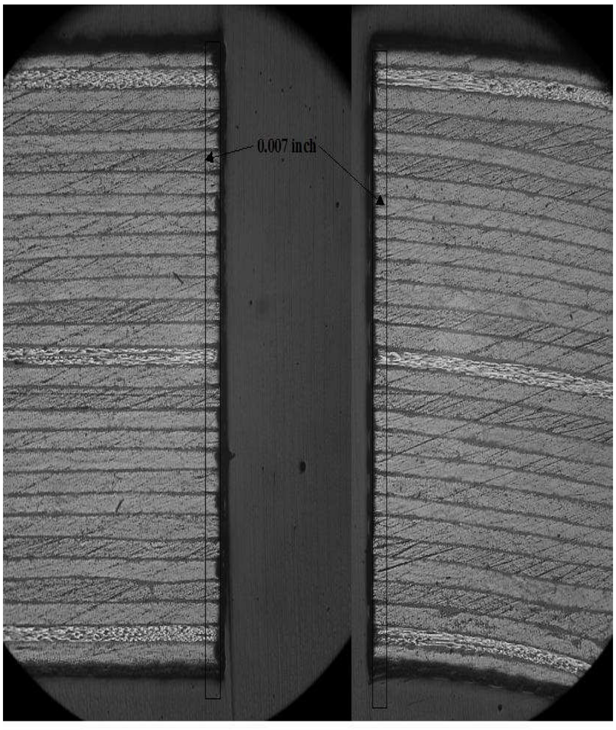
A former Boeing company plant in Tulsa OK has been using CVD coated tools for several years. They are drilling holes in a 12mm thick carbon fiber laminate material. The original tools used were PCD tipped drills but due to a modification in the carbon laminate material they begin to see unacceptable delamination of the carbon fiber layer on the exit side of the hole.

Extensive testing revealed that tool lifetimes were the equivalent for both PCD and CVD drills, but micrographs of hole finish show the CVD coated drill created a much higher quality hole. The photos below (Figure 12 & 13) show cross sectioning of a hole drilled with a PCD tipped tool and one drilled with a CVD coated tool. The holes are both taken near the end of the test cycle of 1000 holes.



Production Test Beam – PCD Drill
BMS 8-276 Form 3 / 3000 RPM 9 IPM Feed

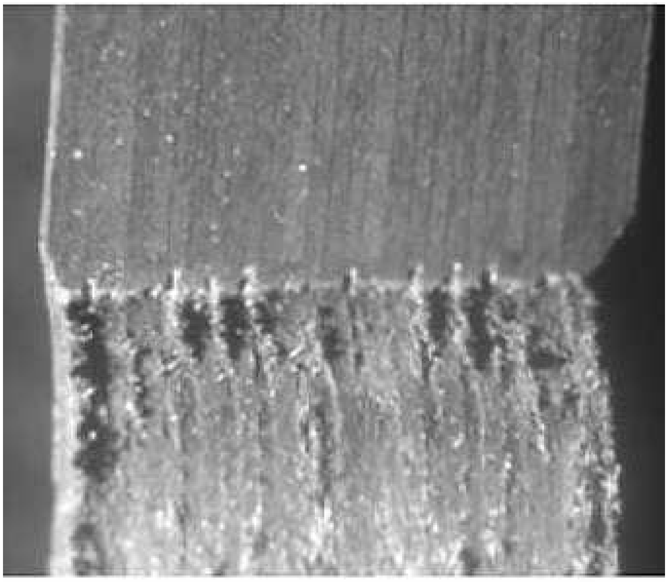
Figure 12



Production Test Beam- CVD Coated Drill
BMS 8-276 Form 3 / 6000 rpm 18 ipm dry

Figure 13

The reduction in fiber breakout was dramatic in this application, and not just on the entrance and exit sides where visual inspection is normally done. Micrographs of the sectioned holes revealed the PCD tools were also creating a significant amount of fiber pullout throughout the depth of the hole (Figure 14). This damage was not apparent during normal visual inspection and only discovered during this evaluation of relative tool life.



Engineering Test Beam BMS 8-276 Form 3 Material

Figure 14

Trimming or side milling of this material also presents significant challenges. A standard 3/8" 2 flute carbide tool will wear out in less than 20 inches of operation. While the operation can be done effectively with a bonded grit tool or even a burr-cut carbide router, a hand finishing operation is then required to clean up the cut. In the same operation, the CVD diamond tool produced a clean, burr free surface for over 250 inches. Typically trimming is not a tool intensive step in most production operations, but for long runs and large dimension parts, the advantage can be dramatic.

GRAPHITE

With the rapid development of electrical discharge machining (EDM), which uses a graphite electrode to create molds for the casting industry, the machining of graphite has become commonplace. The very dense graphite materials used are extremely abrasive, and once again ideal for using CVD diamond coated tooling. A CVD diamond tool will last 10 to 15 times longer than uncoated carbide. And since the diamond tool can be run at much higher speeds, CVD coatings combined with modern auto loading machining centers and high-speed spindles can produce a dramatic increase in productivity. Electrode machining can now be done around the clock with tool lifetimes of 60 to 80 hours.

METAL MACHINING

High silicone aluminum and metal matrix materials are also extremely difficult to machine with standard tooling. These materials are gaining in popularity due to their light weight and high strength, but they are typically very abrasive to machine. One new aluminum based material called SXA is used for space-based mirror mounts and other lightweight thermally sensitive structural applications. This material will wear out a standard carbide tool in less than 10 inches of machining. The 15x improvement from the CVD coated tool is still a relatively short machining cycle, but it does make it possible to accomplish something between tool changes.

Another application that illustrates the abrasion resistance of diamond films is drilling holes in high silicone aluminum materials. The graph below (Figure 15) shows a comparison with uncoated carbide drills using 390 aluminum (18% silicone). The conditions were 10,000 RPM, 250 cm/min, and no coolant - using a 6.1mm drill with a simple 4 facet point to drill a 2.5cm blind hole.

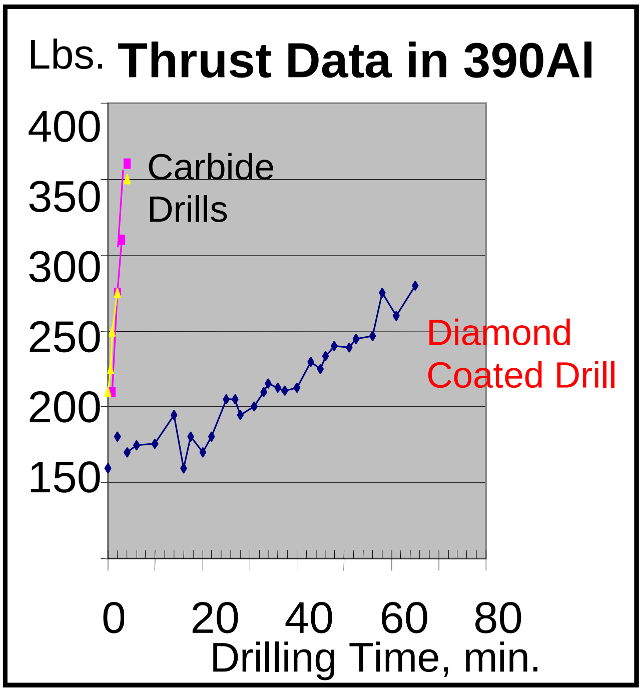


Figure 15

The test data show uncoated carbide wearing out very quickly, failing in less than 5 minutes. The CVD diamond-coated tools typically completed 70 minutes of drilling with the forces still below end of life (350 lbs. Force). Note that this is also another application where the cutting forces are lower for the CVD tool, in spite of the thick diamond coating (22 microns).

RECOMENDED MACHINING CONDITIONS

If your plant is using tungsten-carbide tooling already, you pretty much know how to use CVD diamond. It requires the same setup as tungsten-carbide for optimum performance: rigid tool holding, high quality spindles and solid work piece fixtures. But remember, the diamond cutting edge can survive a much higher temperature and so the tool can be run at a higher speed. The basic advice is to run at your highest effective spindle speed and then increase your feed rate until you have the same chip load per rotation as you would when running your carbide tools under full load. The full range of cutting speeds and feeds for specific materials are available on the web sites of all the major CVD diamond tool coaters.

ECONOMICS

And so, is it worth it? CVD diamond coated tools are typically priced at 4 to 6 times the cost of uncoated tungsten-carbide tooling, but for that price you receive 10x to 20x increase in lifetime. This translates into net tooling cost reductions from 40% to 80%. Additionally, the increased tolerance control and uninterrupted machining can have a big impact on overall productivity. And if your spindle is capable of high speeds (+15,000 rpm) you can take full advantage of CVD diamond's properties to increase your production rates.

If we are comparing to PCD tooling we have seen that the CVD tool will have equal or better performance in many applications. The cost of the CVD tool is approximately equal to the regrinding cost of the much more expensive PCD tool. A single use tool also has advantages related to the necessary inventory control and breakage loss during handling and regrinding of the PCD tooling.

CONCLUSION

Like any new product, CVD diamond tools will need to prove their value on your shop floor before they really make sense to you. But CVD diamond has become a mature technology, which has the potential to dramatically reduce tooling cost and perhaps solve some problems at the same time. There are now several companies producing diamond-coated tools for the aerospace industries. Many of the standard tools in use today are available in these company's catalogs. If you are willing to provide carbide tools ground from a suitable grade of carbide, the major diamond coaters will usually coat those tools as free samples for evaluation in your particular application.

ACKNOWLEDGEMENTS

This work was accomplished with the help of very talented development engineers from Boeing Company facilities in Auburn, WA and Tulsa OK.

CONTACT

Chris Engdahl
V.P. Technology
Crystallume
cengdahl@crystallume.com

Ed Francis
V.P. Imagineering
Crystallume
efrancis@crystallume.com