Breakthroughs in Wiredrawing

The development of industrial diamonds

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US Synthetic Wire Die

History

DIAMOND. Even the mention of the word fills the mind with a multitude of thoughts and images. The Greek word for diamond is "Adamas" meaning unconquerable and indestructible. Diamond is the transparent form of pure carbon, a natural crystalline substance that is the hardest material known to man. Natural diamonds are one of the oldest items in existence, nearly 3 billion years old or two thirds the age of the Earth itself; they were formed and crystallized eons ago under incredible heat and pressure deep within the earth then pushed to the surface through volcanic forces where they were scattered along rivers and into oceans.

As a result of the inherent benefits of diamond, it is no wonder that scientists and engineers have sought methods to replicate diamonds and manufacture them through a repeatable process. It wasn't until the mid 1950s, when a small research team at General Electric achieved this major breakthrough. Using a high-temperature, high-pressure apparatus, the superpressure team was finally successful at converting ordinary graphite into the hardest material known to man: diamond. The ability to duplicate nature's secret has sparked interest in applying diamond to a large number of applications—including diamond wire dies—that previously appeared impractical.

Today's wire manufacturers know that the right material makes all of the difference. For wire professionals looking to reduce the total cost of production without sacrificing quality, diamond wire dies are the perfect choice. Wire dies that contain industrial diamond technology are simply more abrasion resistant, which helps wire makers maintain tolerances longer than other traditional, metal-based dies.

As more and more wire manufacturers consider applying diamond dies within their wire business, it's important to understand the basics of industrial diamond material and its development. In the early days of industrial diamond manufacturing, diamond synthesis led to the development of polycrystalline diamond (PCD). This material has several important advantages over single crystal diamonds. First, PCD offers a much greater toughness due to the random orientation of the natural cleavage planes found in individual crystals, providing more uniform wear and toughness than a single crystal diamond. Additionally, PCD provides more flexibility in size and shape than is feasible in single crystal diamonds, allowing a wider variety of tools to be made.

To more fully understand the advantages of PCD in wire dies, the following sections will summarize the sintering basics of diamond, discuss the innovations of press technology, and look at the future of industrial diamond technology in the wire die industry.

Sintering Basics

Diamond sintering is a complex process that induces a change within the carbon molecular structure taking it from the slippery van der Waals bonds found in between the graphite planes to the strong hexagonal close pack sp3 bonds found in diamond. In order to achieve this transformation, massive amounts of pressure and heat must be applied to a sample of graphite similar to the pressure and heat present in the earth during the natural formation of diamond. For example, diamond sintering conditions may be over 1400° Celsius and may exceed 1,000,000 psi. Figure 1 is a depiction of the carbon phase diagram that outlines the diamond stable region. The small diagrams on the right are models of the molecular structure in both the diamond and graphite states.

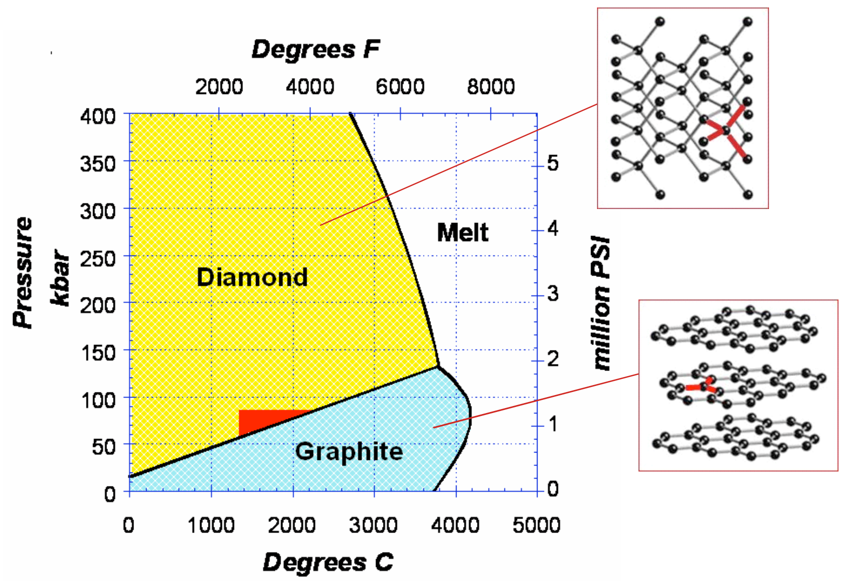

Figure 1 Carbon Phase Diagram

The transformation from man-made synthetic diamond crystals to PCD uses similar conditions of extreme heat and pressure, the main difference being the use of small diamond crystals, or diamond grit, as the raw material rather than graphite. The sintering of PCD, however, requires the use of a catalyst to facilitate the proper diamond bond creation at points where diamond crystals are in contact. The presence of catalyst material, together with high-pressure diamond crystal contact point, allows the formation of additional diamond bonds, resulting in a continuous lattice of diamond. Scanning Electron Microscope (SEM) photos of the diamond grains before and after sintering are show in Figure 2.

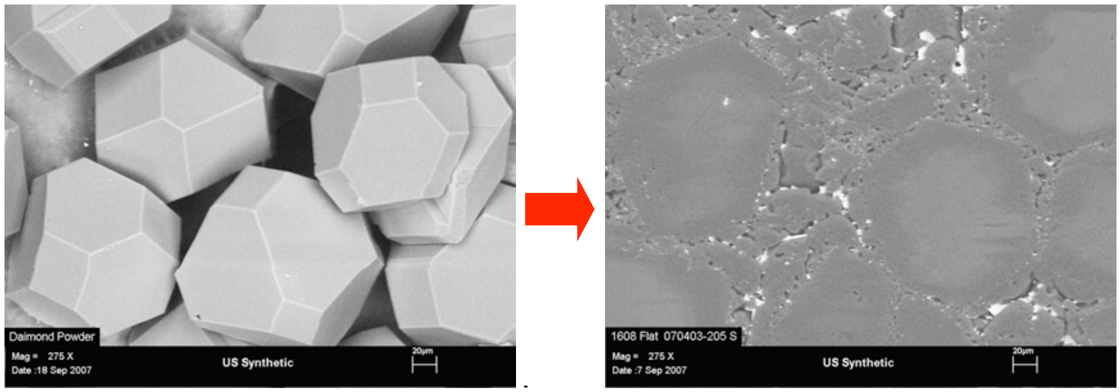

Figure 2 Polycrystalline Diamond Transformation

A large high-pressure press is needed in order to generate the extreme pressures required for sintering. While there are different types of presses being used with varying efficacy, they all use the same basic principle to achieve high pressures. High pressure press designs typically use a hydraulic or screw technique to apply pressure to a large cylinder. This large cylinder is then mechanically stepped down to a small area of only a few square inches. Once the pressure has been applied then the high temperature is created using a simple heating element such as cylindrical graphite heater (shown in Figure 3). The raw materials are placed in a small container inside the heating element. Electrical current is then applied to the heating element and the electrical resistance of the graphite causes the heating element and inside material components to heat up.

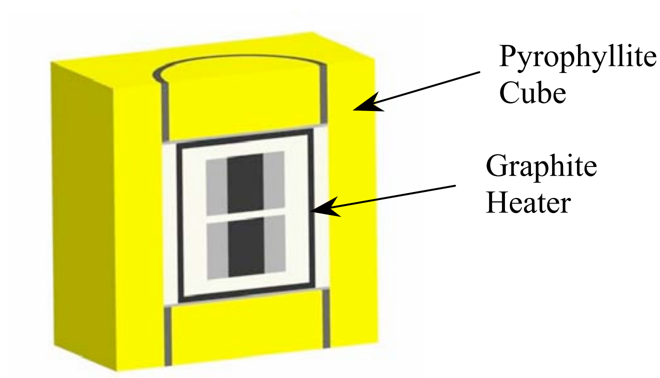

Figure 3 Cube assembly

Once the science of diamond synthesis is understood, the application of this science becomes the challenge. Particularly, how do you contain 1,000,000 psi of pressure? Traditional seals and gaskets are not capable of handling this type of load. Even compressive strengths of metals and carbides are significantly below this pressure requirement. The key is a material known as pyrophyllite. This naturally-occurring material has the ability to resist a shear load as it extrudes between the anvils. This extrusion does three important things: first, it has the ability to deform allowing the pistons to fully extend; second, it creates friction and effectively prevents leakage of the pressurized assembly; and third, it provides support to the anvils to create a more isostatic condition.

Another challenge in working with high pressure is finding materials that can handle the loading. Mechanical, thermal, and cyclical loading reduce the life of all press components. In order to achieve the needed component life, careful attention must be placed on material specifications, tolerances, and maintenance programs.

Press Configurations

The original press configuration for achieving the needed high-temperature, high-pressure conditions for sintering diamond was termed a belt design (an example can be seen in Figure 4). The original superpressure group at GE designed and built a press that had two opposing hydraulic rams that entered a tapered annulus (cylindrical rings similar in function to a belt). This first belt design has been improved upon and is now in use extensively around the world.

Figure 4 Belt Press

Tracy Hall, an accomplished industrial scientist and influential inventor that participated in the development of today's belt press design, pursued several other unique press configurations for achieving the temperature and pressure requirements need to create PCD[1]. One configuration that was a significant development in the production of industrial diamond was the cubic press. The cubic press design incorporates six hydraulic rams providing pressure to each of the six sides of a cube. Photos of a cubic press are shown in Figure 5.

[1] Hall, The Chemist, Volume XLVII pp. 276-270, July 1970.

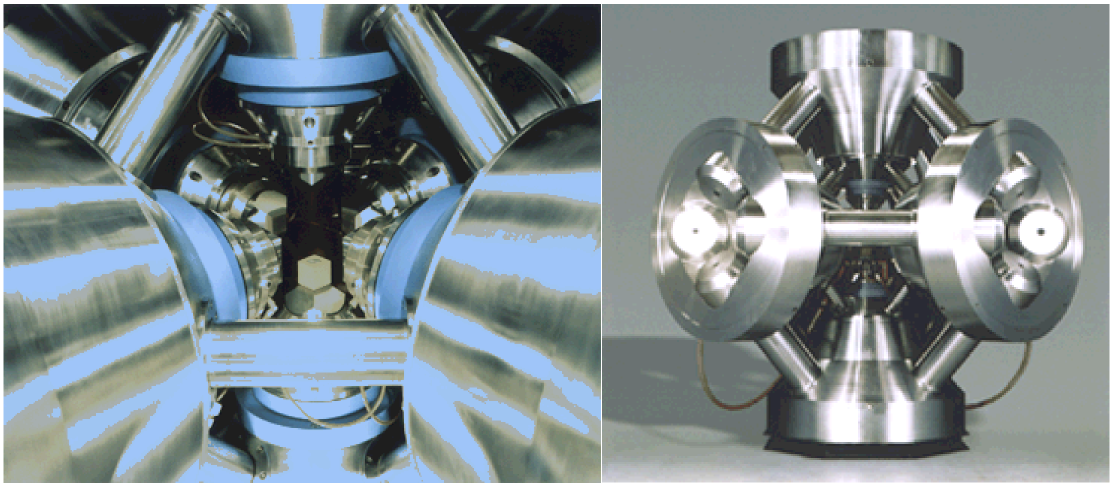

Figure 5 Cubic press

Properties and Applications for Synthetic Diamond

Diamond has several interesting and practical properties (see Table 1). These properties are similar for both single crystal diamonds and PCD. Two of the properties of diamond that generate the most interest are its hardness and thermal conductivity. The hardness enhances its ability to machine or grind other materials. Diamond is the hardest material on earth and as a result is sought after in abrasive wear applications. Thermal conductivity influences the ability of the material to draw heat away from the contact area. Diamond has a thermal conductivity that is 4 times higher than copper and is therefore very efficient in drawing heat away from high-friction, abrasive-wear applications.

Table 1 Extreme Properties of Diamond

Property	Value[2]
Hardness	100 GPa Knoop scale
Thermal conductivity	2,000 W/m-K (4 times copper)
Melting point	4,000°C (500°C above tungsten)
Coefficient of thermal expansion	1.1x10-6 K-1 (< silicon)
Coefficient of friction	0.03 (< Teflon)
Chemically inert	Resistant to all acids and bases
Biologically compatible	Pure carbon

Diamond performs particularly well where abrasion resistance is needed and where there is a thermal component present. Several common applications where these attributes are needed are grinding wheels, metal cutting tools, drill bit inserts, and wire drawing dies.

[2] Physical Properties of Diamond, Chrenko and Strong, General Electric Report No. 75CRD089, October 1975

Diamond presses were first used to manufacture diamond grit. The pressure cell would be loaded with graphite and a catalytic element; after running a high temperature high pressure cycle, small synthetic diamonds would be present in the graphite. These small diamonds were then cleaned and graded by size for use in grinding applications. This diamond grit is produced extensively today for use in grinding wheels, lapping powders, saw blades, and in the production of PCD.

Synthetic diamond is well suited for use as a cutting tool. Cutting tools use both single crystal diamond as well as polycrystalline diamond. Cutting tools use several types of material that include high-speed tool steel, carbide, ceramics, cubic boron nitride (CBN), and diamond. The variety in materials arises due to the tradeoffs made when considering performance, cost, and application.

In the 1970s, PCD was introduced as a drilling insert for oil and gas exploration. The PCD inserts were well adapted to the drilling environment due to the high abrasive wear found on drill bits. Improvements to the PCD material and drill bit design have increased the penetration rate of down-hole drilling dramatically in the last 10 years. Performance is influenced by abrasion and impact resistance.

PCD in Wire Drawing

PCD has been used in wire drawing for over 30 years. The blanks are available in two basic configurations, with and without a carbide supporting ring. Typically larger dies are made using carbide supported blanks. Dies also come in a variety of grain sizes including 5, 12, and 25 micron. Typically, when a bright wire condition is required, the drawing process will use a die with small grain size. The tradeoff is shorter die life. When surface finish of the wire is less of a concern, a larger grain size may be used to extend the life of the die.

Thermally stable blanks are designed for high wire drawing temperatures (i.e., molybdenum and tungsten) and also allow a higher temperature to be used during die fabrication. Most PCD is thermally stable up to about 650° C. When conditions exceed that temperature, the diamond may begin to degrade. Thermally stable PCD may be functional in operating conditions that exceed 650° C, so long as other degradation mechanisms (oxidation, graphitization, etc.) are avoided.

US Synthetic has recently introduced dies made with high-grade PCD during the past year. This unique material has been validated using internal abrasion tests and external wire drawing field tests. Early results for the material show an improvement in life over PCD typically available in the market as shown in Figure 6.

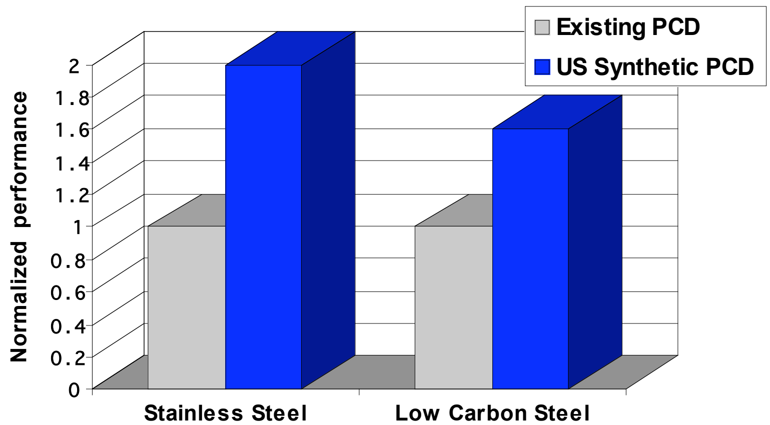

Figure 6 Field test results of US Synthetic PCD Dies

Future of PCD in Wire Dies

There are several exciting developments currently being made in PCD material. There are several variables that may be modified during the sintering process. Two variables that affect the performance of the resulting dies include the diamond feedstock material and the sintering conditions. Once the PCD blank has been sintered, its properties typically do not change unless it is heated to excessive temperatures or otherwise structurally or chemically altered. The key to improving today's wire drawing die is to start with the right PCD blank.

The quality of the diamond feedstock material is critical in producing a high quality PCD blank. Quality is affected by the cleanliness, the shape of the crystals, and the type of diamond grit. There is a variety of diamond grit available worldwide. Higher quality grit requires paying a premium, but the impact on the finished die is substantial. An improvement in materials is expected due to higher quality diamond feedstocks developed over time.

There are a number of significant breakthroughs in PCD that look promising for the wire industry in the coming years. First, Los Alamos National Laboratory and US Synthetic have developed a silicon carbide – PCD material. This material is thermally stable, tough, and extremely wear resistant at high temperatures. These attributes makes the silicon carbide – PCD material a perfect solution to extend the functional life of diamond tools that undergo high temperatures during processing. Abrasion resistance for this material doubles the performance of standard PCD in an abrasion test and achieves a 12x improvement when undergoing a thermal abrasion test (shown in Figure 7). Most thermally stable PCD is achieved by removing the catalyst which results in small voids in the diamond matrix. One advantage silicon carbide has over this type of thermally stable PCD is the absence of voids in this material. Diamond and silicon carbide comprise the entire volume.

A second material currently in development at US Synthetic, is a PCD structure sintered using carbonate materials as the catalyst, rather than traditional metal catalysts. This material has shown an abrasion resistance that is 7 times that of standard grade PCD (see Figure 7). With the absence of a metal catalyst, the material is expected to maintain its abrasion resistance in operating conditions that exceed 1,000° C, so long as other degradation mechanisms (oxidation, etc) are avoided. Similar to the silicon carbide-PCD, this material does not contain any voids in the diamond matrix. The result is a solid structure that excels in abrasion tests.

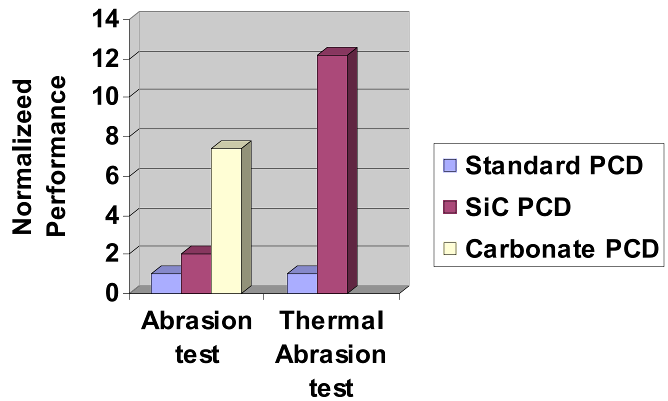

Figure 7 Abrasion Comparison for SiC and Carbonate PCD

Research into improvements and applications for PCD is being conducted throughout the world. In addition to the developments discussed here by US Synthetic, other laboratories are also developing significant advances. There have been several improvements introduced to wire dies during the last 30 years. No doubt the industry will continue to see successful PCD material improvements transition from the laboratory to the field in the future.

For today's wire professionals, PCD wire dies offer a cost-effective way to increase the production life of wire dies without sacrificing quality. The right material does make a difference in abrasion resistance, which helps wire makers maintain tighter tolerances longer than other traditional dies. PCD has a bright future in the wire industry and will likely be a diamond in the rough for wire makers willing to take advantage of it.

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About US Synthetic Wire Die

US Synthetic Wire Die provides finished polycrystalline (PCD) dies that use US Synthetic PCD blanks. Pressing the diamond core and finishing the die to exact specifications gives customers a high-performance, long-lasting product that draws more pounds of wire per dollar. A subsidiary of US Synthetic, a 28-year veteran in the development of PCD for oil and gas drilling inserts, US Synthetic Wire Die builds upon an established reputation for product innovation, customization, "dock to stock" quality, and on-time delivery. US Synthetic Wire Die works directly with customers to provide dies that meet their specific needs.

Visit www.ussyntheticwiredie.com or call (801) 235-9001.

The Author

Mr. Joe Memmott is the general manager of the US Synthetic Wire Die division—overseeing the development, testing, and manufacturing of PCD wire dies. Mr. Memmott also manages business development and overall product design for the wire die business. He received his MBA and MS degrees from Brigham Young University. His studies focused on product development and centered on developing waterjet processes for healthcare applications. Mr. Memmott also spent two years working for Applied Research Associates, modeling the structural integrity of historical buildings.