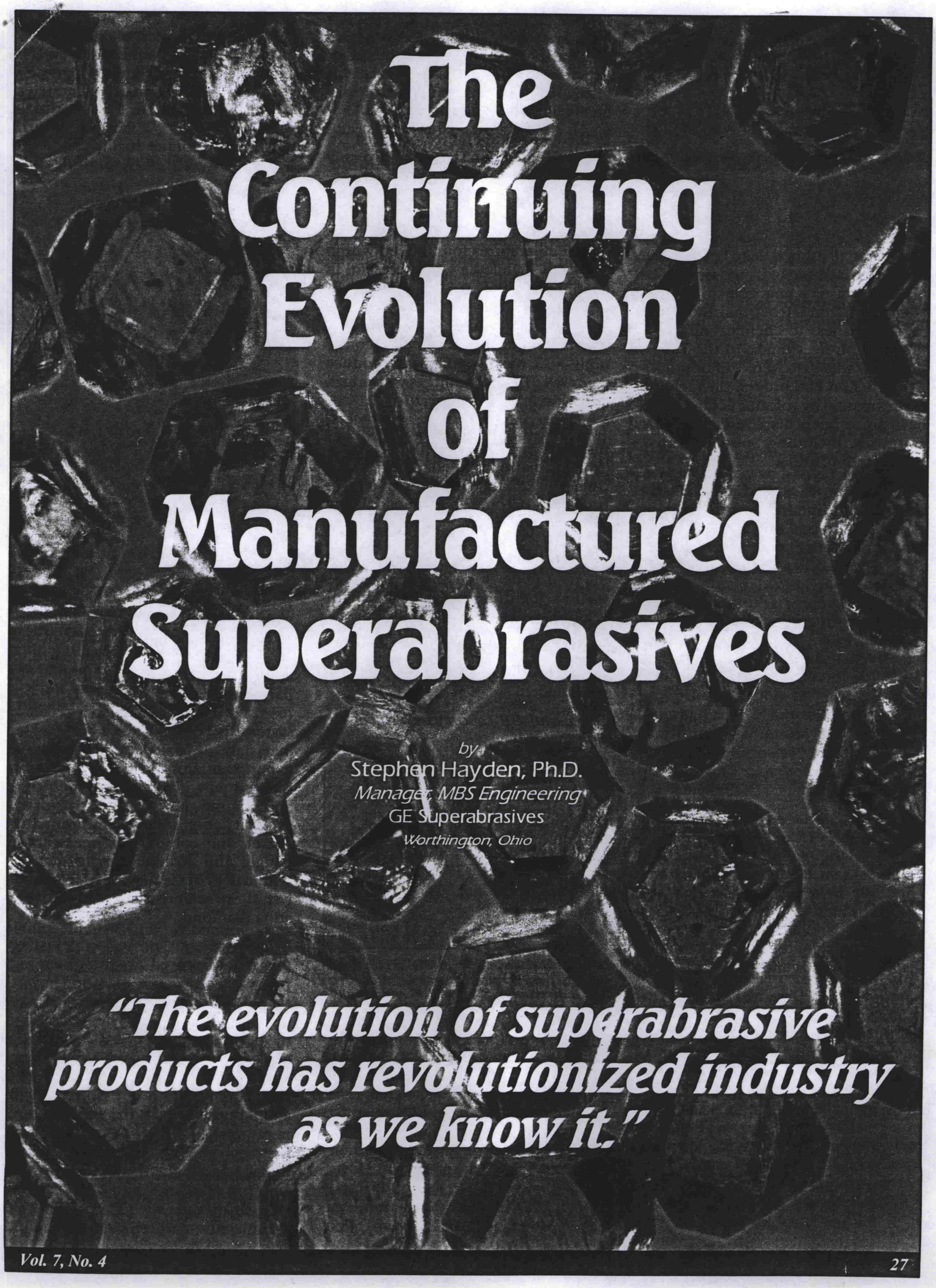

The Continuing Evolution of Manufactured Superabrasives

by
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> *"The evolution of superabrasive products has revolutionized industry as we know it."*

The Beginnings of Manufactured Diamond

Unsuccessful Attempts Creating Diamond

Mankind has been dazzled by the mysteries of the gleaming diamond since it was first discovered centuries ago among alluvial deposits in the riverbeds of India. The glistening, bright, rare material, formed deep beneath the earth's surface, was coveted first for its beauty as a dazzling gemstone, and later for its unmatched hardness and imperviousness to chemical attack or degradation over time. In the 1860s, diamond was discovered in South Africa, where it had broken through the earth's mantel by volcanic action. They have since been discovered in other countries, including South America, Russia and Australia.

Efforts to synthesize diamond date back several hundred years. As early as 1770 Antoine-Laurent Lavoisier, a French scientist, was credited with proving diamond is a crystalline form of carbon, the basic element found in all living matter. Scientists would later discover carbon atoms in graphite are arranged in two-dimensional hexagonal planes stacked one above the other, with each atom attaching to three others in the plane, making the substance slippery to the touch. In diamond, however, the atoms of carbon are packed in three dimensions, with each carbon attaching to four others, forming the hardest material known.

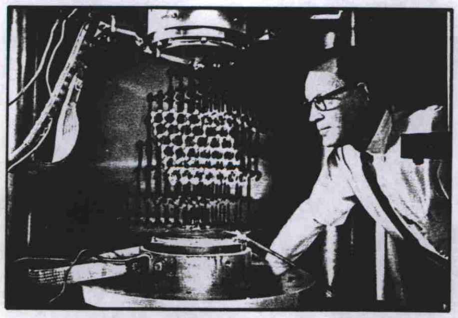
Scientists theorized that if the atomic composition of carbonaceous materials was manipulated, diamond could be made in the laboratory. While it was generally believed this change was caused by high temperatures and high pressures, the exact process was a mystery that fascinated many scientists during the 1800s and early 1900s.

Some believed they had created diamond in the laboratory, only to discover later their experiments could not be replicated. In 1880, James Hannay of Scotland thought he made diamond when he heated a mixture of hydrocarbons, bone, oil, and lithium to red heat in sealed iron tubes. Twelve years later, French scientist Henri Moissan thought he had made a diamond when he superheated carbon and metals to white heat in a special electric-arc furnace, then plunged them into water or molten lead. Claims by these scientists were later dashed by an Englishman, Sir Charles Parsons, who studied their experiments, as well as conducted his own. He concluded no one had ever created a synthetic diamond.

In the 1940s Nobel Prize physicist Dr. Percy Bridgman of Harvard University began a series of experiments supported by an industrial group. Bridgman designed equipment capable of recreating the high pressures and the high temperatures found deep within the earth. While he was successful in heating graphite to 3000°C (5432°F) under pressures of 600,000 psi (4137 MPa) — greatly adding to the understanding of carbon under these conditions — he was also unable to produce diamond. The experiments were abandoned within three years.

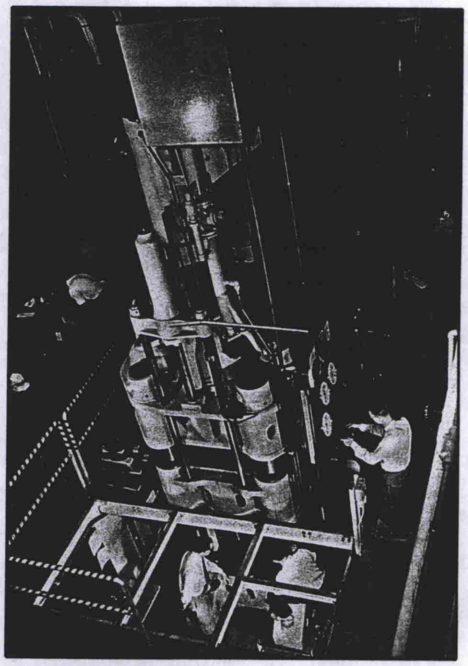
The search for a synthetic diamond resumed in the late 1940s to meet a growing national need. During the Cold War Era, the U.S. industrial force had slowly become dependent on natural diamonds. Diamonds were needed to sharpen cemented tungsten carbide tools used in metalworking, for sawing or drilling stone and concrete, as well as for dressing tools used for grinding wheels and for polishing applications. The only source for these diamonds was overseas. Clearly, a stable, dependable source of diamond was needed.

Successful GE Laboratory Project Begun in 1951



Dr. Herbert Strong from the original diamond team examines press interior, overlay is diamond lattice (white) and graphite lattice (black) for visual atomic structure.

GE vigorously took up the challenge to develop a manufactured diamond in 1951, committing significant resources and appointing a team of 9 scientists including: Abraham L. Marshall, head of the chemistry department; Anthony J. Nerad; head of the mechanical investigations section; Dr. Francis P. Bundy and Dr. Herbert M. Strong of mechanical investigations; Dr. H. Tracy Hall of the chemistry department; Dr. Robert H. Wentorf, a physical chemist; Harold P. Bovenkerk; and James Cheney. The team perfected Bridgman's high-pressure/high-temperature theories. Within two years Dr. Hall created a "belt apparatus", a large hydraulic press capable of producing conditions roughly equivalent to those 256 m (160 mi) below the surface of the earth, or approximately 6895 MPa (1,000,000 psi) and temperatures of 3500°C (6332°F). He also designed a gasketing system to hold the diamond-making materials. It took yet another year of experimentation before the scientists realized that, along with compressing and heating the graphite structure, a catalyst, consisting of molten iron, nickel, and cobalt, was necessary to trigger the atomic transformation. Within days of the discovery of the catalyst, these scientists succeeded in creating diamond.

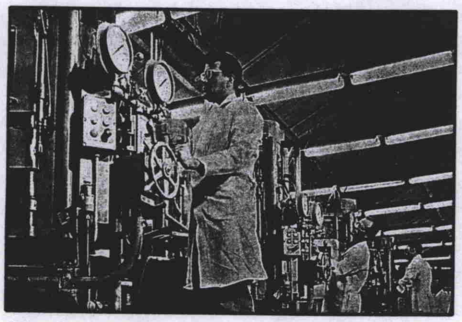


Original diamond press at GE Corporate Research and Development.

Exhaustive tests proved conclusively this manufactured grayish-green and yellow microscopic diamond crystal shared all the salient properties of natural diamond: it scratched glass, had the triangular-faced crystal characteristics of diamond, passed X-ray diffraction patterns identical to those of natural diamond, did not dissolve in acid, and it burned or oxidized at high temperatures. In 1954, GE achieved the first reproducible process for making diamond and spent most of the year refining the process. GE Research Laboratory announced its capability to manufacture and reproduce diamond on February 15, 1955 -- the evolution of manufactured superabrasives had begun.

Introduction of Commercial "Type A" Manufactured Diamond

In October 1957, GE became the world's first mass manufacturer of diamond by introducing Type A diamond.



The first diamond production line.

All diamond, mined or manufactured, has the same hardness. Scientists discovered they were capable of manufacturing crystals superior in performance to mined diamond by "tailoring" or changing crystal properties and form to meet specific applications. When diamond is used as an abrasive, four factors affect its performance: chipping resistance (TI), chipping resistance after thermal cycling (TTI); resistance to macro-fracturing; and shape. Changing temperature, the composition of the catalyst, or either the amount of pressure, or time of growth changes these four characteristics of diamond.

Type A diamond was specifically designed to grind tungsten carbide. These first tiny sand-like diamond grains quickly established a clear performance edge, surpassing mined diamond in many industrial uses.

Later Manufactured Diamond Types And Their Uses

RVG Diamond*

Manufactured diamond continued to expand as a product line. Within the first 10 years of production, operations and engineering developments were refined, and from this, three families of diamond were created for specific applications using resin, metal, electroplated, or vitrified-bond grinding wheels. The first of these families was RVG* diamond, which, when introduced in 1959, replaced the Type A product. This new diamond, which is designed for use in resinoid and vitrified grinding, featured an improved design for grinding tungsten carbide tools versus the original products. RVG* diamond has an elongated, irregularly shaped crystal with rough edges to assure a firm hold in either a resinoid-or vitrified-bond wheel. This diamond also has the unique capability to break down in a controlled manner (characterized by friability) due to its composition of thousands of tightly bonded crystals (known as multicrystallinity). When mined diamonds break, they dull and fail to grind over time. However, its friability allows the manufactured diamond to microchip, in effect to self-sharpen itself by continually producing fresh cutting points on each crystal. To the grinding industry, this means more cost savings by longer production periods with less down time due to wheel change-overs.

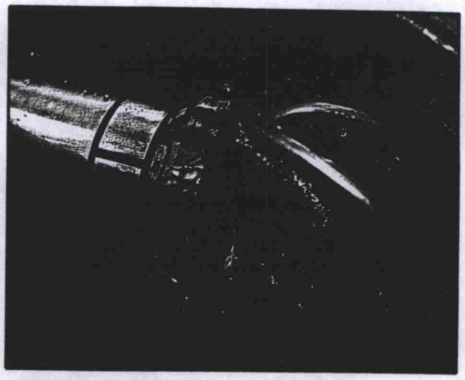
An entire group of grinding products was eventually produced. Nickel-coated crystal and copper-coated crystal products entered the market in 1966. These coatings solved an earlier problem of crystals being pulled out of the resin bond due to high temperatures at the bond-crystal interface. Nickel-coated products are used primarily for wet grinding of cemented tungsten carbide. Copper-coated products, which improve the thermal conductivity of the wheel, were developed for dry grinding of carbide-steel composites. The RVG* family of manufactured diamonds remains an important product line today.

Single-Crystal Diamond Product Lines

The second family of diamonds was made possible when GE began to synthesize large single crystal diamonds -- up to 1/200th of a carat in size -- in 1961. This breakthrough made it possible to offer even more specialized opportunities for grinding, drilling, and sawing with two new products: the first, MBG* metal-bond grinding products and the second, MBS* metal-bond saw diamonds. Improved apparatus design and process control made the manufacture of these products feasible.

MBG Products*

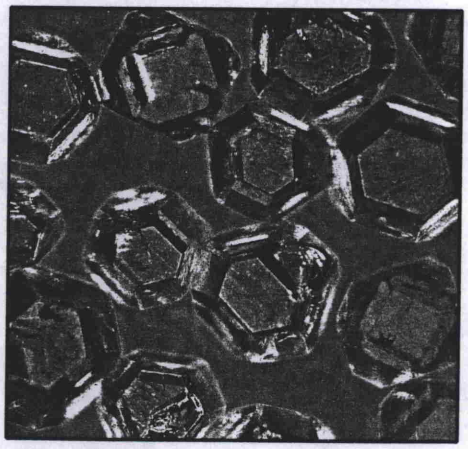
In the MBG* product, each crystal has a distinctive blocky shape and surface texture to give it the required strength and retention for use in industrial applications, such as grinding cemented carbides, sapphires, ceramic materials, and glass; the slicing and dicing of germanium; and electrolytic grinding. The specialized needs of electroplated tools were first met by diamond treated for platability. Other diamond products which feature increasingly strong, angular, single crystals, were added later and completed the metal-bond grinding product line.



Diamond wheels provide speed and precision in grinding optical lenses.

MBS Products*

Metal-bond sawing requires a less friable, stronger, and larger crystal than either RVG* or MBG* products. To meet these specifications a single, tough and uniform crystal is grown.



This well engineered saw diamond reflects the technological advancements in the diamond industry over the last 40 years.

Each crystal approximates a cubo-octahedron, a morphology between a cube and an octahedron, with smooth and regular surfaces for the greatest resistance to fracturing. MBS* products are used in metal-bond saw blades to cut cured concrete, tile, marble, granite, other stone, cement block, brick, and a variety of masonry and refractory materials. MBS* diamond is also effectively used in rotary dressers and in drill bits for exploration and production mining.

Spin-Off Product Development

The growing use of hardened steel, stainless steel, and a wide range of su-

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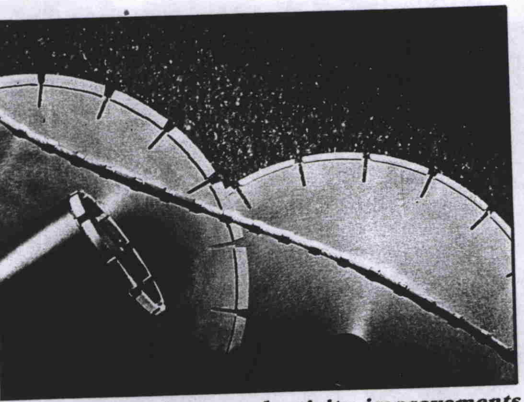
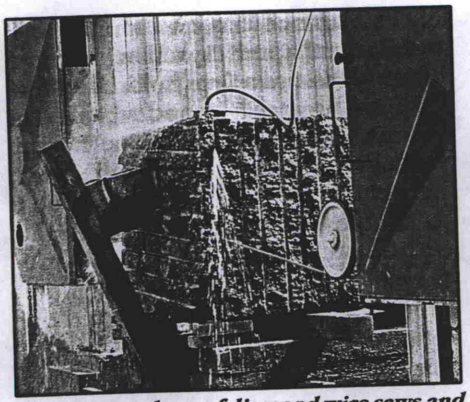


Tremendous productivity improvements have been made with diamond tooling for construction, renovation and stone processing.

peralloys created a need for an abrasive capable of grinding these workpiece materials. Diamond is not effective grinding steel because its carbon solubility is high in ferrous materials at the high temperatures and pressures normally occurring in the grinding and machining processes. When this carbon solubility problem was discovered, scientists already had a noncarbon superabrasive product on the shelf. Cubic boron nitride (CBN), makes it possible to manufacture grinding wheels that are harder, longer lasting, quicker, and that produce a better finished product than aluminum oxide.



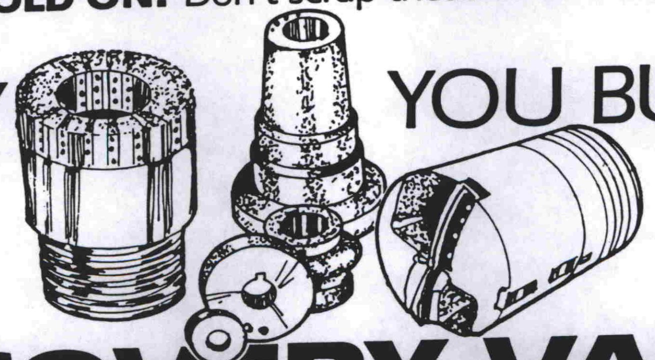
The increased use of diamond wire saws and saw blades has led to a resurgence in the stone processing industry.

Development of Cubic Boron Nitride (CBN) in 1957

CBN is not found in nature. GE scientists invented it in 1957, when they were conducting experiments to produce a substance harder than diamond. The scientists substituted graphite with hexagonal boron nitride, whose arrangement of atoms is similar to graphite, and then used a catalyst of alkali metals and nitrides of lithium, calcium, and magnesium in the high pressure/high temperature diamond manufacturing process. The CBN crystals that were created were not harder than diamond and were, in fact, not as good as diamond for cutting cemented tungsten carbide. However, other uses awaited this material.

Like manufactured diamond, CBN production can be manipulated to meet the need for specific applications. It can be produced either as monocrystals, blocky-shaped large crystals, or strongly bonded microcrystalline, micrometer-size grits, that are irregular in shape. Cubic boron nitride was commercially introduced by GE in 1969 as Borazon* CBN, a superabrasive for grinding hardened steel. It was quickly proven to be far superior to conventional aluminum oxide abrasives. Today there is a family of Borazon* CBN products, each tailored to a specific

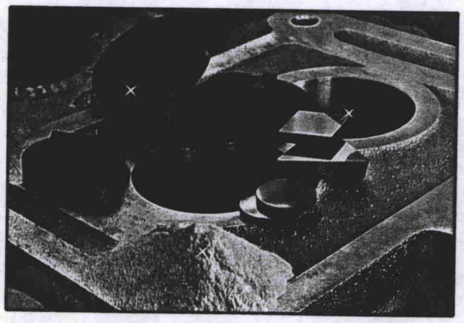
Automotive components can be ground faster with cbn, with more part to part consistency, and a better surface finish.



bond system and/or mode of material removal for grinding tool and die steels, hardened steels, and superalloys.

Development of Polycrystalline Diamond (PCD) and CBN (PCBN) Products

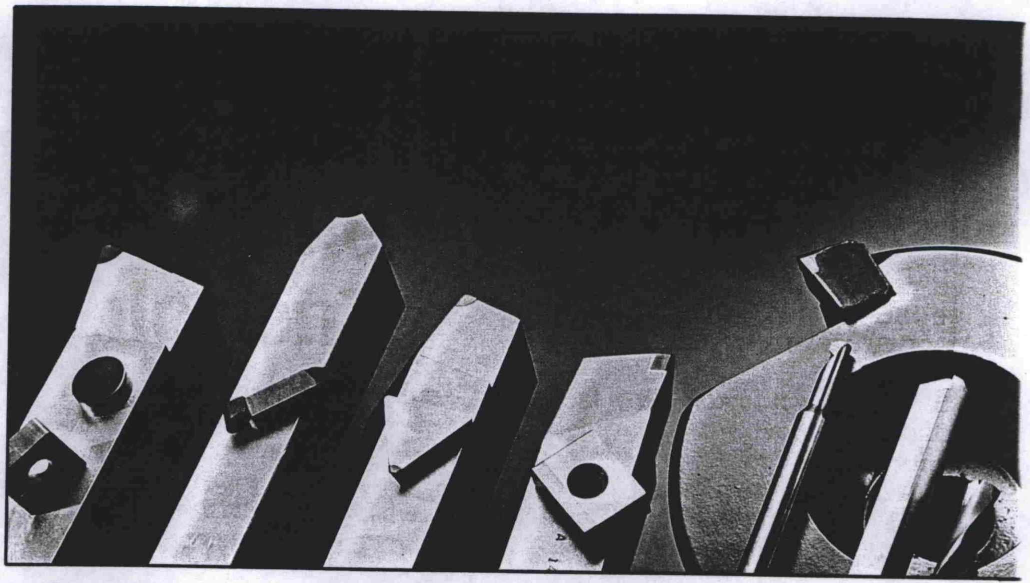
The third family of superabrasives, polycrystalline diamond and CBN products was introduced in 1970 for cutting tool machining applications of nonferrous and nonmetallic materials, especially where the workpiece itself is abrasive. Two of the most important properties of these materials are long-wearing cutting edges and abrasion resistance. Polycrystalline tool blanks are made by sintering and integrally bonding either diamond or CBN particles with a tungsten carbide substrate using a high-temperature, high-pressure process. Here, the diamond or CBN is randomly oriented, making for a uniform tool surface. The tool blanks are finished in various sizes and shapes by using specialized cutting, grinding, and lapping techniques. GE offers a family of such "Compacts" products, each designed for a specific application. Machining applications include: ferrous and nonferrous metal; tungsten carbide; and nonmetallics like plastic, rubber, fiberglass, ceramics, carbon, and graphite. Dressing products are used to form and dress aluminum oxide and silicon carbide grinding wheels; wire dies are used for drawing nonferrous and ferrous wire; while a line of polycrystalline drill diamond serves the drilling industry.



Polycrystalline diamond is made from diamond powder. The abrasion resistance of the diamond and strength of the carbide backing makes a superior cutting tool.

Introduction of PCD Tool Blanks for Machining

Polycrystalline diamond blanks consist of multiple diamond crystals sintered together with a tungsten carbide substrate. PCD blanks have advantageous uses as cutting tools for nonferrous materials and can be used at exceedingly high cutting speeds and material removal rates.



Machining operations using polycrystalline tools offer industry long tool life and deliver more parts per edge.

Die Blanks for Wire Drawing

The development of diamond die blanks in 1974 revolutionized the copper wire industry by providing longer die life, improved productivity, consistent surface finish, and better dimensional control. These blanks currently offer significant advantages over dies made with either single-crystal mined diamonds or tungsten carbide in the drawing of ferrous wire.

PCBN Products for Machining Hardened Ferrous Materials

Polycrystalline cubic boron nitride tool inserts, which were introduced com-

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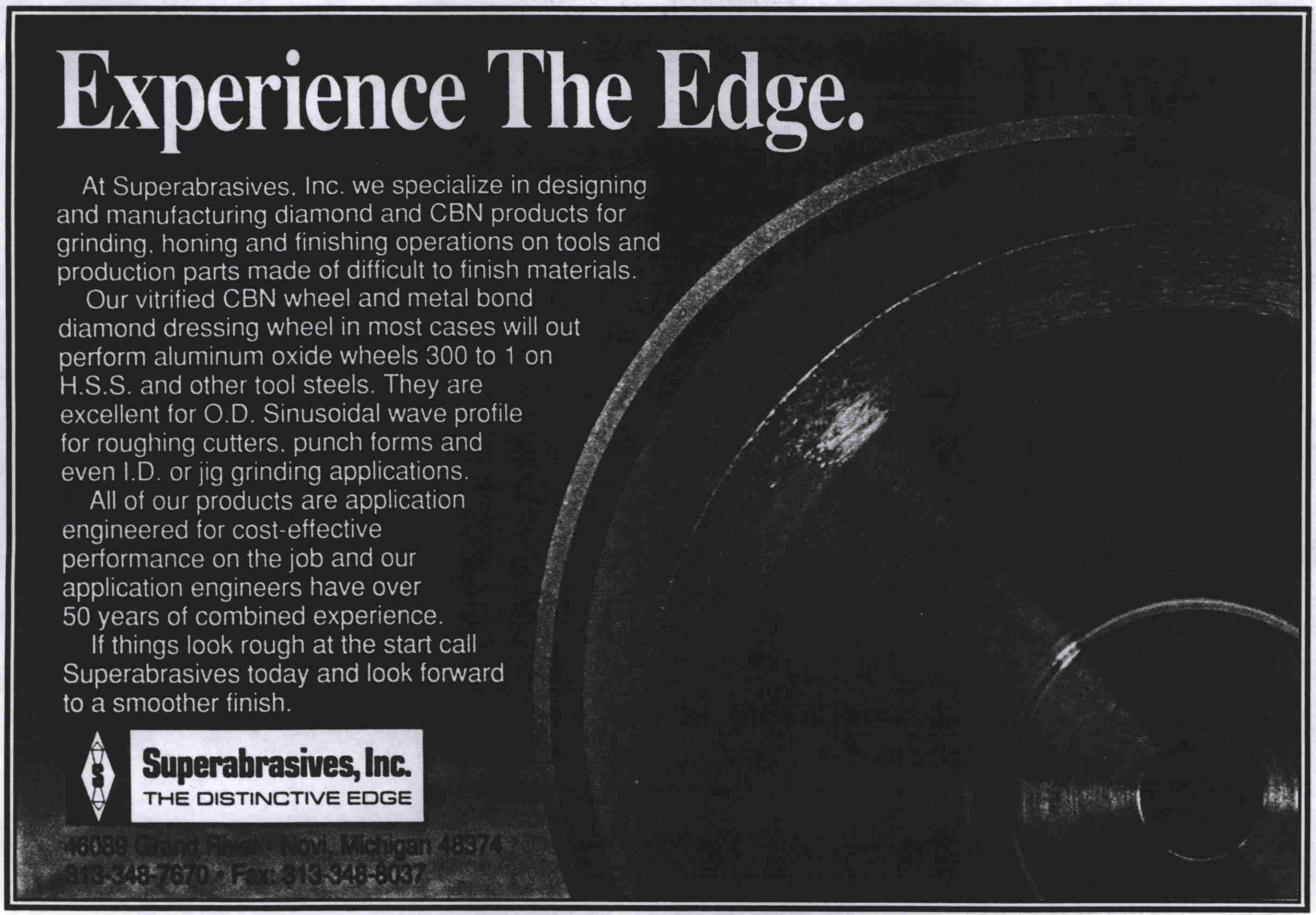

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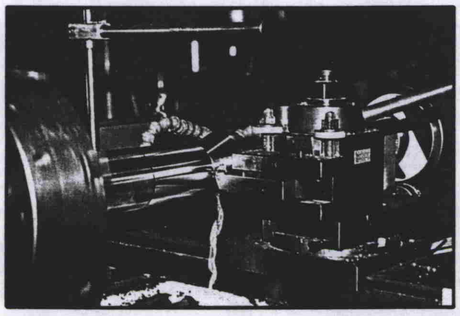
mercially in 1975, consist of a layer of polycrystalline CBN sintered with a tungsten carbide substrate to form an integral blank. These can be braized directly to tool shanks or used as indexable inserts to machine high-temperature alloys and hardened ferrous materials. A new product in which ceramic grains are added to the sintering process, was introduced in 1991. The ceramic component of this product provides high chemical stability, while the PCBN supplies superior hardness and resistance to abrasion and chipping. This product holds tighter tolerances than ceramic tools, while providing resistance to the chemical reaction that can cause cratering in other CBN tools. These new CBN/ceramic inserts perform at high speeds and achieve material removal rates from 4-10 x over conventional grinding.



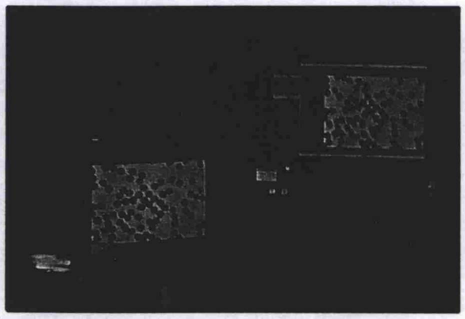
PCBN inserts are making remarkable strides in the machining of hardened steel components.

Diamond for Geological Drilling Applications

PCD drill blanks were introduced in 1976 for drilling applications. They are attached to bit bodies used in drilling wells on and offshore. Today they are also enjoying success in mining applications. PCD drill blanks consist of a layer of polycrystalline diamond integrally bonded to a cemented tungsten carbide substrate, giving a combination of back-up strength, protection against gross fractures, and abrasion resistance. The cutting edges of the self-sharpening PCD blanks allow for more rapid penetration of geological formations than with traditional crushing or fracturing methods.

Thermally-Stable Polycrystalline Diamond for Drill Bits

Thermally-stable drill diamond, introduced in 1982, makes possible core bits that reach new levels of performance in soft-to-medium-hard formations. The large, tough cutting edges of thermally-stable drill diamonds remain sharp throughout the life of the bit because their polycrystalline structure allows the crystals to be continuously exposed during drilling. Thermally-stable drill diamond can be used both as cutting edges and excellent gauge protection on downhole tools. Bits using thermally-stable drill diamond demonstrate excellent core quality at rapid penetration rates.



New diamond characterization system is first ever to accurately control and define diamond properties.

Current Technological Developments in Diamond

Since the introduction of manufactured diamond in 1957, numerous new products have evolved offering end-users increased quality and productivity. The evolution of new superabrasive products continues today to even better serve the material-removal market. For example, consistent diamond quality is a requirement for consistent tool performance. Without greatly improved manufacturing consistency, lot-to-lot diamond characteristics can change enough that tools may fail. The cause of this type of failure is often impossible to determine. Until recently, saw diamond was characterized only by its resistance to chipping (friability). It is well known that specification of diamond by friability alone is not sufficient to exclude changes in diamond that can lead to tool failure. Consequently, in 1992, GE embarked on an extensive technical program to better define and control diamond properties. The breakthrough came in 1994 with a complete definition of diamond shape and a method to control shape during diamond manufacture to assure shape consistency. The shape of saw diamond can be characterized by two features: typical crystal morphology and deviations from this ideal morphology. Crystal morphology generally is cubo-octahedral. However, very few saw diamonds are perfectly cubo-octahedral due to elongation of an axis, surface roughness, and/or chipped edges or corners. Research has shown that these deviations can be characterized by eccentricity.

It has long been known that diamond shape affects tool performance. However, that shape was only evaluated subjectively by visual observation. Even experts often disagreed in their visual evaluations of shape. In order to specify and control shape in diamond products, the shape characteristics had to be quantified, i.e. numbers assigned to them. This required analytical methods to reliably and rapidly measure morphology and eccentricity.

This critical problem was overcome when GE adapted computer technology, originally developed for its aerospace operations, to measure with precise numbers the shape statistics of large populations of crystals. The proprietary computer program measures not only where the population falls on the cubo-octahedral scale, designated as tau (T), but also the eccentricity. GE Superabrasives now uses this computer system in its saw diamond products to assure, for the first time, products with consistent shape characteristics.

Current New Product Development

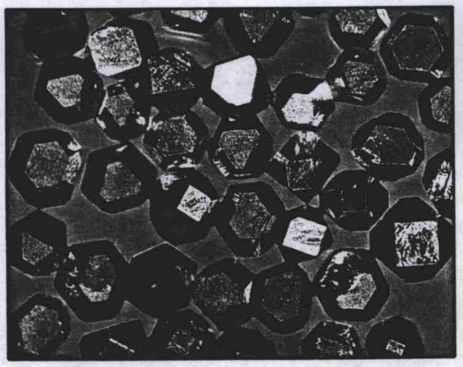
The evolution of superabrasive products has revolutionized industry as we know it. New materials have been created that prior to the advent of superabrasives could never be used due to their abrasion resistance and toughness. Superalloys and thermal sprays now widely used throughout the aerospace industry can only be effectively ground and machined with CBN abrasives. Metal matrix composites, cermets, and ceramic derivatives, rely on the hardness and tailored properties of manufactured diamond products to be shaped and finished for final use in long-life automotive components. In construction and renovation, diamond is now used in creative wire sawing applications for everything from more cost-efficient cutting of stone, to safer and cleaner remodeling or removal of concrete structures.

New machining and grinding centers with robotics, CNC controls, in-cycle measuring probes, laser guides, and multiple computer programs for myriad applications are armed with various shaped and sized superabrasive tools, each with a unique and specific use. These highly-efficient centers require the long-life and quality of superabrasives to achieve maximum productivity.

In the auto industry there are new materials being introduced ranging from nickel alloys to metal matrix composites, powder metals, and hardened steel. New applications are being brought on-line as these materials find uses for components such as brake rotors, engine blocks, cylinder liners, transmissions, and many other automotive parts.

A new area in the aerospace industry is the restoration of aircraft engine components though the use of a thermal spray to build up the worn part surface, and then machining or grinding the deposit to specified dimensional tolerances and surface finish. In laboratory and field comparison tests on nickel-base thermal sprays, PCBN cutting tools have delivered up to 10 x greater productivity than carbide tools, along with a minimum of 2 - 5 x improvement in surface finish, flatness, and dimensional control. The PCBN tools also generated lower cutting forces, leaving higher bond strengths in the part.

GE has also introduced two new premium series of coated saw diamond products designed to improve tool performance in demanding sawing and drilling applications, where crystal retention and/or oxidation have traditionally been problems. A titanium-coated product is generally suitable for cobalt bonds containing iron, steel, and/or bronze. While the chromium-plated product is suitable for cobalt or tungsten carbide bonds containing low levels of iron and/or bronze. These thinly coated diamond products provide toolmakers the opportunity to manufacture tools with improved performance and enhance diamond retention through chemical bonding and suppression of diamond degradation by oxygen and bond constituents.



Thin coatings of titanium and chromium greatly improve bond retention and physical properties of diamond tooling.

innovations occurring annually. Of course, these new product developments require process innovations to support them. The result is higher quality and productivity for the diamond tool manufacturer and end user.

Diamond is used for grinding of various non-ferrous components such as glass, stone and ceramic materials.

CBN products have been developed to match ferrous grinding applications on industrial components from aerospace to automotive.

Today there is a superabrasive product tailored for literally every application or material. As work piece materials get lighter, stronger, and more abrasive, and machines get more complex, superabrasives will play an expanded role in production operations.

With all this achievement in the past 40 years, superabrasive technology continues to evolve with new product innovations occurring annually.

The Technology Department in Ohio, in conjunction with the Corporate Research and Development in New York, continues to push superabrasives evolution to meet the demands of tool fabricators as they strain to provide products that will cut and grind the numerous new materials emerging as we move toward the 21st century.

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