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Boron Nitride Unleashed: Revolutionary Insights into Its Superhard Phases and Machining Aptitude

Bangshidhar Goswami*

Abstract

Exploration from the prehistoric era has proven steel to be a hard substance. According to research, the four main crystalline forms of boron nitride are graphitic, cubic, rhombohedral, and wurtzitic. Better hard materials for industrial processes have been provided by diamond, hard ceramic, and cermet in the process of developing the front of the script, which is descriptive. Turning, cutting, drilling, boring, and grinding of hard materials have been linked to industry usage. In place of the diamond insert that was required for rock drilling for the extraction of natural gas and petroleum, the head crown of the perforation tube has always been the conspirator. Applying compressive pressure under the indenter has been found to increase the indentation strength of wurtzite Boron Nitride (w-BN), which has been proposed as the hardest substance. While the decomposition temperature was 2204°C and subject to self-ignition, solid/liquid BN was not flammable. Because they read as having electrical insulation, reduced thermal conduction, a low coefficient of friction, and oxidation resistance when exposed to temperatures as high as 900°C, white BN lubricant additives have been advantageous for application. The polar B-N bond was accused of interfering with the scope of electron transfer, causing the descriptive issued feature of BN to be devoid of electrical conduction. It has been suggested that boron nitride oil dispersion, which combines fine hexagonal boron nitride particles with mineral base oil, is applicable.

INTRODUCTION

Decisive hardness granted in fabricated formation was opposed by replicated diamond replacement. Detonation is used to create wurtzite boron nitride, a super-abrasive material. Super-abrasive has been associated with cubic boron nitride, which has organized inherent synergism with graphite structure and is now referred to as hexagonal boron nitride. Hexagonal symmetry has led to the development of the wurtzite structure's definitive nomenclature. Two hexagonally close-packed (hcp) lattices penetrated each other, securing the same a3-axis in a displaced state, and a crystallographic analogy resulted. The ethic of crystallinity synergism was discovered to be the brownish-black mineral ZnS. Zinc sulfide in hemimorphic hexagonal crystals was the focus of the defined scheme, or it could have been subject to learning from the fibrous state accused herewith, polymorphous with sphalerite as a focus. Since it is a super-hard material, diamond has been replaced by wurtzite boron nitride (w-BN). However, w-BN has been developed as an III-V compound to support wide band gap materials suitable for cutting-edge electronic devices. The transformation of w-BN phases from hexagonal materials produced under high pressure and high temperature improved mechanical wear observance. On the other hand, by removing the binder, modifying the grain size, and composing formation by n-diamond/n-BN production of similar origin, the material hardness increased.

*Author for Correspondence
Bangshidhar Goswami
E-mail: goswami.b8757@gmail.com

Assistant Professor, Former head of the Department, Metallurgical Engineering, RVS College of Engineering and Technology, Jamshedpur, India

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BN Susceptible Synergism to Diamond

Since the synthesis of boron nitride in its cubic crystallographic structure, c-BN, a substance with unique properties and an incredibly high hardness has been created for use in technical engineering. Due to its superior thermal stability and chemical inertness, c-BN is now increasingly used as a cutting and drilling tool in place of diamond-based tools. For practical purposes, c-BN is the second known hardest material after diamond. The development of using c-BN as a super hard industrial tool competing with diamonds for petroleum extraction, car manufacturing, and other engineering applications was reviewed in this study. To assess the potential for a new generation of super hard materials to replace diamonds in tools and other technological devices, the properties of both single crystals and polycrystalline c-BN in composites and thin films were evaluated.

Our ancestors first used hard stones as tools to shape and sharpen other stones in addition to using them as simple implements like hammers and anvils.

BN Composed Cutting Tool

The present context presents the findings of physical experiments on the polymorphic transformation of the graphite-like boron nitride into the diamond-like state during shock compression. As of the first explosion stage, it has been demonstrated that new technology offers a transition coefficient of up to 95% while frequently avoiding chemical processes. [1]

The first preparation of boron nitride (BN), which is not naturally occurring, was made in the 1840s by an English chemist named W. H. Balmain using molten boric acid and potassium cyanide. At high pressures and shock compression, Russian scientists discovered a modification of boron nitride that resembled wurtzite in 1967. The methods for producing graphite-type BN from wurtzite-type boron nitride by using shock compressions produced by explosive detonation were reported. This chemically extracted wurtzite-type boron nitride product has a total impurity content of less than 0.5%, according to x-ray diffraction and x-ray fluorescence spectrometry analyses. As is common knowledge, explosion technologies are used to transform boron nitride into diamond-like boron nitride, with a transition coefficient slightly higher than 0.5. Graphite BN is typically shock-compressed to create wurtzite BN.

Hardness in Poly-crystal

Due to the difficulty in producing pure w-BN material, there is still disagreement regarding whether single-phase w-BN is harder than diamond despite decades of research. For comparison and verification, the first successful preparation of cubic boron nitride (c-BN) from wBN starting material also took place. It was amply demonstrated by the X-ray diffraction (XRD) and Transmission Electron Microscopy (TEM) that a pure single-phase w-BN compact was generated. The pure single-phase w-BN's microstructure and mechanical characteristics.

Hard by Defected Form

High-pressure metastable materials frequently have exceptional qualities. Here, we create w-BN bulk crystals that are millimeter-sized and disclose a previously unrecognized stabilization mechanism for w-BN. Our results unequivocally show that crystal defects slow down the phase transitions of metastable materials. [2]

A high-pressure polymorph of boron nitride (BN), wurtzite boron nitride (w-BN) is a metastable superhard substance. The challenging question of stabilizing the metastable high-pressure material at atmospheric pressure is of basic scientific significance and promising technological utility. Here, we synthesize millimeter-sized w-BN bulk crystals by means of the hexagonal-to-wurtzite phase change at high pressure and high temperature. Respect used ab initio molecular dynamics simulations and transmission electron microscopy to identify a stabilizing mechanism for w-BN. 3D networks of planar defects, which are constructed from several intersecting (0001) stacking faults and 1010 inversion domain boundaries, can stabilize the metastable high-pressure phase. The 3D networks of planar defects split the bulk w-BN crystal into many nanometer-sized prismatic domains with the opposite crystallographic polarity. Despite the widespread assumption that crystal flaws in materials will encourage our findings unmistakably show the retarding effect of crystal defects on the phase transformations of metastable materials. [3]

Machining by Nano Cubic Boron Nitride (c-BN)

Binder-less nano-polycrystalline diamond and nano-polycrystalline cubic boron nitride is an innovative ultra-hard material that was described [4]. production of a single-phase or binderless nano-polycrystalline diamond made with nano-polycrystalline c-BN, an ultra-hard material, was successful. Regarding the production of synthetic nano-polycrystals, a description of the direct conversion sinter method under static ultra-high pressure and high temperature was published. In order to create the cited hard material without a secondary phase as resolved binder material, fine grains with suggested dimensions of almost tens of nanometers were issued. Compared to convened sinter compact including binder, produced single crystals outperformed proclaim generated high hardness as resolved high strength. Effective use of hard n-BN suggestive issued for affordable, robust, and precise cutting tool. Without secondary phase, accession advent emerged from fine microstructure. Supply of difficult-to-cut materials is guaranteed for the automotive, aerospace, medical, and electronics sectors, among other diverse industries. In contrast to additional professional scheme scoring property respect, as of, increased hard corresponded tough cutting tool material, enhanced cutting efficacy, including increased cutting speed, pros and cons persisted towards industry. As a resolved cemented carbide tool, hard-to-cut material was investigated for competitive efficacy versus ceramic.

Properties of Boron Nitride Nanotube

The tubular nanostructure of a boron nitride nanotube (BNNT) is akin to that of a carbon nanotube (CNT), with atoms of boron and nitrogen arranged in a hexagonal network. Aunique atomic structure. Since BNNT was first created in 1995, there has been much work to be done in order to develop an efficient BNNT production route. This is because BNNT has limited practical uses due to its poor quality and low yield when compared to CNT. However, BNNT synthesis has seen a number of significant advancements in recent years, opening up access to this material and opening the door for the creation of exciting new applications. a hexagonal lattice. It should come as no surprise that BNNT and CNT have some intrinsic qualities in common, such as superior mechanical qualities and high thermal conductivity. At the TPa level, Young's modulus was determined experimentally. Despite possessing a lower yield strength and Young's modulus compared to CNTs, BNNTs were anticipated to exhibit thermo-mechanical stability at elevated temperatures. As an example, BNNTs have a wide bandgap of 5–6 eV and are an excellent insulator, whereas CNTs are semi metallic and semiconducting materials. [5]

Significance in Modern Applications

Boron nitride's exceptional thermal conductivity, chemical stability, and electrical insulation properties have positioned it as a key material in various cutting-edge technologies. From serving as a substrate in high-power electronic devices to acting as a lubricant in extreme environments, BN's role in modern technology continues to expand. As research into BN's properties and applications progresses, likely, its importance in fields such as nanotechnology, energy storage, and advanced manufacturing will continue to grow.

Crystalline Structures of Boron Nitride

Hexagonal Boron Nitride (h-BN)

The most common and stable type of boron nitride (BN) is hexagonal boron nitride or h-BN. Similar to graphite, its structure is made up of layers of nitrogen and boron atoms organized in a hexagonal lattice. These layers are easily able to glide over one another because weak van der Waals forces hold them together. Because of its unique structure, h-BN is a solid lubricant that performs exceptionally well in high-temperature and high-pressure settings. Additionally, h-BN's high thermal conductivity and electrical insulation properties make it an important material for heat management in electronic devices, where it is used as a thermal interface material and an insulating substrate.[6]

Cubic Boron Nitride (c-BN)

Cubic boron nitride (c-BN) is a synthetic material created by subjecting hexagonal boron nitride to extreme pressures and temperatures, similar to the process used to produce synthetic diamonds. c-BN's structure is similar to that of diamond, with each boron atom tetrahedrally bonded to four nitrogen atoms. Unlike diamond, however, c-BN is chemically stable in the presence of ferrous materials, which makes it an invaluable material for cutting tools used in machining steels and other iron-based alloys. Additionally, c-BN's high thermal stability and wear resistance make it suitable for use in abrasives and protective coatings.

Wurtzite Boron Nitride (w-BN)

Wurtzite boron nitride (w-BN) is a less common and relatively less studied phase of BN, which has garnered interest due to its predicted superhard properties. The wurtzite structure is similar to that of zinc blende but with a higher degree of symmetry, which contributes to its theoretical hardness. Some studies suggest that w-BN could be harder than both cubic boron nitride and diamond under certain conditions, making it a promising candidate for ultra-hard materials and coatings. However, the synthesis of w-BN is challenging, and further research is needed to fully understand its properties and potential applications.

Amorphous Boron Nitride (a-BN)

Amorphous boron nitride (a-BN) is a non-crystalline form of BN that lacks the long-range order found in its crystalline counterparts. Amorphous BN is typically produced by chemical vapor deposition (CVD) or other low-temperature synthesis methods and is used in applications where a smooth, uniform coating is required. Its flexibility in terms of processing and deposition makes it suitable for use in thin films, coatings, and composites, where it can enhance the thermal and mechanical properties of the base material.[7]

Synthesis Methods of Boron Nitride

Chemical Vapor Deposition (CVD)

In this process, gaseous precursors such as boron trichloride (BCl_3) and ammonia (NH_3) are introduced into a reaction chamber, where they react at elevated temperatures to form a thin film of BN on a substrate. The CVD process allows for precise control over the thickness, composition, and crystallinity of the deposited BN layers, making it ideal for applications that require high-quality coatings. CVD is particularly useful for producing hexagonal boron nitride (h-BN) films for use in electronic devices, as it allows for the deposition of BN on a variety of substrates, including semiconductors and metals.

High-Pressure High-Temperature (HPHT) Synthesis

The High-Pressure High-Temperature (HPHT) synthesis method is the primary technique used to produce cubic boron nitride (c-BN). In this process, hexagonal boron nitride is subjected to pressures of up to 7 GPa and temperatures exceeding 1700°C, conditions under which it undergoes a phase transition to c-BN. The HPHT process is analogous to the natural formation of diamonds, resulting in a material with comparable hardness and superior chemical stability. However, the high costs associated with HPHT synthesis, as well as the challenges in producing large c-BN crystals, limit its widespread use. Nevertheless, ongoing research aims to optimize this process to improve yield and reduce production costs.[8]

Sol-Gel Synthesis

Sol-gel synthesis is a versatile and cost-effective method for producing boron nitride powders and coatings at relatively low temperatures. “Sol.” Upon gelation and subsequent heat treatment, the precursor is converted into BN. This method is particularly advantageous for producing BN with high surface area and porosity, which is beneficial in applications such as catalysis and adsorption. Additionally, the sol-gel process allows for the incorporation of BN into composite materials, enhancing their thermal and mechanical properties.

Polymer-derived ceramics (PDCs)

Polymer-derived ceramics (PDCs) are an emerging method for synthesizing boron nitride ceramics by using pre-ceramic polymers as precursors. This method involves the pyrolysis of a boron-containing polymer at high temperatures, resulting in the formation of BN. This technique is particularly useful for fabricating BN-based composites and foams, which are used in advanced thermal management systems and high-temperature insulation.[9]

Properties of Boron Nitride

Mechanical Properties

Boron nitride's mechanical properties vary significantly depending on its crystalline form. Cubic BN (c-BN) is renowned for its hardness, with a Vickers hardness of around 45 GPa, making it ideal for cutting tools and abrasives. The exceptional hardness of c-BN is complemented by its high thermal stability, which allows it to maintain its mechanical integrity at temperatures where other materials would degrade. In contrast, hexagonal BN (h-BN) is much softer and exhibits excellent lubricating properties, making it suitable for use as a solid lubricant in high-temperature environments.

Thermal and Electrical Properties

One of the most remarkable properties of boron nitride is its ability to conduct heat while acting as an electrical insulator. Hexagonal BN (h-BN) exhibits a thermal conductivity of up to 400 W/m·K, which is comparable to that of copper while maintaining electrical insulation. This combination of properties makes h-BN an ideal material for thermal management in electronic devices, where it is used as a thermal interface material and an insulating substrate.

Chemical and Environmental Stability

Boron nitride is chemically inert in a wide range of environments, including strong acids, alkalis, and oxidizing conditions. BN's chemical stability is particularly valuable in the form of cubic BN (c-BN), which does not react with ferrous materials, unlike diamond. This property extends the lifespan of cutting tools and abrasives made from c-BN when machining iron-based alloys, where diamond tools would quickly degrade.

Optical and Electronic Properties

Boron nitride exhibits interesting optical and electronic properties, particularly in its hexagonal form (h-BN). h-BN is a wide-bandgap semiconductor with a bandgap of around 5.9 eV, which makes it transparent to visible light and a potential candidate for UV light-emitting devices. Additionally, h-BN's two-dimensional structure and high thermal conductivity make it an attractive material for use in next-generation electronic devices, such as graphene-based transistors and sensors. The unique combination of optical transparency, electrical insulation, and thermal management makes h-BN a promising material for optoelectronic applications.[10-15]

Applications of Boron Nitride

Cutting Tools and Abrasives

Cubic boron nitride (c-BN) is extensively used in the manufacturing of cutting tools and abrasives, particularly for machining hard and brittle materials. c-BN tools are favored in the automotive and aerospace industries for machining hardened steels, cast irons, and superalloys, where conventional tools would fail. The use of c-BN tools results in higher machining efficiency, longer tool life, and better surface finish.

High-Temperature Lubricants

Hexagonal boron nitride (h-BN) is widely used as a solid lubricant in high-temperature applications where liquid lubricants cannot survive. Its stability at temperatures up to 1000°C and its ability to reduce friction make it ideal for use in space exploration, nuclear reactors, and high-performance engines. conditions. The ability of h-BN to form a lubricating layer on metal surfaces also makes it useful in metal-forming processes, where it reduces wear and energy consumption.

Electronics and Optoelectronics

The combination of thermal conductivity and electrical insulation makes boron nitride a valuable material in the electronics industry. Hexagonal BN (h-BN) is used as a substrate for graphene and other two-dimensional materials, where it provides a smooth and chemically inert surface that enhances the performance of electronic devices. BN is also used in the fabrication of high-frequency transistors, LEDs, and other optoelectronic devices. Its wide bandgap and high thermal stability make BN a promising material for future electronic devices that operate under extreme conditions, such as high temperatures or radiation.

Protective Coatings

Boron nitride is used as a protective coating in various high-temperature and chemically aggressive environments. h-BN coatings, on the other hand, are used in metal casting, where they prevent molten metals from sticking to the mold, reducing defects and improving the quality of the final product. BN coatings are also used in the aerospace and nuclear industries, where they protect components from oxidation, corrosion, and thermal degradation.

Catalysis and Adsorption

Boron nitride's high surface area and chemical inertness make it an attractive material for catalytic and adsorption applications. BN-based catalysts have been explored for various chemical reactions, including hydrogenation, oxidation, and dehydrogenation, where they offer advantages such as high selectivity and resistance to poisoning. Additionally, BN's porous structure allows it to adsorb gases and liquids, making it useful in environmental applications, such as gas separation, water purification, and pollutant removal. Recent research has focused on functionalizing BN surfaces to enhance their catalytic and adsorption properties, opening up new possibilities for their use in sustainable chemical processes.[16-20]

Future Perspectives

Advanced Composites

The incorporation of boron nitride into advanced composite materials is an area of active research, with the goal of enhancing the thermal, mechanical, and electrical properties of these composites. BN is also being explored as a filler material in metal-matrix composites, where it can improve wear resistance and reduce thermal expansion. The development of BN-based composites with tailored properties is expected to lead to new applications in the aerospace, automotive, and electronics industries.

Nanotechnology Applications

Boron nitride nanomaterials, such as nanotubes, nanosheets, and nanoparticles, offer unique properties that make them attractive for a wide range of nanotechnology applications. BN nanosheets, on the other hand, are being explored as substrates for two-dimensional electronic devices and as reinforcement materials in polymer nanocomposites.

Environmental Applications

The environmental applications of boron nitride are another promising area of research. BN's chemical stability and high surface area make it an excellent candidate for use in environmental remediation, such as the adsorption of pollutants from water and air. Functionalized BN materials have shown potential in the removal of heavy metals, organic contaminants, and radioactive substances from contaminated environments. Additionally, BN is being explored as a catalyst support for green chemistry applications, where it can enhance the efficiency and selectivity of catalytic reactions. [21-26]

CONCLUSION

The study of boron nitride's superhard phases has opened new frontiers in material science, particularly in the realm of advanced machining technologies. The exceptional properties of cubic boron nitride (c-BN) and wurtzite boron nitride (w-BN)—including their remarkable hardness, chemical inertness, and thermal stability—have positioned them as leading contenders in applications demanding extreme durability and precision.

These developments have not only enhanced the efficiency of cutting tools and abrasives but have also led to the creation of new possibilities for high-performance materials in challenging environments. The continued innovation in the synthesis and application of these superhard boron nitride phases is set to revolutionize industries, driving forward the capabilities of materials used in high-stress, high-temperature operations.

As research progresses, the potential for even greater advancements in the understanding and utilization of boron nitride's unique properties remains vast. This work lays the foundation for a future where boron nitride becomes integral to next-generation machining technologies, offering unprecedented performance and reliability.

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