Boron Nitride Powder—A High-Performance Alternative for Solid Lubrication

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GE Advanced Ceramics is the world's largest producer of boron nitride (BN) powders, shapes and coatings, as well as other specialty ceramics.

Boron nitride powder is a soft, white, lubricious (slippery) powder with unique characteristics that make it an attractive, performance-enhancing alternative to graphite, molybdenum disulfide and other frequently used inorganic solid lubricants. With its superior adherence and thermochemical stability, boron nitride presents an opportunity to formulate new solid lubricants for applications where conventional solid lubricants break down or fail to deliver the desired performance.

This inorganic solid powder retains its ability to lubricate in extreme cold or heat and is well suited to extreme pressure (EP) applications. It is environmentally friendly and inert to most chemicals. It displays excellent electrical insulating properties and maintains those properties in vacuum, unlike graphite.

Current lubrication applications include solid polymer composite shapes, dispersed additives to oils and greases, metal-ceramic electrodeposition coatings, aqueous and oil dispersions used as release agents, and constituents of epoxy coatings, thermal spray coatings and plasma spray coatings.

What is Boron Nitride?

Boron nitride is a highly refractory (heat-resistant, stable) material with physical and chemical properties comparable to graphite.[1] But, unlike graphite, it does not occur naturally in nature. It is typically synthesized from boric oxide or boric acid in the presence of urea or urea derivatives and ammonia, at temperatures ranging from 800° C to 2000° C.

The two common crystalline structures of BN are cubic and hexagonal. Cubic boron nitride, (c)BN, is like diamond, being hard and abrasive; and hexagonal boron nitride, (h)BN, is like graphite, being soft and lubricious.[2]

This paper discusses the key material properties of (h)BN that make it an ideal solid lubricant for high performance applications.

Hexagonal boron nitride powder exhibits the same characteristics of solid lubricants found in graphite and molybdenum disulfide. These include crystalline structure, low shear strength, adherence of the solid lubricant film, low abrasivity, and thermochemical stability.[3] In many instances, (h)BN exceeds the performance levels of these conventional solid lubricant characteristics, particularly adherence and thermochemical stability.

Coefficient of Friction

Until recently, methods for measuring the coefficient of friction or "slip" characteristics of powders were vague at best. For example, the INSTRON method, commonly used for determining coefficient of friction, is unable to discern the difference between various grades of (h)BN powder, although the differences are clearly perceptible by feel. To compare the "slip" of (h)BN to other solid lubricants, a new test apparatus was developed in conjunction with Falex Corporation. See Appendix A.

The results of this test, seen in Figure 1, clearly show that (h)BN yielded the lowest coefficient of friction versus all the other materials tested by this method.

Four-Ball Extreme Pressure Test

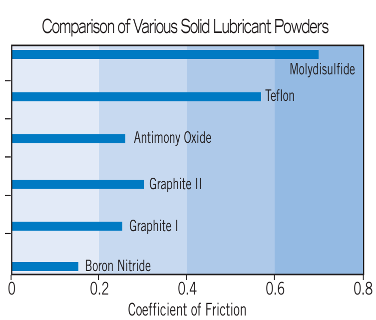
To compare the extreme pressure (EP) characteristics of (h)BN to graphite, molybdenum disulfide and other solid lubricants, Falex 4-Ball EP tests were conducted on Fomblin® oil samples containing 5 wt % of each material. See Appendix B.

Two grades of (h)BN, two grades of graphite, molybdenum disulfide (MoS_2), antimony oxide (SbO_2) and Teflon (PTFE) were tested. Table 2 shows the results of these tests. Both (h)BN samples showed higher weld points than any of the others. (The weld point is the amount of applied weight--kilograms of force [kgf]—that causes the lubricant to break down, allowing welding or metal-to-metal transfer.) Scar data (a pattern of metal removal prior to reaching the weld point) shows that, at baseline loading, one grade of (h)BN has slightly higher values than other solid lubricants; but at 400 kgf, both grades of (h)BN compare favorably to the group. (Baseline loading is defined as the weld point of the pure test fluid that—for this fluid—was 315 kgf.)

Table 2

Sample	Weld Point (kgf)	Average Scar Diameter (mm) @ 315 kgf	@ 400 kgf
Fomblin® (F), control	315	WELD	
F/5% BN (Grade E)	620	0.902	1.024
F/5% BN (Grade B)	620	0.850	0.984
F/5% MoS_2	500	0.861	1.001
F/5% SbO_2	400	0.818	WELD
F/5% Graphite (S4742)	400	0.839	WELD
F/5% Graphite (GP603)	400	0.851	WELD
F/5% Teflon	500	no data	1.11

Figure 1

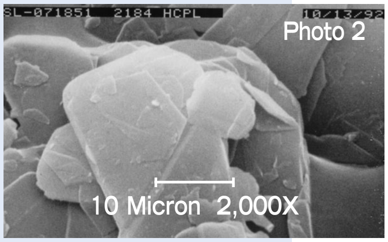


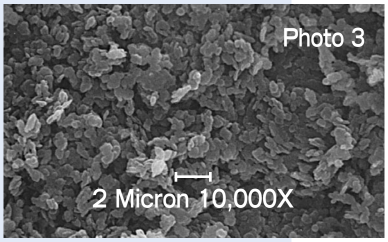
1. Ceramic Industry Materials Handbook, January 1998, p. 79.

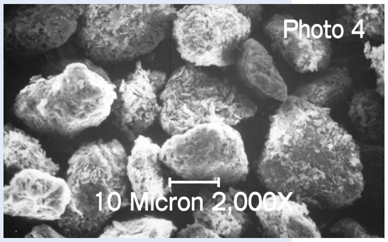
2. D.A. Lelonis, Boron Nitride—A Review, Ceramic Technology International, 1994, A Sterling Publication.

3. H. Sliney, Solid Lubricants, NASA Technical Memorandum 102803, April 1991.

Three grades of (h)BN powder.







A Variety of (h)BN Powders

A variety of powders with different chemical and physical characteristics can be produced by changing the process conditions used to synthesize (h)BN. Photo 1 shows three grades of (h)BN powder. Photos 2, 3 and4 are scanning electron micrographs (SEM's) of these same three powders, clearly illustrating large morphological (shape) differences that produce distinct physical properties and performance characteristics.

Figure 2 compares the crystallinity, physical properties and chemical properties of (h)BN powders synthesized at various temperatures.

Notice that the increase in synthesis temperature is directly related to decreased coefficient of friction, the primary indicator of lubricity.

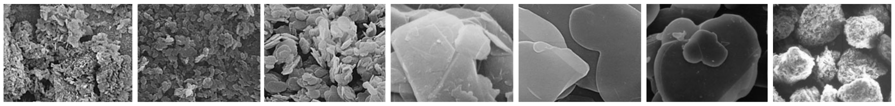
Processing conditions also determine purity, oxidation resistance, high temperature stability, particle size, surface area and dispersibility; additional characteristics that make (h)BN useful as a lubricant or lubricant additive.

Figure 3 presents examples and typical properties of some of the many commercially available (h)BN powders.

Figure 2—Variations of (h)BN

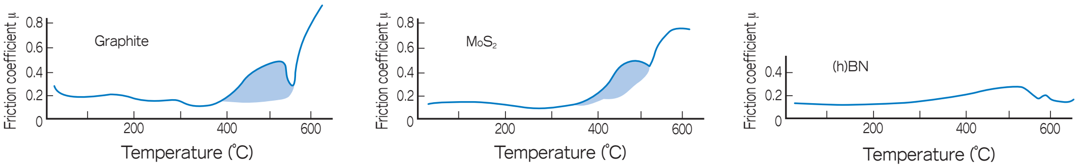
Temperature of Synthesis:	800° C	1400° C	1900° C	2000° C
Surface Area (m^2/g)	50-100	20-50	10-20	<10
Crystallinity	Turbostratic	Quasi Turbostratic	Meso Graphitic	Graphitic
Coefficient of Friction	.6	.4	.2 to .3	.15
Oxygen ($\%O_2$) Content	>5%	1.5-5%	0.5-1.5%	<0.5%

Figure 3—Typical Properties of Various Grades of (h)BN Powders



Grade	A	B	C	D	E	F	G
Oxygen (%)	3.0	2	1	0.3	0.3	0.3	0.4
Crystal Size (μ)	0.1	0.4	6	10	13	45	10
Particle Size, d50 (μ)	10	9	8	11	13	45	150
Surface Area	40	30	14	8	2	0.5	5
Comments	Turbostratic	Crystals < 1μ	High oxygen aids dispersion	Flat platelets	Rounded, flat platelets	Large, single crystal	Polycrystalline agglomerates

Figure 4—Coefficient of Friction at Various Temperatures



Ref. 4 data from R. Deacon.

Thermal Stability

The ability to retain lubricity at elevated temperatures is an important characteristic of (h)BN. Inorganic ceramic materials such as (h)BN have inherent advantages over polymers like PTFE (Teflon) and other low-melting-point materials. BN has an oxidation threshold of approximately 850° C and, even up to 1000° C, the rate of reaction is negligible.

Other inorganic solid lubricants such as graphite and molybdenum disulfide experience major increases in coefficient of friction (lose their lubricity) at between 400° C and 500° C. Figure 4 illustrates the changes in coefficient of friction for graphite, molybdenum disulfide and (h)BN as the temperature increases in air.[4]

4. R. Deacon, Lubrication by Lamellar Solids, Proc. Roy. Soc. 243A, 1957, p. 464.

Table 3 summarizes the results of lubricity tests conducted by NASA on thermally stable materials.[5] Hexagonal boron nitride compares favorably with the other materials and has the lowest coefficient of friction at elevated temperatures of all the materials tested.

Lubrication Uses of (h)BN

A search of U.S. and European patents and applications shows many lubrication uses of (h)BN. These include (h)BN-filled resin shapes used as bearings, sleeves, rings, seals and other sliding components; dispersions in oils and greases; and many coatings with (h)BN constituents used for metalworking, casting, forging and wire drawing. Epoxy/(h)BN coatings, as well as (h)BN coatings applied by electrodeposition and thermal spray, are being used on compressor seals and internal combustion engine components. BN powder also may improve wear rates of metal and ceramic matrix composites.

Table 3

Coefficient of Friction

Material	Room Temperature	450° F
BN	0.3	0.15
$CdCl_2$	0.6	0.17
$CrCl_3$	0.2-0.3	—
PbF_2	0.6	0.6
$MnCl_2$	0.35	0.17
$NiCl_2$	0.45	0.19
SnS_2	0.9-0.45	—
SnO	0.95+	—
SnS	0.95+	0.63
Ta_2S_4	1.15	—
TiC	0.55	—
TiS_2	0.7	0.6
WS_2	0.7-1.6	0.2

Results of Lubricity Tests on Thermally Stable Materials. Ref. 5 data from M. Campbell.

(Note: Different coefficients of friction of (h)BN at room temperature are reported in Table 3 and Figure 4. This is a result of using different test methods and conditions to determine each set of reference data. Values within each reference are comparable. However, values reported in one reference should not be compared to values in another reference.)

Dispersions in Oils, Water and Greases

The use of (h)BN as an oil additive was formerly limited by a lack of powders with particle size distributions appropriate for proper dispersion. Recently developed sub-micron and deagglomerated (h)BN powders, such as powder "B" in Figure 3, are easily dispersed in oils. Powder "C" in Figure 3 has higher oxygen content that is mainly within the lattice structure of the hexagonal BN crystals and therefore not in a soluble form. This lattice oxygen produces crystals with higher surface energy, making them more easily dispersed and suspended.

Table 4

Microhardness and Wear Resistance of Nickel and Nickel-Boron Nitride Composite Coatings

Systems	Hardness (KHN)	Wear Index
Nickel	265	45.5
Ni-BN (5-6%)	380	22.1
Ni-BN (7-8%)	350	20.8

Knoop Hardness Number

Ref. 12 data from M. Pushpavanam et al.

An oil-based die-release agent containing (h)BN is claimed to provide better release properties than when made with graphite.[6]

Aqueous dispersions containing (h)BN powder are also used as lubricating die-release agents. Good lubricity and release qualities over a wide range of high and low temperatures are claimed and, as aqueous suspensions, these dispersions do not contaminate the workplace.[7]

A rock bit grease composition incorporating (h)BN powder as a solid extreme pressure agent offers environmental safety and non-toxicity, compared to greases incorporating lead and other metal extreme pressure agents. And (h)BN is said to be "more effective in increasing the load bearing capabilities of the grease composition than other solid-particle additives."[8]

Electrodeposition/Electrocomposites

Electrodeposition (electroplating) of fine particles of (h)BN (combined with other constituents) has been used to form a self-lubricating, high-wear-resistance, metal-ceramic coating for metal substrates in engine parts.[9, 10]

Several articles have appeared about the anti-friction and anti-corrosion characteristics of nickel-(h)BN composites. These composites exhibit superior friction properties under non-lubricated, high-load conditions. When evaluated on piston bore surfaces, smaller piston clearances were achieved, with reduced wear and friction loss. Claimed benefits include reduced oil consumption and emissions as well as a 3.5% improvement in torque and power.[11]

Increased percentages of (h)BN improve hardness and wear, in spite of (h)BN's soft and easy sliding nature. See Tables 4 and 5. Hardness improvements may result from the uniform distribution of (h)BN particles in the nickel matrix. Lower wear is more easily explained by the glazing and adhesion of the (h)BN particles that remain in place after initial wear, providing effective lubrication and separation of the remaining metal surfaces.[12, 13]

Plasma/Thermal Spray Coatings

Plasma spray coating for abradable seals and similar high-wear surfaces is another important lubricant application of (h)BN. Spray process efficiency and coating properties depend on the type of (h)BN used and how the (h)BN is handled during spraying.[14]
In the case of plasma coatings, the hardness of the coatings decreases as the (h)BN percentage increases, but hardness can be controlled by varying the type and content of (h)BN. See Table 6, next page.

Table 5

Taber Wear Index of Ni-BN Composites

Coating	Cycle I	Cycle II	Cycle III
	Load: 1 kg, CS-10 Calibrase Wheel		
1. Mild steel	5.7	4.9	4.8
2. Ni-BN, 11.8 vol %	5.0	4.5	3.6
3. Ni-BN, 19.6 vol %	4.5	3.9	3.4
4. Ni-BN, 28.8 vol %	3.5	2.5	2.4

Ref. 13 data from G. Bapu.

5. M. Campbell, Solid Lubricants — A Survey, NASA SP-5059(01), 1972.
6. T. Funabashi et al., Japan Patent 0211799A., 1990.
7. K. Ueda et al., Japan Patent 02120397A., 1990.
8. R. Denton et al., U.S. Patent 5,589,443., 1996.
9. T. Urushibara., Japan Patent 04263095., 1992.
10. Y. Harakawa., Japan Patent 57089499A., 1982.
11. K. Funatani et al., Advanced Materials & Processes, December 1994, p. 27-29.
12. M. Pushpavanam et al., Metal Finishing, June 1995, p. 97-99.
13. G. Bapu, Plating & Surface Finishing, July 1995, p. 70-73.

Table 6

Material	Avg. size, µ	Hardness R15Y	DE %	BN ratio
60Al/35BN-1	75	80.0	41	.29
60Al/40BN-1	47	72.6	27	.35
60Al/40BN-2	14	59.8	17	.44
60Al/40BN-3	86	68.6	29	.29
MCrAlY/40BN-2	16	90.0	18	.55
NiCr/40BN-3	76	90.0	19	.55

Ref. 14 data from W. Jarosinski.

Polymer Composites

Because of its similarity to graphite, (h)BN is useful as a solid lubricant additive in a variety of polymer composites—especially those where graphite is currently used. The main advantages of (h)BN include color (white), electrical resistance, high thermal conductivity, chemical inertness, thermal stability and relatively high oxidation temperatures. BN is unaffected in certain corrosive environments such as sulfuric acid.

Test Stand. Falex Friction and Wear Test Machine.

Environmental Issues

Nitrogen and oxygen compounds of boron are extremely stable and do not break down or form other hazardous materials under normal conditions of storage, use or disposal. Hexagonal boron nitride is an extremely stable compound, making it safe to handle. However, the powder is considered a nuisance dust and should not be breathed.

Powders are synthesized at high temperatures, using refined raw materials. The result is high purity with minimal trace elements (typically from 0.03% to 0.5% of soluble boric acid or boric oxide).

No evidence exists that boron nitride, boric acid or boric oxide are carcinogens or pose any toxic hazard, based on a report issued by the National Toxicology Program. Nor are any of these materials considered hazardous by the International Agency for Research on Cancer, the Occupational Safety and Health Administration (OSHA) or the American Conference of Government and Industrial Hygienists (ACGIH, 1994-1995). Boron nitride, boric acid and boric oxide are not considered hazardous chemicals under EPA or SARA guidelines and no regulations exist regarding their use, transport or disposal.

While some references prior to 1970 cite toxicity hazards associated with boron, more recent studies do not support earlier claims and references indicate that previously reported effects of boron are inaccurate.[15,16] In any case, high purity, commercial grade (h)BN powders typically do not contain free boron. All boron is either in the form of a nitride or borate.

14. W. Jarosinski, High Temperature Boron Nitride Abradable Materials, Thermal Spray Conf. Proc., ASM, 1992, p. 691-694.

15. Clayton, Patty's Industrial Hygiene and Toxicology, 4th Ed., Vol. 2, Part F, Chapter 42, p. 4411-4447.

16. Culver, Review of Available Literature on the Effects of Boric Acid on Skin, 1994.

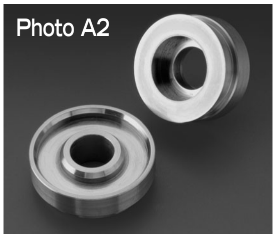
Appendix

A. Falex Coefficient of Friction Test

To effectively measure the coefficient of friction of various solid lubricant powders, a special fixture was designed for use on a standard Falex Corporation friction and wear test instrument (Photo A1). The fixture consists of two rings; the bottom ring has a circular trough that contains the powder to be tested (Photo A2). The top ring, driven by the test instrument, is flat and designed to fit into the trough. Weight is applied to push the ring containing the powder against the flat ring. The torque required to rotate the flat ring is measured by the instrument and calculated as the coefficient of friction.

B. Falex 4-Ball Extreme Pressure Test

The Falex 4-Ball EP Test measures the efficiency of lubricants by driving one ball, forced against three stationary balls by an adjustable weight, in a cup filled with the lubricant. In the case of solid lubricants, the solids are suspended in a test fluid selected for its lack of any performance enhancing additives. See Table 1. The weld point of the pure test fluid (the amount of applied weight that causes the pure fluid to break down and allow a transfer of metal from ball to ball) is the baseline where the testing of the solid lubricants is begun. Weight is increased for each lubricant sample until welding occurs. Performance is evaluated by measuring and comparing the average wear-scar diameters produced on the stationary balls under baseline- and greater-than-baseline weight conditions. The point at which welding occurs is also noted. Results are given in Table 2.



Fixture Rings. Test rings designed to measure friction characteristics of powder materials.

Summary

Hexagonal boron nitride--(h)BN--powder is a solid lubricant that compares favorably with, and in some cases exceeds, the performance of other solid lubricants. Its white color, high-temperature stability, low coefficient of friction, extreme pressure performance, high thermal conductivity, high electrical resistivity, inertness in a wide variety of chemical environments, and environmental friendliness make (h)BN an ideal alternative to other solid lubricants in many high performance applications.

Table 1. Base Fluid Properties

Base Fluid	Fomblin® Y45	Propene, 1,1,2,3,3,3-hexaflouro, oxidized, polymerized
Fluid Content of Suspension	95%	
Viscosity	@ 20° C	470cSt
	@ 40° C	147cSt
	@ 100° C	16.5cSt
Density	@ 20° C	1.91 g/cc

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