

Poco Graphite, Inc.
**Properties and Characteristics
of Graphite**

For the EDM Industry



Edited by R. G. Sheppard, Dwayne Morgan, D. M. Mathes, D. J. Bray

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1987 Poco Graphite, Inc.

POCO Graphite, Inc.

300 Old Greenwood Rd.

Decatur, TX 76234

www.poco.com

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PREFACE

Poco Graphite manufactures a complete family of graphite materials for EDM applications. The physical properties and characteristics of the grades vary by particle size, microstructure consistency, flexural strength, density, and hardness. Many EDMers know these properties are important, but they may not understand the specific effect each of these properties has on the graphite's performance as an EDM electrode. These differences in performance account for the array of EDM graphite grades available. Each is tailored to function at the level of performance required by a specific application.

The purpose of the primer is to introduce the reader to graphite properties and testing techniques so that the unique attributes of POCO become more apparent. Graphite properties and testing have always been a prime concern of Poco Graphite. In order to maintain the quality of POCO materials and develop new grades to meet specific criteria, POCO maintains an extensive testing laboratory. POCO personnel have been active in the development of ASTM standards for graphite testing. Over the years POCO has accumulated data on manufactured graphites, POCO materials as well as competitive materials. This data was used to produce the information in this book.

Machining with the right graphite electrode material for the application is important to the profitability of the job. The appropriate material lasts longer and can be machined without breaking, keeping graphite replacement costs down. Using the right graphite/ work metal combination will allow the job to be run at the most productive speed. To select the best graphite for a particular job, operators must become familiar with graphite classification and understand how the graphite's properties influence its performance and machinability.

POCO's is dedicated to manufacturing graphites that have unique properties that are superior to other manufactured graphites. These are the class of materials upon which POCO has built its reputation for producing the best graphite in the world.

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Chapter 1

Structure & Isotropy

Carbon is found in many different compounds and is the basis for many materials. It is in the food you eat, the clothes you wear, the cosmetics you use and the gasoline that fuels your car. In addition, carbon is a very special element because it plays a dominant role in the chemistry of life. Carbon as charcoal, soot and coal has been used since prehistoric times. Carbon as diamond has also been known since very ancient times. In modern times, it has been determined that soot (amorphous carbon), graphite (another form of carbon) and diamond are all forms of carbon. This book will focus on the properties and characteristics of one of the most important forms of carbon – graphite.

Definition

Carbon, The Element

Carbon is the 6th element on the Periodic Chart and can be found in abundance in the sun, stars, comets, and atmospheres of most planets.

Carbon is a Group 14 element (on older Periodic Charts, Group IVA) along with Silicon, Germanium, Tin, and Lead. (Figure 1-1) Carbon is distributed very widely in nature.

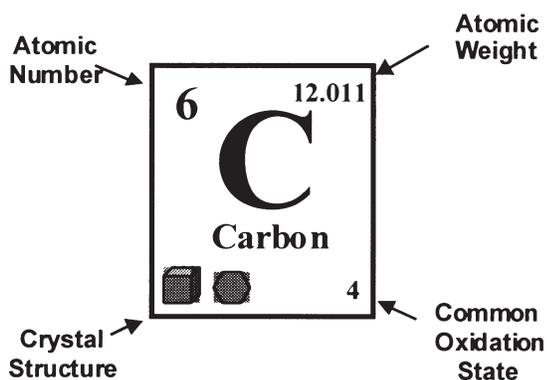


Figure 1-1. Carbon as on the periodic chart

In 1961 the International Union of Pure and Applied Chemistry (IUPAC) adopted the isotope ¹²C as the basis for atomic weights. Carbon-14, ¹⁴C, an isotope with a half-life of 5730 years, is used to date such materials as wood, archeological specimens, etc. Carbon-13, ¹³C, is particularly useful for isotopic labeling studies since it is not radioactive, but has a spin I = 1/2 nucleus and therefore a good NMR nucleus.

Carbon has four electrons in its valence shell (outer-shell). The electron configuration in carbon is 1s² 2s² 2p². Since this energy shell can hold eight electrons, each carbon atom can share electrons with up to four different atoms. This electronic configuration gives carbon its unique set of properties (Table 1-1). Carbon can combine with other

Name:	Carbon
Symbol:	C
Atomic Number:	6
Atomic Mass:	12.0107 amu
Melting Point:	3500.0 °C 3773.15 °K 6332.0 °F
Boiling Point:	4827.0 °C 5100.15 °K 8720.6 °F
Number of Protons/Electrons:	6
Number of Neutrons:	6, 7, 8
Classification:	Non-Metal
Crystal Structure:	Hexagonal Cubic
Density @ 293 K:	Graphite – 2.62 g/cm ³ Diamond – 3.35 g/cm ³
Color:	Black, gray

Table 1-1. Properties of the element carbon

elements as well as with itself. This allows carbon to form many different compounds of varying size and shape.

Carbon is present as carbon dioxide in the atmosphere and dissolved in all natural waters. It is a component of rocks as carbonates of calcium (limestone), magnesium, and iron. Coal, petroleum, and natural gas are chiefly hydrocarbons. Carbon is unique among the elements in the vast number of variety of compounds it can form. Organic chemistry is the study of carbon and its compounds.

The history of manufactured graphite began at the end of the 19th century with a surge in carbon manufacturing technologies. The use of the electrical resistance furnace to manufacture synthetic graphite led to the development of manufactured forms of carbon in the early part of the 20th century and more recently, to a wide variety of high performance materials such as carbon fibers and composites (Figure 1-2).

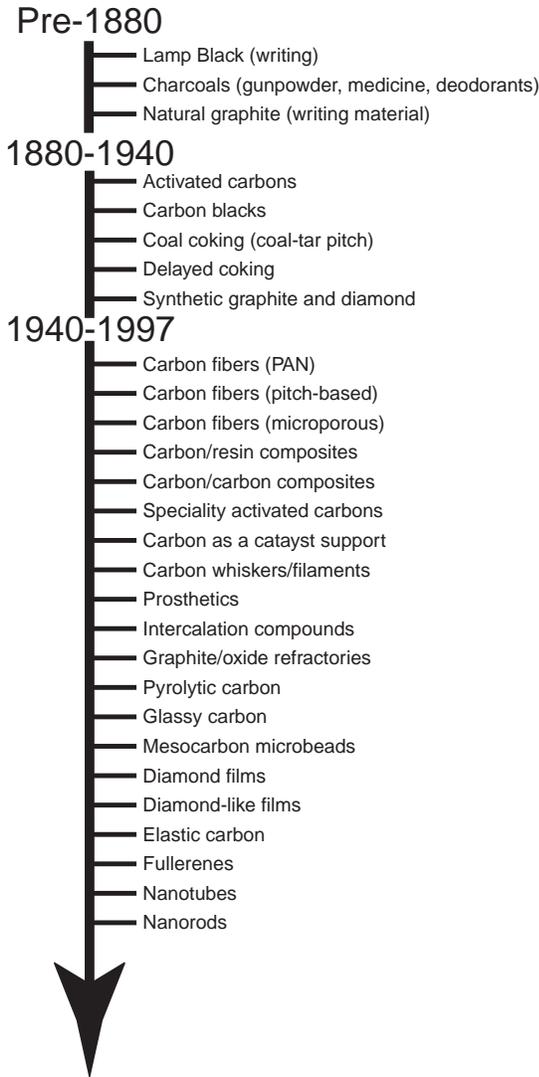


Figure 1-2. A diagram indicating the growth of carbon and graphite materials

Forms of Carbon

Carbon is found free in nature in three allotropic forms: amorphous carbon, graphite, and diamond. More recently, a fourth form of carbon, buckminster fullerene, C_{60} , has been discovered. This new form of carbon is the subject of great interest in research laboratories today.

Carbon alone forms the familiar substances graphite and diamond. Both are made only of carbon atoms. Graphite is very soft and slippery, while diamond is one of the hardest substances known to man. Carbon, as microscopic diamonds, is found in some meteorites. Natural diamonds are found in ancient volcanic "pipes" such as those in South Africa. If both graphite and diamond are made only of carbon atoms what gives them different properties? The answer lies in the way the carbon atoms form bonds with each other.

The forces within and between crystallites determine the extreme difference in properties between these two forms. In diamond, the crystal structure is face-centered cubic (Figure 1-3). The interatomic distance is 1.54 \AA with each

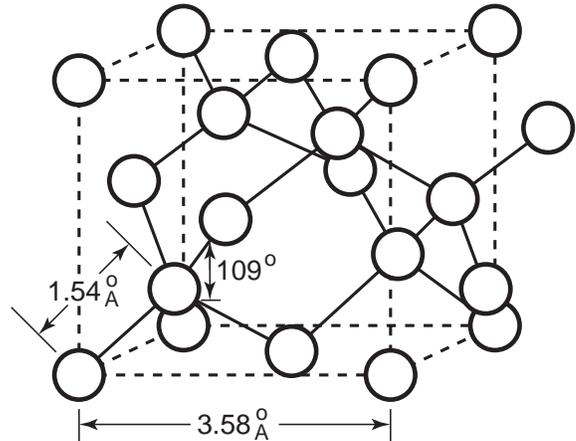


Figure 1-3. The crystal structure of diamond

atom covalently bonded to four other carbons in the form of a tetrahedron. This interatomic distance is close to that found in aliphatic hydrocarbons which is in distinction to the smaller 1.42 \AA carbon-carbon distance found in graphite and aromatic hydrocarbons (1.39 \AA in benzene). This three-dimensional isotropic structure accounts for the extreme

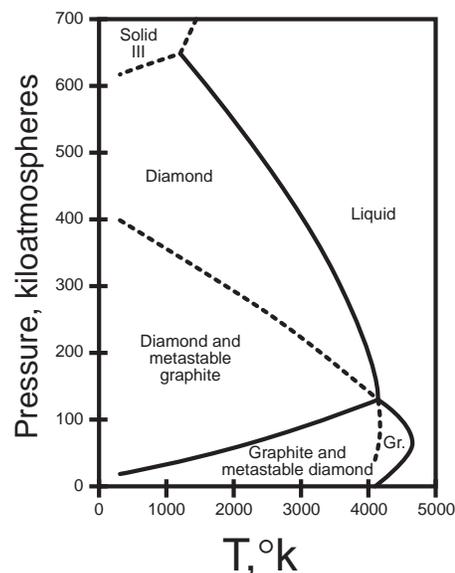


Figure 1-4. The carbon phase diagram

hardness of diamond. Thermodynamically, graphite at atmospheric pressure is the more stable form of carbon. Diamond is transformed to graphite above 1500°C (Figure 1-4).

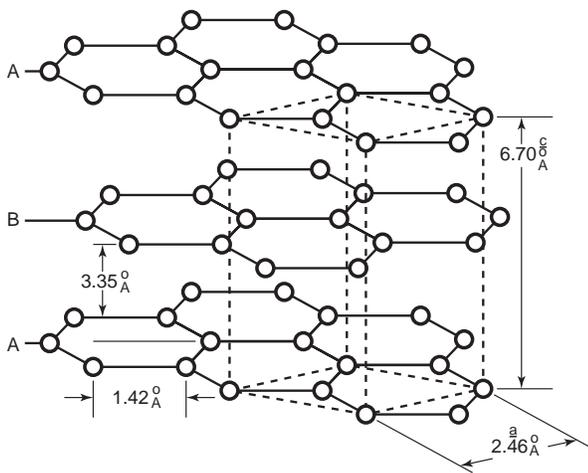


Figure 1-5. The crystal structure of graphite

The structure of graphite consists of a succession of layers parallel to the basal plane of hexagonally linked carbon atoms. The now accepted ideal graphite structure is shown in Figure 1-5.

In this stable hexagonal lattice, the interatomic distance within a layer plane, a , is 1.415 \AA and the interlayer distance, d , between planes is 3.354 \AA . Crystal density is 2.266 g/cm^3 as compared with 3.53 g/cm^3 for diamond. In the graphite structure (sp^2 hybridization), only three of the four valence electrons of carbon form regular covalent bonds (σ -bonds) with adjacent carbon atoms. The fourth or π electron resonates between the valence bond structures. Strong chemical bonding forces exist within the layer planes, yet the bonding energy between planes is only about 2% of that within the planes [$150\text{-}170 \text{ kcal/(gram atom)}$ vs. $1.3\text{-}4 \text{ kcal/(gram atom)}$]. These weaker bonds between the planes are most often explained to be the result of van der Waals forces.

However, Spain^[1] identifies the π orbital, which has a π configuration, and not van der Waals forces as the correct source of bonding between the adjacent layers. In general, the π bands overlap by $\sim 40 \text{ meV}$ to form the three-dimensional graphite network where the layer planes are stacked in the ABAB sequence illustrated in Figure 1-5. Spain concludes in his discussions on electronic structure and transport properties of graphite that the overlap of π orbitals on adjacent atoms in a given plane also provides the electron bond network responsible for the high mobility (electronic) of graphite. This would appear more correct since van der Waals forces are the result of dipole moments, which would not account for the high mobility.

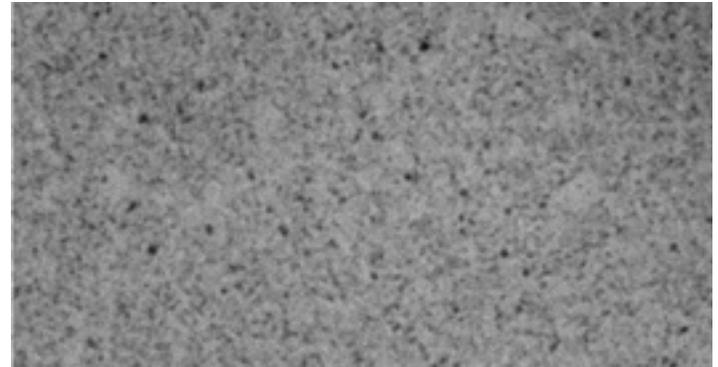
Consequently, weak forces between layer planes account for (a) the tendency of graphitic materials to fracture along planes, (b) the formation of interstitial

compounds, and (c) the lubricating, compressive, and many other properties of graphite.

As previously mentioned for the hexagonal graphite structure, the stacking order of planes is ABAB, so that the atoms in alternate planes are congruent (Figure 1-5). Studies have shown that natural graphite contains 17-22% of a rhombohedral structure with a stacking sequence of ABCABC. In "artificial" or "synthetic" graphite, in the as-formed state, only a few percent at best could be found. However, deformation processes such as grinding substantially increase the percent of rhombohedral structure found in the otherwise hexagonal structure.

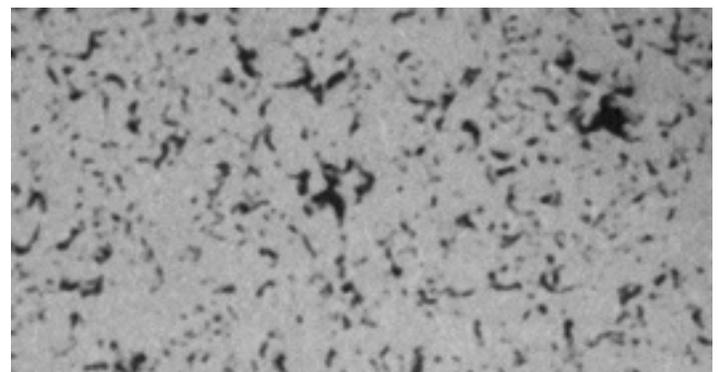
Amorphous carbon, is also referred to as nongraphitic carbon. When examined by x-ray diffraction, these materials show only diffuse maxima at the normal scattering angles. This has been attributed to a random translation and rotation of the layers within the layer planes. This disorder has been called turbostratic. Some of these nongraphitic carbons will become graphitic, upon heating to $1700\text{-}3000^\circ\text{C}$. Some will remain nongraphitic up to 3000°C .

Thus far, the discussion has centered on the crystal structure of graphites. On a more macroscopic level, the structure as routinely examined on a light microscope at magnifications of 100, 200 and 500 times, reveals the porosity, particle or grain size and the general



POCO Ultrafine Graphite (EDM-3)

mag.100x

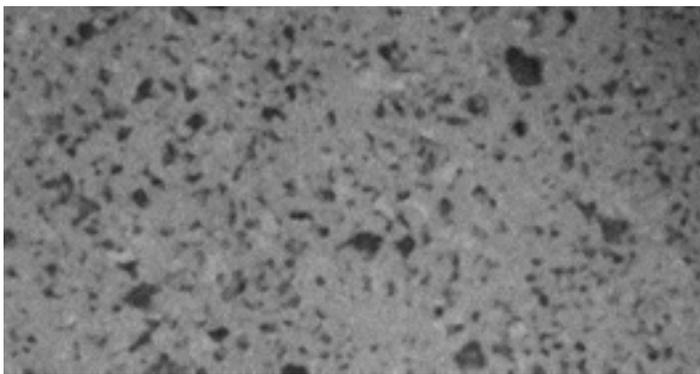


Conventional Graphite

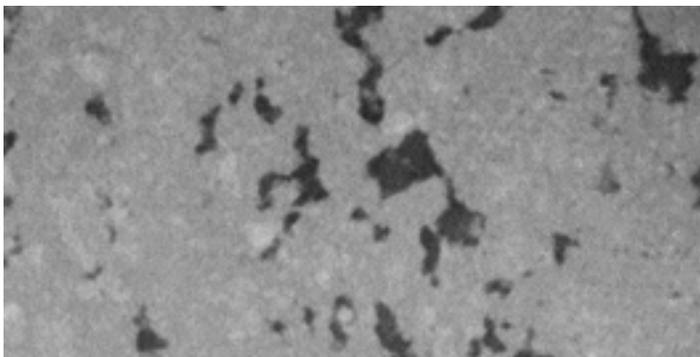
mag.100x

Figure 1-6. POCO graphite vs. conventional graphite under light microscope at 100x magnification

¹Spain, I.L. Electronic Transport Properties of Graphite, Carbons, and Related Materials, Chemistry and Physics of Carbon, 16 (1981), pp. 119.



POCO Ultrafine Particle Graphite (EDM-3) mag.500x



Conventional Graphite mag.500x

Figure 1-7. POCO graphite vs. conventional graphite under light microscope at 500x magnification

microstructure as it is commonly referred. Photomicrographs of POCO EDM-3 graphite as compared to a conventional graphite demonstrates some significant differences as viewed at 100X magnification (Figure 1-6) and at 500X magnification (Figure 1-7). It can be seen from these photos, that vast differences do exist in graphite microstructure. These differences are directly related to raw material and processing parameters.

As seen in the photos, the dark or black regions represent the porosity while the lighter regions represent the graphite matrix. It is this matrix, composed of smaller particles bound together either chemically or mechanically, which is comprised of the crystals stacked layer upon layer. This is more easily seen in scanning electron micrographs (SEM).

The fourth form of carbon, buckminster fullerene, formula C₆₀, whose framework is reminiscent of the seams in an Association Football ("soccer") ball (Figure 1-8), is the subject of considerable interest at present and was only discovered a few years ago in work involving Harry Kroto, a Sheffield University graduate.

Test Methods

The structure of graphite has been determined through such methods as X-ray diffraction, transmission electron microscopy, neutron diffraction and convergent beam electron diffraction. These methods are highly sophisticated

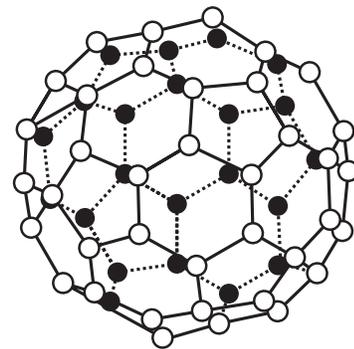


Figure 1-8. Structure of C₆₀, Fullerene

and generally very expensive equipment with a highly skilled operator required. This is normally beyond the scope of typical industrial laboratories. Since this type of testing or analysis is more research oriented, no standard methods will be presented. However, several books have been published on the structure of graphite and the reader is encouraged to review the bibliography in the appendix.

POCO Graphites vs. Conventional Graphites

With regard to crystalline structure, POCO graphite has a typical hexagonal structure. The layer spacings may vary as they are a function of raw material and process conditions which vary from manufacturer to manufacturer. It is reasonable to assume that a certain degree of rhombohedral structure exists also in machined artifacts due to the machining induced deformation mentioned previously. No testing has been done to confirm this.

POCO graphites are also highly isotropic with respect to their structure and properties. The isotropy factor is between 0.97 and 1.03 with 1.00 being perfect. A factor of 1.00 means the properties are identical no matter which direction they are measured in. Many conventional graphites are anisotropic. This means the properties vary depending on which direction you test them in. The high degree of isotropy makes POCO graphites useful in many applications where an anisotropic material would fail. It also allows for maximum utilization of material as machining orientation is of no importance.

Temperature Effects

There are two general types of carbon, those considered to be "graphitizing" carbons and those that are "nongraphitizing". The most significant difference is found in the apparent layer size and apparent stack height. For equal layer sizes, the apparent stack height, i.e. average number of layers per stack, is less for nongraphitizing carbons than graphitizing carbons. The layer stacking is more perfect in graphitizing carbons than nongraphitizing. These apparent sizes and heights are important in the first stages of carbonization.

The structure of graphite with regard to interlayer spacings and crystallite size does change with temperature (Figure 1-9). Interlayer spacing, d , decreases as heat treat temperature increases. Beginning about 1500°C the interlayer spacing, d , decreases sharply from about 3.50 Å to about 3.40 Å by the time the temperature reaches 2000°C. At this point it begins to level off approaching 3.35 Å above 3000°C. The crystallite size, L_a , increases as heat treat temperatures increase. Conversely to the interlayer spacing, d , the crystallite size, L_a , begins a sharp increase about 1500°C and continues to about 2000°C where it begins to level off. The size at < 1500°C is 50 Å and increases to about 400 Å at 2000°C.

A difference will be noted in petroleum coke versus pitch coke. The pitch coke does not increase to the same size as the petroleum coke at the same temperature. It parallels about 75 Å lower beginning about 1700-1800°C. L_a is the basal plane size. L_c , which also increases, is the stacking direction height (Figure 1-5). The total size increases while the interlayer spacing, d , decreases. These changes, along with processing parameters, account for POCO's excellent properties.

Density Effects

Isotropy is independent of density. A high or low density material can be isotropic or anisotropic. The general crystal "structure" is also independent in that the greatest effects on density are due to process parameters. The same crystal "structure" can exist independent of the density of the bulk piece.

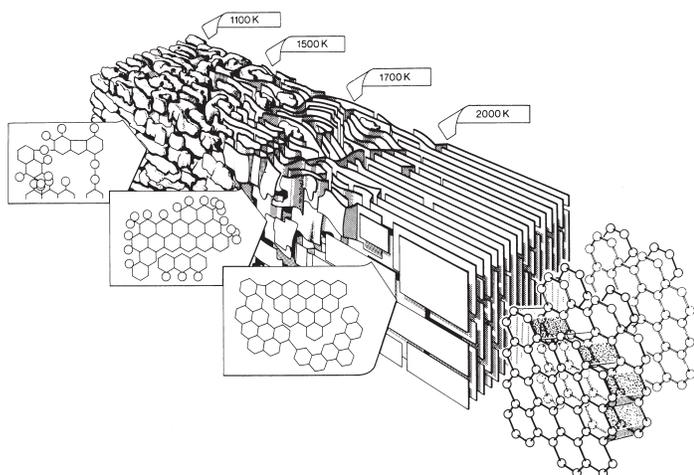


Figure 1-9. A model of changes from mesophase to graphite during heat treatment.

Chapter 2

Apparent Density

Several factors influence density, such as the size and atomic weight of the elements, the atomic packing in the crystal structure, and the amount of porosity in the microstructure. Density is an important property for many applications, but in EDM applications, density value and a photomicrograph of the material should be taken into consideration when comparing materials. Graphites with very large particles and pores can have higher density values than some of the best small particle and pore sized materials. Material grades with high density along with uniformly packed small particles tend to give better wear and finer finishes than materials with high density and large, loosely packed particles.

Definition

The apparent density of solids is the weight, in air, of a unit volume at a specified temperature. Density is ordinarily expressed in grams per cubic centimeter or pounds per cubic foot (1 g/cm³ = 62.4 lb/ft³). To determine the density of a specimen, one would first calculate its volume from the physical dimensions (for a rectangular solid, the volume is equal to the product of the length, width and thickness). Next, the mass would be determined by weighing the specimen. The density is determined by dividing the mass by the calculated volume.

If the specimen were completely homogeneous, with no flaws or voids, this method of determining density would yield the theoretical value. Graphite materials are, however, porous; hence, the term apparent density.

In general, the differences in density of POCO graphites reflect what some of the other physical properties will be. The higher density graphite will, generally, be stronger with a higher hardness value plus improvement in many other properties and characteristics.

The mathematical expression for the determination of density is:

$$D = \frac{W}{V}$$

WHERE: D = Density in g/cm³
 W = Weight of specimen in grams
 V = Volume of specimen in cm³

Or, if the weight is expressed in pounds and the volume is expressed in cubic feet, then the density would be in the units of pounds per cubic foot.

Sample Calculation:

A graphite specimen has a length (l) of 1.000 inches, a

width (w) and thickness (t) of 0.500 inches, and a weight of 7.500 grams. Calculate the apparent density (D).

$$V = l \cdot w \cdot t = 1.000in \cdot 0.500in \cdot 0.500in$$

$$V = 0.25in^3$$

To convert to cm³, multiply by 16.387
 (1 inch = 2.54 cm, Appendix A)

$$V = 4.097 \text{ cm}^3$$

$$D = \frac{W}{V} = \frac{7.500g}{4.097cm^3} = 1.831g/cm^3$$

Test Methods

The standard method commonly used to determine the apparent density of graphite is described in the procedure ASTM - C559 and Research & Development – Analytical Services Laboratory Instruction (TDI) 4.1.1.1 (Appendix B).

For ultrafine-particle graphites, such as the POCO grades, an alternate method of determining apparent density is the “water method”. This is a method that can be used on objects of irregular shape where the volume would be difficult to calculate. Even though the graphite is porous, the intrusion of water into the porosity is slow and the accuracy with this method is ± 1% if the submerged weight is taken quickly.

The general steps in the “water method” are as follows:

1. Support the piece of graphite by a thin wire/thread and weigh the piece of graphite in air.
2. Submerge the piece in a container of water in such a way that the submerged weight can be determined.

3. Calculate the density by the following formula:

$$D = \frac{W_1}{W_1 - W_2} \times D_L$$

WHERE: D = Density in g/cm³
 W₁ = Weight in air (in grams)
 W₂ = Weight in water (in grams)
 D_L = Density of water

POCO Graphites vs. Conventional Graphites

POCO graphites are manufactured in a variety of grades covering the density range from 1.57 g/cm³ to 1.88 g/cm³. The density is a particularly important characteristic of graphite because, in addition to its inherent significance, it has a direct influence on other properties. Generally, the physical and mechanical properties improve as the density is increased; details will be presented in later chapters. Commercial, polycrystalline graphites seldom exceed 80

percent of the theoretical density figure (2.26 g/cm³) due to voids and pores. Single crystal and pyrolytic graphites, because of their highly ordered structures and absence of pores, have densities closely approaching the theoretical value. In comparison to most other materials of construction, graphite has a low density (Figure 2-1). This is a decided advantage for the large majority of applications.

Temperature Effects

The apparent density will be influenced by temperature during the graphitization process. Generally, the higher the graphitization temperature, the higher the density will become. There are other factors which may contribute, but there is an appreciable density increase from 2000°C - 3000°C.

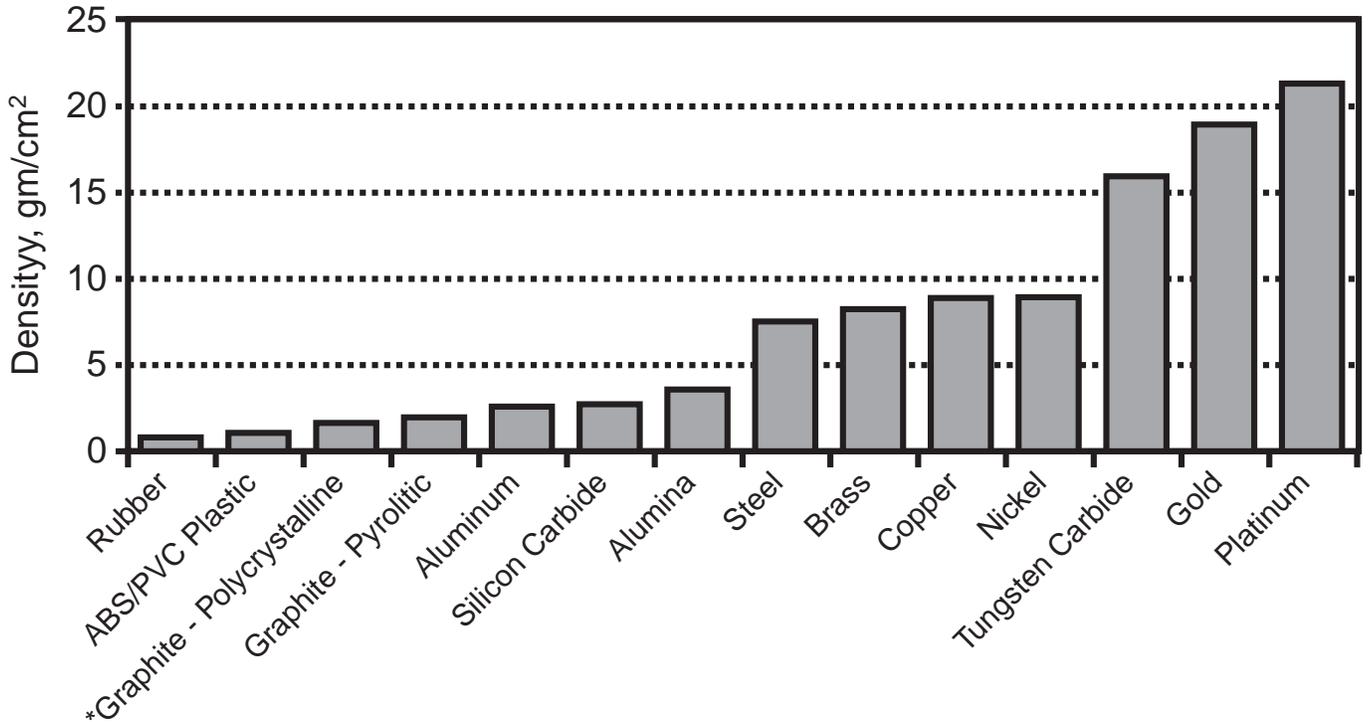


Figure 2-1. Typical densities of various engineering materials

Chapter 3

Porosity

Like density, porosity plays a major role in determining other properties such as strength and hardness. Since all commercial graphites are porous in nature, it is important to understand how to measure this property and what the effect on other properties may be. As the particle size increases so does the pore size of the graphite. The weakest part of any graphite system is the boundary between particles. In EDM the pore size can influence electrode fabrication and the amount of electrode wear.

Definition

The standard definition for porosity, as found in ASTM C709 which has definitions of terms relating to manufactured carbon and graphite, is "the percentage of the total volume of a material occupied by both open and closed pores". When one calculates the apparent density of a material, the pore volume is included in the calculation. This results in typical maximum densities for nonimpregnated manufactured graphites of 1.90 g/cm³. The theoretical density of graphite is 2.26 g/cm³. This means that at the very best case, about 16% of the volume of a bulk piece of graphite is open or closed pores. This porosity plays an important role in many ways as will be discussed later.

The characteristics of the porosity of POCO fine-grained graphites have been studied extensively¹.

Test Methods

There is no recognized ASTM standard for measuring the porosity of manufactured graphites at this time. A number of techniques may be employed for the purpose and are widely in use today. It is important to state the method by which porosity data is determined because each method imparts its own bias.

One of the more widely used methods is mercury porosimetry. Two other methods in use are gas absorption by the BET technique and direct image analysis of the microstructure. The latter is gaining increased acceptance as a means of measuring more accurately the real pore structure. The advent of computer and video equipment have pushed this technique to the forefront of the porosimetry field. There are nonetheless, limitations to this method also.

The mercury porosimetry technique is the method used for the data reported in POCO graphite literature. It involves basically pushing, under increasing pressure, mercury into the pores and as a function of pressure and volume filled, the pore size and pore volume can be determined. There are certain disadvantages of this method, such as:

- (1) The pores are not usually circular in cross section and so the results can only be comparative.
- (2) The presence of "ink-bottle" pores or some other shape with constricted "necks" opening into large void volumes. The pore radius calculated by the Washburn equation is not truly indicative of the true pore radius and capillaries are classified at too small a radius.
- (3) The effect of compressibility of mercury with increasing pressure. This should be corrected for by carrying out a blank run.
- (4) The compressibility of the material under test: This is a problem of particular importance for materials which have pores that are not connected to the surface, e.g. cork. Additionally, pore walls may break under the pressures used if the material under test is relatively weak. This could cause a bias in the data.
- (5) The assumption of a constant value for the surface tension of mercury.
- (6) The assumption of a constant value for the angle of contact of mercury.

POCO has carried out extensive analysis via mercury porosimetry to determine fundamental porosity parameters such as pore size and distribution, pore volume and surface area, reference Exhibit 3-1.

The mercury porosimetry measurements were made on a Micromeritics Instruments Corporation, Mercury Porosimeter, Model 915-2. A surface tension constant of 480 dynes/cm and a wetting contact angle of 140 degrees

$$Pr = -2\gamma \cos\theta$$

were assumed and used in the Washburn equation² where P is pressure in psi, r is the pore radius in cm, γ is the surface tension and θ is the contact angle. A pressure and

¹ Brixius, W.H., Dagdigian, J.V. "Mercury Porosimetry Analysis of Fine-Grained Graphite", Conf. Proc., 16th Biennial Conference on Carbon, p 465-466 (1983).

² Washburn, E. W. , Phys. Rev. 17, 273 (1921)

penetration volume reading were derived from the mercury porosimetry apparatus.

Penetration volume and pressure data were used to generate a printout of pressure, volume, pore size, and percent porosity relationships. Graphical plots were generated to summarize pore size distribution information; percent porosity was plotted as a function of pore diameter.

$$S = 0.0225 \int_0^{V \text{ max}} PdV$$

The surface area was also determined for each sample as described in the relationship³ where S is the surface area in square meters per gram. In addition, the total closed porosity was determined from the theoretical porosity and the observed (open) porosity. Percent open and closed porosity were expressed as a percent of total porosity volume and a percent of the theoretical porosity.

The above porosity parameters are displayed in graphical form as closed porosity versus apparent density and average pore diameter versus apparent density in Figures

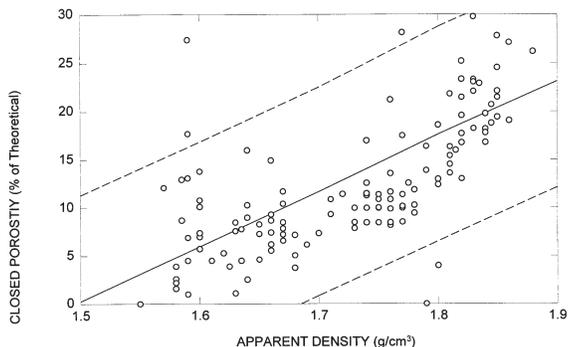


Figure 3-1. Closed porosity vs. density

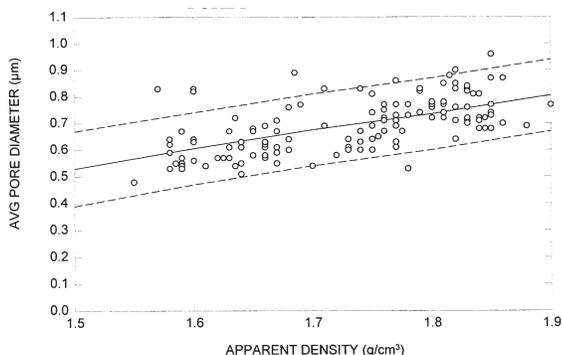


Figure 3-2. Pore diameter vs. density

3-1 and 3-2, respectively. Linear regression analysis was performed to determine the best fit equation (dotted lines represent limits at the 95% confidence level).

The results of these porosimetry studies indicate a linear relationship between average pore diameter and graphite apparent density. That is, as the graphite apparent density increases the average size of the pores increases. Previous in-house photomicrograph studies confirm this observation. Closed porosity was also found to increase with graphite apparent density. As can be predicted on the basis of the above surface area equation and the above observations, surface area varies inversely with graphite apparent density. A greater amount of surface area is observed in the lower density graphite than in the higher density product. At first glance these observations are surprising and may even seem contradictory. Why should closed porosity increase when a concomitant increase in the pore diameter is also observed?

Although cause and effect relationships are difficult to establish, graphite porosity, pore size, and surface area are all physically related to density. Their relationship to density, whether direct or inverse, has implications on the structural properties of POCO graphite. The following physical model is advanced to rationalize the above relationships.

One notes that as graphite density increases, closed porosity and average pore size also increases while graphite surface area decreases. As the graphite structure increases in density, the smaller pores can be imagined to become more and more occluded until they are isolated from the rest of the pore system. As this process occurs the smaller diameter pores are systematically eliminated until only the larger, less complex pores remain. This also creates a larger amount of closed porosity. Thus, not only does the average pore diameter increase as a result of the elimination of small open pores, but pore surface area is reduced since only pores with less branched structures remain.

Mercury porosimetry data on fine-grained graphites reveals a definite relationship between closed porosity and apparent density with the closed porosity increasing as the apparent density increases. The pore size also increases as apparent density increases.

POCO Graphite vs. Conventional Graphites

The pore volume will be the same for all graphite with the same apparent density, but that is where the similarity ends. The pore diameter of POCO's graphites ranges from 0.2 microns nominal, to 2.0 microns nominal, for our various grades and densities. The open porosity ranges from 75% open to 95% open and the pores are generally spherical in shape. The smaller pore size materials have a very large surface area associated with them. Conventional graphites

³ Orr, C., Jr., "Application of Mercury Penetration to Materials Analysis, publication 9-AN-1 from Micromeritics Instrument Corporation, 8.

will, at their best, have typical pore sizes only down to several microns in size. The distribution of pore sizes is very narrow for POCO graphites, while they are generally broader for conventional graphites (Figure 3-3).

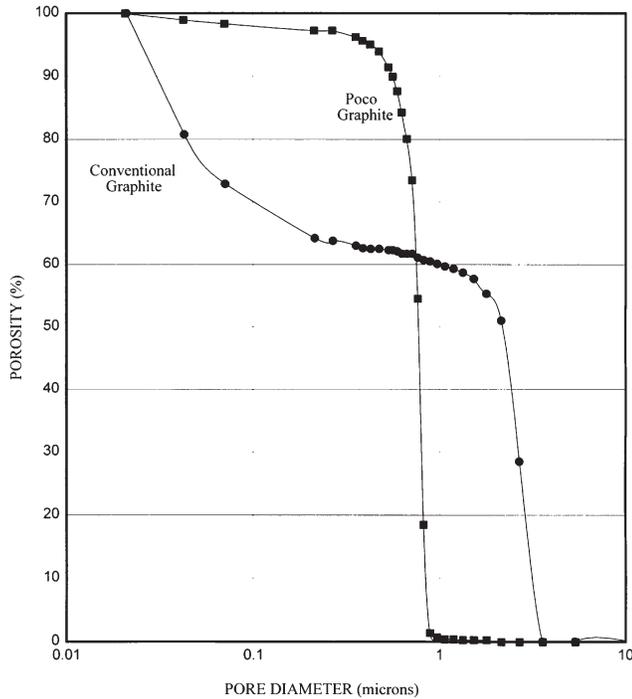


Figure 3-3. Pore size distribution POCO graphite vs. conventional graphite

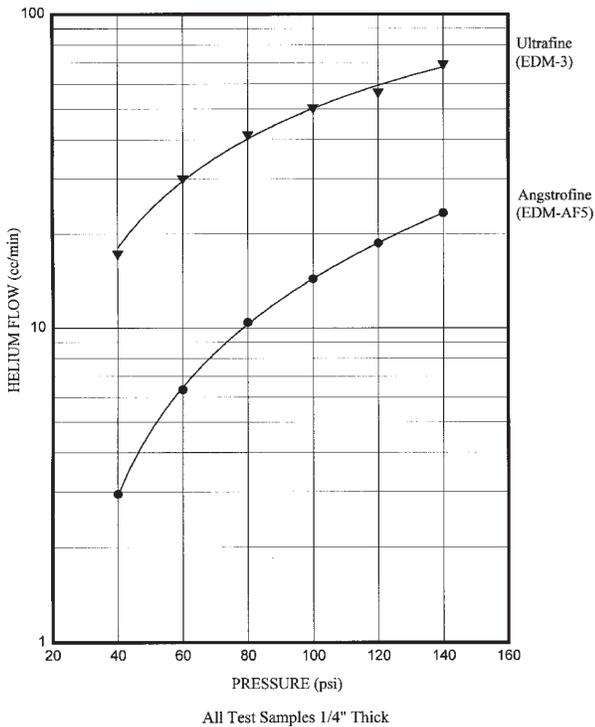


Figure 3-4. Helium flow vs. pressure for some POCO graphite materials

The fineness of the porosity allows POCO materials to be modified to create truly impermeable graphite. With various post-processing techniques, POCO can seal, fill or close the porosity depending on the end application. The high degree of open porosity also allows POCO to purify the material to less than 5 parts per million total impurities. Figure 3-4 shows helium flow data on various grades of POCO graphite. It shows clearly a wide variety of capabilities for POCO graphites. The helium flow test for checking the permeability, like the mercury porosimetry test, has its limits or bias and should be clearly identified when using data generated by it. Permeability is simply the rate of flow of a medium such as a gas or liquid through a material while under a pressure gradient. The pores of POCO graphite are not only uniformly distributed, but are well interconnected so flow can take place through them. There are applications as filters where this is important. Another feature of the small pore size is that some liquids will not generally penetrate the

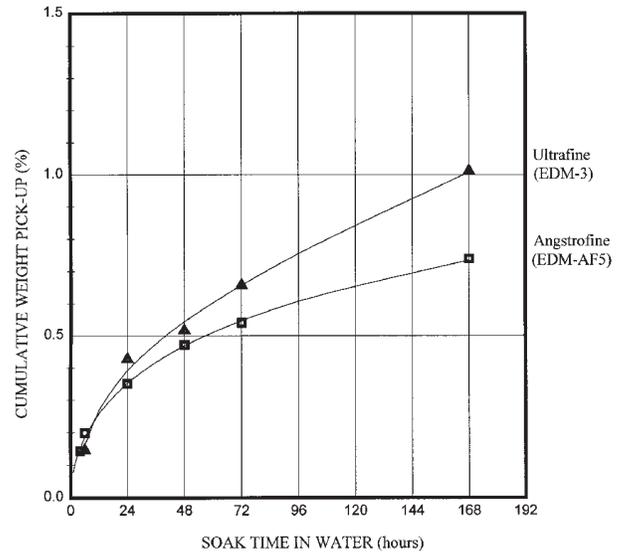


Figure 3-5. Water absorption of POCO graphites

pores readily. For instance, it has been determined, that after soaking in water for seven days, a sample of EDM-3 picked up less than 1% by weight of the water (Figure 3-5). This could be an advantage in some applications. However, in other applications, such as wanting to infiltrate a liquid such as molten copper, very high pressures are required, at high temperatures, to accomplish it.

Temperature Effects

As temperature increases, pores will expand along with the rest of the matrix to the point of opening what were previously closed pores. As graphitization temperature increases, the pores will generally be found to be slightly smaller in size.

Density Effects

Mercury porosimetry data on fine-grained graphites reveals a definite relationship between closed porosity and apparent density with the closed porosity increasing as the apparent density increases. The pore size also increases as apparent density increases. The relationship is linear with closed porosity increasing as density increases and pore size also increasing as density increases. If post-processing densification techniques were employed to raise the density, the pore size and pore volume would decrease.

Chapter 4

Hardness

The hardness of a material is a poorly defined term that has many meanings depending upon the experience of the person involved. Several tests claim to measure "hardness" but are in fact measuring different properties. For example, a static indentation hardness test measures a material's resistance to plastic deformation under static load while a dynamic hardness test expresses hardness as the energy of impact. Other tests may quantify the hardness of a material by a scratch test or wear by abrasion.

The hardness of material is particularly important when fabricating EDM electrodes. Most EDM graphite falls within a Shore hardness range of 45-85. The most machineable materials will be between 55-75 on the Shore scale. Materials exhibiting high hardness and low strengths should be avoided since they will be more brittle and more likely to chip during electrode fabrication. Hardness does not affect EDM performance.

Definition

Although the term "hardness" has comparative significance in an engineering sense, it is generally not considered to be a fundamental property of matter. The index of hardness is generally a manifestation of several related properties. In graphite, for instance, the particle size and porosity, and apparent density have an influence on the hardness value. The hardness value can be changed by the graphitization temperature as well, which generally relates back to a strength characteristic such as shear strength at the crystallographic level. Different hardness testers are influenced by different properties and as a consequence cannot be correlated very well. Comparatively soft materials may be hard in the sense that they can resist abrasion stresses, whereas harder materials in the sense of indentation hardness, may fail completely under the same circumstances. It should be obvious at this point that the term "hardness" is relative and hardness data must be interpreted in relation to the type of hardness tests used.

An appropriate definition of hardness then would be the resistance of a material to permanent deformation of its surface. The deformation may be from scratching, mechanical wear, indentation, or in a broader sense, cutting. Cutting would clearly include machinability as an index of hardness. This is much less precise than conventional hardness testers, but can be an indicator of relative usefulness.

Test Methods

The Brinell hardness test was proposed in 1900 by J. A. Brinell and became the first widely accepted standardized indentation-hardness test for metals. In general, the Brinell hardness test consists of using a 10 mm steel ball to penetrate a materials surface resulting from a 3,000 kg applied load. The loads are typically applied for 30 seconds and the diameter of the indentation is measured with a low power microscope. Soft metals such as

aluminum or copper may require a reduced load of 500 kg to avoid excessive penetration. Steel ball indenters are replaced with tungsten carbide when evaluating very hard metals thus avoiding permanent deformation of the steel ball.

The Vickers hardness test uses a square base diamond pyramid indenter consisting of a 136° included angle between opposite faces of the pyramid. This angle was selected because it best approximates the ratio of indentation diameter to ball diameter exhibited in the Brinell hardness test. One determines the Vickers hardness number by dividing the applied load by the surface area of the indentation, where the area of the indentation is calculated from microscopic measurements of the lengths of the diagonals of the impression. The Vickers hardness technique is the most accurate, and it can be used when evaluating very hard materials and/or thin sheets.

There are two standard test methods for hardness of graphite: C748, Rockwell Hardness and ASTM C886, Scleroscope Hardness.

The Rockwell hardness method utilizes the depth of indentation, under constant load, as a measure of hardness. A minor load of 10 kg is first applied to seat the specimen. The major load is then applied, and the depth of indentation is recorded in terms of hardness. The higher the number the "harder" the material. A variety of indenter sizes and loads are available depending upon the material being tested and its expected hardness. For example, typical indenters used for evaluating metals include a Brale indenter, which has a 120° diamond cone with a slightly rounded point, and 1/16 and 1/8 in. diameter steel balls. Major loads of 60, 100, and 150 kg are used. For graphite, the method specified calls for use of the "L" scale with a 1/4 in. diameter steel-ball indenter and a 60 kg major load. Thus it is necessary to specify the combination of load and indenter when reporting Rockwell hardness results.

Rockwell hardness works well for conventional graphites, but the ultrafine particle POCO graphites are usually off scale on the high side when tested with this method. Another scale and/or a smaller indenter would be more appropriate, but a standard method has not been developed for use. However, a number of our customers specify use of the Rockwell 15T scale for hardness data, which utilizes a 1/16 in. diameter steel-ball indenter and a 15 kg major load. There are a number of factors which affect the accuracy of this method regardless of the scale used. They are listed in TDI 4.1.1.4, Section 5.3.

POCO typically uses the Shore scleroscope hardness (SSH) test, which measures hardness in terms of the elasticity of the material. This is a dynamic hardness measurement technique in which the indenter falls through a glass tube from a known height and impacts the specimen. The degree of hardness is directly related to the height of rebound of the indenter as determined by reading a unitless scale. The higher the rebound, the "harder" the material. There are many factors that affect the reproducibility and accuracy of the data, reference ASTM Standard C886-88. Studies at POCO indicate that sample size, i.e. mass, has a significant bearing on the results as well. The results of a large billet will generally be higher than for a small test sample.

Poco Graphite vs. Conventional Graphites

Since hardness is influenced by a number of other factors, the comparison of POCO to conventional graphites is relative at best. If all factors were held constant, including graphitization temperature and no artificial densification, etc., based strictly on particle size alone, POCO would have a higher hardness number.

Temperature Effects

Generally speaking, higher graphitization temperatures, i.e. up to ~3400° C, soften the material, which results in lower room temperature (RT) hardness values. In most cases, the RT hardness will not change if the graphite is subjected to high temperature applications. For example, repeated heating and cooling of graphite does not change the RT hardness value unless the material is subjected to a temperature higher than its graphitization temperature. In this event the material will be softer.

Density Effects

There is a correlation between hardness and density for the base graphite (Figure 4-1). As density increases, a general increase is seen in hardness. This is associated with the amount of porosity, which basically lowers the resistance to penetration. The lower the density, the greater the pore volume and the less the resistance to the penetrator and, hence, a lower hardness number. If the porosity is filled with a material for densification purposes, the hardness might increase slightly. If, however, a material such as copper, which is very soft and ductile, is introduced into the pores, the overall hardness drops in direct relationship to the volume of copper filling the pores. Hence, a material with 75% open porosity will have a higher hardness when filled with copper than a material initially having 95% open porosity when it is filled with copper.

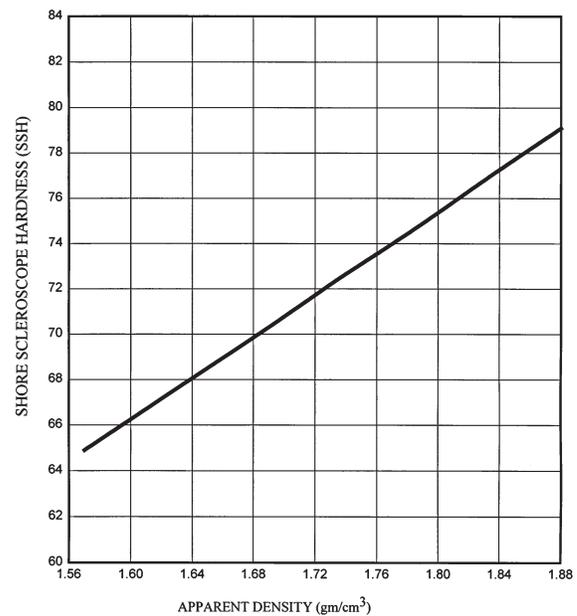


Figure 4-1. Nominal hardness of POCO "Ultrafine" graphites (EDM-1, EDM-2, EDM-3, EDM-4)

Chapter 5

Compressive Strength

Compressive strengths, as a material property, is a good indicator of mechanical properties. High compressive strength contributes to the ability to withstand aggressive tool pressure and clamping during electrode fabrication.

Definition

The easiest strength characteristic of a material to understand and measure is the compressive strength. In general, the compressive strength test consists of determining the maximum amount of compressive load a material can bear before fracturing. However, not all materials will exhibit catastrophic failure in response to compressive loads. Applying a continually increasing compressive force to ductile materials such as gold, copper or iron ultimately causes slip across crystalline planes that result in reforming the atomic or molecular bonds with other atoms. Consequently, it is quite possible to flatten a very ductile material, such as gold, into a very thin sheet (if high enough compressive load is applied). On the other hand, if the material is brittle, such as graphite or many ceramic materials, atomic or molecular bonds cannot be reformed easily; therefore, when crystalline planes begin to slip, catastrophic failure occurs and the material fractures.

The compressive strength of a brittle material is expressed as the maximum force per unit area that can be withstood before failure occurs. It is usually expressed in pounds per square inch, or in kg/cm² in metric units. The mathematical expression for the determination of compressive strength is:

$$C.S. = \frac{L}{A}$$

WHERE: C.S. = Compressive strength
 L = Load required to cause catastrophic failure
 A = Cross sectional area of specimen

Sample calculation:

A graphite specimen with a cross-sectional area of 0.25 square inches fails when a load of 3500 pounds is applied; calculate the compressive strength. To convert to kg/cm², multiply by 0.0703.

$$C.S. = \frac{L}{A} = \frac{3500lbs}{0.25in^2} = 14,000psi$$

Compressive Strength = 984 kg/cm²

If the load, L, is expressed in kilograms (kg) and the cross sectional area, A, is expressed in square centimeters (cm)², then the compressive strength will be in the metric units of kg/cm².

NOTE: 1 psi = 0.0703 kg/cm²

Other units and the appropriate conversion factors are given in Appendix A.

Test Method

The standard method of measuring the compressive strength of a graphite specimen is described in ASTM C695. POCO's method differs in that the specimen used is rectangular rather than a right cylinder. In addition, cushion pads are not used (TDI 4.1.1.14 in Appendix B and Figure 5-1).

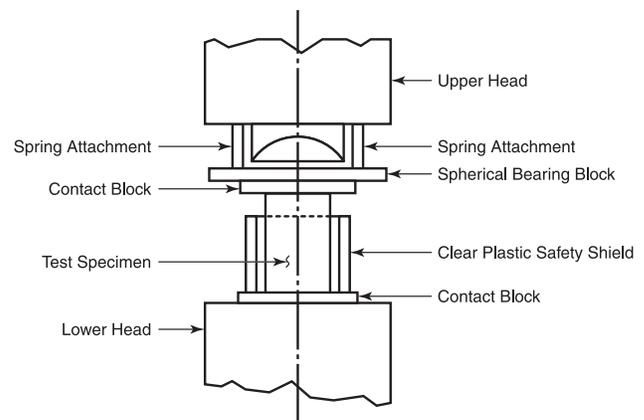


Figure 5-1. Elements of compressive strength load train.

POCO Graphites vs. Conventional Graphites

POCO graphites have high compressive strengths compared to conventional materials. The compressive strengths of POCO materials range from 10,000 psi (703 kg/cm²) to over 30,000 psi (2109 kg/cm²) depending on the grade selected. These values are two to three times higher than most other graphites. The final heat treating temperature used in the manufacture of a carbon/graphite material has a marked effect on its compressive strength; the lower the final temperature, the higher the compressive strength.

Temperature Effects

As the use temperature of a piece of graphite is increased, the compressive strength of graphite increases, up to about 2500°C. This is particularly important in such applications as hot pressing dies, where the material is subjected to both high temperature and high stress levels. Depending on the grade and type of graphite, the increase in strength will be from 15% to 50% higher at 2500°C than it is at 25°C.

The graphitization temperature also has a marked effect on the compressive strength. The lower the graphitization temperature (i.e. the less graphitic the material is), the higher the compressive strength will be. This is readily seen when comparing carbon based material to graphite based material for areas such as mechanical application.

Density Effects

As with many other properties, the compressive strength of graphites changes with apparent density; the higher density having the highest strength. The specific relationship for POCO EDM grades in the “Ultrafine” class is shown in Figure 5-2.

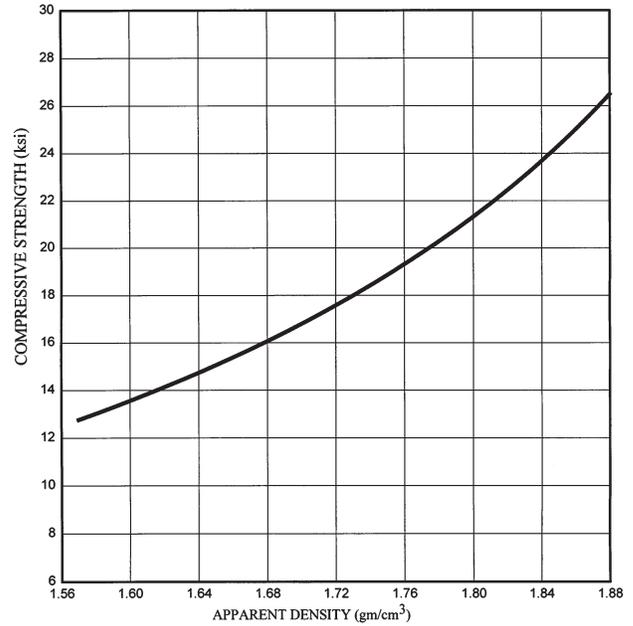


Figure 5-2. Nominal compressive strength of EDM-1, EDM-2, EDM-3, EDM-4 graphite vs. apparent density

Chapter 6

Flexural Strength

Flexural strength is the materials ability to resist an applied bending force and the flexural-strength test measures the force required to bend a beam to failure under 3 or 4 point loading conditions. The data is often used to select materials for load bearing applications while flexural modulus is used as an indication of a material's stiffness.

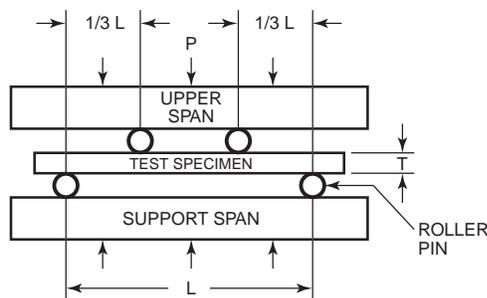
Flexural strength testing is more often preferred over tensile testing when evaluating the strength of brittle materials such as glass and ceramics since tensile tests are often difficult to perform on these material types. However, flexural strength testing yields some information regarding the tensile and compressive strengths of materials in that tensile (stretching) stresses develop on one side of the bent member and corresponding compressive stresses develop on the opposite side. If the material is substantially stronger in compression than tension, failure initiates on the tensile side of the member and, hence, provides information regarding the materials tensile strength.

High flexural strengths are desired in EDM graphite electrodes when it is necessary to machine thin plates or rods, and when making artifacts with close tolerances and fine detail. Applications in which graphite is subjected to high bending stresses, i.e. during orbital machining and/or when using high flush pressures, obviously require the use of high flexural strength materials. High strength also means improved wear resistance, since a stronger material better resists the damaging effects of electrical discharge machining.

Definition

Flexural strength, tensile strength and compressive strength are the three common tests performed to measure the strength of materials. In flexural strength testing, a steadily increasing bending movement is applied to a long bar until the material eventually ruptures. If the material is ductile (like copper), it will bend prior to breaking. However, if the material is brittle (such as chalk or graphite), it will bend very little before it fails catastrophically.

Flexural strength can be defined as the maximum stress in bending that can be withstood by the outer fibers of a specimen before rupturing (refer to the schematic diagram of Flexural Test Fixture in Figure 6-1).



CROSS SECTION OF SPECIMEN



Figure 6-1. Four point loading fixture

The mathematical expression for calculating flexural strength is:

$$F.S. = \frac{PL}{W(T)^2}$$

WHERE:

- F.S. = Flexural Strength in pounds per square inch (psi).
- P = Load in pounds at failure.
- L = Length between outer support roller pins in inches.
- W = Width of specimen in inches.
- T = Thickness of specimen in inches.

Sample calculation:

Assume a graphite specimen 4.0 inches long by 0.75 inches wide by 0.50 inches thick is flexure tested on a fixture with support roller pins 3.0 inches apart. The specimen fails under a 500 pound load; calculate its flexural strength:

$$F.S. = \frac{PL}{W(T)^2} = \frac{500 \times 3.0 \text{ lbs}}{0.75 \times (0.50)^2} = \frac{1500}{0.1875 \text{ in}^2} \text{ psi} = 8,000 \text{ psi}$$

FS=8,000 psi.

To convert to kg/cm², multiply by 0.0703.

Flexural strength = 562 kg/cm².

Test Method

The details of the procedure commonly used for testing the flexural strength of graphite are found in ASTM C651. POCO's method (TDI 4.1.1.13, Appendix B) differs in that

the specimen geometry has a 1:1 ratio in thickness and width rather than the 2:1 width to thickness. The fixture used is not exactly as described either, but with a surface finish of less than 32 micro inches Ra on the sample, the frictional component is minimized, and results are comparable to those obtained with the fixture recommended by ASTM. Regardless of the procedure followed, steps must be taken to avoid factors that bias the results such as improper sample alignment, rough and/or non-parallel surfaces. It is also important to know whether the reported strength values were obtained from three-point or four-point loading.

For example, a test specimen typically has a uniform rectangular cross section but the load may be applied in three or four point as illustrated in Figure 6-2. Note the shaded areas indicating the stress distribution. In 3-pt loading, the peak stress occurs on a single line at the surface of the test

distribution decreases linearly from the area of peak stress on the tensile face, and into the thickness of the bar, until reaching zero at the bottom span supports. The increased area and volume under peak tensile stress, or near the peak tensile stress, in 4-pt loading increases the probability of encountering a larger flaw. The probability of detecting the largest flaw in the specimen during 3-pt loading is minimized since the largest flaw must be at the surface and along the line of peak stress. Consequently, the specimen fractures at either a smaller flaw or within a region of lower stress thus yielding artificially higher strength values in comparison with 4-pt loading results. The strength limit of the material, or even the local stress and flaw size that caused fracture, is not revealed in 3-pt loading. It only indicates the peak stress on the tensile surface at the time of fracture for a given material.

POCO Graphites vs. Conventional Graphites

In a brittle material, such as graphite, the flexural strength is particularly sensitive to flaws or defects in the material. If a flaw is present within span L, i.e. between the outer support pins of the flexural test specimen, then the load P required to break the sample will be reduced. When failure occurs, it is catastrophic. The sample breaks suddenly and, frequently, small chips and flakes of material break away at the point of failure.

POCO graphites have flexural strengths covering the range from 5,000 psi (352 kg/cm²) to over 18,000 psi (1265 kg/cm²). These values are quite high when compared to conventional graphites, which may range from less than 1,000 psi (70 kg/cm²) to around 6,000 psi (422 kg/cm²). The fine particle size and homogeneous structure of POCO graphites contribute to their high flexural strengths. Another important characteristic of this property in POCO graphites is that the flexural strength is the same for samples cut from any direction or orientation of the parent block of material. This characteristic is called isotropy; POCO graphites are said to be isotropic, whereas most other graphites are anisotropic. In conventional graphites that are molded or extruded, the flexural strengths between the “against grain” and “with grain” directions may vary by 30 to 50%.

Temperature Effects

One of the unusual properties of graphite is that it gets stronger as it gets hotter (up to about 2500°C). This is contrary to most materials, which lose strength as the temperature increases. The flexural strength of graphites will increase by 20% - 50% when the test temperature is increased from 25°C to 2500°C.

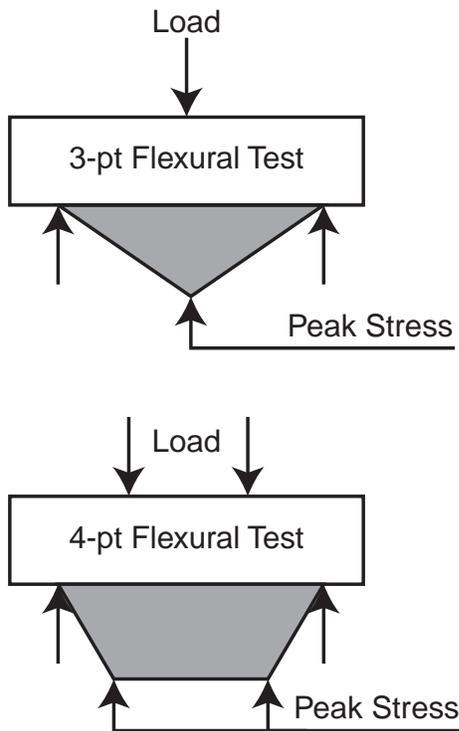


Figure 6-2. 4-pt bend strength < 3-pt bend strength

bar and opposite the point of loading. The stress increases linearly along the length of the bar, and into the thickness of the bar, until reaching zero at the bottom supports.

Unlike the 3-pt bend tests, where the peak stress occurs on a single line opposite the point of loading, 4-pt loading distributes the peak stress over an area that is determined by the width of the sample and the span of the top loading supports, respectively. Observe how the tensile stress

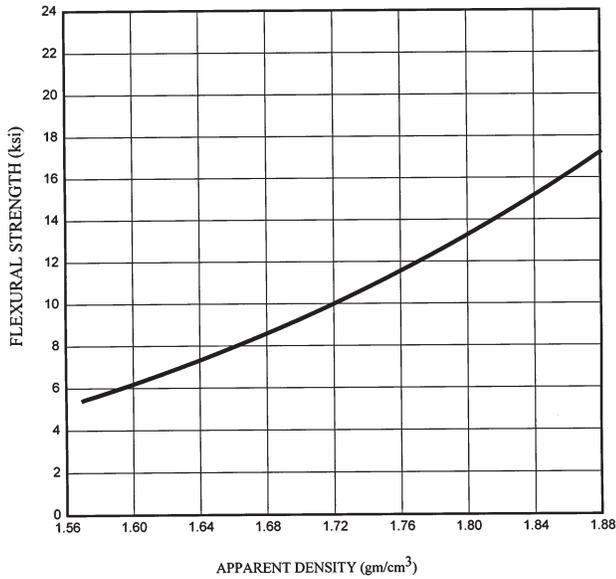


Figure 6-3. Nominal flexural strength vs. apparent density of POCO “Ultrafine” graphite (EDM-1, EDM-2, EDM-3, EDM-4)

Density Effects

Flexural strength, like many other physical properties of graphite, increases with increasing density. For example, nominal flexural strength of Ultrafine grades ranges from 6,000 - 17,000 psi for densities of 1.60 (g/cc) and 1.88 (g/cc), respectively, (Figure 6-3). Angstrofine exhibits the highest flexural strength indicating 18,000 psi.

Chapter 7

Tensile Strength

All solid materials are deformed when subjected to external loads and either fully recover (elastic behavior), or become permanently deformed (plastic deformation), when the load is removed. Thus, materials are typically classified as ductile (metals) or brittle (ceramics) depending upon whether or not the material exhibits the ability to undergo plastic deformation. Brittle materials such as graphite fracture almost at the elastic limit unlike metals, which show plasticity before fracture. This is an advantage in ductile materials since localized stresses are essentially redistributed. Localized stresses continue to build in brittle materials with no local yielding until a crack initiates at one or more points of stress concentration, and spreads rapidly over the section. Fracture, that is generally catastrophic, can also occur suddenly even in brittle materials with no stress concentrations since the yield stress and tensile stress are practically identical.

Consequently, it is extremely difficult to correctly determine the tensile strength of a brittle material, such as graphite. Any imperfection in the material, such as voids, or surface scratches, will cause stress concentrations at that point. Since the stress at this point is higher than the overall average throughout the specimen, a crack will begin to propagate and premature fracture will occur. To alleviate this situation, carefully machined, highly polished specimens are used. Alignment of the gripping apparatus on the specimen is also critical. Even small misalignments could cause premature fracture, resulting in an erroneous (low) value for the tensile strength.

There is no correlation between tensile strength and EDM Properties (e.g. metal removal rate and end wear).

Definition

The tensile strength of a material can be defined as its strength when a pulling force is applied along the length of a sample. If a cylindrical bar of uniform cross-section is subjected to a steadily increasing tensile (“pulling apart”) force along its axis, the material will eventually rupture and tear apart when a large enough force is applied.

Tensile strength, like compressive strength, is expressed in pounds per square inch and is calculated in the same manner as compressive strength, i.e. the applied force at failure is divided by the cross-sectional area of the sample.

Sample calculation:

If a rod with a cross-sectional area of 0.25 in² breaks at a load of 2,000 pounds, then the tensile strength is 8,000 pounds per inch².

$$\text{Tensile Strength} = \frac{\text{Load}}{\text{Area}} = \frac{2,000\text{lbs}}{0.25\text{in}^2} = 8,000\text{psi}$$

To convert to kg/cm², multiply by 0.0703.

Tensile Strength = 562 kg/cm²

Test Method

Reference ASTM Procedure C565 for detailed methods commonly used for tensile testing. Other more sophisticated testing equipment has been developed for this test; one of the better methods uses hemispherical air bearings to eliminate misalignment of the sample.

POCO Graphites vs. Conventional Graphites

The tensile strength of a brittle material, such as graphite, is very sensitive to defects or imperfections in the material. The fine structure and uniformity of POCO graphites result in higher tensile strength for POCO materials as compared to conventional graphites. Typical tensile strength for conventional graphites range from 2,000 psi (141 kg/cm²) to 5,000 psi (352 kg/cm²), as compared to 5,000 psi (352 kg/cm²) to 10,000 psi (703 kg/cm²) for POCO materials. See Table 7-1 for the tensile strengths of various materials.

Typical Ultimate Tensile Strengths of Various Materials	
Material	Ultimate Tensile Strengths (10 ³ psi)
Natural Rubber	> 4
ABS/PVC Plastic	3 - 6
Graphite (Polycrystalline)	2 - 10
Aluminum (Wrought)	13 - 98
Silicon Carbide	3 - 20
Alumina (Ceramic)	20 - 30
Steel (Wrought)	90 - 290
Brass	34 - 129
Copper	29 - 76
Nickel	50 - 290
Gold	19 - 32
Platinum	18 - 30

Table 7-1

Temperature Effects

As the testing temperature of graphite is increased, its tensile strength increases; this is in sharp contrast to the behavior of metals, which show a decrease in strength as temperature increases. In an inert atmosphere (to avoid oxidation), the tensile strength of POCO's graphite in the Ultrafine classification is almost 20,000 psi at 5,000°F (2760°C), as compared to 9,150 psi at room temperature (Figure 7-1). This dramatic change is characteristic of graphite materials, even though most grades do not show the 100% increase that POCO graphites exhibit.

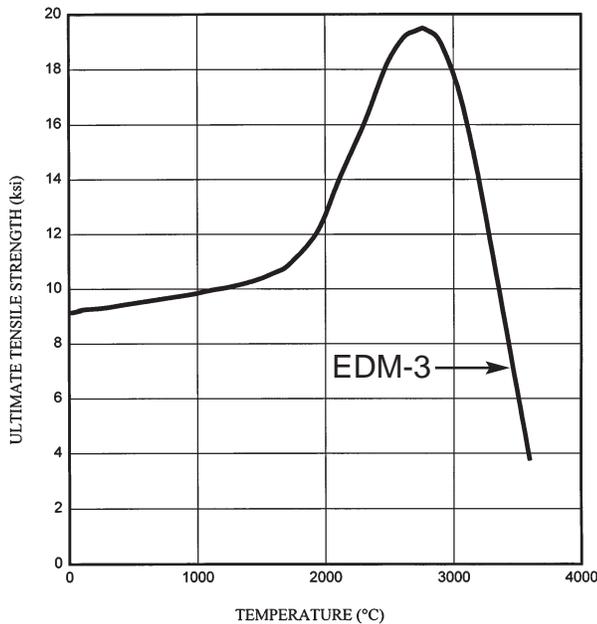


Figure 7-1. Ultimate tensile strength of POCO EDM-3

The final heat-treat temperature of the graphite has a marked effect on its room temperature tensile strength; the lower the heat-treat temperature, the higher the strength. This is similar to the effect seen on other strength characteristics where the less graphitic materials are harder and stronger. The relationship between graphitization temperature and tensile strength is shown in Figure 7-2.

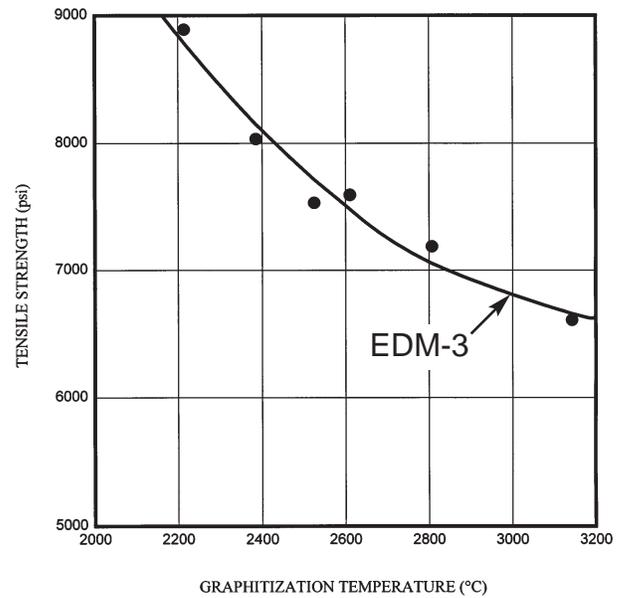


Figure 7-2. Graphitization temperature effect on tensile strength

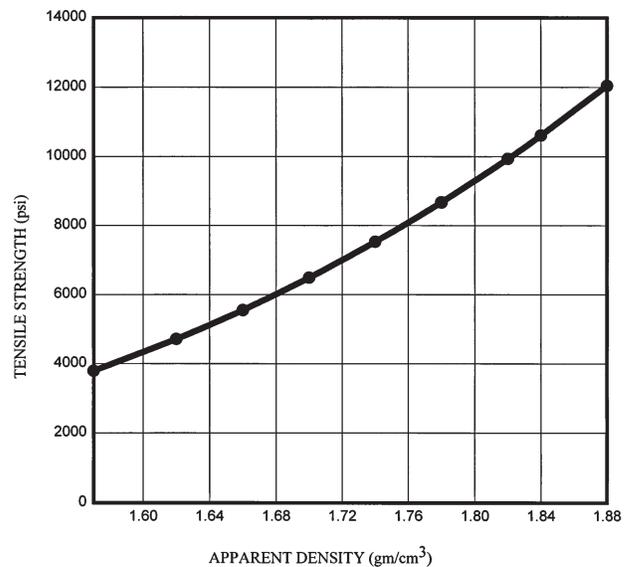


Figure 7-3. Nominal tensile strength vs. apparent density of POCO "Ultrafine" graphite (EDM-1, EDM-2, EDM-3, EDM-4)

Density Effects

The tensile strength of graphite has a strong correlation with density; as the density increases, the tensile strength increases. This is typical of the other strength characteristics of graphites. Figure 7-3 shows the general relationship between density and tensile strength for the POCO EDM graphites. The nominal values of tensile strength range from 5,000 psi (352 kg/cm²) at 1.60 g/cm³ to 8,000 psi (562 kg/cm²) at 1.84 g/cm³.

Chapter 8

Modulus of Elasticity

The modulus of elasticity, or Young's modulus, is a proportionality constant between the stress and elastic strain of a material. Small stresses produce large elastic strains in rubber thereby showing the lowest modulus of any solid material, which typically ranges between 500 psi - 0.5×10^6 psi. Although the modulus of elasticity for graphite ($\sim 1 \times 10^6$ psi) is high relative to rubbers and polymers, it is low when compared with other materials such as metals and other ceramics that can range between 10×10^6 psi to 462×10^6 psi depending on the material. The modulus of diamond is ~ 150 times higher than graphite indicating $\sim 150 \times 10^6$ psi due to the strong covalent bonding. Thus it takes large stress to produce any significant elastic strain in diamond.

Definition

The elasticity of a material is related to a uniformly increasing separation between the atoms of that material. As a consequence, the elasticity is directly related to the bonding between atoms and the respective energies associated therewith. This can be readily demonstrated by showing the general relationship between modulus of elasticity and melting points of various materials. The higher the melting point (i.e. the energy required to disrupt the atom to atom bonds), the higher the modulus of elasticity (Figure 8- 1). The presence of a second phase of differing

Another way of expressing the modulus of elasticity is by referring to Hooke's law, which applies to materials below their elastic limit. Basically, Hooke's law says that the average stress is proportional to the average strain.

$$\frac{T}{e} = E = \text{Constant}$$

WHERE: T = Stress
e = Strain
E = Modulus of elasticity, or Young's modulus.

Stress is the load per unit area and strain is the ratio of change in length to the original length, i.e.

$$T = \frac{P}{A}$$

$$T = \frac{P}{A} \quad e = \frac{\delta L}{L_0}$$

WHERE: P = Load
A = Area
 δL = Change in length ($L - L_0$)
 L_0 = Original length
L = Elongation due to strain

Therefore:

$$E = \frac{P/A}{\delta L/L_0} = \frac{PL_0}{\delta L}$$

Sample calculation:

If a tensile sample with a diameter of 0.220 inch and a gage length of 1.000 inch breaks at 500 pounds with a gage

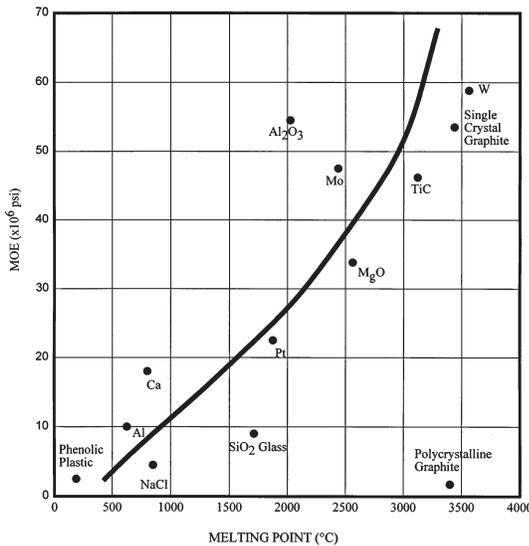


Figure 8-1. Modulus of elasticity vs. melting point for various materials

modulus results in most of the stress being carried by the higher modulus phase. Porosity which is uniformly distributed and continuous constitutes a second phase. The effect on the modulus in materials of less than 50% pore volume can be represented by the relationship:

$$E = E_0 (1 - 1.9P + 0.9P^2)$$

WHERE:

P = Porosity (volume fraction)

E_0 = Original modulus of elasticity.

length increase of 0.008 inch, the tensile MOE would be 1.6×10^6 pounds per inch².

$$E = \frac{PL_0}{\delta LA} = \frac{(500\text{lbs})(1)}{(0.008\text{in})(0.038\text{in}^2)} = 1.6 \times 10^6 \text{psi}$$

The modulus of elasticity is usually expressed in millions of pounds per square inch (10^6 psi), or in GPa in metric units.

Test Method

The standard method of measuring modulus of elasticity for graphite when not determined from samples tested in tension is described in ASTM C747 and C769. The methods are approximations derived from other properties. A more accurate, but also more difficult, means is to attach proper strain measuring gages to tensile strength samples and measure strain along with stress during a tensile test. Then, employing Hooke's law, the modulus can be calculated.

POCO Graphites vs. Conventional Graphites

The modulus of elasticity varies for the many different grades of graphite available; therefore, a significant difference in the modulus for POCO materials compared to conventional graphite is not seen (Table 8-1). The most notable difference, however, is the isotropy of POCO which assures a modulus of the same value in any direction as compared to many conventional graphites being anisotropic.

Temperature Effects

As with the other strength properties of graphite, as temperature increases, the modulus of elasticity also increases, to a point beyond which it begins to drop rapidly. This is typically around 2500°C. The increase can be as much as 25% higher before the drop begins. The final graphitization temperature also has an effect, but is relatively small.

Density Effects

The density relationship is evident with about a 15% - 20% increase in modulus detected as the density increases from 1.63 g/cm³ to 1.83 g/cm³. This follows the same pattern as other strength properties for graphite.

Modulus of Elasticity of Various Graphites			
Material	A.D.(g/cm³)	MOE(10⁶psi)	Remarks
GREAT LAKES CARBON			
H-440	1.75	1.5	Coarse Grain
HLM	1.75	1.8	Coarse Grain
H-463	1.75	1.8	Ultrafine Grain
H478	1.88	2.2	Ultrafine Grain
POCO			
EDM-1	1.63	1.3	Ultrafine Grain
EDM-2	1.68	1.4	Ultrafine Grain
EDM-3	1.74	1.5	Ultrafine Grain
PURE			
P3W	1.60	1.4	Coarse Grain
L-56	1.63	.5	Coarse Grain
P5	1.72	2.4	N/A
P03 1	.82	1.8	Medium Grain
STACKPOLE			
2161	1.66	1.3	Coarse Grain
2020	1.77	1.3	Medium Grain
2080	1.87	1.8	Medium Grain
TOYO TANSO			
SEM5	1.80	2.4	Carbon/Graphite
SEM3	1.85	1.4	Carbon/Graphite
UCAR			
AGSR	1.58	1.6	Coarse
CBN	1.67	1.8	N/A
CS	1.70	2.0 WG*	Coarse
		1.1 AG*	
ATJ	1.76	1.7	Coarse
*Shows typical anisotropy effects			

Table 8-1

Chapter 9

Electrical Resistivity

The electrical resistivity of a material is the reciprocal of its electrical conductivity and values are temperature dependant and affected by impurities. In general, electrical resistivity will not influence EDM Performance. The exceptions would be working with thin ribs and rods. Due to the limited cross sectional area of the electrode, thin ribs could overheat if the ER is too high. When small hole drilling with multiple rods, the ER should be uniform. The speed of the cut is dependent on the slowest electrode.

Definition

The electrical resistivity is that property of a material, which determines its resistance to the flow of an electrical current and is an intrinsic property. The electrical resistance of a substance is directly proportional to the length of the current path, i.e. as the current path increases, the resistance increases. It is also inversely proportional to its cross sectional area, i.e. as the area increases, the resistance decreases. The mathematical expression for the determination of electrical resistivity is:

$$ER = \frac{AR}{L}$$

- WHERE: ER = Electrical resistivity at room temperature
 A = Cross sectional area (in²)
 R = Electrical resistance of the material (Ω)
 L = Distance between potential contacts (in)

Sample calculation:

For a graphite sample with cross-sectional area of 0.25 (in)², distance between the potential contacts of 2.0 inches and an electrical resistance reading of 0.00425 (Ω); calculate the electrical resistivity.

$$ER = \frac{(0.25in^2)(0.00425ohms)}{(2.0in)}$$

ER = 0.000531 (Ω-in)
 ER = 531 (μ-Ω-in)

To convert to micro-ohm-centimeter, multiply by 2.54.

ER = 1349 (μ-Ω-cm)

Test Method

The standard method of measuring the electrical resistivity of a graphite sample is described in ASTM C611. At POCO only two resistance readings are taken, using a special sample holder with eight (8) electrical contacts which takes the equivalent of four readings at once. POCO uses TDI 4.1.1.2 (Appendix B).

POCO Graphite vs. Conventional Graphites

POCO graphites have electrical resistivity values that fall into the range of most conventional graphites. POCO graphites have a range from around 450 (μ-Ω-in) to 1050 (μ-Ω-in). This may be compared to copper, which has a range of 1.1-1.5 (μ-Ω-in) or tool steels ranging from 7.1-7.5 (μ-Ω-in). See Table 9-1 for other common material resistivities.

Temperature Effects

Electrical resistivity varies with temperature¹ (Figure 9-1). As the temperature increases from room temperature to about 700°C, the electrical resistivity decreases. From that point, however, as the temperature increases, the resistivity also increases.

Graphitization temperature also has an effect on electrical resistivity. The higher the graphitization temperature, the lower the electrical resistivity becomes, as measured at room temperature.

Density Effects

Density is a particularly important characteristic of graphite because, in addition to its inherent significance, it has a large and direct influence on other properties. As the density of POCO graphite increases, its electrical resistivity decreases (Figure 9-2).

¹Taylor, R. E., & Groot, H. Thermophysical Properties of POCO Graphite. (West Lafayette, Indiana: Purdue University, July 1978. [NTIS No. ADA060419]), p.16.

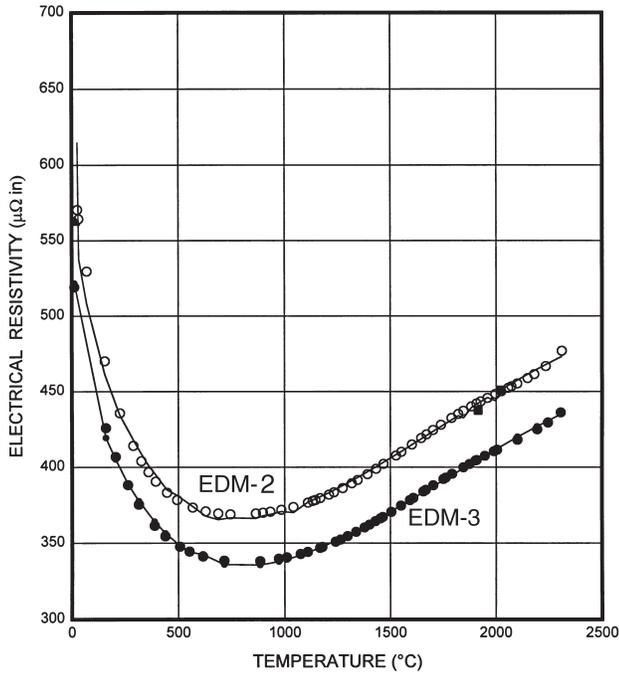


Figure 9-1. Electrical resistivity vs, temperature of POCO "Ultrafine" graphite

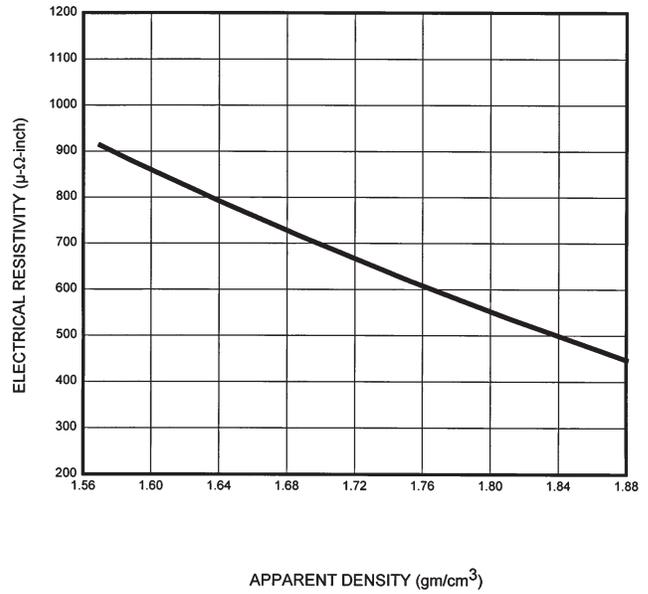


Figure 9-2. Nominal electrical resistivity vs. apparent density of POCO "Ultrafine" graphite (EDM-1, EDM-2, EDM-3, EDM-4)

Typical Electrical Resistivity of Various Materials ¹		
Material ²	Electrical Resistivity Range (microhm-inches)	Comments
POCO graphites	450 - 1000	Polycrystalline graphite
Toyo Carbon graphites	300 - 60	Polycrystalline graphite
Stackpole graphites	550 - 1200	Polycrystalline graphite
Toyo Tanso graphites	400 - 500	Polycrystalline graphite
Copper	1.1 - 1.5	Pure, wrought
Gold	0.9	Pure
Silver	0.6	Pure
Tungsten	2.2	Pure
Carbon steels	7.1 - 7.5	Hardening grades, wrought
Stainless steel	15.7 - 28.3	400 series, wrought
Cobalt base superalloys	36.6 - 74.3	Wrought
Nickel base superalloys	3.0 - 52.4	Wrought and cast
Silicon	6 X 10 ⁶	Semiconductor
Silicon carbide	4 X 10 ⁶	Semiconductor
Silicon nitride	4 X 10 ²⁰	Insulator
Alumina	> 4 X 10 ²¹	Insulator

¹Measured at room temperature in accordance with ASTM C611 and TDI 4.1.1.2.
²Select samples from each manufacturer but not all inclusive

Table 9-1

Chapter 10

Thermal Expansion

Increasing the temperature of a material causes an increase in the amplitude of vibration between atoms subsequently causing a dimensional change. The amount of dimensional change is determined from the bond strength between atoms and the atomic arrangement. Thus, the dimensional change and thermal expansion rates vary between glass, ceramics and metals. Thermal expansion is rarely a factor in EDM applications although can be detrimental if electrodes overheat and the thermal expansion causes the dimensional tolerance to be exceeded. This would be more problematic when machining with copper electrodes, which typically have ~2 times the thermal expansion as compared with graphite.

Definition

The physical dimensions of a body are determined by the number and spacing of its atoms. At temperatures above 0°K, the atoms are always in constant vibration about their positions in the lattice. If energy is added to the material (by heating it), the atoms vibrate more vigorously, causing the macroscopic dimensions of the material to increase.

The coefficient of thermal expansion (CTE) is defined as the change in length of a substance per unit length for a specific change in temperature. If this thermal expansion is hindered in any way, internal stresses will occur.

When two different materials are to be joined permanently, as in the electrical connection to an incandescent lamp or a vacuum tube, it is important that they have nearly the same values of CTE if there is to be no danger of failure from cracking. The same precaution applies to coatings or cladding of one material to another.

The CTE is normally expressed as inch per inch per °C or as inch per inch per °F; with the temperature range over which the CTE is applicable being specified. This is done because for some materials the CTE will change with temperature.

The mathematical expression for the determination of the coefficient of thermal expansion is:

$$CTE = \frac{\delta L}{L (T_2 - T_1)}$$

- WHERE: CTE = Coefficient of thermal expansion
 δL = Change in sample length from the lower temperature to the upper temperature
 L = Sample length at the lower temperature
 T₁ = Lower temperature
 T₂ = Upper temperature seen by sample

Sample calculation:

A two-inch graphite sample is heated from room temperature to 1000°C, and the length uniformly increases until it is 2.0164 inches in length at 1000°C. Calculate the CTE:

$$CTE = \frac{2.0164\text{in} - 2.0000\text{in}}{2.0000\text{in} (1000^\circ\text{C} - 23^\circ\text{C})}$$

$$CTE = 8.39 \times 10^{-6} \text{ (in/in)/}^\circ\text{C}$$

To convert to (in/in)/°F: Divide by 1.8.

$$CTE = 4.65 \times 10^{-6} \text{ (in/in)/}^\circ\text{F}$$

Test Method

The standard method of measuring the coefficient of thermal expansion of a graphite sample is similar to ASTM E228, but there is no specific method for graphite. POCO has a Netzsch DIL 402 E/7 for high temperature (RT-2000°C) studies. In addition, POCO has a vertical silica (vitreous) dilatometer for routine testing from RT-1000°C and follows TDI 4.1.1.5 (Appendix B).

POCO Graphite vs. Conventional Graphites

POCO graphites have high coefficients of thermal expansion compared to conventional materials. The coefficient of thermal expansion of POCO materials range from 7.0 x 10⁻⁶ to 9.0 x 10⁻⁶ (in/in)/°C, depending on the grade selected. These values are two to four times higher than most other graphites (Table 10-1).

Temperature Effects

As the temperature of a piece of graphite is increased, its length will increase. Figure 10-1 illustrates the thermal expansion (AL/L₀) of POCO EDM grades in the Ultrafine classification as a function of temperature. The coefficient of thermal expansion (CTE) is illustrated in Figure 10-2.

COEFFICIENT OF THERMAL EXPANSION		
MATERIAL	10 ⁻⁶ (in/in)/°C	
	HIGH	LOW
Aluminum Alloys (68-212°F)	24.1	22.3
300 Stainless Steels (32-212°F)	18.7	14.9
Copper (68-572°F)	17.6	16.7
Nickel Base Superalloys (70-200°F)	17.8	10.6
Cobalt Base Superalloys (70-1800°F)	17.1	16.2
Boron Nitride (70-1800°F)	7.5	—
Titanium Carbide (77-1472°F)	7.4	6.7
Tungsten Carbide	7.4	4.5
Silicon Carbide (0-2550°F)	4.3	3.9
Silicon Nitride (70-1800°F)	2.5	—
POCO Graphite (70-1832°F)	8.8	7.0

Table 10-1

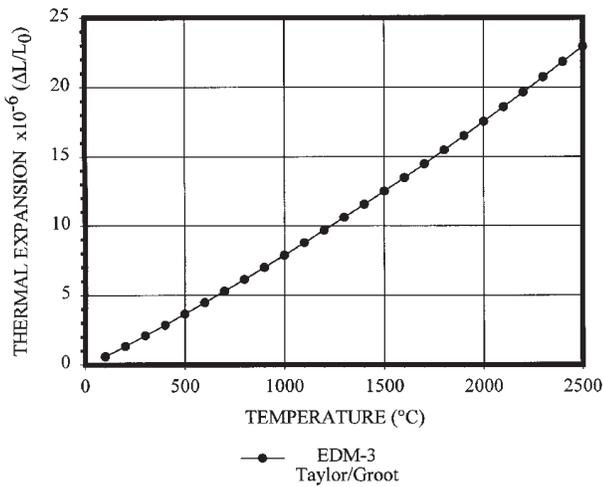


Figure 10-1. Thermal expansion vs. temperature of POCO "Ultrafine" graphite

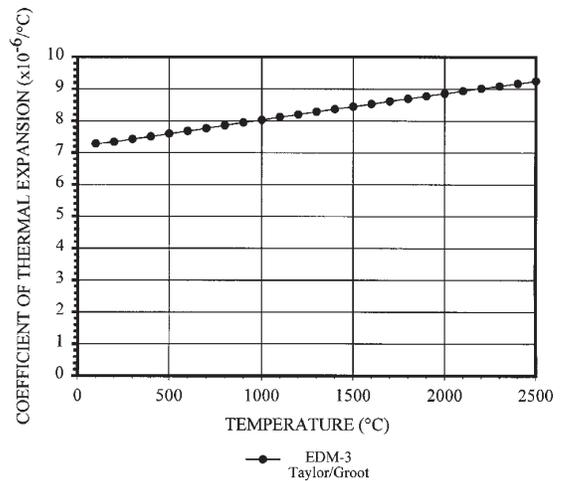


Figure 10-2. CTE vs. temperature of POCO "Ultrafine" graphite

Desity Effects

As with many other properties, the coefficient of thermal expansion changes with apparent density; as the density of the material increases, so will the coefficient of thermal expansion.

Since the higher density material has less porosity, there is less distance for the crystals to move unobstructed as the temperature is increased; therefore, higher density means greater expansion (Figure 10-3).

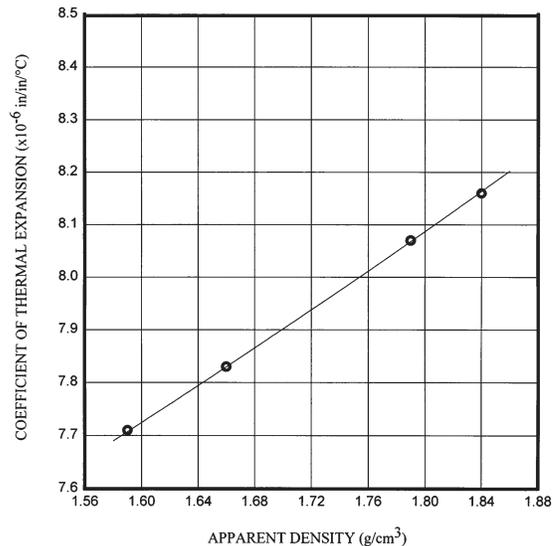


Figure 10-3. CTE vs. apparent density of POCO "Ultrafine" graphite (EDM-1, EDM-2, EDM-3 & EDM-4)

Chapter 11

Thermal Conductivity

Thermal conductivity is the rate of heat flow through a material. Work-piece metal erosion rates are affected by the work-piece thermal conductivity since the EDM erosion process is inherently a thermal process. For example, beryllium copper (BeCu) is an excellent heat sink material with a low melting point relative to tool steel, yet BeCu is more difficult to machine via EDM. High thermally conductive work piece materials may require negative polarity and significant power to obtain efficient metal erosion rates.

Definition

The thermal conductivity of a material is a measure of its ability to conduct heat. A high thermal conductivity denotes a good heat conductor, while a low thermal conductivity indicates a good thermal insulator (Table 11-1).

Typical Thermal Conductivity of Various Materials			
Material	cal/(m °C sec)	(BTU)/(hr ft °F)	(W/m °K)
Natural Rubber	0.034	0.082	0.142
Nickel	2 - 21	6 - 50	10 - 86
Steel (Wrought)	3 - 9	8 - 21	14 - 36
Silicon Carbide	4 - 10	9 - 25	16 - 43
Tungsten Carbide	7 - 21	16 - 51	28 - 88
Brass	6 - 56	15 - 135	26 - 234
Iron (Cast)	10 - 12	25 - 30	43 - 52
POCO Graphite	16 - 29	40 - 70	69 - 121
Platinum	17	42	73
Conventional Graphite	27 - 39	65 - 95	112 - 164
Aluminum	28 - 56	67 - 135	116 - 233
Tungsten	40	97	168
Copper	46 - 93	112 - 226	194 - 391
Gold	71	172	298
Silver	100	242	419

Table 11-1

The mathematical expression for thermal conductivity (K) is:

$$K = \frac{Q\partial X}{A\partial T}$$

WHERE:

- Q = Rate of heat flow through a slab in BTU per hour
- A = Cross sectional area of the slab in feet²
- ∂X = Thickness of slab in feet
- ∂T = Temperature drop across the slab (°F)

Therefore, K is expressed as:

$$\begin{aligned} & \text{(BTU ft)/(hr ft}^2 \text{ °F).} \\ & \text{or} \\ & \text{cal/(meter °C sec)} \\ & \text{or} \\ & \text{Watt/(meter °K)} \end{aligned}$$

Sample calculation:

Assume a flat plate of graphite 0.1 foot thick has a surface area of one square foot. Heat is flowing through this plate at a rate of 1000 BTU per hour; the hotter surface is at a temperature of 1036°F, while the cooler surface is at 1018°F. Calculate the thermal conductivity:

$$K = \frac{Q\partial X}{A\partial T} = \frac{(1000\text{BTU})(0.1\text{ft})}{(\text{Hr})(1\text{ft}^2)(1036^\circ\text{F}-1018^\circ\text{F})}$$

$$K = \frac{(1000\text{BTU})(0.1\text{ft})}{(\text{Hr})(1\text{ft}^2)(18^\circ\text{F})} = 55.5 \left(\frac{(\text{BTU})(\text{ft})}{(\text{hr})(\text{ft}^2)(^\circ\text{F})} \right)$$

To convert to metric system of units, multiply by 0.413 to obtain:

$$K = 22.9 \text{ cal/(meter °C sec)}$$

To convert to SI system of units, multiply by 1.73 to obtain:

$$K = 96.0 \text{ Watt/(meter °K)}$$

Test Method

Historically, two different techniques were employed for determining thermal conductivity over the temperature range of 110° - 3300°K. They are: (a) a comparative rod apparatus from 110°K to 1250°K and (b) a radial inflow apparatus from 1250°K to 3300°K. There is no standard method, associated with graphite, for measurement of thermal conductivity.

However, ASTM C714-72 is routinely used for determining thermal diffusivity and the corresponding results are used to calculate thermal conductivity. POCO deviates from ASTM C714-72 in that this standard requires the use of a flash lamp for sample heating and thermocouples for monitoring temperature. A similar technique employed by POCO utilizes a Netzsch LFA-427 (Laser Flash Apparatus), which has a high intensity laser to heat the sample surface and the resultant temperature change is monitored with an infrared detector (Figure 11-1).

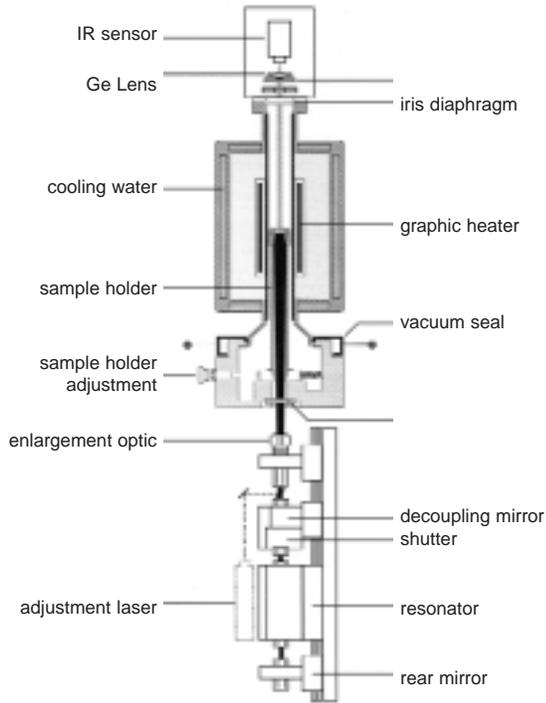


Figure 11-1. Courtesy of Netzsch Instruments, Inc.

Thermal diffusivity measurements involve quantifying the rate of diffusion of heat through a solid where local temperature and temperature gradients vary with time. This is a decided advantage in that thermal diffusivity measurements are nonsteady-state, due to the transient nature of diffusion, thus eliminating the need for determining heat flux and maintaining steady-state conditions. Nonetheless, close control of local time-temperature relationships in the system is required. Thermal diffusivity methods are also preferred over heat flux measurements due to the ease of sample preparation, less material requirements, fast measurements, and one typically obtains accuracy within $\pm 5\%$ when implementing careful measurement techniques. Thermal conductivity is calculated from the relationship:

$$K = \alpha C_p \rho$$

WHERE:

- K = Thermal Conductivity (W/cm °K)
- a = Thermal Diffusivity (cm²/sec)
- C_p = Heat Capacity at constant pressure (J/g °K)
- ρ = Apparent Density (g/cm³)

POCO Graphite vs. Conventional Graphites

From studies on POCO graphite and experimental work on other graphites, it is believed that the conductivity of most graphites is mainly governed by Umklapp type phonon-phonon interactions.

For POCO graphite and most other graphites, thermal conductivity begins to decrease around 27°C (70°F) and continues to decrease as the temperature increases to 3227°C (5800°F). Thermal diffusivity and thermal conductivity results for POCO EDM graphite grades are indicated in Figures 11-2 and 11-3, respectively, as a function of temperature from 23°-1650°C.

It has been reported that above 2727°C (4900°F) electrons contribute about 20 percent to the total thermal conductivity of these graphites. For more highly graphitized graphites and other feedstocks, the results can be different.

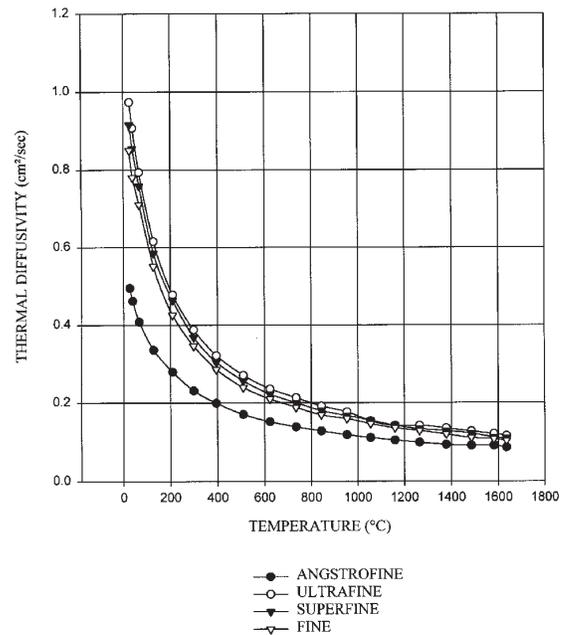


Figure 11-2. Thermal diffusivity of POCO graphites

Density Effects

The density of graphite is significant in its effect, as on the other properties. As the density of POCO graphite increases, its thermal conductivity also increases.

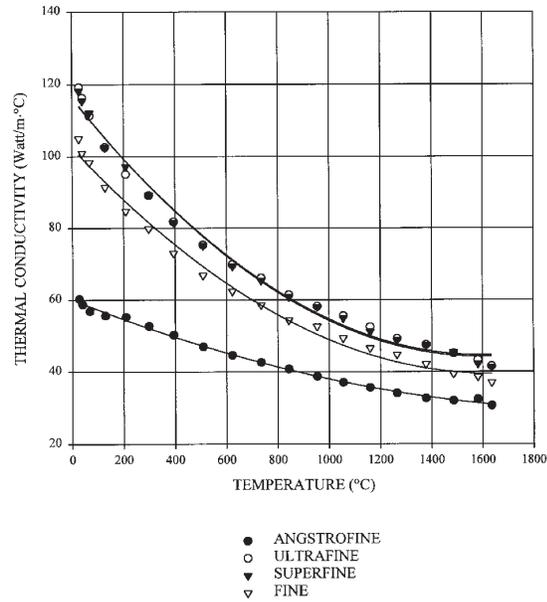


Figure 11-3. Thermal conductivity of POCO graphites

Chapter 12

Thermal Shock

Many materials often fail catastrophically due to induced stresses caused by a rapid temperature change or thermal gradients. In comparison with other materials, graphite has excellent thermal shock resistance. Perhaps this is one reason graphite is an excellent electrode material, however this has not been confirmed and requires investigation.

Definition

The ability of a material to be subjected to sudden thermal gradients without weakening or fracturing is referred to as its thermal shock resistance. The excellent resistance of graphite to thermal shock is due to a unique set of properties. High strength, low modulus of elasticity, and low coefficient of thermal expansion (CTE) are properties, which are most important. This theoretical relationship can be expressed as¹:

$$R = \frac{\sigma_f(1 - \phi)}{\alpha E}$$

(1) WHERE:

- R = Thermal shock resistance
- σ_f = Fracture stress
- ϕ = Poisson's Ratio
- α = Coefficient of thermal expansion (CTE)
- E = Modulus of elasticity

This relationship applies only when the quench is so fast that the surface temperature reaches final value before the average temperature changes.

For conditions when the heating rate is not very high, a second relationship can be established which includes thermal conductivity. This is expressed as:

$$R' = \frac{\sigma_f(1 - \phi)K}{\alpha E}$$

(2) WHERE:

- R' = Thermal shock resistance
- σ_f = Fracture stress
- ϕ = Poisson's Ratio
- K = Thermal conductivity
- α = Coefficient of thermal expansion (CTE)
- E = Modulus of elasticity

Another way to express this would be:

$$R = \frac{KT_s}{\alpha E_T}$$

(3) WHERE:

- R = Thermal shock resistance
- K = Thermal conductivity
- T_s = Tensile strength
- α = CTE
- E_T = Tensile modulus of elasticity

This expression may be a simpler form to use and consequently will be used in the sample calculation.

In either case, the typical properties of carbon and graphite generally yield the best overall thermal shock resistance of all the temperature resistant non-metallic materials available. This is useful for rocket nozzle and re-entry nose-cone applications, among others.

Sample Calculation:

A graphite sample with a thermal conductivity of 0.29 (cal cm)/(cm² sec °C) and a tensile strength of 10,000 psi (703 kg/cm²) has a modulus of elasticity of 1.6 x 10⁶ psi (0.112 x 10⁶ kg/cm²) and a CTE of 8.4 x 10⁻⁶ (in/in)/°C. Calculate its thermal shock resistance.

$$R = \frac{KT_s}{\alpha E_T} = \left(\frac{0.29 \text{ cal} \cdot \text{cm}}{\text{cm}^2 \cdot \text{sec} \cdot \text{°C}} \right) \left(\frac{703 \text{ kg}}{\text{cm}^2} \right) \left(\frac{0.112 \times 10^{-6} \text{ kg}}{\text{cm}^2} \right)$$

$$R = 216.7 \frac{\text{cal}}{\text{cm} \cdot \text{sec}}$$

Test Method

There are no standard test methods for measuring accurately the thermal shock resistance of materials. A number of practical tests are being used for specific applications. One such testing device is described by Sato². Use of the relationships described in Section I are generally

¹Kingery, W. D. J. Am. Cer. Soc., 38 (1955), p.3

²Sato, S., Sato, K., Imamura, Y., & Kon, J. Carbon, 13 (1975), p.309.

accepted for prediction of the thermal shock resistance of a material, but many other considerations must be made such as sample size, stress distribution in the material (i.e. geometry), and stress duration.

POCO Graphite vs. Conventional Graphites

Some early studies³ reported that coarse-particle graphite had better thermal shock resistance than finer particle graphite despite the higher strength of finer particle graphite. The study further indicated a correlation to the binder. If the binder were decreased, the thermal shock resistance also dropped suggesting the thermal stresses were being absorbed by the binder material. Other studies⁴ have shown the precursor material, i.e. tar coke versus oil coke, to have effects on the thermal shock resistance. The oil coke had resistance values about seven (7) times higher than the tar coke.

Generally, due to small particle size and high CTE, POCO may not fare as well as some other graphites in overall thermal shock resistance. Tests at POCO have shown that samples of the Ultrafine, measuring one inch cubed, can survive a 1000°C to 10°C instantaneous change without fracturing in repeated tests. Other tests on POCO graphites have subjected the samples to 335°F to -335°F instantaneous changes without affecting the graphite. A comparison of some thermal shock resistance values for some materials is shown in Table I.

THERMAL SHOCK RESISTANCES		
		$\frac{cal}{cm \cdot sec}$
Titanium Carbide		3.45
Stackpole graphite	(2020)	140
POCO graphite:	(Ultrafine)	217
	(Angstrofine)	233
Ringsdorff graphite:	(EK-82)	252
	(EK-87)	426
UCAR	(ATJ)	329
Toyo Tanso graphite	(Isograph 88)	340
GLC	(Graphnol)	450
Pyrolytic graphite:	(w/grain)	4300
	(a/grain)	0.29

Table I

While the differences are not as great between the various grades as the pyrolytic graphite shows between orientations, it should still be noted that processing vari-

³Kennedy, A. J. Graphite as a Structured Material in Conditions of High Thermal Flux. (Cranfield: The College of Aeronautics, November 1959. [CoA Report No. 121]), p.15.

⁴Sato, S., Hwaji, H., Kawamata, K., & Kon, J. "Resistance and Fracture Toughness Against Thermal Shock of Several Varieties of Graphite." The 22nd Japan Congress on Materials Research - Metallic Materials. (Mito, Japan: March 1979.), 67-68.

ables, starting materials, etc. can influence the thermal shock resistance of graphite. For example, the Ringsdorff EK-87 grade has an average particle size of 20 microns, yet calculated thermal shock resistance is ~23% higher than UCAR ATJ indicating an average particle size of 25 microns. Ringsdorff EK-87 has nearly twice the calculated thermal shock resistance compared with POCO Ultrafine graphite indicating mean particle size of 4 microns.

Temperature Effects

Depending on the type of graphite used and its particular characteristics or properties, and considering shape, size, etc., higher temperature drops could be sustained without affecting the graphite. The temperature starting and ending points may have some bearing on the overall resistance to fracture, because the material will be thermally stressed differently at elevated temperatures. A drop from 1000°C to 500°C may respond differently than from 500°C to 0°C. Little data is available to clearly define what the relationship or limits are for the different types of graphite.

Density Effects

Since generally, strength and thermal conductivity increase with density, higher thermal shock resistance should be found in higher density ranges. However with higher density, higher modulus and CTE are also usually found and these would tend to offset the gains in strength. If the early studies noted in Section III are valid, the coarser particle systems may be more effective than the finer particle systems on an equal density basis. Many factors are involved and well defined tests to measure these effects are not in common use.

Chapter 13

Heat Capacity

Heat applied to water increases its temperature and the amount of heat absorbed in raising the temperature of water 1° under constant pressure is called the water's heat capacity at constant pressure and is often reported in units of cal/(g • °C). Heat capacity is often incorrectly termed specific heat where specific heat is the ratio of the heat capacity of a material to the heat capacity of water, consequently having no units. The confusion between heat capacity and specific heat generally comes from the fact that these values are essentially the same since the heat capacity of water is ~1.0.

Definition

Heat capacity is the quantity of heat required to raise the temperature of a unit mass of material 1°, and the relationship between the two most frequently used units is as follows:

$$1 = \frac{BTU}{lb \cdot ^\circ F} = 1 \frac{cal}{g \cdot ^\circ C}$$

It has been found that the values of heat capacity for all types of natural and manufactured graphites are basically the same, except near absolute zero temperatures. The differences found in measuring the same grade of graphite are as great as the differences in measuring different grades of graphite. Differences as much as nine (9) percent have been found between natural graphite and manufactured graphite at low temperatures (120°K to 300°K), but at higher temperatures the differences for all types of graphite has been found to be less than the experimental error. Table 13-1 shows comparisons to other materials.

Typical Specific Heat of Various Materials		
Material	Heat Capacity Range cal/(g • °C)	Heat Capacity Range J/(g • °K)
Gold	0.031	0.13
Platinum	0.031	0.13
Tungsten	0.034	0.14
Tungsten Carbide	0.04	0.17
Silver	0.056	0.23
Brass	0.090	0.38
Nickel	0.091 - 0.14	0.38 – 0.59
Copper	0.092	0.38
Steel (Wrought)	0.11	0.46
Iron (Cast)	0.13	0.54
Graphite	0.17	0.72
Alumina	0.19	0.79
Aluminum	0.22 - 0.23	0.92 – 0.96
Silicon Carbide	0.285 - 0.34	1.19 – 1.42

Table 13-1

Heat Capacity Equation

The heat capacity at constant pressure (C_p) can be expressed by polynomial functions of the absolute temperature T, with T in °K to give C_p in cal/(g • °C).

Within the temperature interval 0°K to 300°K:

$$C_p = (0.19210 \times 10^{-4})T - (0.41200 \times 10^{-5})T^2 - (0.10831 \times 10^{-7})T^3 - (0.10885 \times 10^{-10})T^4$$

However, below 40°K, this equation has not been reliable in correlation with experimental data. The calculated values are in good agreement (< 2.2 percent) with the experimental values for temperatures above 40°K.

For the temperature range 300°K to 3200°K:

$$C_p = 0.44391 + (0.30795 \times 10^{-4})T - (0.61257 \times 10^{-5})T^2 + (0.10795 \times 10^{-8})T^3$$

This expression yields calculated values within 1.5 percent of the experimental values for the entire temperature range.

Table 13-2 represents the best fit of the values for typical manufactured graphite with proper consideration given to the accuracy of the individual measurements.

Sample Calculation:

Determine the heat capacity of a sample of graphite at 500°C using a differential scanning calorimeter (DSC) and a strip chart recorder to follow the calorimetric response for the temperature scans of 30°C. DSC scans are taken for the sample of graphite, a sapphire reference sample and the baseline for correction of the measured response. The heat capacity, C_p, then is calculated for the graphite using the formula:

$$C_p(\text{graphite}) = \frac{W_S}{W_G} \times \frac{D_S}{D_G} \times C_p(\text{sapphire})$$

WHERE:

- W_S = Weight of Sapphire
- W_G = Weight of Graphite
- D_S = Signal Displacement of Sapphire
- D_G = Signal Displacement of Graphite

Typical Specific Heat of Manufactured Graphites		
Temperature	Heat Capacity cal/(g•°C)	Heat Capacity J/(g•°K)
0	0.0000	0.0000
50	0.0101	0.0423
100	0.0335	0.1402
150	0.0643	0.2690
200	0.0995	0.4163
250	0.1357	0.5678
300	0.1723	0.7214
350	0.2090	0.8750
400	0.2450	1.0258
450	0.2760	1.1556
500	0.3030	1.2686
550	0.3230	1.3523
600	0.3400	1.4235
650	0.3560	1.4905
700	0.3700	1.5492
750	0.3820	1.5994
800	0.3930	1.6454
850	0.4020	1.6831
900	0.4090	1.7124
950	0.4150	1.7375
1000	0.4210	1.7626
1100	0.4320	1.8087
1200	0.4430	1.8547
1300	0.4520	1.8924
1400	0.4600	1.9259
1500	0.4680	1.9594
1600	0.4740	1.9845
1800	0.4860	2.0348
2000	0.4960	2.0766
2200	0.5040	2.1101
2400	0.5110	2.1394
2600	0.5160	2.1604
2800	0.5210	2.1813
3000	0.5270	2.2064
3200	0.5360	2.2441
3400	0.5480	2.2944
3600	0.5800	2.4283
3800	0.6900	2.8889

Table 13-2

Let the weight of the sapphire reference = 0.203 g and a sample of Ultrafine graphite, i.e. indicating a density of 1.82 g/cm³ and measuring 1.5 mm x 6 mm diameter, weigh 0.077 g, respectively. C_p of sapphire is 0.19 cal/(g °C). C_p of graphite at 500°C can be calculated by knowing the displacement as determined from the strip chart recorder.

Assume the displacement (corrected) is 40.0 for the graphite and 52.5 for the sapphire reference.

Therefore:

$$C_P(\text{graphite}) = \frac{0.023g}{0.077g} \times \frac{40.0}{52.5} \times 0.19 \frac{\text{cal}}{g \cdot ^\circ\text{C}}$$

$$C_P(\text{graphite}) = 0.382 \frac{\text{cal}}{g \cdot ^\circ\text{C}} = 1.60 \frac{\text{J}}{g \cdot ^\circ\text{K}}$$

Test Method

The previous example best illustrates how a differential scanning calorimeter (DSC) and a chart recorder may be used in determining heat capacity. However, modern technology has integrated the DSC with computer and software technology thereby eliminating the need for calculating C_p from a chart recorder. Poco Graphite, Inc. currently uses a Netzsch STA-449 Heat Flux DSC for evaluating graphite and other related materials, reference Figure 13-1. Heat capacity calculations are made via software but the fundamental principles remain the same.

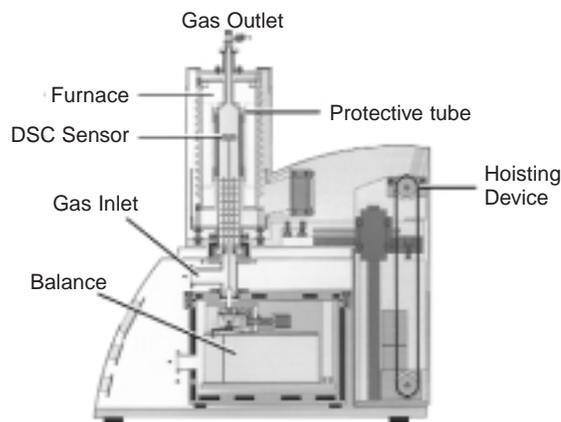


Figure 13-1. Netzsch STA-449

In DSC, a distinction must be made between the recorded baseline in the presence and absence of a sample. Thus, measurements are first taken with an empty sample crucible to determine the instrument baseline. A second run is made to verify the accuracy of the instrument by placing a sapphire reference sample in the sample crucible and taking measurements under the same experimental conditions. The DSC curve rises linearly resulting from the change in heat capacity of the sample as a function of temperature. Sapphire is routinely used as a reference material since it is stabilized, i.e. will not oxidize, and due to the fact that heat capacity for sapphire has been thoroughly investigated and well documented. Once the baseline and accuracy have been established, a third run is made on the sample of interest under the same experimental conditions.

There is no standard test method for determining heat capacity of graphite, but the DSC method is commonly used for heat capacity determination of other materials.

Another simple method which yields approximate heat capacity data is an ice calorimeter. If a body of mass (m) and temperature (t) melts a mass (m') of ice, its temperature being reduced to 0°C, the heat capacity of the substance is:

$$S = \frac{80.1m'}{mt}$$

POCO Graphite vs. Conventional Graphites

POCO graphites have heat capacity values that are in the same range as conventional manufactured graphites. POCO graphites have a range from around 0.72 J/(g·°K) to 1.60 J/(g·°K) between 20° and 500°C (see Figure 13-2¹).

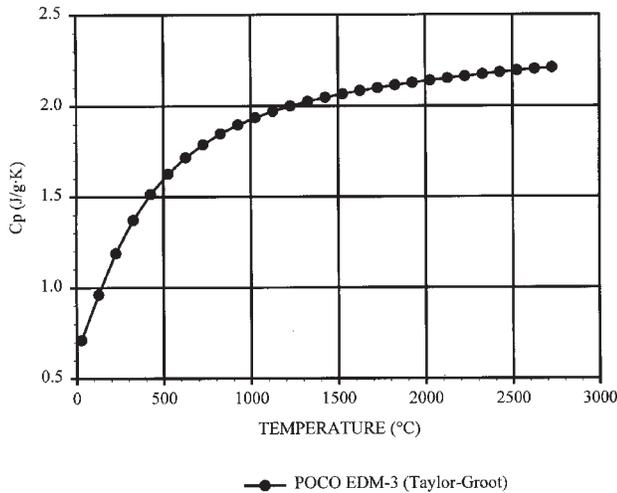


Figure 13-2. Specific heat vs. teperature POCO Graphite

Temperature Effects

The heat capacity of manufactured graphite increases with increasing temperature (Figure 13-3).

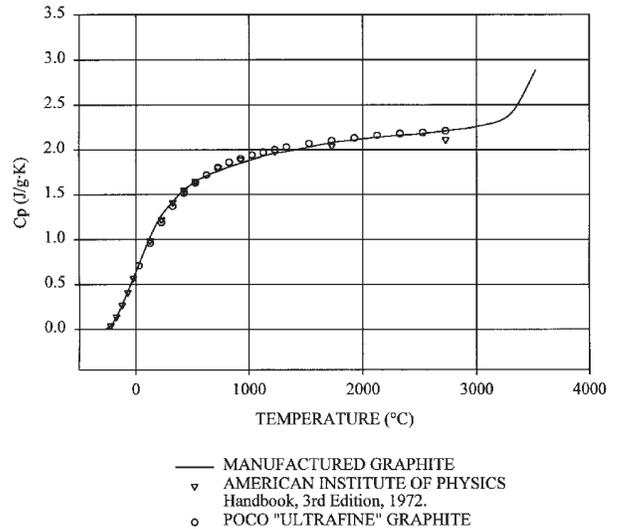


Figure 13-3. Specific heat of manufactured graphite

Density Effects

Heat capacity has no significant change as a function of density. It is intrinsic to the graphite crystal itself and apparently independent of density.

¹Taylor, R. E., & Groot, H. Thermophysical Properties of POCO Graphite. (West Lafayette, Indiana: Purdue University, July 1978. [NTIS No. ADA060419]), p.15.

Chapter 14

Emissivity

There are some applications, particularly in aerospace, requiring materials that can effectively emit radiation. Graphite is well suited due to its unique properties and high temperature applications, although there are no known benefits or requirements in EDM applications for high emissivity.

Definition

A measure of the heat radiating ability of a surface is referred to as emissivity. Total emissivity or spectral emissivity are ways to express it. The total emissivity is defined as the ratio of thermal energy emitted by a material per unit time per unit area to that emitted by a black body over the entire band of wavelengths when both are at the same temperature. A black body, i.e. ideal radiator, is one which absorbs all the radiant energy falling on it and at a given temperature radiates the maximum amount of energy possible over the entire spectrum of wavelengths.

The spectral emissivity is defined as the ratio of thermal energy emitted by a material per unit time per unit area to that emitted by a black-body reference where radiation from both are of the same wavelength and both are at the same temperature. The spectral emissivity of graphite has been measured at 6500 Å. Dull surfaced graphite and polished graphite have had typical values of 0.90 and 0.77, respectively. It has been determined that the emissivity of graphite does vary slightly with temperature. A temperature coefficient of $1.9 \times 10^{-5}/^{\circ}\text{K}$ has been determined. Graphite emissivity has been found to be nearly constant in the wavelength range 2000 Å to 60,000 Å. Spectral emissivity values approaching 0.99 have been measured for graphite near sublimation temperatures of 3600°K. For a specific temperature, at a specific wavelength, normal spectral emissivity can be expressed as:

$$E_{n,\lambda} = \frac{W_{S,\lambda}}{E_{BB,\lambda}}$$

WHERE:

$W_{S,\lambda}$ = Normal spectral radiant energy emitted by a specimen material per unit time, unit area, and unit solid angle.

$W_{BB,\lambda}$ = Normal spectral radiant energy emitted by a black-body reference per unit time, unit area, and unit solid angle.

Normal spectral emissivity written as a function of temperature is:

$$\log E_{n,\lambda} = \frac{C}{2.303\lambda\alpha} \left[\frac{1}{T} - \frac{1}{T_{A,\lambda}} \right]$$

WHERE:

- C = 14,380 micron - °K
- L = 0.65 micron
- T = Temperature of material (°K)
- $T_{A,\lambda}$ = Apparent temperature of material (°K)

For a specific temperature the total normal emissivity can be expressed as:

$$\log E_{n,\lambda} = \frac{W_S}{E_{BB}}$$

WHERE:

- W_S = Normal total radiant energy emitted by a specimen material per unit time, unit area, and unit solid angle.
- W_{BB} = Normal total radiant energy emitted by a black-body reference per unit time, unit area, and unit solid angle.

Total normal emissivity at elevated temperatures can be expressed as:

$$E_{n,t} = \frac{T_{A,t}^4}{T^4}$$

WHERE:

- T = Temperature of material (°K)
- $T_{A,t}$ = Apparent temperature of material (°K)

Emissivity data has usefulness in applications such as aerospace, heaters, pyrometry, etc., but published data is difficult to find.

Test Method

There are no standard methods for measuring emissivity

of graphite, but one method used to measure the emissivity of graphite is described by Grenis and Levitt¹. A schematic of this equipment can be seen in Figure 14-1. The methods of measuring emissivity are wrought with difficulties and results may be biased due to equipment and/or assumptions made

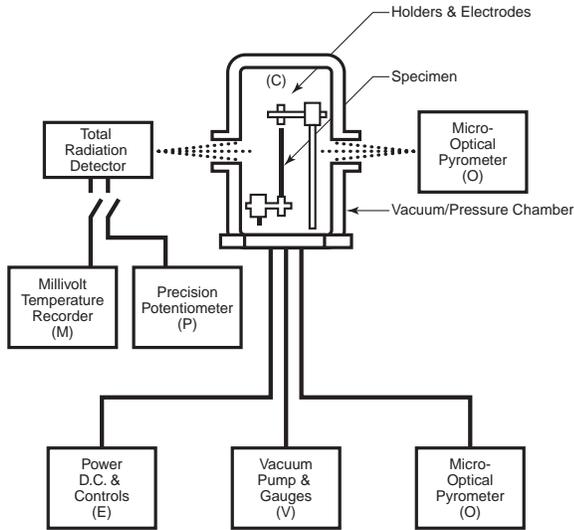


Figure 14-1. Schematic block diagram of the emissivity apparatus

in running the tests. At best, the testing is at a research level and not a routine procedure.

POCO Graphites vs. Conventional Graphites

Very little information on the emissivity of graphite is available. The following information on total emittance of two grades of POCO graphite and pyrolytic graphite has been reported by Cezairliyan and Righini².

The equation for POCO EDM-3 graphite, between 1,700° to 2,900°K is:

$$E = 0.794 + (2.28 \times 10^{-5})T$$

The equation for pyrolytic graphite, between 2,300° to 3,000°K is:

$$E = 0.641 - (5.70 \times 10^{-5})T$$

WHERE:

T is in °K.

The measured values of the total emittance of the graphite specimens are shown in Table 14-1 and again graphically in Figure 14-2.

Total Emittance		
Temperature (°K)	Poco EDM-3	Pyrolytic Graphite
1,700	0.833	—
1,800	0.835	—
1,900	0.837	—
2,000	0.840	—
2,100	0.842	—
2,200	0.844	—
2,300	0.846	0.510
2,400	0.849	0.504
2,500	0.851	0.499
2,600	0.853	0.493
2,700	0.856	0.487
2,800	0.858	0.481
2,900	0.860	0.476
3,000	—	0.470

Table 14-1

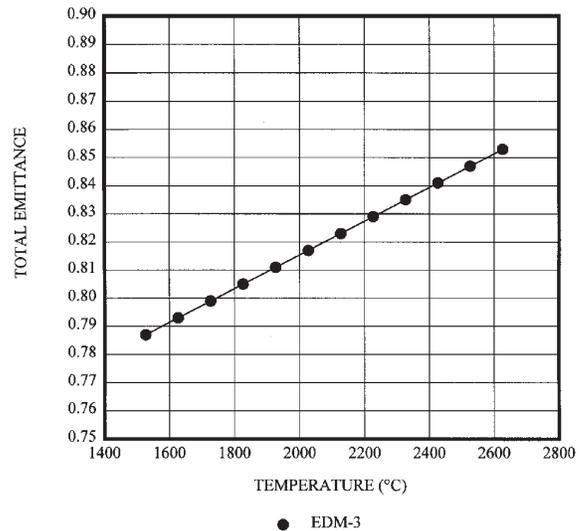


Figure 14-2. Total emittance of POCO graphite

The differences may be associated with layer plane orientation or other crystallographic effects particularly when comparing a pyrolytic graphite to a polycrystalline graphite such as EDM-3.

¹Grenis, A. F. & Levitt, A. P. The Spectral Emissivity and Total Normal Emissivity of Graphite at Elevated Temperatures. (Watertown, Mass.: Watertown Arsenal Laboratories, November 1959. [NTIS No. ADA951659]), p. [14].

²Cezairliyan, A. & Righini, F. "Measurements of Heat Capacity, Electrical Resistivity, and Hemispherical Total Emittance of Two Grades of Graphite in the Range of 1500° to 3000°K by a Pulse Heating Technique," Rev. int. Htes Temp. et Refract., t.12 (1975), p. 128.

Chapter 15

Ash

The level of impurity is significant in semiconductor applications in order to avoid cross contamination in their processes. Consequently, post processing purification runs may be required. This is not the case in EDM grade graphites.

Definition

ASTM C709 defines ash of manufactured carbon and graphite as the “residual product following oxidation of the base carbon as determined by prescribed methods”. This ash or residual product generally results from natural contamination of the raw material used to produce graphite and may be introduced to a lesser extent during processing of the raw material or graphite products. Table 15-1 shows a general listing of typical elements and their level of contamination in graphite bulk product. As will be discussed later, there are means by which the contamination can be reduced or removed.

Typical Purity Analysis Standard Poco Grades Total Ash Range 300-1000 PPM		
Element	Element Detected	PPM Range
Vanadium (V)	Yes	100 - 500
Iron (Fe)	Yes	5 - 300
Nickel (Ni)	Yes	1 - 100
Calcium (Ca)	Yes	5 - 100
Silicon (Si)	Yes	5 - 50
Aluminum (Al)	Yes	10 - 50
Titanium (Ti)	Yes	1 - 50
Potassium (K)	Yes	1 - 20
Sodium (Na)	Yes	1 - 15
Copper (Cu)	Yes	1 - 10
Magnesium (Mg)	Yes	1 - 5
Chromium (Cr)	Yes	Trace to 10
Phosphorus (P)	Yes	Trace to 10
Boron (B)	Yes	1 - 5
Sulfur (S)	Yes	1 - 5
Molybdenum (Mo)	Yes	Trace
Zinc (Zn)	Yes	Trace
Lithium (Li)	Yes	Trace

Table 15-1

Test Method

The standard test method for ash content of graphite is ASTM C561. This technique applies principally to nonpurified graphites of several hundred parts per million (ppm), or

more, of total impurities. The method is generally too crude for good reproducibility on high purity samples.

One of the disadvantages of this method is the potential loss of low melting point impurities due to the temperature at which the test is run. Theoretically, at 950°C as a final test temperature, nothing should be lost that was not already volatilized during graphitization, but as a practical matter, it seems to occur. These are possibly impurities trapped in closed pores that did not successfully escape during the graphitization cycle. The test temperature could be lowered to preclude some of this from occurring, but then the time to complete the test is extended considerably as oxidation is a time-temperature dependent reaction.

It has also been found in previous studies that at higher temperatures (desirable for shorter test cycles), reactions of carbon and platinum, of which the crucibles are made, can occur and consequently bias the test results.

POCO's method, TDI 4.1.1.6 (Appendix B), differs slightly from the ASTM procedure, in that a solid sample is used rather than a powdered sample. The risk of contamination in powdering the sample is nonexistent if a solid sample is used. A standard test cycle for nonpurified material is 24 hours, whereas, a purified material usually takes 48-72 hours to complete the cycle.

Sample calculation:

If a graphite sample weighed 80.0000 grams after drying and was ashed in a 35.0000 grams crucible where the total ash after testing was 0.4 milligrams, the total ash would be 5 ± 1 parts per million.

$$Ash(ppm) = (C - A) / (B - A) \times 1,000,000 = \frac{35.0004 - 35.000}{115.0000 - 35.000} \times 1,000,000 = 5 \pm 1 ppm$$

WHERE:

- A = Crucible weight
- B = Crucible plus dried sample weight
- C = Crucible plus ash weight

If ash % is required, multiply by $\frac{C-A}{B-A} \times 100$.
 Ash % = $0.0005 \times \frac{C-A}{B-A}$

POCO Graphites vs. Conventional Graphites

When discussing nonpurified graphites, POCO graphites are fairly clean, i.e. contain relatively low levels of impurities. However, since graphitization temperature has a strong bearing on the impurities which remain, the ash levels on any product can vary accordingly. There are other process steps which influence the final ash level also.

In material which has been impregnated for densification, contaminants in the raw material used could increase the impurity content as well.

POCO graphites will typically range from 300 - 3000 ppm total impurities, depending on the grade and density. Many conventional graphites fall within this range also, but some will be in the range of 0.1% (1,000 ppm) to several percent (20,000 - 30,000 ppm).

Purified POCO graphite will have less than 5 ppm total impurities. This is one of the best grades of purified graphite available anywhere. The unique nature of the POCO pore structure and relatively clean raw materials aids in allowing this ultra high purity. Typical analysis of a purified POCO graphite is seen in Table 15-2. Purified graphites can be produced in several ways. Simply heat treating to very high

temperatures, usually in excess of 3000°C, will volatilize most heavy elements present. Halogen gases, such as chlorine or fluorine will react with the impurities at high tem-

perature and volatilize off as chloride or fluoride salts. Some elements such as boron are very stable and difficult to remove, especially since they can substitute for carbon atoms in the crystal structure.

Temperature Effects

The only real temperature effect on ash levels comes from the graphitization temperature or a subsequent thermal processing to remove impurities. As mentioned previously, the higher the final thermal treatment, the lower the ash level will usually be.

Density Effects

In POCO graphite, a slight trend has been noted with ash as related to density. Since POCO graphites have increasingly more open porosity as the density decreases, more opportunity for volatilization escape of the impurities during graphitization can occur. Consequently, slightly lower ash levels are typically found for the lower density grades. This may be unique to POCO graphites. The difference is relatively small though, so it is mentioned only in passing as a number of other factors may have more significant effects on the final ash level.

Typical Purity Analysis		
Purified POCO Grades Total Ash Range		
5 PPM or Less		
Element	Element Detected	PPM Range
Silicon (Si)	Yes	Trace to 5
Sulfur (S)	Yes	Trace to 5
Vanadium (V)	Yes	Trace to 5
Calcium (Ca)	Yes	Trace to 5
Boron (B)	Yes	Trace to 5
Aluminum (Al)	Yes	Trace to 5
Magnesium (Mg)	Yes	Trace to 5
Iron (Fe)	Yes	Trace to 5
Molybdenum (Mo)	Yes	Trace
Phosphorus (P)	Yes	Trace
Nickel (Ni)	No	-----
Titanium (Ti)	No	-----
Potassium (K)	No	-----
Sodium (Na)	No	-----
Copper (Cu)	No	-----
Chromium (Cr)	No	-----
Zinc (Zn)	No	-----
Lithium (Li)	No	-----

Table 15-2

Chapter 16

Oxidation

Oxidation does not present a problem during the EDM machining operation. However, there are instances in which one is required to remove moisture in the form of dielectric fluid, or deionized water in the case of Wire EDM (WEDM). The recommended "bake-out" procedure is to place the electrode sample in an oven at 100°C (or 212°F) for at least eight hours in order to remove residual moisture within the porosity, and not to exceed ~175°C (~350°F) for 8 hours to avoid oxidation of non-purified material.

Definition

Oxidation is a chemical reaction that results in electrons being removed from an atom which makes the atom more "reactive", so that it may join with one or more other atoms to form a compound. When talking about carbon and graphite, oxidation is normally thought of as the reaction of carbon atoms with oxygen to form carbon monoxide (CO) and carbon dioxide (CO₂). However, many other gases (besides oxygen) will react with carbon in an oxidation reaction (i.e., CO₂, H₂O, N₂O, etc.). The result of the oxidation reaction is a loss of carbon atoms from the carbon or graphite material, which obviously affects many of its properties and characteristics. If a piece of carbon is allowed to oxidize over an extensive period of time, all the carbon atoms will react to form a gas (or gases) and dissipate leaving nothing behind except for residual ash. The ash is a by-product of metallic impurities, previously held in the carbon, which combined with oxygen to form metallic oxides.

The oxidation of carbon by oxygen (as well as other gases) is highly temperature dependent. No detectable reaction occurs at temperatures up to about 350°C. As the temperature is increased, the rate of reaction increases rapidly, according to the well known Arrhenius expression:

$$\ln K \propto E/RT$$

WHERE:

- T = Temperature
- E = Activation Energy
- K = Reaction rate
- R = Universal Gas Constant

Test Method

To measure the oxidation characteristics of a particular carbon material, a piece of known weight is exposed to the "oxidizing environment" of interest for some period of time, and then reweighed, to determine a weight loss (the oxidation weight loss). There is not a widely accepted standard test for measuring the oxidation characteristics of carbon materials (TDI 4.1.1.7 in Appendix B).

The oxidation characteristics of carbon are usually

expressed in one of two different ways: (1) the percent weight loss in 24 hours at a given temperature, or (2) the temperature at which a sample loses approximately 1% of its weight in a 24-hour period, which is called the oxidation threshold temperature of the material being tested.

Sample calculation:

If a sample originally weighed 10.0000 grams after being dried and 9.9900 grams after oxidation testing, the percent weight loss would be 0.1%.

$$\% WT_L = \frac{WT_O - WT_F}{WT_O} \times 100 = \frac{10.0000 - 9.9900}{10.0000} \times 100 = 0.1\%$$

WHERE:

- WT_O = Initial sample weight (dried).
- WT_F = Sample weight after oxidation testing %.
- WT_L = Percent weight loss.

POCO Graphites vs. Conventional Graphites

The oxidation characteristics of any graphite at the same temperature and atmospheric conditions is dependent on the amount of impurities in the material, the density of the material and the amount of surface area available to react with the oxidizing atmosphere. POCO graphites can be impregnated with a proprietary oxidation inhibitor that can substantially increase its oxidation resistance. Purification also reduces oxidation significantly by removing metallic impurities which act as oxidation catalysts.

As the surface area increases, the oxidation rate increases, too. This is expected as the surface exposure is important to the oxidation process. For purposes of standardization and to minimize the effect of variable SA/V ratios, the use of a sample with a SA/V ratio of 10:1 is used at POCO for testing oxidation rates.

Temperature Effects

The differences in oxidation behavior of the various grades of graphite are widest at the lowest temperatures, tending to disappear as the temperature increases. The "oxidation threshold temperature", defined as that at which a sample loses approximately one percent of its weight in 24

hours, is about 570°C for purified graphite, while nonpurified graphite is about 430°C (Figure 16-1)

The oxidation of graphite is highly temperature dependent. At temperatures up to about 350°C no detectable oxidation occurs. As the temperature is increased, the rate of reaction increases rapidly, according to the Arrhenius equation (Figure 16-2).

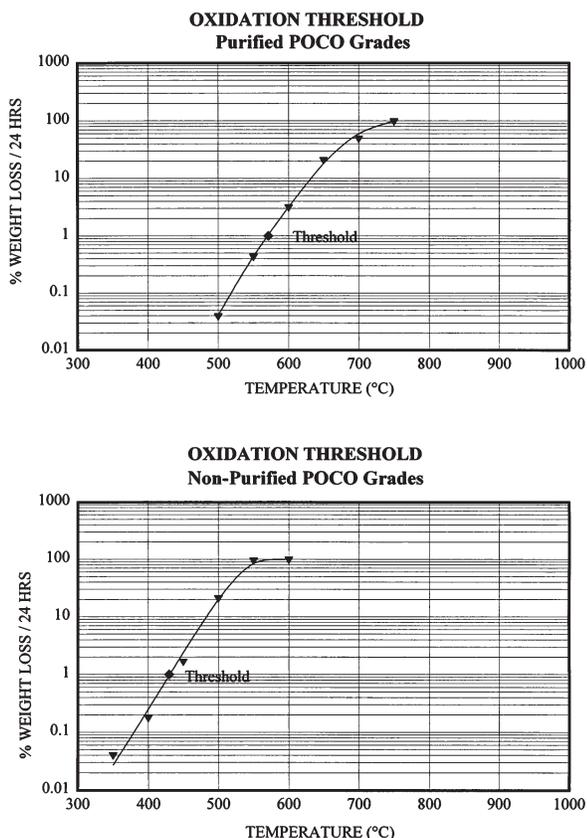


Figure 16-1

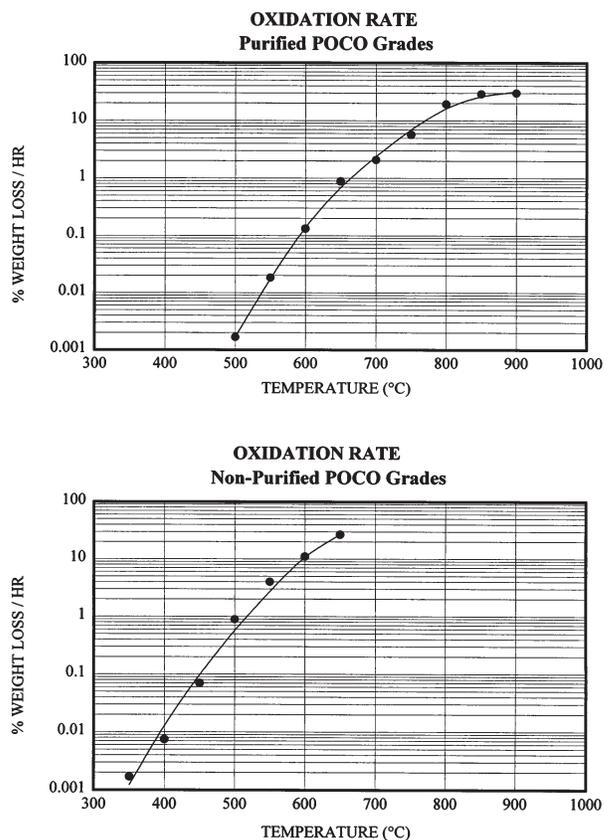


Figure 16-2

Density Effects

Since the oxidation of graphite is a surface reaction, it is known that the rate of oxidation is affected by the porosity of the material. As the percent porosity increases, the apparent density of the material will decrease. Therefore, as the apparent density decreases, the rate of oxidation will increase. However, the effects of impurities and their catalytic action can easily override the density effects. Purified data shows the density difference more clearly, but it is, nevertheless, relatively small when other factors are considered.

APPENDIX A

PREFIX CONVERSION FACTORS		
Prefix	Symbol	Unit Multiplier
giga	G	10^9
mega	M	10^6
kilo	K	10^3
deci	d	10^{-1}
centi	c	10^{-2}
milli	m	10^{-3}
micro	μ	10^{-6}
nano	n	10^{-9}
pico	p	10^{-12}

DENSITY CONVERSION FACTORS		
From	To	Multiply By
g/cm^3	lb/in^3	0.03613
g/cm^3	lb/ft^3	62.428
g/cm^3	kg/m^3	1,000
g/cm^3	g/m^3	1,000,000
lb/in^3	g/cm^3	27.6799
lb/in^3	kg/m^3	27,679.905
lb/ft^3	g/cm^3	0.016
lb/ft^3	kg/m^3	16.0185

LENGTH CONVERSION FACTORS		
From	To	Multiply By
inch	ft	0.0833
inch	m	0.0254
inch	cm	2.54
inch	mm	25.4
feet	in	12.0
feet	m	0.3048
feet	cm	30.48
feet	mm	304.8
centimeter	m	0.01
centimeter	mm	10.0
centimeter	μ	1.0×10^4
microns (μ)	cm	1.0×10^{-4}
microns (μ)	in	3.937×10^{-5}
microns (μ)	ft	3.281×10^{-6}
microns (μ)	m	1.0×10^{-6}
microns (μ)	Å	1.0×10^4
Angstroms (Å)	m	1.0×10^{-10}

STRENGTH CONVERSION FACTORS		
Pressure:		
From	To	Multiply by
lb/in^2	lb/ft^2	144.0
lb/in^2	g/cm^2	70.307
lb/in^2	kg/cm^2	0.0703
lb/in^2	kg/m^2	703.07
lb/ft^2	lb/in^2	6.94×10^{-3}
lb/ft^2	g/cm^2	0.4882
lb/ft^2	kg/m^2	4.8824
kg/m^2	lb/ft^2	0.2048
kg/m^2	lb/in^2	1.422×10^{-3}
kg/m^2	g/cm^2	0.10
kg/cm^2	lb/in^2	14.223
g/cm^2	kg/m^2	10.0
g/cm^2	lb/in^2	0.01422
N/mm^2 (= MPa)	lb/in^2	145.032
N/mm^2 (= MPa)	kg/m^2	101.972×10^3
MN/m^2	MPa	1
N/m^2	lb/in^2	1.45×10^{-4}

ELECTRICAL RESISTIVITY CONVERSION FACTORS		
From	To	Multiply by
Ohm-inch (Ω in)	y cm	2.54
Ohm-inch	y m	0.0254
Ohm-inch	y ft	0.3333
Ohm-inch μ	y in	1.0×10^6
Ohm-feet	y in	12.0
Ohm-feet	y cm	30.48
Ohm-feet	y m	0.3048
Ohm-centimeter	y in	0.3937
Ohm-centimeter	μ y in	393.7×10^3
Ohm-centimeter	y ft	0.0328
Ohm-centimeter	y m	0.01
Ohm-meter	y in	39.37
Ohm-meter	y ft	3.281
Ohm-meter	y cm	100.0
Ohm-millimeter ² /meter	y m	1.0×10^{-6}
Ohm-millimeter ² /meter	y cm	1.0×10^{-4}

COEFFICIENT OF THERMAL EXPANSION		
From	To	Multiply by
(in/in)/°C	(in/in)/°F	0.5556
1/°C	1/°F	0.5556
(in/in)/°F	(in/in)/°C	1.80
1/°F	1/°C	1.80

Conversion constant for 1/°C to 1/°F and 1/°F to 1/°C are true for any dimensional unity, i.e. in/in, cm/cm, ft/ft, m/m.

THERMAL CONDUCTIVITY CONVERSION FACTORS		
From	To	Multiply by
(Btu ft)/(ft ² hr °F)	(cal cm)/(cm ² sec °C)	4.134 X 10 ⁻³
(Btu ft)/(ft ² hr °F)	(Kcal cm)/(m ² hr °C)	148.8
(Btu ft)/(ft ² hr °F)	(kilowatt hr in)/(ft hr °F)	3.518 X 10 ⁻³
(Btu ft)/(ft ² hr °F)	(Btu in)/(ft ² hr °F)	12.00
(Btu ft)/(ft ² hr °F)	(Btu in)/(ft ² sec °F)	3.33 X 10 ⁻³
(Btu ft)/(ft ² hr °F)	(watts cm)/(cm ² °C)	0.0173
(Btu ft)/(ft ² hr °F)	(cal cm)/(cm ² hr °C)	14.88
(Btu ft)/(ft ² hr °F)	(Btu in)/(ft ² day °F)	288.0
(Btu ft)/(ft ² hr °F)	watt/(cm °K)	0.0173
1 calorie = 1 cal = 1 gram cal		
1 Calorie = 1 kilogram cal = 1 Kcal = 1000 cal		

APPENDIX B

RESEARCH & DEVELOPMENT LABORATORY INSTRUCTIONS		
Number	Instruction	Revision Date
4.1.1.1	Apparent Density of Carbon and Graphite Articles	05/96
4.1.1.2	Electrical Resistivity of Carbon and Graphite	06/96
4.1.1.3	Shore Scleroscope Hardness of Carbon and Graphite	03/96
4.1.1.4	Rockwell Hardness of Graphite	06/98
4.1.1.5	Coefficient of Thermal Expansion (CTE) of Graphite	08/98
4.1.1.6	Ash Analysis	05/96
4.1.1.7	Oxidation Resistance Test Method	06/96
4.1.1.8	Oxidation Threshold Test Method	11/96
4.1.1.13	Flexural Strength of Carbon and Graphite	01/96
4.1.1.14	Compressive Strength of Carbon and Graphite	03/96
4.1.1.15	Polishing Samples for Photomicrographs	08/97
4.1.1.16	Microphotography and Examination of Carbon and Graphite	07/98
4.1.1.19	Permeability of Graphite Plates	09/96
4.1.1.22	Equotip Hardness of Carbon and Graphite	08/96

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