Designation: C1836 – 16

Standard Classification for Fiber Reinforced Carbon-Carbon Composite Structures[1]

This standard is issued under the fixed designation C1836; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This classification covers fiber reinforced carbon-carbon (C-C) composite structures (flat plates, rectangular bars, round rods, and tubes) manufactured specifically for structural components. The carbon-carbon composites consist of carbon/graphite fibers (from PAN, pitch, or rayon precursors) in a carbon/graphite matrix produced by liquid infiltration/pyrolysis or by chemical vapor infiltration, or both.

1.2 The classification system provides a means of identifying and organizing different C-C composites, based on the fiber type, architecture class, matrix densification, physical properties, and mechanical properties. The system provides a top-level identification system for grouping different types of C-C composites into different classes and provides a means of identifying the general structure and properties of a given C-C composite. It is meant to assist the ceramics community in developing, selecting, and using C-C composites with the appropriate composition, construction, and properties for a specific application.

1.3 The classification system produces a classification code for a given C-C composite, which shows the type of fiber, reinforcement architecture, matrix type, fiber volume fraction, density, porosity, and tensile strength and modulus (room temperature).

1.3.1 For example, Carbon-Carbon Composites Classification Code, *C3-A2C-4C2*-32*—classification of a carbon-carbon composite material/component (*C3*) with PAN based carbon fiber (*A*) in a 2D (*2*) fiber architecture with a CVI matrix (*C*), a fiber volume of 45 % (*4*), a bulk density of 1.5 g/cc (*C*), an open porosity less than 2 % (*2**), an average ultimate tensile strength of 360 MPa (*3*), and an average tensile modulus of 35 GPa (*2*).

1.4 This classification system is a top level identification tool which uses a limited number of composite properties for high level classification. It is not meant to be a complete, detailed material specification, because it does not cover the full range of composition, architecture, physical, mechanical, fabrication, and durability requirements commonly defined in a full design specification. Guide C1783 provides extensive and detailed direction and guidance in preparing a complete material specification for a given C-C composite component.

1.5 *Units*—The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

1.6 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

C242 Terminology of Ceramic Whitewares and Related Products
C559 Test Method for Bulk Density by Physical Measurements of Manufactured Carbon and Graphite Articles
C709 Terminology Relating to Manufactured Carbon and Graphite
C838 Test Method for Bulk Density of As-Manufactured Carbon and Graphite Shapes
C1039 Test Methods for Apparent Porosity, Apparent Specific Gravity, and Bulk Density of Graphite Electrodes
C1198 Test Method for Dynamic Young's Modulus, Shear Modulus, and Poisson's Ratio for Advanced Ceramics by Sonic Resonance
C1259 Test Method for Dynamic Young's Modulus, Shear Modulus, and Poisson's Ratio for Advanced Ceramics by Impulse Excitation of Vibration
C1275 Test Method for Monotonic Tensile Behavior of Continuous Fiber-Reinforced Advanced Ceramics with Solid Rectangular Cross-Section Test Specimens at Ambient Temperature
C1773 Test Method for Monotonic Axial Tensile Behavior of Continuous Fiber-Reinforced Advanced Ceramic Tubular Test Specimens at Ambient Temperature

[1] This classsfication is under the jurisdiction of ASTM Committee C28 on Advanced Ceramics and is the direct responsibility of Subcommittee C28.07 on Ceramic Matrix Composites.

Current edition approved Feb. 1, 2016. Published March 2016. DOI: 10.1520/C1836-16

[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

C1783 Guide for Development of Specifications for Fiber Reinforced Carbon-Carbon Composite Structures for Nuclear Applications
D3878 Terminology for Composite Materials
D4850 Terminology Relating to Fabrics and Fabric Test Methods
D6507 Practice for Fiber Reinforcement Orientation Codes for Composite Materials
E6 Terminology Relating to Methods of Mechanical Testing
E111 Test Method for Young's Modulus, Tangent Modulus, and Chord Modulus
E1309 Guide for Identification of Fiber-Reinforced Polymer-Matrix Composite Materials in Databases (Withdrawn 2015)[3]

3. Terminology

3.1 *General Definitions*—Many of the terms in this classification are defined in the terminology standards for graphite articles (C709), composite materials (D3878), fabrics and fabric test methods (D4850), and mechanical testing (E6).

3.1.1 *apparent porosity, n*—the volume fraction of all pores, voids, and channels within a solid mass that are interconnected with each other and communicate with the external surface, and thus are measurable by gas or liquid penetration. (Synonym – open porosity) **C242**

3.1.2 *braided fabric, n*—a woven structure produced by interlacing three or more ends of yarns in a manner such that the paths of the yarns are diagonal to the vertical axis of the fabric.

3.1.2.1 *Discussion*—Braided structures can have 2D or 3D architectures. **D4850**

3.1.3 *bulk density, n*—the mass of a unit volume of material including both permeable and impermeable voids. **C559**

3.1.4 *fabric, n—in textiles*, a planar structure consisting of yarns or fibers. **D4850**

3.1.5 *fiber, n*—a fibrous form of matter with an aspect ratio >10 and an effective diameter <1 mm. (Synonym – filament)

3.1.5.1 *Discussion*—A fiber/filament forms the basic element of fabrics and other textile structures. **D3878**

3.1.6 *fiber content/fraction (volume or weight), n*—the amount of fiber present in a composite, expressed either as a percent by weight or a percent by volume. **D3878**

3.1.7 *fiber preform, n*—a preshaped fibrous reinforcement, normally without matrix, but often containing a binder to facilitate manufacture, formed by distribution/weaving of fibers to the approximate contour and thickness of the finished part. **D3878**

3.1.8 *graphite, n*—allotropic crystalline form of the element carbon, occurring as a mineral, commonly consisting of a hexagonal array of carbon atoms (space group P 63/mmc) but also known in a rhombohedral form (space group R 3m). **C709**

3.1.9 *graphitization, n—in carbon and graphite technology*, the solid-state transformation of thermodynamically unstable amorphous carbon into crystalline graphite by a high temperature thermal treatment in an inert atmosphere.

3.1.9.1 *Discussion*—The degree of graphitization is a measure of the extent of long-range 3D crystallographic order as determined by diffraction studies only. The degree of graphitization affects many properties significantly, such as thermal conductivity, electrical conductivity, strength, and stiffness.

3.1.9.2 *Discussion*—A common, but incorrect, use of the term graphitization is to indicate a process of thermal treatment of carbon materials at T > 2200°C regardless of any resultant crystallinity. The use of the term graphitization without reporting confirmation of long range three dimensional crystallographic order determined by diffraction studies should be avoided, as it can be misleading. **C709**

3.1.10 *hybrid, n—for composite materials*, containing at least two distinct types of matrix or reinforcement. Each matrix or reinforcement type can be distinct because of its *(a)* physical or mechanical properties, or both, *(b)* material form, or *(c)* chemical composition. **D3878**

3.1.11 *knitted fabric, n*—a fiber structure produced by interlooping one or more ends of yarn or comparable material. **D4850**

3.1.12 *laminate, n*—any fiber- or fabric-reinforced composite consisting of laminae (plies) with one or more orientations with respect to some reference direction. **D3878**

3.1.13 *lay-up, n*—a process or fabrication involving the placement of successive layers of materials in specified sequence and orientation. **D6507, E1309**

3.1.14 *matrix, n*—the continuous constituent of a composite material, which surrounds or engulfs the embedded reinforcement in the composite and acts as the load transfer mechanism between the discrete reinforcement elements. **D3878**

3.1.15 *ply, n—in 2D laminar composites*, the constituent single layer as used in fabricating, or occurring within, a composite structure. **D3878**

3.1.16 *tow, n—in fibrous composites*, a continuous, ordered assembly of essentially parallel, collimated continuous filaments, normally without twist. (Synonym – roving) **D3878**

3.1.17 *unidirectional composite, n*—any fiber reinforced composite with all fibers aligned in a single direction. **D3878**

3.1.18 *woven fabric, n*—a fabric structure produced by the interlacing, in a specific weave pattern, of tows or yarns oriented in two or more directions.

3.1.18.1 *Discussion*—There are a large variety of 2D weave styles, e.g., plain, satin, twill, basket, crowfoot, etc.

3.1.19 *yarn, n—in fibrous composites*, a continuous, ordered assembly of essentially parallel, collimated filaments, normally with twist, and of either discontinuous or continuous filaments.

3.1.19.1 *single yarn, n*—an end in which each filament follows the same twist. **D3878**

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *1D, 2D, and 3D reinforcement, n*—a description of the orientation and distribution of the reinforcing fibers and yarns in a composite.

3.2.1.1 *Discussion*—In a 1D structure, all of the fibers are

[3] The last approved version of this historical standard is referenced on www.astm.org.

oriented in a single longitudinal (x) direction. In a 2D structure, all of the fibers lie in the x-y planes of the plate or bar or in the circumferential shells (axial and circumferential directions) of the rod or tube with no fibers aligned in the z or radial directions. In a 3D structure, the structure has fiber reinforcement in the x-y planes and in the z-direction in the plate or bar and in the axial, circumferential, and radial directions in a tube or rod.

3.2.2 *axial tensile strength, n*—for a composite tube or solid round rod, the tensile strength along the long axis of the rod or tube. For a composite flat plate or rectangular bar, the tensile strength along the primary structural axis/direction.

3.2.3 *carbon-carbon composite, n*—a ceramic matrix composite in which the reinforcing phase consists of continuous carbon/graphite filaments in the form of fiber, continuous yarn, or a woven or braided fabric contained within a continuous matrix of carbon/graphite. (**1-6**)[4]

3.2.4 *carbon fibers, n*—inorganic fibers with a primary (>90 %) elemental carbon composition. These fibers are produced by the high temperature pyrolysis of organic precursor fibers (commonly, polyacrylonitrile (PAN), pitch, and rayon) in an inert atmosphere. (Synonym – graphite fibers) (**7, 8**)

3.2.4.1 *Discussion*—The term carbon is often used interchangeably with "graphite"; however, carbon fibers and graphite fibers differ in the temperature at which the fibers are made and heat-treated, the amount of elemental carbon produced, and the resulting crystal structure of the carbon. Carbon fibers typically are carbonized at about 2400°F (1300°C) and assay at 93 to 95 % carbon, while graphite fibers are graphitized at 3450 to 5450°F (1900 to 3000°C) and assay at more than 99 % elemental carbon. (**7, 8**)

3.2.5 *chemical vapor deposition or infiltration, n*—a chemical process in which a solid material is deposited on a substrate or in a porous preform through the decomposition or the reaction of gaseous precursors.

3.2.5.1 *Discussion*—Chemical vapor deposition is commonly done at elevated temperatures in a controlled atmosphere.

3.2.6 *infiltration and pyrolysis densification, n—in carbon matrix composites*, a matrix production and densification process in which a liquid organic precursor (thermosetting resin or pitch) is infiltrated/impregnated into the porous perform or the partially porous composite. The organic precursor is then pyrolyzed in an inert atmosphere to convert the organic to a carbon form with the desired purity and crystal structure. The infiltration/pyrolysis process may be iteratively repeated to fill the porosity and build up the density in the composite.

3.2.7 *primary structural axis, n—in a composite flat plate or rectangular bar*, the directional axis defined by the loading axis/direction with the highest required tensile strength. This is commonly the axis with the highest fiber loading. This primary structural axis may not be parallel with the longest dimensional axis of the plate/bar/structure.

[4] The boldface numbers in parentheses refer to the list of references at the end of this standard.

3.2.8 *pyrolysis, n—in carbon matrix composites*, the controlled thermal process in which the hydrocarbon precursor is decomposed to elemental carbon in an inert atmosphere. (Synonym – carbonization)

3.2.8.1 *Discussion*—Pyrolysis commonly results in weight loss and the release of hydrogen and hydrocarbon vapors.

3.2.9 *rectangular bar, n*—a solid straight rod with a rectangular cross-section, geometrically defined by a width, a thickness, and long axis length.

3.2.10 *round rod, n*—a solid, straight elongated cylinder, geometrically defined by a outer diameter and an axial length.

3.2.11 *round tube, n*—a hollow elongated cylinder, geometrically defined by a outer diameter, an inner diameter, and an axial length.

3.2.12 *surface seal coatings, n*—an inorganic protective coating applied to the outer surface of a C-C composite component to protect against high temperature oxidation or corrosion or to improve wear and abrasion resistance. Such coatings are commonly hard, impermeable ceramic coatings.

4. Significance and Use

4.1 Composite materials consist by definition of a reinforcement phase/s in a matrix phase/s. The composition and structure of these constituents in the composites are commonly tailored for a specific application with detailed performance requirements. For fiber reinforced carbon-carbon composites the tailoring involves the selection of the reinforcement fibers (composition, properties, morphology, interface coatings etc), the matrix (composition, properties, and morphology), the composite structure (component fractions, reinforcement architecture, interface coatings, porosity structure, microstructure, etc.), and the fabrication conditions (assembly, forming, densification, finishing, etc.). The final engineering properties (physical, mechanical, thermal, electrical, etc) can be tailored across a broad range with major directional anisotropy in the properties. (**9-12**)

4.2 This classification system assists the designer/user/producer in identifying and organizing different types of C-C composites (based on fibers, matrix, architecture, physical properties, and mechanical properties) for structural applications. It assists the composites community in developing, selecting, and using C-C composites with the appropriate composition, construction, and properties for a specific application.

4.3 This classification system is a top level identification tool which uses a limited number of composites properties for high level classification. It is not meant to be a complete, detailed material specification, because it does not cover the full range of composition, architecture, physical, mechanical, fabrication, and durability requirements commonly defined in a full design specification. Guide C1783 provides direction and guidance in preparing a complete material specification for a given C-C composite component.

5. Carbon-Carbon Composites

5.1 Carbon-carbon composites are composed of carbon/graphite fiber reinforcement in a carbon/graphite matrix. The combination of fibers and carbon matrix, the fiber architecture (the shape and morphology of the fiber preform, multidimensional fiber distribution, and volume content of the fiber reinforcement), the matrix phase composition, microstructure and the composite density and porosity are engineered to give the desired performance properties for the composite. The fibers may have a surface treatment to improve fiber/fabric handleability or to control the bonding between the fiber and the matrix. (**9-15**)

5.2 The mechanical, thermal, and physical properties of carbon-carbon (C-C) composites are determined by the complex interaction of the constituents (fiber, matrix, porosity) in terms of the constituent chemistry, phase composition, microstructure, properties, and fractional content; the fiber architecture; the fiber-matrix bonding, and the effect of fabrication on the constituent properties, morphology and their physical interactions. Each of these factors can be tailored to produce a structure/component with the desired mechanical, physical, and thermal properties. The C-C composite properties can be tailored for directional properties by the anisotropic architecture of the carbon fiber reinforcement. (**9-15**)

5.3 Carbon/graphite fibers are commonly small diameter (5-20 micrometers) continuous filaments produced from polyacrylonitrile, pitch, or rayon precursors. The mechanical and thermal properties of the carbon fibers are strongly dependent on the carbon content, the crystal structure, and the crystallite size and orientation in the fibers. These factors are determined by the precursor chemistry and the processing (spinning, carbonization, and graphitization) conditions. Typically, carbon fibers are classified as either high strength (tensile strength ~ 3-5 GPa, elastic modulus ~ 200-400 GPa) or high modulus (elastic modulus > 500 GPa, tensile strength <3 GPa). Often the carbon fibers have marked differences in mechanical and thermal properties in the axial direction, compared to the radial direction, because of crystal structure anisotropy. (**8, 9**)

5.4 The carbon fibers are commonly consolidated into high count multifilament tows which can be wrapped or layed-up into 1D structures, woven/layed-up/braided/knitted into 2D structures, or woven/braided/knitted/stitched into 3D structures. Each of these fiber structures are fabricated with defined fiber architectures, offering a wide range of bulk fiber content. Different fiber architectures may have marked reinforcement anisotropy, depending on the relative fiber content in each orthogonal direction.

NOTE 1—Many commercially available carbon-carbon composites have a two dimensional woven fabric architecture, consisting of stacked plies. The C-C composite is densified to produce a final structure with orthotropic or quasi-isotropic mechanical and thermal properties.

5.5 The carbon matrix in C-C composites is commonly produced by either of two methods: an iterative liquid infiltration/pyrolysis process or a chemical vapor infiltration process (**1-6**). The two matrix formation processes use different precursors and different processing conditions, which produce differences in the chemistry, crystallinity, morphology, and microstructure (density, pores, and cracks) in the carbon matrix. These two matrix densification processes may be combined for a hybrid carbon matrix.

5.6 In some C-C composite applications an inorganic surface seal coating is applied to the outer surface of the composite to protect against high temperature oxidation and corrosion attack or to improve wear and abrasion resistance. Such coatings are commonly hard, impermeable ceramic coatings.

5.7 The interaction of these three variable factor sets [*(1)* carbon fiber type, properties, coatings; *(2)* fiber content, tow structure, and architecture; *(3)* matrix phase composition and properties, crystallinity, density, morphology, and porosity] can produce C-C composites with a wide range of mechanical and physical properties, along with tailored anisotropic properties in the major directions.

6. Classification of Carbon-Carbon Composites

6.1 *General*—Carbon-carbon composites are classified by fiber type, architecture class, matrix grade, physical properties, and mechanical properties.

6.2 *Fiber Types*—The carbon-carbon composites are *type* classified based on the type of carbon fiber.

6.2.1 *Type A*—Polyacrylonitrile (PAN)-based carbon fibers;

6.2.2 *Type P*—Pitch-based carbon fibers;

6.2.3 *Type R*—Rayon-based carbon fibers; and

6.2.4 *Type H*—A hybrid/blend of two or more types (PAN-, pitch-, or rayon-based) of carbon fibers.

6.3 *Architecture Class*—The carbon-carbon composites are *class* identified based on the fiber reinforcement architecture.

6.3.1 *Class 1*—One-dimensional (1D) filament winding or 1D layups of uniaxial tape;

6.3.2 *Class 2*—Laminates of two-dimensional (2D) fabric plies, 0-90 cross-ply lay-ups of uniaxial tape, or 2-D braids/knits; and

6.3.3 *Class 3*—Three-dimensional (3D) fiber woven, braided, or knitted fiber preforms.

NOTE 2—Some two dimensional laminates are reinforced by limited (<5 % by fiber volume) through-thickness stitching/needling with fiber tows, sometimes called a 2.5D architecture. For the purposes of this specification, stitched/needled (2.5D) architectures are considered Class 3 (3D) composites.

6.4 *Matrix Grade*—The carbon-carbon composites are *grade* classified based on the method of matrix densification.

6.4.1 *Grade S*—Matrix based on infiltration and pyrolysis of thermosetting resins;

6.4.2 *Grade P*—Matrix based on infiltration and pyrolysis of thermoplastic resins (pitch);

6.4.3 *Grade C*—Matrix based on chemical vapor infiltration/deposition with hydrocarbons; and

6.4.4 *Grade H*—Matrix based on a hybrid/combination of resin infiltration (S and/or P) and chemical vapor infiltration (C).

6.5 Table 1 summarizes the classification codes for type, class, and grade of carbon-carbon composites.

6.6 *Physical Properties*—The three physical properties of primary interest for classification are fiber volume fraction, bulk density, and apparent porosity. Table 2 defines a system for classifying carbon-carbon composites based on the fiber volume fraction, bulk density, and apparent porosity.

TABLE 1 Classification Codes for Carbon-Carbon Composites

Order	Property	Classification Codes			
1	Type – Fiber Type	A – PAN base carbon fiber	P – Pitch base carbon fiber	R– Rayon base carbon fiber	H – Hybrid of carbon fibers
2	Class – Fiber Architecture	1 – Filament Wound or 1D laminate of uniaxial tapes	2 – 2D laminate of uniaxial tapes or woven/braided/knitted fabric plies	3 – 3D weave, braid, or knit	
3	Grade – Matrix Type	S –Thermoset Resin	P –Thermoplastic Resin/Pitch	C – Chemical Vapor Infiltration (CVI)	H – Hybrid of Resin and CVI

TABLE 2 Physical Property Classification Level Codes for Carbon-Carbon Composites

	Level Codes				
	6	5	4	3	2
Fiber Volume Fraction (%) by Calculation from Production Information	>60%	50-59%	40-49%	30-39%	<30%
	A	B	C	D	E
Bulk Density (g/cc) by Measurement (Test Method C559 or C838) and/or Immersion (Test Method C1039)	>1.8	1.6-1.79	1.4-1.59	1.2-1.39	<1.2
	2*	2	5	10	15
Apparent Porosity (%) by Immersion (Test Method C1039)	<2%	2-5%	5-10%	10-15%	>15%

6.6.1 These physical properties shall be measured using by the ASTM test standards cited in Table 2.

6.7 *Mechanical Properties*—The two mechanical properties of primary classification interest are ultimate tensile/hoop strength (room temperature–RT) and tensile/hoop modulus of elasticity (room temperature–RT) along the principal axis. Table 3 presents a system for classifying carbon-carbon composite structures based on these two primary mechanical properties.

6.7.1 These tensile properties shall be measured using the test standards cited in Table 3. Averages shall be calculated from a minimum number of test specimens—ten specimens for ultimate tensile strength and five specimens for tensile modulus.

6.8 The carbon-carbon composite (C3) materials classification code shall consist of the abbreviation C3 followed by a hyphen, the type classification by a capital letter, the grade classification in Arabic numerals, the class by a capital letter, a hyphen, the physical property codes in an Arabic numeral-capital letter-Arabic numeral, a hyphen, and the mechanical property codes in two Arabic numerals.

6.8.1 *Examples of Classification Code Designations:*

6.8.1.1 *C3-A2C-4C2*-32*—Classification of a carbon-carbon composite material/ component (*C3*) with PAN based carbon fiber (*A*) in a 2D (*2*) fiber architecture with a CVI matrix (*C*), a fiber volume of 45 % (*4*), a bulk density of 1.5 g/cc (*C*), an open porosity less than 2 % (*2**), an average ultimate tensile strength of 360 MPa (*3*), and an average tensile modulus of 35 GPa (*2*).

6.8.1.2 *C3-P1S-5C10-24*—Classification of a carbon-carbon composite material/component (*C3*) with a pitch based carbon fiber (*P*) in a 1D (*1*) fiber architecture with a thermoset resin base matrix (*S*), a fiber volume of 52 % (*5*), a bulk density of 1.5 g/cc (*C*), an open porosity of 12 % (*10*), an average ultimate tensile strength of 250 MPa (*2*), and an average tensile modulus of 60 GPa (*4*).

7. Keywords

7.1 carbon-carbon composites; carbon fiber; classification; graphite; mechanical properties; physical properties

TABLE 3 Mechanical Property Classification Level Codes for Carbon-Carbon Composites

NOTE 1—Four-point flexure strength and modulus properties are not an acceptable alternative to tensile properties for the classification process, because of the variability produced by different flexure specimen geometries and test configurations.

Mechanical Property	Geometry – Direction	Level Codes				
		4	3	2	1	1*
Average Ultimate Tensile or Hoop Strength[A] (RT) by Test Method C1275 and Test Method C1773	Plate / Bar – Primary Axis 0° Rod / Tube – Axial or Hoop[A]	>400 MPa	300-399 MPa	200-299 MPa	100-199 MPa	<100 MPa
		10	7	4	2	2*
Average Tensile or Hoop[A] Modulus (RT) by Test Methods C1275, C1773, E111, C1198, and C1259	Plate / Bar – Primary Axis 0° Tube / Rod – Axial or Hoop[A]	>100 GPa	70-99 GPa	40-69 GPa	20-39 GPa	<20 GPa

[A] For composite tubes where hoop strength may be the primary strength requirement, the classification system may reference the hoop strength and hoop modulus, rather than the axial tensile strength and modulus. This will be marked by an "H" subscript on the Level Code: A_H, B_H, etc.

REFERENCES

(1) Hatta, H., Weiss, R., and David, P., "Carbon-Carbons and Their Industrial Applications," *Ceramic Matrix Composites–Materials, Modeling, and Technology*, Bansal, N. P. and Lamon, J., editors, Wiley, Hoboken, NJ, 2014, p. 87.

(2) Miracle, D. B. and Donaldson, S. L., editors, *ASM Handbook, Vol. 21—Composites*, ASM International, Materials Park, OH, 2001, p. 165.

(3) Sheehan, J. E., Buesking, K. W. , and Sullivan, B. J., "Carbon-Carbon Composites," *Annual Review of Materials Science*, Vol. 24, 1994, p. 19–44.

(4) Fitzer, E., and Manocha, L. M., *Carbon Reinforcements and Carbon-Carbon Composites*, Springer Verlag, Berlin, 1998.

(5) Palmer, K. R., Marx, D. T., and Wright, M. A., *Carbon and Carbonaceous Composite Materials–Structure Property Relationships*, World Scientific, Singapore, 1996.

(6) Buckley, J. D., and Edie, D. D., editors, *Carbon-Carbon Materials and Composites*, Noyes Publications, Park Ridge, NJ, 1993.

(7) Miracle, D. B. and Donaldson, S. L., editors, *ASM Handbook, Vol. 21—Composites*, ASM International, Materials Park, OH, 2001, p. 35.

(8) Donnet, J. B. and Bansal,, R. C. *Carbon Fibers*, 2nd ed., Marcel Dekker, New York, 1990, p. 55.

(9) Manocha, L. M., "High Performance Carbon–Carbon Composites," *Sadhana*, Vol. 28, February–April 2003, p. 349–358.

(10) Schmidt, D. L., Davidson, K. E., and Theibert, L. S., "Unique Applications of Carbon-Carbon Composite Materials," *SAMPE Journal*, Vol. 35, No. 3, May–June 1999, pp. 27–39.

(11) Tibbetts, G. G., "Carbon Fiber, Filaments and Composites," *Proceedings of the NATO Advanced Study Institute on Carbon Fibers and Filaments, Alvor, Portugal, May 15-27, 1989* Figueiredo, J. L. et. al, Kluwer Academic Publishers, Norwell, MA, 1990, p. 73–94.

(12) Buckley, J. D., "Carbon-Carbon, an Overview," *American Ceramic Society Bulletin*, Vol. 67, No. 2, 1988, p. 364.

(13) Corum, J. M., Battiste, R. L., Liu, K. C., and Ruggles, M. B., "Basic Properties of Reference Crossply Carbon-Fiber Composite," ORNL/TM-2000/29, Oak Ridge National Laboratory, Oak Ridge, TN, February 2000.

(14) Hatta, H., Aoi, T., Kawahara, I., Kogo, Y. and Shiota, I.,"Tensile Strength of Carbon-Carbon Composites: I—Effect of C-C Density," *Journal of Composite Materials*, Vol. 38, 2004, p. 1667.

(15) Hatta, H., Aoi, T., Kawahara, I., Kogo, Y. and Shiota, I.,"Tensile Strength of Carbon-Carbon Composites: II—Effect of Heat Treatment Temperature," *Journal of Composite Materials*, Vol. 38, No. 19, 2004, p. 1685–1699.