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Standard Guide for Testing the Thermal Properties of Advanced Ceramics[1]

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1. Scope

1.1 This guide covers the thermal property testing of advanced ceramics, to include monolithic ceramics, particulate/whisker-reinforced ceramics, and continuous fiber-reinforced ceramic composites. It is intended to provide guidance and information to users on the special considerations involved in determining the thermal properties of these ceramic materials.

1.2 Five thermal properties (specific heat capacity, thermal conductivity, thermal diffusivity, thermal expansion, and emittance/emissivity) are presented in terms of their definitions and general test methods. The relationship between thermal properties and the composition, microstructure, and processing of advanced ceramics (monolithic and composite) is briefly outlined, providing guidance on which material and specimen characteristics have to be considered in evaluating the thermal properties of advanced ceramics. Additional sections describe sampling considerations, test specimen preparation, and reporting requirements.

1.3 Current ASTM test methods for thermal properties are tabulated in terms of test method concept, testing range, specimen requirements, standards/reference materials, capabilities, limitations, precision, and special instructions for monolithic and composite ceramics.

1.4 This guide is based on the use of current ASTM standards for thermal properties, where appropriate, and on the development of new test standards, where necessary. It is not the intent of this guide to rigidly specify particular thermal test methods for advanced ceramics. Guidance is provided on how to utilize the most commonly available ASTM thermal test methods, considering their capabilities and limitations.

1.5 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard. See IEEE/ASTM SI 10.

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, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.7 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

2.1.1 *Specific Heat:*

C351 Test Method for Mean Specific Heat of Thermal Insulation (Withdrawn 2008)[3]

D2766 Test Method for Specific Heat of Liquids and Solids (Withdrawn 2018)[3]

E1269 Test Method for Determining Specific Heat Capacity by Differential Scanning Calorimetry

E2716 Test Method for Determining Specific Heat Capacity by Sinusoidal Modulated Temperature Differential Scanning Calorimetry

2.1.2 *Thermal Conductivity:*

C177 Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded-Hot-Plate Apparatus

C182 Test Method for Thermal Conductivity of Insulating Firebrick

C201 Test Method for Thermal Conductivity of Refractories

C202 Test Method for Thermal Conductivity of Refractory Brick

C408 Test Method for Thermal Conductivity of Whiteware Ceramics

C518 Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus

C767 Test Method for Thermal Conductivity of Carbon Refractories

C1044 Practice for Using a Guarded-Hot-Plate Apparatus or Thin-Heater Apparatus in the Single-Sided Mode

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[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.

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

C1045 Practice for Calculating Thermal Transmission Properties Under Steady-State Conditions
C1113/C1113M Test Method for Thermal Conductivity of Refractories by Hot Wire (Platinum Resistance Thermometer Technique)
C1114 Test Method for Steady-State Thermal Transmission Properties by Means of the Thin-Heater Apparatus
C1130 Practice for Calibration of Thin Heat Flux Transducers
E1225 Test Method for Thermal Conductivity of Solids Using the Guarded-Comparative-Longitudinal Heat Flow Technique
E1530 Test Method for Evaluating the Resistance to Thermal Transmission by the Guarded Heat Flow Meter Technique

2.1.3 *Thermal Expansion:*
C372 Test Method for Linear Thermal Expansion of Porcelain Enamel and Glaze Frits and Fired Ceramic Whiteware Products by the Dilatometer Method
C1300 Test Method for Linear Thermal Expansion of Glaze Frits and Ceramic Whiteware Materials by the Interferometric Method
E228 Test Method for Linear Thermal Expansion of Solid Materials With a Push-Rod Dilatometer
E289 Test Method for Linear Thermal Expansion of Rigid Solids with Interferometry
E831 Test Method for Linear Thermal Expansion of Solid Materials by Thermomechanical Analysis

2.1.4 *Thermal Diffusivity:*
C714 Test Method for Thermal Diffusivity of Carbon and Graphite by Thermal Pulse Method
D4612 Test Method for Calculating Thermal Diffusivity of Rock and Soil
E1461 Test Method for Thermal Diffusivity by the Flash Method
E2585 Practice for Thermal Diffusivity by the Flash Method

2.1.5 *Emittance/Emissivity:*
E408 Test Methods for Total Normal Emittance of Surfaces Using Inspection-Meter Techniques
E423 Test Method for Normal Spectral Emittance at Elevated Temperatures of Nonconducting Specimens

2.1.6 *General Standards:*
C168 Terminology Relating to Thermal Insulation
C373 Test Methods for Determination of Water Absorption and Associated Properties by Vacuum Method for Pressed Ceramic Tiles and Glass Tiles and Boil Method for Extruded Ceramic Tiles and Non-tile Fired Ceramic Whiteware Products
C1045 Practice for Calculating Thermal Transmission Properties Under Steady-State Conditions
C1145 Terminology of Advanced Ceramics
E122 Practice for Calculating Sample Size to Estimate, With Specified Precision, the Average for a Characteristic of a Lot or Process
E473 Terminology Relating to Thermal Analysis and Rheology
E1142 Terminology Relating to Thermophysical Properties
IEEE/ASTM SI 10 American National Standard for Metric Practice

3. Terminology

3.1 *Definitions:*

3.1.1 *advanced ceramic, n*—a highly engineered, high-performance, predominantly nonmetallic, inorganic, ceramic material having specific functional attributes. **(C1145)**

3.1.2 *ceramic matrix composite, n*—a material consisting of two or more materials (insoluble in one another), in which the major continuous component (matrix component) is a ceramic, while the secondary component/s (reinforcing component) may be ceramic, glass-ceramic, glass, metal, or organic in nature. These components are combined on a macroscale to form a useful engineering material possessing certain properties or behavior not possessed by the individual constituents. **(C1145)**

3.1.3 *coefficient of linear thermal expansion,* $\alpha[T^{-1}]$, *n*—the change in length, relative to the length of the specimen, accompanying a unit change of temperature, at a specified temperature. (This property can also be considered the instantaneous expansion coefficient or the slope of the tangent to the $\Delta L/L$ versus T curve at a given temperature.) **(E1142)**

3.1.4 *continuous fiber-reinforced ceramic composite (CFCC), n*—a ceramic matrix composite in which the reinforcing phase(s) consists of continuous filaments, fibers, yarns, or knitted or woven fabric. **(C1145)**

3.1.5 *differential scanning calorimetry (DSC), n*—a technique in which the difference in energy inputs into a test specimen and a reference material is measured as a function of temperature while the test specimen and reference material are subjected to a controlled temperature program. **(E1269)**

3.1.6 *discontinuous fiber-reinforced ceramic composite, n*—a ceramic matrix composite reinforced by chopped fibers. **(C1145)**

3.1.7 *emittance (emissivity), ε (nd), n*—the ratio of the radiant flux emitted by a specimen per unit area to the radiant flux emitted by a black body radiator at the same temperature and under the same conditions. Emittance ranges from 0 to 1, with a blackbody having an emittance of 1.00. **(E423)**

3.1.8 *linear thermal expansion, [nd], n*—the change in length per unit length resulting from a temperature change. Linear thermal expansion is symbolically represented by $\Delta L/L_0$, where ΔL is the observed change in length $\Delta L = L_2 - L_1$, and L_0, L_1, and L_2 are the lengths of the specimen at reference temperature T_0 and test temperatures T_1 and T_2. **(E228)**

3.1.9 *mean coefficient of linear thermal expansion,* $\alpha_L[T^{-1}]$, *n*—the change in length, relative to the length of the specimen, accompanying a unit change of temperature measured across a specified temperature range (T_1 to T_2). **(C372)**

3.1.10 *particulate-reinforced ceramic matrix composite, n*—a ceramic matrix composite reinforced by ceramic particulates. **(C1145)**

3.1.11 *specific heat (specific heat capacity), C* $[mL^{-1}T^{-2}\theta^{-1}]$, *n*—the quantity of heat required to provide a unit temperature increase to a unit mass of material. **(E1142)**

3.1.12 *thermal conductivity,* λ [$mLT^{-1}\theta^{-1}$], *n*—the time rate of heat flow, under steady conditions, through unit area, per unit temperature gradient in the direction perpendicular to the area. **(C168)**

3.1.13 *thermal diffusivity,* [L^2T^{-1}], *n*—the property given by the thermal conductivity divided by the product of the bulk density and heat capacity per unit mass. **(C168)**

3.1.14 *thermodilatometry, n*—a technique in which a dimension of a test specimen under negligible applied force is measured as a function of temperature while the test specimen is subjected to a controlled temperature program in a specified atmosphere. **(E473)**

3.2 *Units for Thermal Properties:*

Property	SI Units	Abbreviation
Specific heat capacity	joules/(gram-kelvin)	J/(g·K)
Thermal Conductivity	watts/(metre-kelvin)	W/(m·K)
Thermal diffusivity	metre/second^2	m/s^2
Coefficient of Thermal Expansion	metre/(metre-kelvin)	K^{-1}
Emittance/emissivity	no dimensions	—

4. Summary of Guide

4.1 Five thermal properties (specific heat capacity, thermal conductivity, thermal diffusivity, thermal expansion, and emittance/emissivity) are presented in terms of their definitions and general test methods. The relationship between thermal properties and the composition, microstructure, and processing of advanced ceramics is briefly outlined, providing guidance on which material characteristics have to be considered in evaluating the thermal properties. Additional sections describe sampling considerations, test specimen preparation, and reporting requirements.

4.2 Current ASTM test methods for thermal properties are tabulated in terms of test method concept, testing range, specimen requirements, standards/reference materials, capabilities, limitations, precision, and special instructions for monoliths and composites.

5. Significance and Use

5.1 The high-temperature capabilities of advanced ceramics are a key performance benefit for many demanding engineering applications. In many of those applications, advanced ceramics will have to perform across a broad temperature range. The thermal expansion, thermal diffusivity/conductivity, specific heat, and emittance/emissivity are crucial engineering factors in integrating ceramic components into aerospace, automotive, and industrial systems.

5.2 This guide is intended to serve as a reference and information source for testing the thermal properties of advanced ceramics, based on an understanding of the relationships between the composition and microstructure of these materials and their thermal properties.

5.3 The use of this guide assists the testing community in correctly applying the ASTM thermal test methods to advanced ceramics to ensure that the thermal test results are properly measured, interpreted, and understood. This guide also assists the user in selecting the appropriate thermal test method to evaluate the particular thermal properties of the advanced ceramic of interest.

5.4 The thermal properties of advanced ceramics are critical data in the development of ceramic components for aerospace, automotive, and industrial applications. In addition, the effect of environmental exposure on thermal properties of the advanced ceramics must also be assessed.

6. Procedure

6.1 Review Sections 7 – 10 to become familiar with thermal property concepts and thermal testing issues for advanced ceramics, specimen preparation guidance, and reporting recommendations.

6.2 Review the test method text and tables in Section 11 for the property you need to determine. Use the text and tables to help select the most appropriate ASTM test method for evaluating the thermal property of interest for the specific advanced ceramic.

6.3 Perform the thermal property test in accordance with the selected ASTM test method, but refer back to the guide for directions and recommendations on material characterization, sampling procedures, test specimen preparation, and reporting results.

7. Thermal Properties and Their Measurement

7.1 *Specific Heat Capacity:*

7.1.1 Specific heat capacity is the amount of energy required to increase the temperature by one unit for a unit mass of material. It is a fundamental thermal property for engineers and scientists in determining the temperature response of materials to changes in heat flux and thermal conditions. The SI units for specific heat capacity are joules/(gram·K). Since the specific heat capacity changes with temperature, a specific heat capacity value must always be associated with a specific test temperature or temperature range.

7.1.2 Specific heat capacity is commonly measured by calorimetry in which changes in thermal energy are measured against changes in temperature. The two common calorimetry methods are differential scanning calorimetry and drop calorimetry.

7.1.3 Differential scanning calorimetry heats the test material at a controlled rate in a controlled atmosphere through the temperature region of interest. The heat flow into the test material is compared to the heat flow into a reference material to determine the energy changes in the test material as a function of temperature.

7.1.4 In drop calorimetry, the test sample is heated to the desired temperature and then immersed in an instrumented, liquid-filled container (calorimeter), which reaches thermal equilibrium. The increase in temperature of the calorimeter liquid/container is a measure of the amount of heat in the test specimen.

7.1.5 In any calorimetry test, the experimenter must recognize that phase changes and other thermo-physical transformations in the material will produce exothermic and endothermic events which will be captured in the test data. The thermal events must be properly identified and understood within the context of the material properties, chemistry, and phase composition across the temperature range of interest.