Irradiation Effects in Ceramics

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(GENIV) NEXT GENERATION NUCLEAR POWER AND REQUIREMENTS FOR STANDARDS, CODES AND DATA BASES FOR CERAMIC MATRIX COMPOSITES

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ABSTRACT

Innovative and novel applications of CMCs are critical to the success of GenIV: Next Generation Nuclear Power (NGNP) plants. Regularity requirements (e.g., Nuclear Regulatory Commission) demand the implementation of test standards, design codes and data bases for CMCs as part of the licensing and approval of this new power plants. Significant progress on standards, codes and databases for heat engine and aero applications has been made since 1991, however new requirements (e.g., durability in extreme temperature and irradiation environments) for CMC applications in NGNP require additional efforts. The current (2006) state of standards, design codes and databases for CMCs is reviewed and discussed. Issues related to development, verification and use of new standards, design codes, and database NGNP applications, including international aspects, are presented and discussed

INTRODUCTION

Ceramic matrix composites (CMCs), although a still-emerging advanced material, may be the only material of choice in Next Generation Nuclear Power (NGNP) plants because of their low thermal expansion, resistance to degradation from irradiation and excellent retention of mechanical properties at elevated temperatures under high pressures.[1] (see Figure 1)

Although CMCs possess many of the critical characteristics of advanced ceramic monoliths (e.g., low density, high stiffness, elevated temperature capability, etc.) they have the advantage of exhibiting increased "toughness" over their monolithic counterparts. [2-3] Continuous fiber-reinforced CMCs exhibit greatly increased "toughness" (i.e., nonlinear energy dissipation during deformation) and therefore provide the inherent damage tolerance, volume/surface area independent properties and attendant increased reliability that are critical in many engineering applications where the brittleness of conventional advanced ceramics makes these materials acceptable.[1]

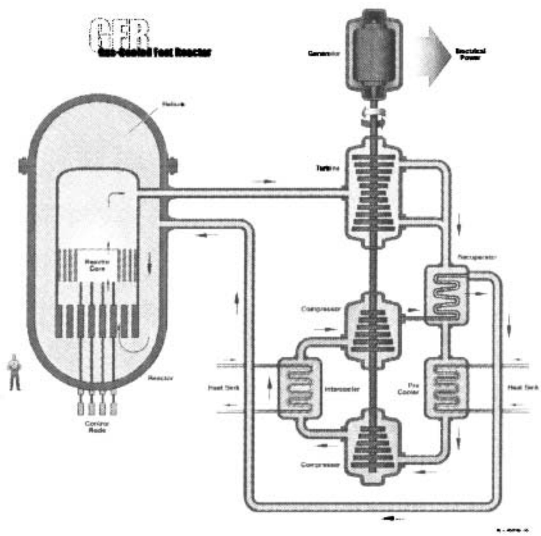

Figure 1 CMC tubes as control rod guides in advanced (GenIV) gas cooled fast reactors

The unique performance of CMCs makes accepted conventional testing and design methods inappropriate. This situation comes just as the characterization and prediction of the thermo-mechanical behavior of CMCs have become the subject of extensive investigations worldwide. The marketplace emergence of CMC prototype/trial products coupled with the relative scarcity of standards (e.g., test methods, practices, guides, classification/terminology, and reference materials) for CMCs and the lack of design codes/data bases for CMCs are limiting factors in commercial diffusion, industrial acceptance and regularity approval[4] of these advanced materials.

In this paper, the issue of standards for CMCs in Gen IV NGNP applications and their extension to design codes and databases is addressed. Standards for CMCs are first defined. This is followed by a discussion of the current status of standards and design codes for CMCs. Finally, some conclusions on the future of standards and codes for CMCs are presented.

STANDARDS

"Standards" as a technical term may have many interpretations[4]. For those in the technical community (e.g., researcher) "standards" may be fundamental test methods or even units of measure. For the end-product user or manufacturer "standards" may be specifications for materials or even requirements for quality control. Commercial standards are equivalent to the rules/terms of information transfer between manufacturers, designers, and product users.[4] Another difference exists between levels of standards: company (internal use and internal consensus); industry (trade use and limited consensus); government (wide use and various levels of consensus); full-consensus (broadest use and greatest consensus).

At this time, there are relatively few (national or international) consensus standards[5] for advanced ceramics and relatively fewer still for CMCs, in particular (see Table 1). For full consensus standards, [i.e., American Society for Testing and Materials (ASTM) Subcommittee C28.07 on Ceramic Matrix Composites, Comité Européen de Normalisation (CEN) Subcommittee TC184/SC1 on Ceramic Composites, and International Organization for Standardization (ISO) Technical Committee TC206 on Fine (Advanced, Technical) Ceramics] various technical and pragmatic issues related to CMC standardization efforts have been presented[5]. Other standards for CMCs, although not full consensus have been introduced through NASA High Speed Research/Enabling Propulsion Program (HSR/EPM) in the United States and Petroleum Energy Center (PEC) in Japan.

Despite these diverse efforts, the paucity of standards has limited the ability to evaluate CMCs on a common-denominator basis and furthermore may be hindering continued development of these advanced materials[4]. Fortunately, although the total number of standards for CMCs is still relatively low, the rate of standards development for CMCs has been increasing. Perhaps more importantly, new efforts within ISO TC206 on Fine Ceramics are aimed at harmonizing existing standards rather than initiating new efforts, thus assisting the introduction of CMC standards.

HARMONIZATION OF STANDARDS

Harmonization of existing standards may play in important role in widespread acceptance and usage of standards for CMCs. An example of such harmonization exists for uniaxial tensile testing which is the most fundamental and, therefore, most common test for CMCs. Currently there are five tensile test method standards for CMCs at room temperature (see Table 1). Of these five standards, three (ASTM, CEN, and EPM) were developed independently. Two others (ISO and PEC) were developed by harmonizing (i.e., choosing the "best" aspects) of the pre-existing standards.

Once aspect of this harmonization is that common terminology allows communication between testers without confusion. In ISO 15733 "Fine ceramics (Advanced ceramics, Advanced technical ceramics)-Test method for tensile stress-strain behaviour of continuous fibre-reinforced composites at room temperature" harmonization has lead to such common terms as fine ceramic and ceramic matrix composite that are defined as follows:

fine (advanced, technical) ceramic, n - A highly engineered, high performance predominately non-metallic, inorganic, ceramic material having specific functional attributes.

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.

In addition to harmonization, ISO 15733 also serves to show the diversity of test methods. For example, no single tensile test specimen geometry has been identified as the "best." As a result, the range of successful test specimen geometries is illustrated in the standard to indicate to users a variety of possibilities (see Figure 2).

Table 1 Selected Test Standards for Ceramic Matrix Composites

Requirement	ASTM	CEN	ISO	EPM (HSR/EPM)	PEC
Bulk CMC, R.T. in Air					
Tension ······ In-plane	C1275	EN658-1	ISO15733	D-001-93	TS-CMC01
······ Transverse	C1468	—	—	—	—
Compression ······ In-plane	C1358	ENV658-2	DIS20504		
Shear ······ In-plane	C1292	ENV12289	DIS20506		—
······ Interlaminar	C1292	ENV658-4	DIS20505		TS-CMC06
Flexure ······ Bending	C1341	ENV658-3		D-003-93	TS-CMC04
······ Shear	—	ENV658-5		—	—
Mechanical Fatigue ······ Tensile	C1360			D-002-93	TS-CMC10
······ Flexural	—			—	—
Density		ENV 1389			
Elastic Constants	C1258				TS-CMC13
Fracture		ENV13234			TS-CMC08 TS-CMC09
Bulk CMC, H.T. in Air/Inert					
Tension ······ In-plane	C1359	ENV1892		D-001-93	TS-CMC01
······ Transverse	—	ENV1893		—	—
Compression ······ In-plane		ENV12290 ENV12291			
Shear ······ In-plane	—	ENV1894			—
······ Interlaminar	C1425				TS-CMC06
Flexure ······ Bending	C1341			D-003-93	TS-CMC04
······ Shear	—			—	—
Mechanical Fatigue ······ Tensile				D-002-93	TS-CMC10
······ Flexural				—	—
Thermal Fatigue					TS-CMC14
Creep	C1337	ENV13235		D-004-93	TS-CMC11
Stress Rupture				D-004-93	
Specific Heat		ENV1159-3			
Thermal Diffusivity		ENV1159-2			
CTE		ENV1159-1			
Ceramic Fiber, R.T. in Air					
Tension	C1557	ENV1007-4			
Diameter		ENV1007-1 ENV1007-3			
Density		ENV1007-2			

ASTM =American Society for Testing and Materials, CEN = Comité Européen de Normalisation, ISO = International Organization for Standardization, EPM = Enabling Propulsion Materials. PEC = Petroleum Energy Center

According to ISO1573, a wide range of properties can be extracted from a single uniaxial tensile test of a CMC as illustrated in Figure 3. Each of these properties (e.g., elastic modulus, proportional limit stress, ultimate tensile strength, modulus of toughness) has explicit formulae for determining it from the stress strain curve.

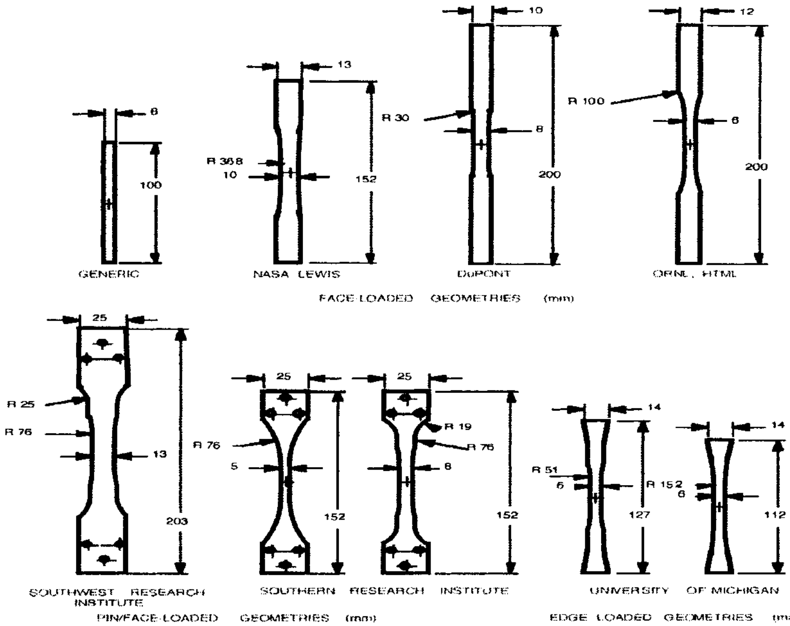

Figure 2 Examples of various tensile test piece geometries contained in ISO15733

For Gen IV gas cooled fast reactor (GFR) applications, a targeted application of CMCs is tubes for control rods. These CMC would be subjected to temperatures of 490 to 850°C at pressures up to 9 MPa of gaseous helium in addition to fast neutron fluence. Standards for mechanical behaviour of CMC tubular components have been addressed only in passing discussions. Standards for irradiation effects of CMCs have not even been proposed.

DESIGN CODES

"Design code" as used in this discussion is not a design manual (i.e., a "cookbook" design procedure that leads to a desired component or system). Instead, design codes are broadly-accepted, general rules for the fabrication of components or systems. A primary objective is the relatively-long safe-life of the design while providing for the reasonably certain protection of life and property. Even though the safety of the design can never be compromised, the needs of the users, manufacturers and inspectors are recognized.

"Design codes" allow flexibility for new designs that are required for performance, efficiency, usability, or manufacturabilty while still providing constraints for safety. Such a wide ranging "design code" incorporates links between materials, general design (formulae, loads, allowable stress, permitted details), fabrication methods, inspection, testing, certification, and data reports, and finally quality control to insure that the "design code" has been followed

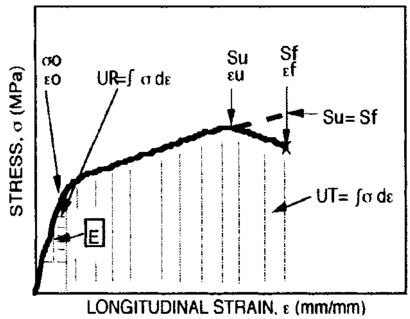

Figure 3 Some explicit parameters extractable from stress-strain curves (ISO15733)

Many of the standards for materials testing, characterization, and quality control are implicit in the "design code". Finally, unlike standards that do not provide for compliance or accountability, "design codes" require compliance through documentation, and certification through inspection and quality control.

There are currently two efforts underway to establish design codes for CMCs: ASME Task Group on Ceramic and Graphite Pressure Equipment and Mil-Hdbk-17 CMC effort. Standards are incorporated in both these efforts to provide consensus methods for determining the properties and performance of materials contained in the "design code". Figure 4 is an illustration of the use of "design by analysis" in which the long-term performance of a component is predicted using an algorithm that requires information on long-term performance of materials determined using standards.

"Design codes" (and imbedded standards) as approved and embraced by industry are particularly important for GenIV nuclear power applications because of the oversight by the U.S. Nuclear Regulatory Agency (NRC). The NRC is the "watchdog" agency of the nuclear power sector and as such is insistent on documentation, best practices and rigorous procedures. Design codes along with their imbedded standards represent debated, balloted and approved consensus documents which are crucial to meeting the approval of the NRC.

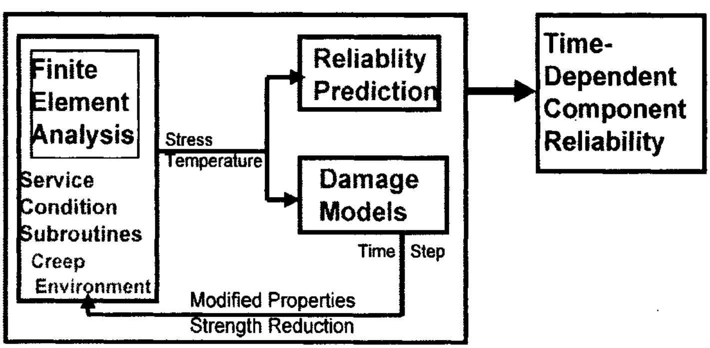

Figure 4 Design by analysis approach for CMC "design code"

CONCLUSIONS

Although the number of standards for CMCs is now over 60 since 1991, these standards have numerous uses including harmonizing international standards, and establishing the basis for determining properties and performance for "qualified materials" within design codes.

Unfortunately, despite this level of development of standards, codes and data bases for CMCs, the current state of standards and codes for CMC applications in GenIV nuclear power generation is inadequate. New standards need to be developed for non-standard tubular shapes under a variety of loading (e.g., tension, flexure, internal pressurization) and environmental (e.g., elevated temperature, high pressure gas and fast neutron fluence). In addition, new design codes must be developed to integrate CMCs into evolving GenIV NGNP applications. Finally, these new design codes must be approved by the U.S. NRC before the use of CMCs in GenIV NGNP applications can be ruled successful.

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