HT-CMC/10th

Bordeaux 22-26 SEPT. 2019

10th International Conference on High Temperature Ceramic Matrix Composites

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10th International Conference on High Temperature Ceramic Matrix Composites - HT-CMC 10

September 22-26, 2019

BORDEAUX CONGRESS CENTER, FRANCE

Organized by:

LCTS
Laboratoire des Composites Thermo Structuraux

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Global population growth and tremendous economic development has brought us to the crossroads of long-term sustainability and risk of irreversible changes in the ecosystem. Energy efficient and ecofriendly technologies and systems are critically needed for further growth and sustainable development. While ceramic matrix composites were originally developed to overcome problems associated with the brittle nature of monolithic ceramics, today the composites can be tailored for customized purposes and offer energy efficient and ecofriendly applications, including aerospace, ground transportation, and powergeneration systems.

The French LCTS laboratory (Laboratoire des Composites Thermo Structuraux) is organizing and will host the 10th International Conference on High Temperature Ceramic Matrix Composites (HT-CMC 10) in Bordeaux, France from September 22-26, 2019. HT-CMC-10 will continue the tradition of successful previous conferences held in Bordeaux (France, 1993), Santa Barbara (USA, 1995), Osaka (Japan, 1998), Munich (Germany, 2001), Seattle (USA, 2004), New Delhi (India, 2007), Bayreuth (Germany, 2010), Xi'An (China, 2013) and Toronto (Canada, 2016). This conference series has been recognized as the global and central meeting event in high-temperature ceramic composite science and technology.

We invite all of you to take advantage of this opportunity to visit the great city of Bordeaux and actively participate in this conference. We are hopeful that this meeting will provide an excellent forum for interaction and friendship with international participants to discuss the latest trends in applications of ceramic technologies for sustainable development. We look forward to your participation in HT-CMC 10.

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ABSTRACT SUBMISSION INSTRUCTIONS

Visit **www.ht-cmc10.org** to submit your abstract until February 15, 2019.

Please contact **Claude Foubert** at secretary-htcmc10@agence-vert.com or +33 247-273-330 with questions.

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TOPIC 1

Computational modeling and design of new materials and processes

This symposium is devoted to broad applications of modeling techniques or sets of techniques to high-temperature ceramic matrix composites-their fabrication, structure and organization, and behavior in use. Modeling may address any scale from angstrom to meters, ranging from ab-initio and atomistic computations to continuum physics, and any physical phenomenon of interest (principally mechanical, thermal, and chemical) considered alone or coupled together. Special attention will be given to experimental verification of models, but papers focused on design and creation of new concepts are also particularly welcome.

PROPOSED SYMPOSIUM SUB-TOPICS:

- Multi-scale modeling
- Thermodynamic computations
- Diffusion, defects, and coupled phenomena
- Computation of mechanical, thermal, and thermomechanical properties
- Simulation of materials processing and degradation
- Image processing and image-based modeling
- Model verification and certification; uncertainty qualification
- Computer-based design, including composition, phases, structure, and organization
- Ceramic genome, data mining, and material informatics

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TOPIC **2**

Fibers and Preforms

Ceramic fibers are the key components of ceramic matrix composites. Although advanced CMC materials are already being developed with fibers available on the market, there is still a demand for fiber materials with even better high temperature performance. Oxide fibers have limitations, due to creep and grain growth, and non-oxide fibers are not long-term stable against oxidation at high temperatures. Research is focused on pushing the performance limits to higher temperatures and to longer life times of the fibers.

For many applications textile preforms made of ceramic fibers are the starting point for manufacturing CMC parts. In the most basic case this can be flat woven fabrics. However, looking at advanced 3D carbon fiber preforms already developed for carbon fiber composites, there is still a challenge for textile machine engineering in order to handle also ceramic fibers. The latest developments of woven textiles aim in the direction of fabrics with large denier roving, which can be produced at lower costs but are demanding in terms of infiltration capability by the ceramic matrix.

PROPOSED SYMPOSIUM SUB-TOPICS:

- New developments in the field of oxide and non-oxide ceramic fibers
- Characterization and evaluation of temperature dependent properties of ceramic fibers
- Performance of ceramic fibers in corrosive environments
- Nanotubes or nanowires as reinforcements
- Textile processing of ceramic fibers for producing fabrics and preforms
- New fabrics for CMCs (High denier woven preforms, braided structures, 3D preforms...)

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Interphases

The fiber/matrix interfacial domain is a decisive constituent of fiber reinforced ceramic matrices. It consists of a fiber/matrix interface or an interphase. Depending on characteristics of this domain, the composite will be either a brittle ceramic or a damage tolerant composite. Furthermore, interface/interphase engineering is an approach to designing composite with respect to service conditions. The key role of interfacial domain is to protect the reinforcing fibers against fracture. Several requirements, that may appear opposite, have to be met:

- The fibers have to be bonded to the matrix, in order to ensure material integrity, and to end-up with a continuous medium,
- Arrest or deflection of cracks initiated in the matrix must be able to take place at interfaces,
- After crack deflection the loads have to be still carried by the matrix, in order to limit fiber overloading,
- In aggressive environments, the interfaces and interphases have to be able to protect fibers against aggression from species and to fulfil the above mechanical functions.

An interface is a surface between two phases, or between the fiber and the matrix. An interphase is a film of one or several layers bonded to the fiber and the matrix. An interphase implies the presence of at least two interfaces: one with the matrix, and one with the fiber and more when the interphase consists of a multilayer.

PROPOSED SYMPOSIUM SUB-TOPICS:

- New developments of interphases for oxide and non-oxide composites
- Characterization and evaluation of interface/interphase characteristics
- Performance of interfaces/interphases in severe environments
- Reinforcement of interfaces/interphases
- Composite behavior/interface characteristics relations

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Oxide/oxide ceramics

Oxide-oxide CMCs are nowadays materials with an appreciable degree of maturity. Well-identified applications are existing in heat generation (terrestrial turbines), in aeronautic propulsion (engine rear plug) and in industry (burners, holders, etc ...). However there still exists an important potential of development with new formulations of matrices, fiber/matrix associations, inclusion of geopolymers, new processing routes, improvement of mechanical performances (especially the strain to failure), not to mention that new, generic or specific applications are still to be considered.

KEY WORDS:

- Processing: chemistry and engineering
- Slurry infiltration
- Sol-gel route
- Geopolymers matrices
- Damage mechanisms and non-linear mechanical behavior
- Creep, environmental degradation
- Combustion environment
- Integration, joining

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TOPIC **5**

Innovative Design, Advanced Processing, and Manufacturing Technologies processing in non-oxide composites: SiC/SiC, C/SiC, hybrid CMCs

Recently fiber-reinforced-ceramic matrix composites (CMCs) have become important material for high temperature applications, e.g. aero-engine components, and CMCs are expected to extend application fields in the near future. Despite (or even because of) extensive research in the past decades, CMCs have still have various unsolved problems, which should be addressed before applications. Advanced researches for the future CMCs are also very important area because most of the recent technologies are based on the past researches. The symposium has been designed to exchange ideas related to (i) Innovative design, (ii) Advanced processing, (iii) Manufacturing technologies in non-oxide composites. SiC/SiC, C/SiC, and hybrid type CMCs including short fiber-reinforced ceramic matrix composites are area to be included in the symposium. Some topics related to processing of CMCs, such as quality assessment, damage of raw materials, cost reduction method are involved in the symposium.

KEY WORDS:

- SiC/SiC
- C/SiC
- hybrid CMCs
- innovative design
- advanced processing techniques
- manufacturing technology

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TOPIC **6**

Additive Manufacturing

Additive manufacturing (AM) is considered a key technology for the industry of the future. It consists in selectively adding materials to realize net shape components in three dimensions. AM machines are controlled by a computer which elaborates a computer aided design (CAD) file to transform it into a real object. AM shows several advantages: shortened development and manufacturing of new components, reduction of production cost (for small series or pieces with complex shape) and the opportunity to create objects whose geometry is impossible to realize with conventional processes. This last advantage is probably the most striking one: it allows designing a component for its performance and no more for its manufacturability.

AM technology is still in a development phase for ceramics, the next challenge is to combine the above mentioned advantages with the peculiar "engineer-able" microstructure of a CMC.

The topics of this Session are meant to give an overview on what is new in ceramic AM on design, processing, testing and applications with the aim to open a discussion on the limits and opportunities of this technology for CMCs.

PROPOSED SYMPOSIUM SUB-TOPICS (NOT LIMITED):

- Emerging additive manufacturing technologies
- Selective laser sintering and stereolithography
- Direct writing technologies
- Fused deposition modeling and 3-D printing technologies
- Laminated object manufacturing and powder bed fusion processes
- Mechanical tests of additively manufactured and joined ceramics and ceramic matrix composites
- Design and modeling of additive manufacturing materials and interfaces
- Additive manufacturing-enabled components and their evaluation in relevant operating conditions

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UHTCs and MAX phases

Ultra-high temperature ceramics (UHTCs) and nano-laminated ternary carbides and nitrides (MAX phases) are families of compounds that display a range of potentially very useful properties. For the UHTCs this includes extremely high melting temperatures (>3000˚C), high hardness and good chemical stability and strength at high temperatures. For the MAX phases it includes unusual combinations of chemical, physical, electrical, and mechanical properties; these materials exhibit both metallic and ceramic characteristics under various conditions.

UHTC materials are typically considered to be the carbides, nitrides and borides of the transition metals, but the Group IV compounds (Ti, Zr, Hf) plus TaC are generally considered to be the main focus of research due to the superior melting temperatures and stable high-melting temperature oxide that forms in situ. The combination of properties make these materials potential candidates for a variety of high-temperature structural applications, including engines, hypersonic vehicles, plasma arc electrodes, advanced nuclear fuels, fusion first walls and divertors, cutting tools, furnace elements and high temperature shielding. Recently, work has been focused on producing ultra-high temperature ceramic matrix composites, UHTCMCs. These materials are typically reinforced with carbon fibres and offer most of the advantages arising from UHTCs but also including much higher toughness and hence capability to resist both mechanical and thermal shock. They are being investigated for a range of applications, from rocket nozzles to thermal protection systems.

MAX phases can have quite complex compositions and their properties include high electrical and thermal conductivity, thermal shock resistance, damage tolerance, machinability, high elastic stiffness, and low thermal expansion coefficients. Some MAX phases are also highly resistant to chemical attack (e.g. Ti3SiC2) and high-temperature oxidation in air (Ti2AlC, Cr2AlC, and Ti3AlC2). They are useful in technologies involving high efficiency engines, damage tolerant thermal systems, increasing fatigue resistance, and retention of rigidity at high temperatures. These properties can be related to the electronic structure and chemical bonding in the MAX phases.

The purpose of this Topic is to bring together interested parties from academia, government and industry in a single forum that allows the bench researchers to interact with designers and engineers to discuss state-of-the-art research and development efforts, what the results mean in a broader context and how to move the technology forward toward near-term and longer term use.

KEY WORDS:

- Processing
- Structure
- Properties
- Testing
- Applications

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TOPIC **8**

Advanced Thermal and Environmental Barrier Coatings: Processing, Properties, and Applications

in memoriam, Dongming Zhu

This symposium focuses on recent advances in ceramic thermal-barrier, environmental-barrier and multifunctional coatings for all types of high temperature ceramic matrix composite (CMC) applications. The symposium will address fundamental aspects of coating sciences and technologies, emphasizing advanced design methodologies; processing; property evaluation and modeling; non-destructive testing and evaluation of advanced thermal, environmental barrier and multi-functional coatings, as well as the coating integration with the ceramic matrix composite systems. Particular emphases are also placed on integrated coating and CMC design, simulation, and performance demonstration; multi-scale modeling and experiment validation of coating processing-microstructure-property relationships; enhanced coating environmental stability, durability, and multi-functionality through innovative coating composition, architecture and processing optimizations; novel, hybrid and sensor embedded coating processing for extreme environments; coating simulative operating condition testing, life prediction and modeling. Special sessions may also be dedicated to advanced thermal and environmental barrier coating case studies on interface and grain boundary phenomena for low diffusion, high fracture toughness, and calcia-magnesium-alumino-silicate (CMAS) resistant coatings for aerospace, automotive, and energy applications.

PROPOSED SYMPOSIUM SUB-TOPICS:

- Thermal and Environmental Barrier Coatings
- Thermal Protection Systems and Ultra-High Temperature Ceramic (UHTC) Coatings
- Coatings to Resist CMAS, Wear, Erosion, Corrosion and Tribological Loadings
- Integrated Coating – Composite Systems and Additive Manufacturing
- Oxidation and Diffusion Barrier Coating Systems
- High-Temperature Vibration Damping Coatings
- Nanostructured and Nanocomposite Coatings
- Functionally-Graded Coatings and CMC Materials
- Multifunctional Coating Systems: Sensing Capability, Performance and Durability
- Advanced Coating Processing Methods, Modeling, and Applications
- Advanced Testing and Non-Destructive Evaluation Methodologies
- Grain-Boundary and Interface Phenomena, Adhesion and Interfacial Properties
- Multi-Scale Modeling of Coating Properties, Mechanisms and Life Prediction
- Computer Simulation and Tool Development for Coating Materials and Systems

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Polymer Derived Ceramics and Composites

The chemical approach based on well-defined preceramic polymers, called polymer-derived ceramics (PDC) route, offers a precise control over chemical composition an microstructure at low processing temperatures, which provides access to a large variety of ceramic compositions and structures (crystalline or amorphous) as well as microstructures (e.g. nanocomposites). Additionally, the PDC route allows exploiting plastic-forming or non-conventional processing techniques to produce advanced ceramic fibers, coatings and matrices, i.e. all the Ceramic-Matrix-Composite (CMC) components. By coupling the PDC route with the generation of a porous network, ceramics with a multiscale porosity can be generated. Thus, this approach makes PDCs of interest for a wide range of engineering and functional applications, in key sectors such as energy, transportation, environment and defense.

The aim of the symposium "Polymer-Derived Ceramics and Composites" is to discuss on the latest developments in the field of PDCs starting from the synthesis of new polymeric systems to structural characterization, microstructure/property correlation, modeling and manufacturing of functional and structural components. Special emphases will be placed on the design of specific components for CMCs like matrices, fibers, and protective or functional coatings, as well as on the potential applications of PDCs in various engineering fields.

PROPOSED SYMPOSIUM SUB-TOPICS:

- Chemistry of new polymeric systems
- Rheological properties of preceramic polymers
- Advanced and innovative fabrication processes, including additive manufacturing
- Plastic-forming techniques
- Porosity network engineering
- Polymer-derived ceramic fibers
- Polymer-derived ceramic matrix composites
- Protective and functional ceramic coatings
- Design of nanocomposites including metal-modified PDCs
- Reinforced foams
- Functional ceramics
- Structural characterization, microstructure/property correlation
- Thermomechanical properties of PDCs
- Chemical reactivity (corrosion...) of PDCs
- Simulation of phase formation, separation and crystallization
- Prediction of ceramic properties in dependency on the precursor
- Thermodynamics of PDCs including CALPHAD
- Prediction of properties using Density functional theory (DFT), Quantum Monte Carlo (QMC) & Phonon calculations
- Application of PDCs in various engineering fields

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Carbon/carbon composites

in honor of Dr. Roland Weiß

Carbon/carbon composites are the oldest and most widely used family of CMC materials. Designed originally for space applications under extreme thermal and mechanical loads and reduced time of utilization, they have diversified their applications to many other fields, among which aircraft and automobile braking, high-temperature industrial reactor parts, etc … The processing techniques are numerous, resulting in a fascinating family of materials with vastly varying properties and performances.
Even though, research and development on C/C composites is still very active, with studies focused on fundamental science (chemistry, mechanics, engineering science) up to the design of innovative carbon-based composites for new applications. This topic encompasses all recent activities on C/C composites, from the most fundamental to the latest applications.

KEY WORDS:

- Matrix processing: polymer, pitch or gas routes
- Protections against oxidation and/or ablation
- Multiscale structure determination
- Non-linear mechanical behavior
- Thermal properties
- Design for specific applications

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TOPIC **11**

Thermomechanical behavior and performance of Composites

This topic is a forum for presentation and discussion of recent research and development activities in mechanical behavior of ceramic matrix composites, at ambient and at elevated temperatures. The symposium will include thermal, mechanical, and environmental behavior of all ceramic matrix composite systems, including oxides and non-oxides. Attention will be given to experimental results for different composite systems (from the smallest to the largest), including constituent content and fiber–architecture effects; developments in elevated temperature testing; developments in test modeling for thermal, mechanical, and environmental conditions; and design considerations for a range of environments and mechanical conditions.

PROPOSED SYMPOSIUM SUB-TOPICS:

- Modeling thermal, mechanical, and environmental behavior of ceramic matrix composites
- Creep, creep-rupture, and fatigue of ceramic matrix composites
- Stress–environment interactions at elevated temperatures
- Elevated temperature test techniques
- Design and transition experiences and realistic component testing of ceramic matrix composites

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TOPIC **12**

Nondestructive Testing and Health Monitoring of Ceramic Composites

Ceramic matrix composites degrade via a variety of mechanisms: transverse matrix microcracks, interlaminar cracks or delamination, oxidation ingress, oxidation/corrosion recession, fiber breakage, unbridged crack growth, etc… To understand composite damage development leading to end of life scenarios it is advantageous to develop techniques that can discern and/or monitor damage development either in-situ or for inspection. Techniques can be based on sound, X-rays, local strains, change in electrical properties, etc… These can be informative to life-modeling efforts either to help develop effective life models or when effective life models are developed to inform the user of the current state of the material. In addition, non-destructive techniques could be effective for quality control during composite component manufacturing in order to discern defects in the composite and/or poor infiltration regions. The aim of this topic is to discuss the latest developments in the areas of non-destructive techniques and in-situ health-monitoring techniques as they relate to inspection, quality control, damage detection, life prediction and/or the prediction of retained properties of ceramic matrix composites.

PROPOSED SYMPOSIUM SUB-TOPICS:

- Ultrasonic inspection techniques for CMCs and CMC components
- X-ray CT inspection techniques for CMCs and CMC components
- In-situ NDE and health monitoring of CMCs and components
- Use of Acoustic Emission to detect damage in CMCs
- Use of Electrical Resistance to detect damage in CMCs
- Digital Image/Volume Correlation (DIC/DVC) strain monitoring at room and elevated temperature
- Relating NDE to retained properties and/or life-prediction

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HT-CMC Joining and Integration issues

Joining and integration issues of CMCs are subject of intense research worldwide, in particular now that CMCs are widely used as structural materials not only for aerospace, but also for commercial aircraft engines, car brakes, key components for energy production, and much more. For some HT applications, the existing CMC joining and integration options may be not suitable. In addition, several joining materials proposed for CMCs have not been properly tested at HT.

The aim of this symposium is to gather expert on these topics, from industry and academia, in order to discuss potential solutions and enable the fabrication and utilization of CMC components for high temperature structural applications. Joining and integration of CMCs include: adhesives, brazing, glass-sealing, diffusion bonding, transient liquid phase bonding, and surface engineering to increase the bon strength.

Reliable methods to test joint strength will also be part of this symposium.

PROPOSED SYMPOSIUM SUB-TOPICS:

- Joining of CMCs and multimaterials
- Joining of CMCs at the nano- and micro-scales
- Design and modeling of CMC joints and interfaces
- Mechanical testing of CMC joined components
- High temperature wetting of CMCs by metals
- Environmental resistance (high temperature, oxidation etc.) of CMC joints
- Nondestructive evaluation technique of CMC joints
- Constructional design issues of CMC joining
- Non-conventional joining methods including flash joining, plasma assisted joining, electrochemical joining and cold joining (T<300 °C)

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CMC Applications in Space Transportation

CMC materials originally have been developed for thermal protection systems (TPS) in reusable spacecraft in the 1970`s and nowadays are state of the art in this challenging application area. Continuous material and process development lead to lightweight and reliable TPS structures of large dimensions and highly complex shaped geometries. Due to the combination of favourable thermal and mechanical properties with low density and high abrasion and oxidation stability, this application area could be extended to CMC structures for hot aerodynamic control surfaces like body flaps or fins.

Another important application area for fibre reinforced ceramics and carbon materials (C/C) are propulsion systems for rocket launchers, reusable spacecraft and satellites. Here the focus is on high temperature stable nozzle extensions, nozzles and combustion chambers as well as on specific components for hypersonic propulsion. Promising new developments are including also low temperature applications in turbopumps.

Beside the high temperature applications, CMC materials and ceramics in general are used for highly precise, lightweight and environmentally stable satellite structures for example in communication systems. Thereby, high specific stiffness and very low coefficient of thermal expansion and long term stability in space environments are the main advantages compared to metals or fibre reinforced polymers.

In this symposium an overview of present CMC, C/C and ceramic applications in space transportation will be given and current development activities and promising future application areas will be discussed. Thereby material, manufacturing, as well as design aspects will be in the focus.

PROPOSED SYMPOSIUM SUB-TOPICS:

- CMC, UHTCMC and C/C materials
- Thermal protection systems and hot structures
- Propulsion systems for spacecraft and satellites
- Hypersonic propulsion
- Hot control surfaces
- Ceramic satellite components and subsystems
- Joining techniques and elements
- Design and modelling of parts in original geometry
- Development activities in novel application areas

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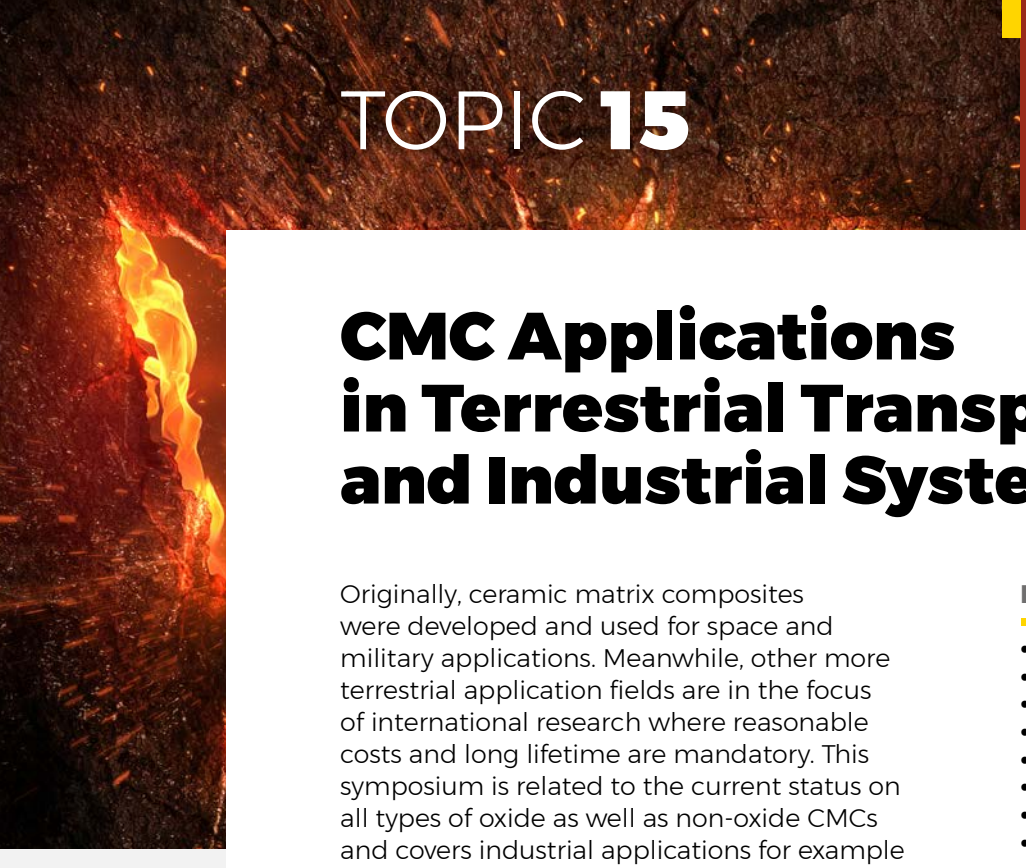
- Heiko Ritter (ESA/ESTEC, The Netherlands)



TOPIC **15**

CMC Applications in Terrestrial Transportation and Industrial Systems

Originally, ceramic matrix composites were developed and used for space and military applications. Meanwhile, other more terrestrial application fields are in the focus of international research where reasonable costs and long lifetime are mandatory. This symposium is related to the current status on all types of oxide as well as non-oxide CMCs and covers industrial applications for example in lightweight transportation systems, combustion environment, heat treatment or other industrial systems and processes. Typically, CMCs are tailored and optimized for specific properties, like high wear resistance and stable tribological behavior in bearings of pumps or brake systems of automotive cars, high-speed trains or high-rise lifts. The high thermal shock resistance in combination with the high oxidation stability of oxide CMCs predestine these composites for innovative applications in heat shields, burner nozzles or charging racks. All kind of application-related contributions to structure-property-relationships and experience in the design of lifetime structures in particular under oxidative conditions are welcome. Also, all cost aspects in the manufacturing and the use of CMCs in industrial systems, including designing, machining, and testing (e.g. NDE) are of interest of this symposium.

KEY WORDS:

- Brake disk
- Brake pad
- Heat shield
- Charging rack
- Ox/Ox
- C/SiC
- SiC/SiC
- Cost analysis

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CMC Application in aeronautic engines

Silicon carbide fibers reinforced silicon carbide based-matrix composites (SiC/SiC CMCs) and oxide fibers reinforced oxide based-matrix composites (Oxide/Oxide CMCs) are probably becoming a major leading alternative for the design and manufacturing of the next gas turbine engines hot parts as airfoils, shroud, combustion chambers and exhaust nozzle. These materials offer higher temperature capability than the current state-of-the-art metallic superalloys and tougher than the corresponding monolithic ceramics. The growing interest in CMC technologies development is directly linked to the new short-term engine design constraints in the context of booming air travel, namely : a drastic decrease of admitted noise and air polluting emissions and a specific fuel consumption decrease.

Building on past materials development efforts in the fields of space launchers and of military aircraft engines, major CMC actors continue to enhance CMC technologies for commercial aircraft engines. Considering this new target, one of the key issues related to this emerging technology is to develop and industrialize materials offering high thermomechanical design allowances and stable lifetime properties, in representative environment. To reach these goals, an important work has been done, in the implementation of thermomechanical behavior and modeling of CMC sub-element and engine CMC part tests.

KEY WORDS:

- SiC/SiC CMC
- Oxide/Oxide CMC
- Thermomechanical behavior
- Design allowance
- Burner rig testing
- Ground engine testing
- Flight engine testing

PROPOSED SYMPOSIUM SUB-TOPICS:

- Recent CMC Technological Improvements for aero gas Turbine Applications
- CMC Thermomechanical Behavior and Modeling: Design allowance
- CMC sub-element Testing in realistic environment and Life Duration approach
- Ground and Flight engine CMC parts tests experiments
- Integration and Attachment between CMC parts and metallic parts: Design and testing methodology

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Advanced materials for sustainable energy (incl. nuclear fission and fusion, industrial gas turbines)

Ceramic matrix composite materials combine favorable thermal and mechanical properties with low density. Composites can replace conventional materials, such as metals or monolithic ceramics, to overcome technical barriers in numerous applications. Beyond aerospace, friction and power generation applications, ceramic matrix composites could be used for new applications where they could be the only solution to reach technical specifications.

This symposium will especially focus on improved and advanced ceramic composite materials for sustainable energy. Whatever gas turbine, solar or nuclear applications (with the advent of new nuclear reactor concepts), there is significant challenge to develop specific CMC materials to meet stringent requirements, i.e., high temperature and/or corrosive environments (including neutron effect). Thus, a systematic approach of modeling, processing, characterization, and in-service performance testing is required to bring new materials in use.

KEY WORDS:

- Nuclear
- Gas turbine
- Solar
- Fusion
- Fission
- Sustainable energy
- Heat exchanger

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