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Ultra-High Temperature Ceramics : Developments for hypersonic applications

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Abstract

Ultra-High Temperature Ceramics (UHTC) are good candidates to fulfil the harsh requirements of hypersonic applications. For more than a decade, ONERA has been actively involved in several programs to develop such materials for different applications (hypersonic flights, propulsion systems ...). In our laboratories, monolithic and composite materials have been investigated as well as several processing methods. In this paper, we present for example the ZrB_2 -SiC and HfB_2 -SiC compositions with $TaSi_2$ or Y_2O_3 additions which have been especially studied in the European Projects ATLLAS and ATLLAS 2. Assessments of several prototypes in realistic environment are also described. Furthermore, based on these material developments, a specific study on the oxidation behaviour of such monoliths from 1200°C to 2400°C with a dedicated test bench using a 2 kW CO_2 laser has been carried out (oxidation under air and water vapour atmospheres). Recently, some work on the manufacturing of Ultra-High Temperature Ceramic Matrix Composites (UHTCMC) has been initiated using slurry infiltration and pyrolysis. The behaviour and properties of these materials are encouraging.

Keywords : Ultra-High Temperature Ceramics, Leading Edges, Injectors, CMC

Nomenclature

ATLLAS	Aerodynamic and Thermal Load Interactions with Lightweight Advanced Materials for High Speed Flight
ATLLAS 2	Aero-Thermodynamic Loads on Lightweight Advanced Structures II
BLOX4	Banc Laser d'Oxydation n°4 (4 th laser oxidation analysis facility)
C/C-SiC	Carbon fibre reinforced silicon carbide composite
CMC	Ceramic Matrix Composite
CTE	Coefficient of Thermal Expansion
EDM	Electrical Discharge Machining
FAST	Field Assisted Sintering Technology
HP	Hot Pressing
PyC	Pyrolytic Carbon
SiC	Silicon Carbide
SIP	Slurry Infiltration and Pyrolysis
UHTC	Ultra-High Temperature Ceramics
UHTCMC	Ultra-High Temperature Ceramic Matrix Composites

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1. Introduction

Hypersonic flights, re-entry vehicles and propulsion applications all require new materials that can perform in oxidising or corrosive atmospheres at temperatures superior to 2000°C and sometimes over the course of a long working life. For re-entry vehicles and hypersonic aircraft, external parts like nose, vertical fins, wing leading edges or flaps are submitted to very high heat fluxes along the flight. Indeed, for hypersonic vehicles for example, performance improvement (lift-to-drag ratio in particular) requires slender aerodynamic shapes with sharp leading edges. However, the thinner the leading edge radius, the higher the temperature. These high heat fluxes are also present for some internal components used for hypersonic vehicle propulsion: injectors, vanes, engine inlets and exits, etc.

Several studies have revealed that Ultra High Temperature Ceramics were particularly interesting to fulfil these requirements [1-5]. UHTCs are compounds made of borides, carbides and nitrides such as ZrB_2 , HfB_2 , ZrC , HfC , TaC , HfN which are characterised by high melting points (Table 1), high hardness, chemical inertness and relatively good resistance to oxidation in severe environments.

Table 1. Properties of some UHTCs

Material	Density (g/cm ³)	Melting temperature (°C)
HfB_2	11.2	3380
HfC	12.8	3900
HfN	13.9	3385
ZrB_2	6.1	3245
ZrC	6.6	3400
ZrN	7.3	2950
TiB_2	4.5	3225
TiC	4.9	3100
TiN	5.4	2950
TaB_2	12.5	3040
TaC	14.5	3800
TaN	14.3	2700

For a few years, the Materials and Structures Department of ONERA is involved in different projects concerning UHTC material developments from manufacturing to thermomechanical assessments of components in realistic environment and oxidation resistance understanding [6-12]. Most of our work on monolithic ceramics has been carried out on diborides of the group IVb (ZrB_2 and HfB_2) which possess very high melting points (>3200°C), excellent thermomechanical properties and a good resistance to oxidation when ~20%vol. SiC is introduced as additive [5,13]. Moreover, in comparison with carbides and nitrides, diborides have also higher thermal and electrical conductivities, which give them a fairly good thermal shock resistance and a good machinability (by using EDM). This last point is appreciable for manufacturing complex shapes. However, the use of monolithic ceramics for high temperature structural applications is limited by some disadvantages (low fracture toughness notably). These issues explain the increasing interest for UHTC matrix composites (UHTCMCs) [14-18]. As a consequence, our recent activities are more focused on continuous fibre reinforced composites in which carbides based compositions have been preferentially investigated (HfC with SiC notably).

This paper presents a synthesis of the results collected on UHTC materials (monoliths and composites) in past and current studies. Several aspects are exposed and notably their manufacturing, their properties, their oxidation resistance, their assessment in realistic environments (arc-jet test, combustion chamber) ...

2. Materials manufacturing

As mentioned previously, two main UHTC material families have been manufactured: monolithic ceramics and composites. Their properties are closely linked with the densification processes, compositions, starting raw materials, microstructures and so on.

2.1. Monolithic ceramics

ZrB₂-SiC and HfB₂-SiC compositions with or without additives have been selected for our studies. Additives as TaSi₂ and Y₂O₃ were used firstly to make the sintering process easier and secondly to enhance oxidation resistance at high temperature. Commercially available ZrB₂, HfB₂, SiC, TaSi₂ and Y₂O₃ powders were employed to manufacture the materials (Table 2).

Table 2. Grade, purity, particle size and measured density of starting powders

Powder	Grade / Supplier	Purity (%)	Particle size d ₅₀ (μm)	Density
ZrB ₂	Z-1031 / Cerac	99.5	8.2	5.97
	Grade B / H.C Starck	>97.8	2.8	5.98
HfB ₂	H-1002 / Cerac	99.5	2.0	10.85
	Grade A / H.C Starck	>97.0	7.6	10.66
SiC	BF12 / H.C. Starck	>98.5	0.6	3.15
TaSi ₂	T-1016 / Cerac	99.5	6.5	9.02
Y ₂ O ₃	Ampere Industrie	99.99	<5.0	4.89

To obtain the selected compositions, starting powders were weighed according to their respective proportions and attrition milled in cyclohexane using ZrO₂ or WC media. Then, the mixtures were dried in a rotary evaporator and sieved down to 50 μm mesh size to avoid agglomeration. Finally, the powder blends were sintered in coated graphite dies (Papyex® + BN) by two different processes :

- Hot Pressing (HP) at Onera,
- Field Assisted Sintering Technology (FAST) also known as Spark Plasma Sintering (SPS) at ICB in Dijon (*FCT System GmbH, HP D 125*) and Mateis in Lyon (*FCT System GmbH, HP D 25*).

ZrB₂, HfB₂ and TaSi₂ powders from Cerac were used only for HPed samples. A synthesis of the sintering parameters of some studied compositions is reported in Table 3.

Table 3. Sintering parameters of several monolithic samples

Method	Sample size	Composition	Reference	Sintering parameters
HP (Onera)	68x68 mm ² plates (maximum)	ZrB ₂ /20vol% SiC/20vol% TaSi ₂	ZST-HP	1700°C/120min/27MPa/Argon
		HfB ₂ /20vol% SiC/20vol% TaSi ₂	HST-HP	1800°C/120min/27MPa/Argon
		ZrB ₂ /20vol% SiC	ZS-HP	1800°C/120min/27MPa/Argon
FAST (Mateis)	Ø20 mm discs	ZrB ₂ /20vol% SiC	ZS-FAST1	2100°C/5min/7MPa/Argon
		HfB ₂ /20vol% SiC	HS-FAST1	2000°C/5min/7MPa/Argon
		HfB ₂ /20vol% SiC/3vol% Y ₂ O ₃	HSY-FAST1	1880°C/5min/7MPa/Argon
FAST (ICB)	Ø60 mm discs (maximum)	ZrB ₂ /7.5vol% SiC	ZS-FAST2	2100°C/15min/50MPa/vacuum
		HfB ₂ /20vol% SiC	HS-FAST2	2100°C/15min/28MPa/vacuum
		HfB ₂ /20vol% SiC/3vol% Y ₂ O ₃	HSY-FAST2	2000°C/15min/28MPa/vacuum

The FAST has the advantage of carrying out compaction, sintering and cooling with high temperature ramps (50°C/min or 100°C/min in these studies to be compared with 10°C/min for HP).

2.2. UHTC Composites

For UHTC composites (UHTCMC), as previously mentioned, materials based on carbides matrix reinforced with continuous carbon fibres have been preferentially investigated (C_f / HfC - 20 vol% SiC in particular). The selected process to obtain these composites was a pressure-assisted Slurry Infiltration and Pyrolysis (SIP) method [19-20.]. This process involves infiltration of a "low-viscosity" slurry into a fibrous preform followed by pyrolysis to obtain the ceramic matrix.

The selected raw materials for these composites were a 2D carbon fibre fabric (Toho Tenax HTA5131, 3K, twill weave 2x2, 282 g/m²) for the reinforcement and a combination of HfC powder (H.C. Starck, $d_{50} = 1.95 \mu\text{m}$, 12.2 g/cm³) plus SiC precursor (Starfire Systems SMP-10) for the matrix. In order to correctly infiltrate the C preform, the attention has been focused on the optimisation of the slurry to obtain a high solid content (>50 vol.%) as well as a low viscosity (<150 mPa.s). Several infiltration procedures have been investigated : one step method (powder + precursor in the same slurry) or multi-step method (powder first and precursor after). For the infiltration phase, a specific metallic mould (40 x 50 mm²) has been used to place the carbon plies and set the final plate thickness (6 plies for $\sim 2 \text{ mm}$ / $V_f > 40 \text{ vol.}\%$ of the mould cavity). The infiltration is realised by applying vacuum on one side of the mould in order to suck the slurry located in a recipient connected to the other side of the assembly. The experiment is stopped when the slurry is seen on the side under vacuum.

After infiltration, samples are dried and hot pressed in graphite die (at 1600°C/24 MPa/1h) under flowing argon to fully transform the precursor in crystalline SiC.

3. Materials characterisation

Concerning the UHTC monoliths notably, a thorough characterisation of their properties has been achieved in several studies and in particular in the European Projects ATLLAS and ATLLAS 2 [10]. Several aspects have been studied: microstructure (X-Ray diffraction), chemical, physical, mechanical, thermal and optical properties (diffusivity, heat capacity, CTE, emissivity), machining behaviour, oxidation resistance in severe environment etc. Only a few of these data are reported in this paper. The bulk density and open porosity of materials were measured by the Archimedes' method. The level of densification was calculated as the ratio of the apparent density on the theoretical density. Microstructures were observed on polished cross-sections using a Scanning Electron Microscope (SEM) equipped with energy dispersive spectroscopy (EDS) for local analysis. Bending flexural strength has been determined by three point flexural tests (test speed 0.3 mm/min, span of 30 mm). Young's moduli were measured by impulse excitation of vibration on bars ($\sim 35.1 \times 5.2 \times 2.1 \text{ mm}^3$) using a Grindosonic MK5 apparatus [21]. Hardness (Hv) and fracture toughness (K_{IC}) were obtained on $\frac{1}{4} \mu\text{m}$ polished surfaces by Vickers' indentation with a load of 98 N. The fracture toughness (K_{IC}) is estimated by crack length measurement of the radial crack pattern formed around Vickers indents [22]. Thermal expansion coefficient were determined up to 1440°C with a heating rate of 5°C/min under flowing argon (20 ml/min) using a SETSYS Evolution SETARAM dilatometer. The oxidation behaviour was studied from 1200°C to 2400°C with a specific test bench using a 2 kW CO₂ laser under air and water vapour atmospheres.

3.1. Monolithic ceramics properties

3.1.1. Microstructure

Densification levels measured on all types of monoliths are superior to 96% of the theoretical density and open porosities lower than 1%. Microstructural aspects of these materials after HP or FAST are presented in Fig 1 and Fig 2. We can see that very fine microstructures are obtained with a good homogeneity and a small grain size. A finer microstructure is observed for TaSi₂-containing materials due to a lower sintering temperature but also to the fact that this compound can act as a grain growth inhibitor.

Fig 1. SEM micrographs of (a) ZrB_2 /20 vol.% SiC , (b) ZrB_2 /20 vol.% SiC /20 vol.% TaSi_2 and (c) HfB_2 /20 vol.% SiC /20 vol.% TaSi_2 monoliths densified by **HP** (in grey, ZrB_2 or HfB_2 ; in black, SiC ; in white, TaSi_2)

Fig 2. SEM micrographs of (a) ZrB_2 /20 vol.% SiC , (b) HfB_2 /20 vol.% SiC and (c) HfB_2 /20 vol.% SiC /3 vol.% Y_2O_3 monoliths densified by **FAST**

3.1.2. Mechanical behaviour

Mechanical properties, at room temperature, of several monolithic samples are reported in Table 4. The mechanical behaviour of these monoliths is really satisfactory. Moreover, it is important to notice than at high temperature some of these properties are sometimes even higher (flexural strength in particular) [7].

Table 4. Density, Young's Modulus, bending flexural strength, fracture toughness, hardness and coefficient of thermal expansion of materials sintered by HP and FAST.

Monolith reference	ρ (g/cm ³)	E (GPa)	σ_f (MPa)	K_{IC} (MPa.m ^{1/2})	H_v (GPa)	CTE (.10 ⁻⁶ °C ⁻¹)
ZST-HP	5,95	446 ± 9	688 ± 79	4,4 ± 0,3	18,1 ± 0,4	7,3 (25-1300°C)
HST-HP	9,09	498 ± 6	869 ± 170	4,6 ± 0,2	18,1 ± 0,6	7,4 (25-1300°C)
ZS-HP	5,36	465 ± 15	451 ± 90	4,3 ± 0,2	20,9 ± 1,9	7,2 (25-1300°C)
ZS-FAST1	5,32	--	468 ± 147*	3,5 ± 0,7	15,3 ± 0,6	7,8 (25-1440°C)
ZS-FAST2	5,65	416 ± 3	584 ± 82	--	--	7,7 (25-1440°C)
HS-FAST2	9,19	479 ± 11	694 ± 91	6,7 ± 0,9	17,5 ± 0,3	7,4 (25-1440°C)
HSY-FAST2	9,04	489 ± 4	843 ± 110	3,9 ± 0,3	21,9 ± 1,1	7,5 (25-1440°C)

*bi-axial flexural strength

Globally, these materials exhibit interesting mechanical properties and they have been applied to manufacture prototypes and realistic components which have been tested (see § 4). However, regarding the fracture toughness of these monolithic ceramics, as predicted they are quite low and similar to that of common silicon nitride ($K_{IC} \sim 3.5 - 6 \text{ MPa.m}^{1/2}$). Thus, as already mentioned, in order to equally dispose of materials with higher toughness levels, a good part of the recent work has been oriented on UHTCMC. These composites could be associated later with other materials to be able to design new components.

3.1.3. Oxidation resistance

Since the first ATTLAS project, several test campaigns have been carried out in order to investigate the thermal and chemical resistance of the monoliths. Most of them were fulfilled with a home-made device (BLOX4) but also in more realistic conditions (close to hypersonic flight for example see § 4). BLOX4 is a facility used for oxidation tests at very high temperatures (up to 2500°C) in controlled atmospheres (H_2O , Ar, N_2 , H_2 , air ...) at pressures ranging from few millibars to 4 bar. Heating of discs samples is ensured thanks to a CO_2 laser (2 kW). Surface temperature of the monoliths is measured with two bicolor pyrometers. A schematic view of this device as well as a $\varnothing 20$ mm disc sample ($\text{HfB}_2/20\text{vol}\% \text{SiC}/3\text{vol}\% \text{Y}_2\text{O}_3$) before and during a test at 1800°C is presented in Fig 3.

In the framework of a recent PhD work three compositions densified by FAST, previously investigated in ATTLAS projects, have been specifically studied at very high temperature under oxidative atmosphere [11-12] :

- $\text{ZrB}_2/20\text{vol}\% \text{SiC}$ (labelled ZS-FAST1 or only ZS),
- $\text{HfB}_2/20\text{vol}\% \text{SiC}$ (labelled HS-FAST1 or only HS),
- $\text{HfB}_2/20\text{vol}\% \text{SiC}/3\text{vol}\% \text{Y}_2\text{O}_3$ (labelled HSY-FAST1 or only HSY).

In this work, all the tests were carried out at a total pressure of 1 bar, under an $\text{H}_2\text{O}/\text{Ar}$ atmosphere (30/70 vol% in Standard Liter). During these tests, once 1000°C is reached (laser power ramp), a temperature ramp of 5°C/s is imposed, allowing the sample to reach the target temperature (between 1200 and 2400°C) where a dwell time is applied before the temperature decrease at the same rate.

Fig 3. Schematic representation of the BLOX4 device, disc sample after machining and surface visualisation during a test at 1800°C

The behaviour of these compositions is greatly dependant of the test temperature. For a dwell time of 20 s we have noticed the following results. Below 1500°C, very thin oxidised layers are formed (according to the initial composition, monoclinic HfO_2 or ZrO_2). At 1550°C, ZS, HS and HSY exhibit a two-layered oxide scale made of a glassy SiO_2 rich layer on the top and beneath an HfO_2 or ZrO_2 layer. At 1900°C, a three-layered oxide scale is observed for all the compositions: a heterogeneously distributed glassy silica rich layer on the top, an HfO_2 or ZrO_2 layer and then a SiC-depleted HfB_2 or ZrB_2 layer. Moreover, some mechanical damages (non-cohesive lamellae) are observed on materials that do not contain Y_2O_3 . At 2200°C, some mechanical issues are detected for ZS samples and a non-adherent oxide layer is present on HS. However, for HSY, oxide layers are still adherent even though the top HfO_2 layer contains cracks. This good behaviour is due firstly to the monoclinic to tetragonal transition of HfO_2 which is less preponderant in HSY than in HS and secondly to the creation of an $\text{Y}_2\text{Si}_2\text{O}_7$ interphase (between HfO_2 and the SiC-depleted HfB_2 layer) that mitigates the thermal mismatch. At 2400°C, only HS has been investigated. For this composition, despite some mechanical damages, the HfO_2 top layer exhibits evidence of sintering and might provide further resistance towards oxidation.

3.2. UHTC Composites properties

It is important to notice that for these materials the development phase is in progress and that several adjustments, on the composition and on the process, are always done. For example, a preliminary work on a PyC fibre/matrix interphase has been carried out (not exposed in this paper). As a consequence, microstructures which are presented in this paragraph (Fig 4) are representative of two types of composites (C_f / HfC – 20 vol. % SiC) manufactured differently according to the information previously mentioned (§2.2). One infiltration step has been applied for the labelled “Composite A” and two for the “Composite B”.

Both composites exhibit a fairly good matrix distribution between the plies however the infiltration process seems still imperfect. Moreover, a few voids and some small cracks are also visible. In fact, some yarns are not completely infiltrated by the slurry and notably their centres. Thus, despite the small grain size of the HfC powder, we can observe a partial filtration of the suspension by the fibres. It is not the case for the SiC precursor which is sufficiently liquid during the infiltration process to correctly penetrate inside the fibre tows. On the other hand, with the thermal treatment applied for densification and pyrolysis, there is no reaction occurring at the fibre/matrix interface which is a good point for further developments.

Fig 4. Microstructure of two Cf/HfC-SiC composites made by SIP

Several UHTCMC have been manufactured during this first development phase. For these materials, final density values are distributed between 5 and 6. No macro-pores are observed and the porosity is principally composed of small voids and cracks. However, the open porosity level is still important (between 21 and 29 vol. %) for a fibre fraction estimated between 30 and 43 vol. %.

Given the results, it is evident that some further work is necessary to optimise the densification step (several infiltrations, new infiltrations parameters, finer grain size ...). Indeed, this is the key to improve the mechanical properties : Young's moduli are around 50 GPa and bending flexural strength around 70 MPa.

Thus the development phase is always in progress in order to increase performances.

4. Realisations and tests in realistic environments

During the development on UHTC monoliths and in particular in ATLLAS projects, we have had the opportunity to assess the materials in diverse facilities to determine their performance. The goal was to test them in more and more representative conditions of a real application. The two most pertinent assessments carried out are exposed below.

4.1. Arc-jet tests

In the first ATLLAS program, a test campaign was carried out under high-enthalpy hypersonic flow in an arc-jet facility of DLR Cologne (L2K) with the support of B. Esser [23]. For each composition sintered by HP (ZS-HP, ZST-HP and HST-HP), four disc-shaped samples ($\varnothing$ 26.5 mm, e = 4 mm) were assayed between 1100 and 1500°C for cumulated duration up to 900s (Fig 5). The resistance of the samples to high enthalpy flow was assessed by several measurements and analysis (weighing, thickness checking, SEM observations ...).

Fig 5. $\varnothing$ 26.5 mm UHTC sample holder and flow field around sample holder during a test at 1500°C

The results of this test campaign were very satisfactory. All the monolithic materials are able to sustain high thermal loads (up to 1500°C/600 s). For each test condition, good material resistance was observed (extremely low mass and thickness variations notably). At 1500°C for example, UHTC samples exhibited a two-layered scale made of a thin protective glassy SiO_2 rich layer on the top and underneath an intermediate layer in the process of being oxidised (SiC-depleted layer). Thus cumulative durations up to 900 s were performed without any problems (for all the selected compositions). A very good sample-to-sample reproducibility and a lack of sensitivity to thermal load cycling have been demonstrated.

As a consequence of the good results obtained in this program, the development has been pushed forward in the ATLLAS 2 project in order to design, manufacture and test uncooled injectors for ramjet engine.

4.2. Uncooled injectors in a ramjet combustor

The main goal of developing UHTC uncooled fin injectors is to ensure a better propulsive efficiency in ramjet engine. During the ATLLAS 2 program, in parallel with a development phase dedicated to UHTC monoliths sintered by FAST (ZS-FAST2, HS-FAST2 and HSY-FAST2), a work has been accomplished in order to define an adequate design for this injectors based on a generic rhombus-shaped injection strut with dimensions around 40 mm in length and 20 mm in height. Injectors were required to contain a fuel feed which should exit at two portholes at the strut's downstream region. The final objective of this work was to validate this uncooled concept in relevant environment (Mach 6 air-breathing flight with stoichiometric combustion) in a MBDA facility (SMR dual-mode ramjet combustion chamber METHYLE) [24].

The first idea was to manufacture injectors made of two components linked via a sliding connection : an upper part in UHTC directly in the flux (injector) and a lower part in CMC connected to the metallic chamber wall (basis). However, due to difficulties during the machining step on UHTC monoliths, an alternative design has been finally selected. This hybrid design was less difficult to realise. It was also made of two components : a leading edge of 1mm radius in UHTC placed in front of the flux and a basis in CMC for the lower part and also for the rear upper part of the injector. An important advantage of this hybrid design was to avoid the passage of the fuel injection tube in two different materials which would imply a perfect control of the tightness between the CMC and the UHTC parts. Some schematic representations of this concept are presented in Fig 6. We can notice than a specific

design of the bottom of the CMC has also been done by the DLR to connect the assembly to the METHYLE test bench.

Fig 6. Schematic representations of the hybrid design selected for the UHTC uncooled fin injector

According to the previous design, two types of hybrid injectors have been manufactured for the test phase: one with an UHTC leading edge made from a HS-FAST2 monolith and another one machined from a HSY-FAST2 monolith. CMC basis of same nature were used for both types of injectors: a C/C-SiC provided and machined by the DLR. As planned, the test campaign has been performed with the MBDA facility to simulate a long duration flight at Mach 6 (Fig 7). During this campaign, hybrid injectors presented in this paragraph but also other injector concepts based on CMC were investigated [9]. The fuel injected through the assembly was a gaseous mixture of H_2 and CH_4 (20/80%) with an equivalence ratio of 1.0. This corresponded to a mass flow of 12 g/s for each strut injector. The incoming air had a recovery temperature of about 1600 K, and no cooling by radiation was possible thanks to a thermal barrier coating on the walls.

Fig 7. METHYLE facility during test at Mach 6 and aspect of the hybrid injectors after the test campaign

As we can see on the pictures of the Fig 7 but also by analysing others parameters observed during the test (surface temperature in particular), the results are very promising. There are just some traces of the flux on the external surfaces of the injectors. So, despite the fact that an assessment of monolithic UHTCs in realistic combustion environment was really challenging, excellent results have

been obtained. Thus, the capabilities of thin uncooled UHTC injectors ($R=1\text{mm}$) to sustain a severe and long test in combustion environment has been demonstrated.

Therefore, thanks to a fruitful collaborative work achieved notably with M. Kuhn from DLR and M. Bouchez from MBDA, hybrid injectors made of UHTC and CMC have been successfully tested in relevant conditions. This success is particularly promising and it paves the way for new realisations (optimised uncooled injectors, fins, rudders, nozzles ...).

5. Conclusions and perspectives

Hypersonic and propulsion applications provide some unique thermal-structural challenges (sharp leading edges, air intakes, uncooled injectors, etc.). In order to fulfil the requirements of these components, some specific materials seem to be compulsory: UHTCs. Indeed, thanks to their unique combination of mechanical, thermal and chemical properties, UHTCs are a promising technology for use in a number of high temperature structural applications.

In this context, for more than a decade, Onera has been involved in several studies. Most of the work has been focused on monolithic ceramics and further programs are still engaged on this way. Indeed, thanks to a new high capacity sintering facility received this year (DCS 200-40 from Thermal Technology LLC), several projects to increase UHTC monolithic properties and their potential uses will begin very soon. Moreover, the demonstration of their ability to fulfil the requirements of ramjet combustor environment is a base to build new projects for more efficient propulsion components.

However, for some structural applications, their toughness performance is not sufficient. That's why a good part of the work recently achieved has been focalised on the development of UHTCMC by a slurry infiltration process. First results are encouraging but some improvements are still necessary to optimise their densification (several infiltrations, new infiltrations parameters, finer powder grain size, new raw materials ...). Indeed, this is the best way to improve their mechanical properties but also to increase their global performances (oxidation resistance notably).

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