Ceramic Matrix Composite behavior enhancement for Gas Turbines Hot Sections

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ABSTRACT

Silicon carbide fibers reinforced silicon carbide based-matrix composites (SiC/SiC CMCs) and Oxide fibers reinforced Oxide based-matrix composites (Oxide CMCs), are probably becoming a major leading alternative for the design and manufacturing of the next gas turbine engines components as airfoils, shrouds, combustion chambers and exhaust. These materials offer higher temperature capability than the current state-of-the-art metallic superalloys and tougher than the monolithic ceramic. The growing interest in CMC technologies is directly linked to the new short-term engine design constraints for dual military and commercial aircraft, namely: an increase of functioning temperature and an increase of mass saving, a drastic decrease of community noise and air polluting emissions and a specific fuel consumption decrease. During the last fifteen years, substantial research efforts have been devoted to evaluating a wide range of CMCs and manufacturing routes. Available experiences, in term of sub-element rig tests and engine ground and flight tests, confirmed the expected gains and provided significant lessons on CMCs behaviour in field service. Furthermore, design tools and tests methods have been optimized for further fine understanding of behaviour, damage tolerance, design criteria and certification approach.

1.0 INTRODUCTION

From a general point of view, Ceramic Matrix Composites [CMCs], through a clever combination of a wide range of fibers and matrices, are designed to tailor thermomechanical responds at high temperature, in a field where the usual metallic materials have reached their limit, or to bring a mass saving due to their low density, with respect to end-use applications [1]. Ceramics fibers and ceramics matrices are inherently resistant to high temperatures, but they are characterized by a brittle behavior as monolithic ceramics. At the opposite, CMCs end up in damage-tolerant material, when the fiber-matrix bonding is properly optimized, usually achieved by a thin layer of an interfacial material referred to as the interphase. Another way to reach a non-brittle behavior, and particularly developed for oxide composites, is to combine the fiber with a weak matrix, obtained by a tailored nano-porosity.

CMCs were initially developed for aerospace applications, successively for the solid rocket nozzle of military missile and civil launchers, for upper stage liquid rocket engine, atmospheric re-entry bodies, and other high temperatures components of missiles. For this domain, generally characterized by very high functioning temperatures but a very short time of use, C_f/C_m CMCs (carbon fiber/carbon matrix) were developed in the 1970s, and are still used today for these applications, including, in some cases an Oxidation Protection System [OPS]. Later on, C/C technology was very successfully transitioned to aircraft brake application, leading to significant mass-production ramp-up.

Due to their great interest as thermostructural materials, considerable investment has been done, in the two last decade, to introduce CMCs technologies in aero-gas-turbines structural components [2,3], where maximum temperatures are relatively moderate compared to rocket propulsion, but where the functioning time in service is very long (life time duration between 1000 to 100.000 hours), in a particularly oxidizing environment. To address the field of aeronautical applications, the approach consisted in successively replacing the carbon fibers then the carbon matrix, which are highly sensitive to oxidation, by carbide and/or oxide fibers and carbide and/or oxide matrices. Today, state-of-the-art, for all actors, which are involved in the ceramization of aero-engines, is to develop and industrialise C_f/SiC_m CMCs, SiC_f/SiC_m CMCs and Ox_f/Ox_m CMCs.

Different manufacturing routes have been developed or are still in development, for processing CMCs reinforced by continuous fibers. The Chemical Vapor Infiltration [CVI] technique is probably the most mature industrial process, considering that it is used today to produce several hundred tons of carbon brake per year. Safran, previously SEP (Société Européenne de Propulsion), used this technology in the 1980s to develop a first generation of SiC/SiC composites, based on Nicalon™ fibers, produced at the time by Nippon Carbon K.K., now NGS (a joint venture between Nippon Carbon, General Electric and Safran). Today, it is the only process which allows depositing interphases on the fibers, meeting the thermomechanical requirements of resulting CMCs. Liquid Silicon Infiltration [LSI] or Melt-Infiltration [MI] is the other process developed up to the industrial stage to produce CMC parts. General Electric, also initiated work, in the 1980s, in MI technology, to optimize and bring to an industrial production stage, the SiC_f/SiC_m CMC HyperComp^{TM} [4]. Now, they have built the complete supply chain for industrial production of several turbines hot sections components [5], particularly, the HP shroud of the LEAP engine, through CFMI (a 50-50 joint venture between General Electric and Safran). Other processes are also under development, such as Polymer Impregnation Pyrolysis [PIP] and Slurry-Cast impregnation. Besides, it is the combination of processes that is most often retained by CMCs manufacturers, in order to reach higher performance as possible and/or to reduce manufacturing costs.

On the other hand, CMC design allowable are dependent on the type of fiber and matrix. Nevertheless, the choice of CMCs manufacturing processes combined to the design of components, including local singularities, is also a main driver of CMC performance. Considering the multiphasic heterogeneous aspect of CMCs, a building block approach is necessary to optimize both easily industrialized parts and design meeting functional requirements. This requires a fine tuned language and engineering tools between mechanics, design and CMC architecture, to end up, after an iterative path, in CMC parts that meet the best compromise between performance, cost and industrialization. Moreover, if it is relatively easy to determine the basic characteristics at a lab scale, complex technological tests often has to be developed, at the early stage of the design justification and to go toward engine tests, taking into account the most representative thermomechanical loads and environments, as possible.

The aim of this paper, after a brief description of the CMC interests for the next aero-engine generation, is to illustrate these different aspects of the CMC technologies, through different examples of Safran experiences, including different types of CMCs associated to different type of component. These results come from several years of studies of Safran Ceramics (previously SEP). A focus will be done on specific tests methodologies development, for a better understanding of damage mechanism and some engine CMCs components tests will be presented.

2.0 DESCRIPTION OF CMC EARNINGS AND GLOBAL ROAD MAP

2.1 BENEFITS OF CMC FOR NEXT GAZ TURBINE ENGINES

CMCs interests and targets are differently defined for military engine and for civil aircraft. However, CMCs technologies often have dual applications in these two fields. Consequently, the main actors that develop

CMCs adopt common basic studies based on key technologies that are needed to design the various materials and associated processes, characterization methods, and components design methods and tools.

The main driver, in the field of the next military vehicles, is an increasing in specific thrust, inducing an overall increase in operating temperature, characterized by the Exhaust Gas Turbine [EGT or T41]. A typical objective commonly targeted by military engine manufacturers is to achieve a EGT of around 3200F [6]. To reach this EGT level, technical activities are directed towards the insertion of advanced CMCs coated by optimized Thermal and Environmental Barrier Coating [T/EBC], in high-pressure turbine, for the design and manufacturing of shrouds, blades and vanes. Introduction of CMC components in turbine hot section significantly improves engine performance by further increasing materials temperature capability, reducing engine weight and cooling requirements. On the other hand, one of the key issues faced by end-users of military aero-engines is durability, particularly for the afterburning section. These components must withstand extreme temperature, as well as rapid thermal cycles, corresponding to the afterburner lights. As the result, exhaust nozzles parts are submitted to heterogeneous thermal flow, pronounced by the overlapping design of the flaps and seals, which generate high thermal stresses.

For the next commercial jet engines generation, CMCs offer improvements over metals, in terms of fuel consumption and polluting emissions reduction, by increasing functioning temperature of turbines, and a mass saving which offers the possibility of introducing additional functions, such as acoustic treatment, to reduce engine noise. The NASA Environmentally Responsible Aviation [ERA] project gives a detailed description of the midterm goals that will have to be achieved in order to meet the next constraints in terms of noise, polluting emissions and fuel burn [7,8]. NASA proposed an estimation of the CMC gains in the next engines: incorporation of 2700F CMC into turbines as HPT and LPT vanes and blades could provide a net overall reduction of 6.0% in fuel burn and a greater than 33% reduction in NOx emissions. At the European level, a working group directed by the Advisory Council for Aeronautics Research and Innovation in Europe [ACARE], have defined very ambitious objectives, to ensure the sustainable development of air transport for the years to come. In particular, this involves reducing perceived noise by 50% (–10 dB), reducing nitrogen oxide (NOx) emissions by 80%, and to exceed the objective of reducing consumption by 15%, all at costs acceptable to the end-users.

2.2 CMC GLOBAL ROAD MAP IN SAFRAN

CMCs offer a real opportunity to introduce a technology breakthrough for aeronautical design and manufacturing components, as described above. Over more than thirty years of basic research and industrial development, Safran has achieved a robust experience in this field. To reach the ambitious objectives of the future engines of military aircrafts, helicopters and commercial aircraft, Safran Ceramics (CMCs Global Research Center of Safran), taking into account the high-level needs and requirements of Safran engine manufacturers, has updated its roadmap, to be able to introduce CMCs in the next engines. As presented in Figure 1, the developments in progress are driven to address a large wide of Engine components for both military and commercial engines (shroud, airfoils, combustion chamber, and exhaust nozzle). The approach is based on oxide CMC below 1800F and SiC/SiC CMC above 1800F, for component temperature functioning. Below 1800F, benefits compared to metallic alloys is essentially the mass saving, including acoustic treatment, especially if the exhaust gas temperature requires changing from Ti-alloy to Ni-alloy. For temperature above 1800F, the CMC benefit is a significant air cooling decrease, resulting in a specific fuel consumption decrease. More precisely, the CMCs technological development, based on an increasing temperature capability, robust thermomechanical properties and acceptable cost for End-users is presented in Table 1 [9].

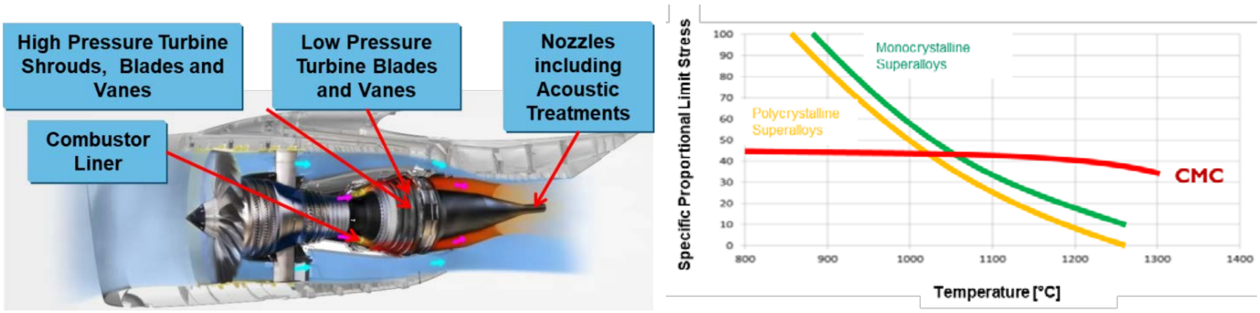

Figure 1: Brief description of candidate components for ceramization in relationship with temperature capabilities compared to metals (Proportionnal limit stress = Limit elastic stress divided by density)

Table 1: CMCs material in Safran, development in progress

	CMC 1500F	CMC 2400F	CMC 2700F
Targeted Components	Exhaust Nozzles including Acoustic treatment	High and Low pressure Blades, Vanes, Shrouds, Combustors liners	
Benefits	Higher temperature than Titanium Mass Saving	Air Cooling decrease, Specific fuel consumption decrease, Mass Saving, Environmental impact	
CMC design T/EBC design	Ox/Ox CMC by liquid route No need of EBC considering max Temp.	SiC/SiC by mixed CVI-MI T/EBC able to Max Temp. of 2700F	CMC without free silicon T/EBC able to Max Temp. of 3000F
Key Issues	CMC Technology cost close to metallic technology Attachment and Integration due to poor Oxide Matrix capability	High Matrix Cracking Stress for reaching acceptable design criteria, below the elastic limit Processes compatible to complex shapes (Vanes, Blades)	

3.0 PAST EXPERIENCES AND COMPONENT IN SERVICE

3.1 IN THE FIELD OF MILITARY ENGINES

The first military application that resulted in full development, addressed the outer nozzle of the military Safran Aircraft Engine M88, powering the French RAFALE fighter. Safran was the first, in 1996, to qualify a CMC component for an entrance in service in an aero gas turbine. Based on C/SiC CMC (SEPCARBINOX$^{®}$A262), including an improved carbon multilayer reinforcement and an enhanced OPS, all mechanical properties and lifetime duration data, in a representative environment, showed that this CMC solution matched the application requirement. Since then, the CMC outer flaps, has been baselined in serial production and more than 15.000 components has been produced today. After more than 20 years of operating use, the in-service behaviour, meets the full life requirements of the M88 engine.

The development of a new self-healing carbide matrix design [10], to improve the oxidative resistance of CMCs submitted to high thermomechanical loads at high temperature, offered new opportunities of components ceramization, in the afterburner section. Thereby, CMCs technologies based on carbon and SiC fibers associated with a CVI SiBC has been evaluated for inner nozzle flaps and flame holders of the M88 engine. Following component design and integration studies, several parts were manufactured, and evaluated on ground engine. For example, C/SiBC (SEPCARBINOX$^{®}$A500), flame holders and C/SiBC inner flaps, were ground tested, following Accelerated Mission Test [AMT], between 200 and 300 hours, including around 40 hours of afterburner lighting. In both cases, representative lifetime tests were achieved with no CMC damage, thus demonstrating the ability of these materials to meet the requirement of a full field service. Evaluation of CMC technology in the exhaust section of a turbine engine of helicopter was also studied, with a SiC/SiBC CMC (CERASEP®A40C). Despite the geometric complexity of the flow mixer, the manufacturing of a full prototype component was a success and this one was flight tested on “Tigre” helicopter, during 130 hours, without any damage [11] (see pictures in Figure 3).

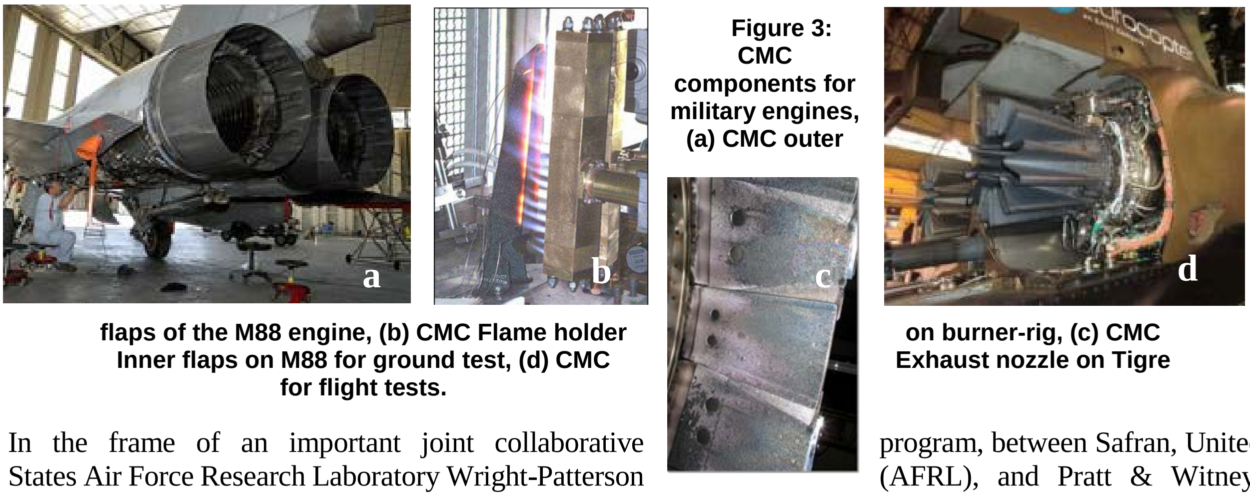

Figure 3: CMC components for military engines, (a) CMC outer flaps of the M88 engine, (b) CMC Flame holder on burner-rig, (c) CMC Inner flaps on M88 for ground test, (d) CMC Exhaust nozzle on Tigre for flight tests.

In the frame of an important joint collaborative program, between Safran, United States Air Force Research Laboratory Wright-Patterson (AFRL), and Pratt & Witney, C/SiBC CMC (SEPCARBINOX®A500) have been evaluated for both F110 and F100 engines that power the F16 and F15 military jets [12]. All US military engines are designed with a convergent-divergent exhaust nozzle. Extensive hardware degradation could appear in service, particularly for components installed in hot-streak locations. After an extensive work of component design and CMC evaluation at coupon level, several divergent seals were manufactured for different phases of engine tests. Ground tests were conducted on an F100 engine during more than 2300 hours; some seals were placed in hot-streak positions. The seals experienced no delamination and appeared visually to be in excellent condition at the end of ground test campaigns. Mechanical post-test analysis was performed for comparison to the as-processed material. The residual strength testing showed only 6% debit. After these positive endurance tests, full nozzles divergent seals were manufactured and were installed on F16 and F15 flight leaders for field service evaluation. In 2015, CMC seals totalized 1500 hours of flights missions on F16, and 1200 hours on F15 (see pictures in Figure 4).

Figure 4: CMCs seals, (a) McEntire JNGB F-16 aft end showing the exhaust nozzle, (b) F-15 at Mountain Home AFB showing the exhaust nozzles of both F100 turbine engines, (c) F100 Ground test

At the end of this representative experiment, some seals showed surface localized spalling and a beginning of wear, starting from the edges for seals.

3.3 IN THE FIELD OF COMMERCIAL AIRCRAFT

Incorporating CMC technology, in combustion chamber liners, aims at reducing cooling airflow needs, thus leading in fuel burn decreases. A full-scale demonstration of CMC liners was performed several years ago by Safran, using the CFM56 engine as a test bed. This work included an overall combustor design and engine integration, and the development of manufacturing technologies, including the effusion cooling. Considering the high thermomechanical required for these kind of components and the long life in service, CMC with Hi-Nicalon fiber and Self-sealing matrix was selected (CERASEP®A415). A full prototype was manufactured and completed by a thermomechanical stresses evaluation at full-scale rig test. A 35% reduction of cooling airflow was achieved. However, additional rig testing would be required prior to engine test, and should include adjustment of the airflow split, in order to enable a thermal profile compatible with HP turbine life [11].

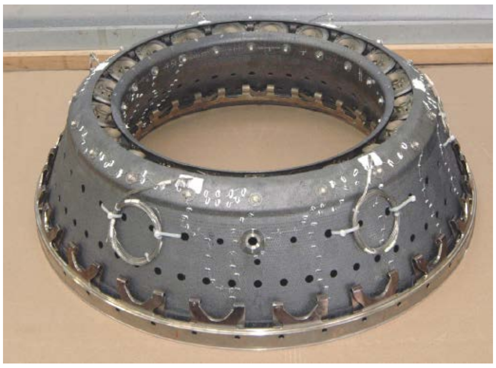

Figure 5: CFM56 Combustion chamber integrating outer and inner liner in CMC.

A major demonstration program in CMC technology evaluation, involves the Low Pressure Turbine blade study (stage 1) on a CFM56 engine. For manufacturing aspects, a first innovative integral texture technology has been developed, based on a monolithic texture, directly obtained by weaving and capable, by shaping operation steps, to realize all the sub-structures of a vane, namely the dovetail, the airfoil and the ancillary functions. Following an important work of partial mechanical tests, in order to optimize design rule and manufacturing rule, a complete LPT1 wheel was manufactured in SiC/SiC CMC (CERASEP®A40C) and integrated in a CFM56, for a real engine test. The subsequent ground test, during several tens of hours of CFM functioning, was the world first [9]. It demonstrated the viability of CMC for the moving part of an aero-engine and highlighted the points to be improved, for a next step development.

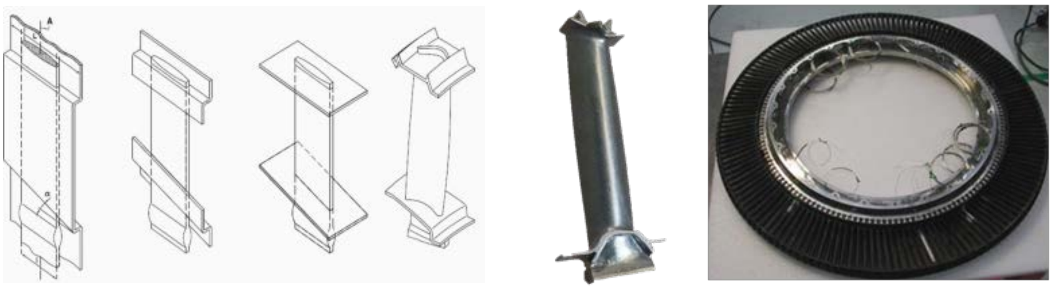

Figure 5: LPT1 CMC blade wheel manufactured and ground tested on CFM56 engine

Another part of interest, in the field of commercial aircraft, is the exhaust unit, for general objectives of mass saving and incorporation of an acoustic treatment. This domain has also been the subject of a major multi-year program, with the aim of designing, manufacturing and testing a complete exhaust, with a low frequency acoustic treatment, for an Airbus A320 type aircraft [13]. Flight test requires intensive components testing. However, based on a SiC/SiC CMC (CERASEP®A40C) for enhanced life duration, an important work was done, from elementary characterization to sub-element tests in order to meet all the requests for a certification file. An example of a thermomechanical test on a part at scale 1 (full size) is presented in Figure 6, the goal was to demonstrate the mechanical ability of the component for life of around 5000 cycles). Prior to the flight program, a full prototype CMC centerbody sustained rig testing for acoustic evaluation on a dedicated GE

Aviation bench, then engine ground testing for performance measurement, and risk mitigation. After that, the prototype accumulated about twenty hours of flight-testing on an Airbus A320. A certification file was built and presented to EASA, and the authorization was obtained in 2015 for a two year commercial flight in operation on a regular Air France line. This two year in service, was successful and allows a significant advance in terms of technical credibility. Many lessons have been learned from this experience, for the next step development, where the main driver is now to propose CMC technology to meet the cost requirements.

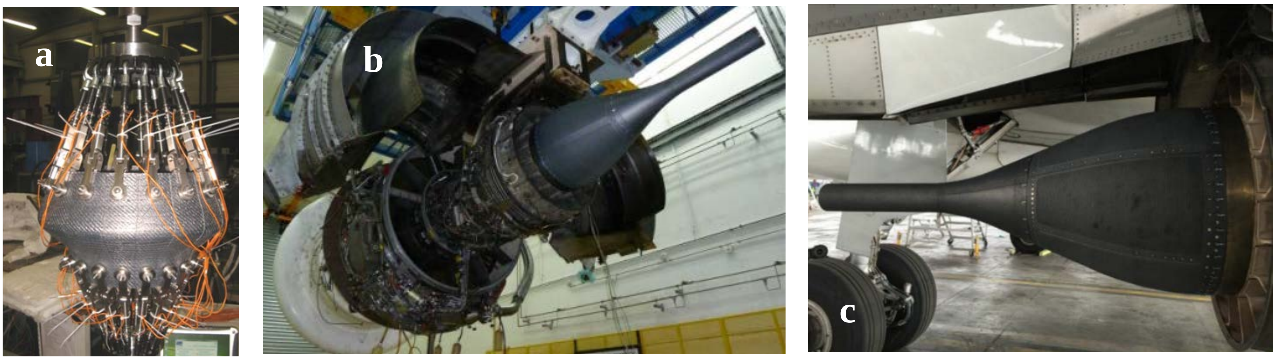

Figure 6: CMCs Exhaust nozzle, (a) Mechanical test on component scale 1, (b) Performance validation on A320, (c) Flight in operation on a regular Air France line.

4.0 KEY TECHNOLOGIES DEVELOPMENT IN PROGRESS

For exhaust section, Oxide CMC is currently the best compromise between performance and cost. CMCs actors generally are developing a pre-preg route based on Nextel™ fibers (N610 and N720 grade). Safran is working on this solution (CERASEP®A100). Nevertheless, to meet the principle goal of this field of application, which remains the cost, another route (Safran proprietary) is under development based on an optimized combination of reinforcement and matrix process (CERASEP®A110).

In the field of hot turbine section components, the SiC/SiC CMC have to be enhanced in terms of thermomechanical performance to meet the requirement of rotating parts, as an example. In order to limit risks of premature damage by oxidation in operating service, a conservative approach is to apply design allowable stress below the elastic limit, which is limited by the Matrix Cracking Strength [σ_{MCS}]. A new CVI/MI SiC/SiC CMC (CERASEP®A600) has been developed to achieve a high and reproducible σ_{MCS}. This one is based on a 3D Interlock Hi-Nicalon-S fiber reinforcement embedded in a high purity CVI carbide and fully dense matrix obtained by powder slurry impregnation and liquid silicon alloy impregnation. The resulting porosity, below 2%, combined with fiber and matrix high modulus, lead to improved mechanical characteristics.

SiC/SiC CMC suffers from poor resistance in the water environment of turbine hot section. This specific behavior is well documented [14,15], as well as the Environmental Barrier Coating [EBC] solutions to solve this problem. The current state of the art is the use of a silicon bond-coat and a rare earth disilicate as top-coat. If it has been clearly demonstrated that EBCs (Y and/or Yb)$_2$Si$_2$O$_7$ have very good resistance in steam corrosion, other damage modes, in service, are to be solved. One of the most damaging is the risk of partial EBC spallation by the effect of oxide growth at the interface, between the bond-coat and the top-coat. A particular effort has been done to improve hermeticity to molecular and ionic diffusion of oxidative species, responsible for oxide growth, in service, by optimizing both formulation and processes of EBC (Safran proprietary).

5.0 CHARACTERIZATION AND BEHAVIORS UNDERSTANDING

CMCs materials exhibit characteristics that are significantly different from metallic alloys. This requires in-depth studies of damage mechanisms under representative conditions and often the development of specific characterization methods. Some examples of behaviour studies, from elementary coupons to sub-element are presented for CVI/MI SiC/SiC CMC, below [16].

5.1 PRECISE THERMOMECHANICAL CHARACTERIZATION, AT MESO AND MACRO SCALE

Beyond the ultimate properties to failure, a fine determination of the first matrix cracks and the following damage has to be performed, within the objective to propose the design criteria, as mentioned above.

Different complex tests have been developed to achieve these data. First, room temperature and high temperature tensile tests coupled with in-situ µCT analysis, has been implemented [17]. This one allowed the detailed description of the damage kinetics for temperature up to 2200F. Furthermore, it has been verified that quasi-static tensile test coupled with Acoustic Emission [AE] and Digital Image Correlation [DIC], led to the same results (see Figure 7).

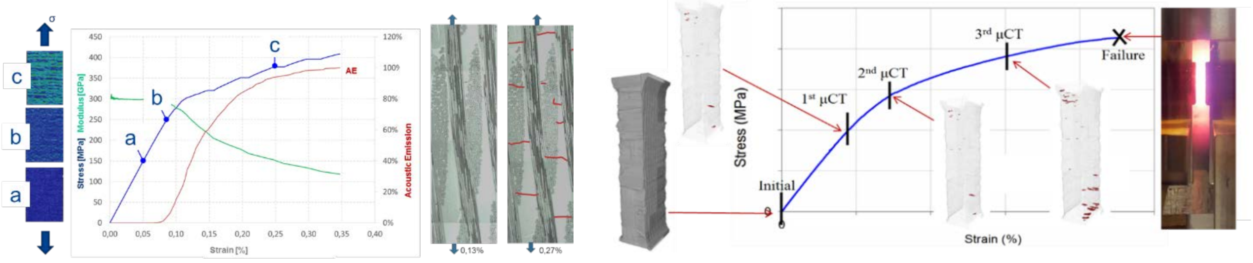

Figure 7: Detailed tensile behaviour analysis of SiC/SiC CMC, by In-Situ µCT test and Quasi-static test with AE and DIC measurements.

To better analyse the damage mechanism of CVI/MI SiC/SiC CMC, other elementary tests have been performed, mainly based on off-axis loading. These characterizations include tensile test in dir. 45°, torsion test and flexural test [18]. For these different loading cases, the same first damage mechanism is detected, in relation with the matric cracking threshold (see Figure 8).

The lifetime determination for stress/strain level close to the matrix cracking stress and in tensile creep and fatigue, for temperatures range of 1500F to 2400F is in progress. The results, for the as-received materials without EBC, show that no failure occurred for stress/strain levels below or equal to the matrix cracking stress. This result was expected, in connection with a non-internal CMC oxidation. Static properties and lifetime properties are summarizes in Figure 9.

5.2 EXAMPLES OF SUB-ELEMENT TESTING IN REALISTIC LOAD CASES AND ENVIRONMENT

Before going through an engine test, an intermediate characterization scale has to be done to determine and analyze, first complex thermomechanical loads met at a specific geometric point of a component and/or for a particular engine operating point, and then the environmental effects.

For example, a sub-element of shroud section, integrating EBC top-coat, has been subjected to several flame rig campaigns [16]. By applying a representative thermal gradient, sub-element is subjected to thermomechanical loading that is met in the engine operating cycle. Particularly, the CMC/EBC interface is loaded in thermomechanical fatigue, in these conditions. The flame rig is multi-instrumented (IR camera, pyrometer, DIC), in order to determine the flux parameters by Finite Element Method Up-dating [FEMU] and then to calculate the mechanical deformations in the component (see Figure 10). Post-test morphological analysis allows detecting cracks, in relation with the local regions where thermal stresses overlap the design criteria. Some tests are run by integrating between flame exposures, several hundred hours of steam corrosion, to introduce an accelerated aging.

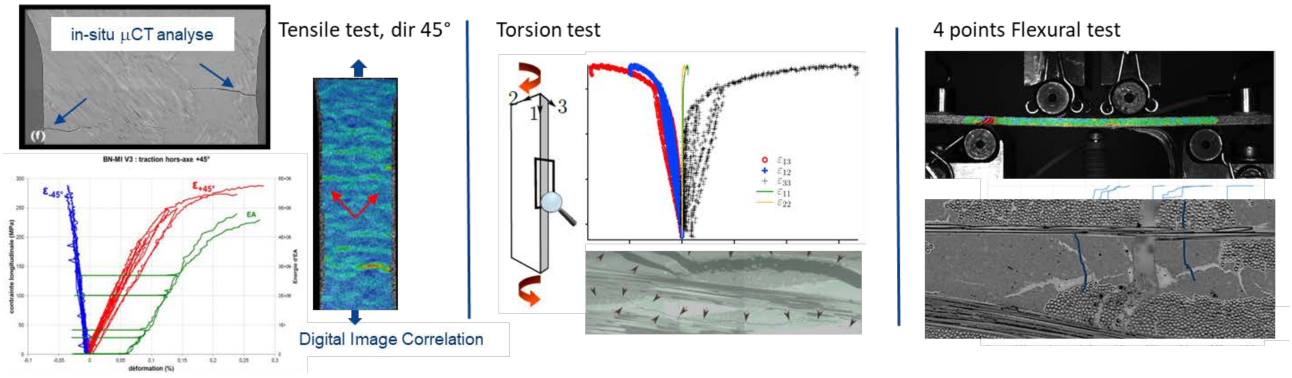

Figure 8: CVI/MI SiC/SiC CMC Off-axis characterization at room temperature, with AE and DIC measurements.

Static Mechanical data	
$\varepsilon 1_{MSC}$ RT (%)	0,065 – 0,075
$\sigma 1_{MSC}$ RT (MPa)	190 – 215
$\varepsilon_{R0,005}$ RT (%)	0,09 – 0,1
σ_{Rup} RT (MPa)	350 – 450
E RT (GPa)	270 – 300
$\tau_{R1.3}$ RT (MPa)	75 – 120

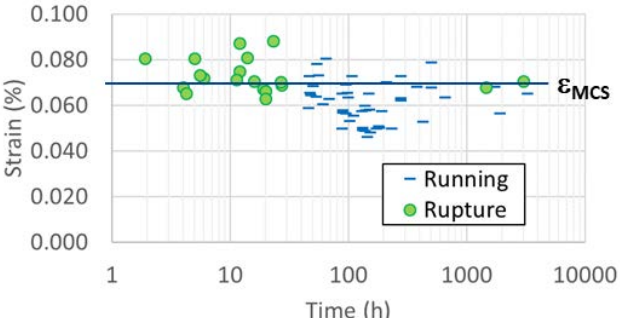

Figure 9: CVI/MI SiC/SiC CMC ((CERASEP®A600) static mechanical data and Wolher curves in tensile creep and fatigue

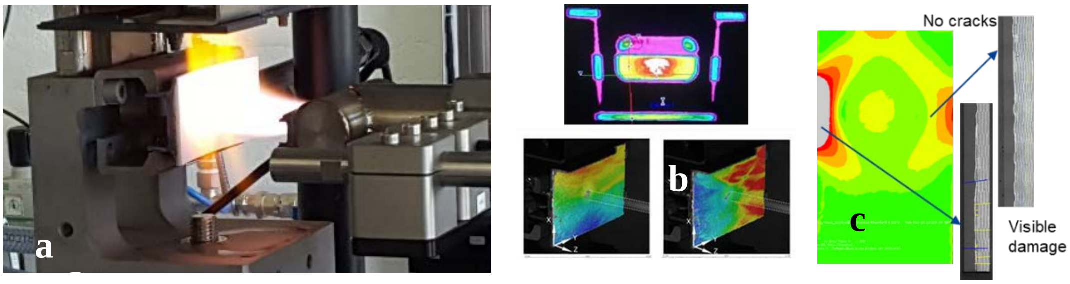

Figure 10: Flame rig test, (a) bench, (b) FEMU analysis, (c) Mechanical deformation and post-test expertise

On similar sub-element types, thermomechanical fatigue aging tests have been performed on a more representative gas burner rig including an O_2/H_2O environment. This burner rig, named MAATRE and located at ENSMA-P' Institute (Chasseneuil, France), has been used for around 100 hours of thermal cycles at Tmax=2400F and P_{H2O} =16 kPa. During this test, another damage mode of EBC was highlighted, characterized by a surface crack network on the hot face, related to spatial and temporal thermal gradients and cooling rate [19]. Others investigations will be done to better understand this damage, including works to optimize the thermal gradient representativeness and to add mechanical loads (see Figure 11).

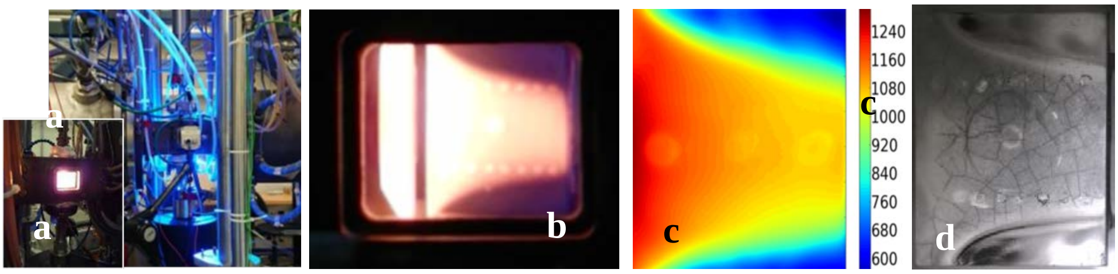

Figure 11: Burner Rig test, (a) MAATRE bench, (b) CMC coupon, (c) hot face profil, (d) crack network on EBC surface.

An experimental setup, based on heat flux CO_2 laser to simulate thermal loading, has been developed in ONERA (Châtillon, France) with various instrumentation enabling kinematic and thermal field measurements. The laser spot heats locally the sample, generating multi-axial thermal gradients. Active air-cooling, at the backside of the sample can increase the through-thickness gradient. Following a complete experimental plan and modelling approach, it appeared that only the effects of thermal expansion mismatch and residual stresses could not explain this particular EBC damage, but that a creep factor was necessary [20].

In the field of hot section rotating parts, one of the key issues is the high loading, at the blade dovetail inserted in the disk. A method has been developed to identify the mechanical behaviour of a CMC root in a metal cell, at room and high temperature (see Figure 12). Following an iterative approach, the design rules and manufacturing processes have been optimized, to increase mechanical resistance of this sub-component and at the end, propose a CMC dovetail meeting the thermo-mechanical requirements, with a stable behavior up to 3 time nominal loads.

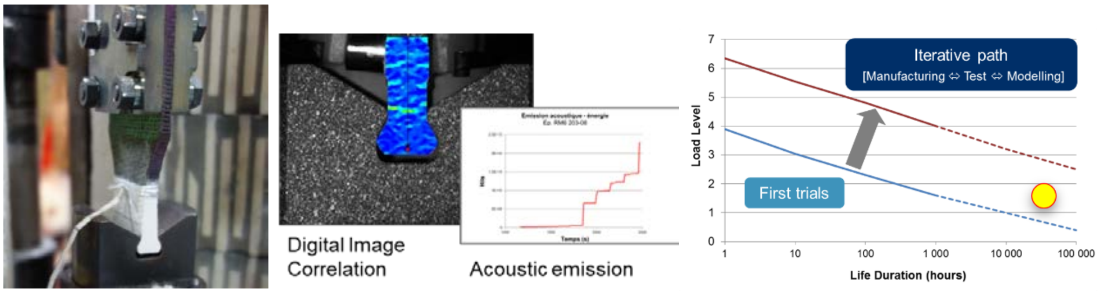

Figure 12: Mechanical test of a CMC dovetail inserted in a metallic cell.

6.0 CONCLUSION

The high thermomechanical properties of CMCs materials offers a real opportunity for the next generation design of both military and commercial aero-engines. The CMC technology development requires an extensive work of thermomechanical damage analysis, based on elementary coupons tests and sub-element part tests, in increasingly representative conditions, including complex thermomechanical load and chemical environments. The CMC ability, to meet thermomechanical constraints and environmental requirements for turbine hot section and exhaust section, is soon being demonstrated. Several CMC parts engine tests and field applications are now available, confirming the expected gains and providing significant lessons on their behaviour in field service. Furthermore, the extensive works that has been done to optimize characterization methods, damage mechanism understanding, thermomechanical modelling, go towards an improvement of the design and manufacturing rules. To pursue the path of CMCs integration in aero-turbines, in the near term, a lot of work remains to be done: increase damage tolerance, increase EBC life robustness, being able to define design criteria, with reasonable margin, develop certification methodology, enhance manufacturing route, to achieve acceptable cost. The mass production of CMC components for gas turbine engine will be a new challenge for engines manufacturers.

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