THE THERMOSTRUCTURAL COMPOSITE NICHE : A GLOBAL APPROACH

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SUMMARY: *This is the text of the opening talk of the ICCM12 Conference. This plenary lecture is traditionally called the Scala Lecture in honor of the foundation of the ICCM Conference in 1975*

KEYWORDS: Thermostructural composites, Carbon-Carbon Composites, Ceramic Matrix Composites, Carbon Brakes , Rocket Nozzle

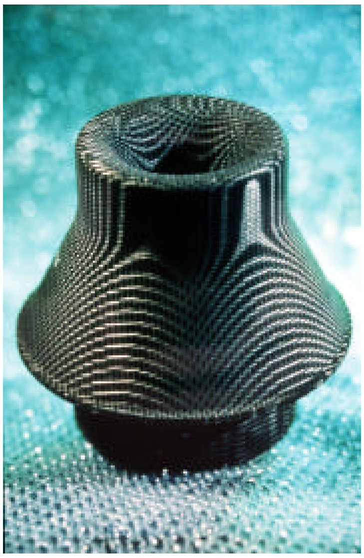
INTRODUCTION

I am not a scientist, and no longer an active player in the field of thermostructural composites. So I will not give a paper as you say in your scientific conferences. I will offer you an informal talk, as befits a pioneer, a grandfather, or perhaps a dinosaur – I will leave it up to you to choose “le mot juste".
Why do we need another presentation on thermostructural composites, in particular on carbon or ceramic matrix composites, called CMCs? Why do we again bring up the subject of this strategic niche inside the giant field of composite materials? Because, we are seeing a convergence of critical new needs and technology breakthroughs. Because this situation opens new opportunities for CMCs, even if we still have progress to make, from both technical and economic viewpoints, to satisfy all customer requirements, hopes and dreams. And because this provides an excellent chance for a new generation of talented researchers and engineers, deploying powerful new tools, and very much used to work in partnerships.

What to do, to seize this opportunity? First to follow what I call, in my bad American language, a global approach. By global I mean an integrated approach bringing together everyone and everything we need.
Second, not to forget the lessons we have learned from an already rich history. I would like to draw on a few concrete examples from my own experience to show how this global approach is applied to thermostructural composites.

RAISON D'ETRE

Why do we need these thermostructural composites? First of all, to bring high thermal capability. To stand up to temperatures of more than one-thousand degrees Celsius. Most other composites, and materials in general, are totally incapable of this performance. Secondly, to obtain greater toughness than monolithic ceramics and graphites which are vulnerable to thermal and mechanical shocks. Last, to provide a much lighter-weight solution than refractory metals. In many ways, CMC's are the perfect material (Fig1). Light and strong like a composite, refractory like carbon or ceramic. The coming of such materials was inevitable.



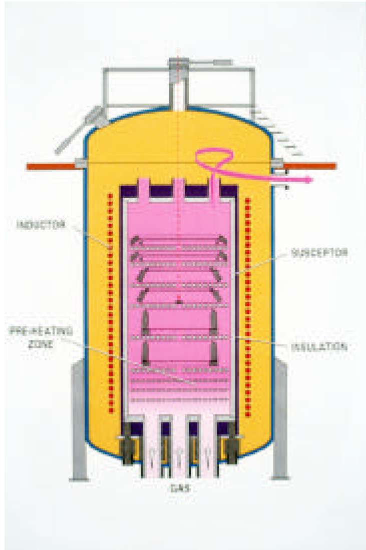


Fig1. 3D weaving construction

Fig2. Induction furnace for chemical vapor inflitration

How do we reinforce a carbon or a ceramic? We can use fabrics, but what about delamination? We can use magnificent 3D weavings or even 4D constructions, but what about the costs? Innovative preformed reinforcements continue to come down the pipe, with the very active cooperation of the textile industry.
But first, we need the right fibers. Seniors saw the development of carbon fibers. We are now entering the era of silicon carbide fibers. I would like to take this opportunity to thank our Japanese and American colleagues for driving progress in this field.

Preforms are densified by introducing matrices, whether carbon or ceramic. We tend to use "chimie douce" processes to avoid damaging the preforms and to limit residual stress. The most common process today is chemical vapor infiltration. It is done in induction furnaces, at 1000°C and under low pressure. (Fig.2)

Fig3. Densification by CVI

Fig.4 Furnace for production of carbon breaks

The gas precursor penetrates the preforms and decomposes inside to deposit the matrix around the fibers (Fig. 3). This gives us thermostructural composites : carbon carbon, carbon ceramic or ceramic ceramic. The first term refers to the fiber, the second to the matrix.

Is there a market for these “miracle” materials? In the beginning, a strategic need for ballistic missiles obviously drove the development of carbon-carbon materials. Rocket motors and reentry vehicles godfathered their development.
Today it is aircraft engines and reusable space vehicle engines, as well as space plane hot bodies, that are driving ceramic-ceramic technologies. “*Give me another 300 degrees*” says Dan Goldin, the NASA Administrator. I don't know if it is C or F. I hope it is F. Once this goal has been met, we will see a big change in the aerospace transportation paradigm.

In the meantime, a mass market emerged. Carbon brakes have taken over steel brakes on commercial airplanes. Today, the worldwide production of carbon disks already reaches one thousand tons a year – practically doubling in the last five years. (Fig.4)

For the first time, the family of thermostructural composites is pulled technically by a strong strategic need, and supported economically by a booming market. All the conditions are satisfied to reenergize technology progress in ceramic-ceramic materials, while, at the same time, expanding the industrial market for carbon-carbon products.

STATE OF THE ART

Where do we stand today?
What is under control?
What do we produce?

As we approach the “*fin de siècle*”, what is the state of the art in the thermostructural composite industry? The following images will give you an idea of where we are.

Fig.5 Carbon Carbon exit cone of the RL10B-2 engine nozzle

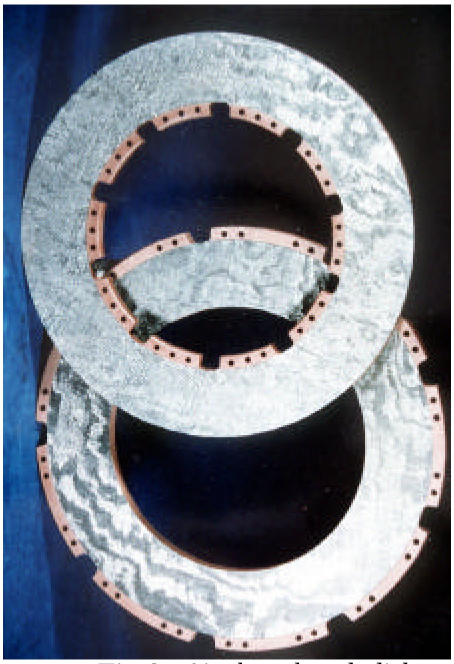


Fig.6 - Airplane break disks

Carbon-carbon is intensively used in solid rocket motors. It has become the material of choice for both large and small nozzles. It gives us efficient, strong and light heat sinks. Here you can see the carbon-carbon throat of the Ariane 5 solid booster nozzle. It’s a big one, with

thick walls – which is a key aspect. This nozzle handles a gas flow rate of more than two tons per second, and the gas temperature reaches three thousand degrees C. The ablation rate is small compared to that of the phenolic carbon composites. At the same time, the specific gravity is only 1,7. Very light compared with the 19 of the tungsten nozzle throats of my youth…
Let me give you another example, this time a thermomechanical shell for a liquid rocket engine nozzle. Here you can see the carbon-carbon extendible exit cone of the RL10B-2 engine nozzle.Fig.5. Once again it's a big one, but this time with very thin walls-which is also a key aspect. Why do customers always ask us for something that's too thick or too thin? In this case, the wall thickness is less than three millimeters. This 2.5 meters long extended exit cone brings the nozzle expansion ratio up to near 300. It provides a spectacular increase of 30 seconds in specific impulse, for an extra weight of only 100 kilos. What a tremendous gain of performance, especially compared with the big efforts needed in terms of propellant chemistry or combustion technology, for much smaller results.

Now we come to airplane brake disks. In this case a set of Airbus disks. Carbon-carbon not only acts like a perfect heat sink, but also like an excellent friction material, till very high temperatures. In addition, on a typical Airbus plane, it offers weight savings of about 600 kilos. (Fig.6)
As many of you probably know, today's winning race cars use carbon-carbon brakes. In the competitive world of Formula One, this has been the case for nearly 15 years. Cars in the famous 24 Heures du Mans race, have also used carbon brakes since 1990.
The racetrack provides advertising. It also brings fast technical feedback, which supports aviation improvements, and paves the way for the luxury car and truck markets. How fast this automotive market will develop? Difficult to say except today for us it is already larger than the military aircraft brake market.(Fig.7)

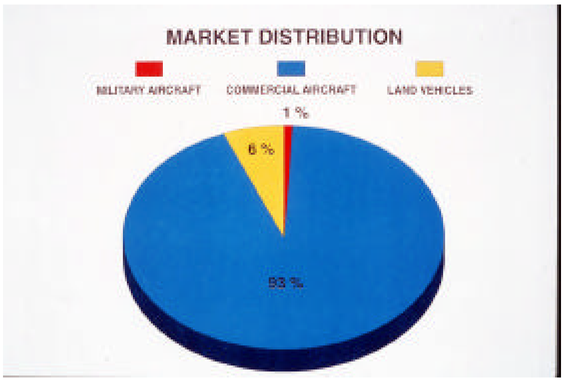


Fig.7 Market distribution

Fig 8. Cementation funace with carbon-carbon tooling

More generally, carbon-carbon composites also encompass various installations involving energy, high temperatures and hostile environments. Here you can see a sophisticated equipment for metal cementation furnaces. (Fig.8) Recently, a brand new plant has been built, starting from this innovative tooling solution.These examples show how, in certain niche markets, carbon-carbon is able to capitalize on its strengths, while not being penalized by its poor oxidation resistance.

To move beyond we had to replace the carbon matrix, or both the matrix and the fiber, by elements which offer greater resistance to oxidation, such as silicon-carbide. This is why we developed carbon-ceramic and ceramic-ceramic materials.For example this other nozzle part, this time for an aircraft engine. This is the outer flap of the Rafale fighter M88 engine nozzle. (Fig.9)

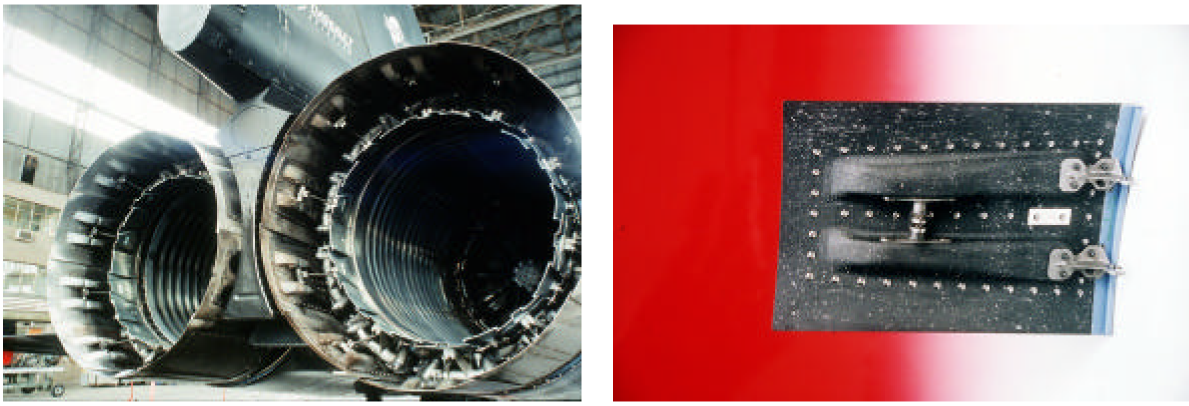


Fig.9 - Rafale fighter engine nozzle

Our aims were relatively limited on this first series production application, since the flap would experience a temperature of only seven hundred degrees. This flap provides 50% weight savings. It also gives us invaluable feedback in terms of both production and operation. For this application a carbon-silicon carbide material was the appropriate solution.

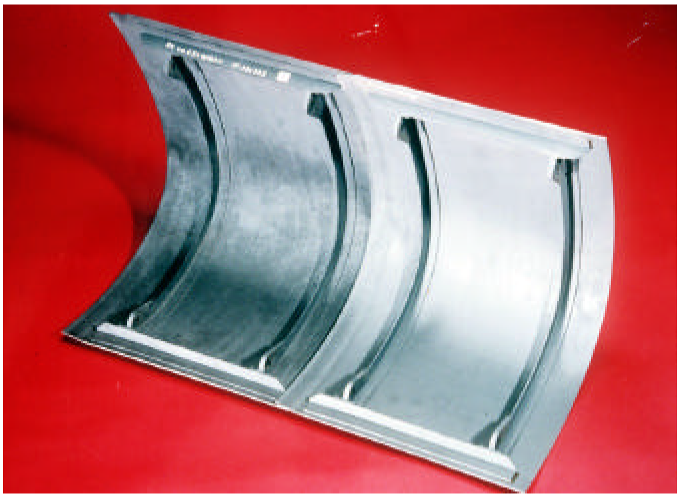


Fig.10 Hermès spaceplane leading edge

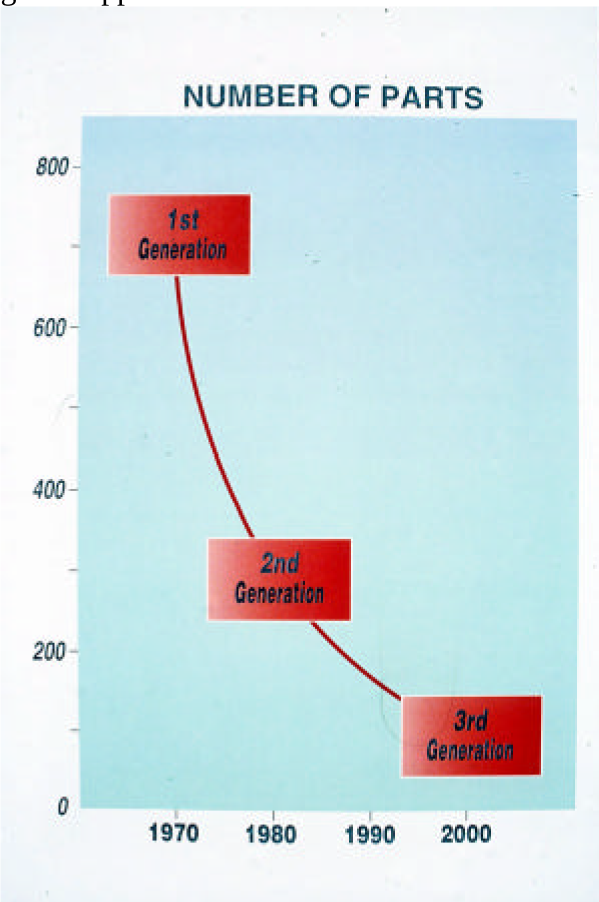
Such a material was also used to make Hermès spaceplane body parts exposed to the most heat during atmospheric reentry. Here is a leading edge for Hermès.(Fig.10) This promising first attempt greatly gave credibility to the principle of reusable launch vehicles. It also helped to better guide research and technology efforts in order to make it feasible.

At the same time, it showed that taking a global approach was absolutely essential in order to come up with designs both simpler and more integrated than this prototype box for Hermès, with so many fasteners. Once again, this was a very beneficial experience in addition to our previous experience in propulsion and braking.

LIBERATED DESIGN

It is obvious that a composite design taking into account the real functional requirements of a whole assembly is generally far better than simply replacing a conventional part with a same size and shape composite part. Every designer knows it and many of them apply this principle.
To get the full benefits of thermostructural composites, we need an even larger degree of design freedom than for other composite materials. There are two main reasons for this. First, thermostructural composites are more and more multifunctional materials. To take advantage of this we need to forget conventional standards and design the right shapes from the beginning. By doing this, we achieve a dramatic reduction in the number of parts. The second reason is that the mechanical properties of these composites are still modest in relation to metal alloys. This means that we need additional design freedom, to avoid concentrated thermal and mechanical stresses in components, and above all in the liaisons between parts.

Both customers and designers must change the rules of the game and apply a functional global approach.



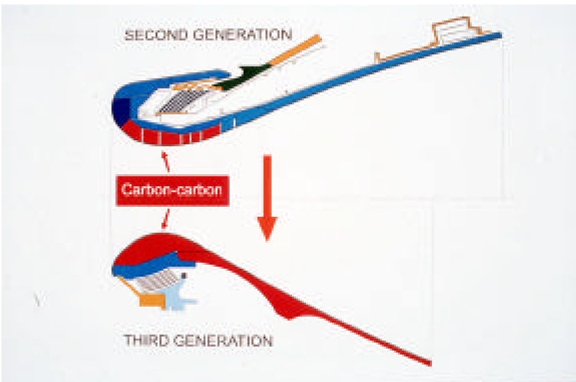


Fig.11 - Comparison between second and third generation engines

To give you an idea of the results of such action, let's consider the changes over time through three generations of solid rocket motors. Here, we have both the experience needed to evaluate this global design approach, and the clear proof of its validity. Fig 11.

- The first generation was more than eighty percent metallic.
- The second generation was fifty-fifty metal and composite.
- The third is more than eighty percent composite.

For a given type of mission, the use of thermostructural composites gave us from the first to the third generation:

- engines that have half the weight and twice the thrust;
- engines with seven times fewer parts;
- engine parts with more simple shapes;
- engines with half the cost;
- engine development using three times fewer tests;
- engine development that costs one third as much;
- engines that are three times as durable;

and a very high reliability – 20 years without an in-flight failure for the second-generation engines (of course I keep my fingers crossed….). Please note, however, that we have only cut engine weight by two. Given the composite to metal density ratio, this should have been nearly three. The global approach led to a different balance of specifications in favour of reliability and cost. Believe me everybody is now very pleased with the result. This is a lesson that should be learned by heart, even though short-term competitive pressures often lead to crime in the long term.

Let's take a closer look at nozzle design evolution.We were proud of our second-generation nozzle. Thanks to the development of the first carbon-carbon, we were able to integrate the nozzle in the combustion chamber. Because of an overall length limit, this gave us significant extra propellant for performance. And once we had developed this integrated nozzle, we could install it on a flexible bearing in order to simplify the control system. This was a revolution in the nozzle concept driven by the materials. And this revolution came through a global approach combining tougher specification, technology breakthrough and design freedom.

But now, we are able to make the third-generation nozzle even simpler, lighter and higher performing, thanks to additional progress in carbon-carbon. Count the number of parts, and check out the respective masses. And see how the nozzle is now completely carbon-carbon, from nose to exit, keeping optimum aerodynamic behaviour all along the mission.

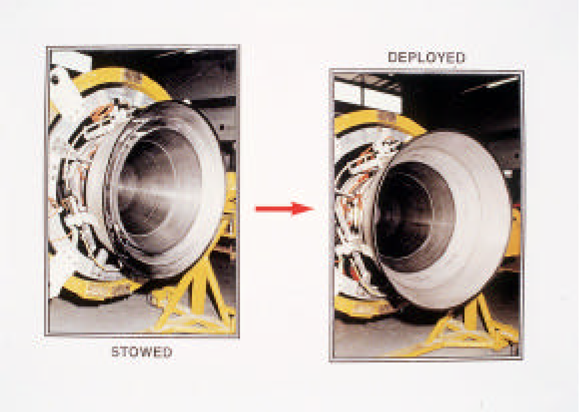


Fig.12 RL10B-2 nozzle

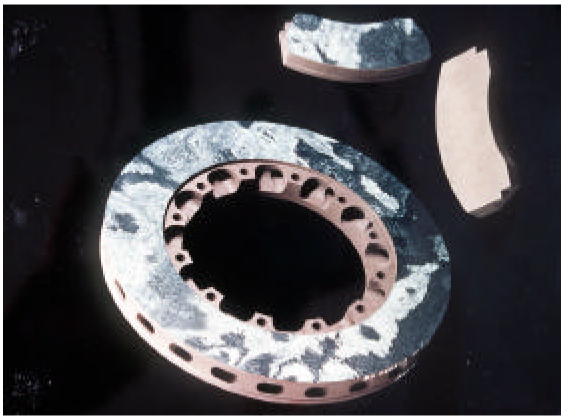


Fig.13 Non woven preform for carbon brakes

And please note that one or two carbon cones could be added to build an extendible exit cone if needed, as we saw on the RL10B-2 nozzle. (Fig.12)

Can we extrapolate from this example? Well, yes … and no. Whatever the answer may be, we have to remember the main guidelines for this global approach to design. We must go to lean architectures, simple shapes, few parts and lightly-loaded liaisons.
Of course, these composites will become more and more complex internally. This is the price to pay to increase reliability and to get lower cost.

Everybody, whether customers, managers or designers, should understand and accept this evolution. To reach the goal, we must not only offer a large degree of design freedom, but also intensify material research and technology efforts, to better create, understand, model and produce these materials. Then, and only then, it will be possible to completely master them, and to predict operational behavior and performance with accuracy all along their life. And of course, in the meantime, we must use thermostructural composites with both determination and caution, by implementing concepts based on robustness and tolerance.

MATERIAL-PRODUCT INTEGRATION

Unlike metal parts, which are made by forming or machining a material, a composite part takes shape at the same time as the material is built. Thermostructural composites are no exception to this rule. In fact, the inherent risks and difficulties are even higher because densification requires heavy industry.

In this sense, the CMC industry is close to the steel industry with blast furnaces in continuous operation. Starting with a textile preform, the densification process produces both the material and the part during a long stay in the furnace. Under these conditions, you can well imagine the importance of process control for quality and reproducibility. It is vital to choose a process which is both simple and, as much as possible, independent of the preform shapes. This is why chemical vapor infiltration continues to be the process of choice, despite the long cycles involved. Compared with other faster processes, it offers a large degree of operational flexibility. Of course, like the steel industry, this process demands heavy capital expenditures. But on the other hand, once you reach volume production, it maximizes labor efficiency. One small team can operate a battery of furnaces.

Let me return to the question of what I would call the rather intimate relationship between product and material. This intimacy should be used to design the material to meet final product specifications, by well adapted construction of the preform. I would like to give you a practical example. In this case, by applying the global approach to a problem, originally trivial, we actually created a non-woven preform industry for carbon-carbon products.

Our story starts back in nineteen eighty. Carbon brakes offered good performance on the Mirage fighter. (Fig13) But the application of carbon brakes to Formula One racing cars turned out to be a problem. The disks were delaminating during operation, due to ventilation holes drilled along the edge. The carbon-carbon used at the time was naturally the same as for nozzles, with a two-D preform based on magnificent satin carbon fabrics that would have looked good in a "haute couture" dress. But this material did not like to be drilled. This may have been a minor concern, compared with the aerospace applications. But it nonetheless drew our attention, because of the new global approach then taking shape. In the end, this

concern led to the following specification: “Construct a robust, delamination-resistant preform for a low-price carbon-carbon material.” Exactly what the doctor ordered for cars!
The field was wide open. The car racing motivated our people. The genius of one creative engineer did the rest. He invented the family of non-woven carbon preforms. No fabrics, no impregnated fabrics, no presses, no resin carbonization. And of course no three-D weaving. Just a set of ugly webs needled together by a sort of fakir’s bed of needles, which could perhaps be more accurately described as a phalanx of fish-hooks. A large enough number of staple fibers driven through the thickness prevents delamination. Interesting, but horrible. Only good for cars, said the aerospace managers.

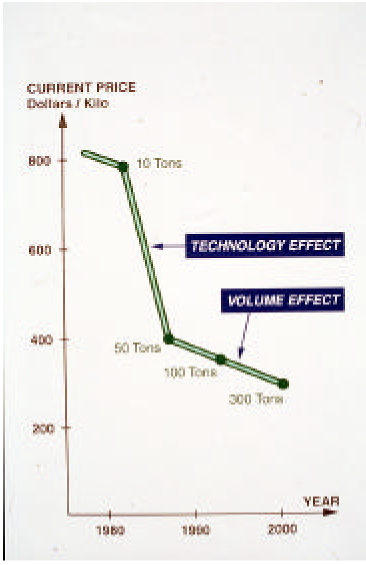


Fig.14 Technology effect on price

Fig.15 Partnership and Progress

With the success of carbon brakes on military aircraft, the commercial airliner market looked very juicy indeed. But with carbon-carbon at the level of 800 dollars per kilo, prospects weren’t very good. The global approach steered us toward the brand-new non-woven material, half the cost and much easier to produce. The decision was made. The brakes were qualified on Airbus. A dedicated plant was opened in France. A license was sold to US industry. Production geared up. Today, in France we produce nearly 300 tons a year, equivalent to more than 100,000 disks. Fig 14
Ironically enough, this same material has come full circle and is now used for propulsion applications. We saw it in various parts of nozzles, as well for the heat sink of Ariane 5 booster nozzle and the thermomechanical shell of the RL10B-2 engine nozzle. It is also a key advantage in expanding industrial applications. Anyway, this is a marvelous example of cross market synergy.

PARTNERSHIP AND PROGRESS

Expertise in thermostructural composites depends on the cross-fertilization of a vast range of scientific disciplines and industrial skills. All along the whole process — from basic research to the end product — a global approach and a long-term vision favors cooperation and synergies. By clearly defining the challenge, this type of approach facilitates durable scientific and industrial partnerships.
(Fig 15)

Progress and success in thermostructural composites depends on the quality of integrated teamwork. For example, our progress in silicon carbide – silicon carbide is reflected in a scientific partnership starting more than twenty years ago. Dedicated to basic research in thermostructural composites, this partnership is now organized as a joint university-industry laboratory. At the top of the diabolo it energizes a network of many labs. It also interacts everyday with our technology melting pot, which is a sort of nozzle throat for our global approach. It created the very first silicon carbide-silicon carbide sample, as well as the first interphase for this material.

Talking of interphases, you may recall that CMCs are inverse composites. That is to say that the failure strain of the ceramic matrix is much lower than that of the fibers. As the load increases, the matrix will be the first element to fail. It is absolutely essential that the cracking of this brittle matrix does not damage the fibers, which are also rather fragile. This is why the third constituent element, called the interphase, located between matrix and fiber, is so vital. It acts like a mechanical fuse, deflecting and dispersing the cracks. Because of this, very extensive work has been done on interphases over the last ten years.

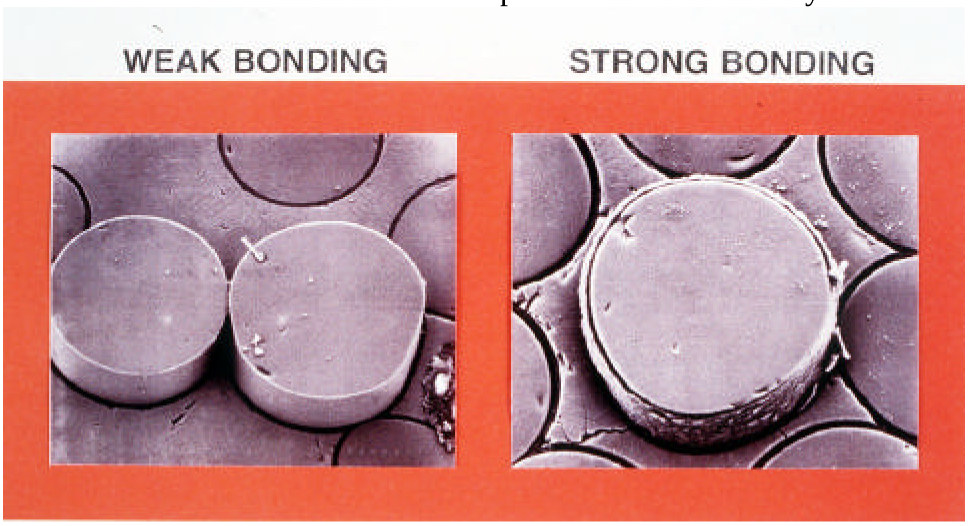


Fig.16 Fiber bonding in CMCs

I would like to briefly review the scientific state of the art. The interphase must transmit loads between fiber and matrix. This means that we should avoid a weak fiber-interphase bonding, one that would allow the fiber to be debonded prematurely. If we can avoid this pitfall, and if the interphase is correctly stratified, it can carry out its role of mechanical fuse, protect the fiber and delay local debonding. Fig 16.

The most commonly used interphase is simply a thin layer of anisotropic pyrocarbon. But researchers are also taking a close look at boron nitride, which displays a similar hexagonal layered crystal structure. However, while these interphases are excellent mechanical fuses, they are still far too sensitive to oxidation. Within the scope of the global approach, our scientists have made a new breakthrough. They have developed self-healing, multilayered interphases, combining a compliant material such as pyrocarbon or boron nitride, with a stiff glass former, such as silicon carbide. Fig17. Oxidation causes the formation of a glass, which in turn heals the crack and protects both interphase and fiber.

Fig.17 - Multilayer interface

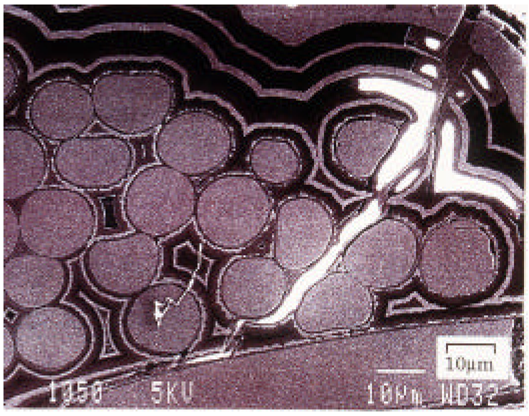


Fig 18 Matrix microcracks patch

Correctly designed and produced, these sorts of zebras should provide a good solution, while awaiting the development of a truly oxidation-resistant interphase. This concept of a multilayered ceramic material has been extended to the matrix itself, to heal its own microcracks. Fig.18.

Here, you can see the result. It becomes a generalized zebra matrix. And you may see, on the next picture how a microcrack can patch itself. This is a spectacular scientific breakthrough. It opens a lot of exciting paths, some already in the technology demonstration phase.

These advantages will be even more marked, since at the same time significant progress has been made on silicon carbide fibers. New formulas, purer than the previous ones, maintain good mechanical properties up to thirteen hundred degrees C. This gain of three hundred degrees has been eagerly awaited for a long time. It has now been achieved, without the fibers losing too much of their textile capability.

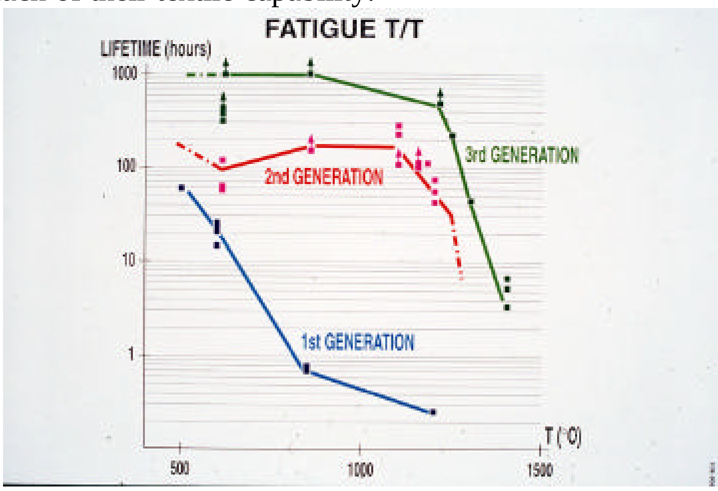


Fig.19 Improvement of fatigue resistance of Ceramic Composite Materials

Mixing all these advances together, (on the interphases, on the matrices, on the fibers) engineers now have a family of materials which are very much superior to the ones they used at the time of Hermes. This chart illustrates the potential fatigue life as a function of temperature for three generations of silicon carbide-silicon carbide materials. No, your eyes are not fooling you: under these very harsh conditions, the material has been improved 100-fold from the first generation to the third one.

Here is the very impressive improvement generated by our scientific partnership. Blended inside the global approach, that I have tried to describe this morning, this technical progress will certainly unleash amazing new opportunities for ceramic matrix composites.

CONCLUSION

Do I need to conclude ? Yes and rather quickly! Do I really need to come to a conclusion? No, because the conclusion will come all by itself in the next few years, driven by a new generation of scientists and engineers. A proactive generation anticipating customer's needs and igniting desires all around. An open minded generation of talents acting in centers of excellence interconnected in partnerships. A brilliant generation modeling not only systems but also materials and processes in total integration. They will ensure the success of thermostructural composites for aerospace, transportation and industrial applications. They will reach out and touch what we have only dreamed of. They will hit the jackpot of the global approach.