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Cost-Effectiveness Concept applied to the development of advanced materials

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Abstract—Now that the aerospace industry is no longer a dream, but a promising market, high performance structural materials are in great need. For such applications, Ceramic Matrix Composites (CMCs) are hopeful candidates. However, one of the most important problems actually hindering CMC research and development is the high cost of common process routes. To try to solve such problem, a new concept for the R&D of advanced materials such as CMCs is proposed, namely, the Cost-Effectiveness Concept (CEC). This concept is one way to bring together scientific and technological targets. In this work, this strategy will be defined and then illustrated in the case of the elaboration of 3D CMCs and of the development of oxidation protection materials.

Keywords: Cost-Effectiveness Concept (CEC); Tyranno-Hex; thin coating; thermal cycling; sol/gel solution.

1. INTRODUCTION

Since ceramic matrix composite research started, 25 years ago, scientists focused on the development of these new materials from a purely scientific point of view. Their main target was the achievement of high performance CMCs and financial aspects were not topical. Now that significant advances have been made, the main question actually highlighted is how to convince industries to go to a larger scale manufacturing stage, since these high performance materials are costly. One way which appears judicious is to try to bridge scientific and industry targets through the concept of cost-effectiveness (Fig. 1). In the main, this concept consists in adding

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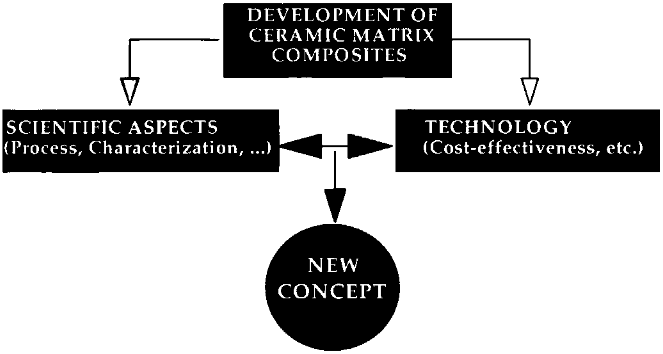

Figure 1. Chart illustrating the two main parts of the Cost-Effectiveness Concept: financial and scientific aspects are brought together.

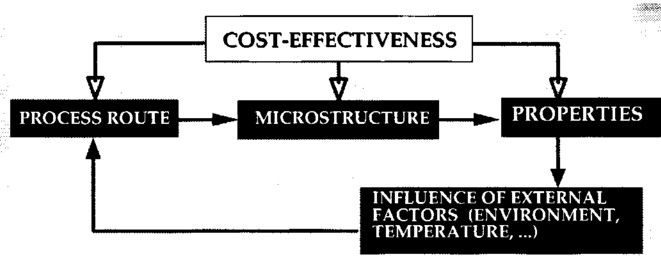

Figure 2. Cost-effectiveness aspects are concerned with all steps related to the development of a new material.

cost-effectiveness considerations at each step of the classical way of developing a given material, as depicted in Fig. 2.

In this work, we intend to introduce two examples of the application of CEC to the development of advanced materials. The first one is the elaboration of 3D ceramic matrix composites using the joint process: Polymer Impregnation Pyrolysis (PIP) and Pulse-Chemical Vapor Infiltration (P-CVI). This technique is aimed to provide small and medium size CMC parts. Whereas the second example is the integral oxidation protection technique of CMCs using glass–ceramics. As space here is limited, those who are interested in more detailed information about these two techniques are invited to check the references that are appended.

2. MATERIALS AND EXPERIMENTS

2.1. Materials

Tyranno-Hex composites, which are coated against corrosion, are made of continuous Si–Ti–C–O fibers (Tyranno Lox-M fibers, UBE Industries Ltd., Japan). The longitudinal Young's modulus, the ultimate tensile stress and ultimate strain of fibers are 190 GPa, 3.3 GPa and 1.8%, respectively [1–3]. This new composite is based on a very high fiber volume fraction ($V_f = 90\%$) and a very low porosity (much lower than 1%). The process route is explained in detail elsewhere [3].

Oxidation-protection materials are processed based on prehydrolysed solutions of sol-gel glass-ceramic powders. This process route, depicted in Fig. 3, is based on the high possibilities of soft chemistry and is one of the shortest and cheapest ways of depositing thin oxidation-protection materials.

2.2. Experiments

Static oxidation tests have been carried out under Xenon lamp heating and natural air-convection. The main features of this apparatus are that a large size specimen up to 50 mm × 50 mm in area can be exposed to a nearly uniform temperature field and equilibrium constant temperature is rapidly attained (in about 20 s) even for a large dimension sample. The temperature range examined was continuously monitored during tests. The glass protected specimens were put into a silicon carbide cylinder and then heated. The temperature of the cylinder (and thus the temperature of the specimen) was controlled by way of two thermocouples bonded at both ends.

Oxidation tests carried out consisted on one cycle test. The specimen was rapidly heated (2 min) up to the test temperature, then kept for 20 min, before cooling down to room temperature (Fig. 4).

Some 4-point flexure tests have been carried out on 3D CMCs as well as on protected Tyranno-Hex materials. Non-notched specimens were used and distances between inner and outer spans were 20 and 40 mm, respectively.

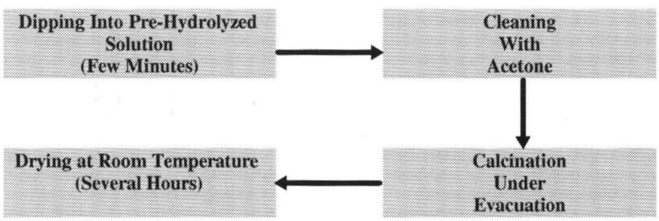

Figure 3. Chart explaining the stages necessary for getting oxidation-protection materials.

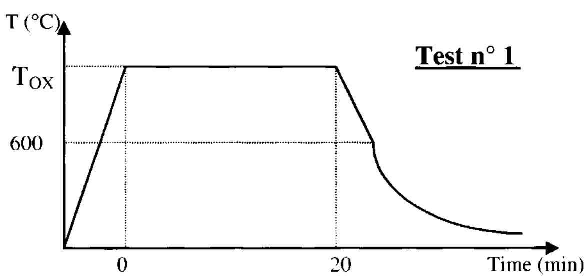

Figure 4. Schedule of the oxidation test performed on protected Tyranno-Hex specimens.

3. RESULTS AND DISCUSSION

Before going to the presentation of the results corresponding to the elaboration and the properties of the 3D CMCs as well as the oxidation-protection using glass–ceramics, we would like to introduce our definition of the concept of cost-effectiveness.

3.1. Definition of Cost-Effectiveness Concept (CEC)

The Cost-Effectiveness Concept applied to the development of advanced materials consists of developing and supervising a long term strategy including a set of steps related to technology survey, R&D, supervision of group's research and researchers, introduction of marketing strategy, etc. with a two fold scope:

(1) Getting high quality and efficiency material properties.

(2) Achieving lowest fabrication cost to fit technological target.

In particular, this implies:

(1) Addition of financial considerations to fundamental materials research.

(2) Analyzing and improving the common process routes for a given material, to get highest performance.

(3) Proposing new process routes.

It is obvious that all the materials which are under study cannot necessarily be cost-effective. Nevertheless, the real target of CEC is the introduction of cost-effectiveness considerations during the design stage of the material. In fact, this concept should be viewed as a long term strategy, which can allow the Management of Research to follow a clear reasoning, able to bring together scientific and technological targets.

However, it is interesting to note that for some very special applications, mainly in the aerospace industry, talking about cost-effective materials is premature, since the target of producing highly reliable materials is far from being achieved. Whereas in the case of some other applications, such as rocket engines, gas turbines, inner flaps of air fighters, etc. the properties are good enough and some applications in air-fighters have been recently reported [4] so that now, the target is to lower the cost.

As detailed hereafter, we have chosen to illustrate the applicability of the cost-effectiveness concept (CEC) in the case of the process route of 3D CMCs using the joint process: PIP and Pulse-CVI and oxidation protection materials using thin films of glass–ceramics.

3.2. Elaboration of 3D CMCs using the joint process PIP and Pulse-CVI

It is well known that the most powerful process route for getting ceramic matrix composites is the chemical vapor infiltration process (CVI). However, it is also well known that this process route is expensive and time consuming. To try to solve such problems, the joint process involving a multiple polymer impregnation pyrolysis (PIP) and Pulse-CVI, was applied to some 3D braided preforms. It should be noted that up to now, the PIP process, which is a cheap and effective way of making CMCs [7], does not provide a ceramic matrix with the same properties as CVI. In the first trial of making 3D CMCs using pure PIP matrix, some cracks were found in as-processed matrix, which can cause a rapid degradation of the performance of the fibers at high temperature, in air. Generally, the differences between PIP and CVI arise from the fact that the densification rate is more important when using CVI. Indeed, at high temperature, the PIP matrix is lower strength than the CVI matrix (the flaws involved in the PIP matrix are larger than in the CVI one). For this main reason, the 3D braided preforms have been densified at first, using the PIP process. Thereafter, Pulse-CVI was applied to get higher densities. This stratagem was aimed to achieve a high quality matrix as external barrier and therefore, when loading such CMCs under tension, highest load are required to propagate the first transverse crack into the P-CVI matrix.

In Table 1, are depicted the results of some batches of 3D braided CMCs, obtained using the joint process. A relative density of 92% is achieved, which is a promising result. To check the mechanical properties of these materials, preliminary 3-point flexure tests at high temperature (in argon) were performed on non-notched specimens of these 3D CMCs and the results are depicted in Fig. 5. As shown, at 1300°C, the flexural strength is around 600 MPa. Even these preliminary results are obtained using small size specimens, tested under flexure tests, they seem to be promising and as a further improvement, we are experimenting with new powders which can allow a higher purity PIP matrix to be obtained, with higher mechanical performances.

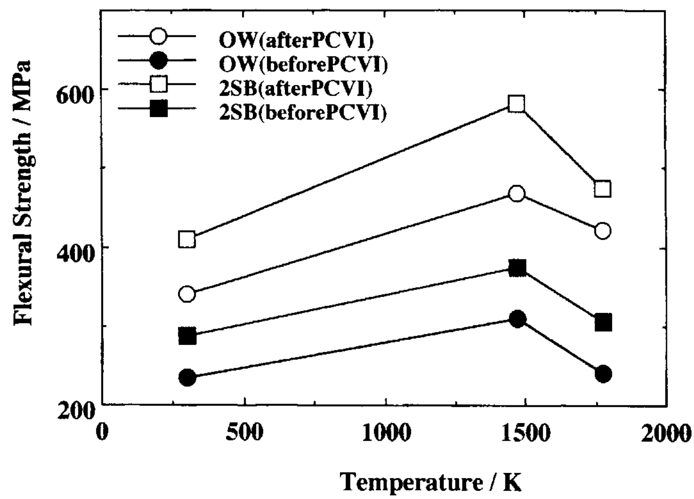

Figure 5. Flexural strength as a function of temperature in the case of some batches of 3D CMCs, tested under argon (OW: orthogonal weave; 2SB: 2-step braid).

Table 1.
Some physical properties of the 3D CMCs developed within this work, using the joint process: Polymer Impregnation Pyrolysis (PIP) and Pulse-CVI (SI refers to slurry infiltration; V_{P1}: porosity before PIP; V_{P0}: porosity before SI; V_{P2}: porosity before PCVI; V_{P3}: final open porosity)

Preform	Thickness (mm)	V_f (%)	V_{SI} (V_{P0}) (%)	V_{PIP} (V_{P1}) (%)	V_{PCVI} (V_{P2}) (%)	V_{P3} (%)	V_{SI}/V_{P0} (%)	V_{PIP}/V_{P1} (%)
OW	4.0	41.9	27.0 (58.1)	17.6 (31.1)	4.3 (13.5)	9.2	46.5	56.6
4SB	4.0	31.4	33.7 (68.6)	20.8 (34.9)	4.6 (14.1)	9.5	49.1	59.6
4SAB	4.0	40.5	27.8 (59.5)	18.0 (31.7)	4.4 (13.7)	9.3	46.7	56.8
2SB	3.2	43.9	25.2 (56.1)	17.0 (30.9)	5.5 (13.9)	8.4	44.9	55.0

3.3. Performance of thin oxidation-protection materials for Tyranno-Hex composites

Another serious problem hindering the use of CMCs as thermal protection barriers in aerospace industries and nuclear reactors, for example, is their extensive oxidation sensitivity at relatively low temperature (starting from 1000°C). Some attempts have already been made to provide oxidation protection. The most popular are the deposit of an interphase layer on the fibers (carbon, boron nitride, nano-layered interphases [5]), a self healing matrix [8] and the bulk protection techniques, which consist of the integral protection of composites using inert coating materials (generally a glass-sealant based on silicon compounds for CMCs and a triple oxidation protection system based on an inner glass-former, then SiC deposited by CVI and an external sealant, in the case of carbon-carbon composites [6]).

In our case, we have conducted some investigations with the aim of coating Tyranno-Hex materials against corrosion. Given the particular process route of these CMCs [1–3], the only technique which can be tried is the integral protection. However, instead of using CVD coatings (costly), we used prehydrolyzed solutions (which is cheaper).

Before going into the results, we would like to recall the mechanical performance of these new CMCs. Tests carried out on non-notched specimens of Tyranno-Hex at high temperature, in air, showed that the performance remains fairly constant up to 1200°C, beyond which a continuous degradation is recorded (Fig. 6a). Whereas in the case of notched specimens (which can simulate the behavior of defects propagating from rivets, involved in structures), a drastic decrease of the mechanical properties occurs between room temperature (RT) and 1300°C (Fig. 6b [1, 2]). Although these results seem to be good, the target is to improve the oxidation resistance of Tyranno-Hex materials by the development of new oxidation-protection materials. The coating materials must be effective, at least, up to 1300°C. For that purpose, some materials such as deposited silica starting from TEOS (Tetra-Ethyl-Ortho-Silane), cordierite (sol–gel) and lithium alumino-silicate (LAS) glass–ceramics (sol–gel) have been tested at coatings and some results are reported below.

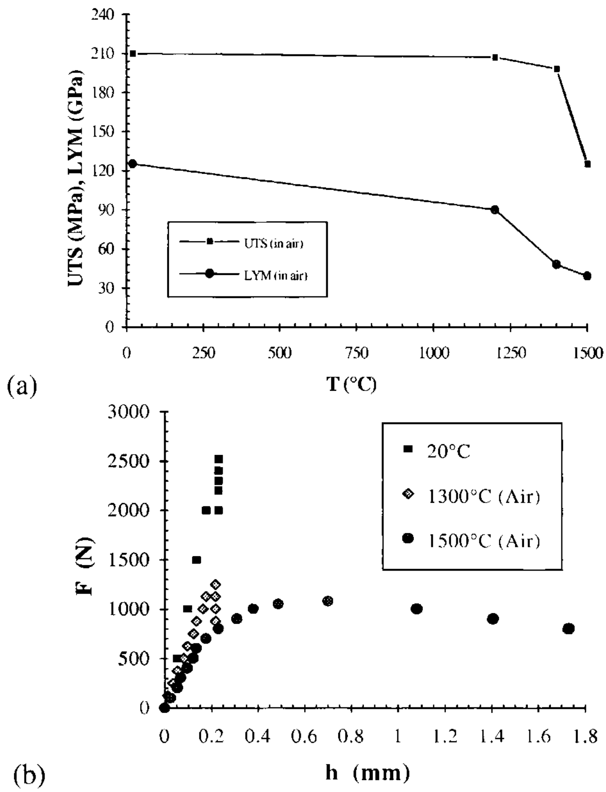

Figure 6. (a) The tensile strength (UTS) and longitudinal Young's modulus (LYM), both plotted as functions of the temperature (in air). (b) Load–displacement relationships for notched 4-point-bend specimens tested at RT and HT in air [1, 2].

Table 2.
Preliminary oxidation tests of thin coating materials

Number	Coating materials	Weight loss $(W_f - W_i)/W_i * 100\%$	Y/N
1	$LiAlTiO_4$	0.085	N
2	$LiAlSi_3O_8$ LAS (I)	0.045	Y
3	$LiAlSiO_4$ (LASO)	0.167	Y
4	SiO_2 (TEOS I)	0.041	Y
5	$LiAlSi_3O_8$ (II)	0.067	Y
6	$LiAlSi_2O_6$	0.014	N
7	$LiAlSiO_4$	0.013	N
8	$TiO_2 + SiO_2$	0.053	N
9	SiO_2 (TEOS II)	0.214	Y
10	$Mg_2Al_4Si_5O_{18}$ (cordierite)	0.2	N
11	TiO_2	0.098	N
12	$2Al_2O_3$-SiO_2 (mullite)	0.17	N
13	$LiAlTiO_4$	0.234	N

Starting from many compositions of the LAS system (Table 2), we have performed one cycle oxidation test at 1500°C on small size specimens. According to the results of preliminary oxidation tests, we have selected three main compositions: LAS, LAS-O and SiO_2. Thereafter, bigger size specimens made of Tyranno-Hex (typically 50 mm long, 10 mm wide and 3 mm thickness) have been coated using

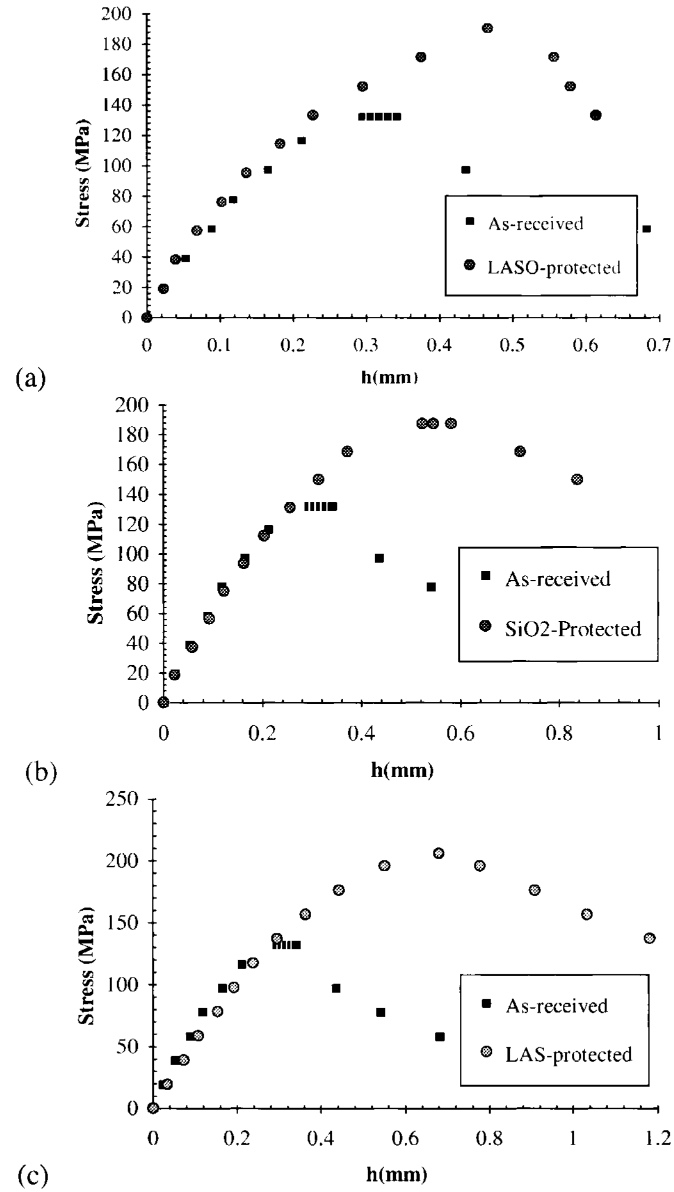

Figure 7. Comparison of the stress–deformation relationships in the case of unprotected and oxidation-protected specimens of Tyranno-Hex, tested in four-point bending tests.

the three materials listed above. Thereafter, four point-flexure tests at 1500°C in air, have been carried out using non-notched specimens and the results are depicted in Fig. 7. For comparison, we have plotted in this figure the results of monotone stress–deformation tests performed on non-protected specimen along with the one of protected specimen. As shown, there is an improvement of the performance of the materials in terms of the maximum stress (up to 60%) and deformation (typically up to 126% for LAS coating) in all cases and therefore the oxidation-protection materials developed seem to be of real interest for protecting Tyranno-Hex CMCs.

4. CONCLUSION

In this work, the concept of cost-effectiveness, which is one way to bring together scientific and technological targets, was introduced. Since CMC research is nearing saturation and therefore needs to be boosted again, some new applications must be found. Some applications can appear by lowering of the cost, without changing the performance: that is the strategy of the Cost-Effectiveness Concept.

For some possible applications (mainly in the aerospace industry), talking about cost-effectiveness is not yet topical, since the CMCs developed up to now have not shown enough reliability. However, in the case of other potential applications (heat engines, gas turbines, inner flaps, ...), financial aspects (especially cost-efficiency) should be introduced to boost CMC research.

Two examples of the application of the CEC have been illustrated in the present article and promising results have been gathered. Further improvements of the performance of these materials are now in progress.

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