THE LONG TERM ELEVATED TEMPERATURE BEHAVIOUR OF MATERIALS : A KEY ISSUE FOR THE NEXT SST

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Abstract

For the 2 configurations of future SST currently studied, Mach 2.05 or Mach 2.4, the pre-design studies indicate that, while titanium alloys will have to be used in heavy loaded areas such as the central wing box, an important share of the structure of the aircraft will have to be made of organic composites to meet the weight requirements associated with the economical objective of fuel consumption reduction. In the Mach 2.05 option, however, for cost and impact resistance considerations, aluminium alloys remain an option for the fuselage skin. This paper details the different problems posed by the utilization of aluminium alloys and organic composites at elevated temperature for long time exposures - creep, thermal fatigue, thermo-oxydation, interactions between creep and fatigue - and presents the work programme running on at AEROSPATIALE and ONERA to deal with these different items. A particular attention is paid to the development of specific tests and the modeling approach developed to predict the behaviour of these materials in the real expected conditions. Results obtained to date on different new aluminium alloys and organic composites from the modified epoxy and bismaleimid families are reported and discussed.

Introduction

The consequences of the drastic economical and technical requirements for the future SCT [1] on the materials selection for the different parts of the aircraft structure have already been detailed and discussed in a previously published conference [2]. The pre-design studies conducted at AEROSPATIALE in the early 90's have resulted in a materials zoning in which polymeric matrix composites, advanced aluminium alloys and titanium alloys play a major part.

From the end of the Concorde programme in the late 70's, AEROSPATIALE has always kept an activity in the field of supersonic flight conditions, including materials. However, in 1989, it was decided to increase our effort on this subject and to launch specific research programmes on aluminium and titanium alloys and carbon fiber reinforced plastics (CFRP). During the first three years, these studies were carried out in close cooperation between AEROSPATIALE and ONERA. Then, in 1992, started a Brite Euram contract on the development of new aluminium alloys for the future SST [3], in which the 2 other partners of the ESRP (European Supersonic Research Programme [4]), BAe Airbus and DASA Airbus, joined AEROSPATIALE and ONERA, together with PECHINEY, British Aluminium, DRA, MIRTEC and ISTRAM. In 1994, started a similar cooperation programme on organic matrix composites between AEROSPATIALE, BAe and DASA, on own funds. This paper presents a statement of the advancement of these different cooperation programes in the fields of aluminium alloys and polymeric matrix composites.

Aluminium Alloys

Most of the development work on aluminium alloys for supersonic applications was carried out in EUROPE during the CONCORDE programme in the early 1960's, and when an improved CONCORDE project was restarted in the 1970's. In the first period, four alloys were competing : 2024, well known for its application on subsonic aircrafts, 2219, widely used for elevated temperature applications in military programmes in the USA, X2020, the first western commercially available Al-Li alloy developed by ALCOA, X 150, an optimized version of the 2001 alloy developed by ONERA and the 2618A, originally RR58 developed for engine applications, which was finally selected. In the second period the

development work was focused on three alloy systems : the CM 003, a modified 2618A in which the minor alloying elements were varied in order to improve the fracture toughness of the alloy, the X3058, a modified 2001 developed by the Fulmer Research Institute and produced by ALCAN and the 2048, a modified 2024 developed by REYNOLDS in the USA.
More recently studies were conducted on aluminum-lithium alloys from different systems : Al-Li-Cu-Mg 8090 in U.K., based on the δ' precipitation, and Weldalite type alloys in USA, based on T1 precipitation which is said to be more stable. Preliminary results indicate that these materials, which are very interesting in the objective of weight reduction, are presenting a good creep behaviour.
Lastly, we have to mention the work of Professor I.J. Polmear, from Monash University of Melbourne, on the effect of Silver additions on the elevated temperature properties of Al-Cu-Mg alloys with high copper content, in relation with the precipitation of Ω phase. This development work on Al-Cu-Mg-Ag alloys was started with Asea Brown Bovery, in Switzerland, in the mid 80s, and is being pursued today in the framework of a France-Australia cooperation programme led by AEROSPATIALE, and also involving ONERA, CSIRO and COMALCO [5].
These development works have resulted in a rather rich bibliography on the influence of the different metallurgical factors on the creep behaviour of the aluminium alloys. Most of the available information deals with the influence of the precipitation system, namely the thermal stability of S' and θ" phases, of the grain size, of the manufacturing process, mainly the effect of cold working after quench or after ageing, and of some minor alloying elements on the creep and thermal stability of the alloys.
All this background, enriched by the complementary studies conducted by AEROPSPATIALE and ONERA between 1989 and 1991, was obviously used in the "NEWAL 150" Brite Euram contract previously mentioned, whose objective was to develop a new aluminium alloy with improved creep resistance and improved fracture toughness over the best known candidates at this date.
The work programme of this "NEWAL" project was divided into two main tasks, corresponding to the study of the two factors assumed to influence directly the creep resistance and the thermal stability of metals :

- Task 1 : selection of the main precipitation system
- Task 2 : optimization of chemical composition and of process parameters

The critical analysis of existing data mentioned previously resulted in the selection of 33 chemical compositions, from the four alloy systems given in table 1, which were DC cast and rolled down to 14 mm thick plates and 1,6 mm thich sheets on laboratory equipments. These 33 alloys were then tested in creep, thermal stability and corrosion. Task 1 ended in january 1995 with the selection of 14 different alloys from 2 precipitation systems on which the effect of minor alloying element and thermo-mechanical process variations are currently being studied.

Alloy System	Main Precipitation System
Al - Cu (2001 type)	θ' (Al_2Cu)
Al - Cu - Mg (2024 or 2618 type)	S' (Al_2CuMg)
Al - Mg - Si - Cu (6013 type)	λ' ($Al_5Cu_2Mg_8Si_7$) β' (Mg_2Si)
Al - Li - Cu - Mg	δ' (Al_3Li) T1 (Al_2CuLi)

TABLE 1 - Selected alloy systems

Results obtained to date [6] are more than encourageing : all the alloys tested in task 2 present a creep behaviour and a fracture toughness much improved as compared to the CM 003, which was, up to now the best reference in terms of creep / damage tolerance compromise. This is illustrated by figure 1 and table 2 which presents examples of creep results in accelerated conditions and of fracture toughness on CCT specimens. Creep life extensions by a ratio of up to 7 in different creep test conditions (including 150 °C / 250 MPa) have been obtained as compared to the CONCORDE alloy, whereas Kc values from R-Curves better than the one of the damage tolerant 2024 T3 reference alloy were measured on the same alloys. If these results obtained on laboratory specimens are confirmed on indutrial products in 1997, the initial dream of developing a new alloy with a low density (less than 2024) combining a creep resistance better than the one of the best existing supersonic alloy (2618A) and a damage tolerance better than the one of the best existing subsonic alloy (2024 T3) will become reality.

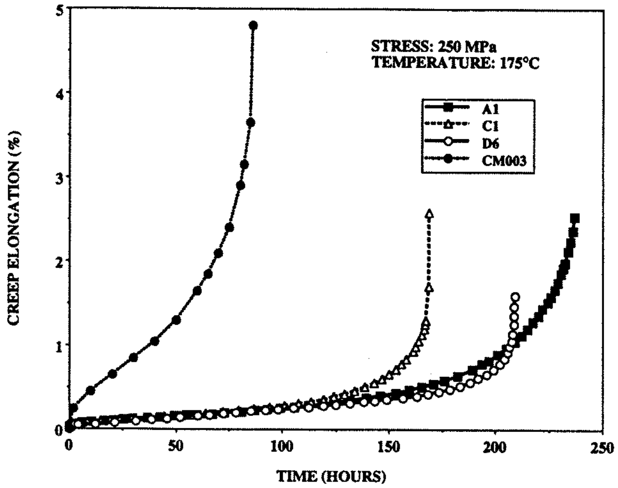


FIGURE 1 - Creep curves at 175°C / 250 MPa

ALLOY	Kc (MPa√m)	Kc0 (MPa√m)
A1 T6	125	90
C1 T6	160	110
D6 T6	158	110
2024 T3	130	90

TABLE 2 - Fracture toughness from R-Curve on 400 mm wide CCT specimens

However, apart from the problem of scaling-up to industrial problems, a lot of investigations are still necessary to assess the effect of the manufacturing processes (forming, succession of annealing treatments, surface treatments ...) on the creep, fatigue and damage tolerance properties of these new alloys.

In parallel to this important work of development of improved alloys, AEROSPATIALE has also started studies on the interactions between creep and fatigue on notched coupon specimens and on specimens representative of technological details such as pocket recess or assemblies. These studies are based on the development of 2 parallel approaches :

- a modelling approach combining thermo-elasto-plastic finite elements and physical-metallurgical prediction of creep damage

- an experimental approach with the development of specific test equipments capable of reproducing close to real conditions exposures on technological specimens.

CFRPs'

It has already been published [2] that composite materials with carbon fibers and polymeric matrices are ad-hoc candidates to achieve the required weight savings on the future SST. Foreseen structural applications are the extreme wing, the flaps, the vertical tail, and a major part of the fuselage.

The main requirements for the candidates are acceptable properties regarding subsonic flight specifications (i.e damage tolerance) and thermal stability in supersonic flight conditions.
The first criterion of selection is the glass transition temperature of the matrix which governs the maximum service temperature for thermoset matrices. Different types of matrices are under investigation for Mach 2.05 applications :

	State of knowledge
"Second generation " EPOXY	- Well-known process - Expected service temp. : 120 °C
Cyanate based systems	- Process similar to epoxy system - New products on the market - Expected service temp. : 150 °C
Thermo-plastic	- Potential "Hot forming" process - Expected service temp. : 180 °C
Bismaleïm ides	- Processing generally with postcuring - Expected service temp. : 180 °C - Low damage tolerance compared to 2nd generation epoxy

IM and HR fibers are used.

The work programme currently under progress may be divided in 2 main research areas :

- the influence of long term thermal ageing on the physical and mechanical properties of composites

- the long term behaviour of CFRPs under complex thermo-mechanical loading

Influence of long term thermal ageing on the physical and mechanical properties of composites

In order to compare the thermal stability of the different types of matrix, thermogravimetric tests have been conducted. Figure 2 shows that epoxy and cyanate systems are comparable for the thermal stability behaviour under the tested

conditions, and are less performant compared to the BMI system.
The influence of thermal ageing on the mechanical properties could be related to the degree of curing of the matrix, but also to the chemical type of the matrix. If we consider figure 3 (isothermal ageing of 2000 hours), a post cure effect is clearly seen on the second generation epoxy, not fully transformed during the initial curing. For the cyanate system, we can see a real mechanical property degradation when the isothermal ageing is performed over 160 °C. On the figure 4, we can see that the mechanical property degradation, or the post cure effect, appears during the first 1000 hours of ageing.

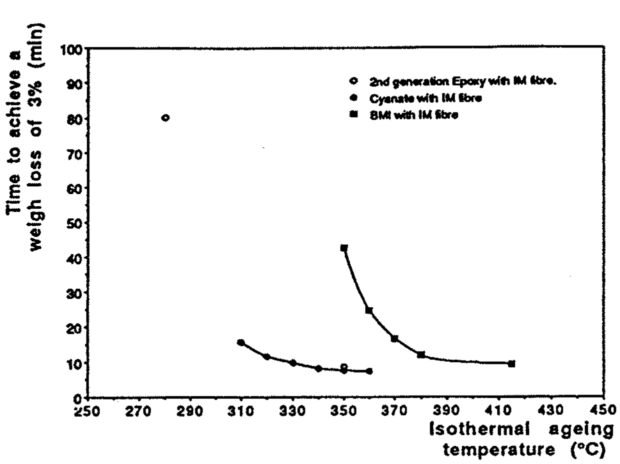


FIGURE 2 - Time to achieve a weight loss of 3%

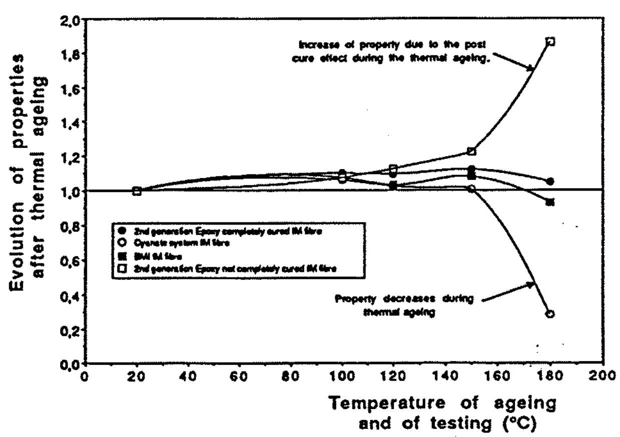


FIGURE 3 - Filled Hole Compression After 2000 Hours Of Isothermal Ageing

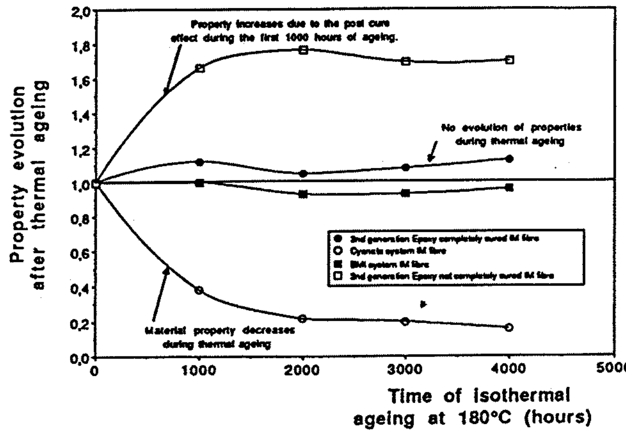
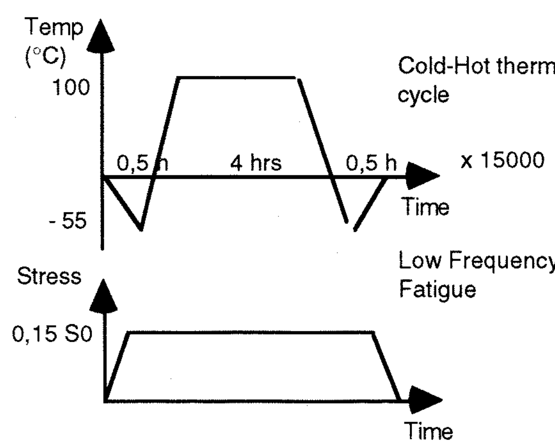


FIGURE 4 - Filled Hole Compression At 180 °C After Isothermal Ageing At 180 °C

These first tests were performed at a higher temperature than the service temperature corresponding to Mach 2.05, in order to obtain in a short time the first tendancy of thermal ageing response for the different families of matrix. In parallel, a work programme is currently under progress to establish data on mechanical and physical properties after thermal ageing under isothermal conditions and thermal cycling conditions up to 40000 hours and more of ageing.

Long term behaviour of CFRPs under complex thermo-mechanical loading

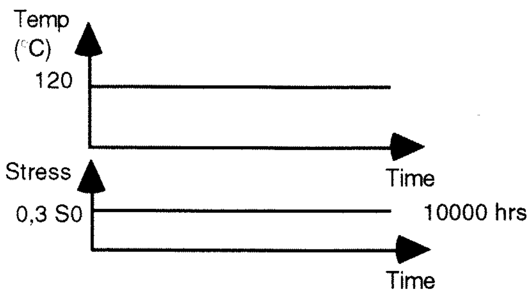
The typical flight spectrum for the future SST, in the hypothesis of Mach 2.05 is the following :



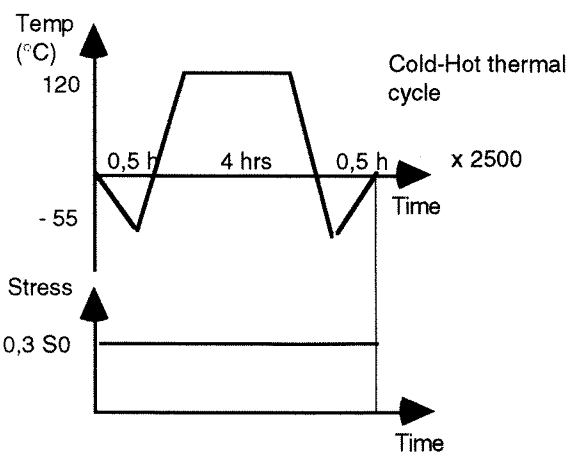
S0 : critical static strength at 100°C

FIGURE 5 - Typical flight spectrum of SST

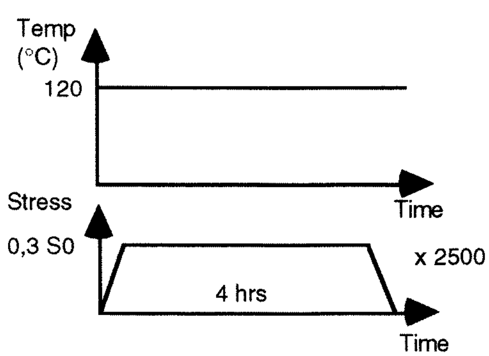
This flight spectrum induces strong creep-fatigue-thermal cycling interactions. In order to test the degrading effects of "cold-hot" thermal cycling and low frequency fatigue cycling compared to classical creep testing , on the residual properties of composites after exposure, 3 specific accelerated thermo-mechanical cyclings have been defined; each cycling type presents 10000 hours at 120°C. Compared to typical flight conditions, maximum temperature has been increased of 20°C and maximum stress has been doubled for test acceleration.



Type 1 : Creep (isothermal ageing/constant load)



Type 2 : "Cold-Hot" thermal cycling at constant load amplitude



Type 3 : "Low Frequency Cycling" at isothermal temperature

Specific testing apparatus have been developed by AEROSPATIALE and CEAT to perform previously described cycling spectra. These various cycling spectra have been applied to 3 composite systems with the same IM fiber : one BMI, one cyanate and one epoxy. First results are available on the cyanate matrix composite, while tests are still under progress for the two other systems. Table 3 presents residual properties after cycling exposure on quasi-isotropic open hole tension (OHT) and filled hole compression (FHC) specimens.

	Loss of stress (% of initial stress)	
	FHC	OHT
Type 1 (creep)	- 3,9	+ 2
Type 2 (therm cycl)	- 10,4	+ 2,9
Type 3 (fatigue)	- 5,7	+ 1,9

TABLE 3 - Effect of cycling on the residual properties of cyanate matrix composites

These first results tend to point out that "cold-hot" thermal-cycling is determinant for compression properties. But this trend needs to be confirmed by analysis of the tests still running on. Furthermore, the duration of the exposure already performed is limited compared to what has to be justified (at least 1,5 time 60000 hours). This means that long term tests have to be carried out and special care have to be paid on the development of reliable models able to predict long term behaviour from short term accelerated tests.

Summary

The pre-design studies conducted at AEROSPATIALE, BAe and DASA indicate that, because of the drastic economical and technical requirements defined for the future supersonic civil transport aircraft, an important share of the structure of this aircraft will have to be made out of polymeric matrix composites and advanced lightweight aluminium alloys.

In order to meet the rendez-vous of the launch of the development programme of this new aircraft, planned at the beginning of next century, AEROSPATIALE, with the help of ONERA, has started as early as in 1989, specific studies on both material systems.

Regarding aluminium alloys, for which we benefit from the huge experience of the CONCORDE programme, studies were oriented in 2 directions :

- the development of improved alloys
- the analysis of the behaviour of aluminium components in creep-fatigue interaction conditions

Concerning the first topic, a Brite Euram contract, coordinated by AEROSPATIALE and involving BAe, DASA, PECHINEY, British Aluminium, ONERA, DRA, ISTRAM and MIRTEC, has resulted in the development of new low density alloys presenting a much better creep resistance than the 2618A CONCORDE alloy combined with a fracture toughness better than the one of the reference 2024 T3 "subsonic" alloy.

As far as Carbon Fiber Reinforced Plastics are concerned, the test procedure for evaluating the damaging of these materials in real cycling conditions have been established, pilot test equipments have been designed and built and tests are running on. Tests performed today in thermal ageing and creep-fatigue-thermal cycling interactions on composites from the 2nd generation epoxy, cyanate, bismaleimide and thermoplastic systems are encourageing. Nevertheless, numerous complementary investigations are still missing to definitely be confident on the possibility of using CFRPs for SST applications.

Aknowledgements

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