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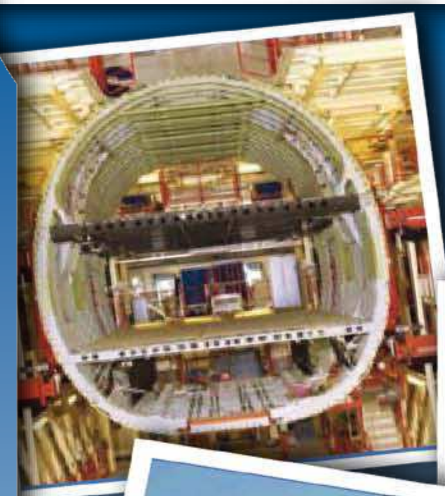
POUR UN PROGRÈS RAISONNÉ, CHOISI ET PARTAGÉ

3AF
La Société Savante
de l'Aéronautique et de l'Espace

MATÉRIAUX AÉRONAUTIQUES
d'aujourd'hui et de demain

AERONAUTICAL MATERIALS
for today and tomorrow



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Aeronautical materials for today and tomorrow

Following the forum organised by the Air and Space Academy (AAE), French Aerospace Society (3AF) and Academy of Technologies, at SAGEM, Paris, 30 November 2012

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INTRODUCTION

Two reasons prompted us to organise this forum:

1. A global vision for "Metallurgy - Science and Engineering" as a whole, following a report prepared in 2011 under the responsibility of Yves Quéré of the Academy of Sciences and André Pineau of the Academy of Technologies. The purpose of this report was to alert the authorities and the public as to the poor state of this discipline in France; it concluded that this worrying situation could become catastrophic if no remedy was found very quickly.
2. The second motivation is more specifically related to aerospace materials, a field in which some interesting and important developments have taken place in France in the areas of metallic alloys and composite materials. So what is the situation today and what can we expect tomorrow?

The Air and Space Academy (AAE) and French aerospace society 3AF have been closely involved in reflexions around the theme of materials through their various commissions and working groups. AAE has prepared written documents and organised conferences on this subject, in particular an international conference on "Flying in 2050" in May 2012.

The aim of the forum was thus to present the state of the art, the progress made and both current and future needs in terms of aeronautical materials.

In order to meet the challenges facing air transport by 2050, it is essential to move forward in certain key areas:

- propulsion systems
- weight
- cost management
- drag
- air traffic management.

In the case of the first three factors, materials are at the very heart of strategic and economic decisions in terms of design and manufacture of turbomachinery and aeronautical and space structures.

The purpose of this forum of 30 November 2012, entitled ***Aeronautical materials for today and tomorrow***, was to present and discuss issues, strategies and both current and future needs in terms of aeronautical materials.

Regarding turbomachinery, a wide range of materials is already available, ranging from metallic materials (steels, titanium alloys, nickel-based superalloys, intermetallic compounds ...) to composite materials (organic and ceramic); others are still under development, with many aspects requiring specific research.

For aircraft structures, the stakes are also very high in terms of the choice of aluminium alloys and organic matrix composites in a context of fierce international competition between aircraft manufacturers (mass transport and business aviation). There again, the options must be considered according to several criteria and not just technology.

Presentations by experts from the aviation industry and materials producers were supplemented by leading researchers with a long experience of working with industry, who brought new ideas on multi-materials design and the appropriate use of “mechanical metallurgy” for the development of stainless steel with very high mechanical resistance and toughness, a key issue for some applications (landing gear, turbine shaft, etc.).

These considerations are illustrated in this dossier by means of concrete examples.

EXECUTIVE SUMMARY

This forum was initiated by AAE and 3AF (Tasadduq Khan) with a strong contribution from 3AF's Materials commission, chaired by Jean-Yves Guédou, and the support of the Academy of Technologies (Prof. André Pineau). It aimed to take stock of the current state of the art in aeronautical materials and medium and long-term trends. The programme included presentations from four major manufacturers (Safran-Snecma, Airbus, Dassault Aviation, Constellium) and two scientists (Y. Bréchet and A. Pineau), and ended with a round table.

- "***Current and future needs in the area of materials for turbomachines and aeronautical equipment***" was presented by Claude Quillien, SAFRAN. These materials have to adapt to the great variety of mechanical constraints and temperatures encountered by the different parts, whilst conforming to many conditions, such as the environmental requirements of the REACH and ROHS directives. In order to reduce weight, increase performance and keep costs down, various paths were defined and explored, whether for "cold parts" (T<200°C), "warm parts" (T<700°C) or "hot parts": organic and ceramic matrix composites (OMC/CMC), intermetallic and refractory intermetallic materials, high temperature type alloys, ...
- "***Materials for aerospace structures: developments and challenges of the future***" was the subject of Yann Barbaux's presentation (Airbus). In this area, we find the same concerns for performance, regulations and costs, to which must be added supply constraints, continuity, availability and competition. For civil transport aircraft, composites have gradually been introduced into thicker parts (CFRP Carbon-fiber reinforced polymer) and thinner parts (CFRP/metal). Hopes are mainly pinned on MMCs (metal matrix composites) and Al-Li and Al-Mg alloys. Much of the presentation was devoted to metal transformation processes (Friction stir welding, direct manufacturing) and surface treatments, and to composite technologies (automation of preforms, thermoplastics, welding, damage detection, resistance to lightning and fire ...), with two main areas of progress: out-of-autoclave cases and bio-based materials.
- Philippe Vautey, Dassault Aviation, gave a presentation on the "***Choice between aluminium alloys and composites for future business aircraft structures***". Business aircraft are optimised for specific needs but the

aluminium/composite debate is as present as it is for commercial aircraft. Some composite materials are already used on the Falcon, for example on the tail panels and fairings. The question of composites is now posed for the fuselage - which could be lighter if Al-Li alloys were used - and the wingbox. Various programmes are directed at composites - DTP Composites, APRICOS, ALCAS, CORAC - and have been or are currently being demonstrated (AR section, wing box). Dassault Aviation remains committed to its policy of small steps and particularly wants to avoid requalification costs.

- "***New alloys and aluminium solutions for aeronautical structures***" was presented by Bruno Dubost, Constellium. Two types of alloys are currently produced: for thick plate (2050 grade), with improved characteristics for fatigue and corrosion resistance, and for thin sheet (2198 grade). By combining design of new parts, thickness optimisation and improvements in density, weight reductions of 15-25% are announced.
- Yves Bréchet's presentation on "***Architectured materials: a bridge between design and materials***" focused on designing materials for intermediate micro and macrostructures, for applications requiring improved features and structural properties. This original approach is based on various intermediate-scale geometry optimisation tools, as well as the intelligent use of disorders. The main conclusions are that, firstly, it is futile to try to homogenise the material and that, secondly, modelling is an indispensable guide.
- "***The tenacity of high resistance steels, some contributions of mechanical metallurgy***", André Pineau's specialist field, plunged the audience into the mysteries of the finer aspects of metallurgy; it is apparently possible either to increase the austenitic phase or amplify disorder in the microstructure of Martensitic phases by thermal treatment. By adding toughening effects, one would achieve the concept of AusMarAging steel.

The round table looked back over the presentations and emphasised the need to maintain an excellent level of metallurgy education in France, as already highlighted in the "Metallurgy and Engineering" report published two years ago. Two main lines of action are needed:

- for higher education and research: train lecturers, through summer schools, or even by creating a French Institute for Metallurgy;
- for industry: promote the development of alloy recycling (Fe, Ti, Al).

Thanks to impeccable organisation, the very high quality of speakers and presentations and large number of participants (127), this forum clearly achieved its objectives.

In the following pages, a detailed account is given of each presentation and the ensuing conclusions.

CURRENT AND FUTURE NEEDS FOR MATERIALS FOR AERONAUTICAL EQUIPMENT AND TURBOMACHINERY

In a context of ever tougher global competition, aeronautical equipment and turbojet manufacturers have to constantly adapt to technical, economic and environmental challenges and meet the demands of customers desirous of having the best product at the lowest price, which also complies with regulations. The materials and processes associated with this technology are clearly at the heart of these challenges:

- **technical constraints**: the aim is for the product to have the highest performance possible; this requires lighter and lighter materials as well as process

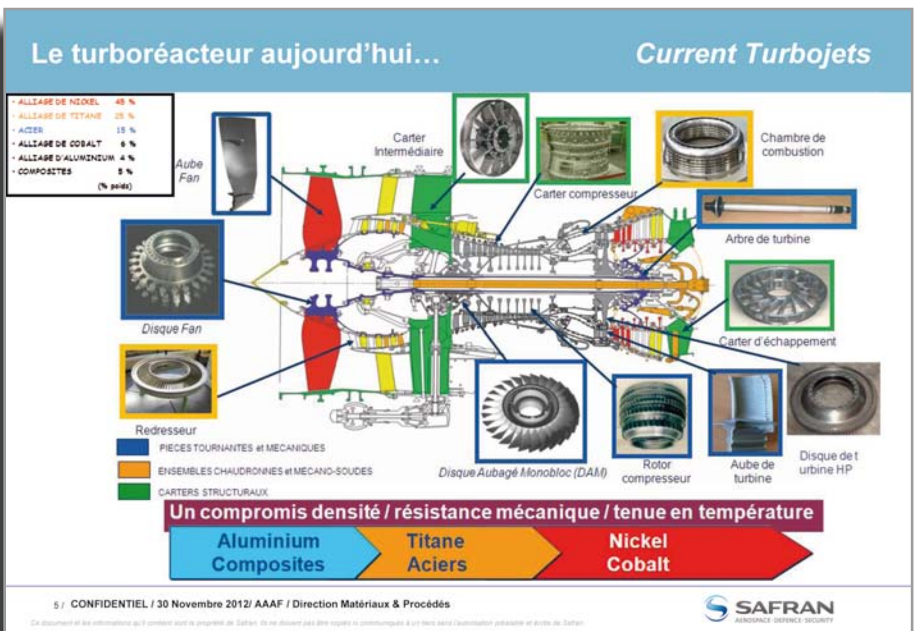


Figure 1: Current Turbojets

solutions with excellent mechanical and temperature resistance and total reliability in the context of ever increasing sustainability;

- **economic constraints**: they are driven by cost reduction at all levels, from design to manufacturing, to the consolidation of networks of suppliers and industrial partners;
- **environmental constraints**: these are associated with societal and political demands for noise reduction and lower emissions but also the availability of materials and processes meeting sustainable development policies (compliance with REACh regulation, recyclability).

The case of the turbojet illustrates the progress made in recent years in bringing to industrial maturity – i.e. to TRL6 (Technical Readiness Level) – materials and process solutions at a lower TRL, with the aim of reducing the weight of components. Because of its thermomechanical stress fields - in particular the high temperature levels for certain components – an aircraft engine is now made up of 85% metallic nickel-based alloys (density 8.2 to 8.6), titanium-based alloys (density about 4.2) and steel alloys (Fig.1).

Weight reduction (Fig.2) is primarily obtained by developing organic matrix composites with a density of less than 2 to replace the aluminium or titanium alloy components in cooler parts. The use of these composites in jet engines, however, is currently limited to parts of the fan, due to the low temperature resistance of the polymer matrix. Research is being carried out to try to determine more refractory

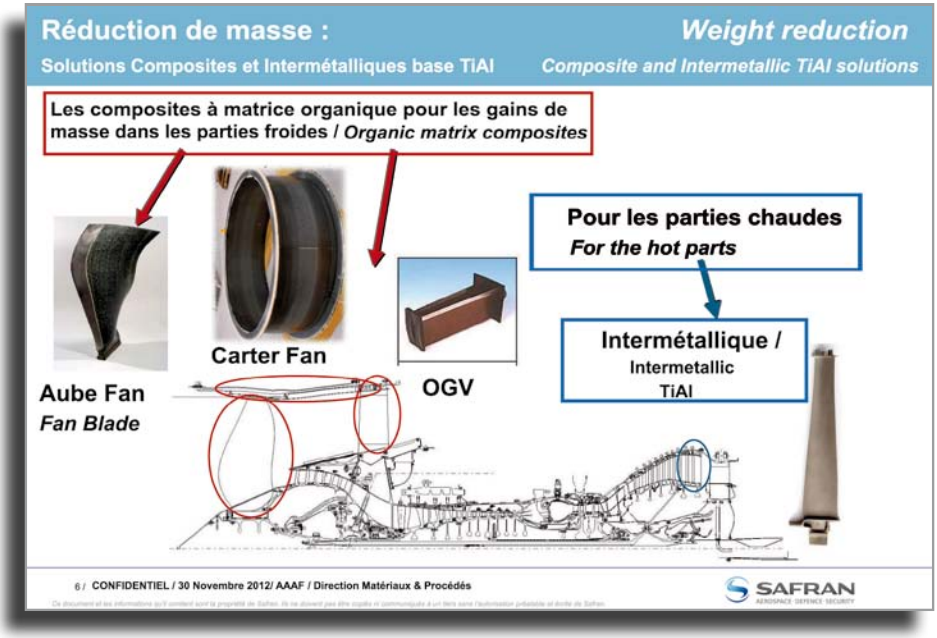


Figure 2 : Weight reduction

resin compositions which would extend the use of these composites to some parts of the low pressure compressors, replacing titanium alloys. These resins would of course have to meet environmental standards, particularly in terms of Health, Safety and Environment (HSE). For the hottest modules of the turbojet, intermetallic TiAl compounds of density 3.9 are useful in view of their high specific resistance to temperatures approaching 800°C: thus the blades of the last stages of low-pressure turbines can be significantly lightened by using titanium aluminide as a substitute for cast nickel alloys. However, industrial utilisation of these materials is particularly tricky and much work has to go into ensuring both robust manufacturing processes and cost management of parts production. In addition, the specific mechanical behaviour of these new types of materials should be integrated into components from design stage, e.g. fault tolerance of intermetallics which have very low plasticity and low toughness in a wide temperature range.

The mechanical strength of steels and nickel and titanium alloys has continued to increase through an optimisation of microstructures by adapting thermomechanical treatments. Titanium alloys are still an indispensable solution to avoid an increase in the weight of the compressors. No new grades are being developed in this area but control over the alloys' microstructures is a constant concern for engine manufacturers in order to make full use of their capabilities. When using grades designed for higher temperatures, i.e. between 550 and 600°C, for example, the adverse effects inherent to these materials, such as the "Dwell effect" which lowers resistance to fatigue at lower temperatures, must be taken into consideration. New,

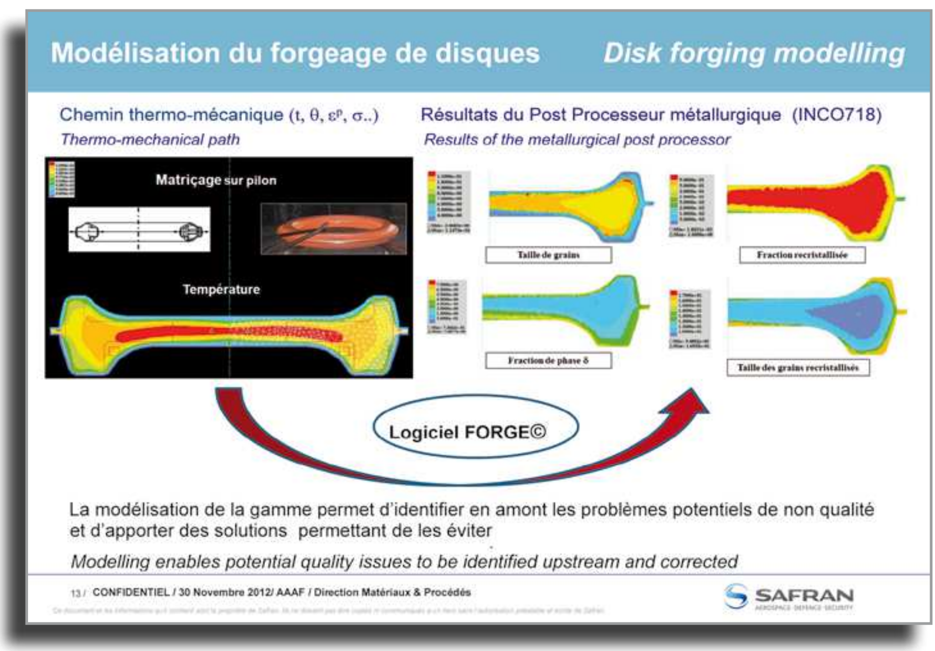


Figure 3: Disk forging modelling

improved grades, on the other hand, are being developed for steels and nickel-based superalloys: some new generation steels thus offer exceptional resistance thanks to dual strengthening mechanisms; the creep resistance of monocrystalline, nickel-based superalloys is enhanced at very high temperatures by the addition of effective but expensive refractory elements (Re, Ru); new grades of forged superalloys prepared conventionally (ingot metallurgy) are entering the market in the U.S. (with the René65), whereas the AD730 alloy being developed by Aubert & Duval is being introduced in Japan and France ; the “powder metallurgy” branch is also still evolving due to a need for higher temperature grades to meet the requirements of turbine disks in very large engines.

To reduce costs it is necessary to improve the reliability and robustness of processes with the immediate positive effect of a reduction in “non-quality”. Action must be taken at all levels: elaboration and initial transformation of the material, solid shaping (forging, rolling) or liquid shaping (moulding), machining, metal assembly, surface treatments. Industrial partnerships must be concluded to this effect with suppliers and subcontractors, i.e. all players in the supply chain. After significant efforts to develop process simulation, some powerful tools are now available to help master processes. Forging is a good example of the advent of industrial process simulation tools based on work undertaken by Snecma more than twenty years ago with CEMEF (material processing research centre) (Figs 3 & 4).

Reducing production costs is also a main goal behind the development of direct manufacturing processes where metal powders are directly bound in a form close to the final part by laser or electron beam.

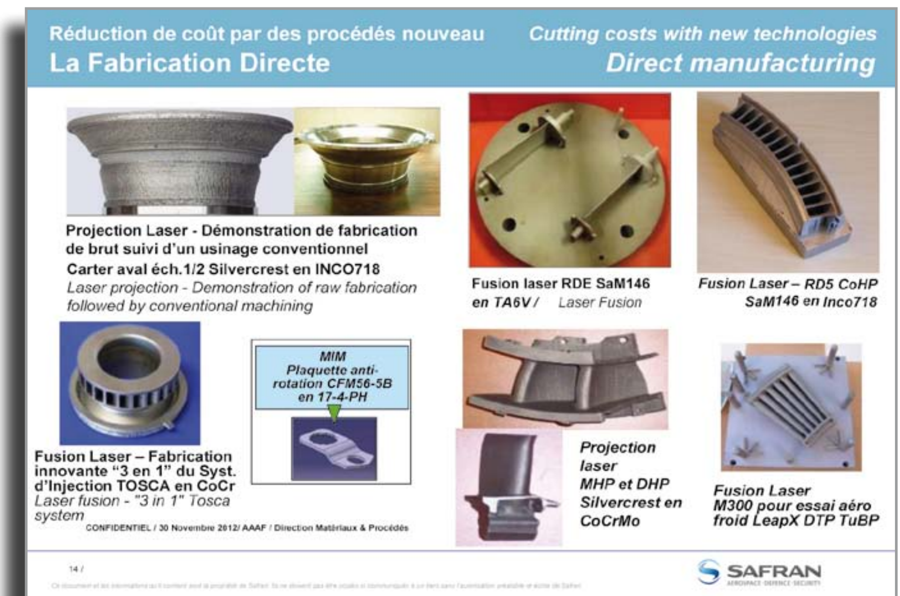


Figure 4: Direct manufacturing

Aircraft equipment is also concerned by weight reduction, which is one way to improve performance. Materials play a key role in achieving these goals. Use of long fibre composites (with titanium or polymer matrix) or titanium alloys with very high strength such as the Ti1023 or the Ti5553 as a substitute for the steels traditionally used in landing gear components can significantly lighten the latter. A similar approach has been adopted for nacelles with deployment of organic composites on large dimension structures and replacement of nickel alloys in the hottest parts by thermo-structural ceramic materials (ARCOCE programme). It should be noted that the introduction of these new materials has required tighter control being exerted over manufacturing costs so as not to undermine the important technical advantage which led to their choice.

Environmental constraints, now governed by EU directives ("REACh" for chemicals substances and "ROHS" regarding electrical and electronic equipment), strongly impact the aerospace industry. Wide-ranging work has been undertaken by engine and equipment manufacturers in conjunction with suppliers to eliminate prohibited substances and materials, develop environment-friendly alternatives and provide equivalent efficacy to the products they replace.

This is still far from finished but concrete results have been achieved to remove cadmium and hexavalent chromium from coatings on steel and aluminium alloys (Figs 5 & 6).

Another promising avenue is to develop high-strength stainless steel that does not require protection.

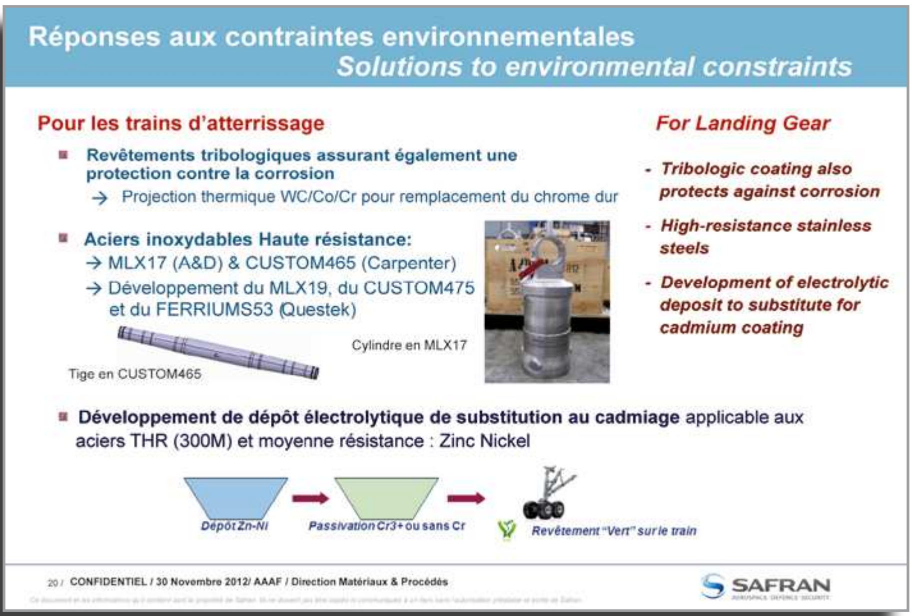


Figure 5: Different solutions to environmental constraints

Figure 6: Different solutions to environmental constraints

Looking further ahead, innovative solutions for the longer term must be identified and researched by means of an effort at least equal to that made for current technologies but concerning materials and processes with a low or very low level of maturity. Uncertainties surround the outcome of the proposed solutions due to technological barriers that must be resolved. The case of materials for very high temperature in turbomachinery, going well beyond the nickel-based superalloys, is a perfect illustration of this: it is a key issue since it holds the promise of removing or at least reducing the flow of cooling air in the turbine blades which would result in a very dramatic increase in efficiency of the machines. A number of materials solutions have been identified; some of these will not work out for various reasons, but it is now necessary to bring them to higher levels of maturity (3 or 4) to support the decision to go ahead with industrial development or not (Figs 7 & 8).

It is likely that some avenues will have to be abandoned before the stage of industrial development, but given their current low levels of maturity - i.e. TRL 2-3 - no avenue can yet be ruled out.

Designing more efficient metal alloys than the current grades will also require innovative development procedures to go beyond the limits of current processes. Processes avoiding all transition through liquid state open the way for the addition of alloying elements in higher quantities than in the melt, prohibited due to chemical and thermo-physical considerations: patents on so-called "meltless" processes, in which metal powder is directly obtained from ore, have been filed with a view to applications with titanium alloys, still undeveloped: the basic objective is to increase the

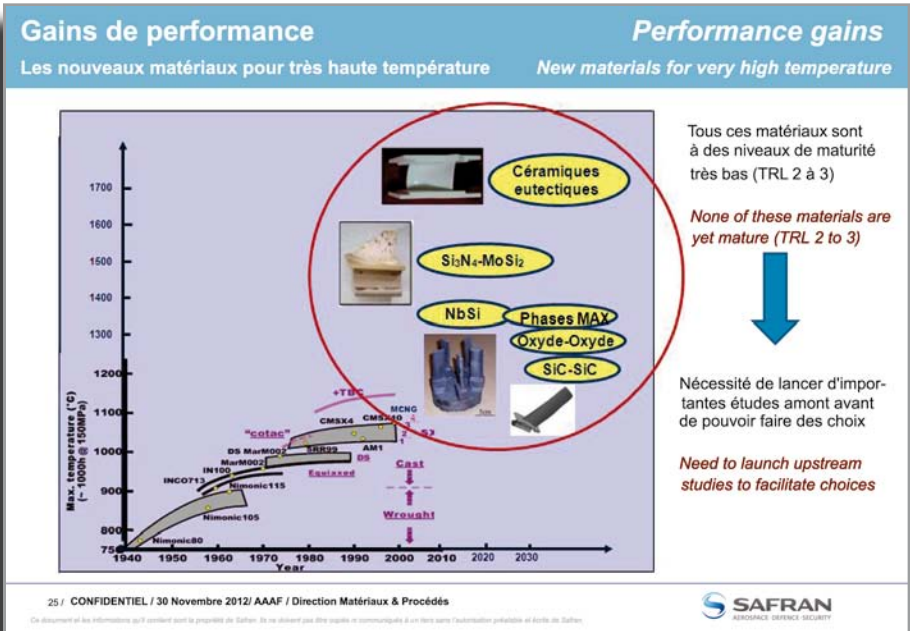


Figure 7: Performance gains

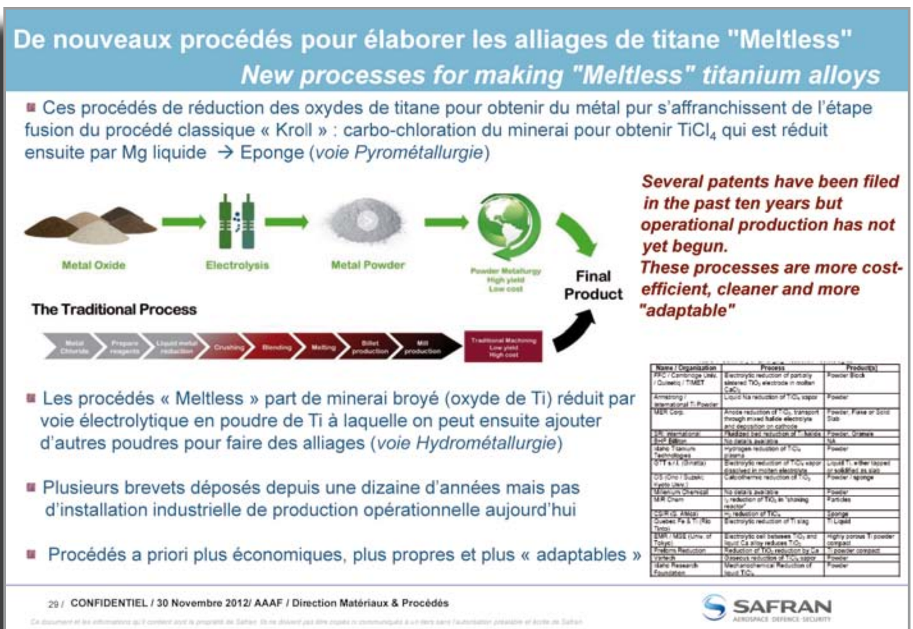


Figure 8: New processes

mechanical and thermal characteristics and also reduce manufacturing costs but these methods also allow for the technical developments mentioned above. The contribution of modelling will be crucial for defining the composition envelopes of materials by simulation. ICME (Integrated Computational Materials Engineering) is meeting with great success in this respect in the United States with major efforts being made in American universities and institutes to develop multi-physics models at different scales: the idea is to start from the design of the material itself through to its properties of use going through all stages of its transformation, at the relevant scales. The main goal is obviously to drastically reduce industrial development and implementation cycles for new materials and processes.

In conclusion, materials and processes are key technologies for aircraft equipment and turbine engines. They should be developed through a partnership between research players (universities, institutes ...) on the one hand and the various links of a now global supply chain on the other. This is the condition for a revolution in aircraft materials in the next 2 or 3 decades which will be conducted under the pressure of external economic and environmental constraints on the part of society.

MATERIALS FOR AERONAUTICAL AND SPACE STRUCTURES
Trends and challenges for tomorrow

The aluminium alloys that a few decades ago made up over 80% of aerospace structures are increasingly being replaced by carbon fibre composites. This development is often at the heart of competition between aircraft manufacturers, as witness the A350 and the 787. In this context of heightened competition, the traditional criterion for selecting materials and processes, a compromise between cost and performance, is increasingly disturbed by other less conventional criteria related to the new reality of a global industry in constant evolution. New criteria might be strategic (such as the positioning of the competition or outsourcing), industrial (such as cycle time, robustness of processes), related to maintenance or linked to

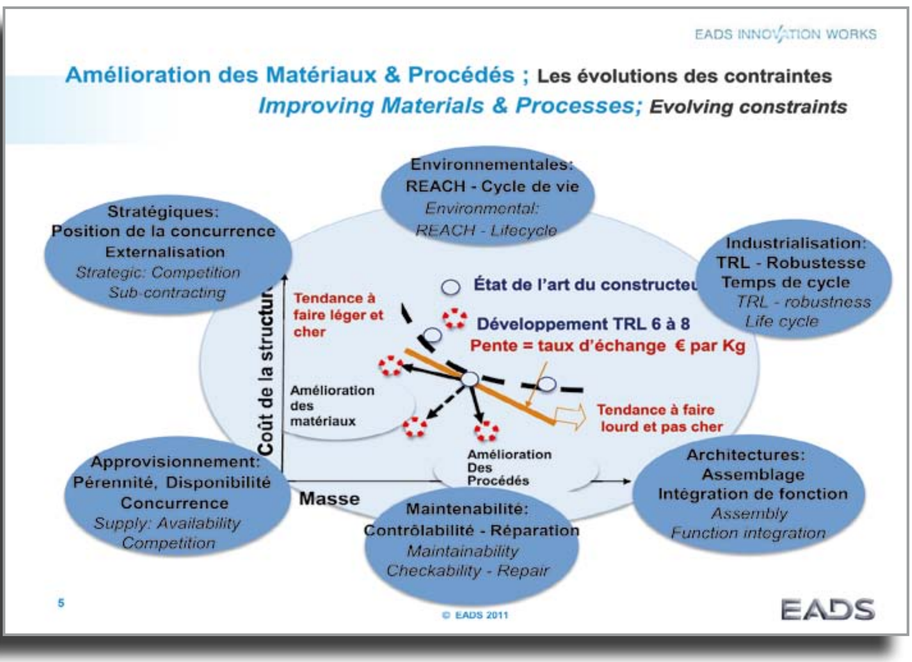


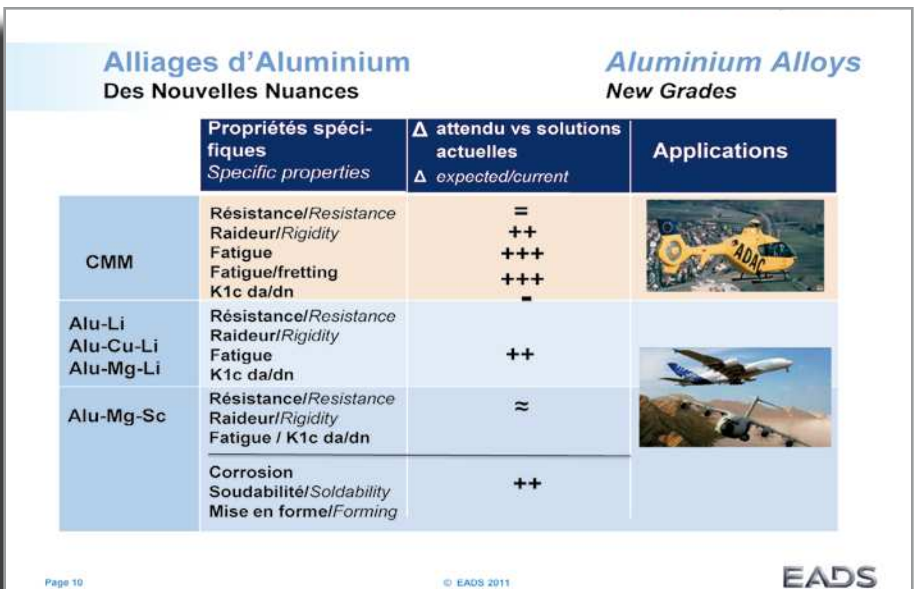
Figure 9: Evolving constraints

environmental concerns embodied by REACH or connected with product life cycle, such as greenhouse gas emissions, recyclability ... (Fig.9).

The choices greatly depend on the type of structure: if one considers an Airbus plane, for example, the different choices between traditional concepts with metallic materials and more recent designs in composite materials will largely be determined by thickness. On the wing where the load flows require greater thickness, composite materials are necessary, with different options in competition for future aircraft. For the fuselage, which requires less thickness and where physical properties such as electrical conductivity can penalise composite materials, future choices are all the more uncertain in that the new considerations mentioned above (environmental, strategic) are likely to play a decisive role. These uncertainties at any rate constitute a driving force to boost innovation and R&D activities for each class of materials.

Metallic materials

In terms of metallic materials, new, more efficient classes of aluminium alloys will be used based on the friction stir welding (FSW) technology. Thus, aluminium alloys with lithium, copper lithium or magnesium lithium will lead to performance improvement of at least 10% on today's solutions. Another class of alloy is under consideration with a view to reducing the cost of implementation and improving durability (corrosion). These are magnesium-aluminium-scandium alloys which present the advantages of better shaping capacity and weldability. However, the sticking point for aluminium alloys, which will need a substantial effort in coming years, concerns resistance to corrosion and protections including surface treatments and paints without chromium VI (Fig.10).



	Propriétés spécifiques *Specific properties*	Δ attendu vs solutions actuelles Δ *expected/current*	Applications
CMM	Résistance/*Resistance* Raideur/*Rigidity* Fatigue Fatigue/fretting K1c da/dn	= ++ +++ +++ -	
Alu-Li Alu-Cu-Li Alu-Mg-Li	Résistance/*Resistance* Raideur/*Rigidity* Fatigue K1c da/dn	++	
Alu-Mg-Sc	Résistance/*Resistance* Raideur/*Rigidity* Fatigue / K1c da/dn	≈	
	Corrosion Soudabilité/*Soldability* Mise en forme/*Forming*	++	

Figure 10: New grades of aluminium alloys

Figure 11: Assembly technology - FSW

These new alloys will need to be associated with FSW technology which could be applied to the fuselage panels (welding of smooth surfaces, welding panels together or welding sections); it will have many applications on structures including on welded tanks like in launchers (Fig.11).

This technology is likely to emerge in the medium term, with large-scale introduction into factories. It is one of the few technologies that should lead to both reductions in cost and weight, thanks to the elimination of many bolted or riveted fasteners, and to reduced thickness in junction areas. Compared to traditional welding of aluminium alloys, which currently applies to Ariane V in particular, FSW for future launchers will lead to both increased performance (due to the use of alloys that are non-weldable with conventional means) and improved strength due to welding in "pasty" phase. To enhance this technology, efforts will need to focus on robotisation, reduced tooling costs and robustness of the process. Cost cutting in tooling and increased robotisation will be facilitated by searching for reduced effort welding conditions; with regard to robustness, efforts should be focused on identifying areas of weldability that exclude the possibility of undetectable faults such as the "kissing bond".

Leaving aside the metal/composites competition, we should mention direct manufacturing technology which, initially applied to titanium alloys, will lead to many applications for structural parts in the medium to long term (Fig.12).

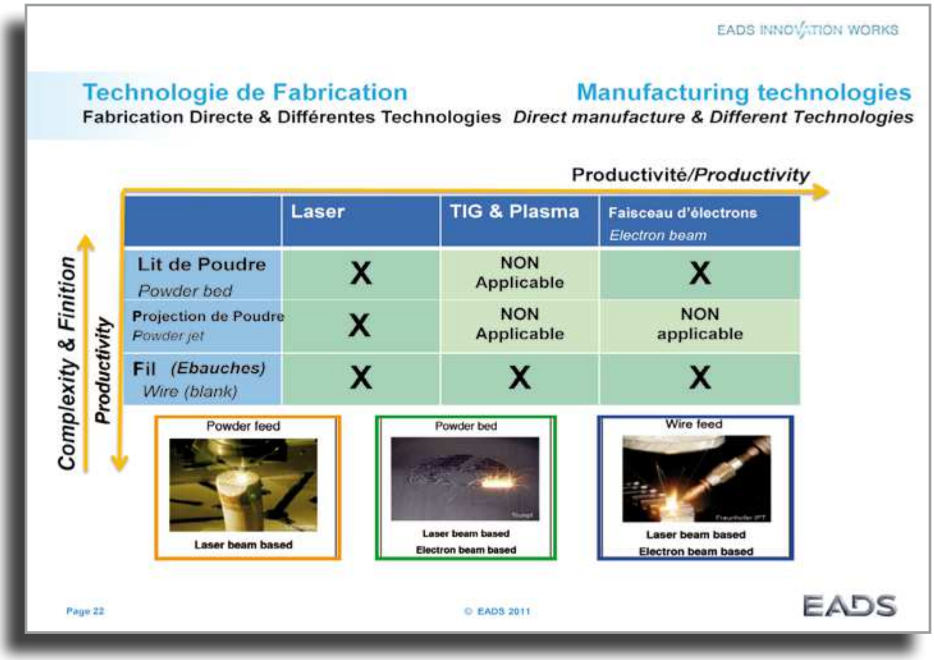


Figure 12: Direct manufacture

If the primary interest of this technology is cycle time (going directly from the digital 3D part to the real part), it also has other major advantages such as reducing the raw material needed (buy to fly), the ability to produce parts that are impossible to machine or to functionalise parts (by varying powders in the preparation). Improvements that need to be made to this technology mainly concern surface state, distortions, mastering residual stresses and gaining maturity with relation to aluminium alloys. In the longer term (5-10 years), significant progress can be expected in terms of productivity through the use of threads (instead of powders) and by reducing weight through the promotion of topological optimisation and functionalisation.

We cannot close the chapter of metallic materials without stressing that more effort must go into sustainable development. Especially for aluminium alloys where the replacement of chromium VI both for surface treatment and in paints will need to be solved in the medium term.

Composite materials

These materials (carbon fibre composites) have a number of important assets:

- larger size of elements and reduction in the number of sub-elements (as compared to metallic components);

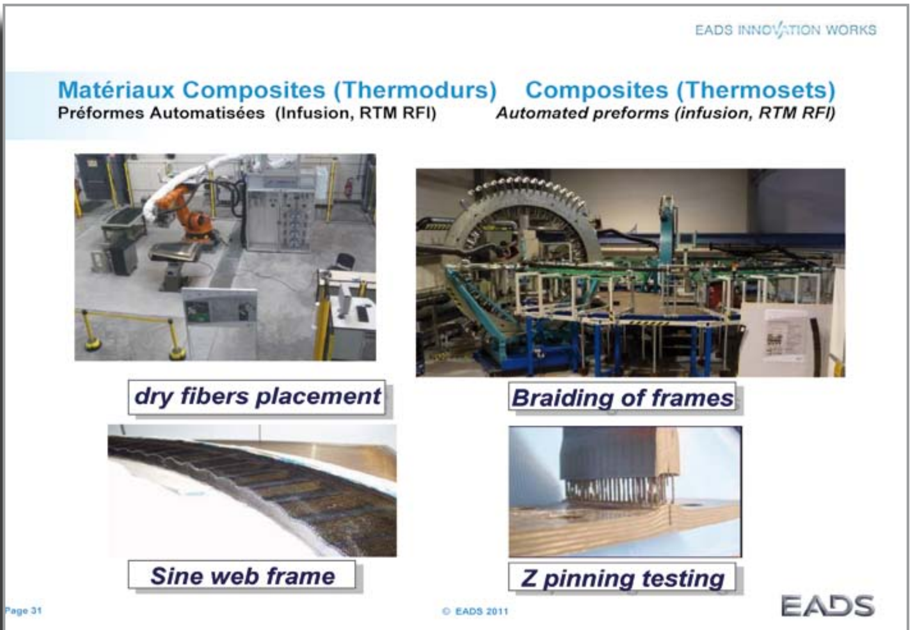


Figure 13: Composites (Thermosets)

- highly automated manufacturing process;
- weight reduction;
- less maintenance required
- and, to a lesser extent, integration of functions on structural parts.

Efforts in recent decades will be pursued to move steadily towards fuller automation, greater function integration and larger parts. In this context of growing productivity another significant development is emerging which is likely to radically alter use of these materials: thermoplastic composites (Fig.13).

These have many advantages: better damage tolerance/resistance, storage at room temperature, no problems of expiry or humidity aging; they are weldable and can be consolidated out of autoclave and, from the point of view of sustainable development, they are less affected by REACH and are easier to recycle. However, the cost of these materials is high for the moment and their consolidation, which must be performed at a higher temperature (than thermosets), is industrially disadvantageous.

Future trends for thermoplastics and thermosets would be for increased automation with thermoplastics being obtained by automatic fibre placement and the realisation of large-scale dry preforms for thermosets incorporating the sub-structure and intended for out-of-autoclave infusion. On thermosets, promising areas to reduce

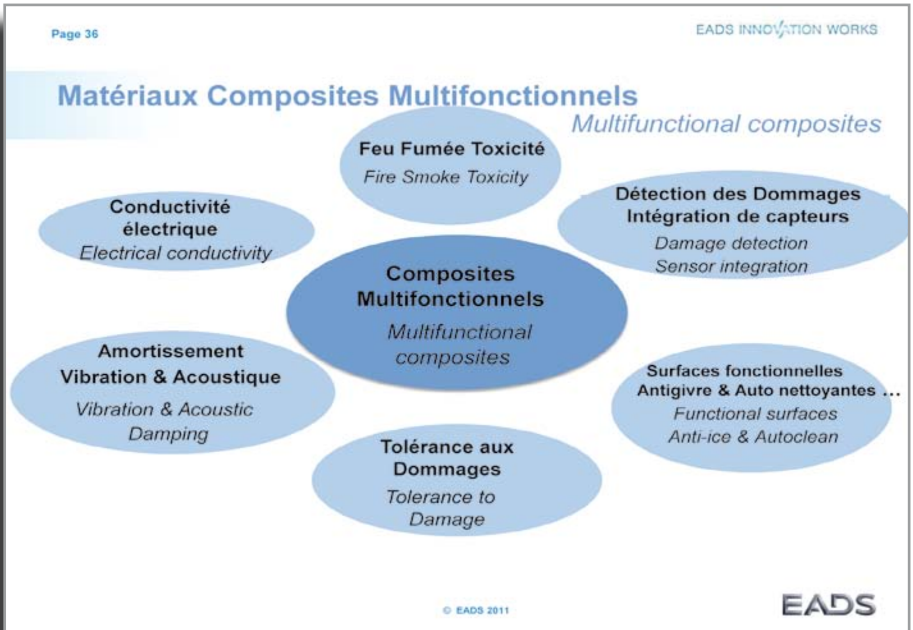


Figure 14: Multifunctional composites

costs will also be the introduction of resins tolerant to variations in polymerisation cycles, and thus the mastering of structure-property relationships.

In terms of the mechanical and physical properties of composite materials, the major avenue for progress is the multifunctionality of these materials. Since the material is manufactured (from fibre/resin components) at the same time as the part, it is relatively easy to add additional components to the resin or the inter-ply to adapt them to the desired functions. Multifunctionality integrates properties such as damage tolerance, fire resistance, electrical or thermal conductivity, shock absorbance, incorporation of sensors, etc. (Fig.14).

Today, the property which influences the choice between metal and composite most strongly is surely electrical conductivity. This property, a major handicap for composite materials in terms of lightning resistance and backfeeding, will require substantial efforts to combat induced extra weight. There are many ways forward including conductivity of the solid part for thicker elements to avoid problems linked to flash butt welding, and surface metallisation to avoid direct damage due to lightning (Fig.15).

Finally on the issue of sustainable development, composite materials present many strengths and some weaknesses for which research must be intensified. In terms of the assets one should mention the absence of penalising surface treatments which are the weak point of aluminium alloys, and especially a reduction in weight which,

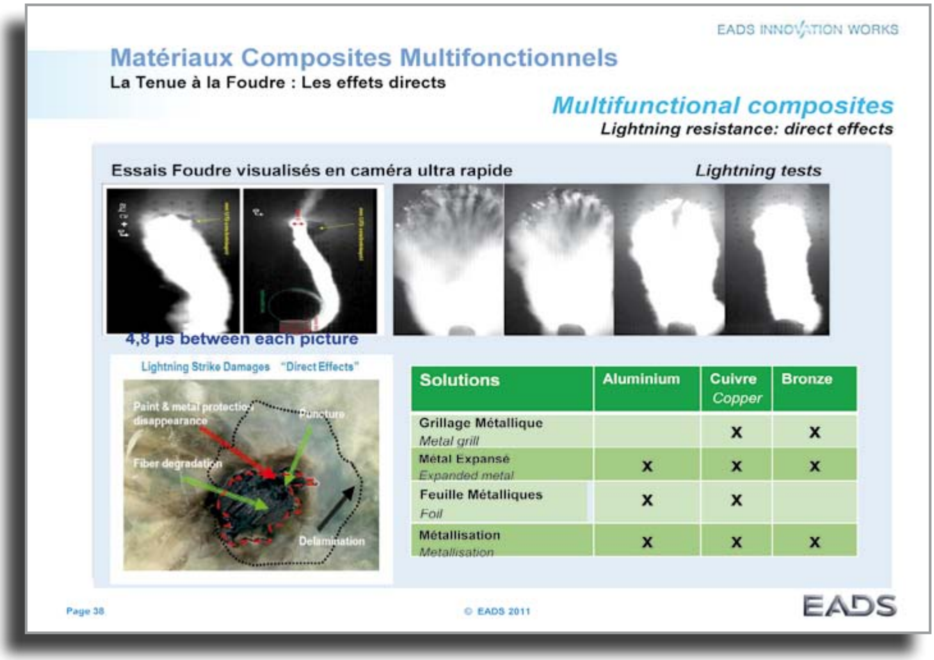


Figure 15: Lightning resistance

for products with a long lifespan such as aircraft, remains the major parameter in terms of CO_2 emissions. In the longer term, the promise of bio-based materials (fibres/resins) is an important asset that must be developed. As regards their weaknesses, progress must be made on thermosetting resins, which are impacted to some extent by REACH and are not recyclable, as well as fibre recyclability.

In conclusion, through the question of the choice of materials (metal / composite), the above presentation has not only summarised the major avenues for R&D progress, but also shows that the materials and processes remain a highly competitive field. With the arrival of new competitors from emerging countries and the increased outsourcing of some structural parts, the R & D effort should not be relaxed (as has been the case in recent years), since materials and processes are fast becoming a critical area for the future and one which will be decisive in upcoming competitions.

In this context, it is important to develop tools to reinforce the field and strengthen partnerships between industry, academia, and the network of small and medium enterprises. On a national level, the technological research institutes or even the AIGLE platform in Dugny should play a leading role in structures for tomorrow, and EADS relies on a strong implication on the part of all its partners in the success of these shared research laboratories.

ARCHITECTURED MATERIALS: A BRIDGE BETWEEN MATERIALS AND DESIGN

Yves Bréchet (High Commissioner for Atomic Energy and Professor at INPG) introduced a new approach to materials in this exposé on the "Materials by design" concept, presented in close cooperation with Professor Michael F. Ashby of Cambridge University.

Yves Bréchet started by summarising the current context of materials and their industrial applications. Requirements on materials are increasing in virtually all modern industrial sectors. They are utilised in more and more severe conditions in terms of temperature and mechanical load and in ever more hostile environments such as oxidizing/corroding atmospheres and are even subjected to radiation in the case of nuclear reactors. Manufacturers must also ensure the integrity of materials while constantly reducing the weight of component parts in order to increase performance. Efforts are made in certain cases to "add" particular features to structural materials (sound absorption, thermal insulation, shock absorption, self-healing...) or, in the case of functional materials, to increase their structural durability.

Moreover, there is an abundance of structural materials, whose numbers have increased steadily over time but have exploded in the past 50 years. We therefore have an abundant choice and competition is sometimes fierce between the different families of materials to designate the material that will best meet the stiff requirements contained in the specifications. In such contexts, modelling becomes increasingly important and it is vital to seek multifunctionality in the different approaches to developing materials (random discovery to tailor-made materials).

The term "architectured materials" describes materials within which matter is distributed on a comparable scale to that of the component, making it possible to meet requirements that would be contradictory for a single material; links between matter, geometry and topology are all optimisation levers (Fig.16).

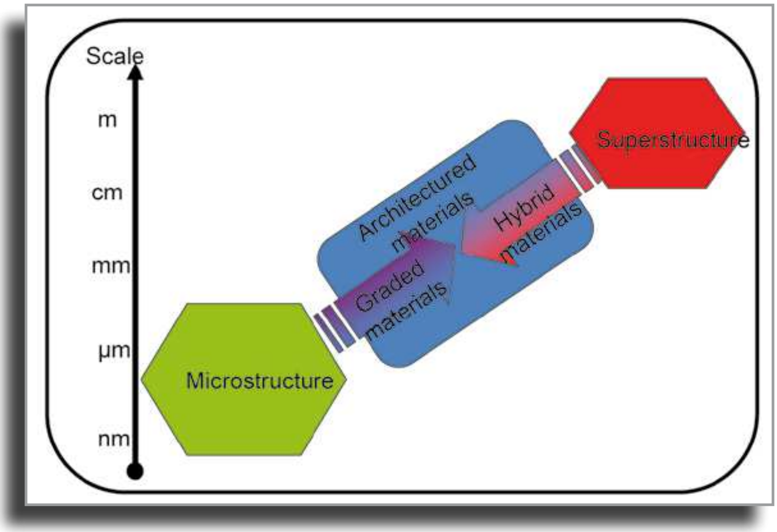


Figure 16: Architectured materials

This very original approach to materials design and applications can be grouped into 4 parts entitled respectively: The case for architectured materials, Microstructure gradients, Tailoring materials with geometry, and Designing multifunctional materials.

The case for architectured materials

To illustrate how contradictions in part 1 can be resolved Yves Bréchet took the case of electric leads, an example of architectured materials par excellence, and examines their architectures. The solution found long ago for this technology was, of course, to combine metal (Cu) and polymer. This combination, described as a hybrid solution, thus meets the specification imposed (good longitudinal electrical conductivity and perfect radial electric insulation). To ensure good flexibility, the architecture adopted is an assemblage of wires surrounded by a polymer coating. Other solutions exist such as “composites” to meet a double requirement (weight and stiffness), “form solution” by assemblage to increase stiffness, and “mixed form and microstructure solution” to obtain simultaneously high stiffness and good mechanical resistance.

Microstructure gradients

Yves Bréchet referred to the steel decarburisation experiments carried out by the team he formed with Professor David Embury at McMaster University. This study demonstrates the possibility of a compromise between mechanical resistance and ductility by introducing a millimetric chemical composition gradient and hence a variation of microstructure.

Tailoring materials with geometry

This part addressed geometric adaptation in order to “shape” materials, making it possible to obtain new functionalities presenting respectively shape optimisation, self-blocking structures and disordered structures (Fig.17).

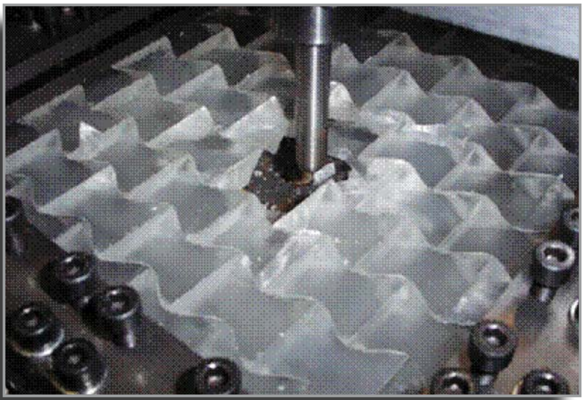


Figure 17a: Plate created through assembly of osteomorphic blocks

Figure 17b: Monolithic plate

In particular fracture can effectively be contained by assembling osteomorphic blocks and optimising, through modelling, various parameters such as friction between blocks, prestressing force applied and size of these blocks.

Designing multifunctional materials

This section was devoted to ongoing design examples of multifunctional materials, derived in particular from his cooperation with ONERA. This involves the joining of hollow metal balls, with the purpose of obtaining structural materials with an additional functionality such as sound absorption or shock mitigation (Fig.18).

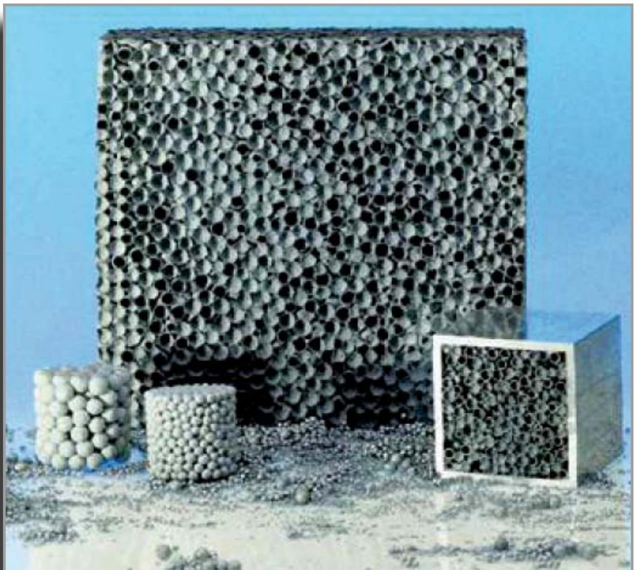


Figure 18: State of the art in architectured materials

He finished his presentation with the following conclusions:

- microstructural optimisation is only one of many approaches to produce “tailor-made” materials;
- millimetric architecture is an efficient variation to meet the needs of multifunctionality;
- the great variety of possibilities offered by the “architecture + microstructure” combination requires the development of modelling tools to achieve new materials;
- these new concepts open up an original approach to design and industrial use of materials.

CHOICE BETWEEN ALUMINIUM ALLOYS AND ORGANIC COMPOSITES FOR FUTURE BUSINESS AIRCRAFT

When designing business jets, as is the case for commercial airliners, the question arises as to the choice between metallic materials and organic composite materials for the different parts of the structure.

For many years, large-scale national and international developments (FUBACOMP, ALCAS projects) have tested breakthrough architectures and technologies in different composite fields, from design stage to manufacture and assembly of large structures.

Commercial aviation has launched itself into organic composite materials for the fuselage and wings of long-haul aircraft. One might think that business aviation would follow this trend. However, its characteristics and specifications (aircraft series, weight, fuselage diameter, maintenance,...) are different. Weight reduction is still an important factor, but it must be balanced out with production costs, retail price and operating costs, including maintenance.

On the last point, business aviation is characterised by low average annual utilisation needs, of the order of 500 flying hours per year. Purchasing price is a determining factor in the customer's decision, which is not the case in commercial aviation where operational and maintenance costs have equal importance. Owners of business aircraft tend to sell their plane within 10 years after its acquisition, well before the first heavy maintenance visits.

In addition to improved density, composites outdo aluminium alloys in terms of fatigue and corrosion resistance. However, and this is particularly the case for the fuselage, weaker aspects include resistance to lightning and especially backfeeding for the many systems, resulting in an increase in weight induced by the addition of metallic elements needed to perform these functions. In addition, since the dimensions of business aircraft are not the same as commercial aircraft, the final sampling is not simply the result of general optimisation of resistance to different stresses. So-called minimum technological values are quickly reached. For a business aircraft fuselage, robustness to small impacts, minimum thicknesses for lightning resistance, shape-holding properties and surface finish, for example, lead to a marginal weight reduction.

For stress flows on wing boxes, on the other hand, studies carried out by Dassault Aviation showed a weight reduction of the order of 15-20% in favour of organic composite materials, without additional manufacturing cost, through the development of composite process automation and extensive integration into structural design.

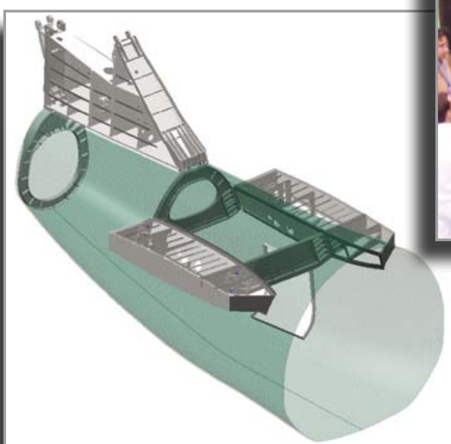


Figure 19: Demonstrator of a Falcon rear section (ALCAS project) made by fibre filament placement

To sum up, on the basis of technologies known to date (TRL>=3), the future Falcon business jets could increase their ratio of composites to aluminium alloys, particularly for large-scale wing-box structures. The fuselage, however, should remain metallic.

The aluminium manufacturing industry is not standing idly by in the face of this competition from composite materials. New metal alloys with lower density than the conventional 2024 (Al.Cu.Mg) are now available on the market: Constellium's 2198 and 2196 for example. These alloys (Al.Cu.Li) have a density lower than 4%, better corrosion resistance and very good mechanical properties. However, the weight reduction anticipated for the Falcon fuselage is very low (once again the problem of technological minima). Another opportunity is the development of aluminium alloys (Al.Mg.Li.) offering a density of 2.55 and so a higher weight reduction (several dozen kilograms). In parallel, the FSW process is under investigation as an alternative to riveting assembly, for economic reasons.

For Dassault Aviation, there is no question of jumping on the bandwagon. Metals and composites will continue to cohabit, with the best use made of each in the right place.

Figure 20: Demonstrator of Falcon front section (FUBACOMP project): concept associating the RTM (Resin Transfer Molding) process with fibre placement and polymerisation by autoclave

NEW ALLOYS AND ALUMINIUM SOLUTIONS FOR AERONAUTICAL STRUCTURES: PROGRESS AND CHALLENGES

For new, future generations of airliners, aircraft manufacturers have high demands in terms of reducing weight, maintenance, costs and manufacturing cycles of aerostructures. These applications have for some years enjoyed, and will continue to justify, significant R & D funding for the development of advanced aluminium-based metallic materials, their manufacturing processes and their integration in the context of now hybrid aircraft.

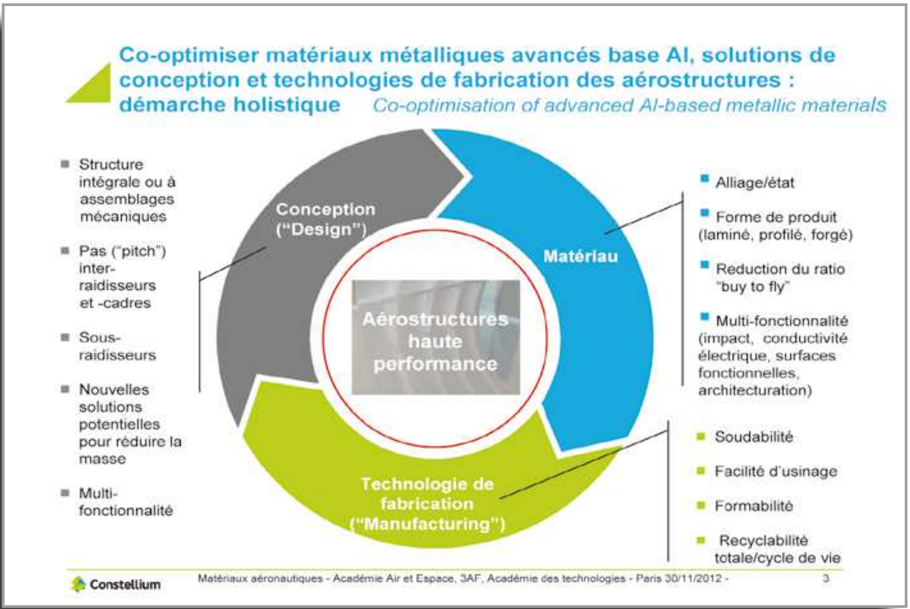


Figure 21: Co-optimise Al-based advanced metallic materials, design and technology for aerostructure manufacture : holistic approach to encourage innovation and co-development

This holistic approach to innovation combines improvements in the performance and functionalities of metallic materials and products, advances in aerostructure manufacturing technology (in particular machining, assembly and forming) and progress in design achieved through co-developments bringing together materials producers and aircraft manufacturers (Fig.21).

Constellium, a leading provider of aluminium products, has responded to this challenge with its AIRWARE® technology: the development of new low-density grades of aluminium alloy of the Al-Cu-Li-(Mg, Ag) family transformed into rolled products (including thick plate for 2050, fuselage sheet for 2198), extruded products (profiled in 2195 and 2196) or forged/die forged products (2050). These alloys, designed to prioritise performance criteria over density gains for products in aerostructures, contain a moderate amount of lithium (around 1% by weight) and are processed in optimum metallurgical states (tempering). They enable significant weight reduction and improvement in aerostructures performance when compared with the reference aluminium alloys introduced at the end of the 1980s and the alloys developed for the A380 (Fig.22).

The melting and casting/solidification of these alloys require specific technologies because of their propensity for oxidation and affinity for hydrogen when in liquid state, so Constellium has designed and launched industrial foundries dedicated to lithium alloys on the sites of Voreppe in 2011 (R & D pilot scale 1) and Issoire in 2012 (production). AIRWARE® technology also recycles production loss and waste and, above all, machining cuttings from downstream manufacture of structural components.

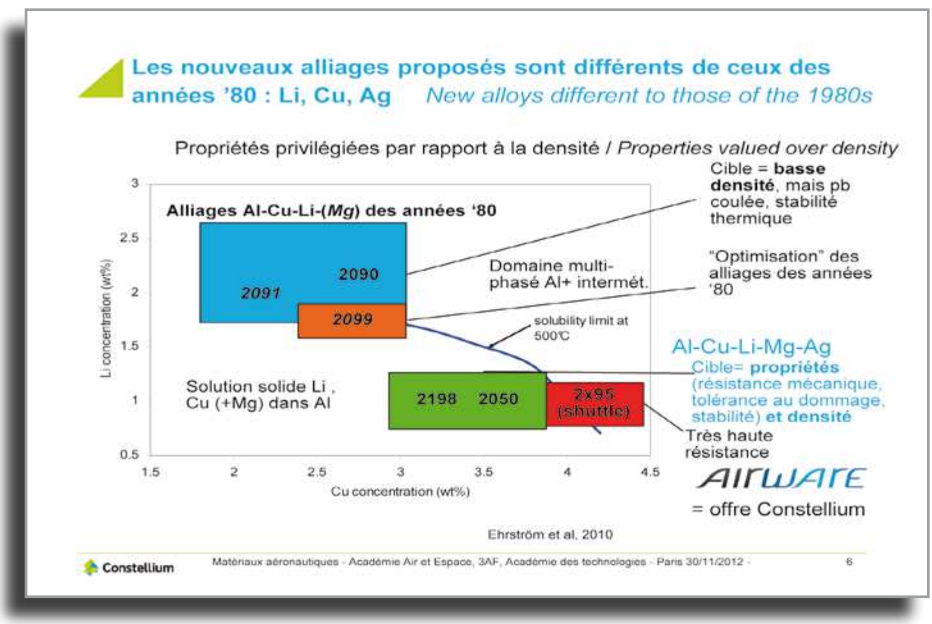


Figure 22: New alloys proposed are different from those of the 1980s: Al, Cu, Ag

This process, which is indispensable for the eco-efficiency of the manufacturing sector and product integration by aircraft manufacturers and their subcontractors, is show-cased in the FUI OFELIA project in coordination with Aubert & Duval, Rexiaa-Lusina, IFMA, the École des Mines and the CEMEF (Fig.23).

Figure 23a: Machining of fuselage frameworks in alloy 2050 (AIRWARE®)

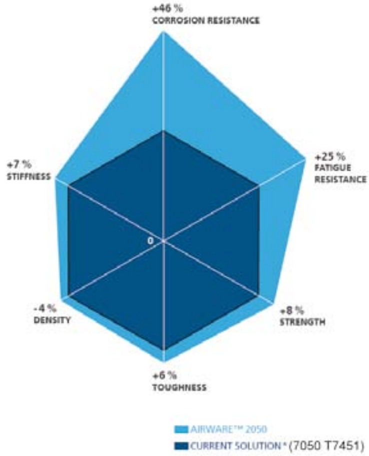


Figure 23b: Comparison of sheet properties of 76mm in 2050 T84 (AIRWARE®) and 7050 T74 (reference)

These products offer exceptional compromises between different properties: they typically attain the mechanical resistance of a 7XXX alloy (Al-Zn-Mg-Cu) combined with the damage tolerance of a 2XXX alloy (Al-Cu-Mg) together with improved resistance to structural corrosion and excellent thermal stability after prolonged holding at moderate temperature. The structural hardening and corrosion behaviour of 2050 and 2198 alloys (Al-Cu-Li family), with metallurgical states T8X (work hardening, annealing after quenching), are primarily governed by the extensive precipitation of phase plates T1-Al_2CuLi of nanometric dimension formed by heterogeneous germination, which is favoured by the hardening after quenching process.

AIRWARE® technology has already been selected for the internal structures of the Airbus A350 XWB (2050) and the fuselage of the Bombardier CSeries (2198) (Figs. 24 & 25).

Weight reduction resulting directly from a 3 to 6% decrease in density of the alloys (without reduction in thickness of the parts) can be added to a further 5–10% reduction due to thickness optimisation, taking into account improvements in mechanical properties (mechanical resistance – damage tolerance); the yield strength-toughness compromise determines the weight of the structures in classic designs. A possible 10 to 15% reduction is therefore possible for a given design (geometry).

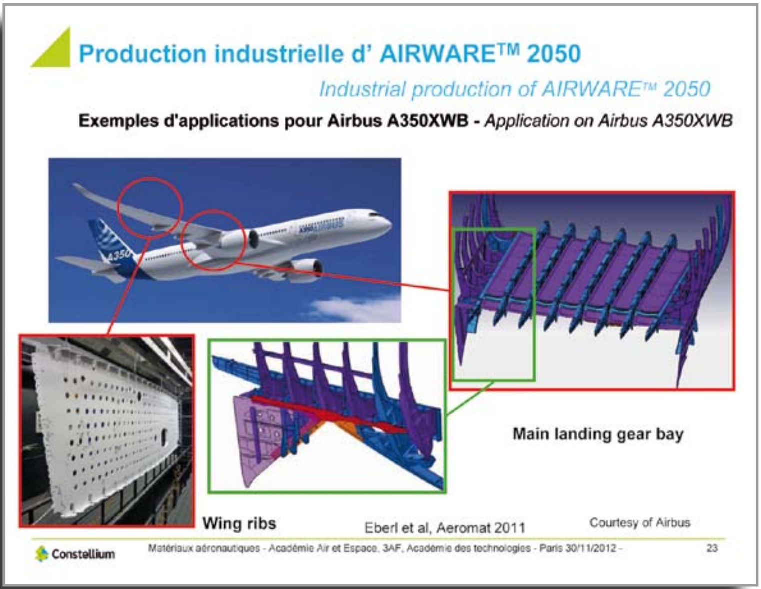


Figure 24: Airware® 2050 on Airbus A350XWB

Figure 25: Airware® 2198 on Bombardier CSeries fuselage

Looking beyond advances in the realm of metallurgy, technological innovations in production and integration procedures of structural parts are set to provide an estimated additional 10% weight reduction. In mechanical design, this is a case of optimising geometries (trailing areas include fatigue cracking, Omega-shaped stiffening sections, sub-stiffeners) and in assembly, glued stiffeners. A holistic approach combining advances in metallurgy of alloys and products transformation processes (AIRWARE®) together with progress in aerostructure application technologies would provide, depending on configuration and stress flow, weight reductions estimated at 15% to 25%, with predictable properties and capability for high aircraft production rates.

Even greater use is made of this integrated approach for future high-performance metal solutions.

Firstly, Al-Cu-Li alloys can potentially improve the compromise between damage tolerance (rate of fatigue crack propagation and tenacity) and mechanical resistance. Progress will result in particular from a better understanding of the mechanisms of hardening by (co-precipitation of nanoscale phases, the relationship between granular structure and properties of wrought products, the structural corrosion of alloys and their improved corrosion behaviour within hybrid aerostructures (with composite parts) as compared with conventional reference alloys. Constellium and its research partners are very active in research on these matters. Such potential for improving mechanical strength and damage tolerance is likely to provide new solutions especially on the upper wing (with high mechanical resistance) as well as on the underside of wings and fuselage (with high damage tolerance) (Fig.26).

Secondly, very low density alloys of the Al-Mg-Li family have great potential uses in thin parts, especially when "technological minima" considerations restrict the possibility for reducing plate thickness of high strength alloys.

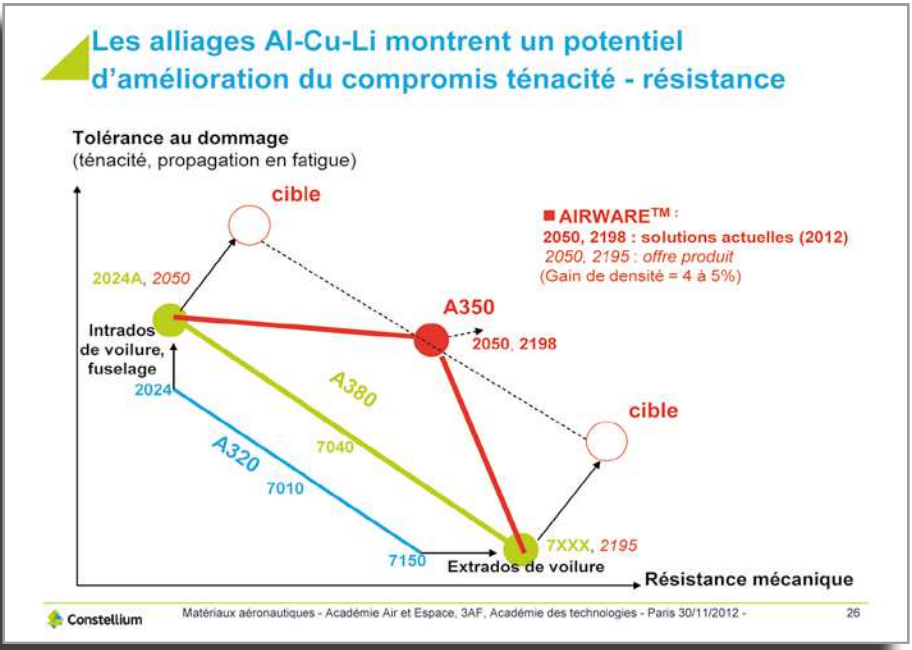


Figure 26: Evolution in damage tolerance – mechanical resistance performance of aluminium products for the A320, A380, A350 and future generations (target).

In the shorter term, improved performance of non-lithium alloys is also an important avenue for R & D.

In the longer term, the potential of multilayer aluminium alloy structures (EML: Engineered Metal Laminates) for improving fatigue cracking is likely to provide aircraft manufacturers with new gains in terms of weight and durability.

In addition, increasing partnerships with manufacturers and progress in design and predictive numerical simulation offer the prospect of significant improvements in operational performance and economic efficiency of the value chain of metal aerostructures through:

- increased integration of materials from design to incorporation via machining, forming and assembly (including friction stir welding (FSW) or linear friction welding (LFW), bonding)
- multifunctional design: adapting the mechanical resistance - damage tolerance combination to the position in the aerostructure (eg. wing), structural health monitoring, aerodynamics (action on the aero-elastic response of the wing, reducing turbulence by architecturing (riblets) or rivets elimination).

In conclusion, in addition to the progress represented by the new AIRWARE® technology in meeting requirements from aircraft manufacturers in terms of weight reduction, durability and industrial performance, Constellium considers there to be room for innovation in the area of aluminium-based high performance metal aerostructures in the future. Breakthrough improvements can be achieved by co-optimising materials, design and manufacturing technologies; performance of alloys constitutes only half of the potential of these new aerostructures.

R & D funding by Constellium aims to provide a range of alloys and technologies for future derivatives of existing aircraft in the medium term and, in the long term, new designs for the next generation of aircraft. A new focus on manufacturing ability nonetheless appears necessary to support future increased production rates; in this case aluminium products are still, or will once again be regarded with great interest by aircraft manufacturers when compared with composite solutions (particularly for the fuselage).

This highlights the importance that must be accorded in collaborative R & D programmes (bringing together producers/transformers, manufacturers, government laboratories) to aluminium-based metallic materials, their manufacturing processes and their integration technology. In France, the new methods being developed (technology platforms, demonstrators) with the creation of Institutes for Technological Research (especially the Jules Verne IRT) offer attractive prospects for relevant R & D projects and innovative co-development ventures with manufacturers. This is also the case in Europe, with the Clean Sky programme carried out under the aegis of the FP 7 and continued in the future Horizon 2020 programme, which should enhance its impact.

HIGHLY RESISTANT (> 2000 MPa) AND VERY TOUGH STAINLESS STEELS (75-150 MPa√m): Dream of mechanical metallurgy and/or industrial reality?

The aviation industry is looking for a number of applications (landing gear, shaft and other heavily loaded structural elements) for highly resistant (2000 MPa), high stiffness (K_{1C} = 75-150 MPa $\sqrt{m}$) steels.

In his presentation, André Pineau (Ecole des Mines de Paris) defends, step by step, with convincing experimental evidence, the thinking that led him to propose the AusMarAging steel concept.

Metallurgical solutions adopted to increase mechanical strength are well-known, in principle. Phase transformations (martensitic transformation) and precipitation hardening (precipitation of carbides of type Mo_2C and rich intermetallic phases such as in Al) are already implemented in maraging types of steel. However, the metallurgic levers that increase toughness remain largely empirical. The description and analysis of these metallurgical means of action are precisely the subject of this presentation.

His presentation was divided into six parts:

1. Introduction
2. Avoiding cleavage fracture
3. Ductile fracture
4. How to increase the work-hardening coefficient?
5. Cumulative hardening effects
6. Conclusions

In the **introduction**, the practical importance of toughness was underlined for industrial applications of high-strength steels such as in the manufacture of landing gear (Figs.27 & 28).

Figure 27: Role of landing gears

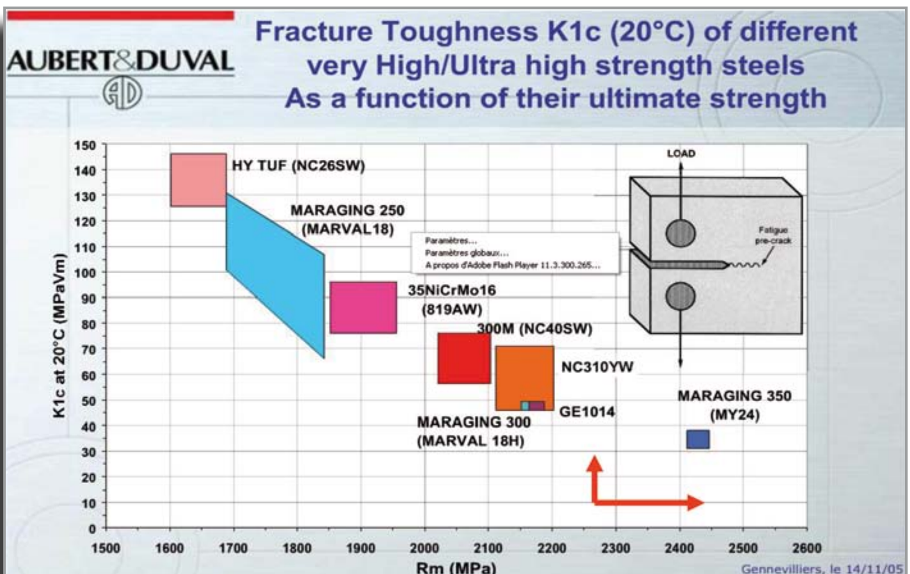
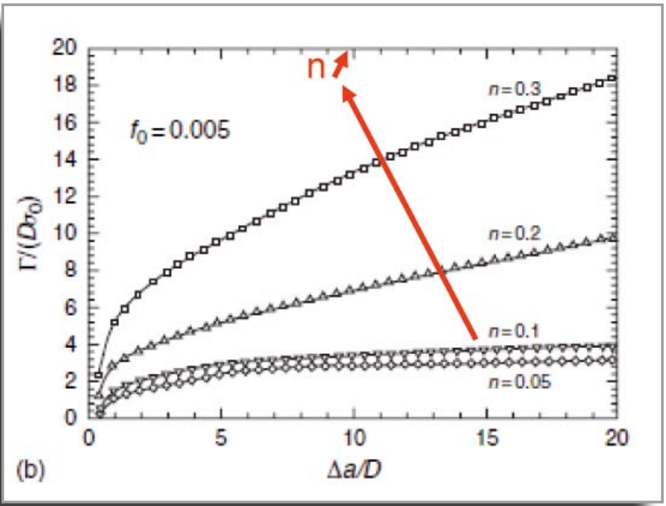


Figure 28: Fracture toughness K1c (20°C) of different very high/ultra high strength steels

To guard against fracture by cleavage, the importance of lowering the ductile-to-brittle transition temperature was mentioned in Part 2. Two relevant metallurgical processes are involved in this: a decrease in the grain size and the addition of nickel. Regarding the addition of nickel, it reduces the sensitivity of the yield strength to temperature change. Regarding the **ductile fracture**, the theoretical arguments in favour of increasing the work-hardening coefficient (n) were developed in Part 3 (Fig.29).

Figure 29: Calculated curves of crack resistance for different hardening coefficients (for an initial porosity volume fraction of f_0 = 0.005)



Part 4 deals with the approach to increase the ***work-hardening coefficient***:

- introducing a small amount of austenite phase or "disorder" in the martensite microstructure (residual austenite or austenite reversion);
- promoting the dual-phase effect by:
  - inter-critical annealing followed by quenching for VHT carbon steels;
  - re-austenitising after intercritical annealing + quenching + tempering for THR alloy steels;
- "Partitioning" of alloy elements (Figs.30 & 31).

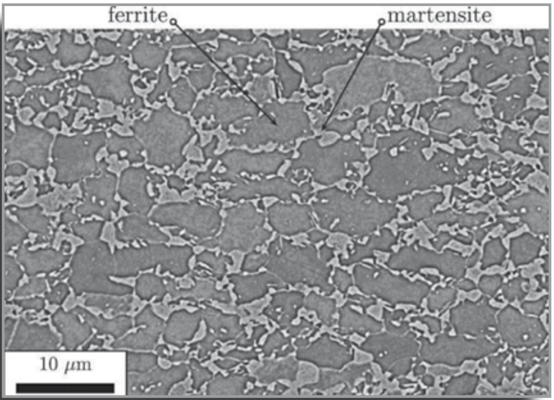
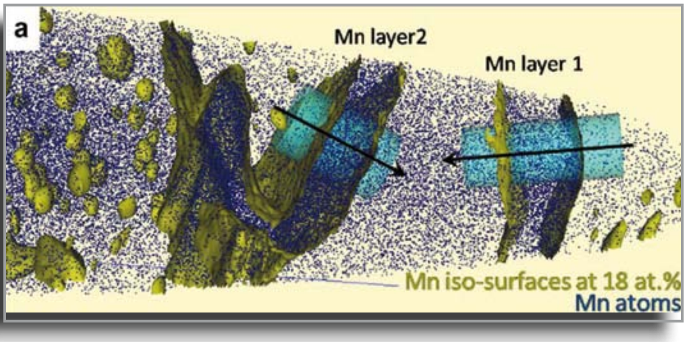


Figure 30: Dual-Phase

Figure 31: Partitioning of Mn



The AusMarAging steel concept (part 5) **aims to combine hardening effects** with the following considerations in mind:

- Combine aging in γ and α phases;
- Aging in γ phase:
  - either with interrupted quenching (if M_S> 20°C) (possibility of lowering M_S by confinement of α "seeds");
  - or by addition of Ni so that M_S before aging is <20°C (~ 25-28% Ni) (need for cryogenic treatment after precipitation in γ phase);
- Hardening in γ phase:
  - by γ' (addition of Ti and/or Al);
  - by γ'' (addition of Nb and/or Ta);
- Solubility of Ti, Al, Nb, Ta lower in phase α than in phase γ, allowing structural hardening of the martensite;
- Possibility of a TRIP effect by controlling the level of residual austenite.

André Pineau's presentation ended with the following conclusions:

- The objectives are almost achieved with R_m = 2000MPa and $K1_c$ = 75-150MPa.m$^{1/2}$.
- These alloys can be considered as "composite" steels with the soft phase very finely dispersed.
- Resistance to corrosion under stress, an important feature for use of these steels, could not be addressed in this presentation.

AIR AND SPACE ACADEMY (AAE)

Established in 1983 in Toulouse on the initiative of André Turcat, the aims of AAE (Air and Space Academy) are the following: "To encourage the development of high quality scientific, technical, cultural and human actions in the realms of Air and Space, promote knowledge in these areas and constitute a focal point for activities."

AAE's eminent membership is co-opted via an elaborate system of patronage and elections so as to promote high level reflection on vital issues. Embracing a broader European dimension in 2007, AAE integrated its European members as Fellows, thus guaranteeing a European and international focus to all of its studies. AAE members hold or have held important responsibilities in their fields and represent the many different facets of air and space activities: pilots, astronauts, scientists, engineers, doctors, industrialists, lawyers, journalists, writers and artists work together and constitute a valuable pool of knowledge.

Members are allocated to sections according to types of activity and interests:

I. Scientific knowledge of air and space
II. Applied science and technology of air and space
III. Human presence and activities in air and space
IV. Ethics, law, sociology and economy of air and space
V. History, literature and arts of air and space

Ad hoc commissions are set up in order to study specific, crosscutting topics. There are four permanent commissions, others exist only for the time required to deal with a particular issue.

On their own initiative, or at the request of an official body, the sections and commissions carry out multidisciplinary studies on essential issues, often leading to the organisation of various types of events (conferences, forums, lectures, training courses …) aimed at bringing together the relevant stakeholders and encouraging an exchange of ideas. Such meetings are also the opportunity to maintain constructive relations with international aerospace institutions and companies.

Following these events, AAE publishes proceedings which serve as a basis for the elaboration of recommendations published either in the form of "Opinions" or more in-depth "Dossiers". AAE publications are widely disseminated to key industrial and political stakeholders and are also available, along with a host of other resources including a regular Newsletter, on the AAE website.

Five sessions are held annually in French and other European cities with the aim of encouraging an exchange of ideas on key issues and taking collective decisions as to future actions. The final session of the year, a public plenary session, traditionally takes place in Toulouse Town Hall. At this plenary session in November, AAE awards prizes and medals aimed at giving international recognition to persons who have made some vital contribution to the fields of air and space.

AAE's partners include public and private organisations, educational establishments, companies, etc. Our partners are invited to all sessions, exhibitions, colloquia and other events and receive all our publications. Over and above the financial and material support they provide, our partners constitute an essential link with the realities of the aerospace world and thus contribute to enriching our reflections. In return, AAE has a duty to objectivity in its deliberations and uses the interface of its wide network of members and associated institutions to encourage suggestions from its partners as to future areas of study.

FRENCH AEROSPACE SOCIETY (3AF)

Created in 1972, 3AF is the French aerospace society. Its mission is to advance the aerospace profession, stimulate progress in the state of the art of aerospace science and technology and represent the profession in public policy discussions. Unite, share, enlighten, advance: 3AF is a forum for knowledge exchange.

- Unite: a network of more than 1500 members, 70 companies from the scientific aerospace community
- Share: 10 international conferences and symposiums per year, experts publications
- Enlighten: A scientific society, an expert pool of knowledge consulted by decision makers and media
- Advance: 20 technical commissions which contribute to advancing the aerospace industry.

Technical committees

The technical committees reunite aerospace experts so as to share experiences, and develop new orientations for research and development activities.

Regional groups

3AF regional groups unite local actors of the aerospace industry and research organizations, and organize conferences, debates, visits. They also promote the aerospace profession to the public.

Congresses

3AF organises international renowned symposiums to provide forums for international discussion and exchange of information about leading edge research and development activities. These conferences allow cooperation opportunities.

Student committee

The Student committee promotes the aerospace profession among students.

International

3AF is the only French aerospace society recognised by the international aerospace federation. 3AF is founder member of the CEAS (Council of European aerospace societies).

Communication

Strategic and scientific publications for experts and political actors, symposium proceedings, position papers, technological articles and interviews…3AF provides a wealth of specific publications to its members which enrich their knowledge and vision of the aerospace field.

Awards

In order to enhance the work of its members, 3AF gives awards to some of its experts for their contribution to the aerospace community.

NATIONAL ACADEMY OF TECHNOLOGIES OF FRANCE

History

The National Academy of Technologies of France (NATF) was first created on December 12, 2000, pursuant to an initiative taken by the Academy of Sciences. The latter had originally set up a Committee (later Council) for Applications of the Academy of Sciences (CADAS). The CADAS was a peer-to-peer entity that provided a forum for exchanges between academic scientists and their industrial counterparts whose mission it is to implement and apply scientific knowledge.

The Academy of Sciences wanted the CADAS to evolve to full national status, as with the other national academies in France and other engineering science academies elsewhere for many decades in most developed industrialised countries. The instatement ceremony took place in the Sessions Chamber of the Institut de France, under the auspices and in the presence of the Minister in charge of Research and Technology.

A major step forward came with the national law on research orientations, N°2006-450 dated April 18, 2006, that made provisions for the NATF to assume the status of a Public Establishment (EPA), the statutes, organisation and legal context were set out in a decree N°2006-1533.

The official ceremony instating the Academy, now an EPA, took place on March 14, 2007, under the auspices and in the presence of Prime Minister, Dominique de Villepin and François Goulard, Minister Delegate for Higher Education, Research and Technology.

Remit

- Producing proposals and recommendations for an optimum use of technologies, for the general benefit of mankind.
- Shedding light on emerging technologies, on related strategic policy decisions, thereby providing an independent approach that draws on numerous, varied and highly-qualified sources.
- Contributing to ongoing societal debates as to the supposed benefits that accrue from implementing technologies, future prospects, not forgetting the issues of associate risk factors.
- Contributing to analyses in regard to training and educational questions, both for vocational and technology intensive areas.
- Enhancing the perceived image of technologies per se and new job qualifications of interest to both younger generations and their parents.
- To raise the level of general interest and understanding by the public at large, through inputs to the information campaigns.

NATF addresses those segments of the public that participate in societal debates, wherever technologies are involved:

- Politicians on both national and international scenes and likewise at regional and local levels,
- Leaders of opinion, press and major associations/charities/foundations,
- Industrialists, entrepreneurs and professional federations and unions,
- The education sector: teachers, students, pupils – and their parents.

EDITORIAL COMMITTEE

In order to meet the challenges facing air transport by 2050, it is essential to move forward in the key areas of propulsion systems, weight, cost management, drag and air traffic management. In the case of the first three factors, materials are at the very heart of strategic and economic decisions.

Closely involved in these aspects for some time, the Air and Space Academy (AAE) and French aerospace society 3AF decided to organise a forum in collaboration with the Académie des Technologies in November 2012 entitled "Aeronautical materials for today and tomorrow".

This ensuing dossier illustrates by means of concrete examples the issues and strategies involved and highlights current and future needs in terms of aeronautics materials.

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