Transition of Advanced Metallic Materials into New Weapon Systems

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ABSTRACT

The United States Air Force has for many years recognized that the introduction of new materials is essential to the competitiveness of new weapon systems. This report presents certain criteria which must be met to ensure that the introduction of new materials can be accomplished successfully. These criteria include system producibility, stability, characterized mechanical properties, predictability and supportability. Several material systems are examined in this report in light of the threat imposed by specific applications and usage environments. The material systems considered include resin matrix composites, advanced metals, metal matrix composites and refractory composites. Testing is discussed as a vital element for obtaining the confidence needed before introducing these new materials to an aircraft.

KEYWORDS

Technology transition, advanced materials, Aircraft Structural Integrity Program (ASIP), resin matrix composites, advanced metals, metal matrix composites, refractory composites

INTRODUCTION

The United States Air Force has for many years recognized that the introduction of new materials is essential to the competitiveness of new weapons systems. Experience, however, has shown that the incorporation of new materials must be done prudently. The USAF has two methods to help ensure that the introduction of new materials can be accomplished successfully. Firstly, before a new material is committed to full-scale development of a weapons system, it is examined by means of the "Technology Transition Criteria," TTC (Lincoln, 1987). This is a process where the material is evaluated in terms of the following five factors.

a. Producibility (can properties be reproduced repeatedly in the product form required for application?)

b. Stabilized Material and/or Processes (are the critical material allowables known for the application?)

c. Characterized Mechanical Properties (are sufficient data generated to properly evaluate the mechanical properties of the material?)

d. Prediction of Structural Performance (can element test data be used to predict the overall structural behavior using current analysis methods?)

e. Supportability (can manufacturing and service damage be repaired?)

Secondly, a program that supports new material introduction is the Aircraft Structural Integrity Program (ASIP). This is a program formalized in MIL-STD-1530A (Anon., 1975) that is initiated at the start of full-scale development and continues until aircraft retirement.

The ASIP got its start in 1958 in response to the loss of several aircraft in the Strategic Air Command because of fatigue cracks in the wing structure. These and other aircraft were lost in the fifties because the structural analysts did not recognize the threat to the structure from cyclic loading and resultant fatigue cracking. The success criteria for aircraft designed at that time was that the structure meet the strength requirements. The initial version of the ASIP imposed a requirement for fatigue analyses and tests (including a full-scale aircraft test) to correct this problem. The approach adopted was the "safe life method" where a scatter factor was used to provide a safe fleet operating life based on factoring the full-scale fatigue test life that was demonstrated. Although this method is still being used with success by some certifying agencies, the USAF found that the manner in which they administered the method did not preclude the use of high stress levels and the use of low toughness materials which made the structure susceptible to manufacturing and in-service damage. There are many examples of safe life problems in the USAF service history. A Strategic Air Command tanker aircraft was qualified for 13,000 flight hours based on cyclic testing in the laboratory. It was found, however, that there were fourteen cases of unstable cracking in the lower wing structure in the flight hour interval from 1,500 to 5,000. To protect the safety of these aircraft the lower wing skins were replaced at 8500 flight hours.

The most publicized of all of the problems in this era was a Tactical Air Command fighter that was qualified for a 4,000 hour life. One of these aircraft failed catastrophically after 100 flight hours because of a preexisting flaw in the high strength steel in the wing structure. A cold proof test was initiated to inspect the other aircraft to preclude the recurrence of the problem. It was evident that the initial version of the ASIP did not consider the threat from preexisting damage and consequently it was revised in 1975 (Anon., 1975) to incorporate the damage tolerance concepts that are used today. The success of the damage tolerance approach for conventional metallic structures indicates that structural analysts now understand the threat to the structure from this type of preexisting flaw.

When graphite epoxy composites were introduced, the threat to these structures was not known to the structural analyst. It was clear that they were quite resistant to cyclic loading and the type of damage that posed a problem to metallic structures. It was first learned that the combined effects of moisture and temperature could significantly reduce the compressive strength of composite structures. It was not until the USAF Wright Aeronautical Laboratories and many other organizations had researched these materials that the remaining threats to them were clearly identified. The Composite Damage Tolerance Program performed by Boeing and Northrop under sponsorship of the Flight Dynamics Laboratory ranked the threats to these structures with impact damage found to be the most significant factor in setting the strains in the structure.

Another threat that must be accounted for is the potential detrimental effects of manufacturing parts at the extremes of the processing parameters. It was found in a recent aircraft procurement that late in the production run the diffusion bonding process in large titanium parts was producing alpha stabilized interface (ASI). This was caused by subjecting alpha-beta titanium to oxygen when the parts were at elevated temperatures. It was suspected that the degradation of the manufacturing dies from repeated usage was the reason for this problem. This resulted in such a significant degradation of strength and fracture properties that large repairs and rejection of some parts were required.

For new materials it is essential to assess each of the threats that could degrade their structural integrity. As a minimum the following candidate threats must be considered either singly, or where appropriate, in combination.

Fatigue Cracking
Corrosion
Stress Corrosion Cracking
Manufacturing or Material Fabrication Flaws (Surface and Embedded)
In-Service Induced Flaws
Lightning Strike
Scratches
Environment (Temperature and Moisture)
Chemical
Biological
Delaminations
Ballistic Impact
High Energy Impact from Tools, etc.
Low Energy Impact (From tool Drop, Hail, and FOD)
Nuclear Weapon Effects

This threat assessment should be accomplished initially in conjunction with the TTC after some parts have been manufactured with processes that are stabilized. It is the intent of this TTC assessment both to screen out materials that are not suitable for the weapon system application and to determine mechanical properties with sufficient precision for an evaluation of structural weight. Consequently, the threat assessment should be planned to produce a timely decision for application of the material for full-scale development. It is also essential during the TTC phase that the magnitude of the threat be defined by the procuring activity.

The threat assessment must be continued after the start of full-scale development of the weapon system so that the parts may be sized and tested to ensure that the production hardware will meet its strength, durability and damage tolerance requirements throughout its design service life. This is accomplished initially with development testing that follows the strength, durability and damage tolerance analyses, and finally through the full-scale testing supported by flight tests.

Advanced Materials - Applications and Threats

Aircraft performance dictates that the lowest possible density (highest specific strength) materials be used for structures. For example, with today's technology, resin matrix composites will be used whenever the environment will allow them. The operating environment is defined by the mission and includes loads, temperatures, and chemical environments. These factors determine where advanced materials can be used to save weight on an airframe or an engine.

Temperature is a good discriminator for material systems. Structural efficiencies are compared for a number of different material systems in Fig. 1. Operating environment may define the optimum material system, but costs cannot be ignored. Costs increase significantly toward the right side of the plot.

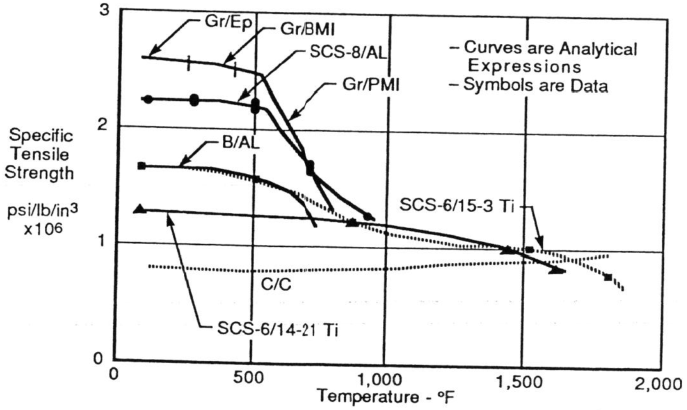

Fig. 1. Structural Efficiency Versus Operating Temperature for Several Candidate Materials

The information from Fig. 1 is plotted in terms of temperature regime in Fig. 2, showing the candidate materials for each flight regime. Resin matrix composites and aluminums are materials generally used at temperatures below 400°F, augmented by aluminums for components that are expensive to fabricate from resin matrix systems or involve excessive risk. Titanium and titanium matrix composites take over at temperatures between 400°F and 1100°F, sharing the lower end of this band with polyimide and high temperature aluminum systems. Advanced titaniums (like Ti_3Al titanium aluminides) take over until 1400°F where TiAl and superalloys are used. Above 1800°F, carbon-carbon and other refractory composites become candidates for limited applications. In addition to the materials identified in Figure 1 and 2, there are a number of advanced materials for cryogenic applications that need to be evaluated.

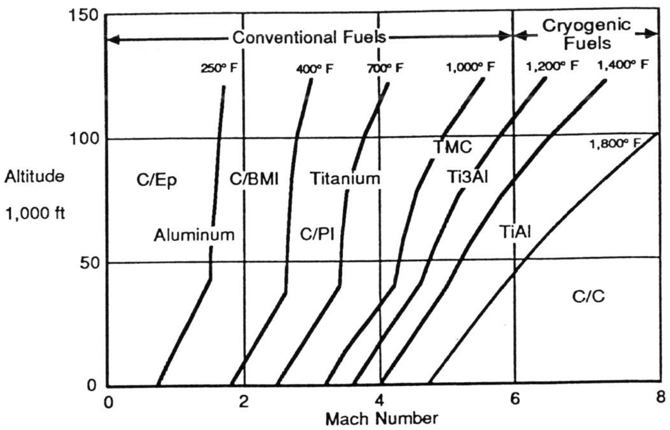

Fig. 2. Material Selection for Different Temperature Regimes

As discussed previously, the Technology Transition Criteria must be met for each material system. To determine the applicability of a material system, we must not only know the environment but the damage threat posed by the application. This requires the user to know and understand the weaknesses of the material, as well as its strengths.

Let's examine some of these material systems in light of the threat imposed by specific applications and usage environments. To address as many of these new material systems as possible, let's choose a high speed fighter aircraft like that shown in Fig. 3. Let's assume this aircraft can reach speeds in excess of Mach 3, so that the more exotic material systems are selected.

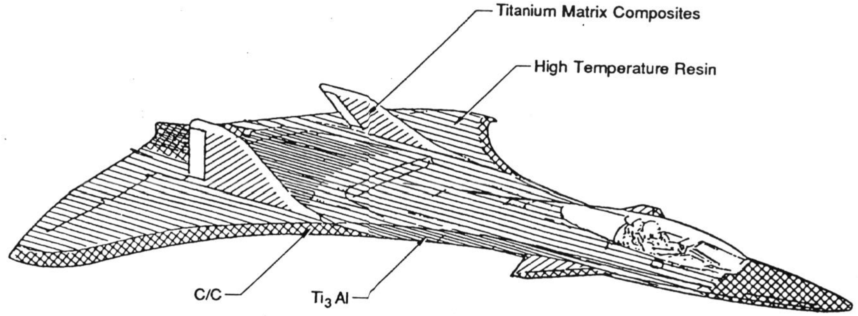

Fig. 3. Potential Application of Advanced Materials

Resin Matrix Systems

In this airframe these materials might see rather limited usage because of the high skin temperatures. Polyimide systems might see application to cooler skin areas. The primary threat to this system is generally impact damage. However, in the design process, out-of-plane loads must be carefully considered. Impact damage is a special concern because visual inspection may not show the level of strength reduction caused by backside or subsurface delaminations. Inspection techniques must be developed that can insure the integrity of the structure or the extent of the damage. Analysis techniques are required that can relate the damage area to the strength loss and the effect of that loss on load carrying capability of the airframe. Repair procedures must be developed that can restore the load carrying capability of the structure, preferably in a field environment.

All of the above concerns have been addressed for carbon/epoxy systems. The failure modes of these systems are known for conventional applications and material manufacturers seek to improve damage tolerance and toughness of these systems. But the application of bismaleimide, polyimide, and thermoplastic systems to cryogenic or hot structures, which see significant thermal cycles during use, produces other concerns that must be addressed: does thermal cycling break down the resin system or release volatiles that delaminate the system at temperature or induce matrix cracking with prolonged usage? The load parameters and material properties that control failure progression must be understood before a manufacturer can have confidence that the structure will provide adequate strength throughout its design lifetime.

Advanced Metals

Metallic systems are relatively well understood from a failure mechanisms point of view. Load discontinuities, holes or notches, have long been recognized as the source for fatigue crack initiation. Here again the environment can influence the failure mode, through residual stresses induced during manufacture or through aggressive chemical or temperature environments that accelerate crack growth. For example, new steels are being developed to replace corrosion susceptible, high strength steels so that corrosion fatigue problems do not limit lives.

Aluminum-lithium materials are beginning to see application because of their lower density and good strength retention at temperature. Some product forms, particularly sheet and extrusion forms, have been transitioned to production in an advanced cargo aircraft. The fatigue and fracture properties in the longitudinal direction appear to be comparable to or better than conventional aluminums. The current Al-Li materials show some unusual failure modes due to the exotic processing currently required to produce them. For example, the rolling required to recover strength properties in sheet products can leave very low properties in the off rolling directions, like 45°. This low strength can limit usage because sheet thickness skins are often primarily loaded in shear, along the 45° direction. Peculiar behaviors like this must be identified and characterized so that applications can be tailored to the material.

Titanium-aluminides offer significant strength to weight benefits for high temperature structures which today require the heavier superalloys. The primary drawback of these materials is their low ductility at low temperatures. This is demonstrated in low toughness at low temperatures and produces greater difficulty in working with the material at low temperatures. This is likely to produce manufacturing defects and low tolerance to either manufacturing or service induced damage. These problems are compounded when powder metallurgy techniques are used to produce the material. Powder metals often exhibit poorer crack growth rates and toughness because of the small grain size and controlled textures used in compacting the material. If the consolidation is not proper, very poor toughness material can result. Of course, powder metallurgy provides the capability of including additives to the alloy to improve the toughness and crack growth behavior, but the materials and processes required to improve these behaviors have yet to be demonstrated in a production environment.

Metal Matrix Composites

Fiber reinforced metals are particularly attractive because of their high temperature stiffness and strength. This is particularly true of titanium matrix composites. These materials differ from resin matrix composites in that the matrix can control the failure mode even in unidirectionally reinforced composites. Matrix strength and stiffness properties can determine when cracking propagates along the fibers or across fibers.

The failure modes of metal matrix composites have been classed by Johnson (Johnson, 1989) as matrix dominated, fiber dominated, and fiber/matrix interface dominated. Matrix dominated fatigue is characterized by early cracking in the matrix which initially isolates fibers from notches, but eventually reduces stiffness and can induce fiber failures and rupture. Fiber dominated fatigue is characterized by early fiber failures that result in an irregular fracture path or by self-similar flaw growth when the matrix strength is high enough to produce fiber failures in front of the crack. Both of these failure modes are influenced by fiber/matrix interaction. Poor fiber/matrix interfaces can induce cracking along the fibers, even when the matrix can withstand higher strains than the fiber.

In titanium matrix composites fatigue failure modes can change as temperatures increase. At low temperatures the stiffness and strength of the titanium matrix are sufficient to drive cracks through the fibers and produce single, transverse cracks, similar to those that occur in unreinforced metals. But at high temperatures, the matrix softens and weakens so that crack initiation and growth behavior become fiber dominated, with cracks unable to penetrate fibers and growing only in the matrix material. Knowing when failure modes can change and what loads control each failure mode will be important considerations for ensuring damage tolerance of structures involving these materials.

Refractory Composites

Refractory composites (e.g., carbon-carbon or ceramic matrix composites) are being proposed for the extremely high temperature structural applications near propulsion systems (e.g., nozzles, ducts, etc) or leading edges of high Mach aircraft. The primary concerns in carbon-carbon and ceramic matrix composites fall into two categories: materials development and design (or strength). To reach the temperature regimes in which carbon-carbon composites excel (above 1800°F), these materials require oxygen inhibiting matrices or coating systems that can tolerant damage. These coating systems can affect strength. Development of an oxygen inhibiting substrate with good strength is key to the acceptance of this material system as a candidate for very high temperature structural applications. Transverse strengths are low and must be improved through weaving, stitching, or stronger substrate systems.

For design of carbon-carbon structures the key concerns are joining or fastening techniques, bearing strength within the composite, translaminar strength, damage tolerance, and repair techniques. These materials do not have much stiffness through the thickness; so how can one maintain torque-up in mechanically fastened joints? How much bearing strength or moment restraint is provided by n-D weave composites in which the fibers are not straight - reducing stiffness? Low velocity impact damage (LVID) will be a large concern for this vehicle, because of its size and the very low translaminar strength exhibited by current systems. Woven materials correct some of this poor strength, at the expense of in-plane properties. Given the low tolerance of refractory composites to low velocity impact damage, repair techniques for these materials must begin to be developed.

Conclusions

There is a link between the maturity of the material and structural systems used in an airframe, the severity of the load and temperature environment expected, and the type of testing required to demonstrate the adequacy of an airframe. Certain criteria must be met in order to use conventional approaches to certification of the structure. These criteria include: system producibility, stability, characterized mechanical properties, predictability, and supportability. Testing must be performed to demonstrate each of these features before a new system may be introduced to an aircraft with confidence.

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