MATERIALS CHALLENGES FOR THE NATIONAL AERO-SPACE PLANE

Terence M.F. Ronald
NASP Joint Program Office
AFSC/NAC
Wright-Patterson AFB, OH 45433

INTRODUCTION

The National Aero-Space Plane Program (NASP) represents a major national initiative in hypersonic technology. It has the goal of developing and demonstrating the technologies for aerospace vehicles capable of cruising at hypersonic speeds and achieving single stage access to space. The specific objective of the program is the construction and operation of an experimental fully reusable flight vehicle--the X-30--that will employ air-breathing liquid-hydrogen-fueled engines and will be capable of horizontal take-off and landing. It will be a piloted research vehicle, designed to expand the envelope of high speed flight in and beyond the atmosphere.

The NASP program is a joint undertaking of Air Force, NASA, Navy, DARPA and SDI, in conjunction with a number of aerospace companies, and is managed by a Joint Program Office at Wright-Patterson AFB, Ohio. Phase 2 of the program, currently underway, involves five prime contractors working in parallel on concepts for the X-30 vehicle. The airframe companies--General Dynamics, McDonnell Douglas and Rockwell International--are responsible for the design of the overall system, including the airframe itself, the cryogenic tank, and structures such as leading edges and nose tip; the two engine companies--Pratt and Whitney and Rocketdyne Division of Rockwell International--are working on concepts for the needed propulsion systems. Phase 3 of the program is scheduled to start in 1990 and will involve the design and construction of research vehicles intended for flight in the mid-1990s.

The overall concept calls for a hydrogen fueled vehicle that will use air-breathing ramjet/scramjet engines. The airframe will make use of non-insulated load-bearing hot structure and will not be protected with thermal tiles--marking one of several significant departures from the Space Shuttle design. Where necessary, the structure will be actively cooled with the hydrogen fuel to keep the temperatures within the capabilities of the materials. The resulting hot hydrogen will be mixed with incoming air and burned in the engines.
The projected structural designs for all areas of the vehicle call for high-stiffness, thin-gauge product forms that can be fabricated into efficient load-bearing components. These in turn require high strength, low density materials that can retain their properties up to temperatures beyond the capabilities of present day commercially available materials. In a basic way, Fig. 1 illustrates the challenges to be faced from a materials and structures point of view. This plot of specific strength vs. temperature shows representative curves for two classes of conventionally used materials, one a titanium alloy and the other a superalloy. To achieve the needed low structural weight fraction, we need to enter the upper right region of the chart. In essence, this implies a requirement for materials that have the temperature capability of superalloys with the density of titanium alloys.

Fig. 1. Specific strength (strength/density) as a function of temperature for several classes of materials.

As indicated in Fig. 1, the major materials classes that have the potential for satisfying these needs are rapid solidification technology titanium aluminide alloys (RST Ti), metal matrix composites based on reinforced titanium aluminides (Ti-Aluminide MMC), carbon-carbon composites (C-C), and ceramic-matrix composites (CMC). These materials form the core of the widespread materials and structures development activities that are a part of the technology program for NASP. The remainder of the paper summarizes where the emphasis lies for these and other materials of interest and illustrates the general activities that are underway, including the properties being developed and the technical hurdles to be overcome in working toward their successful development.
Titanium-based materials in general are considered prime candidates for large-scale structural use in the airframe and engines, including both the outer skin and the internal structure. In sheet form they would provide the basis for efficient, lightweight honeycomb or truss-core structural panels that could be fabricated using superplastic forming and diffusion bonding. As forged or extruded products, they would be suitable for internal support structure and fittings. These materials combine light weight with a demonstrated capability of 1100°F in commercially available alloys, but to achieve the NASP performance goals it is important that their temperature capability be extended higher to minimize the needs for active cooling.

Over the last few years, new classes of higher temperature titanium-based materials have emerged, based on titanium aluminide intermetallics. These materials have essentially the same density as titanium but possess a much higher temperature capability. As a result of developments that have been underway for the last decade or more, two alloy systems have emerged as primary candidates for structural applications: Ti3Al-based (designated α-2) and TiAl-based (γ). The potential temperature capabilities are respectively about 1500°F and 1800°F, giving them a significant advantage in this respect over the best conventional titanium alloys.

The usefulness of these attractive combinations of high temperature strength and low density is offset by the fact that the aluminides are difficult to process and fabricate into structural components. This difficulty stems from their limited ductility and toughness properties at the lower temperature ranges and is compounded by the need for very high processing temperatures. These drawbacks have a particular significance when it comes to working the aluminides into product forms that require a large amount of metal deformation—sheet, for example. Most of the skin structure of the vehicle will consist of honeycomb-core or truss-core panels with minimum-gauge face sheets, and we must be able to convert the materials into the required thin stock.

With the goal of overcoming these deficiencies, new processing methods are being used to modify the aluminide compositions and microstructural features to yield structurally useful materials—in the sense that they have an appropriate balance of strength and toughness and yet retain their low density and high temperature characteristics.

One favored approach uses rapid solidification powder methods to develop the required alloys and associated properties. Much of the NASP-related work in this area is based on a program at Pratt and Whitney that makes use of a rotary atomization process to make the needed powders. In essence, a stream of the molten alloy is dropped onto a high speed rotating horizontal disk, from which droplets spin off into a fast-moving inert gas stream to be rapidly quenched to form powder particles. The powder is subsequently consolidated into a fully dense billet which can then be processed into appropriate product forms. After much effort learning how to contain and control the reactive molten metal, the process is now relatively mature and equipment is in place that is capable of making hundreds of pounds of material a day.
Recent work has greatly improved the characteristics of some of the Ti3Al-based alloys, and sheet products are now available, but the TiAl-based materials still represent a challenge in the sense that economical sheet processing methods remain a development issue. Fig. 2 illustrates a brazed honeycomb-core demonstration panel that uses three classes of titanium-based materials, including face sheets of Ti3Al and TiAl. The Ti3Al sheet was rolled, but the TiAl sheet was made by cutting slices off a hot pressed billet.

Much of the structure of the vehicle will be actively cooled, meaning that hydrogen at a variety of temperatures and pressures will be in intimate contact with the structural materials. We know that hydrogen interacts with most titanium alloys in an adverse fashion, leading to embrittlement. The titanium aluminides appear more resistant than conventional alloys, with the TiAl materials being most resistant; nevertheless, hydrogen-resistant barrier coatings will be needed for all the materials, and their development is an integral part of the program. From an NDE point of view, we will need to know that these coatings can perform their intended function.

**TITANIUM ALUMINIDE COMPOSITES**

Metal matrix composites that use titanium aluminides as the matrix can have significant stiffness and strength improvements over their monolithic counterparts. This is illustrated in Fig. 3, where the curve for Ti3Al MMC represents a matrix reinforced with 33 volume percent SiC fibers (SCS-6 fiber manufactured by Textron). On the NASP vehicle, minimum gauge requirements for panel structures make such materials very attractive.
The basic technical challenge in making these materials is to incorporate the fibers into the matrix without creating adverse reactions at the fiber/matrix interface. The conventional method for fabricating such composites involves taking sheets of matrix material, laying fibers between them, hot pressing the resulting package so that the metal moves between the fibers and adheres to itself, and then stacking several of these layers together and bonding them to make a component. This is difficult to do with the titanium aluminides for several reasons: they have poor formability characteristics, they interact with the fiber at the temperatures and times needed for consolidation, and there is a thermal expansion mismatch between the fiber and the matrix. This last factor can lead to cracking of the low-ductility matrix on cooling from the consolidation temperature or during subsequent thermal cycling of the sort that would be seen in service in the vehicle.

An alternate approach to consolidation being explored under the NASP program involves the use of a Rapid Solidification Plasma Deposition (RSPD) method. GE Research Laboratories are applying the technique to titanium aluminide composite fabrication, using it to deposit the matrix material onto reinforcing fibers that are spiral-wrapped onto a large diameter drum located inside a vacuum chamber (Fig. 4). The matrix material starts as a powder and is fed through a plasma arc to convert it into molten droplets that are immediately deposited onto the drum and rapidly quenched to a solid state. By rotating and translating the drum it is possible to build up a layer of matrix material between and on the fibers. The resultant product can then be slit, stripped off the drum, and stacked together and hot pressed to make a multilayer composite (Fig. 5).
Fig. 4. Preform fabrication of metal matrix composites using Rapid Solidification Plasma Deposition (RSPD).

Fig. 5. Titanium aluminide MMC monotape fabricated using the RSPD process. The monotapes are subsequently hot pressed into a multilayer SCS-6 SiC-reinforced Ti3Al composite, shown in the lower corner. (Courtesy GE).
The RSPD process has been demonstrated successfully with Ti₃Al-matrix materials, and modifications of the process are underway aimed at the production of TiAl-based composites. The equipment itself is now being scaled up to a pilot plant scale that will allow the production of wider sheet material.

In addition to the work on monotape production and composite consolidation methods, alternative fibers such as titanium diboride and titanium carbide are being developed. These fibers have a better thermal expansion match to the matrix materials and may also have better chemical compatibility than SiC at the high temperatures needed for consolidation of the aluminides.

From an NDE point of view, the metal matrix composites represent a special challenge. They must be evaluated in a way that will ensure the integrity of the fiber/matrix bond and also allow the detection of any cracking that results from thermal cycling.

XD COMPOSITES

A third important class of titanium-based materials are known as XD Composites. The XD process was developed by Martin Marietta Research Laboratories and has now been applied to titanium aluminides. It produces a material that contains a fine, close-spaced uniform distribution of second phase particles such as titanium diboride, where the dispersoids are formed and grown in situ, as distinct from being mechanically mixed as a separate additive. As a result of this mode of formation, the interface between the particles and the matrix is clean and well bonded, leading to efficient use of the reinforcement. The process can be tailored to produce a variety of second phase distributions, where the particles can have controlled shapes, ranging from spherical to long needles. Mixtures of different distributions can also be formed, including coexisting sizes, shapes and types of reinforcements. In many cases, once formed, the dispersoids are very stable and can survive through a remelting process, so that the material subsequently can be cast into shaped components without destroying the reinforcement.

The microstructures resulting from the XD process are desirable from several points of view, principally because they lead to materials having higher strength and temperature capabilities than baseline alloys (Fig. 6). They will be useful in their own right as high temperature structural materials, either as sheet or as shaped components, but they also may be a suitable matrix for continuous fiber reinforced metal matrix composites. In addition, the material can be worked into various product forms and the process has been scaled up to the point that 250lb ingots have been cast.

CARBON-CARBON COMPOSITES

Some concepts for the NASP vehicle would make extensive use of carbon-carbon composites. In general, these materials are mature in the sense that they are well characterized, are employed in many applications, and there is a large base of knowledge
available regarding their fabrication and practical use. For example, the material is used as the nose cap and leading edges of the Space Shuttle, where it successfully withstands the high temperatures of re-entry. There are a number of companies that specialize in the fabrication of carbon-carbon components and there are several different methods for making structural shapes.

While carbon-carbon composites have the potential for use as lightweight uncooled structure that could be exposed to temperatures in excess of 2500°F, there are major technical issues to be addressed before they can be used in the load-bearing, thin-gauge structural components required for NASP. These include the special need for oxidation protection schemes that must be effective for the temperatures, times, and thermal cycles to which structures will be exposed in the NASP flight environment. Many protection schemes have been devised that involve multilayer coatings and sealants, together with oxidation inhibitors incorporated into the matrix itself (Fig. 7). These work reasonably well in situations where the material is taken up to a single high temperature and then cooled down again but they face significant problems when subjected to repeated temperature cycling.

Fig. 6. Strength comparison of XD reinforced TiAl alloy with unreinforced counterpart. (Courtesy Martin Marietta).
The basic difficulty with existing protection schemes is that they involve the use of refractory materials such as silicon carbide as outer protection layers. These work well in a chemical sense but they can crack because of the thermal expansion mismatch between the silicon carbide and the carbon-carbon substrate. There is a particular difficulty associated with the use of such coatings in about the 1100 - 1900°F temperature range, where additional coating layers used as crack sealants do not flow readily. Significant advances have been made in the improvement of oxidation protection schemes, especially over the last couple of years, and recent experimental data indicate that cyclic temperature loading can be applied successfully in some cases, at least in small samples.

Fig. 7. Schematic of oxidation protected carbon-carbon composite. The protection scheme involves several layers of coatings plus an inhibitor in the matrix itself.

In addition to oxidation issues, there is a need to gain experience in the design and fabrication of the required large, thin-gauge, shaped structural components required for the NASP vehicle. Combining these requirements with the need for oxidation protection coatings, the successful NDE of carbon-carbon composites will be crucial to their successful use. There is first the initial integrity of the protection scheme to be evaluated, but this may extend to a need to evaluate the materials on the vehicle after a specified number of flights, or perhaps after each flight for some components. This will require the capability to detect very fine cracks in thin multilayer coatings on complex-shaped structural components.
CERAMIC-MATRIX COMPOSITES

These materials offer the potential for use as lightweight structures that could be operated uncooled at very high temperatures. They are of special interest for surfaces adjacent to the nose cap and leading edges and also as engine components and panels. Like carbon-carbon composites, they have the potential for use at temperatures in excess of 2500°F, but they have the additional advantage of a much higher degree of inherent oxidation resistance. Their major disadvantage is their relative immaturity as materials suitable for load-bearing structural components.

The basic reason for the use of reinforcements in ceramics is to alleviate the brittle behavior that is characteristic of most monolithic ceramics. The correct design of the fiber/matrix interface can lead to blunting of cracks that may be formed in the material and hence can improve the "forgiveness" of the material.

There are two general classes of ceramic-matrix materials that are of interest: the glass-ceramic matrix materials, useful up to temperatures of about 2200°F, and the advanced ceramic-matrix composites, potentially important at much higher temperatures. The glass-ceramic matrix materials are relatively well characterized and can be fabricated into many kinds of product forms, including honeycomb-core panels, truss-core panels, and other complex shapes. They would possibly be competitive with the titanium aluminides in some applications. The advanced ceramic-matrix materials--such as silicon carbide fiber reinforced silicon carbide (SiC/SiC)--are not as mature, though a widespread development activity that has been underway in this area for several years holds promise for near-term improvements. A particular interest in these materials stems from their hydrogen resistance, and they may well find use in structures that contact hot hydrogen.

From a practical design point of view, there is an issue with ceramic-matrix materials that evolves from the need to account for cracking that may occur within the matrix of the material during service. The successful application of these materials will require the ability to detect the presence of such cracks after flight use, raising an obvious need for reliable NDE methods.

BERYLLIUM ALLOYS

Beryllium is an available material that is widely used and has some very attractive features, including the fact that it is lightweight--having a low density--and has a very high elastic modulus. These desirable attributes can result in significant weight savings when it is used in stiffness-designed applications. It also has very good thermal conductivity, making it attractive for applications that require the efficient transfer of heat loads from one place to another, as will be the case on the NASP vehicle.

Beryllium also has some basic drawbacks: it has poor toughness properties, a limited temperature capability of about 1000°F, and environmental implications associated with the toxic nature of the oxide. In spite of these problems, beryllium is used
in a variety of day-to-day applications, especially in spacecraft. It can be handled and machined with only modest precautions being required and there is considerable experience with its fabrication and use.

For the NASP program, rapid solidification methods are being used to raise the temperature capability of beryllium. The goal is to introduce dispersoid-forming elements that will lead to a fine, close-spaced distribution of stable compounds that would add temperature resistance. The initial work in this area, conducted at Los Alamos National Laboratories, is showing encouraging progress, making use of melt spinning methods to achieve the necessary rapid solidification rates. The alloys resulting from this activity would be scaled up using processes such as planar flow casting or powder atomization.

COPPER MATRIX COMPOSITES

Because the NASP vehicle would make extensive use of actively cooled structure, there is a particular interest in high conductivity materials, including copper-matrix composites. Copper itself has a good thermal conductivity but is heavy and its upper use temperature is limited by its low mechanical properties. Pitch-based high modulus graphite fibers have excellent thermal conductivity--better than the copper itself in the direction of the fiber--and the incorporation of these fibers into a copper matrix can lead to materials useful for applications such as heat exchangers. The addition of the fibers reduces the density, increases the stiffness, raises the temperature capability of the copper, and significantly improves the thermal conductivity in the direction of the fibers.

One approach to the fabrication of these composites starts with a process developed by Cyanamid. The graphite--in the form of a tow containing about 2000 individual filaments--is coated in a manner that places a layer of copper around each filament. The coated fibers are subsequently stacked together and hot pressed into a fully dense material containing about 50 volume percent of fibers. In practice, cross-plied lay-ups will be used to tailor the thermal conductivity and to account for the directional effects of the fiber.

Additional work in this general area addresses discontinuous reinforced copper composites. These are made by adding alloying elements such as niobium to the copper and applying appropriate processing methods to form a very fine dispersion of the alloying addition. In this way it is possible to strengthen the material without lowering the conductivity of the matrix.

COATINGS

Coatings will play a critical role for all materials important to NASP and are a key part of the development activities for each material system. They can perform several functions, including the control of temperature and protection against the environment. For temperature control, they are designed to have high emissivity and be noncatalytic to recombination of the dissociated gases present in the hypersonic airflow across the vehicle. This can lead to a reduction in surface temperature of
several hundred degrees, as demonstrated for the Space Shuttle. For oxidation resistance, they can provide a suitable barrier that prevents contact of hot oxygen with the underlying material. Such coatings will be needed for most of the titanium aluminides as well as the carbon-carbon composites.

The coating issue that is unique to NASP arises from the need to protect the materials against the effects of hydrogen. Much of the structure of the vehicle will be cooled with the hydrogen fuel as it passes on its way to the engine, by which time it will be in the form of a hot gas. As a result, many of the materials and structures used on the vehicle will be in contact with hydrogen at a wide variety of temperatures and pressures. Hydrogen diffuses readily through most materials and can form brittle compounds within the material, as well as migrating to regions of stress concentration. The development of hydrogen barrier coatings is a critical challenge, especially coatings that are thin, lightweight, resistant to damage, and can be applied to complex shapes, including internal passages.

The probable end result of the various coating needs will be the use of multilayer protection schemes involving several thin layers of materials, each performing a contributing function. The NDE implications include the need to assess the coatings for continuity, uniformity of thickness, and general performance capability.

NASP MATERIALS AND STRUCTURES AUGMENTATION PROGRAM

It is obvious that the achievement of a low structural weight fraction is one of the critical requirements of the NASP program if the vehicle is to achieve its goal of single-stage-to-orbit. Because the successful development of the necessary materials and efficient structural concepts is vital to this requirement, an augmented materials and structures development and scale-up program has been established. The program focuses on the specific goal of advancing the readiness-for-use date of the key classes of materials and structures needed for the X-30 vehicle.

The program is a cooperative effort of the five prime engine and airframe contractors. It is sometimes referred to as the Consortium Program but it is designated officially the NASP Materials and Structures Augmentation Program (NASP Materials ASAP). Though they are in competition for Phase 3 of the NASP program itself, the contractors have taken the materials and structures development activities out of the competitive arena and are working them jointly. The program is funded at a level of $140M over a three-year period, and while it concentrates heavily on the needed materials and processes development, it includes extensive full-scale demonstration component fabrication and testing.

Under mutually agreed upon arrangements, each contractor has taken the lead for a key class of materials, with each company participating in the development activities for all the materials, and each contributing and sharing its Independent Research and Development activities in their respective areas. In addition, a major part of the funding is being transferred to subcontractors---materials developers, suppliers, fabricators, universities, research institutes, etc. The cooperative nature of the activity
allows the companies to focus their activities, avoid duplication of effort, develop common materials specifications, contribute unique facilities and expertise, pool resources, and combine their needs for various subcontractors.

General Dynamics has the lead responsibility for a class of materials designated as refractory composites. This involves principally carbon-carbon composites but also includes ceramic-matrix composites. Rockwell heads the titanium aluminate development and scale-up effort, which includes the Ti3Al and TiAl classes of materials and extends to XD composites. McDonnell Douglas guides the effort on titanium metal matrix composites, comprising SiC-reinforced Ti3Al and TiAl, as well as composites with alternative fiber reinforcements. Rocketdyne has the responsibility for High Conductivity Materials, including copper matrix composites and beryllium alloys. Pratt and Whitney has undertaken the High Creep Strength Materials activity, involving materials and structures intended for hot, actively cooled applications in engine components. This latter area centers on monolithic and reinforced TiAl, using fibers such as titanium diboride, as well as on another class of titanium aluminides based on the TiAl3 composition.

SUMMARY AND ROLE OF NDE

The successful operation of the NASP vehicle will be dependent on the application of a variety of NDE methods. The X-30 will make extensive use of new materials and processes, innovative structural concepts, thin-gauge panels, actively cooled structures, thin protective coatings, and efficient joining methods. The successful employment of all of these will rely on the ability to inspect for integrity and will require that NDE methods be closely linked to life prediction techniques.

The new materials include titanium aluminides, titanium-based metal matrix composites, carbon-carbon composites, ceramic matrix composites, copper matrix composites, and beryllium alloys. In general, these materials will have some properties such as ductility that will be at less than traditionally acceptable values, making reliable pre- and post-flight inspection a vital accompaniment to their successful use.

New processing methods include powder metallurgy fabrication methods, while innovative structural concepts include superplastic forming and diffusion bonding of titanium aluminide composites. These will be more efficient than traditional riveted and fastened structures but will require careful evaluation of joint and bond integrity.

The NASP program represents a number of challenges for structural materials. It will use them in a very wide operating temperature range and will impose complex environmental demands, it will involve the extensive use of low ductility materials such as carbon-carbon composites and titanium aluminides in primary structure, and it will require the early application of new materials and structures concepts. To meet these demanding challenges, the development and scale-up program is building off a base of technology that has been worked for many years and it is approaching the problem in a concerted fashion with a large, dedicated effort that involves a wide variety of organizations, personnel and facilities.