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ADVANCED MATERIALS AND PROCESSES TECHNOLOGY

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# Transparent Armor

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## Introduction

Transparent armor is a material or system of materials designed to be optically transparent, yet protect from fragmentation or ballistic impacts. This class of materials is used in such diverse applications as protective visors for non-combat usage, including riot control or explosive ordinance disposal (EOD) actions. They are also used to protect vehicle occupants from terrorist actions or other hostile conflicts. Each of these systems are designed to defeat specific threats, however, there are general requirements common to most. The primary requirement for a transparent armor system is to not only defeat the designated threat but also provide a multi-hit capability with minimized distortion of surrounding areas. Land and air platforms of the future have several parameters that must be optimized, such as weight, space efficiency, and cost versus performance. Transparent armor windows must also be compatible with night vision equipment. One potential solution to increase the ballistic performance of a window material is to increase its thickness. However, this solution is impractical in most applications, as it will increase the weight and impose space limitations in many vehicles. In addition, thick sections of transparent armor tend to experience greater optical distortion than thinner sections, reducing the transparency. Not surprisingly, new materials that are thinner, lightweight, and offer better ballistic performance are being sought.

Existing transparent armor systems are typically comprised of many layers, separated by polymer interlayers. Figure 1 displays this concept for an advanced ceramic transparent armor system. The first ply is usually a hard face material, designed to break up or deform projectiles upon impact. Subsequent plies are added to provide additional resistance to penetration, and can be of the same material as the front ply. An interlayer material, used to mitigate the stresses from thermal expansion mismatches, as well as to stop crack propagation from ceramic to polymer, separates each of the plies. The final layer is usually a polymer such as polycarbonate that serves to contain the spalling layers. Armor systems such as this can be engineered to provide different levels of protection by changing variables such as the plate material, thickness of plies, interlayer hardness, interlayer thickness, the number of plies, and the order of constituent materials.

Recent efforts at the US Army Research Laboratory (ARL) have heightened the drive to develop new transparent armor material systems. Future warfighter environments will require lightweight, threat adjustable, multifunctional, and affordable armor, which current glass/polycarbonate technologies are not expected to meet. New material systems being explored to meet these requirements

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## Spotlight on Technology:
## Ceramic Thermal Barrier Coatings

Thermal barrier coatings are designed to protect underlying components or structures from high temperatures. The coatings must have a low thermal conductivity, be resistant to spalling and corrosion, and must be mechanically tough.

Thermal barrier coatings were developed to increase the upper use temperature of metallic structures such as those used in engine applications. Higher combustion temperatures result in higher energy efficiencies, thus increasing the operating temperature of a heat engine. This can pay benefits in terms of lower operating costs, increased range and performance. However, what happens when the operating temperature approaches or exceeds the upper use temperature of the metallic components? In aircraft engines, various cooling methods are used for some components, including the injection of cooler air onto or through critical surfaces. This is done at a cost in efficiency. The turbine industry with support from various US Government agencies, including the Department of Defense and the

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include transparent crystalline ceramics such as magnesium aluminate spinel ($MgAl_2O_4$), aluminum oxynitride spinel (AlON), and single crystal sapphire ($Al_2O_3$). Advancements in glass, glass-ceramics, and new polymer systems, are also being explored. These materials and current ARL efforts in these areas will be reviewed throughout this article.

## APPLICATIONS AND REQUIREMENTS

Common military applications for transparent armor include ground vehicle protection, air vehicle protection, personnel protection, and protection of equipment such as sensors. Commercial applications requiring transparent armor include items such as riot gear, face shields, security glass, armored cars and armored vehicles.

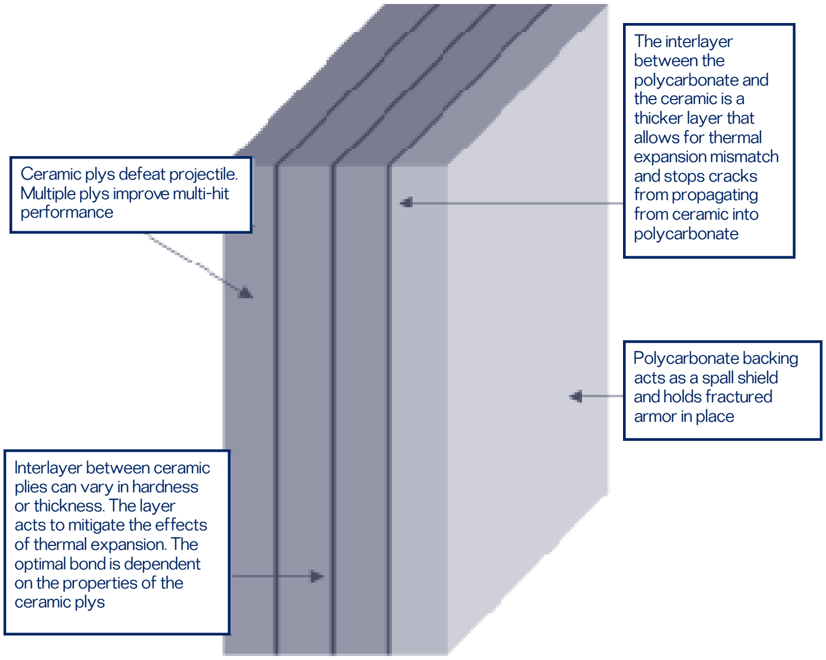

*Figure 1: Schematic of a transparent armor system*

### Visors

With the onset of many new peacekeeping roles within the military, it is necessary to provide a greater degree of protection to the individual soldier. Facial protection via the use of transparent armor is one area of interest within the Army, marked by a recent program within the Army Research Laboratory to improve the current visor design [1]. Two types of visors were marked for improvement, the riot visor and the EOD visor.

#### Riot Visors

Riot visors are typically made from injection-molded polycarbonate that has an areal density of 1.55 lb/ft$^2$. They are designed to defeat threats from large, low-velocity projectiles such as rocks and bottles, and from small, high velocity fragments. It was determined that the riot visor required a 30% improvement in ballistic performance without increasing the weight of the system. Current efforts are looking into the replacement of polycarbonate with transparent polyurethane.

#### Explosive Ordnance Disposal (EOD) Visors

It was determined that the EOD visor required a weight reduction of 30 percent while maintaining an equal level of protection. The ARL attempted to reduce the weight of EOD visors by investigating the use of different materials and constructions including plastic/plastic laminates, glass/plastic laminates, and glass-ceramic/plastic laminates[1]. Ballistic testing of these constructions was carried out on new systems that showed marked reduction in weight from the current design of 4.27 lb/ft$^2$. Polyurethane was shown to increase the

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performance of the system, however, the optimum constructions used fused silica, Vycor, or TransArm, a transparent glass-ceramic.

### Electromagnetic Windows

Many ceramic materials of interest for transparent armor solutions are also used for electromagnetic (EM) windows. These applications include radomes, IR domes, sensor protection, and multi-spectral windows. Optical properties of the materials used for these applications are very important, as the transmission window and related cut-offs (UV, IR) control the electromagnetic regime over which the window is operational. Not only must these materials possess abrasion resistance and strength properties common of most armor applications, but because of the unique high-temperature flight environment of missiles, they must also possess an excellent thermal stability.

EM window materials are also currently being investigated by the army for use in artillery projectiles. Though the optical transparency is not important for this application, a low dielectric constant and a low loss tangent is a must[3]. Future artillery projectiles will be subjected to much higher muzzle velocities (Mach 3), where aerodynamic heating becomes a concern. New window materials must be capable of withstanding 15,000 g's of inertial setback loads with 15,000 rad/s$^2$ of angular acceleration. Available plastic window materials are incapable of surviving in these environments. Prototypes for new systems utilize a glass-ceramic material known as Macor,* for the nose tip, which was chosen for its electrical properties, its high temperature capability, and its ability to be machined. However, replacement ceramics with reduced dielectric constant and higher temperature capabilities are still sought.

### Laser Igniter Window

A laser igniter window for cannon applications[2] is one area that the army is currently investigating. Laser ignition of the propellant has several advantages over conventional systems including increasing the firing rate and simplification of gun design. The window material must maintain consistent mechanical and optical properties throughout multiple firings, and withstand flame temperatures near 2300°C and pressures of 350 MPa. The transparent ceramics sapphire and AlON have been tested for this application, with sapphire yielding the best performance.

### Ground Vehicles

Ground vehicles are one of the largest areas of the application of transparent armor. These vehicles include such equipment as HMMWVs, tanks, trucks, and resupply vehicles. There are several general requirements for the application of transparent armor windshield and side windows in these vehicles. The first is that the armor must be able to withstand multiple hits since most threat weapons are typically automatic or semiautomatic. The windows also must be full sized so that the vehicle can be operated without reducing the driver's field of view. Small windows can increase the ballistic survivability but they can also reduce the operational safety of the vehicle. Some requirements for future transparent armor systems in vehicles[4] include the need for a reduction in weight, as the armor system is a parasitic weight for the vehicle. This parasitic weight can be significant, often requiring enhancement of the suspension and drive train to maintain the vehicle performance capability and payload capacity. Thinner armor systems are also required, as thinner windows can increase the cabin volume of the vehicle. Future systems must also be compatible with night vision goggle equipment while offering laser protection.

Due to their size and shape, the majority of armor windows are constructed of glass and plastic, but reductions in weight and improvements in ballistic protection are needed. Due to the number of vehicles in service, the window dimensions, and the associated costs, improved glasses, glass ceramics and polymers appear to be the new materials of choice. Compositional variations, chemical strengthening and controlled crystallization are capable of improving the ballistic properties of glass. Glasses can also be produced in large sizes, curved, and can be produced to provide incremental ballistic performance at incremental cost. However, the use of a transparent ceramic as a front-ply has been shown to further improve the ballistic performance while reducing the system weight.

A $V_{50}$ test is used to measure the ballistic performance of armor material systems. The test evaluates the velocity (ft/sec) that is required to compromise an armor material, using a 0.22 caliber fragment-simulating projectile (FSP). A chart of $V_{50}$ versus the areal density (lb/ft$^2$) for several transparent armor systems is shown in Figure 2. BAL31 is a commercial glass/plastic laminate while the other materials were constructed with glass, sapphire, AlON, or spinel as a hard face with a polycarbonate backing. It is seen that the use of a ceramic front ply reduces the areal density by as much as 65 percent. This is a significant weight saving over the state-of-the art, and the ballistic performance of the transparent ceramics offers the potential for weight savings on future vehicles.

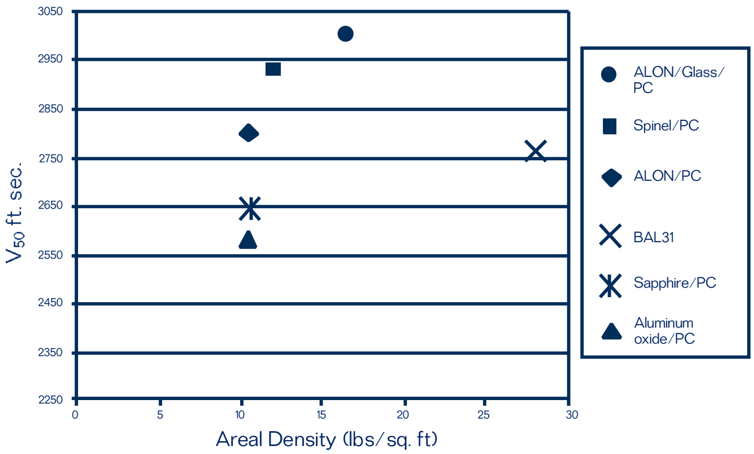

*Figure 2: $V_{50}$ versus areal density for various ceramic-based armor systems*

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### Air Vehicles

Air vehicles include equipment such as helicopters, anti-tank aircraft, fixed wing aircraft, and aircraft that are used in combat and support roles. Transparent armor applications in these vehicles include windshields, blast shields, lookdown windows and sensor protection. Requirements for aircraft systems are similar to those for ground vehicles, and systems are designed for use against 7.62 mm, 12.7 mm, and 23 mm High Explosive Incendiary (HEI) threats. The Army Aviation Applied Technology Directorate has an Advanced Lightweight Transparent Armor Program (JTCC/AS) to develop advanced transparent armor for aviation applications, with the goal to defeat a 7.62 mm PS Ball M 1953 with an areal density no greater than 5.5 lbs/ft$^2$. This constitutes a 35% reduction in weight over currently fielded systems. Optical requirements include a minimum 90% light transmission with a maximum haze of 4%. A second goal of the program is to defeat the blast and fragments from a 23 mm HEI projectile detonated 14 inches from the barrier, without exceeding a 6 lbs/ft$^2$ areal density limit. Many of these systems utilized for military applications would also have use in commercial systems such as law enforcement protection visors, riot gear, and windows in commercial cars, trucks, and busses, as well as architectural requirements in certain buildings and armored automobiles for personal use. The cost/performance trade-off is not as critical in the commercial arena since VIP protection systems can use more exotic and expensive materials to protect against significant threats.

## MATERIALS USED FOR TRANSPARENT ARMOR

### Polymeric Materials

Polycarbonate is the most common plastic used for transparent armor applications. It is an inexpensive material that is easily formed or molded, and offers excellent ballistic protection against small fragments. It is currently used in applications such as goggles, spectacles, visors, face shields and laser protection goggles, but is also used as a backing material for advanced threats. It has been found to be more effective in the thinner dimensions required for individual protection than in the thicker sections required for vehicle protection, and although the material is adequate for many applications, the search for lighter materials has led to investigations into other polymeric materials such as transparent nylons, polyurethane, and acrylics.[6,7] The optical properties and durability of transparent plastics limit their use in armor applications. Investigations[8,9], carried out in the 1970's had shown promise for the use of polyurethane as armor material, but the optical properties were not adequate for transparent armor applications. Since then, Simula Technologies Inc.$^+$ has made improvements to the optical properties of the polyurethane. The results of a ballistic evaluation of an all polyurethane visor showed that it performed better than both polycarbonate (PC) and acrylic (PMMA)[6], on an equal weight basis. This new polyurethane with improved optical properties, is sold by Simula Polymer Systems Inc. as a thermoset plastic that is processed by casting or liquid injection molding. Because of its physical properties, this real polymer known as Sim 2003 shows promise as a replacement for polycarbonate as visor or backing material.

### Glasses and glass-ceramics

Several glasses are utilized in transparent armor, such as normal plate glass (soda-lime-silica), borosilicate glasses, and fused silica. Plate glass has been the most common glass used due to its low cost, but greater requirements for the optical properties and ballistic performance have generated the need for new materials. Chemical or thermal treatments can increase the strength of glasses, and the controlled crystallization of certain glass systems can produce transparent glass-ceramics. Alstom$^{++}$, currently produces a lithium disilicate based glass-ceramic known as TransArm, for use in transparent armor systems.[10] The inherent advantages of glasses and glass-ceramics include having lower cost than most other ceramic materials, the ability to be produced in curved shapes, and the ability to be formed into large sheets.

### Transparent crystalline ceramics

Transparent crystalline ceramics are used to defeat advanced threats. Three major transparent candidates currently exist: aluminum oxynitride (AlON), magnesium aluminate spinel (spinel), and single crystal aluminum oxide (sapphire). Aluminum oxynitride spinel ($Al_{23}O_{27}N_5$), one of the leading candidates for transparent armor, is produced by Raytheon Corporation$^{+++}$ as AlON and marketed under the trade name Raytran. The incorporation of nitrogen into an aluminum oxide stabilizes a spinel phase, which due to its cubic crystal structure, is an isotropic material that can be produced as a transparent polycrystalline material. Polycrystalline materials can be produced in complex geometries using conventional ceramic forming techniques such as pressing and slip casting. Table 1 lists some properties of AlON. Its high cost and the sizes that are currently available limit its application.

Raytheon has produced an 11in. x 11in. curved AlON window, and is currently investigating the scale-up and cost reduction of aluminum oxynitride. The Air Force Research Laboratory (AFRL) is currently funding Raytheon to investigate cost reduction of AlON to produce larger windows, which will allow Raytheon to scale-up AlON such that it can be produced in large sizes at reasonable costs. The Army Research Laboratory is simultaneously investigating transient liquid phase sintering of aluminum oxynitride to reduce processing costs. A reaction sintering technique using a reactive liquid is the focus of the investigation, producing small samples with transmission of 85% and haze of 14% as seen on Figure 3.

Magnesium aluminate spinel ($MgAl_2O_4$) is a ceramic

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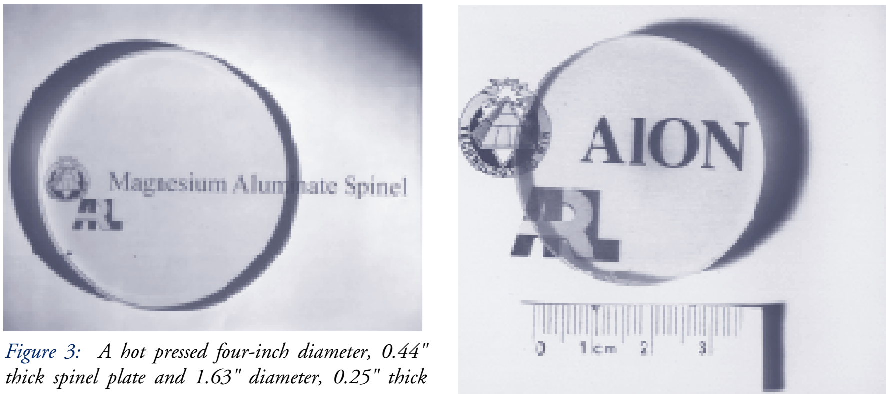

*Figure 3: A hot pressed four-inch diameter, 0.44" thick spinel plate and 1.63" diameter, 0.25" thick AlON produced at ARL*

with a cubic crystal structure and is transparent in its polycrystalline form. Transparent spinel has been produced by sinter/HIP, hot pressing, and hot-press/HIP operations, and it has been shown that the use of a hot isostatic press can improve its optical and physical properties.[14] Some typical properties of spinel are also shown in Table 1. Spinel offers some processing advantages over AlON such as the fact that spinel powder is available from commercial manufacturers while AlON powders are proprietary to Raytheon. It is also capable of being processed at much lower temperatures than AlON, and has been shown to possess superior optical properties within the IR region.[12] Spinel shows promise for many applications, but is currently not available in bulk form from any manufacturer. Efforts to commercialize spinel are underway.

| | | AlON | Spinel |
|---|---|---|---|
| Density | g/cm$^3$ | 3.67 | 3.58 |
| Elastic Modulus | GPa | 315 | 277 |
| Mean Flexure Strength | MPa | 228 | 241 |
| Weibull Modulus | | 8.7 | 19.5 |
| Fracture Toughness | MPa√m | 2.40 ± 0.11 | 1.72 ± 0.06 |
| Knoop Hardness (HK2) | GPa | 13.8 ± 0.3 | 12.1 ± 0.2 |

*Table 1: Selected mechanical properties of AlON and spinel*

For instance, Ceramic Composites Inc.+ is currently investigating hot pressing of magnesium aluminate spinel under a Phase I SBIR sponsored by the Army Research Laboratory. Hot pressing was chosen from a processing technique-based comparative analysis of several processing techniques for producing spinel.[13] Research efforts have focused on hot pressing with additive and hot-press/hot isostatic pressing (HIP), and have been shown to be a successful in producing transparent parts. Additional hot isostatic pressing of the spinel has been shown to improve its optical and mechanical properties.[14] A four-inch diameter, 0.44-inch thick spinel plate, shown in Figure 2, was produced using this technique. It has an 83 percent transmission with 9.32 percent haze. Future plans include a scale-up to ten inch parts.

Single crystal aluminum oxide (Sapphire - Al$_2$O$_3$) is a transparent ceramic. Sapphire's crystal structure is rhombohedral and its properties which are anisotropic, vary with crystallographic orientation. It is currently the most mature transparent ceramic and is available from several manufacturers, but the cost is high due to the processing temperature involved and machining costs to cut parts out of single crystal boules. It has a very high material strength, but is dependent on the surface finish. There are current programs to scale-up sapphire grown by the heat exchanger method or edge defined film-fed growth processes. Its maturity stems from its use in the EM windows and electronic/semiconductor industries. Crystal Systems Inc., which uses single crystal growth techniques, is currently scaling their sapphire boules to 13-inch diameter and larger.

Saphikon, Inc. produces transparent sapphire using an edge, defined growth technique. Sapphire grown by this technique produces an optically inferior material to that which is grown via single crystal techniques, but is much less expensive. Saphikon is currently capable of producing 0.25in. thick sapphire, in 12in. x 15in. sheets. ARL is currently investigating use of this material in a laminate design for transparent armor systems. Scale-up to larger size plates presents several problems including an increase in costs, and an increase in polishing difficulties. An investigation is currently underway by Materials Systems Inc. for bonding sapphire plates together using glass and glass-ceramic bonding materials. Bonding offers the ability to manufacture large windows that may not be achievable in monolithic parts due to lack of capital equipment. Bonded plates have been produced that possess 70 percent of the strength of unbonded material.[13]

## Conclusions

Throughout the military, there is a general push to reduce the weight of fielded systems for the purpose of increasing maneuverability, transportability, and reducing operational costs. The approach discussed here involved reducing the weight of the transparent armor systems. Throughout this article, the improvement in ballistic performance and weight reduction obtainable with the use of transparent ceramic and polymeric materials has been discussed. Transparent ceramics were shown to offer significant ballistic protection at reduced weights over the conventional glass/plastic systems currently in use. Some major issues must be overcome, such as the commercial availability, the shapes and sizes available, and costs, before application into armor systems is viable. Many applications require transparencies greater than 12 inches by 14 inches, with thickness between 0.25 inch to 1 inch, which are currently difficult to obtain with transparent ceramics. This difficulty stems from a current deficit in the capital equipment, such as furnaces, available to produce the larger sizes. Costs are currently very high for the ceramics due to the high purity powders needed, the high processing temperatures, long processing times, complex processing, and high machining and polishing costs. Several programs are now underway that are investigating the cost reduction and scale-up of these materials, and with successful outcomes, may initiate transparent ceramic use for armor applications.

Polymeric material advancements, such as the improvement of the optical properties of polyurethane, have led to a

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Spotlight on Technology

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Department of Energy, has funded programs for the development of ceramic turbine engine components. Structural ceramic components are finding increased use in turbine engines, particularly land-based turbines. In the meantime, thermal barrier coatings have been developed to extend the usable temperature limit of metallic engine components.

Schulz et al described how thermal barrier coatings can improve the life and performance of turbine components compared to uncoated components.[1] Performance is increased with increasing turbine gas temperature. However, with this increased gas temperature comes an increase in the temperature of the metal surface which lowers the component lifetime. The end-user determines the correct balance between performance and component life based primarily on economic considerations. For a given gas temperature, the thermal barrier coating allows for a lower metal surface temperature and thus a longer component lifetime. Similarly, in the case where the metal temperature is a limiting factor and cooling air is required to keep the temperature below the prescribed threshold, a component with a thermal barrier coating requires less cooling air to maintain the same temperature. This translates to increased performance for a given metal's temperature limit.

Typical aerospace applications include the combustor, airfoils, and exit flaps of aircraft engines. In terms of development, coatings were first applied to stationary components followed by rotating components such as airfoils. Automotive applications include after-market coatings on headers and other exhaust system components as well as coatings for the hot areas of the engine including the pistons, cylinders, and valves.

Thermal barrier coatings on stationary components are typically applied using standard thermal or plasma spray techniques. In thermal and plasma spray, molten or semi-molten particles are applied by impact onto a substrate. More highly stressed components such as turbine blades and vanes can have thermal barrier coatings applied using electron beam physical vapor deposition (EB-PVD). EB-PVD coatings tend to be more strain resistant than standard thermal or plasma sprayed coatings.

In order to improve the adhesion between the thermal barrier coating and the metallic substrate, a bonding coat is usually applied. The coating has two purposes. First, to improve the oxidation resistance of the base metal and secondly to "level out" the mechanical stresses that occur as a result of the difference in thermal expansion between the metal and the ceramic coating. Without the bond coat, the thermal barrier coating has a greater tendency to spall and fail because of the expansion mismatch. Bond coatings are selected based on compatibility with the base metal and the thermal barrier coating as well as on the environment encountered during service.

The common problems encountered with thermal barrier coatings range from coating durability to inspection and repair. Because of the thermal cycling inherent in most applications where thermal barriers are applied, thermal barrier coatings are susceptible to cracking or possibly spalling where small pieces of the coating "pop off" upon cooling. These cracks or bare spots in the coating then make the component more susceptible to oxidation or other types of corrosive attack in addition to being subjected to localized heating.

Nondestructive evaluation techniques are used to inspect coating integrity. Among the techniques in use are eddy current evaluation and thermography. Coatings are repaired by first stripping the thermal barrier coating via sandblasting or chemical stripping. The coating is then reapplied using the techniques previously described. Depending on the service conditions the component encounters, repairs can occur several times during the lifetime of the component, as long as dimensional tolerances can be maintained.

Given the success of thermal barrier coatings, it is not surprising that research has continued in efforts to raise the service temperature of coated components and improve the reliability of existing coatings. Improvements in raw materials such as higher purity and stricter control of particle size have been shown to lead to improved microstructures and more durable coatings. Work continues to be performed on new coating compositions and improved application methods.

Functionally gradient materials (FGMs) are perhaps the most exciting development in all types of coatings, including thermal barrier coatings. Like the bonding coat, FGMs serve to level off the differences in properties between the surface coating and the substrate. Unlike the bonding coat, FGM coatings are designed so that there is no discernable interface between one intermediate material to another but rather a smooth transition. Some researchers are accomplishing this by literally building the inter-layers one row of atoms at a time. This technique has the potential of improving the performance of existing materials and the development of new materials previously unattainable through more standard processes.

Thermal barrier coatings are an enabling technology for making heat engines more efficient and powerful. They will continue to fill the niche between super alloys and structural ceramics in turbine engine and other high temperature applications.

## Reference

[1] Schulz, U., Fritscher, K., Leyens, C., Peters, M., Kaysser, W.A., *The Thermocyclic Behavior of Differently Stabilized and Structural EB-PVD TBCs*, JOM-e, http://www.tms.org/pubs/journals/JOM/9710/Schulz/Schulz-9710.html ■

## Titanium Aluminide Intermetallics

Twenty-first century aerospace systems have mission requirements that will demand advanced materials. Simply defined, advanced materials are those with enhanced mechanical and physical properties exceeding those of traditional or established materials. Intermetallic compounds and metal matrix composites are two material systems that have the potential to meet the demands of present and future aerospace vehicles.

Recent structural applications of materials have followed two avenues. One direction seeks new materials with superior strength at elevated temperatures. Another direction involves the development of materials whose strength properties may not exceed those of existing materials but whose strength to weight ratio or specific strength may improve the overall performance of a system.[1] Advanced ceramics are a solution for many applications but after decades of research, it is clear that ceramics cannot be the only answer. As a result, intermetallic compositions of light metals with stability ranges beyond those of conventional alloys have stimulated renewed interest. Successful materials based on titanium aluminides combine low density, reasonable creep properties and oxidation resistance for applications up to 900°C.[2]

Structural materials for applications at high temperatures must have high strength at the service temperature. This implies high creep resistance.[3] Creep resistance depends on two factors, the shear modulus and the diffusion coefficient, which in turn depend on the melting temperature. The Ti-Al phase diagram in Figure 1 shows the α phase composition, $Ti_3Al$ (known as α2), and the γ phase composition TiAl as well as the stoichiometric $TiAl_3$. Phases with high melting temperatures that form low-melting eutectics decrease the phase stability, and become unsuitable for service. The phase diagram demonstrates that any extensive research on intermetallic alloys requires precise knowledge of the high temperature phase boundaries. It is important to understand the effect of interstitial impurities, mainly oxygen, on phase stability. Misinterpretations of this effect have created a large number of versions for the phase diagram.[4]

Since the 1970s, extensive research has been conducted to determine whether ductile titanium aluminides can compete with nickel-base superalloys. Two candidate aluminide materials, alpha-2 (Ti-3Al) and gamma (Ti-Al), have been identified. These materials are of lower density than conventional titanium alloys, have high melting temperatures, and retain their strength and modulus at high temperatures. However, due to limited room-temperature ductility and poor fracture toughness, these materials remain developmental in nature and have not yet been considered for "production" type components. Efforts to improve these properties, many of which are sponsored by the US Air Force, have focused on alloy development and processing methods. Processing technologies such as melting, casting, forging, and machining have been extensively studied. In the past, precision investment cast shapes were made from an alpha-2 base alloy, and a ring for a combustor liner was rolled from the same material. Alpha-2 based titanium aluminides have been considered to have creep strength similar to the Inconel 713 superalloy. Gamma-based titanium aluminides have been compared to the IN-100 superalloys. Both superalloys have limited applications due to (1) fabricability, (2) room-temperature handling, and (3) resistance to embrittlement at elevated temperature.

One of the guidelines for material selection of titanium aluminides is the density of the phase. Intermetallics used for components encountering high tensile loads, such as turbine blades, must have high strength and low weight. In other words, they must have high specific strength. Titanium aluminide intermetallics are light materials, and therefore have a higher specific strength than superalloys, despite their lower overall strength.

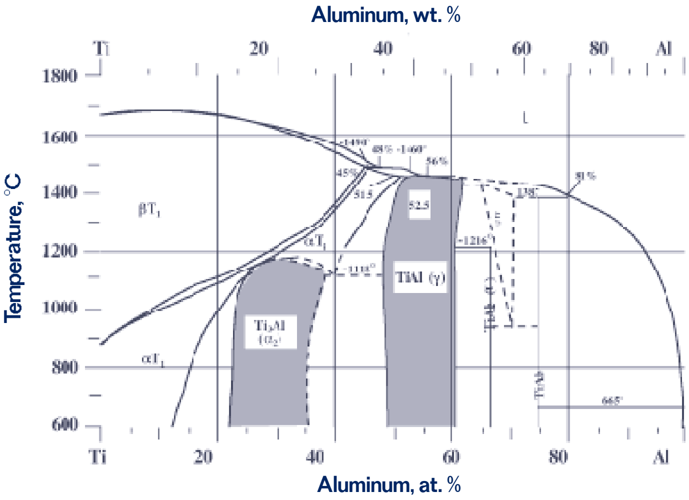

*Figure 1. Proposed titanium-aluminum phase diagram (from Massalski, T.B. (Ed.),* Binary Alloy Phase Diagrams*, 2nd Edn, Vol. 1, ASM International, Materials Park, Ohio, 1990)*

Corrosion/oxidation resistance is also an important criterion when evaluating Ti-Al intermetallics. Improved oxidation resistance can be achieved by adding oxide-forming elements such as Al, Cr, or Si. At the operating temperatures, these three elements can form an oxide layer that protects the intermetallic from further oxidation and corrosion. The oxide layer must adhere well in order to protect effectively and insure mechanical integrity. Adhesion of the layer is improved by adding small amounts of additional titanium to the composition. In environments with temperatures over 1100°C, the rates of diffusion and chemical reaction increase, rendering the passivating oxide layer ineffective.

A final criterion for selection is the processing of the intermetallic. Titanium aluminides are relatively brittle materials. Therefore, the use of processing methods analogous to those of standard metal fabrication is somewhat problematic and must be carefully chosen in order to retain the desirable qualities of TiAl.

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Titanium Aluminide Intermetallics

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### $Ti_3Al$ (α2) Applications

$Ti_3Al$ (α2) is currently produced in ingots of up to 4500 kg. $Ti_3Al$ can be machined, and its sheets can be deformed and bonded through diffusion and linear friction welding. Fusion welding is problematic because of the difficulty with microstructure control. Components of gas turbine engines, such as combuster swirlers, compressor casing sections, and afterburner nozzle seals, have been tested in static structures. Still, $Ti_3Al$ is not commonly used in the aerospace industry, due to increased requirements for strength and oxidation resistance. The chemical instability of $Ti_3Al$ at high temperatures is another aspect hindering the application of $Ti_3Al$ in the aerospace industry. Further stabilization of composition and microstructure is required, in order to improve tensile properties, creep resistance, corrosion resistance, and fatigue characteristics. High susceptibility to stress corrosion cracking, reduced tensile ductility, and creep failure at high temperatures, make $Ti_3Al$ a less popular material than TiAl.

### Applications for TiAl-Based Alloys

Gamma TiAl-based alloys are attractive due to their high specific strength and modulus, lower density, and higher creep and oxidation limit temperatures compared to Ti- and $Ti_3Al$-based alloys. Examples of applications that utilize these properties include non-fracture critical components for the Integrated High-Performance Turbine Engine Technology (IHPTET) program, such as combuster swirlers, blade outer air seals (BOAS), F119 turbine rotor cover plates, and compressor blades

Environmental effects to be taken into account when considering applications for γ-TiAl intermetallics are oxidation resistance, and embrittlement caused by impurities such as oxygen, nitrogen, carbon, and boron. Due to a higher content of Al (compared to $Ti_3Al$), the oxidation resistance of γ-TiAl is higher than the oxidation resistance of α-$Ti_3Al$. The oxidation resistance of γ-TiAl is based on the formation of an oxide layer, in this case aluminum oxide, as opposed to titanium oxide, because $Al_2O_3$ is slightly more stable than TiO. Nevertheless, when the aluminum content is below the 1:1 stoichiometric ratio (i.e. the most ductile titanium aluminide), TiO undergoes further oxidation and forms $TiO_2$ (rutile) which does not protect titanium aluminide from oxidation. Consequently, TiAl that has been optimized with respect to mechanical properties does not have adequate oxidation resistance. The addition of niobium promotes the formation of a protective $Al_2O_3$ layer that can improve the oxidation resistance of these materials.

### Recent developments in Titanium Aluminides

Special emphasis has recently been put on the development of γ-phase titanium aluminides. These alloys offer the potential for component weight savings of up to 50% compared to conventional alloys in 600 to 850°C aerospace applications. The γ class of titanium aluminides possesses a good balance of room-temperature mechanical properties and high-temperature strength retention. Nevertheless, protective coatings for γ-TiAl alloys such as aluminizing treatments, conventional MCrAlY coatings, and ceramic coatings for oxidation resistance, have been unsuccessful due to poor mechanical properties, thermal expansion mismatch between coating and substrate, and chemical incompatibility. Ti-Al-Cr has been identified as a promising coating alloy due to excellent oxidation resistance and chemical compatibility with the γ substrate alloys. However, this coating has proven to be too brittle to give reliable protection. Engineers at NASA's Glenn Research Center have developed a Ti-51Al-12Cr oxidation-resistant coating alloy that offers good compatibility with the γ-phase substrate, and also improves the mechanical properties of the system without sacrificing the oxidation resistance.[5]

TiAl is presently considered for aerospace applications such as compressor variable vane inner shrouds for F119 engines used on the Air Force's F-22. This application requires high specific strength and mechanical properties at elevated temperature, and low thermal expansion (lower than currently used Ni-based superalloys) as primary characteristics. In order to improve these parameters to meet design criteria, short fiber, continuous fiber, or lamellar type reinforcement is incorporated.[6] As with most advanced composites, chemical and mechanical compatibility between the matrix and the reinforcing fibers must be considered. TiAl matrix composites are under consideration in leading edge airfoil structures for proposed hypersonic flight vehicles. The thermal expansion mismatch between the TiAl matrix and the SiC reinforcement typically used in these materials has led to research efforts to develop a suitable interface coating.

TiAl also has potential applications in the automotive industry. For example, a 4 cm diameter turbocharger rotor has been fabricated from cast TiAl. The performance of the TiAl component compared favorably with the same part made of a superalloy.

Despite the qualities that make these alloys attractive, the γ-TiAl-based alloys are limited in their applicability. The same microstructure that provides the high temperature toughness lowers the tensile ductility at room temperature, making fabrication difficult.[7] The single-phase γ-TiAl is brittle, but small additions of aluminum-lean alloys containing small amounts of alpha titanium aluminides, improve the ductility of γ-TiAl. The control of microstructure through thermomechanical processing and heat treatment based on the knowledge of the phase diagram enables improvement of the ductility and toughness combination.

Advances made in the last decade for γ-TiAl have generally been concerned with improvements in mechanical properties through development of processes leading to improved microstructures. For instance, Ti-48Al-2Cr-2Nb, Ti-47Al-2.6Nb-2(Cr+V), and Ti-46Al-5Nb-1W (Allison Alloy 7) have well-established properties, with the exception of fatigue. Fatigue performance is beginning to be characterized in addition to other critical mechanical properties.[8]

McDonnell Douglas Aerospace, now a part of Boeing, has carried out a technical plan to develop an understanding of two-phase Alpha2+Gamma Titanium Aluminides.

Accordingly, design specifications for engines and airframes have been based on the assessment of mechanical properties for each specific application. Phase I of this plan focused on processing, developing wrought processes such as forging and rolling, and investment casting processes to produce plates and bars. Phase II included testing and analysis. Test properties determined were pre-strained tensile strength and creep, interrupted creep, interrupted fatigue, in situ fracture toughness, and in situ fatigue. Three selected microstructures were evaluated: a lamellar structure for application in engines as well as airframes, a cast coarse duplex structure for engine applications, and a rolled fine duplex structure for airframe applications.

While some success in predicting room temperature fatigue properties was achieved, fatigue crack growth at elevated temperatures in γ-TiAl is difficult to predict. This behavior is usually estimated according to the effect of oxide-induced crack closure, but retardation of crack growth is known to occur at approximately 800°C, in vacuum. Further investigation of parameters that affect room- and elevated-temperature fatigue crack growth in γ-TiAl is necessary, in order to expand the applications of this material.

### Titanium Aluminide Applications for the High Speed Civil Transport (HSCT)[9]

In 1997, the National Aeronautics and Space Administration developed the "Three Pillars of Success," a roadmap for aeronautics and space transportation, through the year 2020. "Pillar One" focused on Global Civil Aviation and included goals such as increased safety, reduced subsonic exhaust and noise emissions, as well as increased affordability. The HSCT program came under "Pillar Two" and included enabling technology goals such as reducing overseas travel time by 50%, reducing exhaust emission, and decreasing noise levels. The HSCT program was canceled in 1999, but the High Speed Research (HSR) program that oversaw HSCT, still continues. HSR is a partnership program between NASA, Boeing, General Electric, and Pratt & Whitney. The requirements for stringent control of environmental noise and emission have turned the propulsion system into the focus of this program. Demand for long-term durability, high temperature functionality, and low weight, make TiAl a viable candidate for several critical components in the HSCT propulsion system. TiAl was extensively studied for use in the HSCT exhaust nozzle. Initially, TiAl was selected for the divergent flap, a relatively large component designed for small deflections, because of its high specific modulus and ability to function at high temperatures. However, the cast TiAl divergent flap did not meet the cost and weight reduction goals.

On the other hand, divergent flaps made from wrought sheets of TiAl were much more successful. Consequently, process development had focused on forming and joining techniques for sheet structures. Additional studies have indicated that the utilization of a cast TiAl substructure and wrought TiAl face sheet hybrid sidewall structure for the nozzle sidewall can reduce weight and cost. For this application however, both cast and wrought TiAl lacked the required high temperature strength and fracture toughness.

### Conclusion

The surge for new research into the properties of intermetallic materials is aimed at understanding intermetallic compounds and predicting their crystal structures and behavior. The driving force behind this is the need to replace dense structural materials with monolithic intermetallic materials that can perform in high temperature environments, ultimately achieving more efficient, high-powered gas turbine engines.

However, although intermetallics display excellent specific strength, creep, and oxidation resistance, their lack of ductility generally does not allow these materials to meet design requirements. There is a need to improve the ductility or fracture toughness of the intermetallics, without compromising the desired properties of the material at high temperatures. As aerospace requirements start to emphasize "damage tolerant" designs, fracture toughness and fatigue crack growth rate will become increasingly important design criteria. The development of titanium aluminide matrix composites is critical if these materials are to play a major role in the aerospace industry.[10]

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## P4A: An Affordable Composite Process

The National Composite Center (NCC) located in Kettering, Ohio leads a technical team comprised of Boeing-St. Louis, Boeing-Seattle, Lockheed Martin Aeronautical Systems, Northrop Grumman, and the University of Dayton Research Institute. The team's goal is to demonstrate the feasibility of utilizing emerging preforming technology to produce efficient, low cost chopped carbon fiber preforms for aerospace applications. The Structural Materials Branch, Nonmetallic Materials Division, Materials and Manufacturing Directorate of the Air Force Research Laboratory (AFRL/MLBC) sponsors the program entitled "Programmable Powdered Preform Process for Aerospace" (P4A).

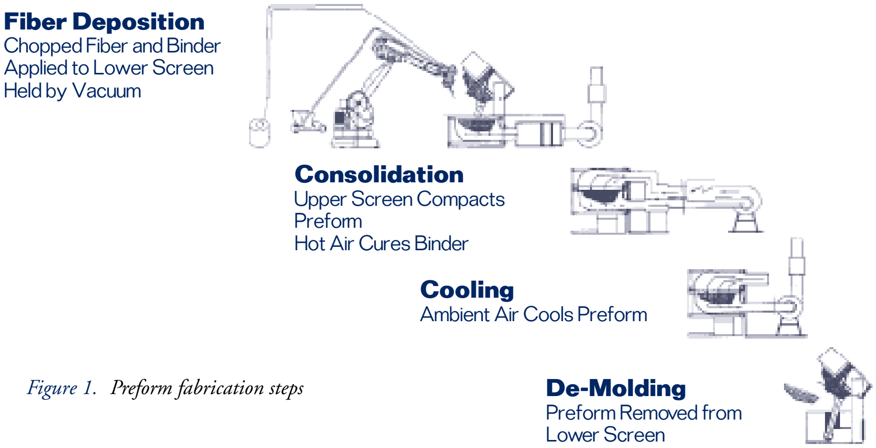

*Figure 1. Preform fabrication steps*

The following success metrics for the program were defined to demonstrate that the P4 method could be adapted to aerospace-grade carbon fibers and resin.

1. Meet target property goals.
2. Fabricate structural complexities representative of aerospace requirements.
3. Demonstrate compelling cost savings over conventional processes.
4. Demonstrate that the process could be enabling so that it could buy its way onto applications.

The success metrics were defined as critical; if met, then further development of the process, structural validation, and transition to development of actual flight hardware would be recommended.

P4A is a fully automated process for chopping and spraying carbon fibers to produce a preform. The compelling attributes of the process include its automation, which provides for the rapid fabrication of preforms with very low "touch labor." It offers the potential for reduced assembly through the ability to form complex geometries and net shapes. Fiber alignment is possible, and additional design flexibility may result from the process' ability to change chopped fiber length and/or orientation "on the fly." Random discontinuous fiber orientations result in lower performance composites when compared to the highly oriented, continuous fiber composites. Random fibers cannot be tightly packed together so there is an upper limit on fiber volume of 35 to 40%. Since fiber alignment is possible in the P4A process, higher fiber volumes to be attained. These oriented fiber composites easily and consistently obtain fiber volumes of 55%. Additionally, rib stiffeners, openings, cores, and other elements may be integrated into the preform during its manufacture. All of this is possible while retaining very low material waste factors. The process consists of four major steps as shown in Figure 1.

The first step is to chop the fiber and spray it via a robotic arm onto the screen through which a vacuum is being drawn. At the same time, a powdered binder is also applied, usually 3 to 5 wt %. The next step is the consolidation of the preform by the passage of heated air through the preform; this sets the binder and holds the compacted preform in position. Passing room temperature air through the preform then cools the preformed fibers and binder. Once the preform is cooled, it is capable of holding its shape with careful handling and is simply removed from the tool and available for resin infusion.

The initial phase of this program successfully demonstrated the feasibility of the P4A process to dramatically reduce the cost of manufacturing carbon fiber-reinforced composite aerospace structures. The P4A process produced oriented discontinuous fiber composites which showed stiffness retention of above 90% and strength retention of 80 to 95% of that of a similar continuous fiber composite. Additionally, the compression after impact (115% to 150%) and the shear strength (120% to 160%) exceeded the continuous fiber composite's properties.

In order to demonstrate the cost reduction potential for the P4A process, two components were selected: the F/A-18 E/F dorsal cover and the C-17 tailcone. The P4A dorsal cover design and the process' ability to fabricate integrally stiffened skins eliminated the need for mechanical fasteners that exist on the baseline F/A-18 E/F dorsal cover. Due largely to this feature, the P4A dorsal cover was 9% lower in weight than the baseline structure and saved an estimated 45% of its cost. Figure 2 shows an integrally stiffened F/A 18 E/F dorsal cover.

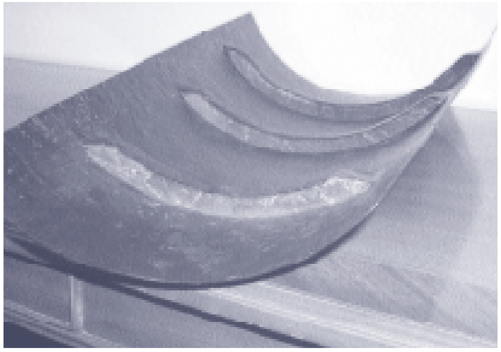

*Figure 2. F/A 18E/F Dorsal Cover*

The YC-15 tailcone, a part of similar geometry but

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P4A: An Affordable Composite Process

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smaller dimensions than the C-17 tailcone, was substituted as the C-17 demonstration component. The YC-15 was an advanced technology demonstrator, which first flew in 1975. In 1996, the YC-15 was brought out of mothballs to continue its mission to explore new technology applications for the C-17 and other transport aircraft. This not only offered essentially the same opportunity to assess the process as the C-17 component, but also offered the potential for flight demonstration if the YC-15 were returned to flying status. The YC-15 tailcone is approximately 4 feet in height and 4 feet in diameter at the base. The baseline design is a bonded rib-stiffened carbon fiber-reinforced epoxy.

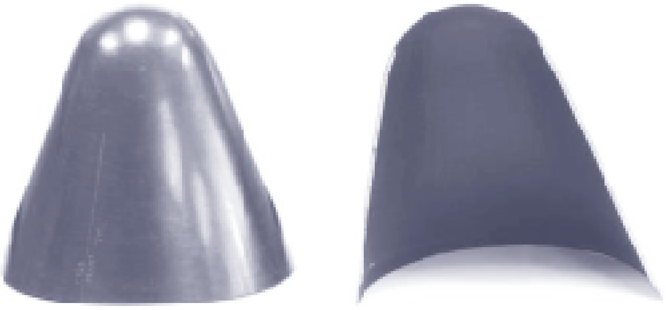

*Figure 3. YC-15 Tailcone*

The P4A YC-15 tailcone resulted in an estimated 84% cost savings with 11% weight increase over the baseline structure due to an added thickness in the cap area. Note, the majority of the weight growth on the YC-15 tailcone was due to the lack of infusion experience with a balsa core used in this configuration and is not related to the P4A process. One of the tailcones produced was successfully fit checked on the YC-15 aircraft. The P4A process is expected to save over 80% of the cost of a C-17 tailcone with only a 2% weight growth. Figure 3 shows both the inside and the outside of the completed YC-15 tailcone.

This process demonstration was accomplished in a laboratory environment and is now ready to be further developed to transition the technology to production applications on operational aircraft. To facilitate definition of a baseline approach for a detailed technology transition plan, several decisions need to be made about P4A process parameters and equipment scale-up requirements. In parallel the program needs to determine the best available carbon fiber material form on which to base the P4A process development and production readiness verification. The requirements must be determined for scaling-up the P4A process hardware and facility to adequately demonstrate production readiness.

The size and complexity of potential production applications now needs to be assessed to determine requirements for P4A process scale-up. The primary objective of this assessment is to identify the issues associated with scaling-up the existing P4A development facility to a size sufficient to fabricate full-scale, full-size aerospace components in a manufacturing environment. At the culmination of this effort, initial layouts for the recommended manufacturing cell will be prepared, along with the associated recurring and non-recurring costs attendant with the scale-up. In addition to the "design" of the recommended P4A manufacturing cell, a survey will identify candidates for P4A. Selection of these candidates will be based on lessons-learned and process experience garnered during earlier P4A activities. Another factor for assessment will be the likelihood or viability of actually implementing the P4A process into future manufacturing plans. Process improvements and refinements specific to the most promising application candidate(s) will be performed on a full-scale, though not necessarily full-size, subcomponent by fabricating multiple preforms, infusing the preforms, and evaluating the resulting composites.

The assessment will be accomplished by conducting three tasks. Two of the tasks will focus on defining preliminary requirements for (1) carbon fiber tow product form(s), and (2) production process scale-up. The third task will provide the basis for defining process equipment scale-up requirements by conducting an application survey of the size and complexity of aerospace structures that are representative of potential near-term production applications.

The close interaction of the team—the Air Force Research Laboratory, NCC, Boeing-Seattle, Boeing-St. Louis, Lockheed Martin, Northrop Grumman, and the University of Dayton Research Institute—is noteworthy and has enabled the continuing successes achieved on this effort.

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*Transparent Armor*

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renewed interest in these materials to reduce the overall weight of armor systems. It has been shown that polyurethane offers superior ballistic performance at a reduced weight, than that of the current polycarbonate backing materials. It is currently being viewed as a replacement material for polycarbonate. With successful insertion of these new materials into transparent armor systems of fielded equipment, a significant weight reduction should be realized, along with an increase in ballistic performance and ability to defeat future threats.

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## Hydraulic Fluids for Military Aircraft

### Background

Hydraulic fluid is a multifunctional component of a hydraulic power or control system. The fluid must transmit power efficiently and act as a lubricant and coolant; it must protect against corrosion, and it should not leak excessively. In addition, hydraulic fluid has to perform specialized functions according to the system design. The fluid has to be compatible with the materials of the system. Also, it should be nontoxic and fire-resistant, and it should exhibit suitable physical properties (e.g., lubricity) over an appropriate time period. The vast array of available fluids further complicates the selection issue. The following factors should be assessed before deciding on a hydraulic fluid:

1. *Temperature* is not a characteristic property of the fluid but a system parameter. However, the physical properties of the fluid, such as viscosity and lubricity, and the chemical properties (e.g., chemical degradation due to oxidation and stress or hydrolysis) depend on temperature. Hence, the importance of understanding the temperature dependence of hydraulic fluid for storage purposes and operating conditions.
2. *Viscosity index* (VI) indicates how the fluid's resistance to flow changes with temperature and pressure. Viscosity affects mechanical friction, pump slippage, cavitation, leakage, power consumption, and the degree to which the system can be controlled.
3. *Compatibility* of the hydraulic fluid with the system implies that the fluid should not react with the materials within the system or with the environment. The compatibility between the seal materials and hydraulic fluids is especially important. The aniline point of the fluid is a measure of the reactivity with the elastomer used to fabricate the seal. Swelling of the seal in the range of 10 to 15% can minimize fluid leakage, and is thus desirable.
4. *Corrosion prevention* is an important attribute of the hydraulic fluid. Most fluids contain rust inhibitors or metal deactivators that coat the surfaces of the system's materials.
5. The *accuracy, promptness, and stability* of the hydraulic system are not an intrinsic property of the liquid, but the result of a combination of properties such as compressibility and viscosity. The stability of the fluid determines the time that the hydraulic fluid can remain operational (e.g., in storage or in service, without significant changes of properties).
6. *Lubricity* is the function of the shear strength of the lubricating film produced by the hydraulic fluid, and is a measure of the ability of this film to support loads occurring during operations.
7. *Compressibility* affects factors such as the power required by the pump to generate pressure, the transmission of power, and the speed of the response to input.
8. *Fire resistance and nonflammability* are a measure of the fluid's ease to ignite, and the tendency of the fluid to support combustion once ignition has taken place.
9. *Formation of insoluble materials* can cause malfunction of the system, by plugging orifices, damaging surfaces, or depositing on working surfaces.
10. The *handling* is improved by considering factors such as toxicity of the fluid, its vapors, and its decomposition products. Fluids containing hazardous or toxic materials must be labeled in accordance with OSHA Standard 29CFR1910.1200, Hazard Communication. Accordingly, a Material Safety Data Sheet (MSDS) must be prepared by the manufacturers, and maintained by the users.
11. *Contamination* causes at least 75% of all of hydraulic system failures. A large percentage of contaminants such as solid particles and heat, is internally generated.
12. *Storage* characteristics are often measured by the oxidation stability of the hydraulic fluid. Special precaution should be taken to avoid contamination of the fluid during storage.[1]

### New Development in Hydraulic Fluids[2]

Aircraft hydraulic systems present a challenge to design engineers, due to constraints that are not encountered in other applications such as the automobile industry where the system pressure generally operates within the 1500 to 2000 psi range. Systems used in commercial airliners run at 3000 psi while military systems use 4000 psi systems. The hydraulic system for aircraft applications must address demands such as internal and ambient pressure conditions, extreme temperature gradients, weight, speed, materials, reliability, compatibility of the fluid with the system, leaks, noise, and redundancy. Commercial systems face temperature ranges of -65°F to +160°F while military systems must respond to a range between -65°F and +275°F and are required to remain fluid at very low temperatures.

Space considerations and the need for low weight (due to actuators that can generate higher torque forces and power from smaller envelopes) dictate the need for higher pressure in the hydraulic system of the military aircraft. The military aerospace hydraulic systems are faced with new challenges because of factors such as (1) new aircraft making greater demands on the system materials, (2) aging aircraft (e.g., harder missions, modifications putting additional stresses on the systems, changes in manufacturing processes for components), (3) fewer military specifications (e.g., dilution of existing specifications, though fluids and lubricants, considered flight critical components, will remain as MIL-SPEC), (4) diminishing of the technical base of fluids and lubricants in the industry, due to downsizing and mergers.

### Evolution of Hydraulic Fluids

Hydraulic fluids have long been studied by the Department of Defense. The goal of these investigations has always been to develop safer, better performing hydraulic fluids. More recently, environmental concerns have also factored in the development of hydraulic fluids.

One of the first fluids developed was MIL-H-5606 which is a highly flammable, petroleum-base hydraulic fluid. This fluid contains additives to improve low-temperature flow and viscosity-temperature characteristics, resistance to oxidation, and antiwear attributes. It is used in systems for automatic pilots, shock absorbers, brakes, flap-control mechanisms, missile hydraulic servo-controlled systems, etc. Ignition of MIL-H-5606 has been attributed as the cause of several past aircraft fires.

MIL-PRF-83282 was developed as a fire resistant, direct replacement for MIL-H-5606. MIL-PRF-83282 is compatible with 5606, as far as seals and system design are concerned. This hydraulic fluid is used in aircraft and missile hydraulic systems, and in airborne engine compressors, and it consists of a synthetic hydrocarbon-base stock with additives.

MIL-PRF-83282 proved to be a far safer fluid than MIL-H-5606 and nearly equal in performance. However, it has higher viscosity at low temperatures than MIL-H-5606, which makes its use questionable for alert aircraft such as strategic bombers. To solve this problem, MIL-PRF-87257 was developed to operate at temperatures as low as -65°F. The performance objectives for MIL-PRF-87257 are the same as the specifications for MIL-H-5606, with the exception of flashpoint:

1. Kinematic viscosity ≤ 2500 cSt at -65°F, and ≥ 3.5 cSt at 210°F
2. Flash point ≥ 340°F
3. Shear stability to 8000 psi at 275°F
4. Improved lubricity over MIL-H-5606
5. Lower volatility

Three base fluids have been used to accomplish these goals: a) Sylahydrocarbon, b) a polyalphaolephin dimer with polymethylmethacrylate (PMMA) added to improve the viscosity index, and c) a polyalphaolephin 10-carbon dimer ($C_{20}$) / trimer ($C_{30}$) blend.

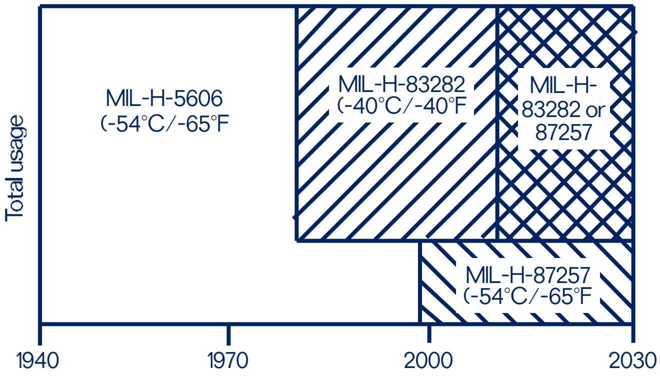

*Figure 1. Historical and future Air Force hydraulic fluid usage[2]*

### Plans for Future

In 1996, the US Air Force awarded a Small Business Innovative Research (SBIR) contract to METSS in Columbus, Ohio. The goal of this program was to develop a biodegradable, direct replacement hydraulic fluid for MIL-H-5606 and MIL-H-83282. The new fluid was to operate in a temperature range between -40°C and +135°C (-54°F and +275°F) and / or -54°C and +135°C (-65°F and +275°F), and had to be compatible with existing hydraulic fluids, seals and system materials. To further limit costs, it was required to be compatible with current hydraulic system design, e.g., it should have similar bulk modulus, pressure viscosity, and density. The Air Force has solicited sample candidates from the industry and has tested certain METSS formulations of the fluids. The US Navy (concerned with shipboard hydraulic spills) and the Air Force have carried out a joint project on biodegradable materials according to ASTM D 5864-95, Standard Test Method for Determining Aerobic Aquatic Biodegradation of Lubricants or Their Components, to determine the ultimate breakdown of the fluid to $CO_2$ and $H_2O$. Future flight tests will also require toxicity evaluation and pump testing for compatibility with the hydraulic fluids.

Figure 1 illustrates the new trends in hydraulic fluid usage with military applications. Future endeavors include producing hydraulic fluids with thermal stability that will withstand increased pressures and higher temperatures. Research will focus on products that minimize military hydraulic fluid fires, and that are environmentally acceptable.

### References

[1] MIL-HDBK-118, 22 September 1993, *Design Guide for Military Applications of Hydraulic Fluids*, pp. 1-5 to 1-9

[2] Gschwender, L.J., Snyder, C.E., Sharma, S.K., Flanagan, S.R., *Advances in US Air Force Hydraulic Fluids*, Journal of Synthetic Lubrication 16-1 35 ISSN 0265-6582, pp. 35-50 ■

### AMPTIAC Wants Your Contributions

We hope you find this issue of the AMPTIAC Newsletter useful and interesting. You can help us to better serve you by your contributions, such as:

- Your comments on what you liked and disliked about the Newsletter
- Your suggestions for AMPTIAC data products and services
- Technical articles, opinion pieces, tutorials, news releases or letters to the Editor for publication in the newsletter

To contact AMPTIAC, use any of the ways listed on the back cover, or use the feedback form on the AMPTIAC webpage. Your contributions are always welcome.

## Products & Technical Training

As you can see from our newsletter, AMPTIAC is in the business of providing technical awareness to the materials community. What you may not know is that AMPTIAC offers a wide variety of products and training courses to promote technical awareness and serve as an educational resource for the community. If you have any questions about any courses we offer, please contact our Training Coordinator, Chris Grethlein at (315) 339-7009 or by e-mail at cgrethlein@iitri.org. If you would like to order one or more of our products, please contact our Product Sales Manager, Gina Nash at (315) 339-7047 or e-mail at gnash@iitri.org.

**Products:** This past year has been an exceptional one for AMPTIAC, with the publication of a wide range of new technical products. Regardless of your specific discipline, there is an AMPTIAC product for you. Among our most notable publications this year:

### General Interest

#### A Practical Guide to Statistical Analysis of Material Property Data

This report has been specially prepared with the materials professional in mind. It bridges the gap between the science of theoretical statistics and the hands-on world of the practicing technician. The first of its kind, this report presents important statistical analysis methods from the standpoint of material property data, demonstrating the importance and relevance of statistics in the day-to-day activities of materials engineers and designers.

**Order Code: AMPT-14** **Price: $100 US, $150 Non-US**

#### Material Selection and Manufacturing for Spacecraft and Launch Vehicles

A first of its kind publication, this State of the Art Report provides a comprehensive overview of the unique requirements, problems, and opportunities faced by engineers designing and manufacturing spacecraft and launch vehicles. The book is authored by Dr. Carl Zweben, a key leader in the materials and space communities over the past several decades. It makes an excellent companion text to our training course on this topic (see training section below). While all material aspects of spacecraft and launch vehicles are addressed in this work, a special emphasis is placed on the important differences between materials used in space and aircraft applications.
Available in February!

### Metals and Corrosion

#### Corrosion Predictive Modeling for Aging Aircraft

Budgetary constraints prevent acquiring new aircraft while encouraging life extension of existing aircraft far beyond their design lives. This critical review and technology assessment highlights the significant and innovative aspects of the US Air Force Program to develop a predictive model for corrosion prevention and maintenance in complex structures. The program is a major step forward in the rather complex task of modeling corrosion and predicting the life of corrodable structures with any engineering relevance. The principles employed in this report to generate predictive capability are generic and applicable to a variety of components and structures.

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#### Life Prediction and Performance Assurance of Structural Materials in Corrosive Environments

Life prediction of structural components is vitally important to safe and cost effective operation of any system in which the materials are susceptible to environmental degradation. Performance assurance which is closely related to life prediction, is equally important to ensure that the system will operate as per design for the duration of its life. This report presents a panoramic view of this field by highlighting the variety of current approaches, identifying the limitations, and discussing directions for future efforts.

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### Ceramics

#### Group IV Metal Carbides: Processing & Engineering Properties

Group IV carbides have shown promise for use in high speed cutting tools and for high temperature applications such as liners for rocket motor throats and components for equipment used in the nuclear industry. Considerable interest in these materials was evidenced in the 1960s and 1970s and several products were brought to market. However, this initial activity apparently was not sustained and interest seemed to wane. The last major review of properties was prepared in 1986. This study looked at current areas of research (both basic and applied) to determine the state-of-the-art.

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### Composites

#### Sensor Technologies to Monitor Resin Transfer Molding (RTM) Processes

The use of sensors in the RTM process allow the operator to monitor the molding and curing processes in real time, yielding higher quality parts with significantly reduce defect rates. Online process control provides output information such as pressure, viscosity, and degree of cure, which when monitored by a computerized control system, such as a neural net, optimizes process parameters and reduces process development time. Sensors are becoming more instrumental in developing parameters for off-line monitoring as well. This report provides a panoramic review of the current and emerging sensor technologies as they apply to the monitoring, modeling, and production of resin transfer molded composite parts.

**Order Code: AMPT-23** **Price: $100 US, $150 Non-US**

#### Technology Survey on Textile Preforms for Composite Processing

This State of the Art Report is a companion to our product on RTM sensor technologies (see above). Authored by the Senior Faculty of the Fibrous Materials Research Center at Drexel University, this book stands out as a singular resource in fiber preform technology. It comprehensively addresses fiber and textile preform technologies as they apply to composite processing, with an emphasis on RTM processing applications.
Available in February!

## Electronic/Optical/Photonic Materials

### Third Order Non-Linear Organic Thin Films for Eye & Sensor Protection - Phtalocyanines and Porphyrins

Optical limiters are devices that strongly limit intense optical beams while exhibiting high transmittance for low intensity ambient light levels. These nonlinear optical devices are currently of significant interest for the protection of human eyes and optical sensors from intense laser pulses, which pose a considerable hazard both in the laboratory and in the field. However, most efforts to develop optical limiting devices based on various mechanisms, including nonlinear absorption and refraction in semiconductors, optical breakdown-induced scattering in carbon particle suspensions, thermal refractive beam spreading, and excited-state absorption have fallen short of the blocking level needed to protect the human eye. This report provides a comprehensive overview of the science behind, and the utility of these optical films. It is specifically written to be understandable and beneficial to the specialist and non-specialist alike.

**Order Code: AMPT-6** **Price: $50 US, $75 Non-US**

### Optical Limiting: An Overview

This report is intended to provide a background adequate for the novice to quickly understand the physical phenomena responsible for optical limiting behavior and the measurements routinely made to characterize the performance of nonlinear materials. In addition, some background is provided on work being pursued to molecularly engineer these materials to enhance their performance and adaptability to real world applications.

**Order Code: AMPT-16** **Price: $50 US, $75 Non-US**

### Infrared (IR) Windows and Dome Materials

This report focuses on the performance of infrared materials, and it is based upon the effort to build a numerical database of these materials. Six initial materials, namely germanium, zinc sulfide, zinc selenide, sapphire, spinel and yttria were chosen after an extensive literature search and through communications with the window and dome community. The report includes a section on long-wave and mid-wave materials, a brief discussion on materials for multi-spectral use and a succinct analysis of the properties of these materials.

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**Training:** AMPTIAC offers technical training courses for the materials professional. These courses are taught periodically at different locations around the country. When there is sufficient interest, we are also able to teach these courses in-house for a specific organization. For information about course schedules and offerings, please contact AMPTIAC.

AMPTIAC is pleased to offer the following courses at this time.

### Material Selection for Spacecraft and Launch Vehicles

The migration to space applications, the unique requirements of the space environment on materials, and an ongoing DoD force reduction all combine to highlight the void in materials expertise in the area of space applications. To fill this void, AMPTIAC, in cooperation with the Air Force Research Laboratory's Materials Directorate (AFRL/ML) and the Air Force Institute of Technology (AFIT), have developed a training course for the materials engineer working on space applications.

This course highlights the significant issues with the space and launch environments and discusses the potential application of many classes of materials in these environments. Prior offerings of this course have been met with the overwhelming approval of the students, who praised the course for its timeliness, relevancy, and value.

Five nationally recognized experts on the unique challenges of selecting materials for spacecraft and launch vehicles provide an intense training experience, covering the spectrum of materials classes for space and launch applications.

### Introduction to Material Design Allowables

One of the greatest challenges facing any design professional is materials selection. Most design professionals don't know how to assess the "goodness" of their materials data. The use of design allowables in the material selection and overall design process provides the reliability and assurance for the hardware and vehicles of the aerospace and military communities. Yet, most engineers who use allowables don't know where they come from, nor what their significance ultimately implies. By understanding the material and mathematical aspects of allowables, design professionals will be able to select materials and perform design analyses with great confidence.

About The Course: The first in a series of courses on applied statistical methods as they apply to the unique requirements of the materials profession, this course is specifically tailored to provide understanding of the unique marriage of material science and statistical analysis that result in design allowables. This course takes a lively and interactive approach, engaging the student in a series of relevant examples and exercises. Topics covered in this introductory course are:

- *Physical Basis for Statistical Behavior of Material Properties* – impact on major material classes, properties, design, and manufacture, and how they ultimately drive design allowables.
- *Data Quality and Pedigree* – discerning "good data" from "bad data", statistical basis for data quality. How data quality helps set allowables.
- *Distributions and Random Variables* – types of statistical distributions and their parameters, extreme values and outliers, physical basis for statistical distributions – Normal, Lognormal, and Weibull distributions.
- *Estimation and Testing* – Recognizing distribution behaviors in test data, determining which distribution best describes a materials' behavior ("goodness of fit"), estimating confidence bounds and tolerance limits, and calculating design allowables.

More advanced courses, which can be custom-tailored to your organization's needs can include any of the following topics: Bivariate and multivariate statistics, contingency tables, regression analysis, residual analysis, analysis of variance (ANOVA), and analysis of non-parametric distributions. Contact AMPTIAC for more information.

## Recent US Patents

| Patent Number | Title |
|---|---|
| 5,480,944 | Interpenetrating Blends Of Linear Polymers And Compatible Fractal Polymers |
| 5,486,280 | Process For Applying Control Variables Having Fractal Structures |
| 5,493,000 | Fractal Polymers And Graft Copolymers Formed From Same |
| 5,518,820 | Case-Hardened Titanium Aluminide Bearing |
| 5,520,832 | Tractor Hydraulic Fluid With Wide Temperature Range (Law180) |
| 5,531,911 | Metal Free Hydraulic Fluid With Amine Salt |
| 5,545,265 | Titanium Aluminide Alloy With Improved Temperature Capability |
| 5,558,729 | Method To Produce Gamma Titanium Aluminide Articles Having Improved Properties |
| 5,609,698 | Processing Of Gamma Titanium-Aluminide Alloy Using A Heat Treatment Prior To Deformation Processing |
| 5,683,825 | Thermal Barrier Coating Resistant To Erosion And Impact By Particulate Matter |
| 5,685,924 | Creep Resistant Gamma Titanium Aluminide |
| 5,700,383 | Slurries And Methods For Chemical Mechanical Polish Of Aluminum And Titanium Aluminide |
| 5,707,724 | Fractal Tube Reinforcement |
| 5,716,720 | Thermal Barrier Coating System With Intermediate Phase Bondcoat |
| 5,746,846 | Method To Produce Gamma Titanium Aluminide Articles Having Improved Properties |
| 5,759,640 | Method For Forming A Thermal Barrier Coating System Having Enhanced Spallation Resistance |
| 5,785,775 | Welding Of Gamma Titanium Aluminide Alloys |
| 5,792,521 | Method For Forming A Multilayer Thermal Barrier Coating |
| 5,822,177 | Electrolytic Capacitor With Fractal Surface |
| 5,823,243 | Low-Porosity Gamma Titanium Aluminide Cast Articles And Their Preparation |
| 5,842,937 | Golf Ball With Surface Texture Defined By Fractal Geometry |
| 5,843,585 | Thermal Barrier Coating With Improved Sub-Layer And Parts Coated With Said Thermal Barrier |
| 5,846,345 | Intermetallic Alloy Based On Titanium Aluminide For Casting |
| 5,848,177 | Method And System For Detection Of Biological Materials Using Fractal Dimensions |
| 5,849,675 | Hydraulic System Using An Improved Antiwear Hydraulic Fluid |
| 5,851,678 | Composite Thermal Barrier Coating With Impermeable Coating |
| 5,852,404 | Apparatus For The Detection And Identification Of Metal Particles, Coolant Or Water In Engine Oil Or Hydraulic Fluid |
| 5,859,919 | Method And System For Measuring Surface Roughness Using Fractal Dimension Values |
| 5,871,820 | Protection Of Thermal Barrier Coating With An Impermeable Barrier Coating |
| 5,873,703 | Repair Of Gamma Titanium Aluminide Articles |
| 5,879,760 | Titanium Aluminide Articles Having Improved High Temperature Resistance |
| 5,908,516 | Titanium Aluminide Alloys Containing Boron, Chromium, Silicon And Tungsten |
| 5,912,087 | Graded Bond Coat For A Thermal Barrier Coating System |
| 5,928,450 | Process Of Making Fractal Tubes |
| 5,942,337 | Thermal Barrier Coating For A Superalloy Article And A Method Of Application Thereof |
| 5,972,424 | Repair Of Gas Turbine Engine Component Coated With A Thermal Barrier Coating |
| 5,972,855 | Soybean Based Hydraulic Fluid |
| 5,981,934 | Photovoltaic Element Having A Transparent Conductive Layer With Specified Fractal Dimension And Fractal Property |
| 5,989,343 | Directionally Solidified Thermal Barrier Coating |
| 6,001,492 | Graded Bond Coat For A Thermal Barrier Coating System |
| 6,001,889 | Polymers With Fractal Structure |
| 6,045,928 | Thermal Barrier Coating System Having A Top Coat With A Graded Interface |
| 6,051,279 | Method And Device For Forming Porous Ceramic Coatings, In Particular Thermal Barrier Coating, On Metal Substrates |
| 6,054,420 | Synthetic Biodegradable Lubricants And Functional Fluids |
| 6,084,285 | Lateral Flux Capacitor Having Fractal-Shaped Perimeters |
| 6,096,940 | Biodegradable High Performance Hydrocarbon Base Oils |
| 6,103,315 | Method For Modifying The Surface Of A Thermal Barrier Coating By Plasma-Heating |
| 6,117,827 | Biodegradable Lubricant Base Oil And Its Manufacturing Process |
| 6,126,400 | Thermal Barrier Coating Wrap For Turbine Airfoil |

### Don't Trash That Data - Recycle It

Retiring? Reorganizing? Running our of storage space? Have to dispose of no-longer-needed materials data? Please, don't trash it! Donate it to AMPTIAC, where it can continue to be of use.

The AMPTIAC Library continually seeks data of interest to the materials community in its five areas of interest: ceramics and ceramic composites; organic structures and organic matrix composites; metals and metal matrix composites; electronics, electro-optics and photonics; and environmental protection and special function materials.

Your test data, failure reports, operational history, and other data can help a colleague in the selection and reliable application of materials in these areas. Please make it available to others through the AMPTIAC Library.

To make a contribution, contact Dave Rose, AMPTIAC, 201 Mill Street, Rome NY 13440-6916. Tel: (315) 339-7023. Fax: (315) 339-7107. E-mail: drose@iitri.org ■

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### Technical Inquiry Service

Readers of the AMPTIAC Newsletter may not be fully aware of the inquiry service available to them through the Advanced Materials and Processes Technology Information Analysis Center.

A real benefit that is derived from any Information Analysis Center is that of being able to obtain authoritative rapid response to one's urgent technical requests. Because AMPTIAC operates as a full-service center within the structure of IIT Research Institute, it is able to draw upon the expertise of a large research organization to provide users of the inquiry service with pertinent information on metals, ceramics, polymers, electronic, optical and photonic materials technologies, environmental protection, and special function materials, including properties, process information, applications, environmental effects and life extension.

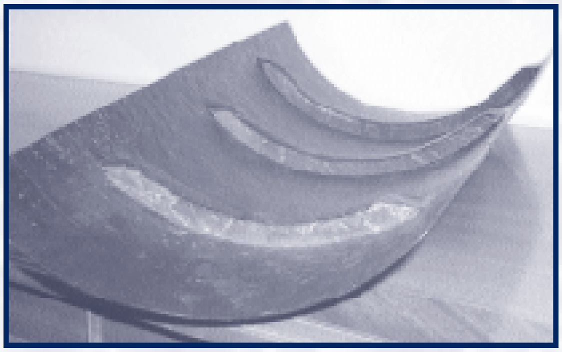
The AMPTIAC technical inquiry service is offered free of charge for the first eight hours of service. AMPTIAC will use all available resources, including Ph.D. level staff members, to ensure that our support is adequate to address your needs. Requests that may require additional time are charged to reflect the amount of effort and level of expertise required to provide a useful answer. Under no circumstance will a user be charged for services without a prior agreement to do so.

AMPTIAC's inquiry service could help save time and money. For more information, contact AMPTIAC by any of the means listed on the back cover of this newsletter.

# AMPTIAC

Advanced Materials and Processes Technology

## Inside this Issue ...



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Advanced Materials and Processes Technology

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that the scaling theory holds providing the time variable is replaced by the number of cycles. Figure 5 indicates that the roughness of the silver surface increases with the number of cycles (1, 5, and 20).

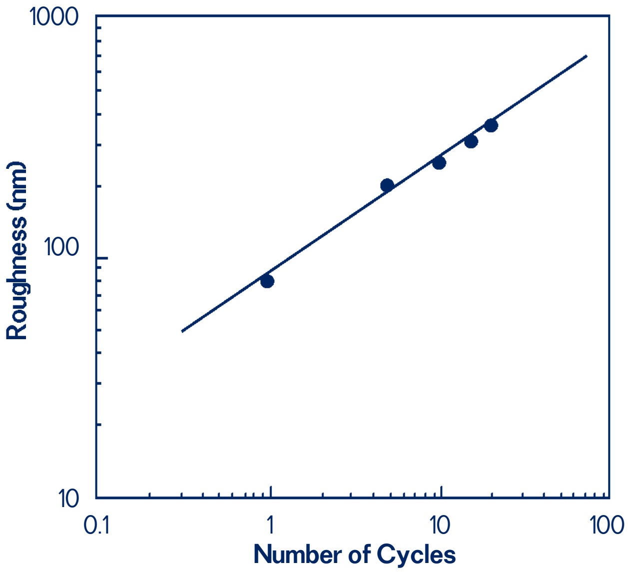

***Figure 4. The roughness vs. number of cycle's n in the electrochemical cyclical growth of silver (log-log plot).***

## Conclusion

Fractal science is a rapidly evolving field. However, the question of whether the new concept of self-affinity and scale invariance can lead to major scientific and technological discoveries, remains. The principles of abstract scale invariance create the model for a group theory, thus placing fractal concepts in that category. In this case, the premise of a scientific discovery commences with the theory, and its application will be the result of experimenting with the new theory. One can argue that by building a system of hypotheses, it is possible to ascertain whether the exponents of the new system coincide with the exponents from an already established system. For example, by obtaining the spectroscopic lines of an unknown compound, one can compare them with the absorption peaks of an already established spectrum, thus being able to identify the new compound. By extrapolation, scientists are hoping that the quantification of disorderly growth phenomena achieved through the definition of growth exponents, will construct the infrastructure necessary for understanding and improving technologies as important as the formation of the microchip and the DNA walk (an abstract surface that is the result of a one-to-one mapping of the genetic code and a self-affine surface).

Any place in materials science where the understanding of surface phenomena is critical could be a potential application for fractal science.

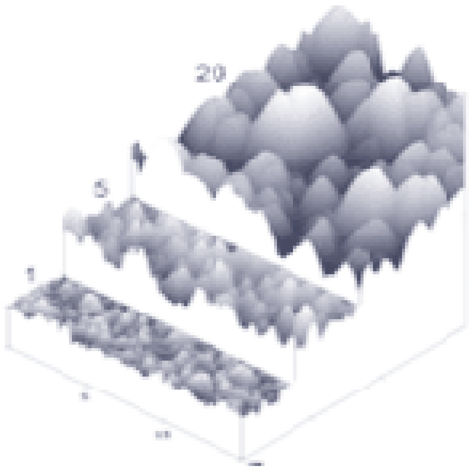

***Figure 5. The roughness of the silver surface increases with the number of cycles.***

In this article, several examples were presented but the possibilities do not end there. Could fractal science be utilized to understand and perhaps predict corrosion rates? The development of MicroElectro Mechanical systems (MEMS) is a growing frontier in materials science with promising potential. Fractal science can be an extremely useful tool in understanding the fabrication and characterization of MEMS devices.

The push toward smaller and faster electronic devices in everything from cell phones to biomechanical applications has been happening for a long time and there appears to be no end in sight for this demand. Application of fractal science can help materials scientists blaze the trail in continuing this trend.

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# Material EASE

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## APPLICATION OF FRACTALS TO MATERIALS SCIENCE

### Introduction

The term "Fractals" refers to the mathematical concept of how vastly different objects can be described using the same mathematical relationships. For example, the coastline of a continent viewed from space will have readily visible distinct attributes such as bays, peninsulas, and relatively straight sections. If we now observe a coastline from an airliner flying at 35,000 feet, we will notice far more detail than an astronaut on the International Space Station. But, in general, the exact same attributes will be seen: bays, peninsulas, and straight sections. Now imagine flying over a beach at 1000 feet. The generic features will still look exactly the same even though the size or scale of these attributes are far smaller than the two previous examples. If we then wanted to represent the coastline using a mathematical curve fitting technique such as spline functions, we could apply exactly the same method for all three scenarios. This demonstrates the concept of fractals.

There are fundamental physical phenomenon resulting from both the processing and application of materials that result in similar scaling behavior as described in the previous example. We will discuss four different materials-related phenomenon and further point out how they can be examined using fractals. Specifically we will discuss the use of fractals in examining thin film deposition processes, fracture mechanics, optical properties of materials, and electrochemical deposition processes. Our intent is to demonstrate the types of materials/processes that can benefit from fractal analysis and as a result, provoke further thought on other physical processes that could benefit from similar approaches.

### Fractal Concepts

The term "fractal" (for fractional dimension) was first used by Benoit Mandelbrot who proposed the concept as an approach to problems of scale in the real world. According to Mandelbrot, a fractal is a curve or a surface that is independent of scale. This phenomenon is referred to as *self-similarity*, which means that any portion of the curve or the surface, if blown up in scale, would appear identical to the whole curve or surface. Figures 1 and 2 display the concept in a simplistic fashion. The first figure demonstrates the transition from one scale to another while the second figure presents various iterations of a scaling process.

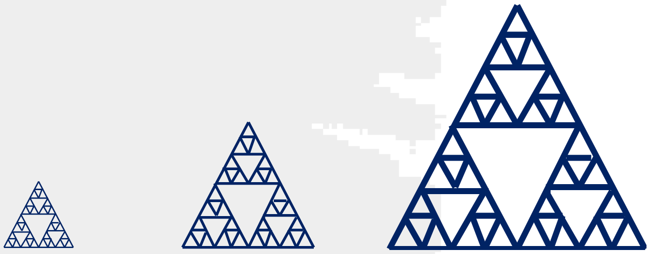

***Figure 1. A fractal looks the same over all ranges of scale***

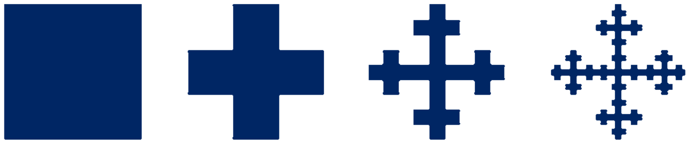

***Figure 2. Forming a cross by iteration of a simple procedure***

There are several examples we can discuss that will illustrate the potential use of fractals to analyze various phenomena. Consider the case of an absorbent paper exposed to a fluidic medium. Regardless of whether we are analyzing a small controlled study or a 20 km long oil spill, the scaling laws will dictate that the efficiency in which dispersed paper can clean up an oil spill can be predicted from a model derived using a small sheet of paper. Fractals can be employed in both two-dimensional and three-dimensional analyses. When a sheet of paper is ignited at one end, the interface formed between the burned and unburned parts spreads with a distinctive morphology. The fire front can be considered as a one-dimensional interface moving through a two-dimensional medium. When a superconductor is placed in an external magnetic field, the flux lines within the superconductor are straight if there are no impurities present. However, when impurities are present, the flux lines acquire a pattern similar to the fire front advancing through paper. In this case these lines can be considered as one-dimensional objects propagating through a three-dimensional medium. Research has established that these seemingly unrelated phenomena have common fractal patterns.

### Examples of Fractals Applied to Materials Science

In the area of materials science, fractals can be used to help analyze surfaces that were formed through some physical process. For instance, some surfaces and interfaces are formed as a result of deposition processes while others are produced by recession processes where surfaces shrink through erosion and etching. Some surfaces are formed by a combination of growth and recession. Fracture produces characteristic surfaces so this phenomenon is also a candidate for fractal analysis. It should be noted that surfaces can change their morphological characteristics by exposure to external influences or environments.

### Thin Film Deposition Processes

Barabasi and Stanley[1] make a case for fractal theory as a method to explore film growth in regimes where roughening is reduced, by claiming that one has to first understand the mechanism leading to roughness. Before proceeding, let's first examine two different methods for depositing thin films, molecular beam epitaxy (MBE) and sputtering. MBE is a technique used to deposit highly ordered and contaminate-free coatings on semiconductor substrates. This process is typically employed to develop high-performance electronic, electrooptic, or photonic materials. A film deposited using MBE is of extreme quality possessing an almost perfect crystal structure. Contrasted to this is sputter deposition which is also known as physical vapor deposition (PVD). Similar to MBE, PVD can deposit films onto a substrate but the quality and purpose of these films are vastly different. MBE deposits atoms in a controlled process that allows the film to grow to a crystalline structure. Conversely, PVD bombards a surface with a plasma that accelerates ions to such a velocity that they become part of the substrate. The major difference in this method is that plasmas have a tendency to etch or remove material from the surface while at the same time adding new material. This process results in a surface morphology vastly different from the defect free MBE deposited films. Fractal scientists and other researchers are trying to establish if erosion such as what results from the PVD process is the inverse of deposition or whether the two phenomena involve entirely different processes. They are also trying to explain the ripple effect observed on the growing surfaces.

Attempting to determine whether MBE and PVD are in fact different manifestations of the same process requires some thought and analysis. The investigators doing this work are employing discrete models that include scaling relations and continuum equations. These tools support the argument that interfaces produced by the growth process are self-affine: by rescaling a part of the surface under question, a transformed fragment becomes statistically indistinguishable from the whole surface from which it was obtained. Self-affinity is a scale transformation for fractal objects that must be rescaled with an anisotropic transformation. In other words, the rescaling under which self-affine surfaces are self-similar has different scaling factors in different spatial directions. The height of the surface obtained by deposition of particles is represented, at any time, by a single-valued function h(x). This function is self-affine if it obeys:

$$h(x) \sim b^{\alpha} h(bx) \qquad (1)$$

where $\alpha$ is called the self-affine roughness exponent, or Holder exponent and it quantifies the roughness of the self-affine function.[1, 4]

The equation above indicates that growth is different (anisotropic) vertically and horizontally. Vertically, the scaling is represented by the factor $b^{\alpha}$ ($h \rightarrow b^{\alpha} h$), and horizontally the transformation factor is b ($x \rightarrow bx$). The rescaling factors, b and $b^{\alpha}$ are as such so that the transformed object (in the new generation) overlaps the object in the previous generation. Accordingly, the roughness exponent, $\alpha$, suffices to characterize the morphology of rough surfaces (although more complicated, multi-affine interfaces do not always follow the same laws of growth).

Many growth and recession cycles can be described with the help of fractal solutions. As discussed above, some film deposition processes include the cyclical building up and breaking down of materials. Fractal science aims to explain the formation, growth, and dynamics of the surfaces obtained through these processes.

## Fracture Mechanics

In recent years, fractal geometry has been used to characterize the irregular forms of fractured materials using a discipline known as quantitative fractography. The fracture surface features are determined by the properties of the materials and also by the initial flaw/defect sizes and stress states. Fracture is the breaking of the atomic bond, and fractography establishes the relationship between the bond-breaking process and the fracture surface topography. Fractal geometry (or the geometry of the degree of roughness) quantifies this relationship. Figure 3 shows a typical fracture surface of Ti-6Al-4V.

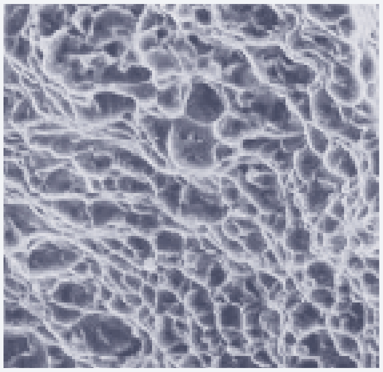

***Figure 3. Micrograph showing dimpled fracture surface of a Ti-6Al-4V tensile specimen. Magnification is 770X.***

Fractal objects are characterized by their fractal dimension, D, which is the dimension in which the proper measurement of a fractal object is made.[2] For example, a 'perfect' square is two-dimensional. In terms of fractal geometry, a square with "bumps" pointing away from the surface has the 2.D* dimension where D* is the fractional part of the fractal dimension representing the degree of tortuosity (roughness) of the square. A square with the dimension of 2.1 (D* = 0.1) is relatively smooth, but a square whose dimension is 2.9 would almost be a volume-filling object.

The next step is to relate the above discussion to an actual fracture surface. One method for determining the fractal dimension for these cases is known as the slit island technique. Accordingly, the length of part, or all of the contour of an island obtained from polishing an embedded fractured surface is measured. The first measurement is of the highest fracture surface. The consequent measurements are of the lower fracture surfaces. The selection of the area to be measured from the entire fractured surface is random. Experimental results have indicated that there is a definite relationship between the fractal dimensional increment, D*, and the fracture toughness of a material. This relationship is represented by the critical stress intensity factor, $K_{IC}$:

$$K_{IC} = E a_0^{1/2} (D)^{1/2} = Y(\theta) \sigma_f c_f^{1/2} \qquad (2)$$

where E is the elastic or Young's modulus, $a_0$ is a parameter measured in length units, $Y(\theta)$ is a geometric constant that depends on the geometry of the crack and loading conditions, $\sigma_f$ is the applied stress at fracture and c is the size of the crack. The relationship between D* and $K_{IC}$ is the result of experimentation. The relationship between $K_{IC}$ and c is based on the theory of fracture mechanics and experimental corroboration.

Chen et al[3] have used fractal analysis to study the fracture behavior of silicon nitride ($Si_3N_4$), which is frequently used as an advanced engine material due to its high intrinsic mechanical properties at elevated temperature. They found that fractal analysis is a useful technique in correlating the fractal dimension, D*, to the material properties and fracture-surface topography. If a family of materials includes either single crystals and large-grained materials, or glass ceramics and fined-grained polycrystalline materials, there is a direct relationship (within the same family) between the fractal dimension, D*, and the fracture toughness. Chen et al have used the slit island contour technique to measure the fractal dimensions from three types of fracture surfaces. It was experimentally established that the fracture surface has a characteristic fractal dimension regardless of stress state and location on the fracture surface. Their research, which was consistent with previous results, validated the use of fractal analysis as a means to characterize material properties. The fractal approach may also explain how atomic fracture and wear processes occur.

The macroscopically measured fracture energy is much larger than that calculated for atomic bond breaking. The scaling rules for this energy have not yet been elucidated. Williford[4] has suggested fractal geometry as an approach to energy scaling, in order to establish a relationship between the fracture energy and the breaking of the atomic bond. Accordingly, a connection between porosity and fractal geometry was first introduced. Within fractal geometry, the number of observed pores increases with a reduction of the scale of observation (greater porosity with smaller dimension). In reality, the nature of the porosity depends on the scale. For example, porosity forms during dimpled rupture. This porosity creates a rough fracture surface that in reality is much larger than the area computed for fracture through breaking atomic bonds (when it is assumed that the fracture surface is smooth). Williford analyzed ductile fracture data for a low-toughness aluminum alloy (7075-T6) by using fractal analysis to energy scaling:

$$E' = k'D^n \qquad (3)$$

where E' is the fracture energy, D is the dimension variable relating to the scale of observation, n is the fractal dimension specific to the material, and k' is the material-dependent proportionality constant. Equation (3) accounts for the discrepancy between the calculated fracture and experimental fracture energies, due to porosity. The value for n varies as a function of the material's ductility, from $n = 1.1\text{-}1.3$ for ductile-fracture surface profiles of a titanium alloy to $n = 2.3\text{-}2.5$ for an ultra-high strength steel, with lower values corresponding to smoother surface and lower toughness. The microscopic features used in the present experimentation were the grain boundary fracture facets (assumed to be half the grain size, in the range 3-100 µm). The next scale down, affecting the discrepancy between calculated fracture energy and experimental fracture energy, involves nanometer scale dislocations. Williford did not include dislocation in his fractal analysis.

In the fractal approach, n-dimensional materials lead to n-dimensional structures being created at various scales as the load is applied. Smaller n-values correspond to smaller fracture energies and more porous structures. The fractal approach led to the conclusion that alumina ceramics, and brittle materials in general, are more porous at the atomic level than the aluminum metal and other ductile materials.

## Optical Properties of Materials

In some cases, fractals can be used to help characterize the optical and dielectric properties of porous fractal structures. Certain optical coating formation processes entail evaporation of ultrafine metallic particles in an inert gas. The particles thus formed coalesce into large clusters that can be described by a fractal dimension, which is scaled compared to the calculated dimension.

Gas evaporation is a technique frequently used to produce small metal particles. The evaporation occurs in a few Torr of an inert gas (such as helium, argon, or nitrogen; occasionally, oxygen is added). The metal atoms collide with other atoms thus losing their energy and nucleating into clusters. Coalescence occurs at high temperatures (200-400°C). At lower temperatures, the clusters form very porous aggregates that can be transported through gas convection in the evaporation chamber and can be collected on a substrate. In order to elucidate whether a fractal structure exists when deposition of metal aggregates occurs, G. A. Niklasson examined electron micrographs[5] of deposited amorphous layers of aluminum, chromium, and nickel particles. A small amount of oxygen was present, in order to obtain an oxide coating on the metal particles. A certain area of the micrograph was chosen to calculate the center-to-center distances between all particles in the selected area. By determining the pair correlation function, it was shown that gas-evaporated coatings of various metal particles can be described by a fractal dimension in the range 1.75-1.90. Finally, a percolation theory was derived from the fractal analysis, by relating the solid phase and the porous space to the percolating cluster.

Niklasson has used fractal dimension theory to predict optical properties of gas-evaporated coatings. Optical properties of gas-evaporated coatings such as oxide-coated particles, and electric conductivity of pure metal coatings were described by a fractal dimension in the range 1.75-1.90 for coatings consisting of various metal particles.

## Electrochemical Deposition Processes

The final example explores the surfaces that are obtained by electrochemical deposition. Depending upon the application, this process can be cyclical in nature. Such a case is the internal charging/discharging cycles experienced by rechargeable batteries. In batteries the metal anode is consumed through the liberation of metal ions from its surface. These ions then migrate through the electrolyte where they are deposited upon the cathode. In rechargeable batteries, the electromotive potential can be reversed. This liberates the accumulated material from the cathode and allows it to redeposit back upon the anode. Failure of batteries occurs when sufficient metal is accumulated on an electrode to induce mechanism failure. The understanding of this cyclical behavior through fractal analysis may lead to the design of accelerated testing and performance improvement of such systems.

Two researchers from the University of Rochester, Yonathan Shapir and Jacob Jorne, developed the cyclical model based on their observations of the growth of organic and inorganic systems.[6] They noticed a correlation between these systems and fractal concepts. Specifically, they noted that growth in bacterial colonies, erosion and sedimentation in rivers, and even tumor growth could be modeled using fractal concepts. Shapir and Jacobs concluded it is possible to apply the scaling approach to cyclical growth processes, provided the number of cycles, n, substitutes the time variable, t, in the scaling relations. Their research group generalized the scaling behavior of cyclical processes by relating them to the scaling of the primary processes or the simplest generic growth processes.

The next step in their investigations was to apply their methodologies to examine the cyclical growth of metal through multiple cycles of electrodeposition/dissolution of silver. In this case, analysis of the electro-deposition process is used to establish the scaling behavior of surface growth. To accomplish this, multiple cycles were conducted using vapor-deposited silver substrates. The roughness of the grown surface behaved as a function of n, the number of cycles, varying, in this case, from 1 to 20. The straight line in Figure 4 indicates