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High Performance Fibers for lightweight ARMOR

Material EASE

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Editorial: Protecting Those Who Protect Us

Materials-related issues are rarely mentioned in the mainstream news, but with the recent controversy surrounding bullet-proof vests there has been significant interest from the media. Bullet-proof vests are quite literally a vital component of the uniform for many of the men and women serving our country, either in law enforcement or in the military, and have been directly attributed with saving thousands of lives.

The issue that has caught the attention of the media is that certain types of vests might fail when they are needed to protect, and law enforcement officers may unknowingly be at risk. The vests in question are made of a Zylon®-based fabric, which has been shown to degrade under high temperature and high humidity conditions, and are currently being used by many law enforcement agencies. The manufacturer of the fiber and the maker of the bullet-proof vests have been involved in a small media war over who's at fault for the potentially unreliable vests.

In response to concerns over bullet-proof vests made from Zylon, the National Institute of Justice (NIJ), which is the research, development and evaluation agency of the Department of Justice, has led an effort to evaluate the reliability of this fiber and the vests made from it. The NIJ has released an interim status report updating the progress of the evaluation and a supplemental report detailing the possible causes of body armor failure in an incident where a Pennsylvania police officer was shot and seriously injured. The supplemental report offers several theories but did not reach any specific conclusions on why the bullet completely penetrated the officer's vest. However, this report and the interim status report also suggest that Zylon is vulnerable to degradation and must be protected from its susceptibilities to provide long-term durability. Meanwhile, the US Military has been pursuing development of the Zylon fiber and its application to body armor, because it can potentially reduce the weight of current body armor by 25%. The study by the NIJ, therefore, is very important in light of the recent controversy and interest from the military.

The military has been supplying its troops with upgraded body armor vests to replace the old Personnel Armor System for Ground Troops (PASGT) vests, but there has been some concern over the reliability of a group of these new vests as well. The new Interceptor® vests, which are made from an improved Kevlar® fiber, feature superior ballistic performance and are substantially lighter compared to the old PASGT body armor. Though there have been claims that the new vests failed to meet the standard requirements, they still are the best available lightweight armor for ground troops and offer better protection than the old vests. The new bullet-proof vests are being worn by soldiers in Iraq and Afghanistan, and together with their composite helmets have been credited with saving many soldiers' lives.

While the media certainly benefits from reporting on these sorts of controversies, it also creates some awareness for materials-related issues and promotes the need for further development and advancement of materials to a broader audience. Reliability of body armor is an extremely important issue, as our military and law enforcement organizations have become dependent on these vests for protecting their most important assets. Further critical evaluation of existing lightweight armor technologies and the development of new materials for armor applications can only lead to better, lighter armor, which will help improve our soldiers' ability to maneuver and survive, and ultimately will keep our military the best equipped in the world.

This issue of the *AMPTIAC Quarterly* features an article on high performance fibers for flexible and rigid lightweight armor applications. Because of the vital importance of body armor and bullet-proof vests and the recent media attention surrounding them, we wanted to publish an article that focuses on the fundamental materials that enable these armors. The article highlights current fiber technologies as well as fibers for future systems, and provides a closer look at what is protecting the officers and soldiers who are on the battlefield protecting our way of life.

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High Performance Fibers for Personnel and Vehicle Armor Systems

Putting a Stop to Current and Future Threats

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INTRODUCTION

Military systems, especially those supporting ground forces, are being transformed to become faster, more agile, and more mobile, as the US faces opponents who use guerilla-warfare tactics and where systems must be quickly moved to operations located throughout the world. As a result, an increased demand for improved lightweight body armor and lightweight vehicle armor has led to the development of new armor materials. High performance fiber materials have been exploited for both applications. For example, they can be used as soft, flexible fiber mats for body armor or as reinforcements in rigid polymer matrix composites (PMCs) for lightweight vehicle armor.

Throughout history, lightweight and flexible materials have been sought to reduce the weight of body armor systems to enhance mobility, while providing protection against specified threats. Early materials included leather and even silk, which were used in conjunction with metal plates to provide the needed protection. The elimination of metals altogether in body armor systems however, did not take place until the Korean War.[1] At that time, a nylon fabric vest and an E-glass fiber/ethyl cellulose composite vest, which had been developed during the course of World War II, were put into service. These vests provided protection against bomb and grenade fragments, which accounted for the high majority of injuries and deaths among soldiers. Although nylon and E-glass fibers continue to find some use today due to their low cost, high performance fibers are now the standard for most fiber-reinforced armor applications. High performance fibers are typically used in the form of woven fabrics for vests and either woven or non-woven reinforcements within PMCs for helmets. Figure 1 shows the Interceptor®* vest and composite helmet currently worn by US military troops. Ceramic insert plates may be used to increase the performance of the Interceptor vests to defeat up to 0.30 caliber threats.[3]

Figure 1. Interceptor Vest and Composite Helmet[2].

Rotary-wing aircraft were used extensively during the Vietnam conflict, and the need for weight reduction fueled the development of lightweight armor for vehicles and aircraft. Since metals were prohibitively heavy for use as armor on aircraft, PMC armor materials were considered. Ceramic faceplates were used with PMCs in aircraft due to the added threat of large-caliber, armor-piercing ammunition. These armor systems were used to protect cockpits in numerous aircraft, as well as cargo areas in transport planes and helicopters. PMC armor technology has since been transferred to ground vehicles, such as the High Mobility Multipurpose Wheeled Vehicle (HMMWV), which is shown in Figure 2.

Figure 2. Armored HMMWV Deployed in Iraq[2].

ENERGY ABSORPTION MECHANISMS

Woven fiber mats and fiber-reinforced PMCs mitigate projectile energy in different ways. The amount of energy absorbed by fibers is largely dependent upon their strain to failure, as depicted in Figure 3a.[4] A fiber mat with high strength and high elongation to failure is thus expected to absorb energy via plastic deformation and drawing (stretching) of the fibers. Additionally, the strain in a fiber is equated to the impact velocity divided by the sonic velocity of the fiber (Equation 1).[5]

$$\varepsilon = \frac{V}{c} \qquad \text{Equation 1}$$

where,

ε – strain
V – impact velocity
c – sonic velocity of the fiber

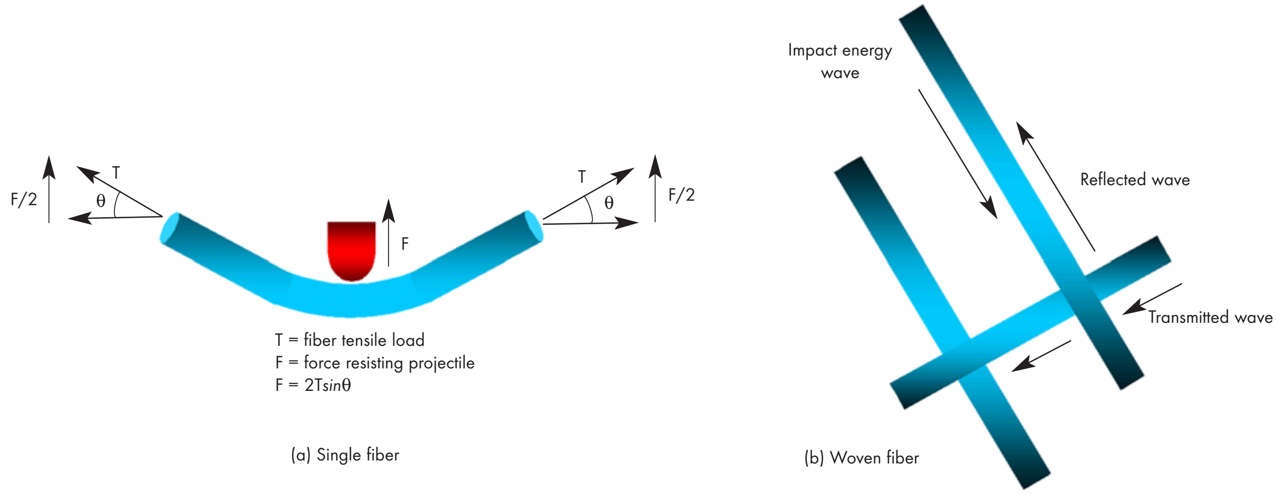

Figure 3. **Fiber Energy Absorption Mechanisms[4].**

The sonic velocity, in turn, is related to the fiber's elastic modulus, as shown in Equation 2. A higher elastic modulus results in the impact energy wave traveling farther down the length of the fiber due to a greater sonic velocity, and thus a greater volume of fiber absorbs the projectile energy.

$$c = \sqrt{\frac{E}{\rho}} \qquad \text{Equation 2}$$

where,

E – elastic modulus

ρ – density of the fiber

A woven fiber mat is effective at absorbing the impact load by dispersing the energy across a network of fibers, as depicted in Figure 3b.

Once fibers are impregnated with a resin matrix their ability to deform may be hindered, and as a consequence they may absorb less energy. In fiber-reinforced PMCs, the fracture process is considered to happen in two phases. High velocity impact will cause localized compression of the composite, and subsequently shearing of fibers and spalling of resin, as depicted in Figure 4a. Once the projectile has slowed, the composite deforms causing fiber stretching, pullout, and delamination of composite layers (plies), as shown in Figure 4b. Stitching composite plies together or three dimensional fiber weaving may be used to reduce delamination and confine damage to a small area.[6] However, this may also result in an increase in fiber damage leading to a decrease in compressive strength after ballistic impact, and thus lower load carrying ability.

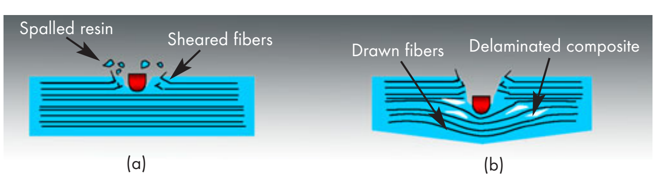

Figure 4. **Fiber-Reinforced PMC Energy Absorption Mechanisms[4].**

HIGH PERFORMANCE FIBERS

High performance fiber materials used in body and/or vehicle armors include S-glass, aramid, high molecular weight polyethylene and polybenzobisoxazole. A new fiber material, polypyridobisimidazole, shows promising results but has not yet been fully tested and validated for armor applications. Continuous fibers are characterized by "denier", which is a measure of the weight, in grams, per 9000 meters (29,530 ft.) of fiber. Thus, when comparing fibers that have the same density, a smaller denier equates to a thinner fiber.

Fibers can be woven together into a number of configurations, some of which are illustrated in Figure 5, to provide varying degrees of performance and flexibility. Fiber structures for armor applications have traditionally been in unidirectional, plain, or basket weave configurations. Unidirectional fiber layers may be rotated 90° with respect to adjacent layers to create a cross-ply fabric. Additional woven structures have been studied for armor applications, such as 3D structures to enhance the multi-hit capability of composites.

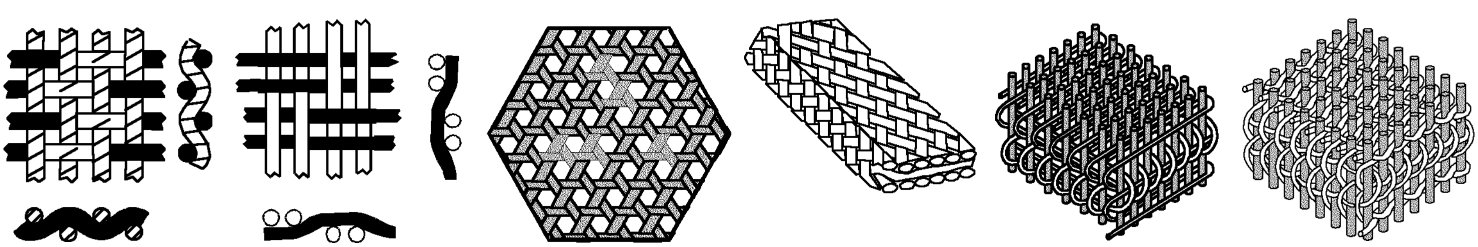

Figure 5. **Woven Fiber Structures[7].**

S-Glass

S-glass, composed of silica (SiO_2), alumina (Al_2O_3), and magnesia (MgO), is characterized by a strength that is roughly 35 to 40% higher than that of E-glass.[8] S-2 Glass is a coated fiber, which has become the preferred fiber in many applications including armors. Its cost is significantly higher than E-glass, but its strength advantage, and consequently performance per unit weight advantage, usually warrants its selection for penetration resistance applications over E-glass. Relative to aramid fibers, S-2 Glass fibers generally have comparable ballistic performance, as measured by the V_{50} Probable Ballistic Limit Test (see sidebar), at a lower cost but higher weight. S-2 Glass has good fatigue and moisture resistance and a low creep rate, but can be susceptible to creep rupture. It can be used at elevated temperatures up to approximately 1380°F.[9]

Aramid

Aramid fibers were developed during the 1960s and first introduced commercially by DuPont in the 1970s under the trade name Kevlar®†. There are foreign companies that also produce commercially available aramid fibers, having the trade names Twaron®‡ and Technora®§. The primary structure of aramid fibers is shown in Figure 6. Modifiers to the primary chain have been added over the years for property enhancements, resulting in the various aramid fibers available today. Kevlar 29, Kevlar 49, Kevlar 129, and Kelvar KM2 are the DuPont aramid fibers that have been used most in armor applications. The Personnel Armor System for Ground Troops (PASGT) bullet-proof vests previously worn by military personnel were made from Kelvar 29. The Interceptor vests, which are currently being worn by soldiers in Iraq and Afghanistan, are made from Kelvar KM2 fiber.

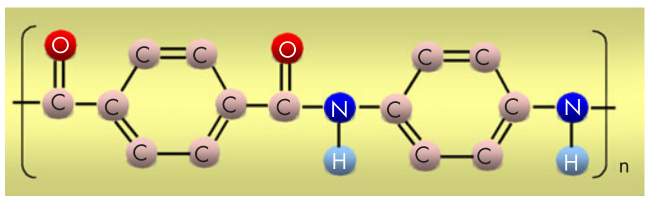

Figure 6. **Aramid Chemical Structure.**

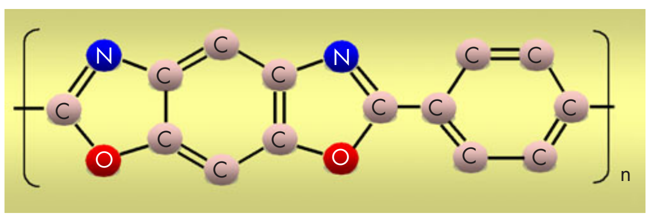

Figure 7. **PBO Chemical Structure.**

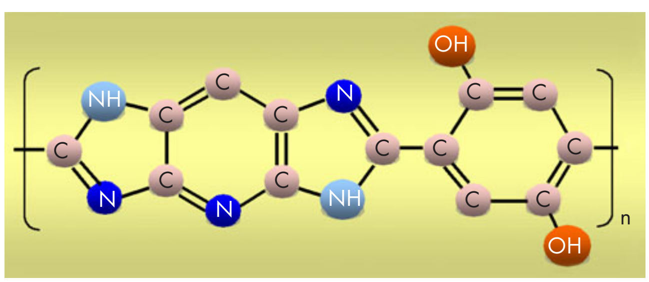

Figure 8. **M5 Chemical Structure.**

Aramid fibers exhibit a decrease in tensile strength when exposed to heat or moisture. At temperatures up to 355°F, a strength loss of ≤ 20% occurs.[10] Strength losses of ≤ 5% at high humidity and room temperature and ≤ 10% under hot water conditions have been observed; however, the strength degradation appears to be reversible. The operating temperature range is -420 to 320°F, with an onset of thermal degradation occurring at about 840°F.[11,12] Aramid fibers are vulnerable to damage from ultraviolet light, with a 49% loss in strength measured after exposure to a Florida environment for 5 weeks.[11] Strong acid and alkaline environments will also attack aramid fibers. The fibers have good fatigue resistance, low creep rates, and are less susceptible to creep rupture than S-2 Glass fibers. Aramid fibers do not naturally bond well to resins, so they are usually chemically coated (sized) prior to their incorporation in composites.

High Molecular Weight Polyethylene

High molecular weight polyethylene (HMWPE) has a simple structure consisting of a repeating ethylene unit $[CH_2\text{-}CH_2]_n$. Two commercially produced HMWPE fibers are Spectra®‖ and Dyneema®#. HMWPE fibers have the lowest density of all fibers currently used for armor applications, with a V_{50} that is higher than both S-2 Glass and aramid fibers per equivalent weight. Their limitations include a lower operating temperature range, creep susceptibility and poor compressive strength. HMWPE fibers have a maximum processing temperature of 250°F, limiting the choice of matrix materials to low temperature curing thermosets or selected thermoplastic resins.[13]

Polybenzobisoxazole

Polybenzobisoxazole (PBO) fibers are a result of the US Air Force's research during the 1980s that looked into developing a stronger fiber than aramids.[12] The repeat unit of PBO, a rigid-rod structure, is shown in Figure 7. PBO fibers have very high tensile strength properties, achieving better penetration resistance than the HMWPE fibers, but suffer from low compressive strength like HMWPE. The decomposition temperature of PBO fibers is about 1025°F, compared to 840°F for aramid fibers.[12]

A commercial PBO fiber is currently on the market under the trade name Zylon®**. Zylon has been shown to undergo tensile strength degradation in elevated temperatures and moisture, and when exposed to ultraviolet and visible light.[14] A 40% loss in strength can occur at a temperature of 176°F and 80% relative humidity. The strength loss after 6 months exposure to daylight is roughly 65%. One theory for the strength loss incurred involves the method in which PBO fibers are being fabricated.[15] The fibers are spun from a solution containing polyphosphoric acid. Although the fibers are washed, dried, and heat treated, some trace amounts of acid may remain on the fibers. The residual acid combined with humid environments, sunlight or oxygen can cause significant degradion of the fiber strength. Further investigations into the strength loss of PBO fibers are being conducted by the National Institute of Standards and Technology, as directed by the National Institute of Justice.[16]

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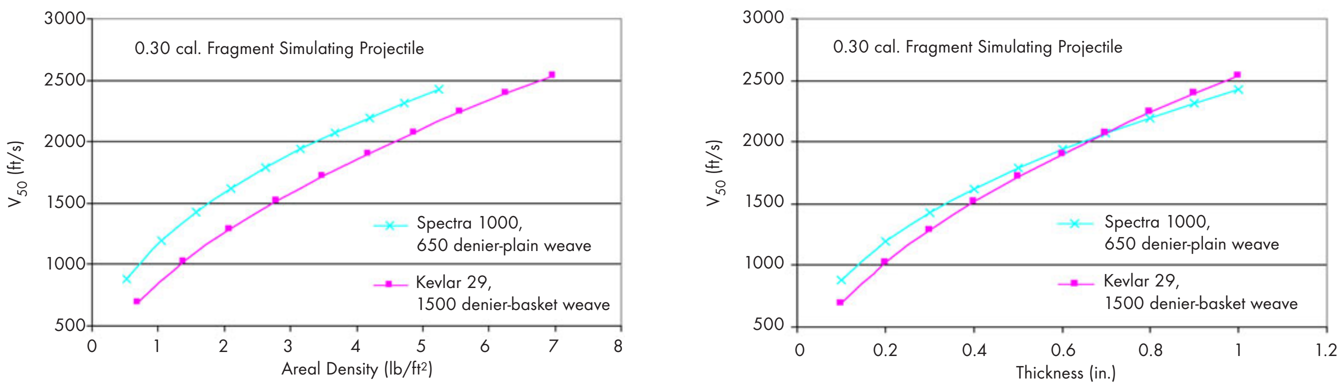
Table 1. Typical Fiber Properties.[a]

Fiber	Density (g/cm³)	Elastic Modulus (GPa)	Tensile Strength (MPa)	Strain to Failure (%)
Glass				
S-glass[10]	2.48	90	4400	5.7
Aramid				
Technora[10]	1.39	70	3000	4.4
Twaron[10]	1.45	121	3100	2.0
Kevlar 29[17]	1.44	70	2965	4.2
Kevlar 129[17]	1.44	96	3390	3.5
Kevlar 49[17]	1.44	113	2965	2.6
Kelvar KM2[18]	1.44	70	3300	4.0
HMWPE				
Spectra 900[17]	0.97	73	2400	2.8
Spectra 1000[17]	0.97	103	2830	2.8
Spectra 2000[19]	0.97	124	3340	3.0
Dyneema[20]	0.97	87	2600	3.5
PBO				
Zylon AS[20]	1.54	180	5800	3.5
Zylon HM[20]	1.56	270	5800	2.5
PIPD				
M5 (2001 sample)[21]	1.70	271	3960	1.4
M5 (goal)[21]	-	450	9500	2.5

[a]The data presented are typical values and thus will vary dependent upon fiber denier.



(a) V_{50} versus Areal Density

(b) V_{50} versus Thickness

Figure 9. V_{50} Comparison of Fabrics[18].

Polypyridobisimidazole

A new high performance fiber – polypyridobisimidazole (PIPD), denoted M5®†† – has been developed at Akzo Nobel and shows promising results. Similar to PBO, it is a rigid-rod structure as shown in Figure 8. Due to strong intermolecular hydrogen bonding, however, its compressive strength is significantly improved over that of PBO fibers. Its decomposition temperature is about 985°F, which is close to that of PBO fibers.[12] The fabrication technologies for M5 fibers are still in developmental phases, as some properties of the fibers fall short of their theoretical potential.

Comparison of High Performance Fibers

As discussed in the section on energy absorption mechanisms, the major properties used to assess probable ballistic performance are the tensile strength, elastic modulus, and strain to failure. Table 1 provides a general comparison of these properties, along with density, for the various high performance fiber materials. Note the difference in tensile strength between Kevlar 29 used for the old PASGT vests and Kelvar KM2 used for the new Interceptor vests. The HMWPE and aramid fibers are used as fabrics for flexible military body armors, whereas S-2 Glass is used in rigid composite armor applications. PBO fibers have not been used for military applications, and M5 is still in developmental stages. Both HMWPE and aramid fibers are also used in fiber-reinforced PMCs for rigid armor applications. Figure 9a indicates that Spectra 1000 fabrics provide a higher V_{50} PBL at a lighter weight than Kevlar 29. Figure 9b shows that Spectra 1000 provides a higher level of protection at the same thickness as Kevlar 29 up until approximately 0.7 inches, where the level of protection provided by the two fibers is approximately equal. At thicknesses greater than 0.7 inches Kevlar 29 outperforms Spectra 1000 in terms of ballistic performance.

RESINS

Resins for fiber-reinforced polymer matrix composite armors can be either thermoplastics or thermosets. In general, thermoplastics offer greater impact resistance and processibility, but lack the thermal and chemical resistance of thermosets.

Table 2. **Thermoset Resin Comparison[23].**

Resin	Advantages	Disadvantages
Polyester	• Low cost • Easy to process • Good chemical resistance • Good moisture resistance • Fast cure time • Room temperature cure	• Flammable • Toxic smoke upon combustion • Average mechanical properties
Vinyl Ester	• Low cost • Easy to process • Low viscosity • Room temperature cure • Moisture resistant • Good mechanical properties	• Flammable • Smoke released upon combustion
Epoxy	• Excellent mechanical properties (superior to vinyl esters) • Good chemical resistance • Good heat resistance • Good adhesive properties with a large variety of substrates • Moisture resistant • Variety of compositions available • Good fracture toughness	• Expensive • Requires high processing temperatures to achieve good properties

Thermoplastics have therefore found limited use in military armor systems in the form of body armor components. Spectra Shield®‡‡, however, is a commercial product that uses cross-ply fabrics sandwiched between layers of thermoplastic resins.[22] Vehicle armors primarily consist of one of the high performance fiber materials discussed earlier in this article along with an epoxy, polyester, vinyl ester, or phenolic thermoset resin.

Epoxy, polyester, and vinyl ester are the primary resin materials for armor-grade composites, while phenolic resins are used in applications that require fire, smoke, and toxicity (FST) control. In some armor composite systems, one of the three primary resins is used for ballistic protection while a phenolic composite backplate provides FST resistance. Epoxies provide the best structural characteristics of all the resins, and are available in a wide range of formulations. They have excellent mechanical properties and good adhesion to numerous materials, but require high processing temperatures to attain a high level of

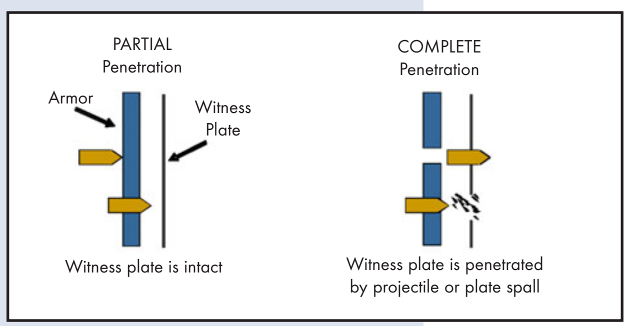
V_{50} Probable Ballistic Limit (PBL)

The V_{50} PBL as defined by MIL-STD-662F, V_{50} *Ballistic Test for Armor* is the most common method for assessing lightweight armor materials for ballistic performance.[i] The final state of a witness plate placed behind the armor panel determines the experimental outcome of the ballistic test, as shown in the figure. Two situations may occur as a result of the ballistic test:

- Complete penetration (evidenced by visibility of light through the witness plate) takes place when the witness plate is completely perforated by projectile or plate spall.
- Partial penetration occurs if no perforation is observed (even if test panel may be perforated) through the "witness plate."

The area corresponding to a velocity range causing a mixture of partial and complete penetration is the Zone of Mixed Results (ZMR).

The V_{50} may be defined as the average of an equal number of highest partial penetration velocities and the lowest complete penetration velocities which occur within a specified velocity spread. A 0.020 inch (0.51 mm) thick 2024-T3 sheet of aluminum is placed 6±1/2 inches (152±12.7 mm) behind and parallel to the target to witness complete penetrations. Normally at least two partial and two complete penetration velocities are used to compute the V_{50} value. Four, six, and ten-round ballistic limits are frequently used. The maximum allowable velocity span is dependent on the armor material and test conditions. Maximum velocity spans of 60, 90, 100, and 125 feet per second (ft/s) (18, 27, 30, and 38 m/s) are frequently used. Disadvantages with this test are the wide latitude of V_{50} values and the absence of specification for specimen size.



Schematic Presentations of Partial and Complete Penetrations[ii].

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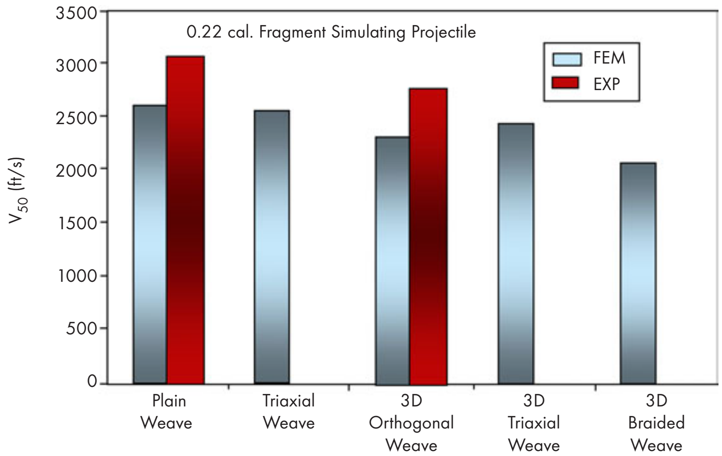


Figure 10. **Ballistic Performance Comparison of S-2 Glass-Based Composite of Weave Structures[24].**

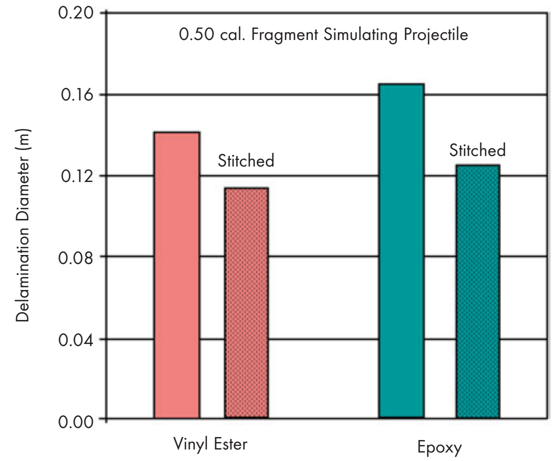


Figure 11. **Effect of Stitching on Ballistic Performance of S-2 Glass Fiber-Reinforced Composites[6].**

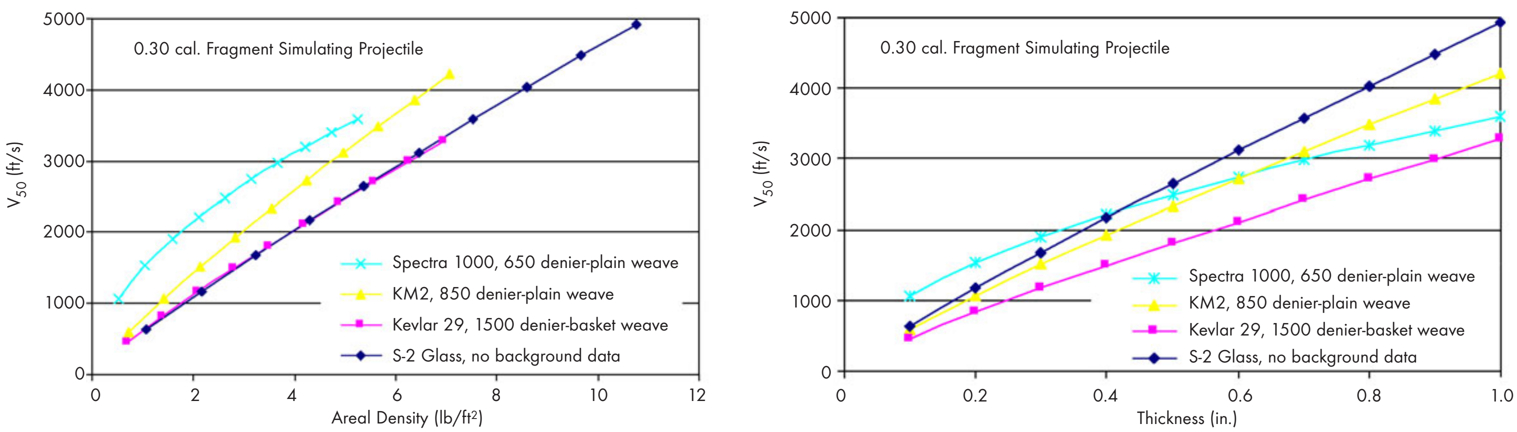
quality. Polyesters and vinyl esters are low cost, easily processed composites with above average mechanical properties, but have low compressive strengths. As a result of this deficiency, they are normally relegated to non-structural applications. Phenolics, like the polyesters, have low compressive strength properties, but provide higher temperature capabilities and low smoke generation upon combustion.

Ease of processing and the potential release of toxic chemicals are concerns with composites. Processing methods, such as resin transfer molding, require resin materials to have low viscosities in order for the finished product to have a low porosity, and thus good performance. In the case of higher viscosity materials, like epoxies, high processing temperatures and/or additives are used to produce the required low viscosity for processing. High processing temperatures, however, correspond to higher costs and may also limit fiber selection, while additives can produce toxic byproducts. The trade-offs of performance, ease of processing, and costs are summarized in Table 2 for the three structural resins. In most applications, vinyl ester resins have replaced polyester resins as they are similar in many properties, but with the added benefit of having superior mechanical properties.

FIBER-REINFORCED PMC ARMOR

The performance of fiber-reinforced PMC armors not only depends upon the fiber and resin material properties, but also the fiber structure, fiber volume, fiber compatibility with the resin, and additives. Most commercial fiber composites for armors consist of unidirectional, plain, or basket weave fiber structures. Weaving fibers does not generally improve the penetration resistance in composites, because the fibers are confined by the resin and the energy can not be effectively transferred to adjacent fibers as is the case of fiber mats. Three dimensional weaves limit delamination and thus improve multi-hit performance of composites. Figure 10 compares the ballistic performance of various woven S-2 Glass fiber composites subjected to a 0.22 caliber fragment simulating projectile (FSP) using finite element modeling (FEM) and experiments (EXP). Through-the-thickness stitching of composite plies is another means of limiting delamination problems, as shown in Figure 11 for S-2 Glass composites tested with a 0.50 caliber fragment simulating projectile at 1550 feet per second.

The ballistic performance of fiber-reinforced PMC armors is largely attributed to the fibers. Maximizing fiber volume in a



(a) V_{50} versus Areal Density

(b) V_{50} versus Thickness

Figure 12. **General Comparison of Fiber-Reinforced PMC Armors[18].**

composite using the top performance weave structure will therefore optimize the ballistic performance of composites. Most PMC armors have fiber volumes in the vicinity of 60 percent. Coupling agents which help bond fibers to resins can influence penetration resistance. For armor applications, fiber pull-out is beneficial under impact loading, since the failure mechanism absorbs energy. Additives, in some cases, are introduced primarily to increase fracture toughness of the composite. Thermoplastics and rubber materials may be used for this purpose. Figure 12 is a comparison of typical V_{50} data of some fiber-reinforced PMC armor materials, and it shows that the performance of the composite materials reflects the performance of the fibers previously displayed in Figure 9.

SUMMARY

High performance fibers provide the means to produce lightweight fabrics for body armor as well as lightweight PMCs for vehicle armor. The availability of different high performance fibers and resins along with the ability to tailor fibers allows versatility in designing fiber-reinforced PMC armors. The development of improved lightweight armor materials will continue to play an important role in the transformation of US military forces to meet present and future threats.

NOTES & REFERENCES

Citation of companies and product trade names does not constitute an endorsement or approval of the use thereof.

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† Kevlar is a registered trademark of the E.I. du Pont de Nemours and Company
‡ Twaron is a registered trademark of the Teijin Company
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†† M5 is a registered trademark of Magellan Systems International
‡‡ Spectra Shield is a registered trademark of Honeywell International, Inc.

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Textile Preforms for Composite Material Technology

This publication is the first and only one of its kind – A panoramic and thorough examination of fiber/textile perform technology and its critical role in the development and manufacture of high-performance composite materials. This product was prepared in collaboration with Drexel University and authored by Dr. Frank Ko, the Director of Drexel's Fibrous Materials Research Center. Dr. Ko is one the world's foremost authorities on fibrous preforms and textile technology.

Order Code: AMPT-19 **Price: $100 US, $150 Non-US**

Computational Materials Science (CMS) A Critical Review and Technology Assessment

AMPTIAC surveyed DOD, goverment, and academic efforts studying materials science by computational methods and from this research compiled this report. It provides an in-depth examination of CMS and describes many of the programs, techniques, and methodologies being used and developed. The report was sponsored by Dr. Lewis Sloter, Staff Specialist, Materials and Structures, in the Office of the Deputy Undersecretary of Defense for Science and Technology.

BONUS MATERIAL: Dr. Sloter also hosted a workshop (organized by AMPTIAC) in April 2001 for the nation's leaders in CMS to discuss their current programs and predict the future of CMS. The workshop proceedings comprise all original submitted materials for the workshop – presentations, papers, minutes, and roundtable discussion highlights and are included with purchase of the above report.

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Blast and Penetration Resistant Materials

This State-of-the-Art Report compiles the recent and legacy DOD unclassified data on blast and penetration resistant materials (BPRM) and how they are used in structures and armor. Special attention was paid to novel combinations of materials and new, unique uses for traditional materials. This report was sponsored by Dr. Lewis Sloter, Staff Specialist, Materials and Structures, in the Office of the Deputy Undersecretary of Defense for Science & Technology.

BONUS MATERIAL: Dr. Sloter also hosted a workshop in April, 2001 (organized by AMPTIAC) for selected experts in the field of BPRM and its application. The workshop focused on novel approaches to structural protection from both blast effects and penetration phenomena. Some areas covered are: building protection from bomb blast and fragments, vehicle protection, storage of munitions and containment of accidental detonations, and executive protection. The proceedings of this workshop are included with purchase of the above.

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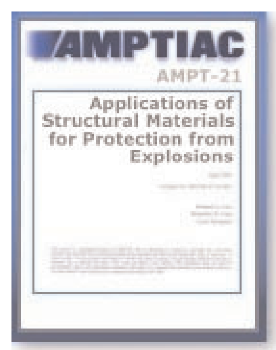
Applications of Structural Materials for Protection from Explosions

This State-of-the-Art Report provides an examination of existing technologies for protecting structures from explosions. The report does not discuss materials and properties on an absolute scale; rather, it addresses the functionality of structural materials in the protection against blast. Each chapter incorporates information according to its relevance to blast mitigation. For example, the section on military structures describes concrete in arches, and concrete in roof beams for hardened shelters. The discussion on concrete is not limited to materials only; rather, it addresses the issue of structural components that incorporate concrete, and describes the materials that work in concert with the concrete to produce a blast-resistant structure. The report also illustrates various materials used for concrete reinforcement.



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MaterialEASE 30

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Material Failure Modes, Part II

A Brief Tutorial on Impact, Spalling, Wear, Brinelling, Thermal Shock, and Radiation Damage

This issue of MaterialEASE *is Part Two of a three part series on material failure modes.* MaterialEASE 29*, published in Volume 9, Number 1 of the* AMPTIAC Quarterly*, introduced the concept of material failure modes and covered fracture, ductile failure, elastic deformation, creep, and fatigue. This article continues the discussion with brief descriptions of impact, spalling, wear, brinelling, thermal shock, and radiation damage. The next* MaterialEASE *article will complete the series on material failure modes, and the three articles taken together will make a valuable desk reference for any professional making material selection and design decisions.* - Editor

INTRODUCTION

The purpose of this article is to briefly introduce several material failure modes. A better understanding of these failure mechanisms will enable more appropriate decisions when selecting materials for a particular application. Even a basic knowledge and awareness can help design engineers to be better equipped in delaying or preventing the failure of a material or component.

Failure can occur in systems with moving or non-moving parts. In systems with moving parts, friction often leads to material degradation such as wear, and collisions between two components can result in surface or more extensive material damage. Systems with non-moving parts are also prone to material failure, especially when certain types of materials are subjected to extreme temperature changes or to high energy radiation environments.

Material failure often manifests itself in the form of cracking, but it can also appear as material disintegration, mechanical property degradation, or even physical deformation. For instance, impact failure can occur by fracture, deformation, or material disintegration, while radiation damage can cause a severe degradation of a material's properties. These failure modes, as well as spalling, wear, brinelling, and thermal shock are described throughout the rest of this article.

IMPACT

The collision of two masses, one of which can be stationary, causes a sudden increase in stress or an intense change in pressure (as in an explosive blast), and may result in impact failure. This shock loading can cause permanent deformation or fracture to one or both of the colliding bodies, which can render that material unable to perform its intended function. Sudden impact loading can result in shock waves which induce localized stresses and strains causing mechanical damage to the material. There are several different types of impact failure including impact fracture, impact deformation, impact wear, impact fretting, and impact fatigue. Each of these will be discussed in some detail in the following sections.

Impact Fracture

The most extreme consequence of sudden shock loading results in fracture. This can be a catastrophic failure mode, as it occurs rapidly under the load of a sudden impact, and it is common in brittle materials, such as ceramics. For example, when a ceramic armor tile is hit with a projectile it likely will sustain multiple fractures. This failure mode is in contrast to impact deformation.

Impact Deformation

The energy imparted to a material during sudden shock loading can be absorbed through deformation. Plastic deformation caused by this sudden shock loading can preclude a structure from performing its intended function. This is a failure mode known as impact deformation, and typically occurs in ductile materials, such as metals.

Impact Wear

Impact wear occurs when a material is repeatedly impacted by another solid mass causing a gradual deterioration of the surface. The impact of large or small masses or particles can cause deformation to the material being impacted. This deformation can result in the ejection of particles from the material's surface, or the formation of near-surface cracks that under repeated impact can cause pieces of the surface to fracture (see description of *surface fatigue wear* in this article). In the case of repeated impact by particles that are very small relative to the size of the material being impacted, the wear that ensues could be considered erosive wear. Erosive wear is the continuous deterioration of a material by a fluid carrying solid particles. When the fluid is traveling in a direction that is normal to the surface of the material, it can be considered impact wear.

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Impact Fretting

Impact fretting is a fretting damage mechanism (see section on *fretting wear* in this article) where the two contacting bodies become physically disengaged momentarily and suddenly resume contact. This occurs while the two materials continue their relative sliding motion causing both fretting and impact damage. This sudden separation and subsequent impact can cause an increase in the fretting wear rate, as an additional damage mechanism is employed.

Impact Fatigue

Impact fatigue is a failure mode obviously related to impact damage, but is briefly described in the section on fatigue failure modes published in *MaterialEASE 29, AMPTIAC Quarterly* Volume 9, Number 1.[1]

SPALLING

Spalling is the deterioration of a component as fragments from the surface break free from the material. This phenomenon can occur through several mechanisms including the formation and propagation of fatigue cracks underneath the surface. This mechanism is related to the *surface fatigue* mechanism, which is discussed in the following section. Another mechanism that leads to spalling involves the propagation of shock waves through to the opposite side of a material after being impacted, which results in significant localized stress and consequently cracking near the surface. This sub-surface cracking causes surface fractures and particles to be dislodged from the material's surface. Similarly, thermal shock can cause spalling failure (see section on *thermal shock* in this article). Spalling can occur in metals or ceramics or even surface coatings; it often occurs in armor materials, gear teeth, and bearings. Figure 1 shows spalling failure of a gear tooth.

Figure 1. **Spalling Failure on the Surface of a Gear Tooth Caused by Surface Fatigue[2].**

WEAR

Wear is a general term used to describe the deterioration of a material's surface caused by frictional forces generated as a result of contact between two surfaces that are moving in relation to one another. Temperature has an effect on the wear rate (rate at which a material deteriorates under frictional forces) because friction generates heat, which in turn can affect the microstructure of the material and make it more susceptible to deterioration. Components such as bearings, cams, and gears are often susceptible to wear. There are several different types of wear, including adhesive wear, abrasive wear, corrosive wear, surface fatigue wear, impact wear, and fretting wear. Most of these will be discussed in some detail in the following sections.

Minimizing or protecting a material's surface from wear can be accomplished through several methods including the use of lubricants and surface treatments.[3] Selecting a material that is resistant to wear, such as one having high hardness (e.g. ceramics), is also a good method to prevent excessive wear. Alternatively, hard coatings such as tungsten-carbide-cobalt can be used to augment the hardness of a component having a relatively soft surface. Surface or heat treatments can also be used to increase the hardness or smoothness of the surface. Exampes include carburizing and superfinishing, which is described in Volume 7, Number 1 of the *AMPTIAC Quarterly*.[4]

Adhesive Wear

Adhesive wear occurs between two surfaces in relative motion as the result of high contact stresses, which are generated because of the inherent roughness of material surfaces. No matter how finely polished a surface is, two materials in contact with each other do not mate completely. This allows localized areas on the surface to sustain a greater percentage of a mechanical load, while the areas that are not in contact with the opposing surface absorb none of the mechanical load. In adhesive wear, the peaks on the adjacent surfaces that do come into contact will plastically deform under pressure and form atomic bonds at the interface (in some cases this is considered solid-phase welding). As the relative motion between the surfaces continues, the shear stress at the now atomically bonded contact point increases until the shear strength limit of one of the materials is reached and the contact point is broken bringing with it a piece of the opposing surface. The broken material can then either be released as debris or remain bonded to the other material's surface. This process is demonstrated in Figure 2. Adhesive wear is also known as scoring, scuffing, galling or seizing (galling and seizure are described briefly below).[3,5]

High hardness and low strength are desirable properties for applications requiring resistance to adhesive wear. However, these properties are somewhat mutually exclusive, which makes composite materials desirable for such applications. Examples of resistant monolithic materials include low strength, high ductility polymers and high hardness, low density ceramics. Sintered copper infiltrated with polytetrafluoroethylene (Teflon™) and lead particle reinforced bronze materials are specific examples of composite materials that are highly resistant to adhesive wear.[3]

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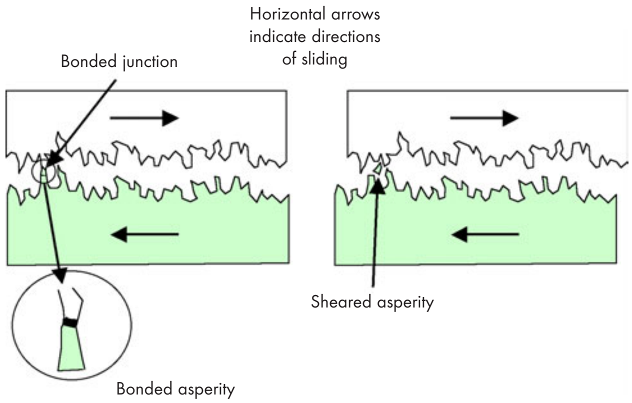

Figure 2. **Illustration of Adhesive Wear Mechanism[3].**

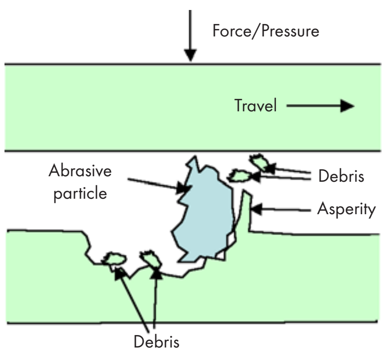

Figure 3. **Illustration of Abrasive Wear Mechanism[3].**

Galling and Seizure

Galling is an extreme form of adhesive wear that involves excessive friction between the two surfaces resulting in localized solid-phase welding and subsequent spalling of the mated parts. This process causes significant damage to the surface of one or both materials. Seizure is even more extreme in that the two surfaces experience a sufficient amount of solid-phase welding such that the two components can no longer move.

Abrasive Wear

Gouging, grinding and scratching are examples of abrasive wear, which occurs when a solid surface experiences the displacement or removal of material as a result of a forceful interaction with another surface or particle. Particles can become trapped in between the two surfaces in contact, and the relative motion between them results in abrasion (displacement and removal of surface material) of the surface that has a lower hardness. This process is demonstrated in Figure 3. Sources of particles can include foreign contaminants (particles originating outside the system), wear debris, or solid constituents suspended in a fluid. Alternatively, abrasive wear can occur in the absence of loose particles when the roughness of one surface causes abrasion and/or removal of material from the other surface. This wear mechanism differs from adhesive wear in that there is no atomic bonding between the two surfaces. Abrasive erosion occurs when a fluid carrying solid particles is traveling in a direction parallel (as opposed to perpendicular which is impact wear) to the surface, and the particles gradually deteriorate the material's surface.

Material hardness is a critical factor in the abrasive wear rate of the surface, as higher hardness results in a lower wear rate. Moreover, if the hardness of the material's surface is higher than the hardness of the abrading particles, then little wear is observed and the particles are likely to be broken into smaller pieces. Materials with high hardness and toughness properties are well-suited to prevent or minimize abrasive wear. Examples of materials that are inherently resistant to abrasive wear include high hardness or surface hardened steels, cobalt alloys and ceramics.[3]

Corrosive Wear

When the effects of corrosion and wear are combined, a more rapid degradation of the material's surface may occur. This process is known as corrosive wear. Films or coatings are often used to protect a base metal or alloy from harsh environments that would otherwise cause it to corrode. If such a coating were subjected to abrasive or adhesive wear causing a loss of coating from the material's surface, for instance, the base metal or alloy could be exposed and consequently corroded. Alternatively, a surface that is corroded or oxidized may be mechanically weakened and more likely to wear at an increased rate. Furthermore, corrosion products including oxide particles that are dislodged from the material's surface can subsequently act as abrasive particles.

Surface Fatigue Wear

Surface or contact fatigue occurs when two material surfaces that are in contact with each other in a rolling or combined rolling and sliding motion create an alternating force or stress oriented in a direction normal to the surface. The contact stress initiates the formation of cracks slightly beneath the surface, which then grow back toward the surface causing pits to form, as particles of the material are ejected or worn away. This form of fatigue is common in applications where an object repeatedly rolls across the surface of a material resulting in a high concentration of stress at each point along the surface. For example, rolling-element bearings, gears, and railroad wheels commonly exhibit surface fatigue.[3,6] Figure 4 illustrates an example of the surface fatigue mechanism.

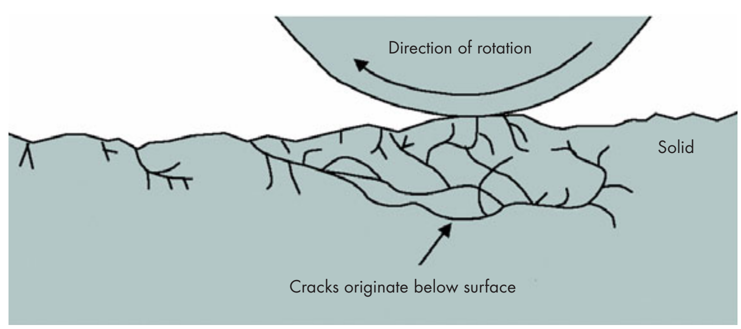

Figure 4. **Illustration of Surface Fatigue Mechanism[3].**

Impact Wear

Impact wear is discussed in the section addressing impact failure modes.

Fretting Wear

Surfaces that are in intimate contact with each other and are subject to a small amplitude relative motion that is cyclic in nature, such as vibration, tend to incur wear. Fretting wear is normally accompanied by the corrosion or oxidization of the debris and worn surface. Unlike normal wear mechanisms only a small amount of the debris is lost from the system; instead the debris remains within the conjoined surfaces. The mated surfaces essentially exhibit adhesion through mechanical bonding, and the oscillatory motion causes the surface to fragment, thereby creating oxidized debris. If the debris becomes embedded in the surface of the softer metal, the wear rate may be reduced. If the debris remains free at the interface between the two materials the wear rate may be increased. Fatigue cracks also have a tendency to form in the region of wear, resulting in a further degradation of the material's surface. Liquid or solid lubricants (e.g. surface treatments, coatings, etc.), residual stresses (e.g. through shot or laser peening), surface grooving (e.g. to enable the release of debris), and/or appropriate material selection for the material pair can help to reduce the effects or prevent the occurrence of fretting wear.[7]

BRINELLING

Brinelling can be very basically defined as denting. When a localized area of a material's surface is repeatedly impacted or is subjected to a static load that overcomes the material's yield strength causing it to permanently deform, it is considered to have undergone brinelling. Bearings are often susceptible to failure by brinelling since an indentation can cause an increase in vibration, noise and heating.[7] Brinelling failures can be caused by improper handling, such as forcing a bearing into a housing, by dropping the bearing, or by severe vibrations, such as those produced during ultrasonic cleaning.[8] Selecting a material with a high hardness or taking extra care during handling and cleaning can help prevent brinelling.

THERMAL SHOCK

Thermal shock is a failure mechanism that occurs in materials that exhibit a significant temperature gradient (indicating a sudden and dramatic change in temperature has occurred). For instance, if the temperature gradient is so large that the material experiences thermal stresses (or strains) great enough to overcome its strength, it may lead to fracture, especially if the material is constrained. An example of the consequence of thermal shock is shown in Figure 5. Awareness of a system or component's operating conditions when selecting materials is important in order to prevent thermal shock failure from occurring. The designer should choose a material that has an appropriate thermal conductivity and heat capacity for the intended environmental conditions. In addition, residual stresses (from shot or laser peening, for example) can help accommodate thermal stresses that are generated during thermal shock, thereby potentially protecting the material from fracture.

RADIATION DAMAGE

The space environment is very unfriendly to most materials due to an array of harsh conditions that can easily and rapidly degrade the material and/or its properties. Degradation of an exposed material often comes as a result of the different types of radiation present in

Figure 5. **Brittle Fracture of a Ductile Weld Material that Is Constrained – Caused by High Stresses Induced from a Rapid 1000°F Change in Temperature. (Photo Courtesy of Sachs, Salvaterra & Associates, Inc.)**

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space. Radiation is not limited to the space environment, however, as there are a number of environments and specific applications that subject materials to this damaging energy (Figure 6).

High-energy radiation, such as neutrons in a nuclear reactor, can damage almost any material including metals, ceramics and polymers.[3] Typically, when a material is subjected to high-energy radiation its properties are altered through structural mutation in order to absorb some of the energy that is incident on the material. For instance, when a metal is exposed to neutron radiation from a nuclear reactor, atoms in the metal are displaced resulting in the creation of defects. These defects can diffuse and coalesce to create crack initiation sites or can simply leave the metal brittle and susceptible to failure through another mechanism. Another portion of the energy incident on the metal is absorbed and converted to heat. Metals are often better suited to withstand radiation energy than are ceramics. Typically, the ductility, thermal conductivity and electrical conductivity are negatively impacted when a metal is exposed to radiation.[3] Ceramics are affected by radiation to varying extents depending on the type of inherent bonding (i.e. covalent or ionic). Ionically-bonded ceramics experience decreases in ductility, thermal conductivity and optical properties, but the damage can be reversed with proper heat treatment (similar to metals). Covalently-bonded ceramics experience similar damage, however the damage is somewhat permanent.[3]

Figure 6. CO_2 Laser Used to Study the Effects of Radiation on Materials[9].

Polymers are especially susceptible to radiation even at low energy levels, such as UV radiation. Damage from radiation in polymers usually manifests itself as cracking. For this reason, polymers have been known for their cracking problems in outdoor applications, where they are constantly exposed to UV radiation. UV blockers, absorbers and stabilizers are often added to polymers used for outdoor applications to augment their ability to withstand incident radiation energy.

CONCLUSION

A number of material failure modes were introduced in this article including impact, spalling, wear, brinelling, thermal shock and radiation damage. These mechanisms can affect metals, polymers, ceramics, and composites in various applications and in many different environments. Thus, it is important to take these failure modes into consideration during the design phases of a component or system in order to make appropriate materials selection decisions.

MaterialEASE 31 will be published in Volume 9, Number 3, of the *AMPTIAC Quarterly* and will contain the final installment of failure modes. These will include uniform, galvanic, crevice, pitting, intergranular, and erosion corrosion; selective leaching/dealloying; hydrogen damage; stress corrosion cracking; and corrosion fatigue.

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... Don't forget to look for Material Failure Modes, Part 3 in the next issue of MaterialEASE!

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Mobile Parts Hospital Update

In Volume 6, Number 3 of the *AMPTIAC Quarterly*, a feature article was published providing an overview of the Mobile Parts Hospital (MPH) and its potential capabilities. Since publication of this article in late 2002 there have been significant developments and successes with the MPH program.

In October 2003, under the guidance of General Paul J. Kern, US Army Materiel Command (AMC) Commanding General, the MPH was deployed to the Forward Repair Activity (FRA) at Camp Arifjan, Kuwait. Since its arrival in Kuwait, it has been manufacturing parts to support Operation Iraqi Freedom. This mobile rapid manufacturing facility has been fabricating parts to repair vehicles and equipment and restore them to working order in Iraq. Two additional Mobile Parts Hospitals have subsequently been deployed to assist in the Global War on Terrorism. One of these units is now operating in Camp Anaconda, Iraq, and the other at Bagram Airbase in Afghanistan.

Thousands of replacement parts have been produced, including parts designed on-site to support soldier's requirements. In less than six months since it arrived in Kuwait it had manufactured over 1600 replacement parts that were not readily available elsewhere, including bolts, brass studs, and pulleys among many other parts. This has led to the repair of M2 Bradley engines and HEMTT 8V92TA and HMMWV engines and differentials. The Agile Manufacturing Cell is able to supply larger parts or parts needed in greater quantities from Detroit, Michigan, where it has access to more raw materials and can perform high-speed machining, welding, heat treating, and plating. When ready the parts are then shipped to the FRA.

There has been a substantial demand for parts manufactured by the MPH, which has been heavily supporting the US Army's Forward Repair Activity in Arifjan, Kuwait, the 368th Engineering Battalion, the 514th Maintenance Company, the 1083rd Transportation Company, and the 3rd PERSCOM Maintenance Office. To date, over 12,000 repair parts have been manufactured by the MPH.

There is one particular success story that exemplifies the support provided to the war-fighter by the MPH. On short notice, the MPH designed and fabricated gun mounts for two 5.56 mm Squad Automatic Weapon (SAW) machine guns to retrofit a HMMWV with additional and more strategic firepower. The MPH team manufactured two pintle assemblies with locking pins consisting of six parts, and delivered them within 5 hours. These gun mounts improved the ability of soldiers who were transporting supplies into Basra, Iraq nightly to defend themselves, as they frequently came under attack. The new gun mounts provided greater vertical as well as 180° rotational mobility so that both sides of the HMMWV could be easily defended during an ambush, and attackers on overpasses and buildings could be easily subdued. Similar mounting hardware has since been fabricated for other weapons such as 0.50 cal. machine guns. As mentioned in our last MPH update (see Volume 8, Number 3 of the *AMPTIAC Quarterly*) this new gun mount was selected as one of the Army's top 10 inventions for 2003.

Further research and development is being done to add capabilities and increase part production in MPH units that will be deployed in the future. The present system is able to build consistent, high quality parts, but the goal is to produce them at a much faster rate. The layer-by-layer powder deposition and laser sintering process in its current status achieves a deposition rate of three cubic inches per hour for fabricating parts. Over the coming year, the laser and ancillary systems will be upgraded to achieve a deposition rate of eight cubic inches per hour. The overall goal is to deposit high quality material at a rate of twelve cubic inches per hour.

The MPH program continues to be a success story, as it is actively supporting the US Military in Iraq, Afghanistan and Kuwait. For more information on the MPH, please refer to our article in Volume 6, Number 3 (2002) and the update in Volume 8, Number 3 (2004) of the *AMPTIAC Quarterly*, which are available in electronic form on the AMPTIAC website at http://amptiac.alionscience.com/quarterly.

DOD Materials and Processes Conferences and Symposia:

Transferring Technology through Collaboration and the Exchange of Information

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INTRODUCTION

Conferences and symposia are productive means for transferring technology and fostering collaboration between organizations and individuals. With the exchange of information, technology development can be advanced to a more practical stage and possibly implemented in ways not previously considered. Furthermore, these meetings are excellent for making connections with subject matter experts who may help in finding solutions to future challenges.

The Army, Navy, Air Force, and other organizations within the Department of Defense participate in, sponsor, or facilitate a number of conferences and symposia. Throughout the calendar year there are many such conferences covering an array of subject areas pertinent to the materials and processes community. This article provides brief introductions to many of the important events hosted, sponsored or attended by the DOD materials and processes community.

GENERAL MATERIALS, PROCESSING, AND MANUFACTURING CONFERENCES

Annual Conference on Composites, Materials, and Structures

The Annual Conference on Composites, Materials, and Structures, commonly referred to as the Cocoa Beach Conference, has been held each year since 1977. The Refractory Composites Working Group (RCWG) directly preceded today's conference.[1]

The RCWG was formed in 1958 by the Air Force Materials Laboratory (AFML) to provide a forum for discussion of refractory coatings. Larry Hjelm and J.J. Gangler oversaw the majority of the workshops, and they required attendees to present data without promoting a product. These meetings were initially known as the High Temperature Inorganic Refractory Coatings Working Group. However, in the early 1960's the name changed to the Refractory Composite Working Group.[1]

While the RCWG held regular meetings, the Ceramic-Metals System (CMS) Division of the American Ceramic Society also held meetings. The two groups overlapped membership and content. In January 1977, the RCWG merged with the CMS Division under the guidance of Jerome Persh, Jim Mueller, John Buckley, Jim McCauley, and Sy Bortz. Today, the Annual Conference on Composites, Materials, and Structures provides a forum for discussion of all high temperature materials crucial to our national defense. The next Cocoa Beach Conference will be held in January 2006. Attendance is limited to qualified individuals.[1]

Defense Manufacturing Conference

The Defense Manufacturing Conference brings together personnel from government, industry, and academia to engage in an exchange of information for the purpose of addressing defense manufacturing capabilities and needs for weapon systems. Topic areas typically include system and subsystem affordability, sustainment efficiency, and domestic technology transfer. DOD, government and industry initiatives are also discussed.[2]

The next conference, sponsored by the Joint Defense Manufacturing Technology Panel, will be hosted by the Office of Naval Research from November 28 through December 1, 2005 in Orlando, Florida. This year's conference will be centered on the theme "Manufacturing in the Changing DOD Environment." Attendance is limited to qualified individuals. Past conferences and their host city are listed in Table 1.

Sagamore Army Materials Research Conference

The Sagamore Army Materials Research Conference began in 1954, and each conference focuses on a materials-related topic. Past themes include risk and failure analysis, residual stress and stress relaxation, corrosion prevention and control, and most recently, transparent materials. The objective of the conference is to provide a forum for scientists and engineers from academia, industry, and the government to discuss the subject of that year's conference and its importance to the Army and the greater DOD materials communities.

Table 1. Past Defense Manufacturing Conferences.

Year	Location
1993	San Francisco, California
1994	Phoenix, Arizona
1995	Dallas, Texas
1996	Miami Beach, Florida
1997	Palm Springs, California
1998	New Orleans, Louisiana
1999	Miami Beach, Florida
2000	Tampa, Florida
2001	Las Vegas, Nevada
2002	Dallas, Texas
2003	Washington, DC
2004	Las Vegas, Nevada

Advanced Materials Conference

The Low-Cost Titanium Workshop, which was held in December 2003, was expanded into the 2005 Advanced Materials Conference to bring together and foster discussion between organizations from industry and government on the development and use of lightweight, advanced materials for ship and ground vehicle applications. This conference is set up to explore from a design standpoint the challenges and new developments regarding the application of advanced materials for the purpose of weight reduction and improved performance. Furthermore, these discussions lead to establishing the status of current advanced materials technology, as well as future directions for research and development. Achieving lower total ownership costs and enhanced manufacturing capability through collaboration of government and industry organizations is a further objective of this conference. Types of materials discussed include titanium, magnesium, aluminum and composites. Attendees typically include scientists, engineers, program managers, fabricators, suppliers, and designers from the DOD, other government organizations and industry. The next Advanced Materials Conference is currently in the planning stages for the Spring of 2006. Attendance is limited to qualified individuals.[3]

CORROSION CONFERENCES

Tri-Service Corrosion Conference

The Tri-Service Corrosion Conference has been hosted fifteen times since being initiated by the Air Force in 1967. The purpose of the conference is to promote interaction among the military services through a forum wherein the Federal Government's corrosion technologists and interested defense contractors have an open exchange of the latest corrosion issues relevant to military systems. Moreover, these conferences provide increased visibility of DOD corrosion control and prevention efforts and promote novel and innovative solutions to DOD corrosion problems.[4]

Table 2. **Past Tri-Service Corrosion Conferences.**

Year	Location
1967	Denver, Colorado
1972	Houston, Texas
1974	Dayton, Ohio
1976	Philadelphia, Pennsylvania
1979	New Orleans, Louisiana
1980	USAF Academy, Colorado
1985	Orlando, Florida
1987	USAF Academy, Colorado
1989	Warminster, Pennsylvania
1992	Plymouth, Massachusetts
1994	Orlando, Florida
1997	Wrightsville Beach, North Carolina
1999	Myrtle Beach, South Carolina
2002	San Antonia, Texas
2003	Las Vegas, Nevada

This exchange of information encourages cooperative efforts which will aid in the development of integrated corrosion prevention and control technologies. Furthermore, these conferences provide the DOD with feedback, assessments, and recommendations from recognized experts in the corrosion field. The overall goal of these interactions between DOD, private industry, academia, and other government agencies is to reduce life cycle costs through advances in corrosion control and prevention technologies.[4]

The next conference will be November 14-18, 2005, in Orlando, Florida, and anyone can attend. The overall goal of this year's conference is "Transcending and Integrating Corrosion Prevention and Control for the Department of Defense."[5] All past conferences and their host city are listed in Table 2.

Air Force Corrosion Program Conference

The Air Force Corrosion Prevention and Control Office brings together DOD organizations annually to discuss the status of their corrosion prevention and control programs. In particular, corrosion requirements, problems, and recently approved materials and processes are discussed. The next conference is scheduled for March 13-17, 2006.[6]

Marine and Offshore Coatings and Corrosion Conference (Mega Rust)

A new conference has been formed by the merging of five related programs. This "Mega Rust" conference, the Marine and Offshore Coatings and Corrosion Conference is the consolidation of the following programs:[7]

- US Navy's Fleet Corrosion Control Forum
- National Paint and Coatings Association's International Marine and Offshore Coatings Conference
- US Navy and Industry Corrosion Technology Exchange "Rust Conference"
- National Shipbuilding Research Program (NSRP) SP-3 Meeting
- Submarine Preservation Conference

This conference focuses on technologies and strategies for controlling corrosion, and is set up to cultivate dialogue between the companies that provide corrosion control technologies and the military or commercial organizations that require corrosion control solutions for various applications. Participants of this conference include personnel from industry, government, and the military. Topic areas include coatings, corrosion control technologies and strategies, and government regulations. The 2005 conference was held in June, and the date for the next conference has not yet been announced.

US Army Corrosion Summit

The purpose of the US Army Corrosion Summit is to identify corrosion issues for the Army Transformation, current corrosion problems on weapon systems, potential corrosion solutions, and corrosion technology gaps. Further objectives of the conference are to share success stories and document

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requirements and capabilities. The conference brings together program managers, engineers, depot and facility personnel, and manufacturers from government, industry, and academia. Specific topics and applications discussed include electronics, armament, helicopters, missile systems, ground vehicles, infrastructure, field maintenance, protective coatings, advanced materials, microelectronics, micro-electromechanical systems, non-metallic material degradation, and environmental issues. The 2006 US Army Corrosion Summit is scheduled for February 14-16, in Clearwater Beach, Florida.[8]

AIRCRAFT AND SPACE APPLICATIONS CONFERENCES

Aircraft Structural Integrity Program

The Aircraft Structural Integrity Program (ASIP) brings together scientists and engineers from the DOD, NASA, FAA and the aerospace industry to exchange information on current technologies in the area of aircraft structural integrity. The focus of the conference is on airframe and engine structural integrity, including design, manufacture, nondestructive inspection, life management and maintenance for both military and commercial aircraft. The 21st ASIP Conference will be held from November 29 through December 1, 2005 in Memphis, Tennessee, and anyone can attend.[9]

National Space and Missile Materials Symposium

The National Space and Missile Materials Symposium draws system engineers, designers, scientists, and managers who are facing the challenges of materials and processes for space and missile applications. The symposium is intended to promote the importance of supporting advanced materials research and technology development to meet the specific challenges associated with space and missile systems. This focus will ultimately help to improve the performance and reliability of both commercial and government systems.[10]

The National Space and Missile Materials Symposium began as an Air Force Research Laboratory Materials Directorate program review in 1996 involving more than 250 engineers and project managers from the Air Force, NASA and industry. Following this successful meeting, a national Tri-Service and NASA sponsored symposium was established in 1998. With continued Tri-Service and NASA sponsorship led by the Air Force, the meeting has become an annual event. The 2005 symposium was held in June, and the date for next year's symposium has not yet been announced. Attendance is limited to qualified individuals.[10]

Joint FAA/DOD/NASA Conference on Aging Aircraft

This conference, which is organized and facilitated by the Joint Council on Aging Aircraft (JCAA), addresses the common issues and technical aspects associated with the aging fleets of military and commercial aircraft. Advancements in the development and implementation of new technology, and managing of aging aircraft systems and fleets are focal points in the presentations given at the conference. Topic areas include preventing or mitigating structural, electrical, avionic, or engine failure; corrosion; non-destructive inspection; and health monitoring.[11] The 9th Joint FAA/DOD/NASA Confernce on Aging Aircraft will be held March 6-9, 2006 in Atlanta, Georgia.[12]

National Thermal Protection Systems Workshop

The purpose of this workshop is to provide a forum where the status of thermal protection system (TPS) technologies and requirements based on the directions of DOD and NASA programs are discussed. The National Thermal Protection Systems Workshop typically covers technologies associated with thermal protection, thermal management, and hot structures that are used for space access, hypersonic and reentry vehicles. Ultimately, the objective of the Thermal Protection Systems Workshop is to develop a National Plan for the development of TPS that will be used in future NASA and DOD space vehicles. All types of TPS materials are covered including metallic and non-metallic materials. Attendance is limited to qualified individuals.

ELECTRONIC AND OPTICAL MATERIALS CONFERENCES

Electromagnetic Windows Symposium

The Electromagnetic Windows Symposium is held once every two years to provide an environment where scientists and engineers from government, industry and academia can exchange information related to the development of radome, antenna window, and optical window technologies. Topics related to the research, development, modeling, testing, and evaluation of electromagnetic windows are typically discussed. Conference organization responsibility rotates between the Navy, Air Force, and Army. The next symposium will be held in San Diego from May 1-4, 2006. Attendance is limited to qualified individuals.[13]

Components for Military and Space Electronics Conference and Exhibition

This conference draws engineers and managers to exchange information concerning issues related to electronic systems and devices for military and space applications. The focus of this conference is on the testing, selection, application, reliability, and failure analysis of electronic components and systems. New technologies, processes, design strategies, and approaches for updating older military systems are also an integral part of the event. The conference typically results in providing a comparison between the application of Mil-Spec electronics and Commercial-Off-The-Shelf products.[14]

HIGH TEMPERATURE POLYMER COMPOSITES CONFERENCE

High Temple Workshops

The High Temple Workshops, which were initiated in 1982 by a Tri-Service/NASA steering group, are a series of workshops that cover the areas of design, development and application of

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high temperature reinforced polymeric composites. The primary purpose of High Temple is to communicate ongoing high temperature polymer composite research among DOD, NASA, other governmental agencies, industry and universities. Over the years, interdisciplinary teams were formed to advance and implement high temperature polymer composites in many applications, such as advanced engine and aero-structure components. These teams continue to make significant advances in composite related technologies, such as fiber-resin interfaces, new chemistries that enhance thermal oxidative stability, high temperature test methods, design-material databases, and low-cost and intelligent processing techniques.[1]

Today, government overviews of federally-sponsored high temperature composites research serve to create an awareness in both the public and private sector. New monomer and polymer chemistries continue to be introduced at High Temple, often before they are published in peer-reviewed journals. Newer technical subjects, such as electron beam curing, low-cost processing and coatings are some of the topics that continue to make High Temple one of the premier composite technical meetings. Past Conferences and their host city are listed in Table 3. The next High Temple meeting is scheduled for February 13-16, 2006 in Austin, Texas. Attendance is limited to qualified individuals.[1]

SURVIVABILITY CONFERENCE

US Army Ground Vehicle Survivability Symposium

The US Army Ground Vehicle Survivability Symposium is set up to provide a forum for technology developers, the acquisition community and the end-user to exchange ideas and discuss the plans for the future of survivability technologies. The ultimate goal of the symposium is to bring the greatest capability to the Soldier rapidly. Typical topics include damage reduction technologies, lightweight armor, and active protection systems. Attendance to this conference is limited to qualified individuals.[15]

Table 3. **Past High Temple Workshops.**

Year	Location
1982	NASA/White Sands Test Facility, New Mexico
1982	Dayton, Ohio
1983	Dayton, Ohio
1984	Hampton, Virginia
1985	Monterey, California
1986	Cocoa Beach, Florida
1987	Sacramento, California
1988	Riviera Beach, Florida
1989	Pasadena, California
1990	Cocoa Beach, Florida
1991	Sparks, Nevada
1992	Cocoa Beach, Florida
1993	Santa Fe, New Mexico
1994	Cocoa Beach, Florida
1995	Santa Fe, New Mexico
1996	Orange Beach, Alabama
1997	Monterey, California
1998	Hilton Head Island, South Carolina
1999	Denver, Colorado
2000	San Diego, California
2001	Clearwater Beach, Florida
2002	Santa Fe, New Mexico
2003	Jacksonville, Florida
2004	Sacramento, California
2005	Point Clear, Alabama

HEALTH MANAGEMENT CONFERENCE

Integrated Systems Health Management Conference

The Integrated Systems Health Management Conference led by the US Air Force Research Laboratory is set up to provide a collaborative and informative environment for those from DOD, industry and academia involved with researching, developing and applying integrated systems and health management (ISHM) technologies. ISHM research and development is directed toward application areas such as flight control systems, aerospace structures, propulsion systems, ISHM architecture, and information management. The 2005 conference was held in August and no date has been announced for the next meeting. Attendance to the ISHM Conference is limited to qualified individuals.[16]

NANOSTRUCTURED MATERIALS CONFERENCE

NanoMaterials for Defense Applications Symposium

Government and industry technical representatives gather at this symposium to collaborate and explore the potential of nanostructured materials for DOD applications. An objective of this symposium is to assist in the advancement of nanomaterials technologies, such that Defense systems will realize their potential in the near future. This symposium is currently sponsored by the Air Force Research Laboratory Materials and Manufacturing Directorate (AFRL/ML), the Army Research Laboratory (ARL), the Naval Research Laboratory (NRL), and the Defense Advanced Research Projects Agency (DARPA). The 4th annual NanoMaterials for Defense Application Symposium, with the theme: "Accelerating the Transition," will be held May 2-4, 2006 in Virginia Beach, Virginia.[17]

FATIGUE DAMAGE CONFERENCE

International Conference on Fatigue Damage of Structural Materials

The purpose of this conference is to bring together experts from academia, industry, government, and the military to discuss advances in the knowledge of fatigue damage to structural materials. Additionally, it is the goal of the conference to discuss advances in the technology of analysis, prediction, theoretical treatment and experimental characterization of fatigue damage.[18] The next conference, which will take place from September 17-22, 2006 in Hyannis, Massachusetts, is sponsored by the Office of Naval Research International Field Office, Office of Naval Research Head-

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quarters, US Air Force Research Laboratory, and the US Army Research Office.

SHIPBUILDING TECHNOLOGY CONFERENCE

ShipTech

This event allows Navy program offices, shipbuilders, suppliers, researchers, and engineers from the DOD, academia and industry to exchange information on shipbuilding technology. Materials and processes are largely integrated in the development of technology for shipbuilding and manufacturing of ship systems. The primary goal of the event is the exchange of technical information to reduce total ownership costs while advancing domestic shipbuilding capabilities. ShipTech 2006 will be held in Biloxi, Mississippi, January 24-25, and anyone can attend.[19]

SUMMARY

Although it is not comprehensive, this article summarized some of the conferences and symposia related to materials and processes technology that are sponsored, administered, or attended by DOD personnel. New conferences and symposia are initiated just about every year, or old ones are combined or split apart to become either more wide-reaching in scope or more focused on a particular subject area. However, this article provides a snapshot of some of the more significant and established events held throughout the year, as well as a few of the recently initiated or changed events. Many of the conferences for 2005 have already been held, and dates and locations have not yet been established for the next meeting. For up-to-date information on conferences and symposia check out the "Mark Your Calendar" page in each issue of the *AMPTIAC Quarterly*, or the Calendar of Events page on the AMPTIAC website: http://amptiac.alionscience.com/NewsAndEvents/eCalendar/.

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[6] http://www.afcpo.com/
[7] http://www.nstcenter.com/
[8] http://www.armycorrosion.com/summit.html
[9] http://www.asipcon.com/
[10] http://www.usasymposium.com/nsmms/default.htm
[11] http://www.agingaircraft.utcdayton.com/
[12] http://agingaircraftconference.org
[13] http://www.usasymposium.com/emws/default.htm
[14] http://www.cti-us.com/ucmsemain.htm
[15] http://www.tacom.army.mil/tardec/nST_v1.2story4.htm
[16] http://www.usasymposium.com/ishm/default.htm
[17] http://www.usasymposium.com/nano/default.htm
[18] http://www.fatiguedamage.elsevier.com/scope.htm
[19] http://www.ncemt.ctc.com/index.cfm?fuseaction=eventinfo&eventid=40

Recent US Patents

Patent Number	Title
6,928,251	Image forming device including frames formed of resin containing no glass fibers
6,928,224	Laser-induced crystallization of transparent glass-ceramics
6,928,220	Sol-gel-derived optical fiber preform and method of manufacture
6,928,200	Ultra-thin polarization mode converters based on liquid crystal materials
6,927,829	Matrix substrate, liquid crystal display device using it, and method for producing the matrix substrate
6,927,823	Method for alignment of liquid crystals using irradiated liquid crystal films
6,927,537	Organic electroluminescence device
6,927,421	Heat sink material
6,927,315	Adhesive composite having distinct phases
6,927,301	Well-defined nanosized building blocks for organic/inorganic nanocomposites
6,927,298	3,4-alkylenedioxythiophenedioxide compounds and polymers comprising monomeric units thereof
6,927,275	Process for producing polyester resins
6,927,269	Functionalized elastomers
6,927,268	Production process for water-absorbent resin
6,927,265	Melt-processible thermoplastic fluoropolymers having improved processing characteristics and method of producing same
6,927,259	Curable base-resistant fluoroelastomers
6,927,185	Porous material and method for preparation thereof
6,926,995	Fuel cell separators and solid polymer fuel cells
6,926,971	Bonded metal components having uniform thermal conductivity characteristics and method of making same

Patent Number	Title
6,926,926	Silicon carbide deposited by high density plasma chemical-vapor deposition with bias
6,926,853	Continuous impregnation of long fibers with resin for manufacturing elongated composite elements
6,926,780	Method of surface self-nanocrystallization of metallic materials
6,926,755	Method for preparing aluminum-base metallic alloy articles without melting
6,926,754	Method for preparing metallic superalloy articles having thermophysically melt incompatible alloying elements, without melting
6,926,496	High temperature turbine nozzle for temperature reduction by optical reflection and process for manufacturing
6,926,127	Friction members made from fiber-reinforced ceramic composite materials and processes for making friction members
6,924,245	Glass ceramic composition, glass ceramic sintered material and ceramic multilayer substrate
6,921,606	Composite films for electrochemical device
6,921,431	Thermal protective coating for ceramic surfaces
6,920,817	Composite armor structure
6,919,289	Methods and compositions for low thermal expansion ceramic
6,919,042	Oxidation and fatigue resistant metallic coating
6,919,035	Metal oxide coated polymer substrates
6,912,944	Ceramic armour systems with a front spall layer and a shock absorbing layer
6,908,517	Methods of fabricating metallic materials

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International Symposium on Superalloys 718, 625, 706 and Derivatives
10/02/05 – 10/05/05
Pittsburgh, PA
Contact: TMS Meetings Services
184 Thorn Hill Road
Warrendale, PA 15086
Phone: 724.776.9000
Fax: 724.776.3770
Email: mtgserv@tms.org
Web Link: http://doc.tms.org

Magnetics 2005
10/24/05 - 10/26/05
Indianapolis, IN
Contact: Scott Gates
Webcom Communications
Phone: 800.803.9488 ext 105
Email: scottg@infowebcom.com
Web Link: www.magneticsmagazine.com

SAMPE Fall 2005 – Materials and Processing Technologies for Revolutionary Applications
10/31/05 – 11/03/05
Seattle, WA
Contact: SAMPE
1161 Park View Drive
Covina, CA 91724-3751
Phone: 626.331.0616
Fax: 626.332.8929
Email: registration@sampe.org
Web Link: www.sampe.org

UNITECR 2005 - 9th Biennial Worldwide Congress on Refractories
11/08/05 - 11/11/05
Orlando, FL
Contact: Customer Service
American Ceramic Society
PO Box 6136
Westerville, OH 43086-6136
Phone: 614.890.4700
Fax: 614.899.6109
Email: info@ceramics.org
Web Link: www.ceramics.org

FABTECH International Forming & Fabricating - Stamping - Tube & Pipe - Welding
11/13/05 - 11/16/05
Chicago, IL
Contact: Society of Manufacturing Engineers
One SME Drive, PO Box 930
Dearborn, MI 48121-0930
Phone: 800.733.3976
Fax: 313.425.3407
Web Link: www.sme.org

2005 USAF Aircraft Structural Integrity Program (ASIP) Conference
11/29/05 - 12/01/05
Memphis, TN
Contact: J. Jennewine
Universal Technology Corporation
1270 North Fairfield Road
Dayton, OH 45432-2600
Phone: 937.426.2808
Fax: 937.426.8755
Email: jjennewine@utcdayton.com
Web Link: http://www.asipcon.com

9th International Ceramic Processing Science Symposium
01/08/06 - 01/11/06
Coral Springs, FL
Contact: Customer Service
American Ceramic Society
PO Box 6136
Westerville, OH 43086-6136
Phone: 614.890.4700
Fax: 614.899.6109
Email: info@ceramics.org
Web Link: www.ceramics.org

The 30th International Conference & Exposition on Advanced Ceramics & Composites
01/22/06 – 01/27/06
Cocoa Beach, FL
Contact: Mark J. Mecklenborg
American Ceramic Society
735 Ceramic Place, Suite 100
Westerville, OH 43081
Phone: 614.794.5829
Fax: 614.794.5882
Email: mmecklenborg@ceramics.org
Web Link: www.ceramics.org/meetings

2006 International Conference on Tungsten, Refractory & Hardmetals VI
02/07/06 - 02/08/06
Orlando, FL
Contact: Metal Powder Industries Federation
105 College Road East
Princeton, NJ 08540-6692
Phone: 609.452.7700 ext 11
Fax: 609.987.8523
Web Link: www.mpif.org/

2006 TMS Annual Meeting & Exhibition
03/12/06 - 03/16/06
San Antonio, TX
Contact: TMS Meeting Services
184 Thorn Hill Road
Warrendale, PA 15086
Phone: 724.776.9000
Fax: 724.776.3770
Email: mtgserv@tms.org
Web Link: http://doc.tms.org

IMAPS/ACerS International Conference and Exposition on Ceramic Interconnect and Ceramic Microsystems Technologies (CICMT)
04/25/06 – 04/27/06
Denver, CO
Contact: IMAPS-International Microelectronics and Packaging Society
611 2nd Street, N.E.
Washington, DC 20002
Phone: 202.548.4001
Fax: 202.548.6115
Email: imaps@imaps.org
Web Link: www.imaps.org

AISTech 2006 – The Iron & Steel Technology Conference and Exposition
05/01/06 – 05/04/06
Cleveland, OH
Contact: Association for Iron & Steel Technology
186 Thorn Hill Road
Warrendale, PA 15086-7528
Phone: 724.776.6040
Web Link: www.aist.org

SAMPE® 2006 Symposium & Exhibition
04/30/06 - 05/04/06
Long Beach, CA
Contact: SAMPE
1161 Park View Drive
Covina, CA 91724-3751
Phone: 626.331.0616
Fax: 626.332.8929
Email: registration@sampe.org
Web Link: www.sampe.org

Fractography of Glasses & Ceramics V
07/09/06 - 07/12/06
Rochester, NY
Contact: Customer Service
American Ceramic Society
Westerville, OH 43086-6136
Phone: 614.890.4700
Fax: 614.899.6109
Email: info@ceramics.org
Web Link: www.ceramics.org

2006 TMS Fall Extraction & Processing Meeting: Sohn International Symposium
08/21/06 - 08/31/06
San Diego, CA
Contact: TMS, Meeting Services
184 Thorn Hill Road
Warrendale, PA 15086
Phone: 724.776.9000 ext 243
Fax: 724.776.3700
Email: mtgserv@tms.org

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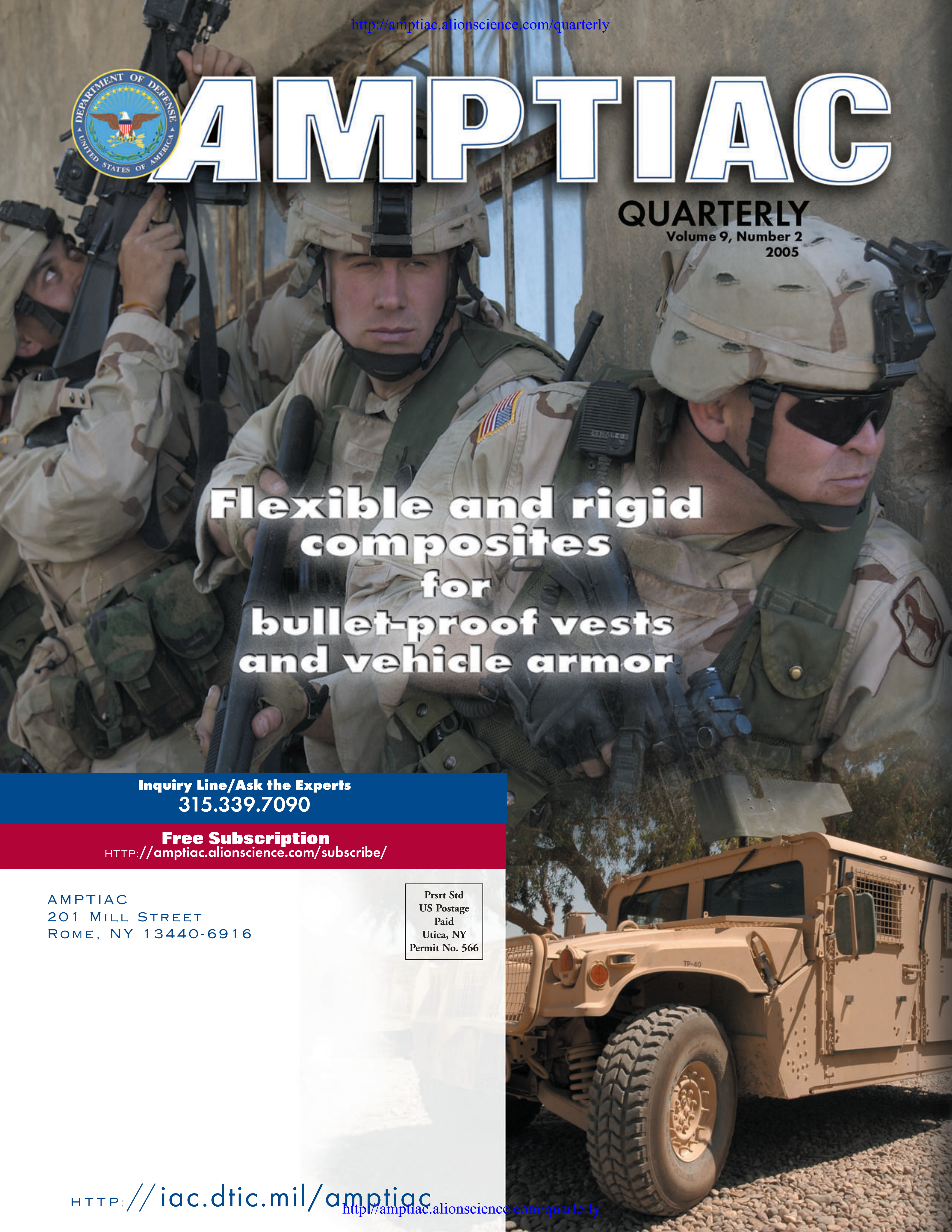

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