Development of Active Systems for Military Utilization

J. Zunino III* and H.C. Lim**
*U.S. Army RDE Command, AMSRD-AAE-MEE-M
Bldg 60 Picatinny Arsenal, NJ, james.zunino@us.army.mil
**Physics Department, University Heights,
New Jersey Institute of Technology, Newark, NJ, hcl4186@njit.edu

ABSTRACT

The US Army is transforming into a lighter yet more lethal "objective force", all while fighting wars in the Middle East. Therefore, advanced technologies and materials are being developed and integrated into current and future weapon systems. These weapon systems must be deployable, be 70% lighter and 50% smaller than current armored combat systems, while maintaining equivalent lethality and survivability. To meet these requirements Army scientists and engineers are capitalizing on new technological breakthroughs. Members of US Army ARDEC are developing active materials and sensor systems for use on various military platforms, incorporating unique properties such as self repair, selective removal, corrosion resistance, sensing, ability to modify coatings' physical properties, colorizing, and alerting logistics staff when weapon systems require more extensive repair. The ability to custom design and integrate novel technologies into functionalized systems is the driving force towards the creation and advancement of active systems. Active systems require the development and advancement of numerous technologies across various energy domains (e.g. electrical, mechanical, chemical, optical, biological, etc.). These active systems are being utilized for condition based maintenance, battlefield damage assessment, ammunition assurance & safety, and other military applications.

Keywords: Army, military, sensors, coatings, active systems

1 INTRODUCTION

In the ever-changing world that the U.S. Army's systems must operate in, there is a need for materials and systems that can thrive and survive in an almost infinite variety of environments. Recent conflicts abroad have led the Army to transform into a lighter more lethal force. This transition requires weapon systems to be deployable, be 70% lighter and 50% smaller than current armored combat systems, while maintaining equivalent lethality and survivability [1]. Army scientists and engineers are capitalizing on new technological breakthroughs in nanotechnology, MEMS, etc. to develop materials and active systems to meet these needs.

Along with these new requirements, there is a thrust to transition from scheduled maintenance to condition based maintenance in order to save resources and improve readiness. The need exists for new solutions for structural health monitoring (SHM), armament assurance, and maintenance. The ability to perform prognostic and diagnostic analyses, in real-time, is a key objective for the Department of Defense (DoD). Active coatings, materials, and structures will allow the military to add more advanced capabilities while maintaining weight and lethality requirements.

The ability to custom design and integrate novel technologies into functionalized systems is the driving force towards the creation and advancement of active systems. Members of U.S. Army ARDEC and their partners are developing such active systems for condition based maintenance, battlefield assessment, ammunition assurance & safety, and for other military utilization.

While most materials are designed to operate in predetermined conditions, advances in chemistry, physics, engineering, and other related sciences allow one to create active materials and systems with the ability to react and respond to their surroundings in real-time. These materials, composites, and coatings systems may involve numerous components or layers integrated together combining functionality and capabilities.

These active materials and systems are currently being developed for various military platforms, incorporating unique properties such as self repair, selective removal, corrosion resistance, sensing, ability to modify coatings' physical properties, colorizing, and alerting logistics staff when weapon systems require more extensive repair [2].

The research being performed will directly and indirectly support the warfighter and allow the U.S. Department of Defense to remain in the forefront of active systems technologies.

2 ACTIVE SYSTEMS

Numerous universities and government agencies are currently investigating nanotechnology, active/reactive materials, and active systems. The majority work in specialized areas for a particular need or application. Many believe that active materials and systems should be designed to meet a given goal, or perform a set function, while others feel that active systems should and can be capable of possessing numerous functionalities in one system. U.S. Army ARDEC is employing a multi-disciplined team including experts in physics, chemistry, engineering, and other sciences to develop and integrate revolutionary technologies to meet military needs.

Rather than one "be all end all" system, the approach taken is to develop numerous technologies as solutions for desired requirements. These active systems not only have to meet operational requirements but energy and cost considerations as well. The ability to tailor properties for specific applications is a key feature in the successful implementation of active systems.

Some key areas of research and development at ARDEC include color modifying coatings, flexible electronics, wireless sensor packages, nanotube development, intelligent nano-clays, alternative fuel/power sources, de-painting/self-repair, material modification, and other military capabilities.

2.1 Materials & Coatings Systems

Nanostructured materials yield extraordinary differences in rates and control of chemical reactions, electrical conductivity, magnetic properties, thermal conductivity, and strength. The small feature size allows multiple systems and functions to be incorporated together and embedded into materials such as metals, polymers, paints/films, composites, etc. This gives one the ability to work at the molecular level, atom by atom, to create smart structures with fundamentally new molecular organization and yield advanced materials that will allow for longer service life and lower failure rates. These technologies will allow one to develop customizable material and coating solutions to meet military user requirements.

There is on-going research with nanotubes and their functionalization, development, and production. Single-walled carbon nanotubes (SWCNT) are being implemented into smart coatings and inks to initiate self-healing, active switching, sensing, color modification, and other functionalities. Nanotubes are also being utilized for power/fuel cells development and electroluminescence. Solubility and polymer wrapping of SWCNTs allows these tubes to be functionalized. Such technological advances have allowed for flexible solar cells to be fabricated using nanotube inks (Figure 1).

Figure 1. Liquid Ink Solar Cell on Flexible Substrate

There are also research efforts focused on the development of chemistries to enable production of single-walled nanotubes with precise but tunable dimensions (properties). Functionalized nanotubes are also being investigated to increase strength, and other properties in composites and other materials. Increasing the strength to weight ratio of structural materials will allow for better more robust systems to be created.

Besides nanotubes, nanoclays or micronized minerals are being added to current materials and coatings to add additional capabilities. The "intelligent clay" (*i-clay)* can be incorporated into coating/paint systems (Figure 2). These i-clays or smart materials rely on their capabilities to respond to physical, chemical, or mechanical stimuli by developing readable signals. They possess the ability to modify or change their properties and structure, in response to changes in their environment. These changes are often reversible but can be designed to be permanent as well.

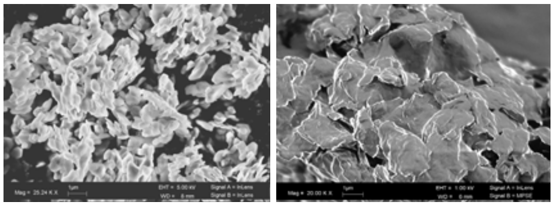

Figure 2. SEM images of sample i-clays

These i-clays can also be incorporated into inks, paints, composites, etc. to add functionalities to current coatings used on Army materiel. Currently the nanoclays (i-clays) are being incorporated in military paint systems to create active coatings. These active coating systems can detect corrosion, humidity, pH, chem/bio agents, etc. via color changes or luminescent properties.

The incorporation of i-clays to act as nanosensors for detecting degradation of coatings/paints as a result of corrosion and/or crack formation for roto-winged aircraft and other Army systems is underway. The i-clay additives are responsive to pH changes (cathodic reaction in oxidative corrosion) or oxidation through color changes as seen in Figure 3.

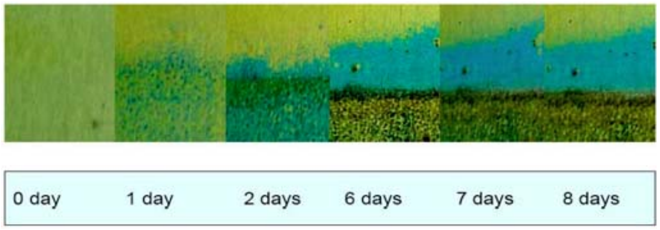

Figure 3. Results of i-clay Smart Coating in Accelerated Corrosion Test

When exposed to potential corrosion environments, the color changes before the actual corrosion and bubbling begins. Beyond the corrosion sensing capabilities, i-clay additives are also being incorporated for barrier properties, de-bonding, and self-repair capabilities. It is hoped that this research will provide solutions to corrosion related problems of military equipment, thus reducing the current multibillion-dollar expense associated with painting/de-painting operations.

Another approach to reduce the DoD's maintenance and painting costs is the development of Teflon-like nanocoatings. The protection of metal surfaces against thermal, chemical, corrosion, and biological injury without major adverse environmental effects remains a challenge. The long-term objective is to develop novel coatings that combine corrosion control, avoidance of chemical and biohazards, and other capabilities to survive harsh military operating conditions.

Metallo-organic composite materials based on a perfluorinated scaffold are of interest to ARDEC. Perfluoroalkyl polymers, such as Teflon, exhibit no C-H bonds and thus are chemically and thermally inert. However, the desired properties of such materials are also obstacles since they do not form strong polymer-metal surfaces bonds and resist the additions of other functionalities. A new, patented class of perfluorinated materials is under development. These materials incorporate metal centers in the central cavity of Phthalocyanine and unlike conventional phthalocyanines all H atoms are replaced by F atoms and -CxFy groups, Figure 4.

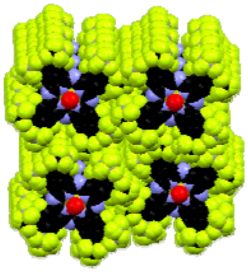

Figure 4. Bundle Assembly of Metallo-Orgnaic Phthalocyanine

These materials are especially of interest since the core is hydrophilic, yet the outer sections are extremely hydrophobic with tested contact angle measurements > 90^o. Table 1 illustrates test results of these material systems.

Substrate **Coating**	**Glass** **Coating effect (°)** **θ absolute value (°)**	**Aluminum** **Coating effect (°)** **θ absolute value (°)**	**Steel** **Coating effect (°)** **θ absolute value (°)**
$F_{64}PcV=O$	**52** **86**	**41** **99**	**26** **138**
$F_{64}PcFe$	**60** **95**	**50** **110**	**22** **132**

θ absolute value (°) for H_2O on Teflon	**115±4**
θ absolute value (°) for H_2O on Polydimethylsiloxane	109

Table 1. Results of Contact Angle Variation Tests

The Teflon-Like properties of metallo-organic polymers developed expressed high thermal, (>300^oC), and chemical resistance. Concentrated H_2SO_4, "Piranha solution" (H_2SO_4 /H_2O_2: "O"), Cl_2, and concentrated KOH were used to test chemical resistance [5]. All metal series, except for Mg showed no reaction. Further testing is underway to better understand the properties of these novel materials and their applicability for military utilization.

Another active system being developed involves thermal indicating polymers. Thermal chromic polymers are under development to alert Army logistic staff of dangerous temperature exposures. These polymers are being created and modified to change color when exposed to desired temperature stimuli. An example is a paint band placed on bullets that turn red if the round was exposed to unsafe temperature levels and maybe a safety concern (Figure 5).

Irreversible indication of the exposure of munitions in multiple thermal bands, 145^oF-164^oF, 165^oF-184^oF and over 185^oF, is possible with thermal polymers. The resulting active coating can be visualy inspected by the human eye to alert if safe temperature ranges were exceeded. More detailed information, including cumulative time of exposure in certain temperature bands, through changes in optical reflectivity can be monitored using a hand-held laser system. The thermal indicating inks and paints can be added directly or added into coating systems to monitor munition items, containers, or any other components where thermal exposure information is desired.

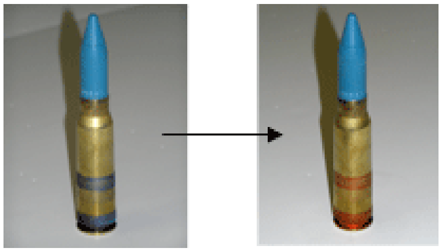

Figure 5. 50 Cal. Round After Exposure at 157^oF

These active coatings systems are capable of monitoring elapsed time-temperature/radiation profiles as well as radiation and UV exposure. This is especially of interest for the monitoring of electronic devices and munitions during transportation and storage. Many munitions become unstable when exposed to temperatures beyond their design parameters.

2.2 Active Sensors Systems

Besides active coating systems, active sensor systems are also being developed. Several military programs are developing flexible electronic capabilities for sensing, communication, data collection/storage, and power alternatives. Using novel inks and nano-materials on various substrates has allowed ARDEC to develop several types of active sensors systems. Some of the sensing capabilities include temperature, damage, scratch, flow, pressure, strain, impact, shock, pH, humidity, chem/bio and acoustics. Other sensors' capabilities are under development.

Several different fabrication and manufacturing techniques are used by ARDEC and its partners. Besides techniques common to the development of microelectronics, MEMS, and the like, material printing techniques have been developed (Figure 6). The shift from typical micro-fabrication processes, often requiring cleanrooms or similar environments, to a material printing process greatly reduces the time and cost associated with active sensor development.

A total of 9 individual sensor modules are fabricated via a materials printer as part of the Active Coatings Technologies Program. The sensor modules include a strain sensor that measures the Young's modulus of substrates' bending (Figure 7); humidity sensor that monitors the moisture of the environment; corrosion sensor that detects the salinity of the liquid degrading the structure; fuse sensor for electrical current overload; acoustics sensor for low sound pressure sensing; pressure sensor which measures the actual pressure of a chamber; vibration sensor that can actively monitor the vibration frequency and shocks during transportation; infrared sensor that is capable of detecting near and far IR radiation; and impact sensor that senses the force impulse acting on the vehicle.

Figure 6. Dimatix Printing System.

In order to ensure better film to substrate adhesion condition the flexible substrates used have been thoroughly pre-cleaned with the 3-cycle standard pre-clean procedure with Plasma Enhanced Chemical Vapor Deposition (PECVD) surface roughness modification.

These sensors are fabricated with an aqueous dispersion of the intrinsically conductive piezo-resistive or piezo-electric polymers containing organic solvents and polymeric binders, sintered nano-particles gold, sintered nano-particles silver and nano-particles carbon. The conductive polymer ink is a hole-injection material (HIM) with a conductivity of a minimum surface resistivity depending on reformulation recipe. The sensors also have good photonic stability and good thermal stability of up to ~210°C.

These sensor suites are constructed on the flexible polyimide substrate membranes of 50 micron thicknesses and encapsulated with layers of dielectric and SiNx. The dielectric layers used are flexible polyimide resist ink that is inert to the ambient environment. The sensors with the final dielectric encapsulation layers are annealed at an elevated temperature of 300º C.

The device's sensing range and sensitivity can be modified by varying the sensing element's polymer thickness. Due the nature of the inks, these sensors can be used in harsh environments such as marine (salt water), outdoor (acid rain), rapidly fluctuating relative humidity and thermal shock conditions.

The utility of the sensor suites, for various weapon system applications, with the Army is on-going. Currently, the sensors are planned for integration into the AH-64 Apache Helicopter, and planned transition to unmanned aerial systems as part of RDECOM's ATO-M, "Embedded Sensor Processes for Aviation Composite Structures" [8]. Other variations of the sensors are being transitioned for ammunition surveillance projects, unmanned ground systems, and other Army projects.

3 CONCLUSIONS

Through the advancement of active systems, capabilities can be added to military assets. This will assist the DoD to protect both national and international interests. The overall goal is to develop active systems to be utilized on current military systems and to transition technologies to the field.

The need to protect our current and future military assets is obvious. It is in DoD's best interest to use the latest technologies to advance the protection of these assets. The current and future technological advances made are leading to the development of novel materials and systems that ultimately will allow the military to advance into the twenty-first century and beyond.

Through its R&D efforts, ARDEC is helping to advance the capabilities of the Army by integrating state–of-the-art technology into and on military systems. These technologies will result in new and modernized weapons systems fielded globally that are capable of meeting current and potential challenges.

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