Development of Materials and Sensors for the U.S. Army's Active Coatings Technology Program

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ABSTRACT

In our ever-changing world, there is a need for materials that can thrive and survive in an almost infinite variety of environments. Most materials are designed to operate in predetermined conditions. Such materials are passive and unable to change based on its surroundings. With advances in chemistry, physics, engineering, and other related sciences these passive materials and coatings can and will have the ability to react and respond to their surroundings in real-time. These materials, composites, and coatings are actual systems with numerous components or layers integrated together to combine functionality and capabilities, limited only by the current state of the technologies of which they are comprised.

The Army must transform into a lighter yet more lethal "objective force", all while fighting wars in the Middle East. New technologies and materials are needed to achieve the transition. Its new platforms must be deployable, be 70% lighter and 50% smaller than current armored combat systems, while maintaining equivalent lethality and survivability [1]. To meet the lighter yet more lethal requirements of the Future Combat Systems, our scientists and engineers need to capitalize on new technologies and breakthroughs in the scientific arena. Novel technologies such as nanotechnology, MEMS, meta-materials, flexible electronics, electrochromics, electroluminescence, etc. are key components in the development of active and reactive materials for the Army.

The ability to custom build and integrate novel technologies into functionalized systems is the driving force towards the creation and advancement of active coatings systems. Active coating systems require the development and advancement of numerous technologies across various energy domains (e.g. electrical, mechanical, chemical, optical, biological, etc.). The U.S. Army is attempting to take these technologies and implement them into an active coatings system though the Active Coatings Technologies Program, thus creating the next generation of coating systems. These technologies give one the ability to work at the molecular level, atom by atom, to create large structures with fundamentally new molecular organization and yield advanced materials that will allow for longer service life and lower failure rates.

The main goal of the ACT Program is to conduct research leading to the development of active materials and coatings 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 U.S. Army Corrosion Office has assembled a team including university support as well as other military and industry representatives. This team is developing multilayered, modular active coatings with numerous functionalities such as self-repair, visual display, artificial intelligence, self-management, sensing package, and corrosion inhibitors, that can be customized as needed

Keywords**:** Active Coatings Technologies**,** Smart Coatings, Army, nanotechnology, sensors, MEMS

1 INTRODUCTION & PROGRAM DRIVERS

The coatings currently applied to tanks, helicopters, and other weapon systems need to better protect their structures and crew since design margins are significantly tighter resulting in much less room for error for these lighter vehicles. The U.S. General Accounting Office (GAO) estimates that the total cost for Department of Defense (DOD) corrosion related problems alone is $20 billion per year, $4 billion of which is related to painting and de-painting operations [2]. The coatings applied to weapon systems today lack the ability to self-correct when environmental conditions and circumstances change, and they do not have the ability to alert the user of potential anomalies such as corrosion, damage or adhesion problems.

The ability to perform prognostic and diagnostic analyses, in real-time, is a key objective for the DOD. Smart coatings, materials, and structures will allow the military to incorporate these advanced capabilities while maintaining weight and lethality requirements.

The U.S. Army Corrosion Office (ACO) at Picatinny Arsenal, NJ is addressing issues of military coatings systems by developing coatings capable of collecting, analyzing, managing, and adapting to data from the environment in real-time. If an anomaly such as a scratch or degradation from corrosion is detected, embedded sensors will analyze the data and initiate a response. The response may result in the coating self-healing if a crack exists or the coating's color patterns may change via electroluminescence and/or electrochromics to visually display corroded areas on the tank, if desired.

There have been major advances in the Active Coatings Technologies program. These advances include researching into MEMS and Nano devices in order to create coating systems that will self correct and identify areas of weakness. These devices will be crucial in the coating process; helping the Army move into the lighter realm. Self correcting coatings will significantly cut costly repairs. The research is ongoing and will continue looking at smaller electronics and related technologies that will better help the Warfighter.

2 DISCUSSIONS

The ability to custom build and integrate technologies into functionalized systems is the driving force towards the advancement of active coatings systems. Active coating systems require the development of numerous technologies across various energy domains (e.g. electrical, mechanical, chemical, optical, biological, etc.). Advancements in nano-technologies, MEMS, polymers, composites, flexible electronics, and numerous other areas allow the DOD to improve and create faster, lighter, and more lethal systems. The U.S. Army is attempting to take these technologies and implement them into an active coatings system though the Active Coatings Technology Program, thus creating the next generation of coating systems.

Nanostructured materials yield extraordinary differences in rates and control of chemical reactions, electrical conductivity, magnetic properties, thermal conductivity, strength, and fire safety. The small size allows for numerous 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 coatings solutions to meet military user requirements.

The ACO has assembled a team including university support as well as other military and industry representatives. This team is developing multilayered, modular active coatings with numerous functionalities such as self-repair, visual display, artificial intelligence, self-management, sensing package, and corrosion inhibitors, that can be customized as needed. An illustration of the Smart Coatings System is depicted in Figure 1.

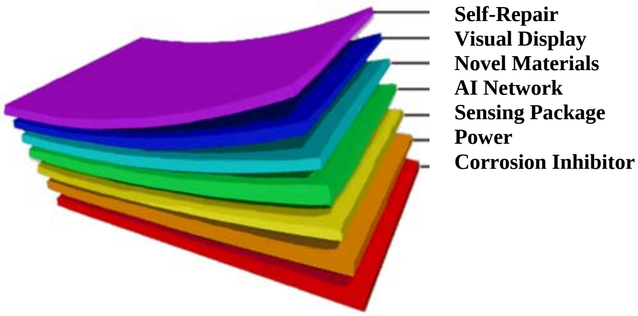

Figure 1: Smart Coatings System

For example, an Active Smart Coatings System will be corrosion resistant and consist of embedded flexible sensors capable of: 1) collecting data from the current surroundings, 2) processing and managing data, and 3) transmitting data real-time to onboard and/ or monitoring sites. When an anomaly or defect occurs, the coating or material will alert the user allowing for condition based maintenance rather than scheduled based, resulting in cost and time efficient repairs. This transition will save the DOD valuable man power, time, supplies, and money.

There are numerous universities and government agencies working on active/reactive materials and active coatings systems. Most are trying to work in specialized areas to develop active coatings for a particular need or application. Some believe that active coatings should be designed to meet a given goal, or perform a set function, while others feel that active coating systems should and can be capable of possessing numerous functionalities in one system. The US Army ARDEC along with researchers from the New Jersey Institute of Technology (NJIT), Clemson University, and several other partners are steadily working towards developing a Active Coating Systems as described above. The multi-disciplined team includes experts in physics, chemistry, engineering, and other sciences trying to develop and integrate revolutionary technologies into an active coating system to meet military needs.

2.1 Development of Materials and Sensors

The development of new and advanced materials and sensors is a key are key requirements to develop active/reactive systems. As part of the Army's Smart Coatings and Active Coatings Technologies Programs, a vast array of materials and devices are being research and developed. To date, several working prototype modules have been developed under these programs. Areas of research have and will continue to 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 technologies capabilities desired by the military.

The materials and sensors developed will allow the DOD to increase capabilities by adding functionalities to current and future systems. These added capabilities will allow for real-time structural health monitoring of systems, advances in non-destructive evaluation, and cost and time savings for military and commercial sectors.

2.2 Nanotube Development

One area of research involves working 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. A corrosion-barrier coating system with an active p-n (positive & negative doped) junction layer at the bottom and a passive top layer has been fabricated. The resulting charge modulation of the junction coating provides active corrosion protection as well as corrosion sensing capabilities.

Nanotubes are also being utilized for power/fuel cells development and electroluminescence. The use of p-n junction SWCNT coatings as photovoltaic modules with the bottom layer functioning as a proton exchange membrane (PEM) fuel cell will provide power while electroluminescence serve as a modifiable display. Solubility and polymer wrapping of SWCNTs has lead to the ability to functionalize these tubes. Such technological advances have allowed for flexible solar cells to be fabricated using nanotube inks (Figure 2). Beyond that, is the development of chemistries that enable the 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 or structural materials will allow for more robust systems to be created. Work is also being performed to develop cost effect methods of development and scale-up of SWCNT production reducing the cost and making such materials practical and affordable.

Figure 2. Liquid Ink Solar Cell on Flexible Substrate

2.3 Color Modification

Color modification methods include using electrochromics, electroluminescence, intelligent clays (i-clays), nanotubes, and chemical additives to control and adapt color change capabilities on demand. Chromic materials may radiate, loose color, become translucent/transparent, or just change properties induced by external stimuli.

The chromic materials for the Smart Coatings Prototype (Figure 3) were chosen and integrated to change color to alert of a problem, then change back to their initial state once the stimuli was change or removed (Figure 4).

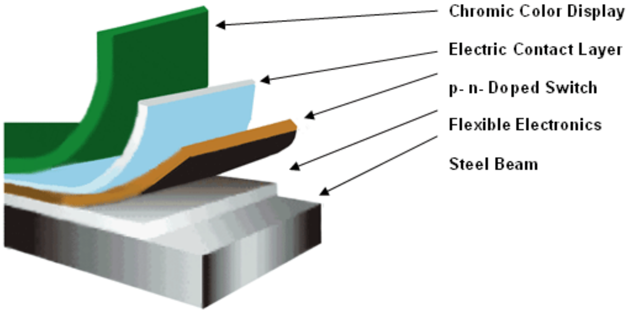

Figure 3. 2005 Smart Coatings Prototype Schematic

Figure 5. Chromic Color Response

Other chromic materials are used by the ACT Program to change color and remain in that state to serve as a marker or warning. Thermochromics are being developed to alert Army logistic staff of dangerous temperature exposures. These active coatings are capable of monitoring elapsed time-temperature/radiation profiles. This is especially of interest for the monitoring of devices and munitions during transportation and storage. Many munitions become unstable when exposed to temperatures beyond there design parameters.

Monomers of conjugated polymers are being optimized to provide color indicators to alert logistic staff when temperature exposures exceed safe levels. An example is a paint band placed on bullets that turns red if the round is exposed to unsafe temperature levels and maybe a safety concern (Figure 6). The indicators will also provide duration of exposure by quantitative monitoring of light reflection or absorption from the coatings using light from a hand-held laser.

Figure 6. 50 Cal. Round After Exposure Over 157^{o}F

Nanoclays or micronized minerals may also be incorporated into active systems to add additional capabilities. The “intelligent clay” (*i-clay)* can be incorporated into coating/paint systems. 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. Responses may range from simple sensing, to advanced corrective action such as self-repair**.** The addition of i-clays and other materials can convert passive coatings into active coating systems. There are numerous applications for i-clays including, protection of materials, membranes for controlled drug release, coatings, chromic applications, sensitive and selective sensors. The creation and development of intelligent nanoclays (i-clays) for corrosion, humidity, pH, & chem/bio agents via color changes or luminescent properties within active coatings is also underway. These i-clays can be incorporated into inks, paints, composites, etc., to add functionalities to current coatings used on Army materiel, automobile, planes, ships, etc.

Active Smart Coatings integrated with i-clays were tested to demonstrate "early warning of corrosion" sensing capabilities and barrier properties. The ability to sense corrosion and material degradation, at the molecular level, allows i-clays to serve as an early warning system to alert users when and where corrosion occurs. It is hoped that this research will provide solutions to corrosion related problems of military equipment, thus reducing the current multimillion-dollar expenses associated with painting/de-painting operations.

2.4 Integrated Sensor Systems

The ACT and Smart Coatings, as well as others military programs, are developing flexible electronic capabilities for sensing, communication, data collection/storage, and power alternatives. Flexible electronics have been developed allowing us to create several types of flexible sensors. Some of the sensing capabilities include temperature, damage, scratch, flow, pressure, strain, impact, shock, pH, humidity, and acoustics. Other sensors capabilities are under development. The sensors will be selected and integrated into a tailorable sensor suite to develop custom systems and smart structures. Added capabilities will allow for real-time structural health monitoring of systems, advances in non-destructive

These technologies and modules are designed to be integrated into active coating systems to have these coatings possess desired functionalities. The ability to have active, adaptive coatings systems that act more like a living entity than a typical passive coating system allows the coating to be utilized for military and civilian applications.

The ACO, along with NJIT, has developed prototype systems to assist with structural health monitoring and condition based maintenance. The embedded electronics can potentially sense changes in the beam in real-time and alert the user of anomalies such as damage, corrosion, cracks, etc. allowing non-destructive testing and evaluation. The data can be collected and saved or used as an early warning system giving real-time status of the supports.

CONCLUSIONS

As technologies are developed and advanced, more capabilities can be added into military systems helping the U.S. Department of defense protect both national and international interests. The overall goal is to develop 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 advances made in nanotechnology and MEMS 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. Corrosion, material degradation, and coating failures are a serious cost driver for our military. Current coatings on military systems are not capable of self-sustainment, or alerting the user of potential anomalies that can cost the DOD billions of dollars per year as well as the loss of equipment and lives.

The Active Coatings Technologies Program is helping to address this issue 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.

REFERENCES

[1] *Future Combat System (FCS)*: Article. www.globalsecurity.org.

[2] *Cost of Corrosion Report to Congress Jan 02:* National Association of Corrosion Engineers (NACE) 2002.

[3] Research performed on the *Technology Demonstration for the Prevention of Material Degradation Program*, U.S. Army Corrosion Office, U.S. Army ARDEC-RDECOM, Picatinny Arsenal, NJ.

[4] Research performed on the *Smart Coatings™ Materiel Program*, U.S. Army Corrosion Office, U.S. Army ARDEC-RDECOM, Picatinny, NJ.

[5] J. Zunino III, et al. *U.S. Army Development of Active Smart Coatings™ System for Military Vehicles,* NSTI, Nanotech 2005.

[6] J. Zunino III, et al. *Development of Active Sensor Capabilities for the U.S. Army's Active Smart Coatings System,* 2005 Tri-Service Corrosion Conference. Department of Defense & NACE.

[7] "Material corrosion determination via Young's modulus measurement using flexible membrane force sensor," H. C. Lim, M. Pulickal, S. Liu, G. A. Thomas, J. Zunino, and J. F. Federici, Sensors and Actuators A.

[8] "Environmentally Friendly Methods for Polymeric Paint Removal," W. Feng, K. Park, Y. He, J. L. Zunino III, M. Xanthos, Polymer Processing Society