Keynote Paper

Nano-technology for armor: hype, facts, and future

Mick Maher, Defense Applied Research Project Agency,
650 Randolph St, Arlington, VA 22222

ABSTRACT

Over the past two decades, nanotechnology has offered the promise of revolutionary performance improvements over existing armor materials. During that time there was substantial effort and resources put into developing the material technology and supporting theories, with only limited emphasis placed on understanding the ballistic event, mechanisms that drive armor performance, and the dependent nature of the threat. As a result, this large investment in nanotechnology for armor has not produced improved performance on the ballistics testing range, and armor nanotechnologies have never been fielded.

No matter what the platform, armor systems have several functions that they have to perform in order to function properly. In order to defeat a threat, armor systems are designed to: deform/deflect the threat; dissipate energy; and prevent residual debris penetration. To date there is no definitive answer as to what material properties drive the system behavior of these functions at high rates in response to a specific threat, making the adaptation of nanotechnology that much harder. However, these functions are now being considered with respect to the material system and armor mechanism being utilized, and nanotechnology is beginning to be shown as an effective means of improving performance.

When looking at the materials being used today, there are examples of nanotechnology making inroads into today's latest systems. Nano-particles are being used to manipulate grain boundaries in both metals and ceramics to tailor performance. Composite materials are utilizing nanotechnology to enhance basic material properties and enhance the system level behaviors to high rate events.

While the anticipated revolution never occurred, nanotechnology is beginning to be utilized as an enabler in the latest armor performance improvements.

KEYWORDS: Armor, Nanotechnology, Ballistics

1.0 INTRODUCTION

Material scientists have been looking to exploit the fusion of increased computational power, novel synthesis methods, and greater understanding of material behavior through new characterization techniques to realize the potential of nanotechnology for over twenty years. Due to the conflicts in Iraq and Afghanistan, there were significant efforts to use nano-materials in armor during this period. To date, none of these efforts have been successfully transitioned to an acquisition program.

The organized insurrections in both countries created a new environment for our warfighters. Asymmetric warfare denied a safe zone. Insurgents had closed the range on a ground vehicle engagement from 2 kilometers to 2 meters. Targets were no longer selected for military value alone, but to maximize disruption to operations, deflate morale, and manipulate public opinion. Suddenly, the protection of vehicles and personnel that were never meant to be in harm's way had become a top priority.[1]

By 2003, nanotechnology had enjoyed over a decade of increasing funding and attention as the promising technology of the future. At the time, the technology was advancing steadily but very few of the potential benefits had

Micro- and Nanotechnology Sensors, Systems, and Applications IV, edited by
Thomas George, M. Saif Islam, Achyut Dutta, Proc. of SPIE Vol. 8373, 83731P
· doi: 10.1117/12.923025

been realized. In fact expectations for the technology were set extremely high even while the technology was at a very low level. The technology was expected to have revolutionary impact on the technical community. In 1991 Charles Joslin reported, "There's no doubt in my mind that nanotechnology and nanoscience will be to the 21st century what genetic engineering has been to the last two decades of this century, and probably more".[2] Members of this community may have felt compelled to demonstrate a quick and visible success to justify the elevated funding levels and attention that nanotechnology was receiving.

Vehicle armor technology is very unique, if not from a requirements perspective, from a business case perspective. If successful, the technology will be subjected to classification issues since it clearly has an impact on the vehicle's performance and vulnerability. Security requirements between armor research, engineering development, and acquisition require intimate knowledge of the relevant security class guides. Technically, armor research involves understanding of threats, material behavior, and engineering mechanisms, all at high rate. Traditionally, this has been accomplished through an Edisonian approach, limiting the number of sites that have the capability to provide the full spectrum of services to take a technology from basic research to fielded solution. Finally, armor funding levels have been very cyclical. The interest in, and focus on, armor from both the academic and commercial sectors has followed these cycles. For these reasons, armor technology is one of the few technologies where the expertise and knowledge base resides within the government.[3] While small, the involvement of this community is essential to be successful.

Nanotechnology was about to be thrust into an area where it wasn't ready to support. It was a perfect storm, where the nanotechnology community wanted to prove its worth, the military desperately needed a solution, and the expert community was overcome by the increased activity requiring their technical support. It should also be noted that the majority of the efforts were legitimate; however, there were nanotechnology projects where the proponents' expertise was neither in nanotechnology or armor, and were the direct result of the availability of funding. These projects would ultimately reflect poorly on the community.

2.0 THE HYPE

Using nanotechnology for armor was first seriously considered around 2002. In fact there was an Army Research Office workshop in 2001 that considered nanotechnology to enable a 500% increase in ballistic performance at 20% of the weight. In addition to this benefit, nanotechnology was also championed as an enabler of: chameleon camouflage; exoskeletons; interactive multifunctional clothing; energy harvesting, conversion, and storage; and finally waste disposal, recovery, and recycling.[3]

The interest in nanotechnology for protection began with the potential for these technologies to improve the structural performance of the armor materials. This quickly became entwined in the multifunctional aspects of the technology pitch. Even leaders of nations were becoming involved; for example, with President Clinton launching the National Nanotechnology Initiative in 2000 and the former Prime Minister of Israel, Shimon Peres specifically addressing soldier nanotechnology saying, "A nano-uniform for American soldiers will be lighter than cotton, but protect them against bullets and gas, regulate their body temperature, and enhance their strength. They can easily lift 120 kg. with one hand. This new uniform will be available in three years".[4] The suit should have been available in 2007. The hype raised many concerns among the armor community. It was difficult enough to develop and field armor, never mind including all the multifunctional and system integration that these new technologies would require. More importantly, metrics and performance were being quoted without any test data to support the claims and with little understanding of the ballistic event.

Understanding the ballistic event was a source of particular frustration for the armor community. Armor solutions start with the threat. Technologies were being pushed without regard to threat. It was not out of the question to see the results for a 9mm hollow point lead bullet solution get scaled up for shape charges, IEDs, and long rod penetrators. Many of the new nano-armor designers failed to recognize that even among a single caliber, there are many types of bullets with very different performances. In addition, the effects of rate were often overlooked or were compared to an inappropriate scale. The blast community is currently being inundated with solutions that do well for car crashes. A blast event is an order of magnitude faster.[5]

The case was being made that better properties made better armor. One of the biggest issues is that, even today, it is not clear what properties need to be enhanced to improve armor performance. Nanotechnology for armor has been focused around the three main classes of materials used for armor; composites, metals, and ceramics. Composite technologies have included using carbon nanotubes (CNT) as matrix filler and a reinforcing material, with and without more traditional fiber reinforcements. In addition inorganic nanoparticles have been used as matrix fillers and modifiers to the reinforcing fibers. The metal and ceramic nanotechnologies have included using CNTs and inorganic nanoparticles to modify and interrupt the grain structure of the base material. The reference to nanotechnology has also included the control of microstructure through processing of these materials. All of this effort was developing better static mechanical properties without regard to rate effects yet those same properties were being used to sell nano- as the next armor technology. Contributing to the hype effect is that often, the quoted properties were theoretical and had not been realized experimentally.

Good armor solutions are often a combination of materials and mechanisms. This is necessary to avoid designing a finesse solution that addresses only one threat or one set of conditions. Finesse solutions can be tempting because they often test as the most efficient standalone solution. The efficiency is lost when the solution gets integrated onto a vehicle and requires more weight or additional mechanisms to provide robust protection. The complexity of the armor solution is what complicates the material property question. Even among a single mechanism passive armor, the various material layers perform very different functions and require very different properties as seen in Figure 1. The strain rate at which these layers are engaged is even complex, in that there are orders of magnitude difference between impact and the final effects of the event.

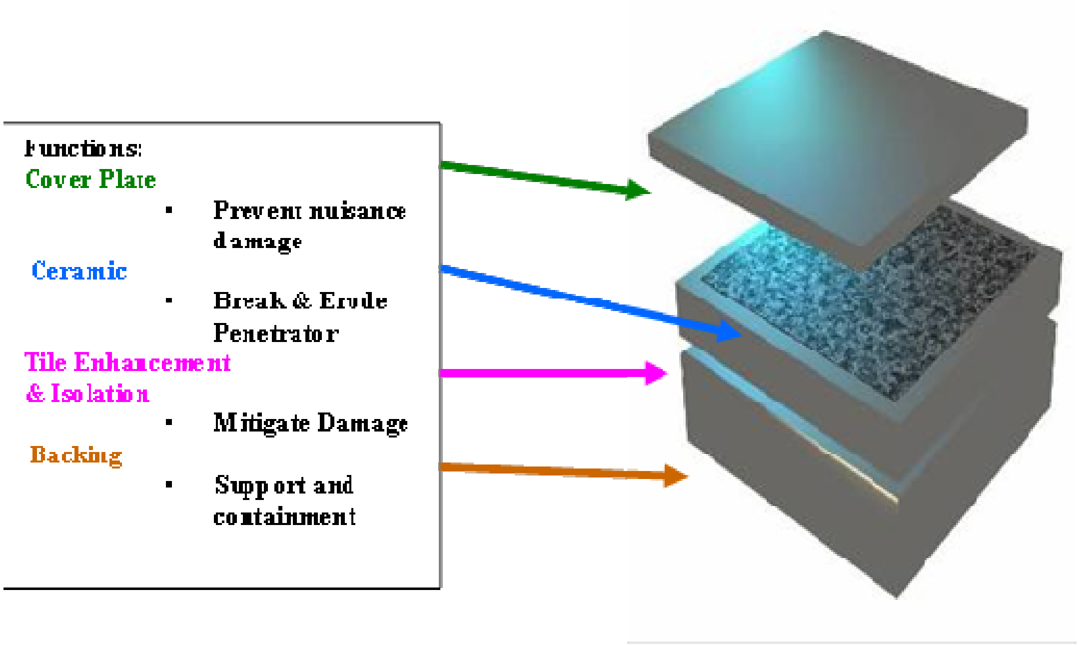

Figure 1: Representative passive composite armor layers and associated functions.

Technologists, not just nanotechnologists, often overlooked the constraints of the application. Armor and structure make up to 30-50 % of a vehicle's gross weight.[6] In addition, whether body armor or vehicle armor, the unit volumes can be significant. From 2007-09, over 12,000 MRAP vehicles were produced.[7] The sheer volume that would be required to satisfy the end use requirement was not considered in many of the nanotechnology pitches. The pull that created the need for new technology approaches was now becoming the bane of nanotechnology. CNT-based solutions were between one to four orders of magnitude higher price than the incumbent they were trying to replace. Not only was this not acceptable to acquisition community but it was unaffordable for the R&D community. Due to the scale and quantity of test articles, the cost to produce and test one material could easily consume an organization's research budget.

What testing was done did not support the claims that nanotechnology would improve armor performance. It was becoming increasingly apparent that the incorporation of nanoparticles into any of the systems was acting as a failure initiation site. While the damage zones were greatly reduced, the actual performance of the armor material was reduced. The ability of the nanotechnology community to engage the armor community was impeded by the lack of understanding of the projectile defeat mechanisms, the mechanisms by which armors fail, and how to interpret the test results. The hype shifted from potential to excuses.

The nanotechnology community underestimated the responsibility that goes with armor research especially during this time of great need. The technology maturity of these armor solutions was very low yet they were often sold as vehicle ready. In truth, there was very little data beyond static property data. The material coupon and ballistic panel portion of the development cycle was bypassed and point solutions were being presented based on the researchers' past experience, correlation to existing solutions, and their intuition. Little regard was given to the materials repeatability, availability, and any scale-up that would be required if the armor solution was successful. A concern among the armor community was raised about would happen if a solution was successful. Now the military knew a solution was available but there was no path to support the certification, efforts and supply chain to support the warfighter. The century had begun with nanotechnology portrayed as the technology of the future now triggered a guarded response from the reviewers.

3.0 CURRENT STATE OF ARMOR AND NANOTECHNOLOGY

With operations overseas winding down and the corresponding decline in attacks, the focus on armor has diminished. Armor funding has remained relatively steady with research focus moving from supporting current operations to addressing fundamental research in armor materials and mechanics. Nanotechnology for armor still continues but with a focus on understanding fundamental material behavior. With the communities returning to the areas of expertise and engaging in real collaboration, more progress has been made in the last two years than the previous decade. The focus on desired functionalities from the armor mechanics and materials perspective, is giving the nanotechnology community areas where the technology can be appropriately applied. Nanotechnology now has a place on the development roadmap for each of the major material classes with efforts in characterization, processing, and modeling.

Both, the armor and nanotechnology communities are currently working together on understanding the effects of nano- particles and microstructures in ceramics and ceramic matrix composites on high strain rate behavior. By not focusing on an armor solution, significant advances have been made in developing material models that represent the processing and high strain rate behavior. These models have enabled insight into how these particles can be used as controlled defects to toughen the response of these materials as a strike face. This is useful since the ceramic is being used as a strike face to break up and erode the penetrator. Toughening of the ceramic material enables the material to remain intact and engaged with the penetrator and thereby improve the ballistic performance theoretically. Other research is looking at the processing and how this can be used to control particle dispersion and microstructure.

Similar efforts are being conducted for metals and metal matrix composites. This class of materials can be used in multiple layers of the armor solution; from strike face through the backing. While the focus on the ceramic research has been how to use nanotechnology to toughen the behavior, the metal research has been on increasing strength. An example of a successful development is the work done on trimodal aluminum. Through a coordinated effort that involved multiple scale behaviors a material was developed that has strength approaching rolled homogenous armor at aluminum weights as shown in Figure 2.[8]

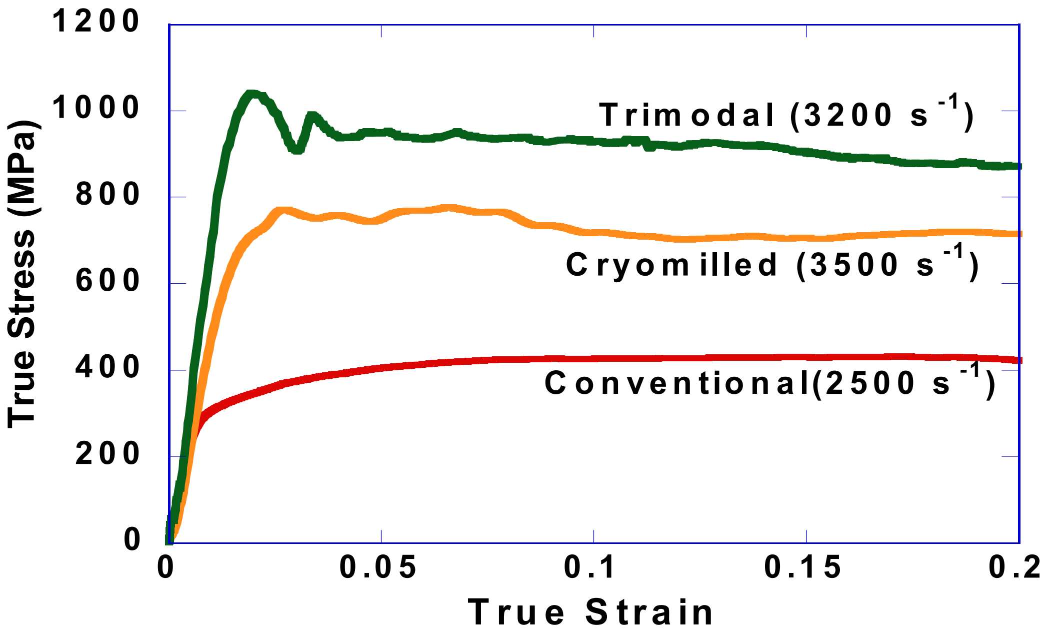

Figure 2 – Trimodal aluminum stress-strain comparison

Nanotechnology and composite materials have produced the most significant collaborations. Composite and hybrid materials by there very nature enable the incorporation of nanotechnology through its components such as the reinforcement or matrix materials. Research efforts are being conducted on particle dispersion, particle-fiber interactions, low-cost CNT production, CNT reinforcement behavior, and nanomaterials as a fiber component. One of the most successful efforts has been the assessment of how nanoparticles at the fiber-matrix interface interact with the reinforcing fiber. Studies have been conducted from the basic research on the indentation charecteristics of ballistic fibers to evaluation of fiber textures on ballistic performance as seen in Figure 3.[9]

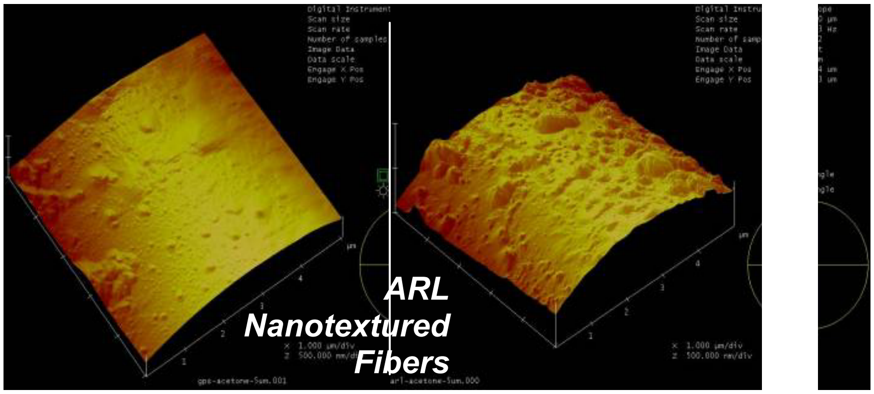

Figure 3- Comparison of fiber textures

4.0 FUTURE DIRECTIONS

With refocus on fundamental research, actual shortcomings of nanotechnology are being addressed. In particular, the computational tools are being developed to gain better insight into the behavior of the materials under high strain rate conditions. Integrated computational materials science and engineering (ICMSE) is becoming an essential tool in the design of these material systems and how they can be incorporated into armor. Also, the issue of cost is now being addressed with a new focus on material formats, large scale batch production, and continuous production.

With the breadth of threats, environments, and platforms that armor technology has to address, armor will never be a single material solution. Instead, armor systems are envisioned to be a combination of active and passive solutions with multiple materials providing specific functionalities to enable the desired performance. Nanotechnology is seen as a key enabler with ability to offer improved electrical and mechanical properties, increased surface area, and functional control at the nano- and micro-scale. The key is to smartly integrate the technology to maximize the desired effect.

The integration of nano-materials is expected tobe greatly enhanced with the increased use of ICMSE methodologies. The ability to use the increased computational power with new experimental techniques to understand and gain insight how materials behave at high strain rates at the nano- and micro-scale is expected to enable armor designers to make the most effective use of nanotechnology.

The increased focus on the production of nanomaterial is expected to bring the costs of integrating these materials into armor systems more in line to what the platforms can bear. There have been two thrusts that have been critical in this area. The first is developing the processes to produce nanomaterial at a much lower cost. This includes new synthesis routines, as well as replacing batch processes with continuous processes. The second approach has been to provide nanomaterial in a format that is more easily integrated into final solutions. This includes blended powders, “fuzzy” fibers, fiber mats, preconsolidated sheets and ingots.

Finally, as nanotechnology has matured technologically as an industry, the armor community is becoming more confident about using the materials. For this reason alone, the application of nanotechnology in armor looks promising. From a technological standpoint, the behavior of these materials is now much more understood with experimental data to support the benefits and weaknesses in a given application. From a business perspective, nanotechnology companies are now focused on how they market into a system, not provide the solution.

5.0 CONCLUSIONS

Early on, the application of nanotechnology was poorly managed. The armor community had become very jaded after many years of promising presentations, followed by supplied positive results that created more questions, only to be disappointed by a failure on the range. As the technology has matured, researchers and engineers from both communities have put that rocky start behind them and are now looking at the fundamental science and engineering of both the material and the application to enable their use. In addition, as the nanomaterial supply chain has become stable and focused cost, there is promise that it could become affordable as an armor material. While not ready for armor acquisition programs now, nanotechnology is now on a much better path to integration, and maybe meets the promise of twenty years ago.

6.0 ACKNOWLEDGEMENT

The author would like to acknowledge and thank Dr. Ernie Chin and the US Army Research Lab for their support and assistance in providing information that allowed for the completion of this paper and associated presentation.

7.0 REFERENCES

[1] Martin, J., "Dragon's Claws: The Improvised Explosive Device (IED) as a Weapon of Strategic Influence," Master's thesis: Monterey, CA: The Naval Postgraduate School, December 2007.

[2] Joslin, C., "Trends, Forecasts, and Analyses", Inside R&D, 20, No. 35, pg. 2 (1991).

[3] Army Research Office (2001). Nanoscience for the Soldier Workshop, Army Research Office. 2001.

[4] Malsch, I., "Shimon Peres dreams of a nanowar," http://www.nanoforum.org, news, Apr. 16, 2004.

[5] Tank Automotive Research, Engineering and Development Center (TARDEC), Materials for Ground Vehicle Survivability Workshop, TARDEC, 2011.

[6] Ibid.

[7] Nathan Hodge, "U.S. Army Looks to Boost MRAP Procurement," Jane's Defence Weekly, 16 May 2007

[8]Cho, K, **"**Trimodal Aluminum Composites for Survivability", Nanotechnology for Defense Conference, 2009

[9] Jensen, R., McKnight, S., "Nano-Textured Fiber Coatings for Energy Absorbing Polymer Matrix Composite Materials", Proceedings for the Army Science Conference (24th), 2005