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Foreword

Army focused research team on functionally graded armor composites

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Abstract

With the emphasis on smaller but more mobile combat forces to meet a broad range of mission requirements, future weapon platforms and upgrades will require materials to do better, do more, weigh less, size less and cost less. Metal matrix composites (MMCs) are such material candidates for niche Army applications such as armor, armaments, and vehicle structures. Under the shadow of shrinking resources, a focused research team (FRT) composed of the US Army Research Laboratory (ARL), academia, and small business was assembled to address MMC issues for Army applications. The immediate focus of this team is on the development of MMCs with a tailored ceramic-to-metal through-thickness gradient known as functionally graded armor composites (FGACs). The goal is to provide the science and technology to deliver a high space and mass efficient armor material for ballistic protection against light to medium threats. Technical issues being addressed by this team encompass the role of microstructure in affecting the dynamic flow and ballistic performance of FGACs, high-resolution non-destructive evaluation (NDE) techniques, joining FGACs to dissimilar materials, and the availability of versatile low-cost near-net-shape processing of FGACs. In this paper, highlights from these activities are presented. They include high-strain-rate testing and modeling, apertureless near-field optical scanning microscopy (ANSOM) of FGACs, micro- and nano-scale self-propagating high-temperature synthesis (SHS) reactions, ballistic evaluation, and pressure assisted casting. These efforts represent key technologies necessary for prompt delivery of FGAC technology to the warfighter.

Keywords: Weapon; Metal matrix composites; Army; Armor

1. Moving toward the 21st century

The fall of the Berlin Wall marked the beginning of a new era of changes in US military strategies. The need to deter global nuclear warfare and direct major conflicts are no longer a high-priority threat. Recent US military missions in Panama, Southwest Asia, Somalia, Haiti, and Bosnia illustrated the advantage of well-prepared, small, mobile, and lethal combat forces that can rapidly respond to a broad range of missions in limited regional conflicts. These anomalous post-Cold War transformations have also highlighted the need to strategize and assess warfighting requirements to win future conflicts. The Army After Next (AAN) project was established by the Army in 1996 to develop a vision of future Army requirements looking out 25–30 years. Early results from this study have pointed toward the need for physically agile forces with 'leap-frogging' technologies in support of the air mechanization concept to counter and overmatch emerging major threats [1,2].

The lack of a major power that can pose a legitimate threat in the near future has catalyzed a series of deep defense budget cuts in recent years. Expenses from unplanned military operations have further deepened the cuts into defense investments in the Research Development Test and Evaluation (RDT&E) Budget. The defense RDT&E FY98 budget request is 24% less than that for FY89 [3] Further cuts are anticipated following recommendations from the quadrennial defense review [4].

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2. Meeting the challenge

With this severe funding constraint, defense research and development (R&D) policy makers are under tremendous pressure to establish a balanced investment portfolio to meet the technological needs for a more mobile and lethal force in the near future and a long-term stake in incubating innovations to overmatch difficult to predict threats. This challenge imposes the need to promote R&D in paving the road for readiness in short-term and long-term technology insertion. This is reflected in the Army's science and technology master plan. In addition to the requirement that Army R&D programs must meet the warfighter's needs and be backed by strong user involvement, the commercial prospectus with spin-off and spin-on potentials of this technology is also appealing. Consequently, defense laboratories are now undertaking this complex challenge while battling enormous political constraints and an ever-eroding budget. Scientists and engineers are engaged in not only identifying and conducting 'good' research, but developing the infrastructure necessary to transition science and engineering its technology to the users expeditiously. In order to "execute fundamental and applied research to provide the Army the key technologies and analytical support necessary to assure supremacy in future land warfare" [5], the Weapons and Materials Research Directorate (WMRD) of the US Army Research Laboratory (ARL) formed extended laboratory collaborations (ELCs) with focused research teams (FRTs) to meet this challenge.

3. Extended laboratory collaboration

Part of the solution to meet both near- and long-term R&D requirements is a cohesive strategic plan for smart selection, promotion, and acceleration of basic research programs. A key role of ARL is to identify, advance, apply, and transition fundamental breakthroughs to technological capabilities accessible to Army acquisition. This is particularly challenging for materials technology. Since it is an enabling technology, materials successes are often shadowed by the enhanced capabilities of the material system. Recent funding cuts have limited the broad investment necessary in basic research. The purpose of the ELC is to provide a strategic 'seeding ground' for Army-unique sciences and opportunities to leverage resources in addressing key technical challenges under today's fiscal reality.

The ELCs are collaborative university-ARL programs in well-defined science and technologies with high-payoff potential for meeting future Army requirements. A critical ingredient to the success of ELCs is the day-to-day collaboration between the Army researchers and the university professors, post-doctorates, and graduate students. This interaction is facilitated by 'cooperative research agreements' (CRA) between ARL and universities. Research projects under the ELC umbrella have a concise scientific transitional path into Army's in-house efforts directly tied into research and technology objectives crucial to future warfighting capabilities. The ELCs provide a platform with a process and infrastructure established to stimulate and capture ideas, as well as to expedite development of high-payoff innovations.

The Weapons Materials Division (WMD) of ARL has three ELCs: the Dendritic Polymer Materials Research Program at Michigan Molecular Institute, the Advanced Materials Characterization Collaborative Program at Johns Hopkins University, and the Composite Materials Research Program at University of Delaware. These programs encompass a high-payoff portfolio that addresses the need for lightweight metallic, ceramic, and polymeric composites for armor and armaments, and barrier materials for chemical-biological protection. Under these programs, WMD coinvestigators provides the strategic focus for bridging innovations and fundamentals with Army relevancy. An 'open' laboratory environment is fostered to maximize ARL scientist–faculty–student interactions. WMD and ELC collaborators are coupled as coinvestigators and have mutual access to complimentary equipment at their respective university and Army research facilities. When appropriate FRTs are formed to accelerate specific short- and long-term programs with high technological transition potentials, it often involves extended collaboration between academia, government, and industry. One example of this collaboration is the FRT on functionally graded armor composites (FGACs).

4. Army focused research team on functionally graded armor composites

4.1. Rationale

Weight reduction for present and future Army systems is critical to rapid deployment of military contingencies. Ultralight weapon platforms will be the cornerstone for dominating the future battlefield. Some military strategists have called for radical weight reduction in future Army platforms that requires non-existent technology (Fig. 1). Novel materials, structures, and design concepts are needed to meet this 'tall' challenge. The notion of FGAC is one such materials technology on the horizon.

The concept of FGAC evolved from the development of discontinuously reinforced metal matrix composites (MMCs) for ballistic protection. Discontinuously reinforced MMCs are typically a two-component system

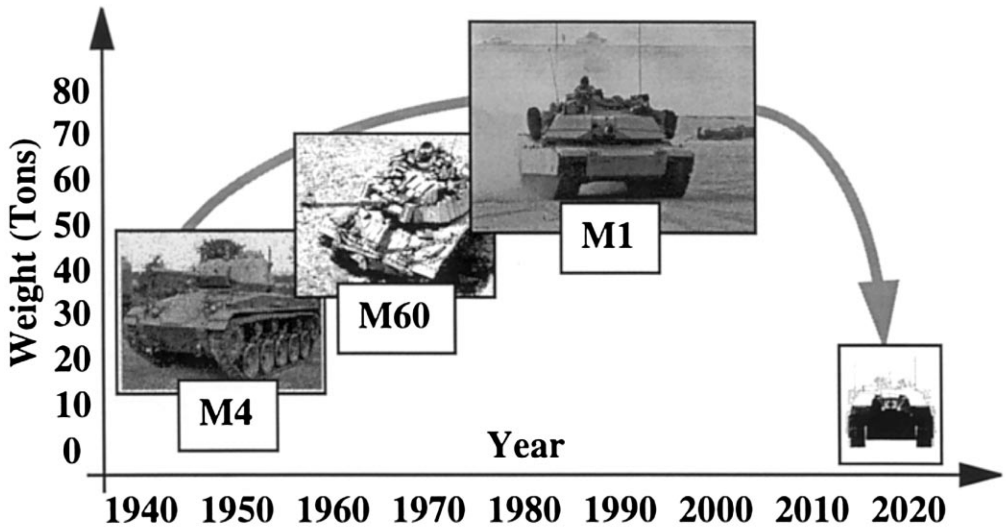

Fig. 1. Radical weight reduction for future ground vehicles.

consisting of a dispersed ceramic phase in a metallic matrix (Fig. 2).

In recent years, ceramic-particle- and whisker-reinforced MMCs have emerged as an affordable material candidate for commercial and military applications. MMC heat management packaging in electronics [6] and automotive brake and structural components are in wide use today. On the military side, MMCs are used in jetfighters as structural and high-temperature engine components. The Army is conducting applied research to further exploit MMCs for vehicle trackshoes and helicopter landing gears. The recognition of MMCs as a maturing materials technology stimulated exploratory research to investigate the armor potential of this material. Earlier studies demonstrated promising ballistic attributes for MMCs [7]. Improved penetration resistance was observed with high-strength ceramic-particulate-reinforced MMCs. The hypothesis that MMCs exhibit excellent work hardening under dynamic loading supports the observed ballistic performance [8].

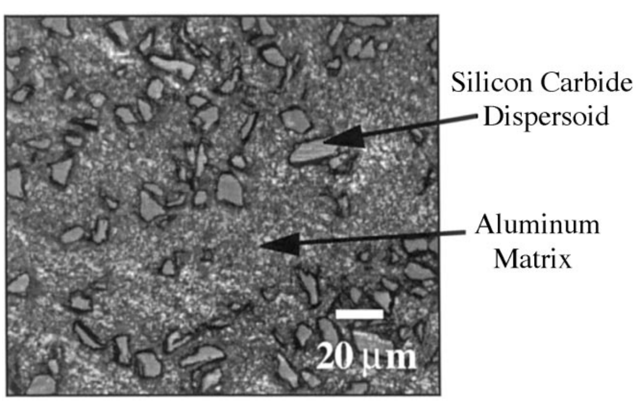

Fig. 2. Typical micrograph of a discontinuously silicon carbide particulate-reinforced aluminum matrix composite.

However, the work hardening can be limited by the microstructural damage from shock wave interactions. The concept of FGAC is intended to further enhance the ballistic space and mass efficiency of MMCs by tailoring the through-thickness incorporation and distribution of various reinforcement morphology, size, and chemistry to mitigate shock damage.

The present armor package scheme to defeat light to medium threats typically consists of a hard frontal surface and a softer backing. The hard frontal materials are typically ceramics or hardened metallics. Aluminum and fiber-reinforced polymer composites are commonly used for backing the harder frontal materials. The purpose of the hard surface is to blunt and to induce a destructive shock wave on to the projectile upon impact. The softer backing materials act as a ‘catcher’ for residual broken fragments in preventing target penetration. In this armor scheme, the hardest frontal material will typically provide the best level of ballistic protection. However, a hard material is also typically brittle and exhibits a large collateral damage area from dynamic impact (Fig. 3).

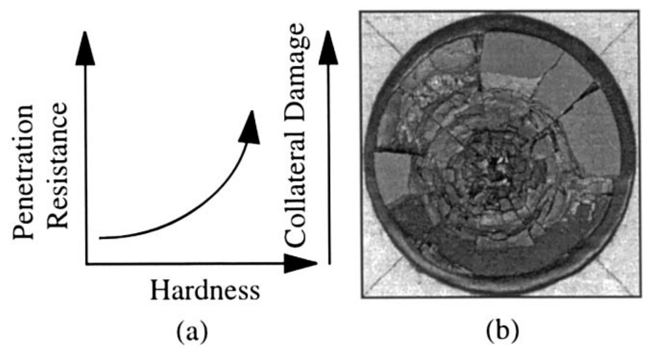

Fig. 3. (a) Typical trend in armor ceramics. (b) Typical collateral damage on armor ceramics suffered from a ballistic impact.

This limits the point-to-point multi-hit capability of such an armor material scheme. The mechanistic scheme behind FGAC is to disrupt the shock wave in order to minimize collateral damage during a ballistic event. The hypothesis is to tailor perturbations through microstructural design that prolongs projectile-through-target material dwell time. The extended dwell time promotes breakup of the projectile prior to the occurrence of complete penetration or unacceptable collateral damage of the armor material. To engineer such a material requires an in-depth understanding of the fundamentals behind the complex constitutive relationship correlating all the interacting components in a microstructure with ballistic rate loading and deformation. Furthermore, to deliver this technology to the user will require the capabiity and availability of flexible low-cost FGAC manufacturing for timely and affordable acquisitions.

4.2. Goals

The purpose of the FRT on FGAC is to emphasize and integrate basic research in MMCs with the design, fabrication, and implementation of FGAC technology. Selected technical issues were identified and are being addressed by this FRT. They include advancing the understanding of microstructural influence on dynamic responses, developing ultrahigh resolution non-destructive evaluation techniques for interfacial analysis, joining FGACs to dissimilar materials, identifying projectile-to-target material interactive mechanisms, and developing low-cost processing technology for flexible manufacturing of FGAC.

4.3. The functionally graded armor composite-focused research team

The WMD is the strategic focal point and guiding agent for FGAC-FRT. These research efforts, though tightly integrated, are organized under three activities with respect to the nature of their efforts: fundamental, applied, and process technology. The fundamental activities are primarily conducted under the ELC's Advanced Materials Characterization Program at Johns Hopkins University. The goal of this collaboration is to gain a basic understanding that will guide the design and processing of FGACs. The applied activities, a WMD in-house effort, is to fill the fundamental and the application gap in identifying and capturing breakthroughs for acceleration for specific technology insertion. The process technology focuses on developing an economically feasible and technologically flexible manufacturing capability for FGACs. Two contractors under the Army Small Business Innovative Research (SBIR) grants are active in pursuit of this goal. The WMD provides guidance and linkage among all these activities. Highlights of the fundamental activities, focusing activities, and process technology activities are briefly described next.

4.3.1. Fundamental activities

The present knowledge of the role of microstructure in dynamic deformation is very limited. There is no model today that can fully simulate nor predict deformation and fracture during a ballistic event at the microstructural level. The immediate fundamental focus of the FGAC-FRT is to develop semi-empirical models, tools, and analyses to provide qualitative material design guidance for processing FGACs.

At Johns Hopkins University, a research project is in pursuit of understanding the influence of microstructural morphologies on high-strain-rate deformation and damage accumulations in MMCs. Split Hopkinson Bar compression and tension experiments coupled with detailed microstructural analysis on aluminum MMCs are performed to develop semi-empirical models to better quantify the effects of reinforcement shape, size, and distribution on plastic flow [9]. The object of the present study is to identify and quantify key microstructural features that will dominate the dynamic response of MMCs. The strategy is to build upon the basic understanding of MMCs to develop predictive tools for designing FGACs (Fig. 4). Early results of this study also identified the need to better characterize the interfaces in MMCs. Softening due to interfacial and particle damage from high-rate loading was identified. These findings are being correlated with ballistic studies at WMD. Future work will include shock physics studies that will lead to the development of material design concept for mitigating damage in the FGAC.

To better explore the nature of reinforcement–matrix interfaces in FGACs, apertureless near-field scanning optical microscopy (ANSOM) is being pioneered at Johns Hopkins University [10]. This technique entails the analysis of optical power modulation brought on by a probe-sample separation induced by through-thickness ultrasonic signals (Fig. 5). ANSOM has the potential to hurdle characterization capability to analyze interfaces and microstructures at nano-scale resolution in air. This effort is a vital link between tailoring the interfaces to minimize dynamic damage and low-cost processing constraints in producing such an interface. Selected model systems and well-characterized MMCs are being used to explore and optimize the capabilities of this technique.

A third research effort at Johns Hopkins University under the FGACFRT focuses on the development of nano-scale multi-layer self-propagating, exothermic reaction foils, a spin-off of the self-propagating high-temperature synthesis (SHS) technology. These reaction foils can be ignited by a simple electrical spark to provide a burst of localized heat with no atmospheric

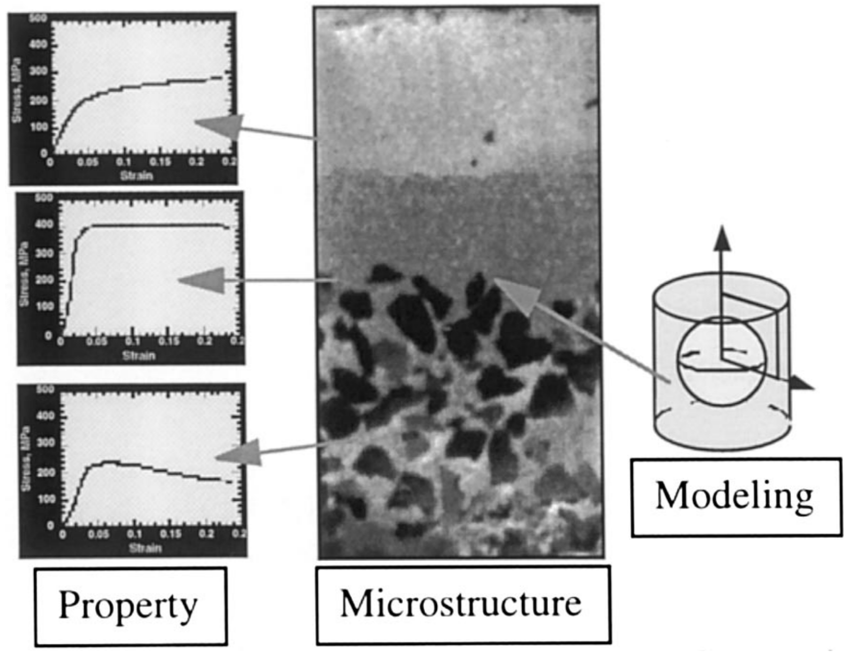

Fig. 4. Strategy to 'functionally graded armor composite design': Understanding and model the relationship between properties and microstructure.

requirements (Fig. 6) [11]. This investigation entails the application of thermodynamics and kinetics in optimizing compositional design of the exothermic reaction [12]. Availability of this technology will enable development of complex integration of various dissimilar materials into a FGAC (e.g. the use of exothermic reactions in a FGAC as a reactive protective scheme). The Army self-propagating, exothermic reaction foils are also applicable to potential field repair and joining FGAC to a wide range of structural surfaces. Furthermore, Army insertion of any such new technology in the future will reduce the logistical burden on operational repair and maintenance. Having a foil technology for modular armor repair and installation is highly desirable.

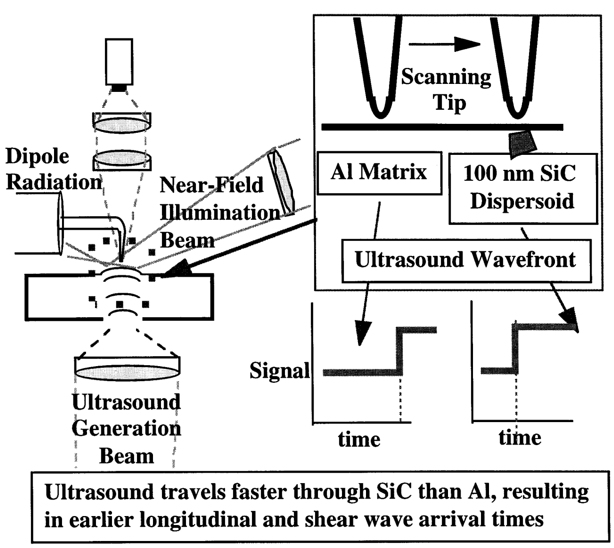

Fig. 5. Schematic of apertureless near-field scanning optical microscopy (ANSOM) for sub-micron analysis of metal matrix composites.

4.3.2. Focusing activities

The WMD is the executing organization for the development of armor materials for the Army and the Department of Defense (DoD). Over 40+ years of ballistic data and phenomenological knowledge on dynamic impact resides in WMD. As the focal point for armor materials research, this resource is coupled with military strategists to form bases for projecting future armor materials requirements. As the technical focal point for the development of FGAC, WMD guides and captures significant technological breakthroughs and further exploits these notions to meet specific immediate and future requirements for potential fielding. Ear-

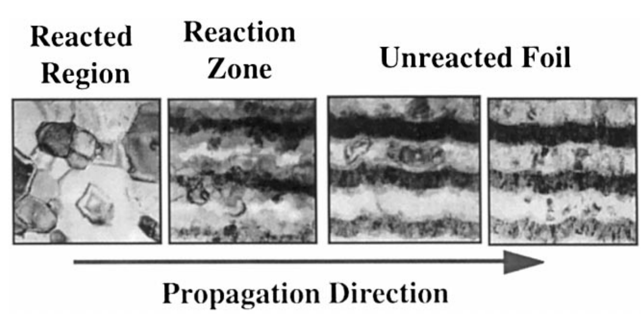

Fig. 6. Transmission electron micrographs of the reacted region, reaction zone, and unreacted region of a self-propagating exothermic nano-A-B reaction foil.

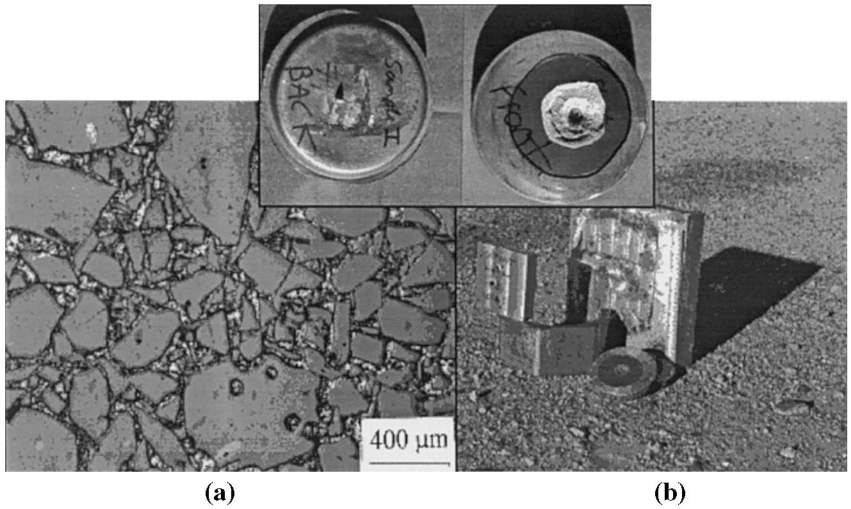

Fig. 7. (a) Micrograph and (b) ballistic plates of functionally graded silicon carbide-reinforced aluminum.

lier processing and ballistic studies on MMCs [13], along with phenomenological understanding in defeating a projectile, had led to the concept of FGAC. Research efforts are in progress to evaluate the ballistic integrity and dynamic fracture mechanisms in commercially available MMCs and FGACs. Materials produced under the process technology activities are carefully characterized and these findings are disseminated and shared among the collaborators to guide fundamental research and necessary manufacturing improvements. Future research in this activity will include microstructural and acoustic impedance studies on ultra-high-strength amorphous matrix composites and spray-formed submicron grain size in situ composites.

4.3.3. Process technology activities

Both Material Electrochemical Research Corporation and Metal Matrix Cast Composites, Incorporated are engaged in developing quality low-cost FGACs through SBIR programs. Both collaborators are developing novel preform and casting techniques flexible enough to satisfy a variation of design gradients and morphologies. Cost, flexibility and quality are the keys to success for these programs. Feasibility in producing sizable and thick section FGACs has been demonstrated (Figs. 7 and 8).

Promising ballistic performance has been demonstrated in these FGACs. Future goals include improvement in process optimization and control in the through-thickness distribution of particulates and whiskerization in the FGACs.

5. Concluding remarks

An overview of the purpose, structure, and goals of the FGAC-Focussed Research Team is previously provided. The FRT concept takes full advantage of the ELC philosophy and leverages small business innovative research opportunities. At first glance, this seems like a way to repackage research, but, in fact, it is a response to the recent change in global affairs. Basic research is needed, more than ever before, to nucleate new concepts and unorthodox solutions for future warfighting capabilities. This, however, is curtailed by the prospect of a continual eroding budget coupled with the post-Cold War military draw-down. A major shift from the traditional paradigm of pursuing research is necessary to secure the future technological lead during this challenging period. Instead of (a) seeding a number of research efforts; (b) incubating a selected number of high-payoff potentials; (c) transitioning these potentials into in-house activities; and then (d) bringing them to specific applications for the

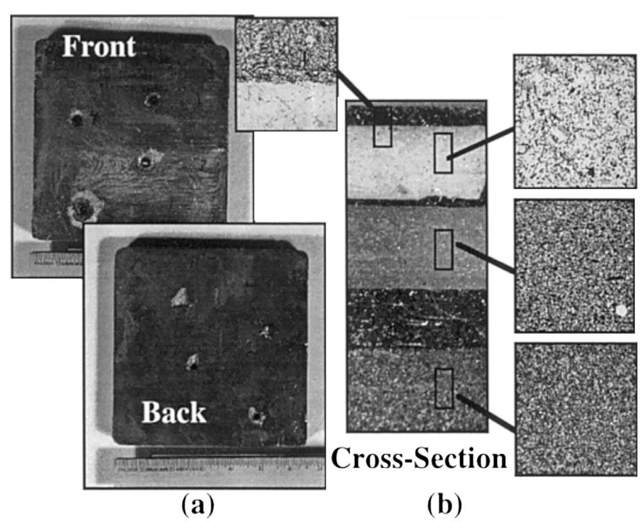

Fig. 8. (a) Ballistic plate and (b) cross-sectional micrograph of aluminum oxide particules-reinforced aluminum laminate composites.

Army, a cohesive research program linking basic science to technology development conducted in parallel is the roadmap to success. This is possible through tight collaborations at the individual investigator level. The fluidity of today's political situation necessitates the need to execute and promote the importance of collaborative research in overcoming fundamental barriers in attaining a tangible performance requirement. Defense research laboratories are now, more than ever before, highly focused on conducting basic research, applied research, technology demonstration, and delivery of technological advantage to the warfighter in a comprehensive and near-seamless process

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