REACTIVE NANO-LAYERED BIMETALLICS FOR NON-DESTRUCTIVE DEBONDING OF MUNITION COMPONENTS

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ABSTRACT

The U.S. Army Research Laboratory (ARL) has demonstrated that a bonded bimetallic stratified nano-composite structure can, with a small electrical or thermal initiation, completely and quickly (<10 ms) separate two adhesively coupled surfaces. The bimetallic layers are typically composed of metals such as nickel/aluminum or titanium/aluminum that are vapor deposited onto surfaces. To date these bi-layer films have been deposited onto brass, aluminum, graphite composite, and mylar. Unlike other debonding approaches, this method allows for fast, remote and on-command separation of structurally bonded materials. ARL has engineered the materials to create directly applied reactive nano-coatings that allow new methods of assembling and separating structural systems. The technology is being developed to meet critical design needs for development of a non-lethal frangible 155MM artillery munition.

BACKGROUND

ARL has teamed with the Armaments, Research, Engineering, and Development Center (ARDEC); the Edgewood Chemical and Biological Center (ECBC); Program Manager (PM) Close Combat Systems; General Dynamics; and others to develop and field a non-lethal artillery munition that can be used to shape the battlefield. A key element to fielding this non-lethal munition is the ability to reduce the impact damage of the payload vehicle. A fragmented case design can meet the impact requirements for this munition (Garner et al, 2004). However, to selectively fragment the non-lethal case, a technology is required that allows a structural load to be carried through the munition aeroshell until payload delivery, after which, structural bonds through the adhesive can be rapidly degraded thereby fragmenting the aeroshell in a controlled, predictive manner.

Although commercial technologies, such as ElectRelease (EIC, 1999), are available for separating adhesive layers, the design elements associated with utilizing the commercial adhesives are inconsistent with the mission needs. ARL has invested significantly in the development of various debonding technologies in support of RAH-66 Comanche and other future military platforms. As a leading designer of debonding technologies, ARL has developed three critical debonding materials systems, including shape memory alloy (SMA) debonding, chemical foaming agent adhesive degradation, and reactive nano-composite debonding. SMA debonding works by applying a stress load on the adhesive interface, resulting in a high strain field in the adhesive/substrate interface that effectively weakens the bond strength to near zero. The chemical foaming agent degradation method applies the principals of foam manufacturing to an adhesive system, allowing a foaming agent to “erupt” at a selected temperature. The blowing of the foam induces through-thickness degradation of the adhesive that reduces the mechanical load carrying performance of the adhesives to extremely small loads. The nano-composite approach causes a physical change of the metal interface to mechanically de-couple the metal surface from the adhesive. The mission needs for the non-lethal munitions effort dictated that the disbonding event occur quickly, be easy to initiate, and provide enough load capability for the launch event. The reactive nano-composite approach was selected as the most viable technical design. The decision to further develop the reactive nano-composite application was based on the flexibility of the design, which allows the incorporation of numerous adhesive materials, providing higher probability of success. Additionally, the reactive nano-composite provides the highest reaction rate of all the known design strategies in the literature and in commercial practice, without employing heavy equipment. The reactive nano-composite debond technology is applicable to the non-lethal munitions mission due to the high structural loading and high rate of travel in the proposed non-lethal munition. To facilitate additional capability and provide 100% separation of bonded systems, ARL has engineered the reactive nano-composite as a freestanding foil structure, i.e., nanofoils, and as reactive coatings, i.e., nano-coatings, that can be directly incorporated into the munition designs.

NANO-LAYERED BIMETALLIC DEBOND TECHNOLOGY

The reactive nano-layered bimetallics are typically produced by sputter-deposition of alternating 10-100

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nanometer thick bilayers of metallic or inter-metallic materials onto optically polished surfaces, such as silicon, glass, or cleaved mica (Barbee and Weihs, 1996). The bilayer constituents and thicknesses can be chosen on the basis of their reaction temperatures and their propagation rates [typically 1-10 m/s], where the propagation rate is typically inversely proportional to the bilayer thickness. Nano-composite reaction stability appears linked to the sharpness of bilayer interfaces on the nanometer scale and the total number of bilayers (Mann et al, 1997). 'Stable' infers that the nano-composite reaction wavefront self-propagates until the medium is completely consumed and 'unstable' refers to the reaction wavefront self-extinguishing. Typical bilayer systems are aluminum/nickel (Al/Ni) or aluminum/titanium (Al/Ti) with the total bilayer thickness in the 0.1-0.3 micrometer range. The nano-layered bimetallic, or nano-composite, system is depicted in Fig 1.

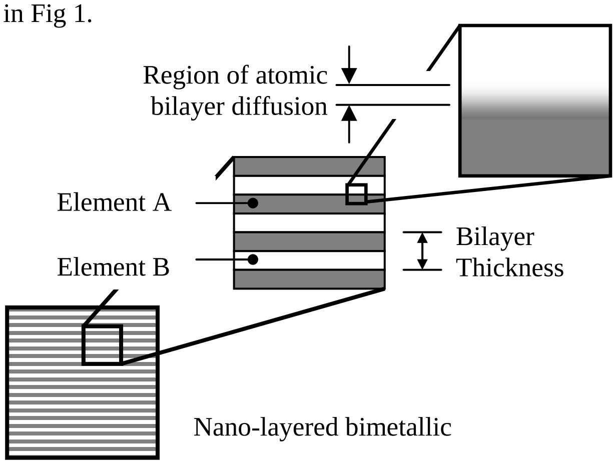


Fig 1: Nano-composite illustrating composition, bilayer thickness, and bilayer diffusion region.

The nano-layered bimetallic systems were first developed for joining applications (Barbee and Weihs, 1996). In joining applications, the stratified nano-layered bimetallic structure is cleaved from a polished deposition surface to produce a freestanding, reactive structure - suitable for insertion between components to be reactively joined. For this application, the nano-layered bimetallic is a freestanding material and is referred to as a nanofoil. Similarly, the nano-layered bimetallic debond approach was first demonstrated using the stratified nanofoil structure sandwiched in the bondline as depicted in Fig. 2 (Minnicino and Sands, 2004).

The nano-layered bimetallic debond approach was expanded in the development of reactive coatings that are applied directly onto metallic/non-metallic substrates of interest by direct-current magnetron sputtering (DCMS). In this configuration, the nano-composite systems are referred to as nano-coatings. The nano-coating debond approach is illustrated in Fig. 3.

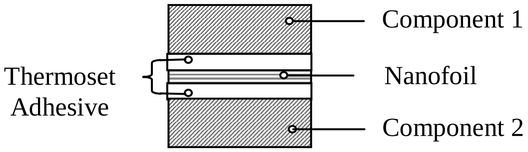


Fig. 2: Debonding approach where freestanding nano-composite (nanofoil) is sandwiched between the adhesive layers of the bondline

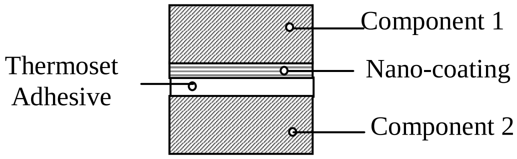


Fig 3: Nano-coating debond approach where the nano-composite is directly deposited on Component 1.

The bilayer thicknesses and regions of atomic diffusion were investigated using Ruthererford Backscattering Spectrometry (RBS). An energy spectrum of 2 MeV He ions elastically backscattered via RBS from a 4-period bilayer stack of Ni/Al nano-composites deposited by DCMS is shown in Fig. 4. The periodic variation in yield from the two constituents can be directly converted into their relative thicknesses and interfacial diffusion, which governs exothermic rates and initiation sensitivities (e.g., nano-composite stability) (Blobaum et al, 2003). The ability to rapidly and accurately measure the multilayer structures on a nano-scale greatly facilitates optimization of bilayer deposition processing for achieving the desired propagation rates and initiation levels.

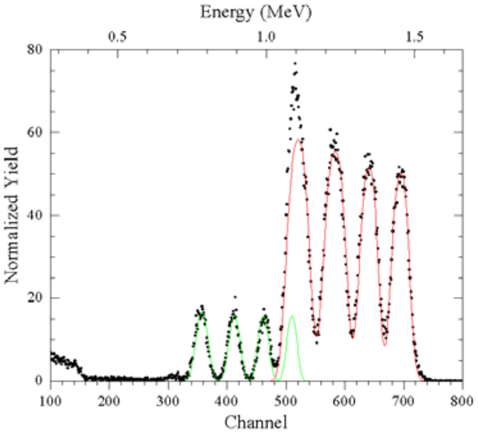


Fig 4: RBS spectrum of ARL 4-period array of sputtered Ni [85 nm]/Al [45 nm] nano-layer stack.

RESULTS & DISCUSSION

The nano-composite debond technology has both commercial and military applications. The nano-composite debonding technology is of primary importance to ARL's development of a non-lethal frangible 155MM artillery munition aeroshell seen in Fig. 5. ARL's recent efforts have focused on integrating the debond technology into the aeroshell. During the integration process, the designer must be aware of some important considerations, including the bond strength and the initiation energy threshold.

A commercially available free-standing nanofoil and an ARL directly deposited nano-coating both show good adhesion and have both been demonstrated as a feasible debond technology. However, these two rapid and complete debond approaches have their advantages and their disadvantages.

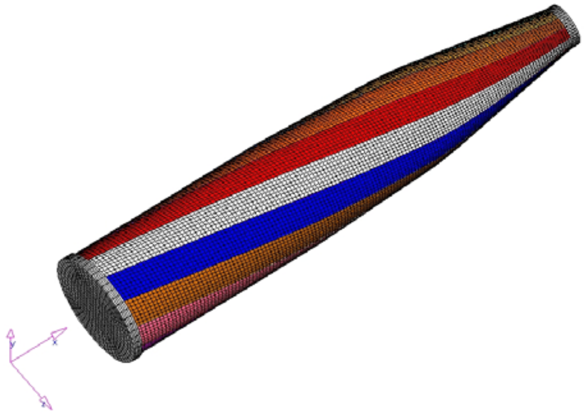


Fig. 5: Finite element model of ARL frangible aeroshell concept.

The freestanding nanofoil approach requires judicious selection and application of adhesive on both sides of the nanofoil positioned between the components. Testing the lap-shear strength of the joint using aluminum substrates indicated that the nanofoil bonded well with the adhesive. The observed failures were cohesive. The results of this test are shown in Table 1.

Besides bond strength, this arrangement does have other difficulties. One difficulty is that the nanofoil has to be sufficiently thick for placement purposes. In our research, it was found that thin nanofoils (~25 micrometers thick) often fractured either during placement of the nanofoil into the bondline or during adhesive cure due to the small pressure applied to achieve strong bonds. Nanofoil fracture potentially causes multiple reaction wavefronts or prevents the propagation of a reaction wavefront. These situations are illustrated in Fig 6. In Fig 6a, looking down onto the outer surface of the nanafoil, the nanofoil is partially cracked. In this case, the reaction wavefront propagates around the crack. In Fig 6b and Fig 6c, the nanofoil has completely fractured into two separate pieces. In these cases, the reaction wavefront can "arc" across the crack and continue as depicted in Fig 6b or become "arrested" at the crack as seen in Fig 6c. As Fig 6 suggests, the controlling difference between Fig 6b and Fig 6c seems to be the size of the separation between the two nanofoil pieces, as experimentally observed.

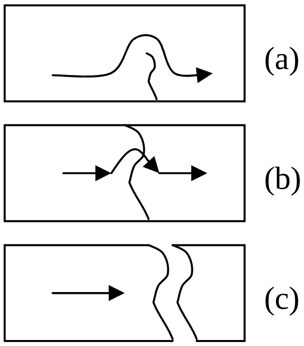


Fig. 6: Thin nanofilm fracture and possible reaction wavefront paths.

Controlling adhesive flash in paste and film adhesives is a difficulty for both nanofoils and nano-coatings; however, it is a larger problem for nanofoils. With paste adhesives, the pressure is applied uniformly and excess resin in the bond line is forced out of the interfacial area to the thickness offered by bond line control agents. During this flow, the nanofoil is floating on the resin bed, and alignment issues result. Excess resin outside of the film surface area, can bridge the sample surfaces together, providing additional bond strengths limiting easy separation after the reaction of the foil. However, this difficulty is often minor and although the pieces are not fully debonded, the residual strength is reduced. Sensitivity of the foil occasionally resulted in premature ignition of these foils during the process of removing the excess flash. A typical example of adhesive flash is shown in Fig 7 on a substrate of a lap-shear joint. This figure shows how the adhesive flow allows bridging between the substrates, as evidenced by thickened edges. The excess adhesive bonds to edge surfaces of the lap joint.

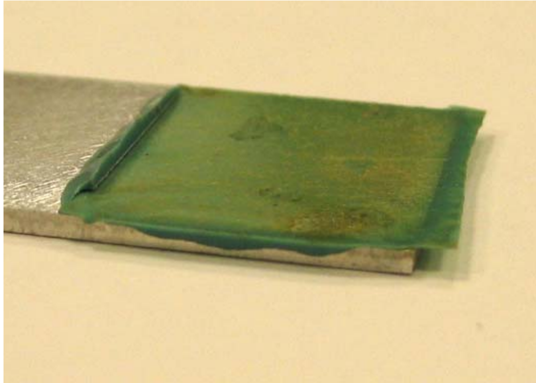


Fig 7: Test specimen showing adhesive flash

The direct deposition nano-coating approach is beneficial because it reduces the number of interfaces (adhesive layers), which increases performance, reduces bond line thickness, and greatly simplifies component fabrication. This debond approach is depicted previously in Fig 3. Additionally, the nano-coating can be significantly thinner and remain workable because the substrate provides the stiffness. Another reason is that adhesive flash can be overcome since the coating can be designed larger than the adhesive contact area. Unlike the nanofoil approach, the nano-coating approach has the disadvantage of needing the substrates at the time of deposition and having deposition equipment capable of depositing uniformly over the bond-area, which can be quite large and have significant curvature.

Of primary concern with respect to the nano-coating approach was the interfacial strength of the coating to the substrate, specifically composite substrates. To determine the level of adhesion between the nano-coating and the composite substrate, six samples were deposited with different substrate surface treatments before the deposition process. Also, the outer material was varied to determine its effect on interface strength. The experimental matrix is seen in Table 2. In samples A, B, D, and F, the composite substrate failed between plies. Testing indicates that plasma cleaning increases the adhesion strength between the nano-coating and the adhesive. Testing also indicates that Ti outer layer nano-coatings adhere better to the composite substrate compared to Al outer layer nano-coatings. This is consistent with known issues of galvanic corrosion between aluminum and carbon fiber (Boyd et al, 1991).

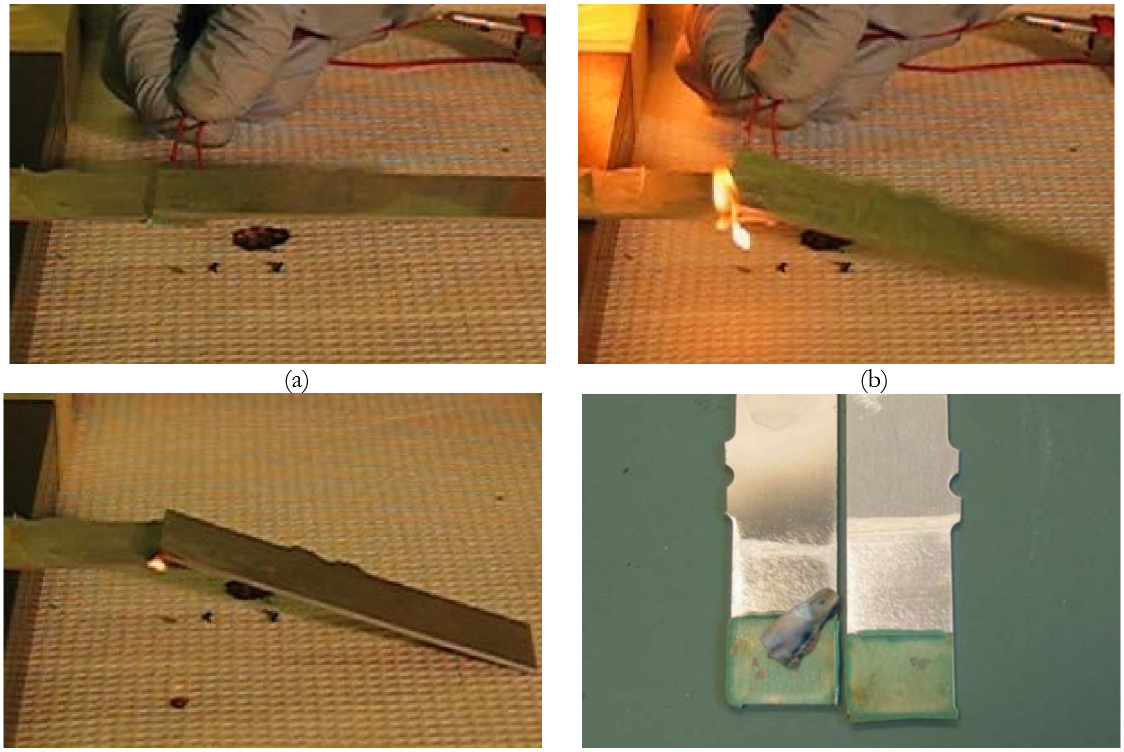
The general debond process is shown in Fig. 8. Specifically, Fig. 8 shows the nanofoil debond approach where the nanofoil was sandwiched between two adhesive layers as described by Fig. 2. To initiate the reaction, two leads were connected to a 9V battery. These leads were then placed in contact with the nanofoil's edge at the bondline as shown in Fig. 8a, thereby completing the electrical circuit. Fig. 8b shows that the reaction propagates until all of the nanofoil is consumed. The result is complete failure of the bondline and separation of the two substrates as shown in Fig. 8c and Fig. 8d.

Table 1: Nanofoil adhesion tests

Sample	Test Description	Max Load (lbf)	Stress (psi)	Average Stress (psi)	Failure Type
A		1216	2661		Cohesive
B	Incomplete Adhesive Coverage	678	-		Adhesive
C		911	2064	2103	Cohesive
D	Bowed Lap Sample	354	-		Cohesive
E		712	1583		Cohesive
A1	Condition @ 250° F for 1 hr	1258	2810		Cohesive
B1	Condition @ 250° F for 1 hr	937	1980		Cohesive
C1	Condition @ 250° F for 1 hr	1309	2361	2406	Cohesive
D1	Condition @ 250° F for 1 hr	1103	2084		Cohesive
E1	Condition @ 250° F for 1 hr	1248	2797		Cohesive

Table 2: Nano-coating adhesion tests

Sample	Surface Treatment	Outer Layer	Max Load (lbf)	Stress (psi)	Failure Type
A	Plasma clean Ar-O_2	Control	477	1212	Substrate
B	Plasma clean Ti w/ magnet	Ti	300	1088	Substate
C	Plasma clean Ti w/o magnet	Ti	477	1612	Cohesive
D	Plasma clean Al w/o magnet	Al	398	738	Substate
E	None	Ti	346	1208	Adhesive
F	None	Al	353	1048	Substate



(a) (b)

(c) (d)

Fig 8: Demonstration of nanofoil debond technology in a lap shear joint configuration. (a)-(c) are discrete frames of the debond event and (d) is the resulting debonded aluminum substrates and consumed nanofoil.

CONCLUSION

The research presented demonstrates the importance of applying engineering design principles to improve commercial products for military applications. The existing technology in reactive nanofoil development was investigated and used to demonstrate feasibility of rapid separation of bonded structures. The presented study demonstrates the feasibility of manufacturing the nanofoils and nano-coatings, and principles for applying this technology to provide separation of bonded structures, including the non-lethal 155MM artillery aeroshell. The characteristics of the nano-coatings and the value of nano-coating capability for military specific applications are reviewed. A qualitative assessment of materials performance is also presented.

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